Flexibility Envelopes for Power System Operational Planning

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***Abstract*—Modern power systems are undergoing a transitional phase, increasingly incorporating renewable energy sources (RES) to harness their economic and environmental benefits. The main challenge with this transitional phase is the management of the increased variability and uncertainty in the power balance. Legacy operation and planning practices are gradually seen as becoming inadequate or ill-adapted in addressing this challenge. One particular gap in the state of the art, which is of great importance, is estimating the operational flexibility potential of individual power system assets and their aggregation at the system level. System operators need to evaluate and plan ahead flexibility adequacy for their power systems in order to ensure feasible and economical operation under high RES penetration. Likewise, asset owners need to integrate the notion of asset flexibility as part of their investment and operations decisions. To this end, we propose the concept of the flexibility envelope to describe the flexibility potential dynamics of a power system and its individual resources in the operational planning time-frame. We demonstrate that the resulting envelope dynamics can be a starting point for flexibility adequacy planning in systems with highly variable generation.**

***Index Terms*—Flexibility, power generation dispatch, power system operations, power system planning, renewable power generation.**

I. Introduction

A GLOBAL trend is currently in effect, whereby power systems are moving away from fossil-based electricity production and toward renewable sources of electricity, primarily wind and solar power. Many countries have set up ambitious targets for integrating renewable energy sources (RES). This integration seeks to harness the economic and environmental benefits of RES, such as energy security and mitigating climate change [1].

However, prevailing weather conditions dictates the output of most RES, thus making them *variable* and *uncertain* due to their erratic nature [2]. This poses a great challenge to system operators when having to balance power production and consumption, which must be carried out in real time. In fact, it is expected that current power system operation and planning practices will become grossly obsolete with the increasing penetration of RES in power systems around the globe [3]–[5].

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Traditionally, system operators have had to deal with variability and uncertainty resulting mainly from demand and random generation/transmission outages. Generally, they have always had enough lead time and ample capacity to prepare generation in advance to deal with such circumstances [6]. On the contrary, under high RES penetration, the netload (i.e., load less RES output) exhibits higher magnitudes and rates of variability [7] with higher uncertainty. This reduces the available lead time, creates requirements for large and sudden ramping events, and causes frequent start-ups and shut-downs for dispatchable generating units [8], [9], thus warranting the rethinking of traditional operation and planning practices to suit better 1) shorter decision-making lead times; 2) faster changeability; and 3) higher uncertainty. In addition, other resources in the system will be required to alter their generation and/or consumption in a variable manner and fast enough to overcome those three challenges—the basic premise behind *power system flexibility*.

A. Defining Power System Flexibility

The concept of flexibility in power systems has been formally introduced only recently and has been officially recognized by organizations like the IEA [1] and NERC [10], [11]. Concurrently, academic research and industry reports have begun to emerge and assess flexibility in power system operation and planning. Currently, the two main research frontiers in this area are in terms of long-term flexibility planning and short-term operational flexibility scheduling. Currently, there is no universal definition of power system flexibility. Different authors and groups have contributed their own definition, which we discuss shortly here.

Flexibility is defined in [6] as "the ability of a system to deploy its resources to respond to changes in netload, where netload is defined as the remaining system load not served by variable generation." A definition in [1] states that "flexibility expresses the extent to which a power system can modify its electricity production and consumption in response to variability, expected or otherwise." From an operational point of view, flexibility is seen in [4] as "the potential for capacity to be deployed within a certain time-frame" to respond to changes in netload. Similarly, Makarov *et al.* [12] and Dvorkin *et al.* [13] define operational flexibility "in terms of power capacity (MW), ramp rate (MW/min), i.e., the ability to increase energy production with a certain rate, and ramp duration (min), i.e., the ability to sustain ramping for a given duration [13]." A lower level definition is adopted in [14], where flexibility

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is said to encompass controllability and observability information about the underlying power system which is constrained by the dynamics of its resources. Tying technical flexibility with economics, Ma *et al.* [9] defines flexibility as "the ability of a power system to cope with variability and uncertainty in both generation and demand, while maintaining a satisfactory level of reliability at a reasonable cost, over different time horizons." Similarly, flexibility is defined in [15] as "the system's capability to respond to a set of deviations that are identified by risk management criteria through deploying available control actions within predefined time-frame and cost thresholds."

Therefore, a power system must be flexible in its resources, operation, and planning to permit the integration of higher RES targets. The more flexible a power system is, the more variability and uncertainty it can handle, and the more RES levels can be achieved. This can be realized by diversifying the resources available in the power system, such that they exhibit various flexibility characteristics and flexibility costs, as argued in [16]. The challenge then becomes how to manage and optimize this flexibility potential according to system needs in the most economical way.

Having excess reserve capacity does not necessarily ensure power system security, especially under significant RES penetration [17]; this capacity must also be "flexible" enough to be deployed in good time. The system operator must validate the rampability of reserve capacity implemented by its portfolio of resources, subject to transmission constraints. This portfolio has to be capable of providing power set-point adjustments (both upward and downward), within the time scales and power volumes entailed by the realization of the netload variability and uncertainty, and within the transmission capacity of the network. The design of the transmission network can have a significant impact on the flexibility provided by resources. In addition, the locations of flexibility resources are highly relevant due to potential congestion [18]. In this paper, we do not perform transmission planning, nor do we consider the network's topology when performing flexibility planning. For considerations of space, we are not addressing the effect of the transmission network on flexibility envelopes nor the inherent flexibility of the grid itself. These are important matters which are planned for future research.

B. Objective

The object of this paper is the presentation of a systematic methodology to describe the behavior of power system resources' flexibility as needed by unit commitment and economic dispatch tools. Here, we define the flexibility of a power system resource at time t as the power capacity this resource could potentially deploy in τ units of time later, as seen at time t [4]. It is better characterized by limit behavior as time progresses, which corresponds to a *flexibility envelope* or *cone*. Therefore, to ensure adequate system flexibility, the flexibility cone for the entire power system must enclose, reasonably well, the corresponding cone of flexibility needs arising from RES integration.

II. State of the Art in Power System Flexibility Planning

The objective of short-term flexibility planning is to ensure economical and feasible operations by committing the right power system resources and prepositioning them correctly ahead of time. This is generally done directly in the context of day-ahead unit commitment and predictive economic dispatch. With unit commitment, reserve capacity is scheduled and, in the case of economic dispatch, the available generation capacity is deployed to meet the current levels of netload. Inappropriate short-term operation planning may lead to insufficient flexibility in real-time operation—inadequate power capacity combined with potentially inadequate maneuverability—which in turn may lead to undesirable situations such as out-of-merit dispatch, involuntary load shedding, unnecessary renewable generation curtailment and, potentially, widespread blackouts. As mentioned above, unit commitment problem formulations generally attempt at resolving this problem. However, they only focus on getting the capacity right but not its ramping ability.

The main challenge is managing the increased *variability* and *uncertainty* arising in the netload, as a result of higher RES penetration. *Variability* arises because RES have maximum generation limit that changes with time, while *uncertainty* arises because this limit cannot be known with perfect accuracy [19]. In particular, under high RES penetration, the impact of intra-hourly variability and uncertainty can become substantial enough to put significant stress on reserve requirements in terms of necessary capacity and its ability to ramp, both upward and downward. It is thus our ambition that all devices (producing and/or consuming power) in the power system can participate collectively in balancing power across the system, by exploiting their upward and downward flexibility, i.e., by providing flexible reserve.

Conventionally, reserve types have been categorized according to their required deployment response time and the duration during which resources providing them have to maintain their deployed capacity. The three main categories are frequency containment reserves (primary/instantaneous), frequency restoration reserves (secondary/fast), and replacement reserves (tertiary/slow) [20]–[23]. So far in the literature, the emphasis has been on quantifying the required reserve capacity, while assuming that the committed resources provided sufficient rampability. Such an approach is unlikely to guarantee system's security under significant RES penetration; a more systematic approach is desired.

Flexibility, on the other hand, quantifies in a more general way reserve capacity dynamics of power system resources over a time continuum—the horizon of potential flexibility deployment. This allows for a more rigorous consideration of reserve requirements in terms of both capacity and rampability. The heuristic distinction between the various reserve types is no longer explicitly needed, thus allowing the various power system resources, including demand-side management and energy storage systems, to contribute collectively to the whole spectrum of reserve requirements. Henceforth, one must ask: to what extent does the recent literature on short-term planning

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quantify and plan reserve requirements in light of the emerging concept of flexibility?

Estimating flexibility requirements is directly related to quantifying the netload random process. This can be modeled exogenously or endogenously with respect to the planning problem. The exogenous approach quantifies the netload random process in terms of a probability distribution or a statistic (e.g., standard deviation), which is then used to impose an explicit reserve requirement constraint in the generation planning optimization model. This quantity could be static for all planning periods, or it could be dynamic and specific to each period. The endogenous approach models netload random process stochastically (e.g., scenario-tree formulation), which is then integrated into the planning problem and solved via stochastic programming techniques. In the latter case, there is no explicit reserve requirement constraint, as it is implicitly accounted for via the need to satisfy the power balance constraint in each of the scenarios [24], [25].

In the case of an exogenous approach, some techniques map the probability distribution or its statistics directly to a reserve requirement for a certain time-frame such as the 10-min spinning reserve [3], [26]. Other techniques relax the reserve requirement by first mapping the probability to a reliability criterion [7], [20], [27], [28], which allows for insufficient flexibility as long as the reliability criterion is met. Yet, other techniques further relax the reserve requirement by optimizing the reserve cost against the actual benefit of its availability [17], [28], [29]. The benefit is improved operational cost and/or feasibility of the planning problem, since directly mapping the netload random process to reserve requirements can be a stringent constraint during planning.

On the other hand, the endogenous approach of quantifying the netload random process is suitable for stochastic-based planning (e.g., stochastic unit commitment). The main advantage here is that fully hedging against scenarios that have much lower probability of occurrences may not be needed, considering the higher reserve cost associated with these scenarios [4]. The endogenous stochastic approach is surveyed thoroughly in [30].

More or less, the above various approaches followed the conventional wisdom of quantifying reserve capacity for the 10- or 15-min duration (i.e., spinning reserve requirement) and for the 1-h duration (i.e., load following requirement). At best, a constraint is imposed on those two categories to be able to linearly ramp to the full capacity within the entailed time-frames. However, the essence of the flexibility concept goes beyond merely defining reserve requirements statically for two time-frames; this does not satisfactorily capture the full intra-hourly characteristics (i.e., variability and uncertainty) of the netload random process, which we attempt to accomplish via quantifying the flexibility requirement envelope for a continuum of deployment time-frames.

That being said, some recent approaches divert from the conventional wisdom. The "flying-brick" concept in [12] and the "probability-box" concept in [13] quantify reserve requirements based on statistical analysis of variability for a range of intra-hourly durations. The proposed envelope follows along the same lines but acknowledges the time-evolution of reserve

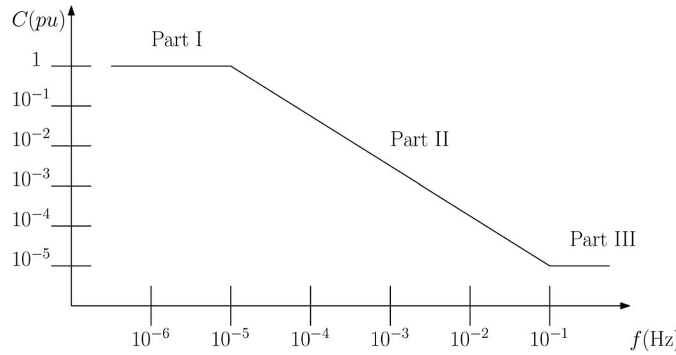

Fig. 1. Schematic representation of the periodogram of wind generation output variability on a log–log scale [4]. Note: 10^{-5} Hz ≈ 24 h and 10^{-4} Hz ≈ 1 h.

requirements, which resembles the shape of an envelope or a cone. Essentially, the "flying-brick" and the "probability box" are a "boxed" version of the proposed envelope, when transforming the envelope into the capacity-ramp-duration space. That is, the envelope carves out some of the empty space within the boxes. This empty space in the "flying/probability" boxes may end up imposing unnecessarily costly reserve requirements on the system.

Via the flexibility envelope concept we introduce in this paper, we provide a new basis for the development of power system operation tools which could be used to: 1) assess and visualize the probable range of RES excursions in terms of time (i.e., the flexibility requirement envelope); 2) do the same for power system resources (i.e., the flexibility envelope); and to 3) optimally match power system resources as countermeasures to RES variability and uncertainty. For instance, the work presented in [31], describing how the "flying-brick" concept integrates within an energy management system (EMS), could be redone in the same context using flexibility envelopes.

The developments here are carried out taking a North American power system operation planning approach. Nonetheless, the concept of flexibility envelopes could still be used in electricity systems where bilateral transactions and energy-only market clearing are used to carry out short-term generation planning, as in most European countries. Envelopes could be useful primarily for transmission system operators (TSO) and flexibility resource owners in preparation for the balancing mechanism. Flexibility requirement envelopes could be used by the TSO to determine how much flexibility resources need to be procured to run the balancing mechanism reliably and economically. Moreover, in the case of flexibility resource owners, they could calculate their own flexibility envelopes while trading off gate-closure market positions for wider or smaller ranges of flexibility to be offered in the balancing mechanism with the objective of profit maximization.

III. Flexibility Requirement

Statistically, several studies [16], [32], [33] have shown that wind (and solar) generation output variations exhibit a considerable range of ramping characteristics as reflected by the frequency content of its power spectral density. Fig. 1 shows a

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schematic representation of the *periodogram* (a statistical estimate of the power spectral density) of wind generation output variations. There are three distinguishable parts in the periodogram [4], [16]. Part I essentially indicates that over long enough time spans (i.e., low frequencies), the wind generation output will vary on average between zero and full capacity (1.0 per unit). Part II exhibits a linear profile in log–log scale, which is known as the Kolmogorov spectrum [16]. The wind generation output variations roll off exponentially as $f^{-5/3}$, indicating that variations in the output decrease as timescales become shorter. Part III is flat at nearly zero magnitude, indicating that at high frequencies (i.e., very short time intervals), the output variations are essentially filtered out by the mechanical and electrical inertias of wind turbines. There are two main conclusions to take from this analysis. First, managing variability and uncertainty arising from RES integration requires a pool of resources with diversified flexibility characteristics to provide a matching spectrum of reserve dynamics [4], [16]. Second, it is not unlikely that the RES output can vary between zero and its maximum within 1 h. Given this empirical information, one can argue that there is inherently some value in exploiting the fact that RES output variations are well bounded within an hourly time-frame.

A. Quantifying the Envelope

The concept of an envelope implements the empirical findings illustrated above, by quantifying intra-hourly reserve capacity and rampability requirements for a 1-h period. Typically, the forecast RES output is held constant during each hourly planning period k, whereas the actual RES output deviates from this forecast in real time. These intra-hourly deviations during the kth hour $w(k,\tau)$ are modeled here as step changes, with respect to the constant RES forecast output, taken over a range of subhourly time durations $\tau \in [0, 60]$ min

$$w(k,\tau) = \hat{P}_{\mathrm{RES}}(k) - P_{\mathrm{RES}}(k+\tau) \quad (1)$$

where $\hat{P}_{\mathrm{RES}}(k)$ represents the RES forecast for hour k and $P_{\mathrm{RES}}(k+\tau)$ is the realization of the RES output within hour k, measured τ minutes later.

A probability distribution of $w(k,\tau)$ can be computed empirically for every τ, by constructing a relative frequency plot. This yields a stationary probability distribution that is a function of the variability calculation interval τ only. Finally, plotting the 95% (or in general δ) percentile of the probability distribution at all τ's produces an envelope that encompasses the vast majority of plausible realizations of reserve capacity requirements, whereas the slope of the envelope implicitly encompasses the majority of plausible realizations of reserve ramping requirements.

It must be noted that we take a *parametric* approach in this paper to quantify the flexibility requirement envelope. Other papers, e.g., [13], argue in favor of the *nonparametric* approach, based on an empirical study of the *goodness-of-fit* of various parametric distributions, although they leave out the Laplace distribution. It is beyond the scope of this paper to assess the relative merits of each approach. The ultimate goal here is to have an adequate statistical representation of the behavior of the envelope.

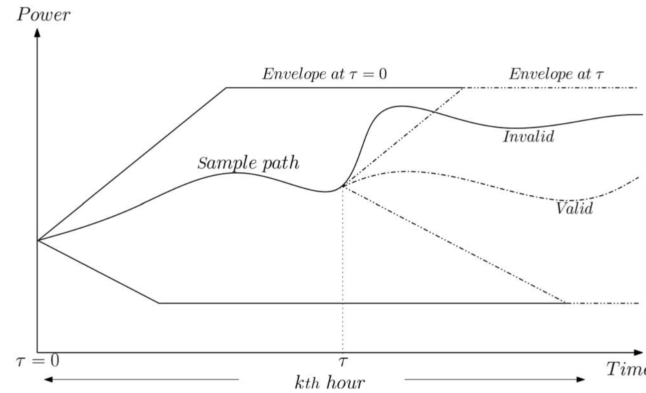

Fig. 2. Schematic illustration of RES output consistency with its envelope.

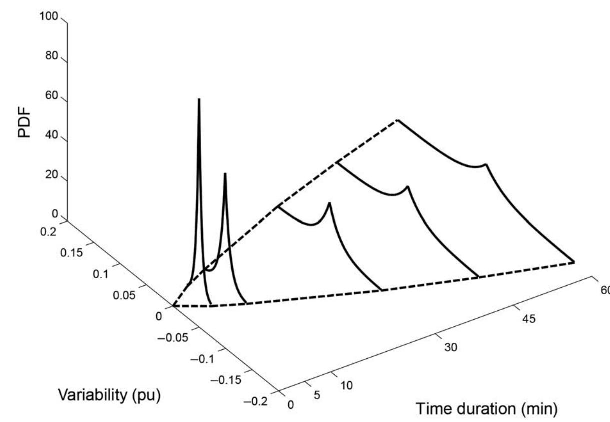

Fig. 3. Flexibility requirement envelope arising from fitting the Laplace distribution to step changes of wind generation output as a function of τ.

Since $w(k,\tau)$ is assumed to be stationary random process (i.e., dependent on τ only), the per unit envelope is time-invariant and is therefore valid for all times and for all RES output levels. An implication of time-invariance forward compatibility, as shown in Fig. 2, means that a sample realization cannot break the bounds of successive envelopes drawn at any time instant τ. Therefore, enclosing the flexibility requirement envelope by the aggregate envelope of flexibility resources needs only be done at the beginning of the kth hour to ensure adequate flexibility planning. However, in real-time operations, the envelope must be optimized repeatedly, while the netload random process is being realized, because merit-order dispatch is in direct conflict with flexibility planning—it seeks to minimize dispatch costs at the expense of undermining future flexibility.

B. Example: Wind Power Variability

It has been shown in [32] and [34] that the wind generation random process is well fitted by a Laplace distribution. Fig. 3 shows the fitted Laplace distribution for the wind generation data analyzed in [32] for $\tau \in \{5, 10, 30, 45, 60\}$ min. The flexibility requirement envelope can be constructed by computing the interval $[-\delta^{-}_{95\%}(\tau), \delta^{+}_{95\%}(\tau)]$ that encloses 95% of

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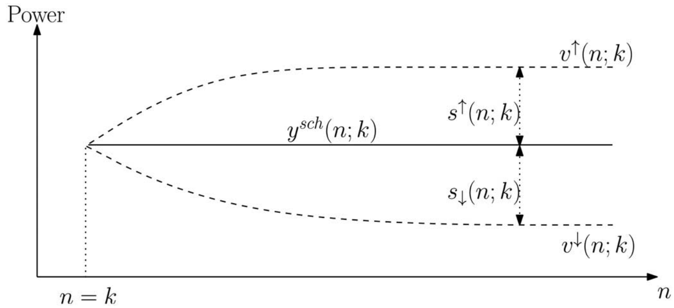

Fig. 4. Schematic illustration of the concept of a flexibility dynamics for a scheduled flexibility resource.

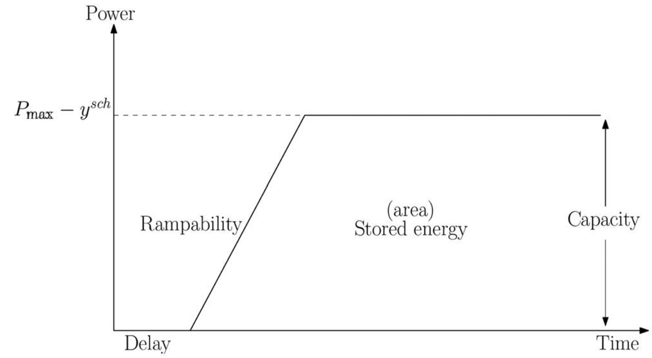

Fig. 5. Illustrative example of a generic upward flexibility envelope.

the probability using the Laplace probability density function. Fig. 3 shows the shape of the envelope for the wind generation data.

IV. Quantifying the Flexibility of Power System Resources

We formulate next the dynamics of the flexibility envelope for a generic power system resource analogous to the flexibility requirement envelope. The flexibility envelope may also model an aggregation of resources such as a collection of smaller individual resources. The model abstracts from technology-specific details by describing the power output dynamics only in term of capacity and rampability. However, complexities may arise primarily because the internal dynamics and constraints of the flexibility resource are nontrivial and time-dependent. Equally important, the flexibility envelope conveys the strong coupling of energy delivery and primary, secondary, and tertiary reserves.

A. Modeling Flexibility Potential Dynamics

To begin with, we distinguish between *flexibility potential dynamics* and *flexibility envelope dynamics*. Working in discrete time where $\tau = n\Delta$ for $n = 0, 1, \ldots, N$ such that $N\Delta = 60\ \text{min}$, $s^{\uparrow}(k,n)$ and $s^{\downarrow}(k,n)$ describe the upward and downward, respectively, flexibility potential dynamics of a single resource evaluated at the kth hour for delivery n intra-hourly time steps in the future. Both are quantified by the difference between the scheduled power trajectory, $y^{\text{sch}}(k)$ and a feasible upward $v^{\uparrow}(k,n)$ or downward, $v^{\downarrow}(k,n)$, deviation from the scheduled power trajectory—see Fig. 4. Therefore, the two coupled equations describing the flexibility potential dynamics of a single resource are as follows:

$$s^{\uparrow}(k,n) = v^{\uparrow}(k,n) - y^{\text{sch}}(k) \tag{2}$$
$$s^{\downarrow}(k,n) = y^{\text{sch}}(k) - v^{\downarrow}(k,n) \tag{3}$$

where $v^{\uparrow}(k,0) = v^{\downarrow}(k,0) = y^{\text{sch}}(k)$ for all k.

Here, the scheduled trajectory is assumed to remain constant during each hour. A planned deviation from the constant level, to be distinguished from failures, is a realization of flexibility deployment via ED decisions and/or ancillary service deployment in real-time operation. More importantly, assuming that $y^{\text{sch}}(k)$ stays constant during each hourly period yields a time-invariant flexibility envelope, since the same maximum upward and downward deviations can be reproduced at any successive intra-hourly time step n. This way, the flexibility model of resources is mathematically compatible with the flexibility requirement envelope model.

B. Calculating the Flexibility Envelope

The flexibility envelope of a power system resource $(\hat{s}^{\uparrow}, \hat{s}^{\downarrow})$ can be estimated recursively from the flexibility potential dynamics by maximizing the deviations $(v^{\uparrow}, v^{\downarrow})$ at each sub-hourly time step n

$$\hat{s}^{\uparrow}(k,n) = \hat{s}^{\uparrow}(k,n-1) + \max\{v^{\uparrow}(k,n) : v^{\uparrow}(k,n) \in \mathcal{V}^{\uparrow}(k,n)\} - y^{\text{sch}}(k) \tag{4}$$
$$\hat{s}^{\downarrow}(k,n) = y^{\text{sch}}(k) - \hat{s}^{\uparrow}(k,n-1) - \max\{v^{\downarrow}(k,n) : v^{\downarrow}(k,n) \in \mathcal{V}^{\downarrow}(k,n)\} \tag{5}$$

where the sets $\mathcal{V}^{\uparrow}(k,n)$ and $\mathcal{V}^{\downarrow}(k,n)$ represent the dynamical limitations of the power system resource in hour k and intra-hour time step n.

For simplicity, if we consider linear time-invariant (LTI) power system resources only, we can identify four characteristics (constraints) describing the intra-hourly flexibility envelope dynamics, as illustrated in Fig. 5. These are m-step delays (6) and (7), capacity (8) and (9), rampability (10) and (11), and energy storage constraints (12) and (13), which apply for all k and n

$$v^{\uparrow}(k,n) = y^{\text{sch}}(k); \quad 0 \le n \le m \tag{6}$$
$$v^{\downarrow}(k,n) = y^{\text{sch}}(k); \quad 0 \le n \le m \tag{7}$$
$$y^{\text{sch}}(k) \le v^{\uparrow}(k,n) \le P^{\max} \tag{8}$$
$$P^{\min} \le v^{\downarrow}(k,n) \le y^{\text{sch}}(k) \tag{9}$$
$$0 \le v^{\uparrow}(k,n+1) - v^{\uparrow}(k,n) \le R^{\uparrow} \tag{10}$$
$$-R^{\downarrow} \le v^{\downarrow}(k,n+1) - v^{\downarrow}(k,n) \le 0 \tag{11}$$
$$e(k,0) - \sum_{m=0}^{n} v^{\uparrow}(k,m)\Delta \ge E^{\min} \tag{12}$$
$$e(k,0) + \sum_{m=0}^{n} v^{\downarrow}(k,m)\Delta \le E^{\max} \tag{13}$$

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where $m \geq 0$ is some response delay, $P^{\max}$ and $P^{\min}$ are, respectively, the maximum and minimum power levels of the resource, $R^{\uparrow}$ and $R^{\downarrow}$ are, respectively, its up and down ramp limits, $E^{\max}$ and $E^{\min}$ are the maximum and minimum energy storage levels of the resource, while $e(k, 0)$ is the initial energy stored in the resource at the beginning of hour k.

V. Comparison to Stochastic Optimization

Scenario-based stochastic optimization has been proposed widely as a methodology to address the variability and the uncertainty of RES as part of short-term power system planning, especially for unit commitment; see, e.g., [25], [30]. The advantages of stochastic optimization in this respect are many. First, it serves to determine here-and-now generation planning decisions while having foresight of how the system netload may evolve. Typically, this is done with the help of scenario trees. Moreover, stochastic optimization approaches may not be fully hedged against some extreme low-probability high-consequence events [4]. Lastly, transmission constraints can be handled without much difficulty in stochastic optimization approaches [35], [36].

On the other hand, stochastic optimization has significant challenges in performing generation scheduling under uncertain and variable RES. Its first challenge pertains to the construction of adequate scenario trees to represent credibly the possible time evolution of the netload [25], [37]. In order to obtain accurate representations, one has to have a large number of scenarios which, in turn, increases the size of the problems to solve. This is compounded with the fact one needs to define variables and constraints for each possible realization in the scenario tree. Therefore, stochastic optimization formulations are yet to emerge as viable practical industry solutions.

The approach we propose based on flexibility envelopes circumvents those dimensional hurdles by ignoring the different likelihood of specific netload trajectories enclosed within the flexibility requirement envelope. All possible netload trajectories enclosed by the envelope are treated equally, and only those at the boundary matter to the generation planner. Moreover, it is much simpler to obtain flexibility requirement envelopes than to build good scenario trees because all that is needed to determine a flexibility requirement envelope is historical/forecast error information. At the same time, envelope-based planning is much less computationally intensive than stochastic optimization because it is not necessary to carry variables and constraints which apply to all netload scenarios contained within the envelope. We believe that the current approach can be readily adapted to include transmission limits. This, however, remains out of the scope of the paper.

VI. Illustrative Example

This simplified example illustrates the advantage of flexibility planning with economic dispatch in a rolling-horizon scheme. At every time step, the decision-maker solves the conventional economic dispatch problem, while also ensuring that the projected aggregate flexibility envelope of committed resources encloses the projected flexibility requirement

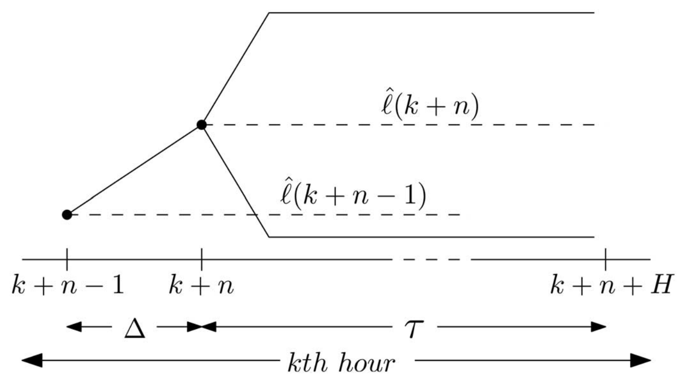

Fig. 6. Schematic representation of FE-RHED.

envelope, moving forward. The process is repeated at every economic dispatch time step, yielding a receding-horizon scheme. We shall call this the *flexibility envelope receding-horizon economic dispatch* (FE-RHED). This approach will be compared to the *myopic economic dispatch* (M-ED) and *economic dispatch with a spinning reserve requirement* (SR-ED). The M-ED approach solves the conventional economic dispatch problem without considering spinning reserve or any flexibility requirement envelope. The SR-ED approach solves the conventional economic dispatch problem, while ensuring that sufficient spinning reserve is available for the next 10 min, which is generally the current industry practice.

Let there be I flexibility resources with generation levels $\{g_i\}_{i=1}^{I}$, maximum linear ramping rates $\{R_i\}_{i=1}^{I}$, and distinct incremental costs $\{c_i\}_{i=1}^{I}$. Let there be two slack resources capable of providing an infinite amount of flexibility, in both capacity and ramping. One slack $S^{\uparrow}$ provides upward flexibility when there is generation deficiency. The other slack $S^{\downarrow}$ provides downward flexibility when there is generation excess. The slack resources are priced at a much higher cost than the I resources to be used as a last resort, when the economic dispatch problem is not feasible.

The long-term averages on the use of $S^{\uparrow}$ and $S^{\downarrow}$ are seen as estimates for the expected energy not served (EENS) and the expected energy curtailed (EEC), respectively. They will be used as metrics to assess the relative advantage of the FE-RHED approach against the SR-ED and M-ED approaches.

A. Optimal Operations Planning With FE-RHED

Fig. 6 illustrates the FE-RHED approach schematically. There are N economic dispatch time steps within a single unit commitment hour k, of length $\Delta = 60/N$ min. For each dispatch $\{g_i\}_{i=1}^{I}$ of the I flexibility resources, the individual and aggregate flexibility envelopes can be computed over a planning horizon of length H future time steps. The problem, hence, is to choose the cost-minimizing dispatch at the current time $k+n$ that will meet the current netload forecast $\hat{\ell}(k+n)$, while ensuring that the aggregate flexibility envelope encloses the flexibility requirement envelope over the horizon $k+n+\tau$, where τ varies from 1 to H. Here, we assume that the envelope's horizon is discretized with the interval Δ as well. This is repeated at every economic dispatch time step $k+n$, where n

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varies from 0 to N. The following linear program describes this procedure for a single economic dispatch time step $k+n$, given the previous optimal dispatch at $k+n-1$ and the projected envelope over the horizon $k+n+\tau$ for $\tau = 1, \ldots, H$

$$\min \sum_{i=1}^{I} c_i g_i(k+n) + c_S \left[S^{\uparrow}(k+n) - S^{\downarrow}(k+n)\right] + \sum_{\tau=1}^{H} \gamma(\tau) c_{v_S} \left[v_S^{\uparrow}(k+n+\tau) - v_S^{\downarrow}(k+n+\tau)\right] \quad (14)$$

subject to

Dispatch constraints at $k+n$

$$\sum_{i=1}^{I} g_i(k+n) + S^{\uparrow}(k+n) + S^{\downarrow}(k+n) = \hat{\ell}(k+n) \quad (15)$$

$$g_i^{\min} \leq g_i(k+n) \leq g_i^{\max}, \qquad i = 1, \ldots, I \quad (16)$$

$$-R_i \leq g_i(k+n) - g_i(k+n-1) \leq R_i, \qquad i = 1, \ldots, I \quad (17)$$

$$S^{\uparrow}(k+n) \geq 0 \quad (18)$$

$$S^{\downarrow}(k+n) \leq 0. \quad (19)$$

Resource flexibility envelopes for $k+n+\tau$, $\tau = 1, \ldots, H$ *and* $i = 1, \ldots, I$

$$g_i^{\min} \leq v_i^{\downarrow}(k+n+\tau) \leq g_i(k+n) \quad (20)$$

$$g_i(k+n) \leq v_i^{\uparrow}(k+n+\tau) \leq g_i^{\max} \quad (21)$$

$$-\tau \cdot R_i \leq v_i^{\downarrow}(k+n+\tau) - g_i(k+n) \leq 0 \quad (22)$$

$$0 \leq v_i^{\uparrow}(k+n+\tau) - g_i(k+n) \leq \tau \cdot R_i. \quad (23)$$

Envelopes matching for $k+n+\tau$, $\tau = 1, \ldots, H$

$$\sum_{i=1}^{I} \left(v_i^{\uparrow}(k+n+\tau) - g_i(k+n)\right) + v_S^{\uparrow}(k+n+\tau) \geq \min\left(\ell^{\max} - \hat{\ell}(k+n), \sqrt{\tau}\lambda\right) \quad (24)$$

$$\sum_{i=1}^{I} \left(g_i(k+n) - v_i^{\downarrow}(k+n+\tau)\right) - v_S^{\downarrow}(k+n+\tau) \geq \min\left(\hat{\ell}(k+n) - \ell^{\min}, \sqrt{\tau}\lambda\right) \quad (25)$$

$$v_S^{\uparrow}(k+n+\tau) \geq 0 \quad (26)$$

$$v_S^{\downarrow}(k+n+\tau) \leq 0. \quad (27)$$

There are three distinct sets of constraints in the above problem. Constraints (15)–(19) ensure that the combined resources balance the netload at time step $k+n$, while respecting the capacity ramping limitation of resources as they ramp from their previous dispatch at $k+n-1$. Constraints (20)–(23) bound the flexibility envelope of each resource $i = 1, \ldots, I$ at time steps $k+n+\tau$, where τ varies from 1 to H, again while respecting the capacity and ramping limitations of the resources. Constraints (24)–(27) ensure that the aggregate flexibility envelope encloses the flexibility requirement envelope at time steps $k+n+\tau$. The evolution of the upper and lower half envelopes of flexibility requirement over the receding horizon is described in the right-hand sides of (24) and (25), respectively. Here, the half envelopes grow at the rate of λ MW/Δ and saturate once the maximum and minimum possible netload are reached.

We emphasize here that the problem (14)–(27) is solving the economic dispatch at time $k+n$ projecting the potential evolution of the netload up to H subhourly time steps ahead. Therefore, envelopes are always calculated based on the current state of the system when the economic dispatch is computed. So, if in between the current dispatch time and the previous subhourly dispatch step flexibility has been used, the envelopes of resources which have deployed flexibility are updated based on their current operating point.

The primary objective (14) is to minimize the cost of dispatch associated with the current dispatch time step $k+n$, while enforcing the aforementioned three sets of constraints. Ideally, the I resources should have enough flexibility to ramp from the previous time step $k+n-1$, while ensuring that there is still enough flexibility to enclose the projected flexibility requirement envelope, moving forward. However, due to poor planning in the past or a lack of sufficient flexibility, the I resources may not be able to collectively position themselves at time step $k+n$ to balance the current netload or to ensure proper enclosure of the projected flexibility requirement envelope. Consequently, the decision-maker may have to deploy slack resources [in the form of load shedding ($S^{\uparrow}$) and generation curtailment ($S^{\downarrow}$)] to avert dispatch infeasibility.

Deploying slack resources is undesirable and thus is priced much higher than the other resources. They are to be used as a last resort when the problem becomes infeasible. On the other hand, feasibility at $k+n$ can be improved by relaxing the flexibility requirement envelope; this is done via the slack variables $v_S^{\uparrow}$ and $v_S^{\downarrow}$, in (24)–(27). Relaxing future flexibility requirement comes at a cost, since it may lead to poor prepositioning of the I resources at the current time, which, in turn, may affect future flexibility availability. Therefore, the cost of envelope relaxation is reflected in the third term of (14). The cost is also discounted at a rate of $\gamma(\tau)$ to reflect that near-term flexibility is more valuable than long-term flexibility. A reliability criterion [7] or a cost/benefit analysis [38] can also be used to limit the use of the slack resources.

Thus, the problem in (14)–(27) becomes that of balancing the current flexibility requirement (i.e., the ability to ramp from the previous dispatch time step to a feasible positioning at the current time step) with the future flexibility requirement (i.e., enclosing the projected flexibility requirement envelope), while balancing the system's current netload. The tradeoff depends on how the I resources, the slack resources, and the envelope's slack variables are priced relative to one another in (14).

B. Simulation Setup

A toy system consisting of five flexibility resources will be used to simulate the dispatch operations of a single hour, with the objective of showing that the FE-RHED approach leads to

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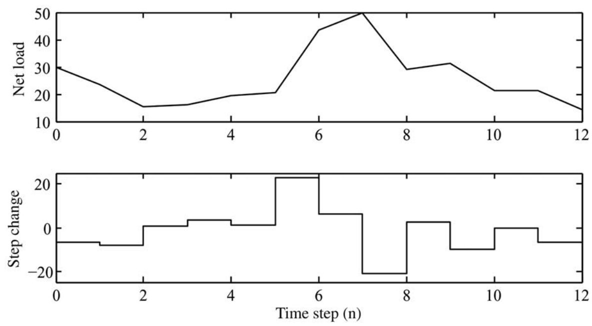

Fig. 7. Single realization of netload random process with caps on RES capacity and ramping rate.

TABLE I
RESOURCES' CAPACITY, RAMPING, AND COST CHARACTERISTICS

	$g^{\max}$ (MW)	$g^{\min}$ (MW)	R (MW/5 min)	c ($/MWh)
1	10	2	3.07	20
2	10	2	3.07	40
3	10	2	3.07	60
4	10	2	3.07	80
5	10	2	3.07	100
$S^{\uparrow}$	∞	0	∞	1000
$S^{\downarrow}$	0	$-\infty$	∞	1000
$v_S^{\uparrow}$	∞	0	∞	1000
$v_S^{\downarrow}$	0	$-\infty$	∞	1000

less load shedding and less generation spillage than the M-ED and SR-ED approaches.

1) Time Resolution: The hour is discretized into $N = 12$ time steps of length $\Delta = 5$ min. This means dispatch decisions are obtained every 5 min, and the netload varies randomly every 5 min as well. The projected envelopes are discretized at 5-min for $H = 12$.

2) Netload Model: The load is constant at 50 MW throughout the hour. The RES output varies randomly according to a Laplace distribution characterized by $\beta = 10$ MW/5 min. There is 40 MW of RES capacity, and the RES maximum 5-min step change is $\lambda = 1.63 \cdot \sqrt{2} \cdot 10 = 23.05$ MW/5 min. This corresponds to the 90th percentile of the Laplace distribution. Therefore, the netload $\ell(k+n)$ can vary between 10 and 50 MW, and the 5-min step changes in the RES realizations are bounded between 0 and λ. The RES forecast for the hour is 20 MW, meaning that $\hat{\ell}(k+n) = 30$ MW for $n = 0$ in Fig. 7.

3) Flexibility Resources: There are five identical flexibility resources which are given fixed incremental costs. There are two slack resources priced at a much higher cost than the other five resources. Table I shows the capacity, ramping, and cost characteristics of flexibility resources, slack resources, and envelopes' slack variables. The combined ramping of flexibility resource is two thirds of λ computed above, to simulate flexibility scarcity.

4) Dispatch Policies: The linear program described in (14)–(27) is used to simulate the FE-RHED, M-ED, and SR-ED approaches for $N = 12$ time steps. In the case of FE-RHED, the horizon is set to 1 h, $H = 12$. In the case of M-ED, the horizon length is set to zero, such that there is no reserve planning looking forward. In the case of SR-ED, the horizon length is set to 10 min with a 10-min discretization, such that there is only one step looking forward to plan the 10-min reserve as per NERC's requirement. For all policies, the discount factor in (14) is set to one.

5) Performance Metrics: To assess the quality of the dispatch decisions made through the various policies, we calculate the energy served for each realization j ($\mathrm{ES}_{i,j}$) and the expected energy served (EES_i) by each resource i. In addition, we compute the energy not served (ENS_j) and the energy curtailed (EC_j) for each realization j, from which we obtain the EENS and the EEC for all J realizations of the netload random process

$$\mathrm{ES}_{i,j} = \sum_{n=1}^{N} g_{i,j}(k+n)\Delta, \quad i = 1,\ldots,I; j = 1,\ldots,J \tag{28}$$

$$\mathrm{EES}_{i,J} = \frac{1}{J}\sum_{j=1}^{J} \mathrm{ES}_{i,j}, \quad i = 1,\ldots,I \tag{29}$$

$$\mathrm{ENS}_j = \sum_{n=1}^{N} S_j^{\uparrow}(k+n)\Delta, \quad j = 1,\ldots,J \tag{30}$$

$$\mathrm{EENS}_J = \frac{1}{J}\sum_{j=1}^{J} \mathrm{ENS}_j \tag{31}$$

$$\mathrm{EC}_j = \sum_{n=1}^{N} -S_j^{\downarrow}(k+n)\Delta, j = 1,\ldots,J \tag{32}$$

$$\mathrm{EEC}_J = \frac{1}{J}\sum_{j=1}^{J} \mathrm{EC}_j \tag{33}$$

where $g_{i,j}(k+n)$, $S_{i,j}^{\uparrow}(k+n)$, and $S_{i,j}^{\downarrow}(k+n)$ correspond to the realizations of the economic dispatch decisions at time step n for random netload realizations $j = 1,\ldots,J$.

Because of the power balance imposed by (15), the sum of the expected values (29)–(33) should converge to the expected netload energy (ENLE) requirement

$$\mathrm{ENLE}_J = \frac{1}{J}\sum_{j=1}^{J}\sum_{n=1}^{N} \ell_j(k+n)\Delta \tag{34}$$

which should be 30 MWh given the forecasts for the load (50 MW) and the variable generation (20 MW). To assess convergence of the dispatch simulations, we calculate the incremental change in ENLE_J and ensure that it is less than the desired accuracy ($\epsilon = 0.01$ MWh here)

$$|\mathrm{ENLE}_J - \mathrm{ENLE}_{J-1}| < \epsilon. \tag{35}$$

Hence, once we have simulated J realizations of the netload random process and that it affects the value of ENLE_J by less than $\epsilon = 0.01$ MWh, we stop.

C. Simulation Results and Discussion

Table II displays the EES values for each of the flexibility resources for the hour of operation and for each economic dispatch approach. Table III shows the EENS, EEC, and ENLE

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TABLE II
EXPECTED ENERGY SERVED (EES) BY RESOURCES (MWH)

	M-ED	SR-ED		FE-RHED	
	Benchmark		Change (%)		Change (%)
1	8.26	6.97	–15.6	6.49	–21.4
2	7.37	6.56	–11.0	6.26	–15.1
3	5.99	6.00	0.3	6.01	0.4
4	4.61	5.45	18.2	5.75	24.8
5	3.79	5.04	33.1	5.52	45.8
Expected dispatch cost ($)	1567	1702	+8.6	1753	+11.9

TABLE III
EXPECTED ENERGY NOT SERVED (EENS), EXPECTED ENERGY CURTAILED (EEC), EXPECTED NETLOAD ENERGY (ENLE), AND TOTAL EXPECTED COST IMPLICATIONS

	M-ED	SR-ED		FE-RHED	
	Benchmark		Change (%)		Change (%)
EENS (MWh)	0.73	0.37	–48.5	0.29	–61.0
EEC (MWh)	0.74	0.39	–47.2	0.31	–58.6
ENLE (MWh)	30.01	30.01	–	30.01	–
Expected total cost ($)	3037	2462	–18.9	2353	–22.5

values for each economic dispatch approach as well. The percentage changes are taken with respect to the M-ED approach. By inspection of the tables, we can see how imposing a spinning reserve requirement in SR-ED shifts part of the dispatch from cheaper resources to the more expensive ones. Imposing the envelope in FE-RHED further shifts the dispatch from cheaper resources to the more expensive ones. Out-of-merit dispatch operation leads to an increase in cost as shown in Table II, but leads to a decrease in load shedding (EENS) and RES curtailment (EEC), as seen in Table III. Although there has been an increase in the dispatch cost, we see that the overall system cost (accounting for dispatch, load shedding, and generation curtailment) has dropped in a nonnegligible fashion with both SR-ED and FE-RHED.

By inspection of Fig. 8, we can see how the spinning reserve requirement attempts to tighten the distribution of EC and ENS in comparison to the M-ED (middle plot), whereas the envelope requirement further tightens the distribution in comparison to SR-ED (bottom plot). The tightness of the histogram implies how well each economic dispatch approach is capable of mitigating system imbalances and thus maintaining power balance as dispatch operations move forward in time.

Hence, there are advantages in properly capturing the underlying system netload variability envelope through its systematic encapsulation. The first main advantage lies with the reductions in the expected values of ENS, EC, and their corresponding variances. Second, we have to emphasize that this has been achieved at the price of very little computational cost increases, in comparison to a dispatch problem formulation based on multiscenario stochastic optimization.

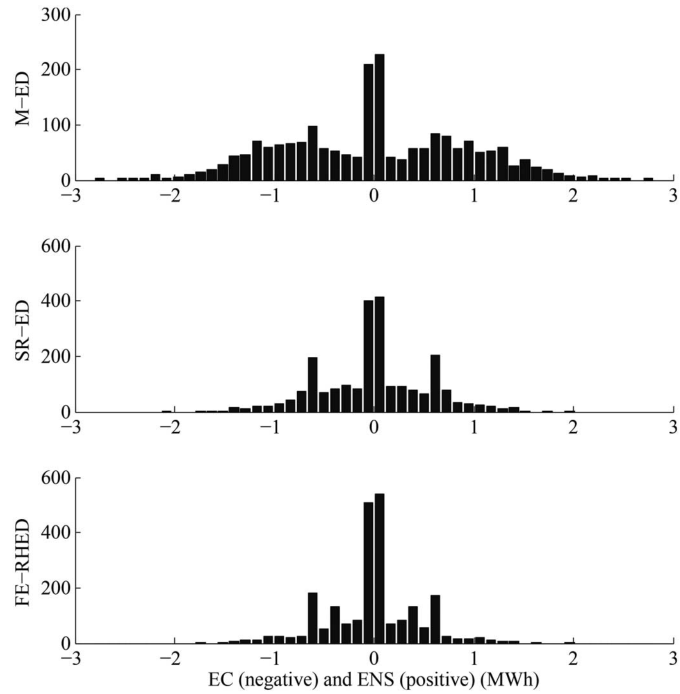

Fig. 8. Histograms of EC and ENS for each dispatch approach.

VII. CONCLUSION

Power system flexibility is an emerging concept there to complement traditional capacity adequacy planning in modern power systems. Flexibility adequacy emphasizes on timely delivery of reserve capacity as much as it emphasizes on the capacity itself. However, current operational and planning practices do not address satisfactorily flexibility requirement and typically assume sufficient rampability of allocated reserve capacity. This can have great impact on short- and long-term operations planning when significant amounts of non-dispatchable generation are present. In this paper, we emphasized the need to model the intra-hourly flexibility potential dynamics of power system resources through the notion of flexibility envelopes. We presented a case study illustrating the value of the flexibility envelope concept in the context of a receding horizon economic dispatch with highly variable generation. The dispatch approach based on flexibility envelopes, as expected, can decrease energy not served and energy curtailed in comparison to more traditional approaches. Its computational complexity is well under that of other approaches which consider an explicit representation of generation variability and uncertainty (e.g., stochastic optimization, dynamic programming). Ongoing work in this area is addressing some of the longer term flexibility planning issues, including flexibility investment, along with the addition of transmission constraints in long- and short-term planning.

REFERENCES

[1] International Energy Agency, "Harnessing variable renewables: A guide to the balancing challenge," OECD/IEA, Paris, France, Tech. Rep. 61-2011-17-1P1, 2011.

[2] E. Lannoye, D. Flynn, and M. O'Malley, "The role of power system flexibility in generation planning," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Detroit, MI, USA, 2011, pp. 1–6.

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[3] S. T. Lee and Z. A. Yamayee, "Load-following and spinning-reserve penalties for intermittent generation," *IEEE Trans. Power Appl. Syst.*, vol. 100, no. 3, pp. 1203–1211, Mar. 1981.
[4] F. Bouffard and M. Ortega-Vazquez, "The value of operational flexibility in power systems with significant wind power generation," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Detroit, MI, USA, 2011, pp. 1–5.
[5] L. Xie *et al.*, "Wind integration in power systems: Operational challenges and possible solutions," *Proc. IEEE*, vol. 99, no. 1, pp. 214–232, Jan. 2011.
[6] E. Lannoye, D. Flynn, and M. O'Malley, "Evaluation of power system flexibility," *IEEE Trans. Power Syst.*, vol. 27, no. 2, pp. 922–931, May 2012.
[7] R. Doherty and M. O'Malley, "A new approach to quantify reserve demand in systems with significant installed wind capacity," *IEEE Trans. Power Syst.*, vol. 20, no. 2, pp. 587–595, May 2005.
[8] N. Troy, D. Flynn, and M. O'Malley, "The importance of sub-hourly modeling with a high penetration of wind generation," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, San Diego, CA, USA, 2012, pp. 1–6.
[9] J. Ma, V. Silva, R. Belhomme, D. S. Kirschen, and L. F. Ochoa, "Evaluating and planning flexibility in sustainable power systems," *IEEE Trans. Sustain. Energy*, vol. 4, no. 1, pp. 200–209, Jan. 2013.
[10] North American Electric Reliability Corporation, "Accommodating high levels of variable generation," NERC, Princeton, NJ, USA, Tech. Rep., 2009.
[11] North American Electric Reliability Corporation, "Special report. Flexibility requirements and potential. Metrics for variable generation: Implications for system planning studies," NERC, Princeton, NJ, USA, Tech. Rep., 2010.
[12] Y. Makarov, C. Loutan, and P. de Mello, "Operational impacts of wind generation on california power systems," *IEEE Trans. Power Syst.*, vol. 24, no. 2, pp. 1039–1050, May 2009.
[13] Y. Dvorkin, D. S. Kirschen, and M. A. Ortega-Vazquez, "Assessing flexibility requirements in power systems," *IET Gener. Transm. Distrib.*, vol. 8, no. 11, pp. 1820–1830, Nov. 2014.
[14] A. Ulbig and G. Andersson, "On operational flexibility in power systems," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, San Diego, CA, USA, 2012, pp. 1–8.
[15] T. Zheng, J. Zhao, F. Zhao, and E. Litvinov, "Operational flexibility and system dispatch," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, San Diego, CA, USA, 2012, pp. 1–3.
[16] J. Apt, "The spectrum of power from wind turbines," *J. Power Sources*, vol. 169, no. 2, pp. 369–374, 2007.
[17] M. Ortega-Vazquez and D. Kirschen, "Should the spinning reserve procurement in systems with wind power generation be deterministic or probabilistic?" in *Proc. Int. Conf. Sustain. Power Gener. Supply*, Nanjing, China, 2009, pp. 1–9.
[18] E. Lannoye, D. Flynn, and M. O'Malley, "Transmission, variable generation, and power system flexibility," *IEEE Trans. Power Syst.*, vol. 30, no. 1, pp. 57–66, Jan. 2015.
[19] E. Ela and M. O'Malley, "Studying the variability and uncertainty impacts of variable generation at multiple timescales," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1324–1333, Aug. 2012.
[20] L. Soder, "Reserve margin planning in a wind-hydro-thermal power system," *IEEE Trans. Power Syst.*, vol. 8, no. 2, pp. 564–571, May 1993.
[21] F. Galiana, F. Bouffard, J. Arroyo, and J. Restrepo, "Scheduling and pricing of coupled energy and primary, secondary, and tertiary reserves," *Proc. IEEE*, vol. 93, no. 11, pp. 1970–1983, Nov. 2005.
[22] Y. G. Rebours, D. S. 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.
[23] European Network of Transmission System Operators for Electricity, "Supporting document for the network code on load-frequency control and reserves," ENTSO-E, Brussels, Belgium, Tech. Rep., 2013.
[24] F. Bouffard, F. Galiana, and A. Conejo, "Market-clearing with stochastic security—Part I: Formulation," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 1818–1826, Nov. 2005.
[25] F. Bouffard and F. Galiana, "Stochastic security for operations planning with significant wind power generation," *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 306–316, May 2008.
[26] S. Chan, D. C. Powell, M. Yoshimura, and D. Curtice, "Operations requirements of utilites with wind power generation," *IEEE Trans. Power Appl. Syst.*, vol. 102, no. 9, pp. 2850–2860, Sep. 1983.
[27] R. Doherty and M. O'Malley, "Quantifying reserve demands due to increasing wind power penetration," in *Proc. IEEE Power Tech*, Bologna, Italy, 2003, vol. 2, pp. 1–5.
[28] M. Matos and R. Bessa, "Setting the operating reserve using probabilistic wind power forecasts," *IEEE Trans. Power Syst.*, vol. 26, no. 2, pp. 594–603, May 2011.
[29] M. Ortega-Vazquez and D. Kirschen, "Estimating the spinning reserve requirements in systems with significant wind power generation penetration," *IEEE Trans. Power Syst.*, vol. 24, no. 1, pp. 114–124, Feb. 2009.
[30] J. Kiviluoma *et al.*, "Short-term energy balancing with increasing levels of wind energy," *IEEE Trans. Sustain. Energy*, vol. 3, no. 4, pp. 769–776, Oct. 2012.
[31] Y. V. Makarov, P. V. Etingov, J. Ma, Z. Huang, and K. Subbarao, "Incorporating uncertainty of wind power generation forecast into power system operation, dispatch, and unit commitment procedures," *IEEE Trans. Sustain. Energy*, vol. 2, no. 4, pp. 433–442, Oct. 2011.
[32] M. Nazir and F. Bouffard, "Intra-hour wind power characteristics for flexible operations," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, San Diego, CA, USA, 2012, pp. 1–8.
[33] D. Lee and R. Baldick, "Analyzing the variability of wind power output through the power spectral density," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, San Diego, CA, USA, 2012, pp. 1–8.
[34] W. Lin, J. Wen, S. Cheng, and W.-J. Lee, "An investigation on the active-power variations of wind farms," *IEEE Trans. Ind. Appl.*, vol. 48, no. 3, pp. 1087–1094, May/Jun. 2012.
[35] Y. Dvorkin, H. Pandzic, M. A. Ortega-Vazquez, and D. S. Kirschen, "A hybrid stochastic/interval approach to transmission-constrained unit commitment," *IEEE Trans. Power Syst.*, vol. 30, no. 2, pp. 621–631, Jul. 2014.
[36] L. Wu, M. Shahidehpour, and Z. Li, "Comparison of scenario-based and interval optimization approaches to stochastic SCUC," *IEEE Trans. Power Syst.*, vol. 27, no. 2, pp. 913–921, May 2012.
[37] J. Morales, A. Conejo, and J. Perez-Ruiz, "Economic valuation of reserves in power systems with high penetration of wind power," *IEEE Trans. Power Syst.*, vol. 24, no. 2, pp. 900–910, May 2009.
[38] M. A. Ortega-Vazquez and D. S. Kirschen, "Optimizing the spinning reserve requirements using a cost/benefit analysis," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 24–33, Feb. 2007.

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