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Assessment of Operation Reserves in Hydrothermal Electric Systems with High Wind Generation

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Abstract—In this paper, we propose a method to analyze the amount of operation reserves procured in a system based on two stages. The first stage is a detailed hourly unit commitment and the second stage is a simulation model with a shorter time period. The method is applied to the Spanish hydrothermal system and several cases are analyzed to determine the impact of the time period in the use of the operation reserves.

Index Terms—Mixed-integer programming, operating reserves, unit commitment, economic dispatch, wind power uncertainty.

I. INTRODUCTION

According to the UE targets, renewable generation (RES) has to play an important current and future role in the decarbonization of the electricity generation. In particular, wind power is largely contributing to produce electricity in many systems. In the short-term system operation, the uncertainty of the resources (namely, conventional and renewable generation and demand) is hedged by means of the operation reserves. The stochastic nature of wind generation, observed as variability and uncertainty in the resource, may impact the dimensioning of the operation reserves.

In this paper we present a framework to analyze the amount of operation reserves required in a hydrothermal system to deal with wind power and demand uncertainties. We use a combination of optimization and simulation models to analyze, as in [6] and [10]:

- On the one hand, the effect in the operation reserve usage of the hourly energy-block operation planning versus the 5-min economic dispatch and
- On the other hand, the impact of the uncertainty in the use of the operation reserves procured

The operation planning of the system is formulated as a tight and compact hourly Unit Commitment (UC) solved as a MIP optimization problem, based on [2] and [7]. Hydro units are represented into the system in an aggregated manner. The aggregation level coincides with the one used to bid in electricity markets. The operation cost determined by the hourly UC is re-evaluated through a 5-min time step Economic Dispatch (ED) simulation under hundreds of out-

of-sample uncertainty scenarios. Other alternative time steps, e.g., an hour, a half an hour or a quarter of an hour, for the ED are analyzed and their impact on the operation reserves usage.

The previous analysis is done for the Spanish hydroelectric system to see the effects of the current amount of operation reserves procured by the System Operator (SO).

The principal contributions of this paper are:

- A detailed representation of the power system short-term operation in an energy-based UC including startup and shutdown ramps of thermal units, based on [7] and [8]. By proposing a more accurate UC model, the system will be able to better operate the unit's flexibility in real-time. This UC model also includes an aggregate representation of the hydro power plants and their ability to provide operation reserves.
- A validation framework that resembles the real-time operation where the day-ahead hourly UC decisions are re-evaluated in shorter time periods under many realizations of the uncertain parameters.
- The analysis of the results in the application to a real hydroelectric system

The remainder of this paper is structured in this way. Section II briefly describes the power system representation of the thermal, hydro and renewable power plants. Section III presents the framework combining scheduling and evaluation stages to illustrate the real system operation. Sections IV and V describe the UC and simulation models respectively. In section VI we show the setup of the Spanish system case study. Section VII reports the analysis of the results and, finally, section VIII compiles the conclusions extracted.

II. POWER SYSTEM REPRESENTATION

This section briefly describes the main characteristics of the generation units.

The model accurately represents the startup and shutdown power trajectories of a thermal unit when increasing production from zero up to the minimum load or vice versa, see Figure 1. Taking into account these pre-established

trajectories of the thermal units modifies the use of operation reserves by the system and has impact on the system operation feasibility and costs. The mathematical formulation of the selection of any of the possible startup and shutdown trajectories in a UC is detailed in [8].

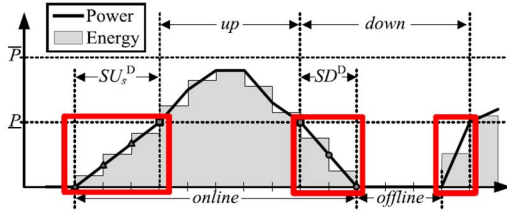


Figure 1. Startup and shutdown power trajectories.

This model also takes into account the up and down secondary reserves, up and down power ramps, minimum up and down times, see references [2] and [7].

Whereas the thermal generation is usually represented by individual physical units, the hydro generation presents different options regarding its modeling. The selection of the suitable hydro subsystem representation is significantly conditioned by the available data and the number of units to deal with.

1. A first option is to consider a detailed hydraulic model, with time-space connections and individual physical unit representation. Very accurate and detailed solutions can be obtained. However, in a very complex system, such as the one considered in this paper, it is in general not possible to use this type of modeling due to the computational burden and, specially, data requirements involved.
2. A second option is to use an aggregated model for each different hydrological basin, as in [3]. Although the computational burden is significantly reduced, lot of details are lost in the process.
3. Assuming the application of the analysis to the Spanish case, we use a simplified representation of the hydro subsystem based on the so called market programming units, because the market and system operation is recorded based on these units. These units represent either one hydro unit or a group of hydro units belonging to the same generation company and basin, which are geographically linked.

Renewable generation is introduced into the planning model as an upper bound hourly capacity. This allows curtailment if no enough renewable generation can be integrated into the system (e.g., because of technical or economic reasons).

III. OPERATION VALIDATION

The validation of the system operation is made based on two stages:

- *Scheduling stage*: planning of day-ahead hourly UC of the hydro and thermal units with a predefined RES generation scenario. Commitment decisions are taken at this scheduling stage.

- *Evaluation stage*: simulation of real-time system operation (ED for different time periods from 5 to 60 minutes) for many scenarios, once the hourly commitment of thermal units is already decided. The operation costs are determined for this real-time operation.

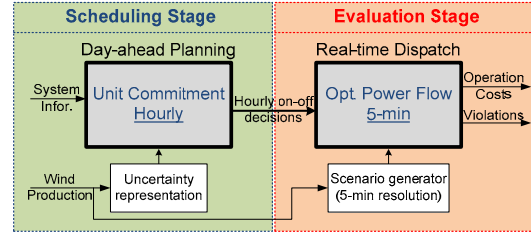


Figure 2. Operation validation scheme.

IV. UC MODEL

This section describes the mathematical formulation of the optimization hydrothermal UC problem, based on [2] and [7]. Introducing RES uncertainty in a UC model can be made in several ways, see [6]. One is a deterministic model, which considers the expected RES production. Another is a stochastic model, which considers many RES generation scenarios. And finally, other is a robust model, which allows the operation of the system under any (the worst) scenario. The stochastic model increases in size with the number of scenarios while the robust model is a deterministic model with some additional constraints to deal with the budget of uncertainty. In this paper, we have chosen to present the deterministic formulation for clarity purposes given that it is the most commonly used method in practice for real systems. However, in [6] we analyzed the stochastic and robust approaches.

The UC model presented in this section is generalized to allow different time periods, although we are using 1 hour as the time period. All the data and variables correspond to the end of the time period.

1.1 Notation

Indices

n	Time period
t, h	Thermal and hydro unit
g	Thermal and hydro units
l	Type of startup (cold, warm, etc.)

Parameters

D_n	Demand	MW
d_n^{2u}, d_n^{2d}	Secondary up and down reserve requirements	MW
d	Duration of the time period (1 h for the UC)	h
ig_n	RES generation forecasted	MW
$\bar{p}_t, \underline{p}_t, \bar{p}_h, \underline{p}_h$	Maximum and minimum thermal and hydro output	MW
f_t	No load cost	€/h
v_t	Variable cost	€/MWh
v_t^{2u}, v_t^{2d}	Up and down reserve variable cost	€/MW
v'_t	Energy not served (ENS) cost	€/MWh
su_t^l, sd_t	Startup and shutdown cost	€
rup_t, rdw_t	Ramp up and down	MW/h
tsu_t^l, tsd_t	Time for startup type l and shutdown	h

tu_t, td_t	Minimum up and down times	h
$P_t^{tsu,l}, P_t^{tsd}$	Output at each type of startup and shutdown for thermal units	MW
$\bar{p}_h^{2u}, \bar{p}_h^{2d}$ $\underline{p}_h^{2u}, \underline{p}_h^{2d}$	Maximum available up and down reserve for hydro unit	MW
ρ_h	Efficiency pumping-turbining	p.u.
E_h	Available energy for hydro unit	MWh

Variables

Variables are represented by capital letters.

UC_{nt}	Commitment decision	{0,1}
SU_{nt}^l, SD_{nt}	Startup for type l and shutdown decisions	{0,1}
P_{nt}^T	Total thermal output	MW
E_{nt}^T	Total thermal energy	MWh
P_{nt}	Output above the minimum load	MW
P_{nh}, C_{nh}	Hydro output and consumption	MW
P_{nt}^{2u}, P_{nt}^{2d} P_{nh}^{2u}, P_{nh}^{2d}	Up and down secondary reserve of thermal and hydro units	MW
IG_n	RES generation	MW
PNS_n	Power not served	MW
ENS_n	Energy not served	MWh

1.2 Formulation

The total variable cost of the system includes all the costs:

$$\min \sum_{nt} su_t^l SU_{nt}^l + \sum_{nt} sd_t SD_{nt} + \sum_{nt} f_t \cdot d \cdot UC_{nt} + \sum_{nt} v_t E_{nt}^T + \sum_{nt} v'_t ENS_{nt} + \sum_{nt} v_t^{2u} \cdot d \cdot P_{nt}^{2u} + \sum_{nt} v_t^{2d} \cdot d \cdot P_{nt}^{2d}$$

Power balance between generation and demand

$$\sum_t P_{nt} + \sum_h P_{nh} - \sum_h C_{nh} + IG_n + PNS_n = D_n \quad \forall n$$

Up and down secondary reserve system requirements

$$\sum_t P_{nt}^{2u} + \sum_h P_{nh}^{2u} \geq d_n^{2u} ; \quad \sum_t P_{nt}^{2d} + \sum_h P_{nh}^{2d} \geq d_n^{2d} \quad \forall n$$

Constraints in the capacity of thermal units

$$P_{nt} + P_{nt}^{2u} \leq UC_{nt} (\bar{p}_t - \underline{p}_t) - SU_{nt} (\bar{p}_t - \underline{p}_t) \quad \forall nt$$

$$P_{nt} + P_{nt}^{2u} \leq UC_{nt} (\bar{p}_t - \underline{p}_t) - SD_{n+1t} (\bar{p}_t - \underline{p}_t) \quad \forall nt$$

$$P_{nt} - P_{nt}^{2d} \geq 0 \quad \forall nt$$

Total thermal output including startup and shutdown trajectories

$$P_{nt}^T = P_{nt} + UC_{nt} \underline{p}_t + \sum_{n'=1}^{tsd_t} SD_{n-n'+1,t} P_t^{tsd} + \sum_{n'=1,l}^{tsu_t^l} SU_{n-n'+1+tsu_t^l}^l P_t^{tsu,l} \quad \forall nt$$

Energy as a function of the power

$$E_{nt}^T = d(P_{nt}^T + P_{n-1t}^T)/2 \quad \forall nt$$

$$ENS_n = d(PNS_n + PNS_{n-1})/2 \quad \forall n$$

Up and down ramps of thermal units

$$P_{nt} - P_{n-1,t} + P_{nt}^{2u} \leq rup_t d \quad \forall nt$$

$$P_{nt} - P_{n-1,t} - P_{nt}^{2d} \geq -rdw_t d \quad \forall nt$$

Commitment, startup and shutdown logic of thermal units

$$UC_{nt} - UC_{n-1,t} = SU_{nt} - SD_{nt} \quad \forall nt$$

Minimum up and down times of thermal units, based on [11]

$$\sum_{n'=n+1-tu_t}^n SU_{n't} \leq UC_{nt} ; \quad \sum_{n'=n+1-td_t}^n SD_{n't} \leq 1 - UC_{nt} \quad \forall nt$$

Type of startup of thermal units depending on the previous offline time

$$SU_{nt} = \sum_l SU_{nt}^l ; \quad SU_{nt}^l \leq \sum_{n'=tsu_t^l}^{tsu_t^{l+1}-1} SD_{n-n',t} \quad \forall nt$$

Constraints in the hydro energy production and available up and down secondary reserves for the scope of the model

$$\sum_n d(P_{nh} + P_{n-1h})/2 \leq E_h \quad \forall h$$

$$\sum_n d(P_{nh}^{2u} + P_{n-1h}^{2u})/2 \leq P_h^{2u} ; \quad \sum_n d(P_{nh}^{2d} + P_{n-1h}^{2d})/2 \leq P_h^{2d} \quad \forall h$$

Bounds on the variables

$$0 \leq P_{ng}^T \leq \bar{p}_g \quad \forall ng$$

$$0 \leq C_{nh} \leq \bar{p}_h \quad \forall nh$$

$$0 \leq P_{ng} \leq \bar{p}_g - \underline{p}_g \quad \forall ng$$

$$0 \leq P_{nt}^{2u}, P_{nt}^{2d} \leq \bar{p}_t - \underline{p}_t \quad \forall nt$$

$$\underline{p}_h^{2u} \leq P_{nh}^{2u} \leq \bar{p}_h^{2u} ; \quad \underline{p}_h^{2d} \leq P_{nh}^{2d} \leq \bar{p}_h^{2d} \quad \forall nh$$

$$0 \leq IG_n \leq ig_n ; \quad 0 \leq PNS_n \leq D_n \quad \forall n$$

$$UC_{nt}, SU_{nt}, SD_{nt} \in \{0,1\}$$

V. SIMULATION MODEL

The simulation model determines the ED of the system in shorter time periods (e.g., 5 up to 60 minutes) than the previous hourly UC model and considers stochasticity in the demand and uncertainty in RES generation. It is based on the previous formulation but the UC decisions are fixed for the ED model. Besides, the upper and lower bounds of each unit output are updated by including the operating reserves previously scheduled for this unit in the UC model. All the infeasibilities that may appear in the EC will be translated into ENS with a high impact in the objective function.

This model determines the use of the secondary reserves scheduled before hand by the UC model. The reserve usage is associated, on the one hand, to the smoother demand given that the time steps are shorter and, on the other hand, to the stochastic events that may happen. Depending on the stochasticity of the random variables the reserve provision made by the planning model will be acceptable or not.

VI. SPANISH SYSTEM CASE STUDY

It is assumed that all the data needed to feed the UC and simulation models have been obtained, to the possible extent, from publicly available sources. The sources of information are the electronic office portal of the Ministry of Industry, Energy and Tourism [13] for the static data of the generating units (like name, technology, and fuel used), whereas the operational parameters are estimated from the electricity market data [9] and from the ancillary services market [1].

1.3 Estimation of thermal unit characteristics

To estimate the thermal-unit physical characteristics, we used the historical generation output data available in [1]. The recorded data have two features that make it useful to estimate these parameters: data at unit level and hourly based. The minimum load and maximum capacity, ramping capabilities and startup and shutdown ramps were estimated

for every thermal unit individually. Also, a startup and shutdown curve is developed by considering the number of hours previous to a startup. Then, we can define the type of startup.

Minimum up and down times were assumed for every type of thermal unit. These values are taken from [14]. The accuracy of the values was analyzed with the historical output data from the system operation.

For this case study the economic data regarding no load costs, variable costs, startup and shutdown costs were determined based on [14] and our own expertise in the Spanish system keeping the merit order of the units.

1.4 Estimation of hydro unit characteristics

For the hydro subsystem, as opposed to the thermal subsystem, the parameters used in the model are not static. For example, the maximum power output of a hydro power plant depends on the reservoir level. This is true for a physical hydro unit, but even more important for the programming units, in fact the parameters used to model the programming units are not technical limits since they are aggregated power plants.

The maximum (minimum) power generation of a programming unit is the maximum (minimum) power generation registered in a specific time period. And finally, the energy use is the total energy generated by a programming unit in a specific time period.

Hydro parameters vary from one simulation period (day or week) to another. In order to run the UC and simulation models for a future period, it will be necessary to estimate those parameters.

1.5 Other parameters

The system demand is provided in an hourly basis for the hourly planning model and then smoothed with a centered moving average of 3 hours to obtain a plausible short-term demand with 5, 15 or 30-minutes time periods.

The amount of secondary upward and downward reserves are estimated according to the grid code, see [12].

The cost of the ENS was set to 10000 euros/MWh to best represent realistic values.

1.6 Estimation of load and wind power forecast error

The forecast errors of the demand and wind power are taken as the difference between the Viable Program Schedule (PVP) after clearing the market and the First Intraday Market (PHP1), [9], where the agents can fix the previous market results. These are not properly forecast errors because they can also include some of the generation agents' strategies in their positions in the electricity market but they can be considered as a good approximation. The same time range uncertainty has also been analyzed in [4]. In Figure 3, we show the histogram of the historical errors computed from the 2015 hourly data taken from [1] and the normal approximation. The average error for the load is 1.48 % and for the wind power 2.41 %. Similar values are reported in [5].

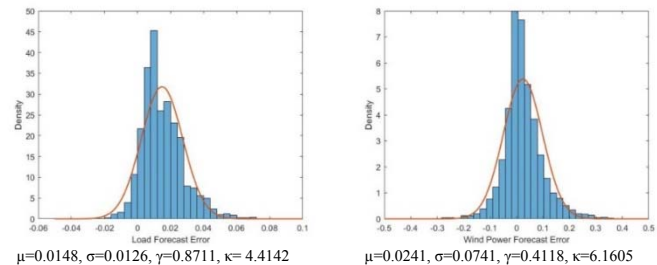


Figure 3. Load and wind power forecast errors: mean, standard deviation, skewness and kurtosis.

Time series of the demand and wind power historical forecast errors have been approximated with an ARIMA(3,0,0) model and, then, 200 Monte Carlo scenarios are generated independently to simulate future values of the forecast errors. These forecast errors are added to the original demand and wind power data for obtaining plausible outcomes.

VII. ANALYSIS OF THE RESULTS

We have run the planning model with an hourly basis for a specific day (Tuesday June, 23¹) of the 2015 to analyze the impact of the secondary operating reserves provided this day under the uncertainty in demand and wind generation. It is important to notice that we are evaluating a single day and therefore the conclusions are exclusively limited to that analysis. We define the reference case as the one with the operating reserves really provided that day. We have added two sensitivity cases with 90 and 110 % of the values of upward and downward reserves. For each case we analyze the ED in periods of 5, 15, 30 and 60 minutes. All the results presented in Table 1 correspond to the dispatch operation costs of the simulation model and are written as a percentage of the case with 60 minutes given that only the direction of the sensitivity effect is relevant.

From Table 1 we can see that the impact of the amount of upward and downward secondary reserve is very high because the infeasibilities are evaluated at ENS cost. That means that, in real operation, the system operator will resort to tertiary reserve many times because no enough secondary reserve has been provided. This behavior is equivalently reproduced for all the different time periods (5 to 60 minutes) of the EC. Changes in operation cost are asymmetric, increasing the reserves does not reduce the costs as much as decreasing them. In the last row of Table 1 we present the mean number of hours (violations) in percentage with respect to the reference case for all the scenarios where there is ENS associated to the impossibility of supplying the demand with the procured reserves. The asymmetry can also be observed with the violations of the constraints for the same time period. Likewise, it is clearly shown that violations decrease significantly when the time period decreases.

¹ This day presented an average demand of 29404 MW and an average wind power of 3787 MW. The peak demand was 35230 MW at 13 h and the peak wind power was 5765 MW at 20 h. This non-simultaneous peaks stress the system and that was the reason for choosing this particular day.

		60min	60min	60min	30min	30min	30min	15min	15min	15min	5min	5min	5min
Operation Cost	[%]	100	110	90	100	110	90	100	110	90	100	110	90
Mean	[%]	100	84	123	99	83	122	99	83	121	99	83	121
StdDev	[%]	79	63	94	78	63	93	78	62	93	78	62	93
Best	[%]	52	52	52	52	52	52	52	52	52	52	52	52
Worst	[%]	406	361	452	404	359	450	403	358	449	402	357	448
Violations	[%]	100	101	219	103	72	157	96	53	101	88	53	128

Table 1. Relative operation costs and violations for the different cases with respect to the reference case (hourly UC).

Figure 4 shows the variation of the objective function in p.u. for all the wind and demand scenarios for the ED with a 5-minute time period. Values are plot in increasing order. For the other three cases the results are very similar. There are many scenarios with almost no change in the objective function but in few of them the impact is extraordinary, indicative of lack of operation reserves in those cases. That effect is essentially related to the long tails of the forecast errors distributions.

The uncertainty of the operation costs for the twelve cases analyzed associated to the load and wind power forecast errors is fully appreciated in the boxplot of Figure 5, showing again that in few cases there is no enough reserve procurement. On each box, the central mark indicates the median, and the bottom and top edges of it indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the plus symbol.

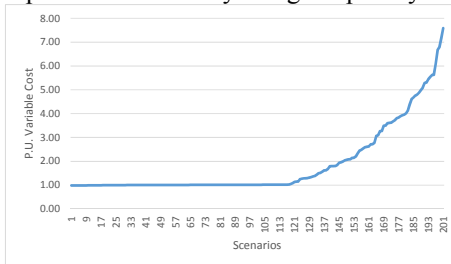


Figure 4. Operation costs in p.u. for the ED with 5-minute time period in increasing order.

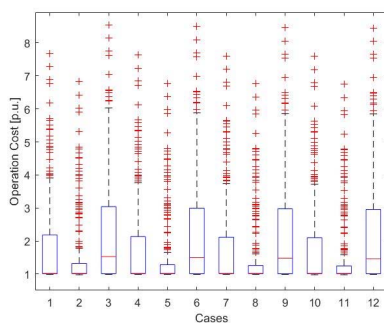


Figure 5. Operation costs in p.u. for the different cases (in the same order as in Table 1).

VIII. CONCLUSIONS

In this paper we propose a combination of scheduling and evaluation models to mimic real-time operation that supports the analyses of the amount of operating reserves required to cope with the uncertainty of the resources. The scheduling model is a detailed hourly unit commitment while the evaluation model is a shorter time step economic dispatch.

We analyze the case study of the Spanish system. From these analyses we can extract the following conclusions:

- Frequent resort to additional operation reserves due to load and wind power forecast errors. Asymmetry with respect to over or under dimension of the reserves
- Number of number of hours with shortage of operating reserves decreases when the time period also shrinks
- In a market environment the reduction of the unit market clearing period would reduce the operation reserve requirement/usage.

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