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Power-Capacity and Ramp-Capability Reserves for Wind Integration in Power-Based UC

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***Abstract*—This paper proposes a power-based network-constrained unit commitment (UC) model as an alternative to the traditional deterministic UCs to deal with wind generation uncertainty. The formulation draws a clear distinction between power-capacity and ramp-capability reserves to deal with wind production uncertainty. These power and ramp requirements can be obtained from wind forecast information. The model is formulated as a power-based UC, which schedules power-trajectories instead of the traditional energy-blocks and takes into account the inherent startup and shutdown power trajectories of thermal units. These characteristics allow a correct representation of each unit's ramp schedule, which defines its ramp availability for reserves. The proposed formulation significantly decreases operation costs compared to traditional deterministic and stochastic UC formulations while simultaneously lowering the computational burden. The operation cost comparison is made through 5-min economic dispatch simulation under hundreds of out-of-sample wind generation scenarios.**

***Index Terms*—Mixed-integer programming, operating reserves, power-based UC, power-capacity reserves, ramp-capability reserves, unit commitment.**

NOMENCLATURE

Upper-case letters are used for denoting parameters and sets. Lower-case letters denote variables and indexes.

A. Indexes and Sets

$g \in \mathcal{G}$	Generating units, running from 1 to G.
$b \in \mathcal{B}$	Buses, running from 1 to B.
$\mathcal{B}^{\mathrm{D}}$	Set of buses in $\mathcal{B}$ with demand consumption.
$\mathcal{B}^{\mathrm{W}}$	Set of buses in $\mathcal{B}$ with wind power injection.
$l \in \mathcal{L}$	Transmission lines, running from 1 to L.
$t \in \mathcal{T}$	Hourly periods, running from 1 to T hours.

B. Parameters

D_{bt}	Power demand on bus b at the end of hour t [MW].
Γ_{lb}	Shift factor for line l associated with bus b [p.u.].
Γ^{P}_{lg}	Shift factor for line l associated with unit g [p.u.].
$\overline{F}_l$	Flow limit on transmission line l [MW].
$\overline{P}_g$	Maximum power output [MW].
$\underline{P}_g$	Minimum power output [MW].
RD_g	Ramp-down capability [MW/h].
RU_g	Ramp-up capability [MW/h].
SD_g	Shutdown ramping capability [MW/h].
SU_g	Startup ramping capability [MW/h].
W_{bt}	Nominal forecasted wind power at end of hour t [MW].
$\overline{W}_{bt}$	Upper bound of the forecasted wind power at the end of hour t [MW].
$\underline{W}_{bt}$	Lower bound of the forecasted wind power at the end of hour t [MW].
$W^{\mathrm{R}-}_{bt}$	Ramp-down forecasted wind requirement for the whole hour t [MW/h].
$W^{\mathrm{R}+}_{bt}$	Ramp-up forecasted wind requirement for the whole hour t [MW/h].

C. Decision Variables

1) Day-ahead schedule decisions:

r^{-}_{gt}	Down power-capacity reserve scheduled [MW].
r^{+}_{gt}	Up power-capacity reserve scheduled [MW].
$r^{\mathrm{R}-}_{gt}$	Down ramp-capability reserve scheduled [MW/h].
$r^{\mathrm{R}+}_{gt}$	Up ramp-capability reserve scheduled [MW/h].
u_{gt}	Binary variable which is equal to 1 if the unit is producing above $\underline{P}_g$ and 0 otherwise.
v_{gt}	Binary variable which takes the value of 1 if the unit starts up and 0 otherwise.
z_{gt}	Binary variable which takes the value of 1 if the unit shuts down and 0 otherwise.

2) Dispatch decisions:

p_{gt}	Power output above minimum output at the end of hour t [MW].
$\widehat{p}_{gt}$	Total power output at the end of hour t, including startup and shutdown trajectories [MW].
$\overline{r}_{gt}$	Reserve deployment to provide the upper-wind dispatch $\overline{w}_{bt}$ [MW].
$\underline{r}_{gt}$	Reserve deployment to provide the lower-wind dispatch $\underline{w}_{bt}$ [MW].
w_{bt}	Wind dispatch for the nominal wind case W_{bt} [MW].
$\overline{w}_{bt}$	Wind dispatch for the upper bound wind $\overline{W}_{bt}$ [MW].
$\underline{w}_{bt}$	Wind dispatch for the lower bound wind $\underline{W}_{bt}$ [MW].

D. Functions

$c^{\mathrm{F}}_{gt}(\cdot)$	Fixed production cost [$].
$c^{\mathrm{V}}_{gt}(\cdot)$	Variable production cost [$].

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I. Introduction

In recent years, high penetration of variable generating sources, such as wind power, has challenged independent system operators (ISO) in maintaining a reliable power system operation. The deviation between expected and real wind production must be absorbed by the power system resources (reserves), which must be available and ready to be deployed in real time. To guarantee this availability, the system resources must be committed in advance, usually day-ahead, by solving the so-called unit commitment (UC) problem.

A. Literature Review

1) Dealing with Uncertainty in UC: Stochastic and robust optimization have gained substantial popularity for UC optimization under parameter uncertainty. In the stochastic optimization approach, the stochasticity can be represented through an explicit description of scenarios and their associated probability [1], [2]. This approach presents however some practical limitations: 1) it may be difficult to obtain an accurate probability distribution of the uncertainty; and 2) a large number of scenario samples is required to obtain robust solutions, which results in a computationally intensive problem (often intractable).

The robust optimization approach partly overcomes these disadvantages 1) by requiring moderate information about the underlying uncertainty, such as the mean and the range of the uncertain data; and 2) by immunizing the solution against all realizations of the data within the uncertainty range. However, it may be too conservative, since the objective function is to minimize the worst-case cost scenario, which may never be realized in practice. To deal with overconservatism, 1) a parameter commonly called budget-of-uncertainty is introduced in the optimization problem to control the conservatism of the robust solution [3], [4]; and 2) more recently, [4] proposes an unified stochastic and robust UC model that takes advantage of both stochastic and robust optimization approaches, where the objective is to achieve a low expected total cost while ensuring the system robustness.

Although the computational burden of adaptive robust UC does not depend on the number of scenarios, it requires solving a mixed integer programming (MIP) problem together with a bilinear program to obtain the worst-case scenario. This problem is considerably more complex to solve than a pure MIP, requires ad-hoc solving strategies [3], [4], and it can also considerably increase the computational burden of UC problems.

In short, although stochastic and robust UCs are powerful tools to deal with uncertainty, they are computationally intensive. This is the reason why traditional deterministic formulations remain valid and widely used by ISOs worldwide. This motivates the development of improved deterministic formulations that better exploit the flexibility of the power system and better face wind uncertainty.

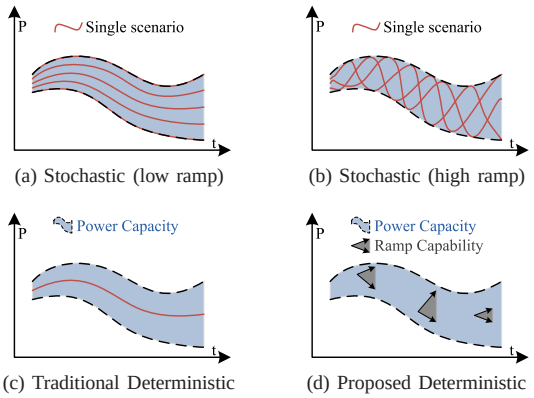
2) Power-Capacity and Ramp-Capability Reserves: In order to solve the day-ahead UC considering wind generation, it is necessary to take into account uncertainty. As the wind power forecasting error can be significant 24 hours in advance, the range of possible values of wind power for each hour of the following day can be very broad. As a consequence, ISOs need to schedule some power-capacity reserve to guarantee that committed system resources will be able to cope with any value of wind generation that can be realised within that range.

When getting closer to the real time, for instance one hour in advance, the range of possible values for the next hour is smaller. However, even within such short time interval, wind generation can increase or decrease its value at a rate that will require that conventional generators adapt their output to follow that ramp to keep the demand-supply balance. Therefore, apart from the day-ahead power-capacity reserve, it will be necessary to ensure that for any hour, the committed system resources will be able to cope with the expected maximum ramp of variation of the wind generation. Thus, a ramp-capability reserve is also needed.

To illustrate the need of a clear differentiation between power-capacity and ramp-capability reserves, consider the following example. Figs. 1a and 1b show two different set of wind scenarios which present the same power-capacity uncertainty ranges, but completely different ramp-capability uncertainty ranges. Dealing with the scenarios in Fig. 1b requires higher ramp-capability, although both set of scenarios demand the same power-capacity requirements. In fact, some power systems have experienced short-term scarcity events caused by resources with sufficient power capacity but insufficient ramp capability [5]. In response, ISOs are developing market-based ramping products, thus making a clear difference between power-capacity and ramp-capability requirements [5], [6].

A stochastic UC implicitly captures both reserve requirements through scenarios; e.g., Figs. 1a and 1b show how the shape of the set of scenarios implicitly guarantee that the system can provide different ramp-capability reserve requirements, even though the power-capacity reserve requirements are the same. However, to correctly represent these reserve requirements, a large number of scenarios is needed, resulting in a high computational cost. On the other hand, the traditional deterministic UCs can only ensure a given power-capacity reserve, see Fig. 1c, but it cannot guarantee different ramping requirements to deal with either of the scenarios in Figs. 1a and 1b. Although deterministic UC remains the ISOs' dominant practice nowadays due to the low computational burden, it does not efficiently exploit the system flexibility to deal with the specific requirements imposed by wind generation uncertainty.

3) Power-based UC: Conventional day-ahead UC formulations fail to deal with ramp capabilities appropriately. Inefficient ramp management arises from applying ramp-constraints to energy levels or (hourly) averaged generation levels; consequently, energy schedules may not be feasible [7]. In addition, traditional UC models assume that units start/end their production at their minimum output. That is, the intrinsic startup and shutdown power trajectories of units are ignored. As a consequence, there may be a high amount of energy that is not allocated by UC but is inherently present in real time, thus affecting the total load balance and causing a negative economic impact [8]. For further details of the drawbacks of conventional UC scheduling approaches, the reader is referred to [9], [10] and references therein.



(a) Stochastic (low ramp) (b) Stochastic (high ramp)

(c) Traditional Deterministic (d) Proposed Deterministic

Fig. 1: Different approaches to deal with wind uncertainty

To overcome these drawbacks, [10] proposes the power-based UC (or ramping scheduling) approach. This approach uses piece-wise linear power trajectories for both generating units and demand instead of the commonly established staircase profile for energy blocks. The use of an instantaneous power profile allows the model to efficiently schedule reserves and ramping resources. In comparison with conventional UC models, the power-based UC approach guarantees that, first, energy schedules can be delivered and, second, that operating reserves can be deployed respecting the ramping and capacity limits of generating units. In addition, the model takes into account the normally neglected power trajectories that occur during the startup and shutdown processes, thus optimally scheduling them to provide energy and ramp, which help to satisfy the power demand.

B. Power-Capacity and Ramp-Capability Reserves in Power-Based UC: An Overview

This paper proposes a deterministic power-based network-constrained UC model as an alternative to the traditional deterministic UCs to deal with wind generation uncertainty. The proposed UC gives flexibility to the power system to face wind uncertainty. This flexibility is provided by drawing a clear distinction between power-capacity and ramp-capability reserve requirements (Fig. 1d), and by optimally dispatching wind generating units. Allowing a different value for ramp-capability reserve requirements results in a more realistic setting, as discussed above. Wind dispatch flexibility is modelled by considering curtailment in the UC formulation. Curtailment may appear due to either economic reasons or technical reasons, e.g., insufficient network capacity. This flexibility helps to reduce the reserve requirements since part of the uncertainty can be faced by curtailment, as practiced in ERCOT and MISO. Introducing other renewable energy sources to the formulation is straightforward if they can be curtailed.

The model is formulated as a power-based UC, which schedules power-trajectories instead of the traditional energy-blocks, and it takes into account the inherent startup and shutdown power trajectories of thermal units. These characteristics allow a correct representation of unit's ramp schedule [7], [8] which define their ramp availability for reserves [10].

The formulation is represented as a mixed integer programming (MIP) problem, which has become the leading approach in the electricity sector due to significant improvements in MIP solvers. The core of the proposed MIP formulation is built upon the convex-hull and the tight-and-compact formulations presented in [8] and [11], respectively, thus taking advantage of their mathematical properties. These formulations improve the convergence speed by reducing the search space (tightness) and at the same time increasing the searching speed with which solvers explore that reduced space (compactness).

This paper presents an extensive numerical study on the IEEE 118-bus test system, where the proposed formulation is compared with the stochastic and with the deterministic approaches. To perform comparisons and to obtain an accurate estimate of the performance of each UC policy, the hourly commitment obtained from each UC approach is evaluated through a 5-min economic dispatch for hundreds of out-of-sample scenarios.

C. Contributions and Paper Organization

The principal contributions of this paper are as follows:

1) A practical deterministic mixed-integer programming (MIP) UC formulation that explicitly includes a pre-specified nodal power-capacity and ramp-capability reserve requirements, which can be obtained from wind forecast information; unlike traditional deterministic UCs [10], [12], which only consider power-capacity reserves. The proposed formulation explicitly models the interdependency between the power-capacity and ramp-capability reserves; i.e., providing ramp-capability means providing power-capacity, but providing power-capacity does not necessarily mean providing a given level of ramp-capability.
2) Although the proposed UC formulation optimizes over a nominal wind scenario, it also includes the worst-case wind scenario proposed in [13], and so the UC solution guarantees that the system has enough flexibility to adapt to any wind uncertain realization. The level of conservatism of the solution is controlled by the reserve parameters and wind curtailment flexibility. That is, once the reserve requirements are fixed, the proposed UC reshape these requirements by considering curtailment.
3) The proposed deterministic UC can be used by ISOs to ensure that enough power-capacity and ramp-capability resources are available to deal with wind uncertainty in real-time operation. ISOs can also adjust the level of conservatism of the solution by adjusting the reserve requirements, based on their preferences and on their available information of wind uncertainty.
4) A validation methodology that mimics the real-time operation of the power system where the day-ahead UC decisions are dispatched against different realizations of wind uncertainty. The idea is to take the (hourly) UC decisions as fixed, and to run an economic-dispatch model with a detailed time representation (a granularity of 5-min time intervals) for many wind scenarios, independently. From each execution (which is a deterministic

problem) it is possible to compute the corresponding operational cost, the number start-ups, etc. By comparing the average of these values, their dispersion, and the worst case solutions, it is possible to compare the effectiveness of different UC decisions.

The remainder of this paper is organized as follows. Section II details the mathematical formulation of the different operating reserves (power-capacity and ramp-capability) and their links with the ramp schedules. Section III presents some numerical examples as well as a comparison with the deterministic and stochastic UC approaches. Finally, concluding remarks are made in Section IV.

II. Mathematical Formulation

This section presents the proposed mathematical formulation of the power-based UC. This section first discusses the relationship between the wind uncertainty range and the power system reserve requirements. The next part is devoted to modelling the reserve constraints for generating units and the network constraints. Finally, the objective function is defined.

A. Wind Uncertainty Range and Power System Requirements

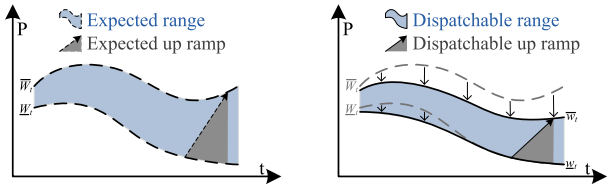
The first step is to define the level of reserves. In this paper, two different type of reserves are defined based on power-capacity and ramp-capability uncertainty ranges of wind production. These uncertainty ranges are defined by the expected minimum and maximum variations of power-capacity and ramp wind production, see Fig. 1d. Power-capacity uncertainty range: the wind power production in node b at time t is expected to be within the power-capacity range defined by the lower and upper bounds $\left[\underline{W}_{bt}, \overline{W}_{bt}\right]$. Ramp-capability uncertainty range: the wind production in node b at time t is expected to ramp within the range defined by the maximum ramp down and ramp up $\left[W_{bt}^{\mathrm{R}-}, W_{bt}^{\mathrm{R}+}\right]$.

Notice that, similarly to the deterministic uncertainty sets in robust UCs [3], the power-capacity and ramp-capability uncertainty ranges defined here are deterministic and must be set by ISOs. These ranges can be based on, for example, wind forecast (with a given confidence level) and/or historical information.

Similarly to traditional deterministic UCs, the proposed model also requires a nominal profile of wind production W_{bt} as input data. This nominal wind profile must be defined by ISOs (e.g., as the most expected wind production), where the only limitation is that the nominal value of wind production must be defined within the ranges of wind power-capacity $\left[\underline{W}_{bt}, \overline{W}_{bt}\right]$ and ramp-capability $\left[W_{bt}^{\mathrm{R}-}, W_{bt}^{\mathrm{R}+}\right]$.

For the sake of clarity, this section first introduces a formulation (1)-(5) for the power system requirements where wind curtailment is not allowed. Then, the flexibility that brings the fact that wind generation can be curtailed is taken into account in (11)-(15).

1) Power System Requirements Without Allowing Wind Curtailment: Once the wind uncertainty ranges for power-capacity $\left[\overline{W}_{bt}, \underline{W}_{bt}\right]$ and ramp-capability $\left[W_{bt}^{\mathrm{R}+}, W_{bt}^{\mathrm{R}-}\right]$ are defined, the power system must supply demand and reserves for these ranges:



(a) Forecasted range (b) Dispatchable range

Fig. 2: Forecasted and dispatchable wind uncertainty ranges

$$\sum_{g\in\mathcal{G}} \widehat{p}_{gt} = \sum_{b\in\mathcal{B}^{\mathrm{D}}} D_{bt} - \sum_{b\in\mathcal{B}^{\mathrm{W}}} W_{bt} \quad \forall t \tag{1}$$

$$\sum_{g\in\mathcal{G}} r_{gt}^{+} \geq \sum_{b\in\mathcal{B}^{\mathrm{W}}} \left(W_{bt} - \underline{W}_{bt}\right) \quad \forall t \tag{2}$$

$$\sum_{g\in\mathcal{G}} r_{gt}^{-} \geq \sum_{b\in\mathcal{B}^{\mathrm{W}}} \left(\overline{W}_{bt} - W_{bt}\right) \quad \forall t \tag{3}$$

$$\sum_{g\in\mathcal{G}} r_{gt}^{\mathrm{R}+} \geq \sum_{b\in\mathcal{B}^{\mathrm{W}}} \tilde{W}_{bt}^{\mathrm{R}-} \quad \forall t \tag{4}$$

$$\sum_{g\in\mathcal{G}} r_{gt}^{\mathrm{R}-} \geq \sum_{b\in\mathcal{B}^{\mathrm{W}}} \tilde{W}_{bt}^{\mathrm{R}+} \quad \forall t \tag{5}$$

where (1) is a power balance at the end of hour t. Note that the energy balance for the whole hour is automatically achieved by satisfying the power demand at the beginning and end of each hour, and by considering a piecewise-linear power profile for demand and generation [10].

Equality (1) ensures that the system provides the power and ramp requirements for the wind nominal case. Constraints (2)-(3) and (4)-(5) guarantee that the system can provide the maximum power and ramp deviations from the nominal case, respectively. Parameters $\tilde{W}_{bt}^{\mathrm{R}+}$ and $\tilde{\mathrm{W}}_{bt}^{R-}$ are the maximum up and down ramp deviations from the nominal ramp, respectively, and are obtained as follows:

$$\tilde{W}_{bt}^{\mathrm{R}+} = W_{bt}^{\mathrm{R}+} - \left(W_{bt} - W_{b,t-1}\right) \quad \forall b \in \mathcal{B}^{\mathrm{W}}, t \tag{6}$$

$$\tilde{W}_{bt}^{\mathrm{R}-} = W_{bt}^{\mathrm{R}-} - \left(W_{b,t-1} - W_{bt}\right) \quad \forall b \in \mathcal{B}^{\mathrm{W}}, t \tag{7}$$

Notice that the right sides of (2)-(5) are (input) parameters, this means that ISOs must define the requirements for up (2) and down (3) power-capacity reserves as well as up (4) and down (5) ramp-capability reserves. The following section shows how these reserve requirements are reshaped by the model when allowing wind curtailment.

2) Power System Requirements Including Wind Curtailment: Now, the flexibility that brings the fact that wind generation can be curtailed is taken into account. Thus, the possible dispatched wind range that results from the UC may (shrink) be different from the forecasted range; that is, both power-capacity and ramp-capability reserve requirements may shrink by allowing wind curtailment, as shown in Fig. 2.

To allow curtailment in the formulation, the wind-dispatch variables are bounded by their associated wind forecast

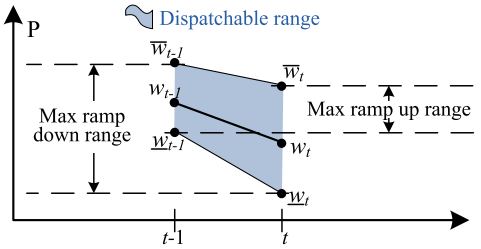


Fig. 3: Maximum ramp up and down within the wind dispatchable range

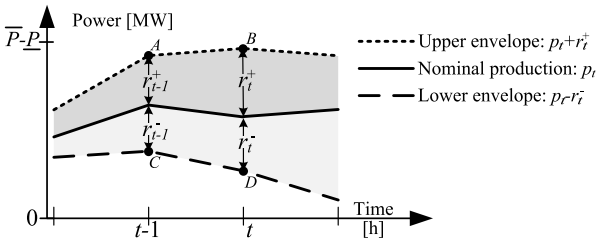


Fig. 4: Unit's operating range for power capacity

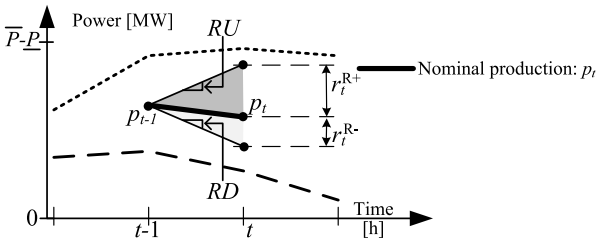


Fig. 5: Unit's operating range for ramp capability

bounds:

$$0 \leq \underline{w}_{bt} \leq \underline{W}_{bt},\ 0 \leq w_{bt} \leq W_{bt},\ 0 \leq \overline{w}_{bt} \leq \overline{W}_{bt} \quad \forall b \in \mathcal{B}^{\mathrm{W}}, t \tag{8}$$

and the auxiliary variables $w_{bt}^{\mathrm{R}+}$ and $w_{bt}^{\mathrm{R}-}$ are defined as the maximum ramp up and down range, exceeding the nominal wind production values, that can fit within the dispatchable wind range:

$$w_{bt}^{\mathrm{R}+} = (\overline{w}_{bt} - w_{bt}) + \left(w_{b,t-1} - \underline{w}_{b,t-1}\right) \quad \forall b \in \mathcal{B}^{\mathrm{W}}, t \tag{9}$$

$$w_{bt}^{\mathrm{R}-} = (\overline{w}_{b,t-1} - w_{b,t-1}) + (w_{bt} - \underline{w}_{bt}) \quad \forall b \in \mathcal{B}^{\mathrm{W}}, t \tag{10}$$

where these equations can be obtained from Fig. 3. Note that the dispatchable wind range for period t is defined by the lower bound $(\underline{w}_{b,t-1}, \underline{w}_{bt})$ and upper bound $(\overline{w}_{b,t-1}, \overline{w}_{bt})$ wind dispatches. The maximum possible ramp up within this range is given by $\overline{w}_{bt} - \underline{w}_{b,t-1}$ (Fig. 3), then the maximum possible ramp-up deviation from the nominal wind dispatch ramp $(w_{bt} - w_{b,t-1})$ is $w_{bt}^{\mathrm{R}+} = \left(\overline{w}_{bt} - \underline{w}_{b,t-1}\right) - (w_{bt} - w_{b,t-1})$, which is (9). Similarly, $w_{bt}^{\mathrm{R}-}$ defined by (10) can be obtained.

Then (1)-(5) can be reformulated to allow wind curtailment:

$$\sum_{g \in \mathcal{G}} \widehat{p}_{gt} = \sum_{b \in \mathcal{B}^{\mathrm{D}}} D_{bt} - \sum_{b \in \mathcal{B}^{\mathrm{W}}} w_{bt} \quad \forall t \tag{11}$$

$$\sum_{g \in \mathcal{G}} r_{gt}^{+} \geq \sum_{b \in \mathcal{B}^{\mathrm{W}}} (w_{bt} - \underline{w}_{bt}) \quad \forall t \tag{12}$$

$$\sum_{g \in \mathcal{G}} r_{gt}^{-} \geq \sum_{b \in \mathcal{B}^{\mathrm{W}}} (\overline{w}_{bt} - w_{bt}) \quad \forall t \tag{13}$$

$$\sum_{g \in \mathcal{G}} r_{gt}^{\mathrm{R}+} \geq \sum_{b \in \mathcal{B}^{\mathrm{W}}} \inf\left(\tilde{W}_{bt}^{\mathrm{R}-}, w_{bt}^{\mathrm{R}-}\right) \quad \forall t \tag{14}$$

$$\sum_{g \in \mathcal{G}} r_{gt}^{\mathrm{R}-} \geq \sum_{b \in \mathcal{B}^{\mathrm{W}}} \inf\left(\tilde{W}_{bt}^{\mathrm{R}+}, w_{bt}^{\mathrm{R}+}\right) \quad \forall t. \tag{15}$$

The infimum functions in (14) and (15) guarantee that the ramp requirement do not exceed the scheduled wind range by choosing the minimum value between the forecasted ramp requirement and the maximum possible ramp within the scheduled wind range. An MIP equivalent formulation for the infimum function in (14) and (15) is provided in Appendix A.

In short, (11) ensures that the system provides the power and ramp requirements for the wind nominal case; (12) and (13) guarantee that enough up and down power-capacity reserves are scheduled, respectively; similarly, (14) and (15) ensure enough up and down ramp-capability reserves, respectively.

B. Individual Unit's Constraints

This section presents a set of constraints that guarantee that a unit can provide any power trajectory within its scheduled ramp-capability $r_{gt}^{\mathrm{R}+}, r_{gt}^{\mathrm{R}-}$ and power-capacity r_{gt}^{+}, r_{gt}^{-} reserve ranges. Fig. 4 shows how the nominal case and the power-capacity reserves define upper and lower envelopes for units' operation.

1) Commitment Logic: The relation between the commitment, startup and shutdown variables is given by:

$$u_{gt} - u_{g,t-1} = v_{gt} - z_{gt} \quad \forall g, t. \tag{16}$$

Constraints imposing the minimum up/down times and different startup types are also included, see [10].

2) Total Power Output for The Nominal Production: The proposed formulation considers slow- and quick-start units. For the sake of brevity, this section only presents the set of constraints for quick-start units, which can startup within one hour:

$$\widehat{p}_{gt} = \underline{P}_g \left(u_{gt} + v_{g,t+1}\right) + p_{gt} \quad \forall g, t. \tag{17}$$

The slow-start units are included into the formulation by only modifying (17), thus including shutdown and different-startup power trajectories that take longer than one hour. The reader is referred to [8], [10], [11] for further details.

3) Power-Capacity Reserves: The upper and lower envelopes must be within the unit's capacity limits, see Fig. 4:

$$p_{gt} + r_{gt}^{+} \leq \left(\overline{P}_g - \underline{P}_g\right) u_{gt} - \left(\overline{P}_g - SD_g\right) z_{g,t+1} + \left(SU_g - \underline{P}_g\right) v_{g,t+1} \quad \forall g, t \tag{18}$$

$$p_{gt} - r_{gt}^{-} \geq 0 \quad \forall g, t \tag{19}$$

4) Ramp-Capability Reserves: The unit's nominal production defines the ramp-capability that is available in every

period, see Fig. 5:

$$p_{gt} - p_{g,t-1} + r^{\mathrm{R}+}_{gt} \leq RU_g u_{gt} + \left(SU_g - \underline{P}_g\right) v_{g,t+1} \quad \forall g,t \tag{20}$$

$$-p_{gt} + p_{g,t-1} + r^{\mathrm{R}-}_{gt} \leq RD_g u_{gt} + \left(SD_g - \underline{P}_g\right) z_{gt} \quad \forall g,t \tag{21}$$

In these constraints, the terms $\left(SU_g - \underline{P}_g\right) v_{g,t+1}$ and $\left(SD_g - \underline{P}_g\right) z_{gt}$ ensure that $r^{\mathrm{R}+}_{gt}$ and $r^{\mathrm{R}-}_{gt}$ respect the startup (SU_g) and shutdown (SD_g) ramping capabilities of the units. However, if one wanted to ensure ramping constraints only on variables p_{gt}, the inequalities $-RD_g \leq p_{gt} - p_{g,t-1} \leq RU_g$ would have been enough since the units' startup (SU_g) and shutdown (SD_g) ramping capabilities are imposed by (18).

5) Relationship Between Power-Capacity and Ramp-Capability Reserves: The following constraints ensure that the unit operate within the ramp limits on either the upper or lower envelopes, respectively:

$$-r^{\mathrm{R}-}_{gt} \leq r^{+}_{gt} - r^{+}_{g,t-1} \leq r^{\mathrm{R}+}_{gt} \quad \forall g,t \tag{22}$$

$$-r^{\mathrm{R}-}_{gt} \leq r^{-}_{gt} - r^{-}_{g,t-1} \leq r^{\mathrm{R}+}_{gt} \quad \forall g,t \tag{23}$$

where (22) and (23) can be obtained from Fig. 4, see Appendix B for further details.

The available up (down) ramp-capability $r^{\mathrm{R}+}_{gt}$ ($r^{\mathrm{R}-}_{gt}$) is bounded by the maximum upwards (downwards) power change that is possible within power-capacity operating range, $C \rightarrow B$ ($A \rightarrow D$) in Fig. 4:

$$r^{\mathrm{R}+}_{gt} \leq r^{-}_{g,t-1} + r^{+}_{gt} \quad \forall g,t \tag{24}$$

$$r^{\mathrm{R}-}_{gt} \leq r^{+}_{g,t-1} + r^{-}_{gt} \quad \forall g,t. \tag{25}$$

Constraints (24) and (25) guarantee that once the unit is scheduled to provide ramp-capability reserve, there is a scheduled power-capacity range that can allow this ramp-capability deployment.

Finally, all these reserve variables are defined as positive:

$$r^{+}_{gt}, r^{-}_{gt}, r^{\mathrm{R}+}_{gt}, r^{\mathrm{R}-}_{gt} \geq 0 \quad \forall g,t. \tag{26}$$

In summary, constraints (18)-(26) guarantee that the unit can provide any power trajectory within its scheduled ramp-capability and power-capacity reserve ranges.

C. Network Constraints

The work in [13][1] shows that by finding a feasible dispatch for the lowest expected wind bound $\underline{w}_{bt}$, all other possible wind realizations within the uncertainty range are feasible. That is, all scenarios can become $\underline{w}_{bt}$ by curtailment. Consequently, all scenarios can be dispatched and, in the worst case, the maximum quantity of wind that can be dispatched for any scenario would be $\underline{w}_{bt}$. Now, by ensuring a feasible dispatch for the upper expected wind bound $\overline{w}_{bt}$, the formulation guarantees that wind scenarios up to $\overline{w}_{bt}$ can also be dispatched.

Now, the units' reserve deployments for the upper ($\overline{r}_{gt}$) and lower ($\underline{r}_{gt}$) expected wind bounds are obtained. These reserve deployments must be within the scheduled power capacity limits:

$$-r^{-}_{gt} \leq \overline{r}_{gt}, \underline{r}_{gt} \leq r^{+}_{gt} \quad \forall g,t \tag{27}$$

and they must also satisfy ramp limit constraints:

$$-r^{\mathrm{R}-}_{gt} \leq \overline{r}_{gt} - \overline{r}_{g,t-1} \leq r^{\mathrm{R}+}_{gt} \quad \forall g,t \tag{28}$$

$$-r^{\mathrm{R}-}_{gt} \leq \underline{r}_{gt} - \underline{r}_{g,t-1} \leq r^{\mathrm{R}+}_{gt} \quad \forall g,t. \tag{29}$$

Finally the transmission capacity constraints are enforced for both the upper and lower expected wind bounds:

$$-\overline{F}_l \leq \sum_{g\in\mathcal{G}} \Gamma^{\mathrm{P}}_{lg} \left(\widehat{p}_{gt} + \overline{r}_{gt}\right) + \sum_{b\in\mathcal{B}^{\mathrm{W}}} \Gamma_{lb}\overline{w}_{bt} - \sum_{b\in\mathcal{B}^{\mathrm{D}}} \Gamma_{lb} D_{bt} \leq \overline{F}_l \quad \forall l,t \tag{30}$$

$$-\overline{F}_l \leq \sum_{g\in\mathcal{G}} \Gamma^{\mathrm{P}}_{lg} \left(\widehat{p}_{gt} + \underline{r}_{gt}\right) + \sum_{b\in\mathcal{B}^{\mathrm{W}}} \Gamma_{lb}\underline{w}_{bt} - \sum_{b\in\mathcal{B}^{\mathrm{D}}} \Gamma_{lb} D_{bt} \leq \overline{F}_l \quad \forall l,t. \tag{31}$$

The demand balances for these scenarios are guaranteed by (11) together with:

$$\sum_{g\in\mathcal{G}} \overline{r}_{gt} = \sum_{b\in\mathcal{B}^{\mathrm{W}}} \left(w_{bt} - \overline{w}_{bt}\right) \quad \forall t \tag{32}$$

$$\sum_{g\in\mathcal{G}} \underline{r}_{gt} = \sum_{b\in\mathcal{B}^{\mathrm{W}}} \left(w_{bt} - \underline{w}_{bt}\right) \quad \forall t \tag{33}$$

and the nominal wind production must be within its upper and lower wind dispatches:

$$\underline{w}_{bt} \leq w_{bt} \leq \overline{w}_{bt} \quad \forall b \in \mathcal{B}^{\mathrm{W}}, t. \tag{34}$$

Notice that total reserve deployment for the upper wind dispatch (32) is negative, this means that the power system must decrease its overall generation when wind production is above the nominal value. Notice in (32) and (33) that the power-capacity reserve requirements are provided by $\overline{r}_{gt}, \underline{r}_{gt}$ then these variables provide the limits on r^{-}_{gt}, r^{+}_{gt}. In other words, variables $\overline{r}_{gt}, \underline{r}_{gt}$ will be equal to either r^{-}_{gt} or r^{+}_{gt}. Therefore, (28) and (29) are more constrained and dominate (22) and (23), that is, (22) and (23) are then redundant.

Constraints (12) and (13) ensure that the units can provide the required power-capacity reserves, and constraints (30)-(34) guarantee that there is transmission capacity available so these power-capacity reserves can be deployed to places in the network where these reserves are required.

D. Objective Function

The objective function of the proposed UC model is to minimize the operational cost incurred to provide the nominal wind scenario:

[1] A similar result can be concluded from theory of adaptive robust optimization for LP problems [14]. Note that the uncertainty affecting every one of the constraints (upper bound of wind dispatch, i.e., $w_{bt} \leq \xi_{bt}$) is independent of each other, and the uncertainty set is defined as a continuous interval (i.e., $\underline{w}_{bt} \leq \xi_{bt} \leq \overline{w}_{bt}$). Due to these specific characteristics, the fully adaptive solution of the second-stage problem, which is LP, is equivalent to the static (or non-adaptive) one (i.e., $w_{bt} \leq \underline{w}_{bt}$), as proven in [14] and further discussed in [15]. This simple MIP formulation of the adaptive robust problem is possible because all second-stage variables are linear, although the first-stage variables are integer [16].

$$\min \sum_{t\in\mathcal{T}}\sum_{g\in\mathcal{G}}\left[\underbrace{c^{\mathrm{F}}_{gt}\left(u_{gt},v_{gt},z_{gt}\right)}_{\text{Day-ahead schedule}}+\underbrace{c^{\mathrm{V}}_{gt}\left(\widehat{p}_{gt}\right)}_{\text{Dispatch}}\right] \quad (35)$$

As (35) does not capture the effect on the cost of deploying the scheduled reserves, it is possible to add a weighted sum of the cost terms that correspond to the cases in which the generators deploy all their upper and lower capacity reserves:

$$\min \sum_{t\in\mathcal{T}}\sum_{g\in\mathcal{G}}\left[\underbrace{c^{\mathrm{F}}_{gt}\left(u_{gt},v_{gt},z_{gt}\right)}_{\text{Day-ahead schedule}}\right.$$
$$\underbrace{\left.+(1-\alpha)\,c^{\mathrm{V}}_{gt}\left(\widehat{p}_{gt}\right)+\alpha\left(\frac{c^{\mathrm{V}}_{gt}\left(\widehat{p}_{gt}+\overline{r}_{gt}\right)+c^{\mathrm{V}}_{gt}\left(\widehat{p}_{gt}+\underline{r}_{gt}\right)}{2}\right)\right]}_{\text{Dispatch}} \quad (36)$$

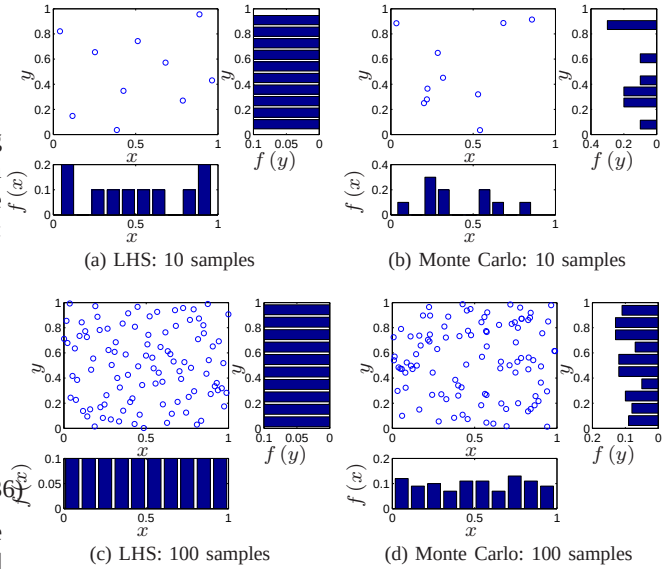
where the weight α gives the flexibility to ISOs to give priority to dispatches around the nominal value ($\widehat{p}_{gt}$) or around the extremes ($\widehat{p}_{gt}+\overline{r}_{gt}$ and $\widehat{p}_{gt}+\underline{r}_{gt}$), hence ISOs can set α according to their preferences. Notice, however, that α should be small ($\sim$ 0.1), giving higher priority to the nominal dispatch, since wind production is usually normal-like distributed (most of the samples are around the nominal value rather than on the extremes). Section III-B1 shows a sensitivity analysis for different values of α.

The day-ahead schedule costs counts the fixed production cost $c^{\mathrm{F}}_{gt}(\cdot)$ which is composed by the no-load, shutdown and different startup costs, depending on how long the unit has been offline [10]. The dispatch costs counts the variable production cost $c^{\mathrm{V}}_{gt}(\cdot)$ that is calculated based on the units' energy production, which can be easily obtained from $\widehat{p}_{gt}$ [10].

III. Numerical Results

The performance of our proposed approach is evaluated using the modified IEEE 118-bus test system, available online at www.iit.upcomillas.es/aramos/IEEE118_SUSD-Ramps.xls, for a time span of 24 hours. The system has 118 buses; 186 transmission lines; 54 thermal units; 91 loads, with average and maximum aggregated levels of 3991 MW and 5592 MW, respectively; and three wind units, with aggregated average and maximum production for the nominal wind case of 867 MW and 1333 MW, respectively. The power system data are based on that in [2] and it was adapted to consider startup and shutdown power trajectories. All tests were carried out using CPLEX 12.6 [17] on an Intel-i7 3.4-GHz personal computer with 16 GB of RAM memory. The problems are solved until they hit a time limit of 7200 seconds or until they reach an optimality tolerance of 0.05%.

This section first shows the procedure used to evaluate the performance of the UC solutions. Then, Section III-B performs sensitivity analysis of the proposed formulation in terms of the objective weight and uncertainty range. Finally, Section III-C compares the performance of the proposed approach with the traditional deterministic and stochastic approaches.



(a) LHS: 10 samples (b) Monte Carlo: 10 samples

(c) LHS: 100 samples (d) Monte Carlo: 100 samples

Fig. 6: Latin hypercube sampling (LHS) vs. simple Monte Carlo simulation: Uniform distribution fit in two dimensions x, y and their resulting probability densities $f(x), f(y)$.

A. Evaluating Approach

1) Scenario Generation: The scenarios are created assuming that the wind production follows a multivariate normal distribution with predicted value W and volatility matrix Σ [4]. Monte Carlo simulation is one of the sampling strategies most commonly used to create scenarios [1]. However, Monte Carlo sampling requires a very large number of samples to explore the whole area in the experimental region and to recreate the input distributions. In addition, a problem of clustering arises when a small number of samples are created. These problems are illustrated in Figs. 6b and 6d.

To overcome these drawbacks, Latin Hypercube Sampling (LHS) is used to generate scenarios for the uncertain wind production. The idea in applying LHS is to optimally distribute the samples to explore the whole area in the experimental region, avoiding the creation of scenarios that are too similar (clusters) [18]. Furthermore, LHS can recreate the input distribution with a relatively small number of samples. Fig. 6 compares LHS with Monte Carlo sampling for a small (10) and a large (100) number of samples in two dimensions. Note how LHS better explore the experimental region and also presents fewer clusters than Monte Carlo sampling.

2) Scheduling and Validation Stages: To compare the performance of the different UC approaches, this paper makes a clear difference between the scheduling stage and the validation stage. The computational experiments proceed as follows.

1) Scheduling stage: solve the different UC models and obtain the hourly commitment solutions, using 20 wind scenarios for each of the three wind units. Fig. 7 shows the aggregated wind production of these wind scenarios. For this study case, the nominal profile of wind production W_{bt} was computed as the middle value of the power-capacity uncertainty range, i.e., $\left(\overline{W}_{bt}+\underline{W}_{bt}\right)/2$.

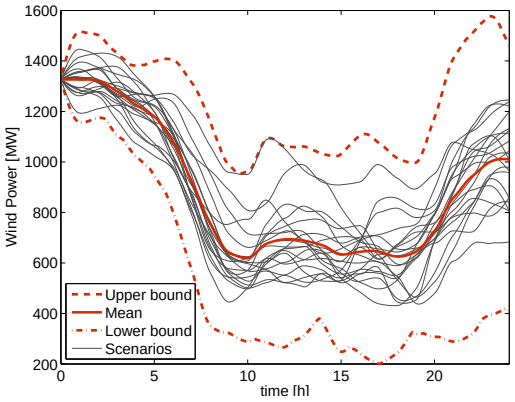


Fig. 7: Representation of wind uncertainty over time, scenarios and bounds

2) Out-of-sample validation stage: for each fixed UC solution, solve a 5-min economic dispatch problem repetitively for a set of 200 new wind scenarios. Notice that around the 20% of these out-of-sample scenarios fall outside the uncertainty bounds shown in Fig. 7.

The scheduling stage uses the 20 scheduling wind scenarios (Fig. 7) to define the wind uncertainty ranges for power-capacity $\left[\overline{W}_{bt}, \underline{W}_{bt}\right]$ and ramp-capability $\left[W_{bt}^{\mathrm{R}-}, W_{bt}^{\mathrm{R}+}\right]$, which are needed by the proposed UC formulation to define the power-capacity and ramp-capability reserve requirements, respectively (as discussed in Section II-A):

$$\overline{W}_{bt} = \sup_{s}\left(W_{sbt}\right) \quad \forall b \in \mathcal{B}^{\mathrm{W}}, t \tag{37}$$

$$\underline{W}_{bt} = \inf_{s}\left(W_{sbt}\right) \quad \forall b \in \mathcal{B}^{\mathrm{W}}, t \tag{38}$$

$$W_{bt}^{\mathrm{R}+} = \sup_{s}\left(W_{sbt} - W_{sb,t-1}\right) \quad \forall b \in \mathcal{B}^{\mathrm{W}}, t \tag{39}$$

$$W_{bt}^{\mathrm{R}-} = \sup_{s}\left(W_{sb,t-1} - W_{sbt}\right) \quad \forall b \in \mathcal{B}^{\mathrm{W}}, t \tag{40}$$

where $\sup(\cdot)$ and $\inf(\cdot)$ are the supremum and infimum functions, respectively. The parameter W_{sbt} is the wind power [MW] in bus b at end of hour t for scenario s, which belong to the set of the 20 wind scheduling scenarios.

In the 5-min economic dispatch, penalty costs for the violation of some constraints are introduced to mimic the high costs due to corrective actions in real time operations. The penalty costs are set to 10000 and 5000 $/MWh for demand-balance and transmission-limits violations, respectively, as suggested in [19] (similarly to [3], [4]). These penalty costs represent the expensive real-time corrective actions that an ISO needs to take in the event that the actual system condition significantly deviates from the expected condition, such as dispatching fast-start units, voltage reduction or load shedding. Notice that these demand-balance and transmission-limits violations are only allowed in the 5-min economic dispatch (validation stage) and not in the UC (scheduling stage) problems, allowing these violations with high penalty costs also helps finding solutions to infeasible dispatch problems.

The performance of the UC strategies are shown in eight aspects, two related with the scheduling stage and six with the validation stage. These aspects, presented in Tables I to III, are described as follows. Scheduling stage: 1) the fixed production costs described in Section II-D (UC [k$]), and 2) the number of startups (# SU). These two aspects indicate the commitment decisions that were needed by each approach to prepare the system to deal with the given wind uncertainty. Validation stage: 3) the average dispatch costs (Average), indicates the economic efficiency of the UC decision; 4) the volatility of these costs (Std), represented by the standard deviation of dispatch costs, which indicates the reliability of the real-time dispatch operation under the UC decision; 5) the dispatch cost of the worst-case scenario (Worst), indicates how robust the UC decision is against the worst-case scenario (from the 200 out-of-sample scenarios); 6) number of scenarios where there were violations in either demand-balance or transmission-limits constraints (# Sc); 7) total number of these violations (# Tot); and 8) total accumulated energy that could not be accommodated, demand-balance violations (MWh). The last three aspects also indicate how robust the UC decision is against different wind scenarios.

Table I: SENSITIVITY OF OBJECTIVE WEIGHT α

α	Scheduling Hourly		Validation: 5-min Economic Dispatch					
			Dispatch Costs [k$]			Violations		
	UC [k$]	# SU	Average	Std	Worst	# Sc	# Tot	MWh
0	52.026	14	771.115	14.351	814.471	2	2	0.038
0.1	51.986	14	770.823	14.365	814.223	2	2	0.038
0.2	51.949	14	770.970	14.348	814.087	2	2	0.048
0.3	51.986	14	770.806	14.364	814.206	2	2	0.038
0.4	51.961	14	770.928	14.392	814.201	2	2	0.038
0.5	51.351	13	771.642	14.361	814.667	2	2	0.038
0.6	51.259	13	771.822	14.408	815.037	0	0	0.000
0.7	50.446	14	772.659	14.325	815.602	1	1	0.004
0.8	50.623	14	772.657	14.378	816.045	5	5	0.108
0.9	50.435	14	772.725	14.327	815.951	5	5	0.108
1.0	49.824	13	773.503	14.355	816.718	5	5	0.108

B. Sensitivity Analysis

1) Changes of Objective Weight α: The performance of the proposed approach is tested under different α and the results are shown in Table I. Notice that the performance does not change considerably. The maximum values of the Average, Std and Worst-case dispatch cost are 0.6% above the minimum values. These small changes are because the model guarantee feasibility through a set of hard constraints; however, the results may change considerably if one relaxes the demand-balance and transmission constraints by introducing penalty-cost violations (i.e., depending on the value of α, large violations may appear since their weigh in the objective function can be insignificant, then not guaranteeing a feasible deployment of reserves in real-time operation). Henceforth, α is set to 0.1.

2) Changes of Uncertainty Range: Table II shows the results in the scheduling and validation stage for different values of the uncertainty range, from 0 to 100%. The 100% uncertainty range is defined by the bounds shown in Fig. 7, and the 0% is equivalent to a deterministic UC using only the nominal wind case. These ranges were equally changed to the power-capacity and ramp-capability ranges. It can be clearly observed that the larger the considered uncertainty range, the UC costs and number of startups increase because

Table II: SENSITIVITY OF UNCERTAINTY RANGE

%	Scheduling Hourly		Validation: 5-min Economic Dispatch					
			Dispatch Costs [k$]			Violations		
	UC [k$]	# SU	Average	Std	Worst	# Sc	# Tot	MWh
0	46.705	10	1067.017	575.205	5479.411	103	1744	5884.536
10	46.906	10	1018.959	505.127	5017.905	101	1492	4928.511
20	46.725	10	966.994	461.833	4797.448	87	1259	3883.190
30	47.443	11	877.291	337.356	3905.236	53	759	2102.645
40	47.941	12	825.176	228.394	3130.061	31	308	1052.421
50	47.973	12	795.862	134.644	2317.292	16	145	460.961
60	48.691	13	780.770	67.952	1617.704	11	77	165.247
70	51.583	13	772.493	26.906	1039.311	6	39	43.814
80	51.442	13	770.863	14.830	831.475	4	12	3.647
85	51.930	14	770.535	14.522	814.291	3	6	2.008
90	51.911	14	770.562	14.384	814.089	2	2	0.038
95	51.934	14	770.740	14.382	814.246	2	2	0.038
100	51.986	14	770.823	14.365	814.223	2	2	0.038

the UC solutions become more conservative. Consequently, the dispatch costs and violations decreases.

Through different uncertainty ranges, there is a significant reduction in the Average and Std dispatch costs. This significant reduction is closely related to the violations reduction and its associated costs, which represent the expensive emergency actions that the ISO has to take to maintain system reliability.

Notice that the uncertainty range of 85% presents the lowest average dispatch costs. This indicates that the uncertainty range can be slightly reduced without sacrificing the efficiency and robustness of the UC solution. One can observe in the ranges (85% and above) presenting few violations that considering lower uncertainty levels leads to better economic benefit, but worse risk performance, which is represented by the standard deviation of the dispatch cost. Using this information, a proper tradeoff can be made by decision makers.

Henceforth, the uncertainty range is set to 100%.

C. Comparing the Proposed Approach with the Traditional-Deterministic and Stochastic Approaches

The proposed UC formulation (ResRPC), which includes ramp-capability and power-capacity reserves, is compared with the traditional deterministic-reserve modelling (DetRes) and the stochastic (StchOpt) UC approaches. All three models are based on the power-based UC proposed in [10].

To obtain the commitment strategies of all UC approaches, the 20 wind scenarios shown in Fig. 7 are used, as described in the scheduling stage in Section III-A. These scenarios are assumed to be the only information available for the scheduling stage. Therefore, these data are used to describe the different wind uncertainty representation required by the different UC approaches. The proposed approach ResRPC uses the nominal wind production together with minimum and maximum bounds of power-capacity and ramp-capability, which are obtained from this set of scenarios [as previously defined by (37)-(40)]. The stochastic approach StchOpt uses all 20 scenarios. Finally, the deterministic approach DetRes uses the nominal wind production and two hourly reserves, upwards and downwards which are defined as $\sum_b \left(W_{bt} - \underline{W}_{bt}\right)$ and $\sum_b \left(\overline{W}_{bt} - W_{bt}\right)$, respectively.

1) Reliability of Dispatch Operation: Table III compares the performance of the different UC approaches. From the scheduling stage, one can observe that DetRes commits the largest quantity of resources, because this is the only approach that cannot readjust (optimize) the given level of reserves by considering wind curtailment. That is, the reserve requirements for the deterministic approach results in a larger quantity of committed resources. On the other hand, ResRPC presents lower FxdCost than Stch, but ResRPC started two more units. This difference is because ResRPC scheduled more flexible units (smaller with higher ramps) which usually present lower fixed costs but higher variable costs.

Table III: BETWEEN DIFFERENT UC POLICIES UNDER THE 200 OUT-OF-SAMPLE WIND SCENARIOS

	Scheduling Hourly		Validation: 5-min Economic Dispatch					
			Dispatch Costs [k$]			Violations		
	UC [k$]	# SU	Average	Std	Worst	# Sc	# Tot	MWh
ResRPC	51.986	14	770.823	14.365	814.223	2	2	0.038
StchOpt	54.765	12	808.971	200.096	2903.841	28	259	611.473
DetRes	55.492	16	857.199	279.813	3254.877	55	611	1793.881

From the validation stage in Table III, the following can be observed:

1) The Average and Std dispatch costs of StchOpt are around 6% and 40% lower than DetRes, respectively. This clearly shows the advantages of the stochastic strategy over the deterministic one, as expected.
2) Although DetRes committed the largest quantity of resources, it is the least robust. This is mainly because the deterministic approach only models the network constraints for the nominal case and it cannot guarantee that the committed reserves can be deployed. This is in contrast to ResRPC and StchOpt, where generating units are committed taking into account that power must be delivered to specific places in the network where the uncertainty appears.
3) The Average dispatch cost of StchOpt is around 5% higher than ResRPC, and the Std for StchOpt is more than an order of magnitude higher (13.9 times). Similarly, the total quantity of violations and the energy unbalance of StchOpt is more than two (130 times) and four (16k times) orders of magnitude higher than ResRPC, respectively.

In short, the proposed approach ResRPC presents a better economic-benefit and risk performance than the deterministic and stochastic approaches for this study case. Consequently, ResRPC offers more robust commitment decisions which lead to a better system reliability.

Although LHS is used to represent the space of scenarios adequately, the performance of StchOpt may be improved by introducing a larger quantity of scenarios in the scheduling stage or by a better scenario sampling. To observe the performance of ResRPC and DetRes compared with a "perfect" stochastic approach, the economic dispatch validation is carried out using the same scenarios used by StchOpt in the scheduling stage. Table IV shows the performance of the different UC approaches under the 20 scheduling scenarios. For this case, StchOpt presented the lowest Average dispatch cost, around 0.3% lower than ResRPC, but the Std and the Worst-case are higher than ResRPC. Notice that StchOpt

Table IV: BETWEEN DIFFERENT UC POLICIES UNDER THE 20 SCHEDULING WIND SCENARIOS

	5-min Economic Dispatch Simulation					
	Dispatch Costs [k$]			Violations		
	Average	Std	Worst	# Sc	# Tot	MWh
ResRPC	770.863	12.360	795.588	1	1	0.002
StchOpt	768.793	21.888	848.723	2	12	5.729
DetRes	803.457	119.146	1263.678	3	36	71.670

Table V: PROBLEM SIZE AND COMPUTATIONAL BURDEN OF THE DIFFERENT APPROACHES

	Problem Size [#]				Computational Burden	
	Constraints	Nonzero elements	Continuous variables	Binary variables	CPU Time [s]	Nodes explored
ResRPC	36141	1074712	21096	6520	90.45	250
StchOpt	225141	5600307	169776	6376	867.88	819
DetRes	18093	315424	11016	6376	8.75	29
5-min dispatch	157594	15711648	276195	0	82	0

presented constraint violations in two scenarios even though these scenarios were used in the scheduling stage. This is because the scheduling stage considers a simplified hourly piece-wise linear approximation of the 5-min smooth power profile of the set of scenarios shown in Fig. 7.

2) Computational Performance: Table V shows a comparison of problem size and computational burden between the different approaches. Notice that all three formulations have almost the same quantity of binary variables, but ResRPC has around 2.2% more than the others. This is due to the modelling of the infimum function that ResRPC requires, see Section II-A.

When comparing the number of constraints, nonzero elements and continuous variables, ResRPC is around twice the size of DetRes, and StchOpt is more than 12 and 6 times larger than DetRes and ResRPC, respectively. On the other hand, the CPU time of ResRPC is around an order of magnitude higher than that of DetRes, and one lower than that of StchOpt. Finally, unlike DetRes and ResRPC, the problem size and computational burden of StchOpt highly depends on the quantity of scenarios that it considers.

Table V also shows the computational performance of the 5-min economic dispatch simulation used for the validation stage. The 5-min optimal dispatch is an LP problem (0 binary variables), solved for the fixed hourly commitment UC decisions. The dispatch problem is significantly larger than the UC formulations because it is solved for 144 periods (5-min time step for 24 hours); however, its computational burden is low (average 82 seconds per scenario) because the problem is LP.

IV. CONCLUSIONS

This paper presented a deterministic power-based network-constrained UC formulation as an alternative to the traditional deterministic UC under wind generation uncertainty. The formulation draws a clear distinction between power-capacity and ramp-capability reserves to deal with wind production uncertainty. The model is formulated as a power-based UC, which schedules power-trajectories instead of the traditional energy-blocks and takes into account the inherent startup and shutdown power trajectories of thermal units. The formulation is compact since it only needs two reserve requirements and therefore keeps the advantages of deterministic UCs, unlike the stochastic approach for which problem size depends on the quantity of scenarios. Study cases showed that the proposed formulation significantly decreases operation costs compared to traditional deterministic and stochastic UC formulations while simultaneously lowering the computational burden. The operation cost comparison was made through 5-min economic dispatch simulation under hundreds of out-of-sample wind generation scenarios. As future studies, the performance of the proposed formulation should be compared with the traditional stepwise energy-block formulations under both stochastic and robust approaches for different power systems.

APPENDIX

A. MIP Equivalence for The Infimum Function

Inequality (41) seeks x to be greater than or equal to the minimum value between the parameter A and the variable y:

$$x \geq \inf(A, y). \tag{41}$$

An MIP equivalent of this non-linear function is:

$$x \geq A - a^+ \tag{42}$$
$$a^+ - a^- = A - y \tag{43}$$
$$a^+ \leq A\delta \tag{44}$$
$$a^- \leq B(1-\delta) \tag{45}$$
$$\delta \in \{0,1\}, \quad a^+, a^- \geq 0 \tag{46}$$

where (43)-(46) impose $a^+ = A - y$ if and only if $y \leq A$ and 0 otherwise. Variables a^+, a^- and δ are auxiliary, and B is a parameter representing the maximum possible value of the difference $A - y$. Therefore, the value of B for the infimum functions in (14) and (15) are set as $\overline{W}_{b,t-1} + W_{bt} - \tilde{W}_{bt}^{R-}$ and $\overline{W}_{bt} + W_{b,t-1} - \tilde{W}_{bt}^{R+}$, respectively.

B. Ramping Constraints on Envelopes

The following inequality is obtained by reorganizing the ramp-up constraints (20) and (22):

$$r_{gt}^+ - r_{g,t-1}^+ \leq r_{gt}^{\mathrm{R}+} \leq RU_g u_{gt} + \left(SU_g - \underline{P}_g\right) v_{g,t+1} - p_{gt} + p_{g,t-1} \qquad \forall g,t \tag{47}$$

where its left side together with its right side ensure

$$\left(p_{gt} + r_{gt}^+\right) - \left(p_{g,t-1} + r_{g,t-1}^+\right) \leq RU_g u_{gt} + \left(SU_g - \underline{P}_g\right) v_{g,t+1} \quad \forall g,t \tag{48}$$

which imposes the ramp-up on the upper envelope, $A \rightarrow B$ in Fig. 4.

Likewise, by reorganizing the ramp-down constraints (21) and (22), the following inequalities are obtained:

$$-r_{gt}^+ + r_{g,t-1}^+ \leq r_{gt}^{\mathrm{R}-} \leq RD_g u_{gt} + \left(SD_g - \underline{P}_g\right) z_{gt} + p_{gt} - p_{g,t-1} \qquad \forall g,t \tag{49}$$

where its left side together with its right side ensure

$$-\left(p_{gt}+r^{+}_{gt}\right)+\left(p_{g,t-1}+r^{+}_{g,t-1}\right)\leq RD_g u_{gt} + \left(SD_g-\underline{P}_g\right)z_{gt} \quad \forall g,t \quad (50)$$

which imposes the ramp-down constraint on the upper envelope, $A \rightarrow B$ in Fig. 4.

Similarly, (20) and (21) together with (23) guarantee the ramp-up and -down constraints on the lower envelope, $C \rightarrow D$ in Fig. 4.

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