Methods for Assessing Available Wind Primary Power Reserve

Ye Wang, Herman Bayem, Maria Giralt-Devant, Vera Silva, *Member, IEEE*, Xavier Guillaud, *Member, IEEE*, and Bruno Francois, *Senior Member, IEEE*

***Abstract*—To ensure power system security with very high wind generation (WG) penetration, the participation of wind generators in primary frequency control is essential. Previous studies have shown the technical capability of wind turbines to participate in primary frequency regulation at a wind farm level. In order to analyze, the contribution of wind power to primary frequency regulation at system level one needs to quantify the amount of primary reserve from conventional sources that can be displaced. This amount of reserve depends on the aggregated variability of WG during each reserve provision time-interval. This paper presents a statistical approach to assess the impact of intrahour wind power variability on the volume of primary reserve that can be provided from WG. Furthermore, the effectiveness of different reserve allocation strategies is compared. The proposed approach is applied to a case study based on real-wind data measurements from the French island of Guadeloupe. Results show that for a small isolated system neglecting WG intrahourly variability leads to an overestimation of its contribution to primary reserve.**

***Index Terms*—Instantaneous available reserve, primary frequency control, primary reserve, reserve allocation, wind farms, wind variability.**

I. Introduction

WIND generation (WG) capacity is increasing over the last years mainly, partly, due to political incentives for the development of low carbon generation. This development has been particularly important in European power systems [1]. The integration of large penetrations of WG, due to its variability, uncertainty, and nonsynchronous grid connection, poses several technical challenges such as frequency control problems [2]. The variability and uncertainty of WG increase the need for operational flexibility and reserve requirements, respectively [3], [4]. Moreover, during periods of high WG, less conventional synchronous generators are required to balance generation and demand. The fact that WG displaces conventional synchronous generation reduces both the total system inertia and the number of groups available to provide frequency response services. This situation is more critical in island systems that have a limited number of conventional power plants and a relatively small kinetic energy base [5].

As a consequence, in order to integrate WG and ensure system security and reliability, newly connected wind turbines (WTs) are required to contribute to primary reserve [6]. This capability is currently required by the grid code of several systems, such as the Irish and Nordic systems [7], [8]. Moreover, if WG should be curtailed because of system constraints such as minimum inertia, reserve provision, and network congestion, the curtailed energy can be used to provide upward reserves. The benefits of using WG to provide frequency regulation and reserves have been detailed in [9]. Some independent system operator/regional transmission organization (ISO/RTO), as Denver-based Public Service Company of Colorado (PSCO) [10], have already applied it.

In recent years, significant research efforts have been done in the design of primary frequency controllers for wind plants [11], [12]. As a result, the technical capability of WTs for providing primary frequency regulation has been proved by different studies and demonstration projects [13], [14]. Different control methods, such as a speed-droop control [15] and fuzzy logic control [16], are used as primary frequency controllers that enable WTs to maintain a power margin and to release the stored reserve to the grid during low-frequency conditions by adjusting their active power according to the frequency variation [17], [18]. Furthermore, the obtained fast response from WTs increases the system robustness by reducing frequency excursions following to grid disturbances [28]. Previous research works about the contribution of the WT primary frequency control are based on dynamic simulations performed over a time horizon of several minutes and have effectively confirmed the technical capability of WG's participation to frequency control.

The problem of quantifying the aggregated volume of primary reserve that can be provided by the WG fleet has received less attention. In fact, in order to quantify the contribution of WG primary frequency control to system security, one needs to estimate the amount of conventional generation primary reserve that can be displaced by WG.

The variable nature of WG output impacts the amount of reserve that can be provided by WTs at different periods. Moreover, the uncertainty in the forecast of WG at different time-scales adds further uncertainty to the reserve provided by WTs. The impact of wind forecast errors depends on the lead-time between the decisions of reserve placement and can be

Manuscript received April 17, 2014; revised August 25, 2014; accepted October 26, 2014. Date of current version December 12, 2014. This work was supported by Electricité de France Recherche & Développement (EDF R&D), Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME), and Maitrise Energétique Des Entrainements Electriques (MEDEE) 10. Paper no. TSTE-00159-2014.

Y. Wang, H. Bayem, M. Giralt-Devant, and V. Silva are with the Electricité de France (EDF) Division, Economie, Fonctionnement et Etudes des Systèmes Energétiques (EFESE) Department, Electricité de France Recherche & Développement (EDF R&D), Clamart 92141, France (e-mail: ye.wang@edf.fr).

X. Guillaud and B. Francois are with the University Lille Nord de France, Lille F-59000, France, and also with the Ecole Centrale de Lille (ECLille), L2EP, Villeneuve d'Ascq F-59650, France.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSTE.2014.2369235

reduced by the possibilities of redispatch closer to real time and the increase in the wind forecasting accuracy [19].

Recent works have investigated the wind reserve allocation at a single farm level. For example, Chang-Chien *et al.* [21] proposed to allocate primary reserve to each turbine according to the available wind speed. However, the ancillary services, especially the frequency control services, should be managed from a system point of view by taking into account the wind smoothing effect. In addition to frequency response dynamics, other requirements such as the minimum time interval that the primary reserve service needs to be held for needs to be taken into account. For example, in the ENTSO-E synchronous system, the deployed primary reserve must be held for at least 15 min for security concerns [20]. This time interval is likely to increase to 30 min in the future. The variability of WG during the reserve deployment period will impact the volume of primary reserve that can be expected from variable generation sources, such as WG.

The allocation of primary reserve to WG cannot be done in the same way as for conventional generation since wind output experiences significant variability. For example, the reserve allocation obtained from a security-constrained unit commitment (SCUC), performed a day ahead for hourly time-steps [22], needs to be converted into a "firm" wind reserve level, given wind intrahourly variability. Failing to do so can lead to a risk of overestimating the volume of primary reserve that can actually be provided from WG.

This paper addresses the impact of wind power variability between two SCUC time-steps, using an approach based on statistical analysis of WG variability. In order to analyze the effect of wind variability, a perfect forecast of wind output is assumed. This allows us the assessment of the maximum amount of "firm" wind primary reserve that meets the expected technical requirements. Uncertainty in the forecast can be included in the future as an additional layer to this analysis.

A practical example of the estimation of "firm" wind primary reserve from WG is quantified by using the proposed approach and real wind data measurement for the French island of Guadeloupe. The efficiency of using different reserve allocation strategies to handle WG intrahourly variability and maximize the amount of wind primary reserve is also analyzed.

The paper is organized as follows. In Section II, the amount of instantaneous wind power reserve is estimated by considering wind variability within a 15-min interval and with two different reserve allocation strategies. In Section III, the proposed methodologies are validated and further explored through an island power system case study. Section IV compares the use of a combination of reserve allocation strategies to the use of each strategy separately. Sections V and VI present the discussion and conclusion, respectively.

II. Instantaneous Wind Power Reserve

A. Strategies for Reserve Allocation

Wind upward reserve strategies consist in using the part of the maximum output that is curtailed, as shown in Fig. 1, to displace some of the primary reserve from other sources.

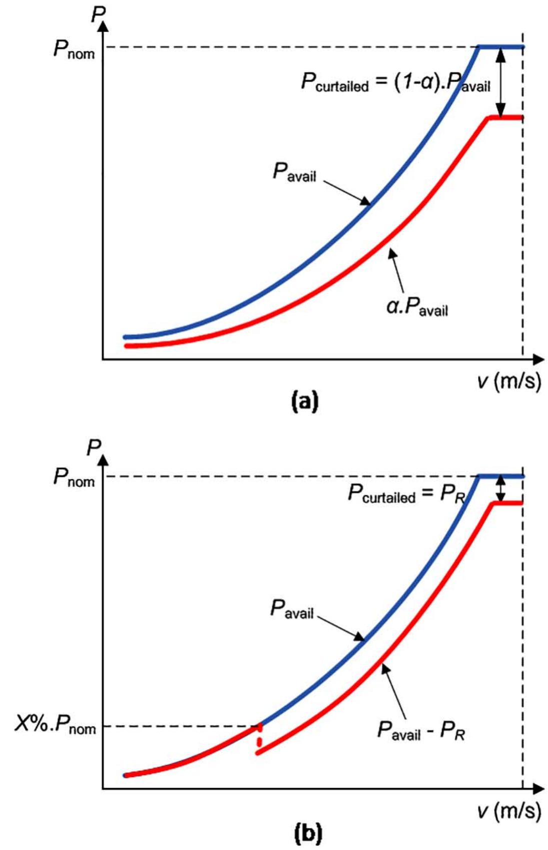


Fig. 1. Operating principle of both reserve allocation strategies. (a) PCS and (b) CCS.

The first reserve allocation strategy proposed is the "proportional curtailment strategy" (PCS). This strategy leads to a curtailed power ($P_{\mathrm{curtailed}}$) proportional to the maximum available power (P_{avail}) [Fig. 1(a)]. The parameter α may vary theoretically from 1 (no reserve) to 0 (total curtailment)

$$P_{\text{curtailed}}(t) = (1-\alpha)\cdot P_{\text{avail}}(t). \tag{1}$$

Dynamic simulations have shown that with an adequate controller, WTs are able to keep a percentage of their available power as primary reserve throughout all the operating zones [23]. The value of α can be defined so that a certain amount of wind reserve is provided. This amount of reserve can be obtained from system stability studies or an SCUC.

The PCS is easy to implement and provides a continuous variation of the reserve power. The curtailed power changes according to wind variability.

The second strategy is called "constant curtailment strategy" (CCS). The wind power is curtailed in order to get a constant reserve power as for conventional generators [Fig. 1(b)]

$$P_{\text{curtailed}} = P_R. \tag{2}$$

This power curtailment is possible over a certain output level. For example, if the WG is less than $X\%$ of the nominal power (P_{nom}), no reserve will be provided in this low-power operating zone. The technical feasibility of the CCS should not raise problems, as it is part of the regulation capacities required by the Danish TSO for the "Horns Rev" offshore wind farm [24].

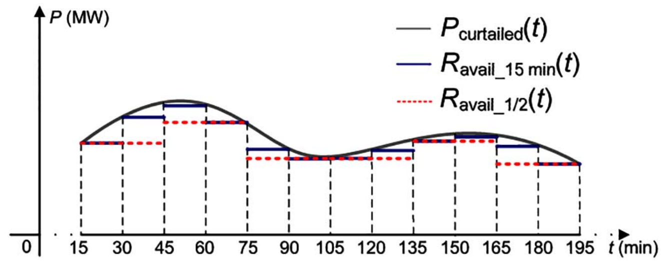


Fig. 2. Wind variability while providing reserve from wind farms with the PCS (for 15-min and 30-min time steps).

The CCS enables a finer control of the curtailed WG; however, its application leads to a discontinuity of the wind farm power generation when enabled.

Therefore, further comparison of these two reserve allocation strategies should be performed by considering the impact of their application on the instantaneous reserve availability.

B. Measuring the Instantaneous Reserve Available

1) Current Rules for All Generators: Traditionally, primary reserve is provided from conventional generators. In the French continental system, this reserve is scheduled a day ahead for every half-hour period. The day-ahead scheduled power setpoints of power plants and primary reserve allocation can be modified in intraday if necessary.

Regarding the technical requirements of primary reserve, French grid codes [25], [26] require that primary power reserve is fully available in less than 30 s and its provision must be held for 15 min, after a power imbalance. The 15-min duration of the primary frequency control is considered necessary to enable the restoration of the primary power reserve by the tertiary frequency control [27].

The application of current rules needs to be analyzed when WTs contribute to primary reserve, as their curtailed power is variable during each dispatch step, especially when the PCS is applied.

In order to ensure the availability of wind reserve during at least 15 min, it is essential to consider the minimum value of the curtailed wind power during each dispatch time step, as illustrated in Fig. 2. Thus, the notion of the instantaneous available reserve ($R_{\text{avail\_}H}$) for the corresponding scheduling period (H) can be defined as

$$R_{\text{avail\_}H} = \text{MIN}(P_{\text{curtailed}}[t_0, t_0 + H]). \tag{3}$$

This means that for a given time interval (15 min, half-hour, 1 h, etc.), a constant amount of wind reserve should be scheduled by taking into account the lowest wind power output expected during each time interval.

2) Definition of the Efficiency Indicator for Reserve Allocation: Considering the example of Fig. 2, it is possible to see that instantaneous curtailed wind power cannot be directly translated as the "firm" available reserve that meets the technical requirements. The difference between the curtailed power (grey line) and the "firm" available reserve (Fig. 2) (blue and red lines) represents the amount of curtailed generation that does not contribute to the "firm" available reserve ($\text{MWh}_{\text{curtailed,unused}}$). This results in a loss to the wind farm operators and to the system. In order to measure the quality of the WT reserve allocation strategies, an efficiency indicator (η) is proposed

$$\eta = \left(1 - \frac{\text{MWh}_{\text{curtailed,unused}}}{\text{MWh}_{\text{curtailed,total}}}\right) \times 100\% \tag{4}$$

where $\text{MWh}_{\text{curtailed,total}}$ is the total curtailed WG during the scheduling interval.

For a given reserve allocation strategy, the higher the corresponding efficiency indicator, the lower the "unused" curtailed energy, and therefore the better is the strategy. The efficiency is used in Section III as a metric to compare the performance of the two proposed strategies.

III. Case Study on an Island Power System

A. Data and Assumptions

The approaches described in Section II are applied to a case study based on the French Guadeloupe Islands. This archipelago is located in the eastern Caribbean Sea and is composed of five interconnected islands. The installed wind capacity was about 27 MW in 2010 and the load demand is 260 MW. Currently, according to the French feed-in tariff and purchase obligation scheme, renewable energy sources have priority in the dispatch and do not participate in the frequency control. In order to benefit from the high potential for wind energy in this Island, a previous study showed that some primary reserve has to be supplied by wind farms. This is true if we want to operate the system above a certain "critical" wind penetration rate. This is needed since for these penetration rates, the remaining conventional generators cannot provide enough reserve to cover the most critical incident and the system will encounter dynamic frequency problems due to the reduction in inertia [28].

B. Guadeloupe's Wind Power Variability

The statistical studies described hereafter are based on the analysis of historical instantaneous WG data from three wind farms. Data were recorded with 15-min steps from January 1, 2011 to March 31, 2011. It should be noted that our study is based on a rather limited dataset and the results presented have the purpose of validating the methodologies by using real measurements.

The dataset is enough for the purpose of characterizing the potential of the instantaneous available reserve that can be provided from a single wind farm and from a group of farms (referred to as "aggregated wind farm"). These three farms with 2.1-, 3-, and 3.3-MW rated capacities present a good geographical dispersion in the archipelago. This diversity leads to an important smoothing effect at the aggregated farm level. The installed capacity (IC) of the "aggregated wind farm" (8.4 MW) represents about one-third of the WG capacity of Guadeloupe (27 MW).

The cumulative distribution function (CDF) of the Guadeloupe's 15-min wind variability is shown in Fig. 3.

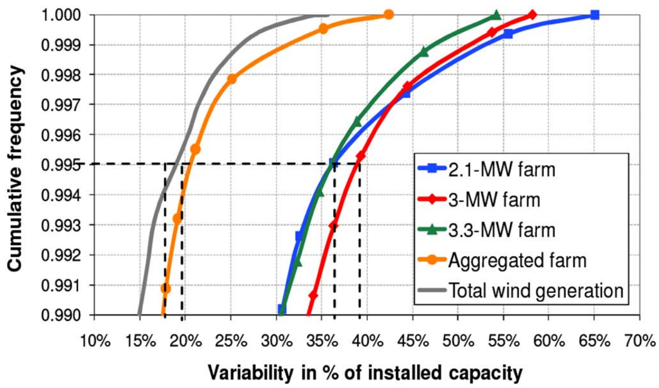


Fig. 3. CDF of wind power fluctuations at 15-min intervals (zoom on the last percentile).

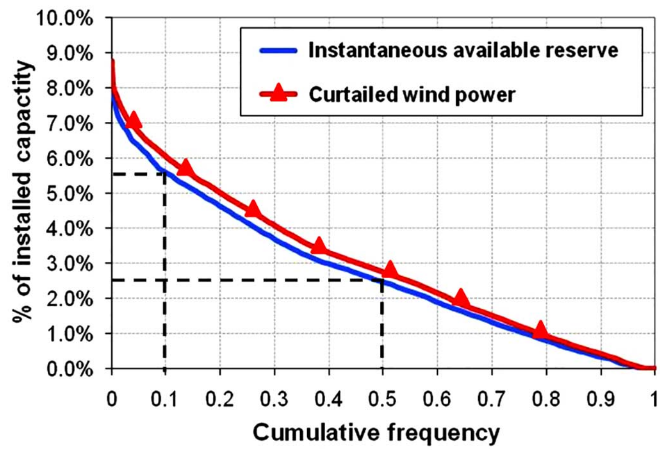


Fig. 4. Duration curve of the instantaneous available reserve and of the curtailed power of the aggregated wind farm (application of the PCS).

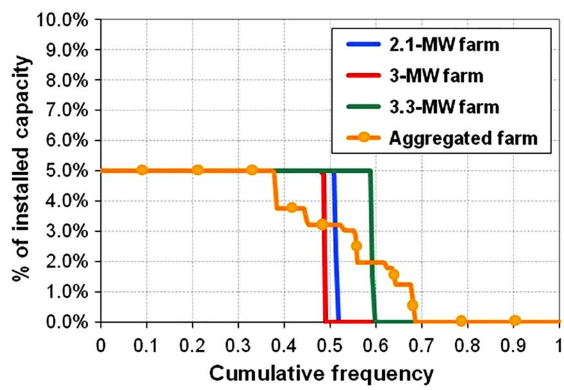


Fig. 5. Duration of the instantaneous available reserve of the three wind farms and of the aggregated farm (application of the CCS).

The results reveal that 99.5% of the 15-min power fluctuations of an individual wind farm can reach more than 35% of its IC. The 15-min fluctuations are reduced to 20.5% and 19% of the IC for the aggregated farm and for the whole island, respectively. The variability of Guadeloupe's wind power is significant due to the small size of the island.

The variability of the "aggregated farm" is close to that of the total grid-connected WG and much lower than that of a single WF. Hence, in order to take into consideration the geographical smoothing effect, it is important to perform system-wide studies, even for small isolated power grids.

C. *Potential of Instantaneous Available Reserve*

The performance of the WT primary frequency control is characterized by assessing the maximum instantaneous "firm" available reserve, obtained by using different strategies. This "firm" reserve takes into account the possible "waste" of curtailed energy due to wind variability inside a scheduling interval. The objective is to find out which strategy leads to a higher instantaneous "firm" reserve, while incurring the same energy curtailed to the "aggregated" wind farm.

The PCS was first applied by considering a curtailment of 10% of the maximum instantaneous available WG of the "aggregated farm." As wind power varies, the obtained curtailed power also varies during each 30-min dispatch time step. In order to ensure the "firmness" of wind reserve, the available reserve was calculated by considering the minimum value that is observed for each 30-min period [cf. Fig. 2 and (3)]. The amount of reserve is, therefore, smaller than that of the curtailed power, as shown in Fig. 4.

The analysis of the "firm" reserve contribution of the aggregated wind farm (Fig. 4) with the PCS with a curtailment of 10% of the IC shows that the amount of reserve (that can be allocated to wind) is higher than 2.5% of the IC of the aggregated farm during 50% of the time and higher than 5.5% of the IC during 10% of the time.

In order to be able to compare the CCS strategy with the PCS, we define the strategy parameters, so that the same amount of curtailed energy is obtained. One possible combination of parameters is to curtail a constant power equal to 5% of the rated capacity of each wind farm whenever its power output is higher than or equal to 20% of its rated power, i.e., 0.2 p.u. (per unit). Thus, the total curtailment from the three wind farms, during the considered period (from January to March), is almost identical using both reserve allocation strategies (542 MWh with the PCS, 539 MWh with the CCS).

With the CCS, the amount of reserve provided by a single wind farm is binary. It is equal to either 5% of IC (i.e., the value of the curtailed power) or zero. Since the three sites are subject to different wind speeds, the reserve availability is switched at different frequencies. The duration of the "firm" available reserve of the aggregated farm includes, therefore 2^3 "steps," which correspond to the number of discrete states of individual farm's reserve. However, in practice, wind reserve should be allocated to each turbine. For a given number of turbines (n), the "real" reserve characteristic would contain 2^n "steps" and would thus be much smoother. From the instantaneous available reserve curve (shown in Fig. 5), we can conclude that the implementation of the CCS leads to a reserve amount of the aggregated farm superior to 3% of its rated power during 50% of the time and a constant reserve amount (equal to 5% of IC) during 37% of the time.

Since the WG variability of the "aggregated farm" is quite close to that of the total WG in the system (Fig. 3), it is assumed that the results could be generalized to all WFs in

TABLE I
ESTIMATED AMOUNT OF INSTANTANEOUS AVAILABLE WIND RESERVE ON THE GUADELOUPE ISLAND

	PCS		CCS	
Cumulative frequency (%)	50	10	50	37
Instantaneous available reserve (p.u.)	> 2.5	> 5.5	> 3.0	= 5.0
Reserve amount in (MW= with 70 MW of IC	> 1.75	> 3.85	> 2.1	= 3.5

TABLE II
EFFICIENCY INDICATORS OF THE RESERVE ALLOCATION STRATEGIES

	2.1-MW farm (%)	3-MW farm (%)	3.3-MW farm (%)	Aggregated farm (%)
η_{PCS}	86	85	88	91
η_{CCS}	90	88	91	91

the Guadeloupe Island (under the same average wind speeds). For example, as shown in Table I, for the future scenario with 70 MW wind capacity, the potential of the instantaneous available reserve that could be provided by WG depends on the strategy:

1) with PCS is greater than 3.85 MW for 10% of the time. This contribution represents more than 15% of the minimum primary reserve currently required (about 25 MW);
2) with CCS is equal to 3.5 MW for 37% of the operation time, i.e., 14% of the primary reserve requirement.

This study shows that WG can provide a significant potential of instantaneous primary reserve in spite of its short-term variability. With an expected considerable IC, the contribution of wind power to power reserve could, therefore, cover, at least in part, the growth of the grid minimum reserve requirements.

IV. COMPARISON OF THE RESERVE ALLOCATION STRATEGIES

A. Reserve Quantification Over an Operating Period

1) Calculation of Efficiency Indicators: As a first step, it is assumed that power reserve is distributed to WTs all the time throughout the whole studied period. As explained before, in order to curtail the same amount of energy in the "aggregated farm" with both strategies, we require a curtailment of 10% of the instantaneous available power with PCS and 5% of each individual farm IC, for periods when its output exceeds 0.2 p.u. with CCS.

The efficiency indicators for each strategy, for the aggregated farm and for individual WFs, were first calculated according to (4), and are shown in Table II. With the PCS, the reserve allocation efficiency, at the aggregated farm level, is higher compared to that at a single farm level. With CCS, the efficiency is almost identical for the aggregated and WF levels. This shows that PCS benefits more from the smoothing effect, therefore reserve allocation at a large power system level using this strategy would be more efficient.

2) Definition of the Average Reserve and Application With Wind Reserve Provided During All Scheduling Periods: The

TABLE III
COMPARISON OF THE RESERVE ALLOCATION STRATEGIES WITHIN THE AGGREGATED WIND FARM DURING THE OVERALL STUDIED PERIOD

	Curtailed production (MWh)	Average reserve (% of installed capacity)	Efficiency indicator (%)
PCS	542	2.7	91
CCS	539	2.7	91

duration characteristic of the instantaneous "firm" available reserve provided with both reserve allocation strategies, depicted in Figs. 4 and 5, cannot be directly compared, as they represent only a statistical distribution of the amount of reserve for a given frequency of occurrence. In order to perform this comparison, an average reserve ($\overline{R}$) is defined as

$$\overline{R} = \frac{\sum R_{\text{avail\_}H \times H}}{\text{Total hours}} \tag{5}$$

with H, dispatch time step.

For an equivalent amount of wind energy curtailment, both strategies lead to a similar amount of primary reserve, during the studied period (Table III) and present almost identical efficiency at the scale of several farms. This comparison is based upon a reserve allocation throughout the whole operating period and shows that both strategies are equally efficient.

Nevertheless, the participation of WTs in primary frequency control can be discussed when their output is low, as other conventional generators are connected to the grid and would provide sufficient primary reserve. However, the system may require an enhancement of primary frequency control due to dynamic constraints and then sources that have a faster response, such as wind farms, are required.

B. Reserve Potential Over the Required Allocation Period With Wind Reserve Participation Limited to High Instantaneous Penetration Scheduling Periods

In this section, the performance of both strategies is assessed when wind reserve is required only during "critical" periods with an instantaneous wind penetration above a critical value.

1) Definition of the Critical Operating Point (OP) of the Aggregated Farm: The core of the method is to identify the required period of wind power reserve allocation, from the overall operating time of wind farms.

In a power system, for a given demand [$d(t)$ in MW], the system operator can identify the corresponding critical instantaneous wind penetration rate τ_c. Above this rate, the contribution of WTs to primary reserve is essential for system security. In fact, when the penetration level of WG is increased, some of the conventional power plants that would have been online without wind power could be disconnected. Beyond an accepted "maximum" penetration rate, the required minimum reserve may no longer be guaranteed with a small number of conventional generators and should be partially allocated to WTs. In order to generalize results, the method detailed in [29] is used to identify the periods for which wind contribution to primary reserve is critical.

TABLE IV
CRITICAL OPs OF THE GUADELOUPE SYSTEM AS A FUNCTION OF THE TOTAL INSTALLED WIND CAPACITY

Wind IC (MW)	70	80	90	100	110	120
OP_c (%)	58.0	50.8	45.1	40.6	36.9	33.8

From an operational point of view, if the power produced by the wind farms (P_w) exceeds the critical WG ($d(t)\ .\ \tau_c$), a certain amount of primary reserve should be provided by the WTs.

The overall OP of the total wind farms can be defined as the ratio of the produced wind power (P_w) to the total IC (P_{inst})

$$\text{OP}(t) = \frac{P_w(t)}{P_{\text{inst}}} \times 100\%. \tag{6}$$

Hence, it can be deduced that WTs should provide primary reserve when the overall operating point ($\text{OP}(t)$) exceeds a critical value ($\text{OP}_c(t)$) that can be defined as follows:

$$\text{OP}_c(t) = \frac{d(t) \cdot \tau_c}{P_{\text{inst}}} \times 100\%. \tag{7}$$

Otherwise, the contribution of wind farms to the primary frequency control could not be mandatory. This method enables the identification of periods corresponding to high WG during which the primary reserve provided by WTs has a greater value for the system operator.

Ideally, from an operational point of view, the critical wind penetration rate should be calculated for each scheduling period by using a multiperiod SCUC solved with a fine time resolution ($<15\,\text{min}$). For small systems, this should be coupled with stability studies. The simplified approach used in this work is, however, deemed sufficient to perform the analysis on reserve allocation strategies that minimize the impact of intrahourly variability.

2) Application: The considered scenario corresponds to a recorded off-peak consumption. As shown in [29], the wind penetration rate in Guadeloupe should be limited to 29% ($\tau_c = 29\%$) in order to guarantee the minimum reserve required for system security. This critical rate is obtained by considering a simplified optimized unit commitment of the Guadeloupe system with linearized frequency limits. This "worst" case corresponds to the minimum load with $d(t) = 140\,\text{MW}$.

According to (7), the critical OP of the Guadeloupe wind farms can be obtained from

$$\text{OP}_c = \frac{140 \times 29\%}{P_{\text{inst}}} \times 100\%\ \text{(Guadeloupe)}. \tag{8}$$

The obtained results for different installed wind capacities are shown in Table IV.

As almost the same 15-min wind variability was observed for the "aggregated farm" and for the total WG (Fig. 3), the critical OP of the "aggregated farm" is assumed to be equal to that of the total wind farms in Guadeloupe for the sake of simplicity. For a given wind IC, primary reserve will be allocated to the three WFs, whenever the OP of the aggregated farm is higher than the above-calculated OP_c.

The increase in the wind IC leads to a higher possibility of having a strong wind power output. Accordingly, the OP_c is smaller for large WG capacities. This means that the higher the IC, the higher the number of scheduling periods when WTs should contribute to primary reserve.

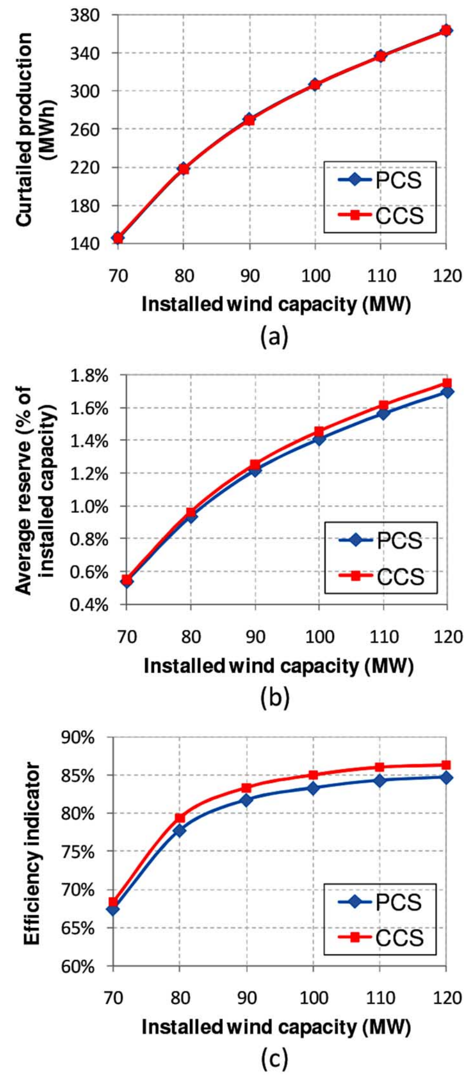


Fig. 6. Comparison of the reserve allocation strategies during the required period [(a) total curtailed WG; (b) average reserve in percentage of the IC of the aggregated farm; (c) efficiency indicator].

To compare PCS and CCS reserve allocation strategies, the same previous parameters are used: 10% of the maximum instantaneous available wind power is curtailed when PCS is applied, while the amount of constant reserve kept with the CCS is adapted for each installed WG capacity. This leads to a total curtailed WG energy, during the required reserve allocation period, equivalent for both strategies [see Fig. 6(a)].

Fig. 6(b) and (c) presents the average upward reserve provided by WG and the efficiency indicators for each strategy. These values increase with the total WG capacity. The results shown in Fig. 6 indicate that both strategies have similar efficiencies.

The obtained results show that both strategies seem equally "efficient" for real-time reserve allocation and allow providing almost the same amount of average reserve by curtailing identical values of WG. The performance of the strategies has

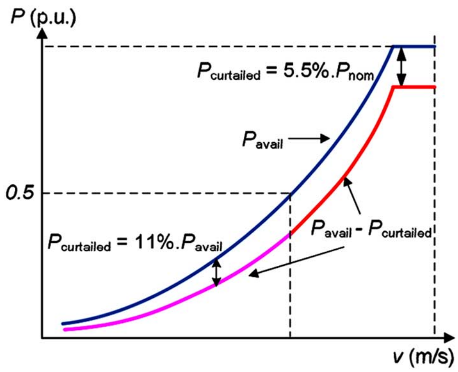


Fig. 7. Proposed combined strategy.

been confirmed for both cases with reserve provided for all scheduling periods or only during periods of high winds.

Each strategy seems to have its own interesting features (see Section II-A). It raises the question whether a combination of both strategies can benefit from the advantages of each strategy and thus leads to a more efficient reserve allocation.

C. Benefits of Combining Reserve Allocation Strategies

In this section, we propose a "combined" approach, which consists in applying the CCS at high wind speeds and the PCS when the power output of WTs is relatively low. This strategy presents the following advantages.

1) It allows a good control of the wind reserve quantity at each dispatch time-step during high wind situations, i.e., during the period when the participation of WTs in the primary frequency control is required.
2) Reserve could be provided from WTs at any time without incurring a discontinuous WG output, which would also maximize the wind farm frequency response characteristics (MW/Hz) [30] with the participation of all turbines.
3) The application of the PCS at lower levels of production can take advantage of the smoothing effect and leads to a better global efficiency of the reserve allocation.

This combined strategy is applied to the Guadeloupe case study in order to compare its performance with single strategies (PCS or CCS alone). The parameters of the combined strategy are: 5.5% of the rated capacity (P_{nom}) of each farm curtailed when its power output exceeds 0.5 p.u. and 11% of the maximum instantaneous power curtailed when its production is below 0.5 p.u. (Fig. 7). In this way, the total wind energy curtailed in all the three WFs remains the same as in previous cases (about 540 MWh in three months).

Fig. 8 illustrates the duration characteristic of the "firm" reserve, which can be provided by the "aggregated wind farm" when the combined strategy is implemented. It can be read on this figure that an amount of reserve higher than 2% and 4% of the IC can be provided during 60% and 30% of the time, respectively.

The efficiency indicator of the combined reserve allocation strategy is calculated by using (4) (Table V) and is compared with the PCS and the CCS (Table III). The results show that

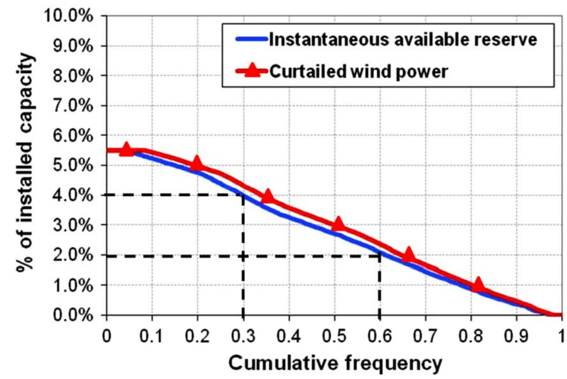


Fig. 8. Duration curve of the instantaneous available reserve and of the curtailed power of the aggregated wind farm with a 30-min time step (application of the combined reserve allocation strategy).

TABLE V
SUMMARY OF THE MAIN CHARACTERISTICS OF THE PROPOSED COMBINED STRATEGY

	Curtailed production	Average reserve (% of installed capacity)	Efficiency indicator (%)
Combined strategy	535 MWh	2.75	93

TABLE VI
GENERAL COMPARISON OF THE THREE RESERVE ALLOCATION STRATEGIES

	Efficiency	Implementation simplicity	Suitability for wide range sites	Control of curtailed WG
PCS	+	++	++	–
CCS	+	+	+	++
Combined strategy	++	–	–	+

with the proposed combined strategy, it is possible to obtain a higher "firm" wind reserve from the "aggregated farm" while curtailing less WG.

Although only a specific combination of the PCS and the CCS has been studied in this section, the improvement in terms of efficiency can be observed. This combined approach seems interesting for enlarging wind reserve potential and worth being taken into account while choosing the reserve allocation strategy to be applied to wind farms. However, it should be noted that the actually implemented WT controllers are generally not sophisticated enough and in most cases a very precise parameter-setting of different reserve allocation strategies could not be implemented.

An overall comparison of the three reserve allocation strategies is summarized in Table VI.

V. DISCUSSION

Results presented in this paper, in particular the case studies using real-measured data, are dependent on the wind regime. Since the statistical analyses are performed using a small dataset (3-month production records) and for a specific power system (the Guadeloupe Island), some conclusions cannot be generalized. However, the main contributions of this paper concern the methods to characterize the impact of intrahour wind variability (inside each scheduling interval) on the amount of "firm" wind reserve and the comparison of different wind reserve strategies are valid and general. If more data are available, similar studies can be performed by using the proposed methods.

The overall reserve allocation to each generator for each scheduling period can be obtained from an SCUC. However, this problem is often performed one day ahead with hourly (30 min) resolution and used hourly average values of wind, demand and other stochastic sources. The methodology proposed in this paper can be used to perform a "finer" allocation of the wind reserve hourly average, obtained from the SCUC (see [9]) and eventually updating this allocation closer to real time. Future works will be devoted to the coupling of the proposed approaches with an SCUC that takes into account dynamic security constraints.

The notion of instantaneous available reserve only characterizes the maximum potential of real-time primary reserve that can be provided from WTs. In practice, according to the current rules, a day-ahead or an intraday scheduling of primary reserve is required in the European synchronous power grid. Nowadays, forecasting errors of WG cannot be neglected, so the only way to ensure a satisfactory level of wind reserve availability during the day consists in taking into account a power margin the day ahead for covering forecast errors. The result is, of course, a change in the amount of wind reserve that can actually be dispatched in real time. Here wind prediction errors would affect the CCS more than the PCS, as the application of the former strategy is highly dependent on an accurate prediction of each wind farm's power output. However, reserve can be distributed at a system level when the PCS is used. Hence, reserve allocation can benefit from smaller wind prediction errors. In this paper, the maximum potential of wind reserve is proved interesting for power systems, future works of the authors will, therefore, focus on assessing the impact of wind prediction errors on primary reserve allocation.

VI. Conclusion

According to today's policies and grid codes, the primary reserve is sized to cover the most critical instantaneous incident, e.g., the loss of the largest online power plant, for both European interconnected power systems and French islands. The displacement of conventional power plants by WG reduces the number of available groups providing reserve. Therefore, with the increase in WG, especially when wind penetration exceeds a certain critical value, it would be essential that WG contributes to primary frequency control in order to ensure the system security.

This paper has presented a method for assessing the system-wide potential of the instantaneous wind primary reserve and has compared different reserve allocation strategies.

First, the impact of WG variability on the amount of real-time available wind reserve is assessed. Indeed, only the amount of reserve that can be maintained for at least 15 min can be considered as "firm" reserve. This implies that a part of the curtailed WG would be "lost" to cover the variability within a 15-min period. Statistical studies show that although wind power varies highly over time (especially in islands), it can provide a very interesting potential of instantaneous available reserve.

Two reserve allocation strategies are studied, which are the PCS and CCS, respectively. A methodology is proposed for comparing both strategies by using the recorded data of the Guadeloupean WG. Our results show that at the level of a few farms, almost the same amount of instantaneous available reserve can be provided with both strategies by curtailing the same quantity of wind power, regardless of whether reserve is distributed over the entire operating time of wind farms or only during the required period of WTs' participation.

Finally, the advantages of combining both reserve allocation strategies are also highlighted, as the combined approach can further improve the efficiency of the reserve provision.

References

[1] European Wind Energy Association (EWEA). (2008). *Pure Power—Wind Energy Scenarios up to 2030 European Wind Energy Association (EWEA)* [Online]. Available: http://www.ewea.org

[2] J. Brisebois and N. Aubut, "Wind farm inertia emulation to fulfill Hydro-Québec's specific need," in *Proc. IEEE PES Gen. Meeting*, Detroit, MI, USA, Jul. 2011, pp. 1–7.

[3] K. De Vos, A. G. Petoussis, J. Driesen, and R. Belmans, "Revision of reserve requirements following wind power integration in island power systems," *Renew. Energy*, vol. 50, pp. 268–279, 2013.

[4] H. Holttinen *et al.*, "Methodology to determine operating reserves due to increased wind power," *IEEE Trans. Sustain. Energy*, vol. 3, no. 4, pp. 713–723, Oct. 2012.

[5] N. Hamsic *et al.*, "Increasing renewable energy penetration in isolated grids using a flywheel energy storage system," in *Proc. Int. Conf. Power Eng. Energy Elect. Drives (POWERENG'07)*, Setubal, Portugal, Apr. 2007, pp. 195–200.

[6] European Network of Transmission System Operators for Electricity (ENTSO-E). (2013, Mar. 8) *ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators, ENTSO-E Final Draft Network Code* [Online]. Available: http://networkcodes.entsoe.eu/connection-codes/requirements-for-generators/

[7] Nordel. (2007, Jan. 15). *Nordic Grid Code 2007 (Nordic Collection of Rules)* [Online]. Available: https://www.entsoe.eu

[8] Eirgrid. (2011, Mar. 15). *EirGrid Grid Code v3.5* [Online]. Available: http://www.eirgrid.com

[9] V. Silva, "Value of flexibility in systems with large wind penetration," Ph.D. dissertation, Imperial College London, London, U.K., Oct. 2010.

[10] L. Bird, J. Cochran, and X. Wang, "Wind and solar energy curtailment: Experience and practices in the United States," NREL, Denver, Tech. Rep. NREL/TP - 6A20 - 60983, Mar. 2014.

[11] K. V. Vidyanandan and N. Senroy, "Primary frequency regulation by deloaded wind turbines using variable droop," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 837–846, May 2013.

[12] A. Zertek, G. Verbic, and M. Pantos, "A novel strategy for variable-speed wind turbines' participation in primary frequency control," *IEEE Trans. Sustain. Energy*, vol. 3, no. 4, pp. 791–799, Oct. 2012.

[13] R. G. de Almeida and J. A. Peças Lopes, "Participation of doubly fed induction wind generators in system frequency regulation," *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 944–950, Aug. 2007.

[14] J. F. Conroy and R. Watson, "Frequency response capability of full converter wind turbine generators in comparison to conventional generation," *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 649–656, May 2008.

[15] J. Morren, S. W. H. de Haan, W. L. Kling, and J. A. Ferreira, "Wind turbines emulating inertia and supporting primary frequency control," *IEEE Trans. Power Syst.*, vol. 21, no. 1, pp. 433–434, Feb. 2006.

[16] V. Courtecuisse, B. Robyns, B. Francois, S. Plumel, and J. Deuse, "Fuzzy logic based primary frequency control of variable speed wind generators," in *Proc. Int. Conf. Power Eng. Energy Elect. Drives (POWERENG)*, Setubal, Portugal, Apr. 2007, pp. 630–635.

[17] I. Erlich and M. Wilch, "Primary frequency control by wind turbines," in *Proc. IEEE PES Gen. Meeting*, Minneapolis, MN, USA, Jul. 25–29, 2010, pp. 1–8.

[18] L. Ruttledge, N. W. Miller, J. O'Sullivan, and D. Flynn, "Frequency response of power systems with variable speed wind turbines," *IEEE Trans. Sustain. Energy*, vol. 3, no. 4, pp. 683–691, Oct. 2012.

[19] N. Chen, Z. Qian, I. T. Nabney, and X. Meng, "Wind power forecasts using Gaussian processes and numerical weather prediction," *IEEE Trans. Power Syst.*, vol. 29, no. 2, pp. 656–665, Mar. 2014.

[20] Y. Rebours, D. Kirschen, M. Trotignon, and S. Rossignol, "A survey of frequency and voltage control ancillary services—Part I: Technical features," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 350–357, Feb. 2007.

[21] L. R. Chang-Chien, C.-M. Hung, and Y.-C. Yin, "Dynamic reserve allocation for system contingency by DFIG wind farms," *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 729–736, May 2008.

[22] D. Bertsimas, E. Litvinov, X. A. Sun, J. Zhao, and T. Zheng, "Adaptive robust optimization for the security constrained unit commitment problem," *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 52–63, Feb. 2013.

[23] Y. Wang, X. Guillaud, J. Duval, and B. Francois, "Enhanced design of a deloaded wind turbine controller for frequency regulation participation," in *Proc. 9th Int. Workshop Large-Scale Integr. Wind Power Power Syst.*, QC, Canada, Oct. 18–19, 2010, pp. 327–368.

[24] Energinet, "Wind turbine connected to grids with voltage above 100 kV," *Technical Regulation TF 3.2.5*, Dec. 2004.

[25] RTE. (2004). *Mémento de la sûreté du système électrique* [Online]. Available: http://www.rte-france.com

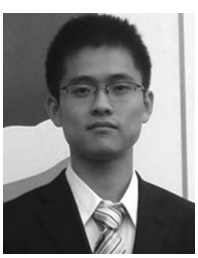
[26] EDF SEI, *Référentiel technique HTB relatif aux prescriptions techniques de conception et de fonctionnement pour le raccordement d'une installation de production d'énergie électrique au réseau public HTB $\geq$ 50 kV des Zones Non Interconnectées*, Dec. 2008.

[27] ENSTO-E. (2012, May). *Operational Reserve Ad hoc Team Report, Final Version* [Online]. Available: www.entsoe.eu

[28] Y. Wang, G. Delille, H. Bayem, X. Guillaud, and B. Francois, "High wind power penetration in isolated power systems—Assessment of wind inertial and primary frequency responses," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 2412–2420, Aug. 2013.

[29] Y. Wang, "Evaluation de la performance des réglages de fréquence des éoliennes à l'échelle du système électrique: Application à un cas insulaire," Ph.D. dissertation, L2EP, Ecole Centrale de Lille, 2012.

[30] P. Kundur, *Power System Stability and Control*. NewYork, NY, USA: McGraw-Hill, 1994.



Ye Wang was born in China, in 1986. He graduated in multidisciplinary engineering from Ecole Centrale de Lille, Villeneuve-d'Ascq, France and received a second Master's degree in electrical energy and sustainable development from the University of Science and Technology of Lille, Villeneuve-d'Ascq, France, in 2009, and the Ph.D. degree in electrical engineering from Ecole Centrale de Lille, Villeneuve-d'Ascq, France, in 2012.

Currently, he is with the Economic and Technical Analysis of Energy Systems (EFESE) Department, EDF R&D, as a Research Engineer. His research interests include power system analysis, real-time simulation, and renewable power integration analysis.

Herman Bayem was born in Cameroon, in 1979. He graduated from the National Advanced School of Engineering, Yaoundé, Cameroon, in 2003, and studied at EPFL Lausanne, Lausanne, Switzerland, where he received the Advanced Master degree in energy in 2006. He holds, since 2009, the Ph.D. degree in electrical engineering from the University of Paris, Paris, France.

Currently, he is with EDF R&D as a Research Engineer in Power System. His research interests include range from wind turbines and PV modeling to renewable energy integration studies, especially using probabilistic methods.

Maria Giralt-Devant received the Electrical Engineer's degree from the Ecole Supérieure d'Electricité, France, in 2007, the Post-Master degree specialized in energy engineering and management from the Ecole des Mines de Paris, Paris, France, in 2008.

Currently, she is a Researcher with EDF R&D, Economic and Technical Analysis of Energy Systems Department.

Vera Silva (S'06–M'08) received the B.Sc. and M.Sc. degrees in electrical engineering from the University of Porto, Porto, Portugal, in 1999 and 2003, respectively, and the Ph.D. degree in electrical engineering from the Imperial College London, London, U.K., in 2010.

She is a Senior Engineer with the Department of Economic and Technical Analysis of Energy Systems, R&D Division of EDF SA. Before joining EDF, she held a position of Assistant Professor with the Polytechnic Institute of Porto, Porto, Portugal (2000–2005) and a research position with the Imperial College London, London, U.K. (2005–2009). Her research interests include integration of variable generation into power systems planning and operations, flexibility, demand side management, and electric vehicles.

Xavier Guillaud (M'04) received the Ph.D. degree in electrical engineering from the University of Science and Technology of Lille (USTL), Villeneuve-d'Ascq, France, in 1992.

He joined the Laboratory of Electrical Engineering and Power Electronics of Lille (L2EP), Lille, France, in 1993. Since 2001, he has also been working on the integration of dispersed generation in electrical grids. He is a Professor with the Department of Electrical Engineering of Ecole Centrale de Lille, Cité Scientifique, Villeneuve d'Ascq Cedex, France. His research interest includes the modeling and the control of power electronic systems.

Bruno Francois (M'96–SM'06) was born in Saint-Amand-les-Eaux, France, on January 19, 1969. He received the Ph.D. degree in electrical engineering from the University of Science and Technology of Lille (USTL), France, in 1996.

He is with the Laboratory of Electrical Engineering and Power Electronics of Lille (L2EP), Lille, France, and is a Professor with the Department of Electrical Engineering of Ecole Centrale de Lille, Cité Scientifique, Villeneuve d'Ascq Cedex, France. His research interests include advanced energy management systems, planning, operation, power system control, microgrids, and smart grids.