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Storage management by rolling stochastic unit commitment for high renewable energy penetration

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ABSTRACT

This paper presents a unified unit commitment and economic dispatch model that integrates storage devices for the short-term operations scheduling of power systems with high renewable penetration. The presented model is a single multi-hour look-ahead real-time tool that uses multiple time resolution to contain computational requirements. The decisions for the first time interval are binding while the decisions of the remaining scheduling horizon are advisory. Adopting this approach, storage facilities are more efficiently utilized, by constantly adapting their energy injection/withdrawal schedule based on updated system information, thus, alleviating the problem of defining the appropriate stored energy level during economic dispatch. The proposed model is presented in both deterministic and stochastic frameworks. The operational impacts of storage and the benefits of implementing stochastic optimization are validated via extensive simulations using data from the Greek Interconnected Power System.

1. Introduction

The integration of Renewable Energy Sources (RES) in the energy generation mix poses challenges to the system operators (SO) mainly due to the uncertainty they add to the power system. In order to deal with increased power system uncertainty stemming from increased RES injections, scientific literature has focused on the detailed modeling of uncertainty so that the SO several-hour ahead decisions (i.e. day-ahead unit commitment) are more efficient. To this end, stochastic [1], and robust [2] unit commitment (UC) have been presented as viable alternatives. However, the efficiency of all these approaches is limited by the fact that the traditional market timelines are not challenged, therefore the scheduling lead times are still high and, therefore, the volume of uncertainty can remain high. SOs in the US are aware of these issues and have already begun to restructure their short-term operations by implementing rolling UC with hourly granularity backed with frequently updated forecasts [3], fast-start UC [4] and real-time dispatch with look-ahead capabilities (e.g. next hour) [5] to manage the forthcoming wind energy variations. However the multiple scheduling level approaches create, in turn, other problems like the high coordination complexity between the multiple scheduling levels [6], ramp shortage in real time due to the different resolution used by the various scheduling layers [7], and difficulty in accurate modeling of thermal generator start-up and shut-down procedures [8]. To address the problems of the approaches found both in SO practices and scientific literature, we have presented in Ref. [9] the idea of unified unit commitment and economic dispatch as a real-time tool that uses an extended scheduling horizon and multiple time resolution to reduce the computational requirements. The model yields more efficient operation compared to current multi-level scheduling models [10] and the use of stochastic optimization further improves its performance [11].

RES generation can be efficiently accommodated in the generation mix for penetrations up to 30% only by updating the current operational practices [12]. However, for very high RES penetrations, updating the operational practices is not sufficient and the integration of other flexibility sources like storage is necessary. Storage is deemed as a multi-purpose device [13] since it can provide various services to the power system: (a) load-levelling, (b) provision of ancillary services, and (c) as investment deferral. In this paper, we investigate the effect of storage on the short-term scheduling, i.e. timeframes from several minutes to 36 h ahead.

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Nomenclature

Indices and sets

$i \in I$	Generating units (slow and fast) $I = I^{slow} \cup I^{fast}$
$j \in \mathcal{J}$	Storage units.
$s \in \mathcal{S}$	Scenario realizations.
$t, \tau \in \mathcal{T}$	Time intervals (of variable duration)

Parameters

$C_i^e(p_i)$	Piecewise linear approximation of the hourly variable cost function of generator *i*, in €/h.
C_i^{up}	Start-up cost of generator *i*, in €.
C^{VLL}	Value of lost load (VLL), considered 5000 €/MWh.
C^{VLW}	Value of lost wind power (VLW), considered 150 €/MWh.
$E_j^{max(min)}$	Maximum (minimum) energy capacity of storage unit *j*, in MWh.
E_j^{end}	Ending energy level of storage unit *j*, in MWh.
$P_j^{c(d)}$	Maximum charge/discharge power output of storage unit *j*, in MW.
$P_i^{max(min)}$	Maximum (minimum) power output of generator *i*, in MW.
$P_{i\tau t}^{syn(des)}$	Power output of generator *i*, at synchronization (desynchronization) phase, during time interval *t*, that starts (shuts down) at time interval τ, in MW.
$\hat{P}_t^{\ell(w)}$	System load (wind power) forecast during time interval *t*, in MW.
$P_{ts}^{\ell(w)}$	System load (wind power) during time interval *t*, in scenario *s*, in MW.
$R_i^{up(dn)}$	Ramp-up (ramp-down) rate of generator *i*, in MW/h.
$R_t^{+(-)}$	System requirement in upward (downward) reserve during time interval *t*, in MW.
$T_{it}^{syn(des)}$	Synchronization (desynchronization) time of generator *i*, at time interval *t*, in time intervals.
$T_{it}^{up(dn)}$	Minimum up (down) time of generator *i*, at time interval *t*, in time intervals.
Δ_t	Duration of time interval *t*, in hours.
$\eta_j^{c(d)}$	Charge (discharge) efficiency rate of storage unit *i*.
π_s	Probability of realization of scenario *s*.

Variables

$a_{t(s)}^{\ell(w)}$	Load shedding (wind power curtailment), during time interval *t*, in scenario *s*, in MW.
$e_{jt(s)}$	Energy level of storage unit *j*, at the end of time interval *t*, in scenario *s*, in MWh.
$p_{it(s)}$	Power output of generator *i*, during time interval *t*, in scenario *s*, in MW.
$p_{it}^{syn(des)}$	Power output of generator *i* during the synchronization and soak (desynchronization) phase, at time interval *t*, in MW.
$p_{jt}^{c(d)}$	Power charge (discharge) rate of storage unit *j*, in MW.
$r_{it}^{+(-)}$	Contribution of generator *i* in upward (downward) reserve, during time interval *t*, in MW.
$r_{jt}^{+(-)}$	Contribution of storage unit *j* in upward (downward) reserve, during time interval *t*, in MW.
r_t^{w-}	Contribution of wind resources in downward reserve, during time interval *t*, in MW.
u_{it}	Binary variable which is equal to 1 if generator *i* is on during time interval *t*.
$u_{it}^{syn/des/disp}$	Binary variable which is equal to 1 if generator *i* is in synchronization/desynchronization/dispatchable operating phase, during time interval *t*.
$y_{it}\,(z_{it})$	Binary variable which is equal to 1 if generator *i* is started-up (shut-down) during time interval *t*.

The incorporation of storage in the unit commitment is not new [14–16]. However, most of the works examine the scheduling of storage on a day-ahead level without validating the schedule in real-time, which is of paramount importance. When assessing the integration of storage in a combined day-ahead and real-time framework, an important issue emerges: how to define the optimal energy level of the storage devices in the end of the economic dispatch period, considering their day-ahead energy injection/withdrawal schedule in order to avoid depletion/repletion of the stored energy. There is, obviously, no straightforward answer and existing literature has not adequately addressed the issue so far. Pozo et al. [17] present a stochastic unit commitment model with storage that uses sub-hourly intervals in the second stage (real-time market), however they do not investigate how to choose the appropriate battery state of charge in the real-time market, which is a second-stage decision. Li et al. [18] are the first to address the issue in the context of a stochastic unit commitment with batteries. They present a way to obtain the appropriate state-of-charge of batteries in real-time based on the Euclidean distance between the post-stage wind scenario and the day-ahead wind scenario. However, this approach remains heuristic and sub-optimal. Additionally, they use hourly real-time intervals, therefore the effect of storage on a sub-hourly framework is not investigated.

This paper aims to address the aforementioned issue by presenting an appropriate short-term scheduling framework for the efficient integration of storage devices in power systems with high RES injections. To this end, we extend the idea of Unified Unit Commitment and Economic Dispatch (UUCED), presented in Refs. [9–11], by including an efficient generic modeling for storage devices. The UUCED is a real-time tool with a look-ahead horizon of up to 36 h and multiple time resolution that unifies all scheduling functions from the day-ahead level to real-time operation. By frequently rescheduling the energy injection/withdrawal schedule of storage, the real-time injection/withdrawal of energy is optimally determined in anticipation of extended forecast conditions and the problem of defining the optimal energy level of storage devices during real time operation is alleviated. We have presented a preliminary demonstration of this idea solely in a deterministic framework (where point forecasts were used, instead of scenarios) in Ref. [19]. In this paper, we fully develop the idea, by presenting the generic storage modeling in both a deterministic (d-UUCED) and a stochastic (s-UUCED) framework. Additionally, the operational impacts of storage within the deterministic and stochastic UUCED modeling, are investigated via annual simulations, using data from the Greek Interconnected Power System. Several performance indices are calculated and compared to test cases without storage. Finally, the benefits of using stochastic optimization for the scheduling of storage devices in the context of UUCED are investigated.

The remainder of the paper is organized as follows: Section 2 provides the description of the deterministic and stochastic UUCED model. Section 3 presents the test cases and results and, finally, conclusions are drawn in Section 4.