Unified System-Level Modeling of Intermittent Renewable Energy Sources and Energy Storage for Power System Operation

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***Abstract*—The system-level consideration of intermittent renewable energy sources (RES) and small-scale energy storage in power systems remains a challenge as either type is incompatible with traditional operation concepts. Noncontrollability and energy constraints are still considered contingent cases in market-based operation. The design of operation strategies for up to 100% RES power systems requires an explicit consideration of nondispatchable generation and storage capacities, as well as the evaluation of operational performance in terms of energy efficiency, reliability, environmental impact, and cost. By abstracting from technology-dependent and physical unit properties, the power nodes modeling framework presented here allows the representation of a technologically diverse unit portfolio with a unified approach, while establishing the feasibility of energy-storage consideration in power system operation. After introducing the modeling approach, a case study is presented for illustration.**

***Index Terms*—Active power control, balancing, curtailment, dispatch, energy storage, intermittent generation, load management, power nodes, renewable energy sources (RES).**

I. Introduction

ELECTRICITY generated from renewable energy sources (RES) is often not dispatchable and the forecast of its production over time is bound to uncertainty. Today, electricity generated by wind power contributes up to around 20% of the electricity demand in some countries, meaning that wind power production at times exceeds local power demand. Solar photovoltaic (PV) installed capacity exceeded 17 GW in Germany in 2010. Considering the ongoing large-scale deployment of intermittent RES [1] as well as energy policy scenarios and government plans for up to 100% RES supply [2], [3], the consideration of system operation and economic frameworks that are oriented toward the nature of intermittent RES and energy storage become increasingly relevant.

Power systems require a continuous balance between energy supply and demand. To achieve this balance, anticipated energy demand is procured in power markets based on forecasts, while the continuous power balance is maintained by an arrangement of automatic control schemes, supervised by human operators [4]. Experiences with increasing levels of fluctuating RES in-feed give a taste of the challenges power systems will face in the future [5]. What these challenges will be exactly and how they can be addressed is the topic of ongoing research.

Energy storage units have long been considered as a means for improved integration of fluctuating RES. Studies have shown potential benefits of energy storage for variability and prediction accuracy improvement, each with respect to a specific operational context, such as market integration, ancillary services and power system reliability [6]–[9]. As shown in [9], the specific control law or operation objective makes a significant difference to the specific benefits energy storage may provide. The combined value of energy storage in power systems under mixed operating modes is better understood if a complete operation scenario is considered. Software tools support scenario design, varying in scope, temporal and spatial resolution [10]. Scenario tools combine central decision variables with existing data as input, to produce an output enabling scenario evaluation. Evaluation criteria typically include operation costs, total energy (produced, consumed, wasted, shedded, and so on), and CO_2-emissions, which are all important for investment or energy policy decisions.

The well-known energy hub concept [11] focuses on multicarrier energy networks. It allows the study of synergies that the combination of electricity, natural gas, and network infrastructures may provide for energy dispatch [12], infrastructure reliability [13], and investment decisions under uncertainty [14]. Energy storage is one element of the concept, but is not necessarily considered. This powerful representation has a complexity that limits studies with energy hubs to defining a common level of detail (granularity) for all considered energy systems. Like the energy hub, the power nodes framework has been developed for the study of future (hypothetical) energy scenarios and is aimed specifically at the analysis of

Manuscript received September 23, 2010; revised June 30, 2011; accepted June 30, 2011. This work was financially supported through the research projects "Local Load Management" (Swisselectric Research) and "IRENE 40—Infrastructure Roadmap for Energy Networks in Europe" (European Commission, FP7). The work of K. Heussen was supported through the research project Coherent Energy and Environmental System Analysis, partly financed by the Danish Council for Strategic Research.

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Digital Object Identifier 10.1109/JSYST.2011.2163020

future power system operation, which requires a multistage simulation environment [15]. Prior studies evaluating power system operation with increased RES and energy storage, e.g., [16], utilized multistage simulation environments which were founded on existing tools and operation concepts. For future power systems, however, operation and control principles and market structure are subject to redesign. A structured simulation environment can provide the context necessary for experimental development and systematic assessment of new operation strategies. The purpose of this paper is to provide a generic framework that invites experimentation, to overcome conceptual limitations built into contemporary system operation simulators. The power nodes framework facilitates the consideration of energy storage, fluctuating generation and other types of nonconventional energy resources by providing a conceptual model for energy storage as well as for different levels of controllability over power system units [17]. Based on the power nodes extension of classical grid models, we introduce a model decomposition for operation functions in different planning stages and operation time-scales.

A. Power System Dispatch and Operation Planning

Traditionally, the dominant part of dispatchable power generation is based on energy stored in combustible fossil fuels. Dispatchable generation is scheduled in anticipation of demand. In this context, (spot) market prices are mainly driven by marginal generation cost [18].

In case of constraints on the producible electric energy, e.g., due to a limited reservoir size in hydro power plants, operation decisions are driven by opportunity costs due to expected future prices and available storage levels [19]. Thus, energy constraints—inherent to all kinds of energy storage—induce a different dispatch logic. For fluctuating RES, available energy has to be absorbed into the grid or curtailed for every time instant. As the energy itself is free, costs to be recovered are predominantly investment costs into RES conversion apparatus, limited in capacity and lifetime. All available energy will thus be offered to the market.[1] Aiming at recovery of investment cost, nondispatchable RES therefore tend to be price-takers. Planning is fundamental to power system operation, but there is an unavoidable discrepancy between planned and actual operating conditions. With increasing intermittent RES in-feed, both prediction errors and continuous variations will increase and need to be dealt with using adequate control reserve scheduling.

B. Controllability of Intermittent RES

Fluctuating power in-feed from wind turbines and PV arrays is predictable to a certain extent [8]. Nowadays, information on the forecasted future power in-feed is included in the power plant day-ahead dispatch in areas with significant RES penetration. Forecast errors are balanced via intraday power trading and conventional control reserves, not by the intermittent generators themselves. Curtailment of intermittent power in-feed is typically only employed as an abnormal measure. The utilization of on-line control measures for intermittent generation units, such as partial generation curtailment [20], [21], has been included in the grid code of countries with significant wind power penetration. This kind of controllability, however, remains limited by the availability of the primary energy carrier, e.g., the wind force. The challenge of systematically integrating such methods into power system operation and control constitutes another motivation for the present work.

[1]Current regulatory schemes often prioritize RES in energy markets, which may induce negative prices in extreme situations, e.g., inflexible power system operation conditions, as reported in, e.g., [5].

C. Controllable Energy Storage for Power Systems

All forms of energy storage entail energy conversion processes. In addition to reversible energy storage in the form of pumped hydro, batteries, flywheels, and so on, a very important form is heat storage. Methods to increase the controllability of loads with inherent storage are emerging, such as control strategies for household appliances with thermal inertia and for prospectively large numbers of electric vehicles connected to the grid [22], [23]. Ubiquitous controllable energy storage is likely to have positive effects on system operation, ranging from security-relevant power reserves to loss reduction on the distribution system level [24]–[26]. Flexibility is valuable [6]. However, current grid operation frameworks do not directly support the specific properties of energy storage. For instance, only power reserves are considered by system operators, whereas the energy required for control actions is not visible to the operator and is settled in post-operation. Due to storage dynamics and associated inter-temporal dependencies, energy and ramp-rate constraints, as well as other controllability limitations are particularly relevant for dispatch problems. Here, the methodology of model predictive control (MPC) is especially suitable [27]–[29].

D. Novel Control Structures

The additional degrees of freedom that energy storage and increased controllability over RES in-feed and loads provide, can only be utilized if a suitable control architecture is established. Several novel control structures, often utilizing aggregation principles, have been proposed in this context, including: virtual power plants [30], cells [31], or microgrids [32]. Comprehensive performance assessment of different operation and control approaches constitutes a challenge in itself [33]. The remainder of this paper is structured as follows. The power nodes framework is introduced in Section II, then Section III develops a multistage formulation of the power node equations. Section IV outlines a multistage environment for simulation and assessment of planning and real-time operation based on the power nodes concepts. The concept is illustrated by a case-study in Section V, followed by conclusions in Section VI.

II. Power Nodes Framework

The basic premise of the power nodes approach is that any power source or sink connected to the electric power system requires the conversion of some form of energy into electric power, or vice versa. These forms may be termed “supply” or

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

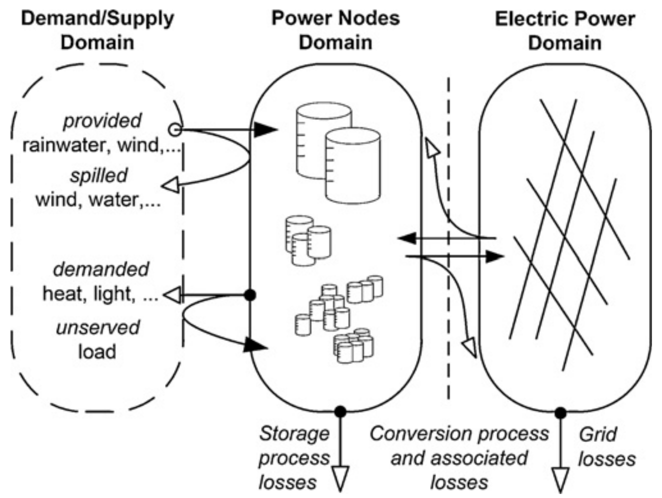

Fig. 1. Illustration of the three-domain concept. The power node and grid domains are model-internal domains, both are considered integral parts of the electric energy system. The domain of demand/supply processes is considered external, indicated by the dashed frame. Arrows indicate energy (or power) flows that are accounted for. Empty arrowheads indicate energy that is exchanged with the environment, while black arrowheads indicate energy flows into or across the modeled domains.

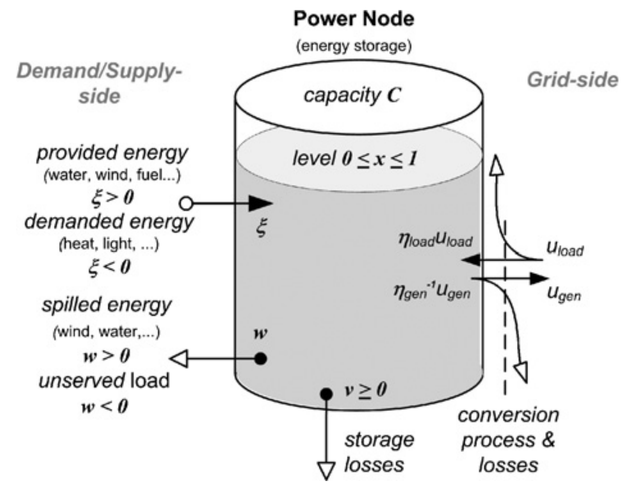

Fig. 2. Notation for a single power node.

"use-forms" of energy, respectively. The degrees of freedom available for fulfilling the power balance in the electric grid arise from the freedom that the supply-forms and use-forms of energy provide, either by being controllable or by offering inherent storage capacity.

Abstracting from the physical properties and the internal composition of a supply-process or use-process including the associated energy conversion processes, we represent it from a grid-perspective as a single lumped unit with characteristic parameters, a "power node."

A. Domain Models

The introduction of a generic energy storage perspective adds a modeling layer to the classical modeling of power systems, as illustrated in Fig. 1. In the resulting enhanced model, the electro-mechanical domain of the electric grid is interfaced with the pregrid power node domain, which represents conversion processes and an associated energy storage functionality. A third, external, domain accounts for the demand/supply processes consuming energy from and feeding energy into the power node domain. As shown in Fig. 1, these processes may be thought of as externally driven, e.g., intermittent renewable energy supply, or fully controllable, e.g., fuel supply for dispatchable generators.

For ensuring model consistency, it is important to define unambiguous domain interfaces. Generally, these are exchanges of energy, or power, in continuous time. For instance, the exchange between the power node domain and the Grid domain is defined as the active power fed into or consumed from the grid. In the case of a dynamical grid model, the inertia of synchronous machines is part of the Grid domain, and thus the active power interface is equivalent to the mechanical power exerted by the prime mover of a synchronous generator. Grid losses are modeled inside the electro-mechanical Grid domain, while pregrid losses, such as storage and conversion losses, are accounted for in the power nodes domain. This clear separation allows the power nodes framework to integrate with a number of different physical network representations common in power systems modeling (see Section II-C).

All supply and demand processes are connected via a power node to the electricity grid. Consequently, the total energy provided to or demanded from the grid may differ from the actual energy served or utilized by external processes. All considered modes of energy flow are illustrated by arrows in Figs. 1 and 2. This mathematically redundant choice of flow modes establishes a formalized interpretation (see Section II-D) of real-world effects that cause supplied energy to be lost, or demanded energy to remain unserved. For example, energy conversion implies conversion losses, power in-feed from wind turbines may be curtailed, and a load may get disconnected from the grid. In order to evaluate the overall system performance, it is necessary to keep track of these losses and to account for the energy value associated with them. For this purpose, balance terms as presented in Section II-E can be utilized.

B. Model of a Single Power Node

Consider the structure of a single power node consisting of the elements illustrated in Fig. 2. In comparison with Fig. 1, the provided and demanded energies are lumped into an external process termed ξ, with $\xi < 0$ denoting use and $\xi > 0$ supply. The term $u_{\mathrm{gen}} \geq 0$ describes a conversion corresponding to a power generation with efficiency η_{gen}, while $u_{\mathrm{load}} \geq 0$ describes a conversion corresponding to a consumption with efficiency η_{load}.

The energy storage level is normalized to $0 \leq x \leq 1$ with energy storage capacity $C \geq 0$. Fig. 2 illustrates how the storage serves as a buffer between the external process ξ and the two grid-related exchanges u_{gen} and u_{load}. Internal energy losses associated with energy storage, e.g., physical, state-dependent losses, are modeled by the term $v \geq 0$, while enforced energy losses, e.g., curtailment/shedding of a supply/demand process, are denoted by the waste term w, where $w > 0$ denotes a loss of provided energy and $w < 0$ an unserved demand process. This labeling for the power node equation provides a generic embedding of energy conversion and storage processes.

1) *Generic Model:* The dynamics of an arbitrary power node $i \in \mathcal{N} = \{1, \ldots, N\}$, which may exhibit nonlinear effects in the general case, are described as follows:

$$\begin{aligned} C_i\,\dot{x}_i \quad &= \quad \eta_{\text{load},i}\,u_{\text{load},i} - \eta^{-1}_{\text{gen},i}\,u_{\text{gen},i} + \xi_i - w_i - v_i \qquad (1)\\ \text{s.t.} \quad &(a) \quad 0 \le x_i \le 1\\ &(b) \quad 0 \le u^{\min}_{\text{gen},i} \le u_{\text{gen},i} \le u^{\max}_{\text{gen},i}\\ &(c) \quad 0 \le u^{\min}_{\text{load},i} \le u_{\text{load},i} \le u^{\max}_{\text{load},i}\\ &(d) \quad 0 \le \xi_i \cdot w_i\\ &(e) \quad 0 \le |\xi_i| - |w_i|\\ &(f) \quad 0 \le v_i \quad \forall\, i = 1, \ldots, N. \end{aligned}$$

Depending on the specific process represented by a power node and the investigated application, each term in the power node equation may in general be controllable or not, observable or not, and driven by an external process or not. Internal dependencies, such as a state-dependent physical loss term $v_i(x_i)$, are feasible. Charge/discharge efficiencies may be nonconstant, e.g., state-dependent: $\eta_{\text{load},i} = \eta_{\text{load},i}(x_i)$, $\eta_{\text{gen},i} = \eta_{\text{gen},i}(x_i)$.

The constraints (a)–(f) denote a generic set of requirements on the variables. They are to express that (a) the state of charge is normalized, (b), (c) the grid variables are nonnegative and bounded, (d) the supply/demand and the curtailment need to have the same sign, (e) the supply/demand curtailment cannot exceed the supply/demand itself, and (f) the storage losses are nonnegative. Ramp-rate constraints, especially constraints on the derivatives $\dot{u}_{\text{gen},i}$ and $\dot{u}_{\text{load},i}$, can be included for power system studies under dynamic operating conditions (see Table I). Apart from the listed constraints, there may be additional ones imposed on the variables, e.g., in order to define certain standard unit types with characteristic properties (see Section II-D). The explicit mathematical form of a power node equation depends on the particular modeling case. Most importantly, the notation provides technology-independent categories that can be linked to the evaluation functions given in Section II-E.

2) *Modeling Power Nodes without Storage:* Power nodes can also represent processes independent of energy storage, such as fluctuating RES generation or conventional generation and load. A process without storage implies an algebraic coupling between the instantaneous quantities ξ_i, w_i, $u_{\text{gen},i}$, and $u_{\text{load},i}$; storage-dependent loss does not exist ($v_i = 0$). Equation (1) degenerates to

$$\xi_i - w_i = \eta^{-1}_{\text{gen},i}\,u_{\text{gen},i} - \eta_{\text{load},i}\,u_{\text{load},i} \qquad (2)$$

which holds for both externally driven processes and controllable power generation. The waste term w_i is particularly relevant for external supply and demand processes which are not directly controllable, while there is the option to curtail them. Examples are intermittent power generation ($\xi_{\text{drv},i}(t) \ge 0$) and classical load ($\xi_{\text{drv},i}(t) \le 0$). For a fully controllable supply process such as a conventional generator, either the grid-related variables $u_{\text{gen},i}$, $u_{\text{load},i}$, or the power exchange with the environment through ξ_i can be considered controlled variables. ξ_i then accounts for example for primary energy usage.

TABLE I
UNIT PROPERTIES DEFINED BY POWER NODE EQUATION CONSTRAINTS

Variable(s)	Constraint(s)	Implication
$u_{\text{gen},i}$,	$u_{\text{gen},i} = 0$	Load
$u_{\text{load},i}$	$u_{\text{load},i} = 0$	Generator
	$u_{\text{gen},i} \cdot u_{\text{load},i} = 0$	One-conv.-unit storage
	–	Two-conv.-unit storage
C_i	$C_i = 0$	Nonbuffered unit
	$C_i > 0$	Buffered unit
ξ_i	$\xi_i = 0$	No external process
	$\xi_i \ge 0$	Supply process
	$\xi_i \le 0$	Demand process
ξ_i, w_i	$\xi_i = \xi_{\text{drv},i}(t) \wedge w_i = 0$	Noncontrollable
	$\xi_i = \xi_{\text{drv},i}(t)$	Curtailable
	ξ_i arbitrary, $w_i = 0$	Controllable
v_i	$v_i = 0$	Lossless storage
	$v_i > 0$	Lossy storage
$\dot{u}_{\text{gen},i}$	$\dot{u}^{\min}_{\text{gen},i} \le \dot{u}_{\text{gen},i} \le \dot{u}^{\max}_{\text{gen},i}$	Ramp-rate-constr. gen.
$\dot{u}_{\text{load},i}$	$\dot{u}^{\min}_{\text{load},i} \le \dot{u}_{\text{load},i} \le \dot{u}^{\max}_{\text{load},i}$	Ramp-rate-constr. load

3) *Model-Specialization to Affine Model:* Specializations and simplifications of the generic model are relevant for practical tasks such as controller design and implementation. Here we present the example of a simplified affine model which is suitable for describing a wide range of processes with state-dependent losses, such as heat storages that lose energy to the environment due to a difference between internal storage temperature and ambient temperature. For this purpose, a linear dependence of v_i on the storage state x_i is assumed, while the efficiencies η are assumed constant in order to eliminate nonlinearities

$$\begin{aligned} C_i\,\dot{x}_i \quad &= \quad \eta_{\text{load},i}\,u_{\text{load},i} - \eta^{-1}_{\text{gen},i}\,u_{\text{gen},i} + \xi_i - w_i \qquad (3)\\ &\quad -a_i\,(x_i - x_{\text{ss},i}) \end{aligned}$$

subject to the same constraints as (1). The steady-state storage level $x_{\text{ss},i}$ refers to the steady-state of the differential equation in the absence of inputs, e.g., the thermal equilibrium of a thermal storage with the ambiance, and a_i is a nonnegative loss coefficient.

C. Mapping from Power Nodes to Grid Domain

Consider a grid composed of M busses denoted by $m, n \in \mathcal{M} = \{1, \ldots, M\}$ and a set of N power nodes $i \in \mathcal{N} = \{1, \ldots, N\}$, representing a number of single or aggregated units. A mapping can be formulated by index sets $\mathcal{N} \to \mathcal{M}$. The power node indices are divided into sets $\mathcal{N}_m \subseteq \mathcal{N}$ associated with one bus each; having the properties $\mathcal{N}_m \cap \mathcal{N}_n = \emptyset$ for $m \neq n$, and $\bigcup_{m\in\mathcal{M}} \mathcal{N}_m = \mathcal{N}$.

The net power injection to a grid node $m \in \mathcal{M}$ is thus

$$P_{\text{netinj},m} = \sum_{i\in\mathcal{N}_m} u_{\text{gen},i} - \sum_{i\in\mathcal{N}_m} u_{\text{load},i}. \qquad (4)$$

The power systems literature offers many options for power system modeling, depending on the relevant study questions. In principle, the power nodes domain can be interfaced with many grid model types, such as DC or AC power flow, static or dynamic grid models, due to the clear separation from the electro-mechanical domain.

D. Characterization of Unit Properties

There is only a limited number of practical unit types. As discussed in Section II-A, the kinds of energy flows available in the generic power node model allow for a wide range of unit types. A given practical unit type is thus classified by its characteristic subset of the possible modes of energy flows. A "unit" in the power nodes framework is an arbitrary generation, load, or storage device, or a group of devices aggregated to behave as one unit. The type distinction is established via a set of constraints on the variables (energy-flow concepts) used in (1), i.e., $u_{\text{load},i}$, $u_{\text{gen},i}$, C_i, x_i, ξ_i, v_i, and w_i. These constraints hold in addition to the principal constraints (a)–(f) in (1), thus providing a classification of units with different properties.

Table I establishes a set of basic properties defining the operational behavior of a unit modeled as a power node. The interpretation of constraints is given in the following.

1) $\boldsymbol{u}_{\text{load/gen},i}$: a pure generation process implies that $u_{\text{load},i} = 0$ at all times; a pure load cannot inject power, expressed by $u_{\text{gen},i} = 0$. In a bidirectional conversion system, both variables can assume nonzero values; both conversions can happen at the same time (e.g., pumped hydro with independent turbine and pump), or not (e.g., inverter-connected battery).
2) $\boldsymbol{C}_i$: unit is modeled with ($C_i > 0$) or without energy storage capabilities ($C_i = 0$).
3) $\boldsymbol{\xi}_i$: supply ($\xi_i > 0$) or demand ($\xi_i < 0$) processes. For pure electricity storage (battery), $\xi_i = 0$ holds.
4) $\boldsymbol{\xi}_i, \boldsymbol{w}_i$: controllability of power exchange via an external process. If ξ_i is driven by an external signal $\xi_i = \xi_{\text{drv},i}(t)$, e.g., induced by intermittent supply, it may either be curtailable (no further constraint on w_i) or noncontrollable (no curtailment possible $w_i = 0$). If ξ_i is not externally driven, the unit is controllable.
5) $\boldsymbol{v}_i$: lossless if $v_i = 0$; lossy otherwise.
6) $\dot{\boldsymbol{u}}_{\text{load/gen},i}$: additional rate-constraints may be applied to the grid variables, to model physical limitations on the rate of change of a power conversion process.

Based on these properties, all unit types relevant for establishing the energy-balance in a power system can be classified and modeled inside the power nodes framework. A classification of unit types is included in [17]. Additional constraints may be considered for specific applications.

E. Performance Evaluation via System-Level Balances

The embedding of all energy units in the power nodes notation provides an energy-accounting framework. The performance of operation and control strategies can be evaluated on the basis of this framework: in form of instantaneous quantities, characterizing the current operational state of the system; or as time-integrals, serving to evaluate the system performance over a certain time span.

Examples for power balance terms indicating the current system state include the following.

1) Power supplied to grid
$$P^{\text{grid}}_{\text{gen}}(t) = \sum_{i\in\mathcal{N}} u_{\text{gen},i}(t).$$
2) Power consumed from grid
$$P^{\text{grid}}_{\text{load}}(t) = \sum_{i\in\mathcal{N}} u_{\text{load},i}(t).$$
3) Currently stored energy
$$E_{\text{stored}}(t) = \sum_{i\in\mathcal{N}} C_i x_i(t).$$
4) Power supply curtailed
$$w^{+}(t) = \sum_{i\in\{i|w_i>0\}\subset\mathcal{N}} w_i.$$
5) Power demand not served
$$w^{-}(t) = \sum_{i\in\{i|w_i<0\}\subset\mathcal{N}} w_i.$$
6) Power conversion loss
$$P_{\text{loss}}(t) = \sum_{i\in\mathcal{N}} \left(\frac{1-\eta_{\text{gen},i}(t)}{\eta_{\text{gen},i}(t)} u_{\text{gen},i}(t) + (1-\eta_{\text{load},i}(t))\, u_{\text{load},i}(t) \right).$$

All of the above quantities can be restricted to certain unit types by placing restrictions on the index i. For example, the consideration of all noncontrollable nonbuffered generation units would require a summation over the index $i \in \{i|C_i = 0 \wedge \xi_i = \xi_{\text{drv},i}(t) \geq 0 \wedge w_i = 0\} \subset \mathcal{N}$.

Energy balance terms can be derived by integration over power balance terms in the time interval $[t_1, t_2]$, such as follows.

1) Electric energy supplied to grid
$$\int_{t_1}^{t_2} P^{\text{grid}}_{\text{gen}}(t)\, dt.$$
2) Primary energy supplied
$$\int_{t_1}^{t_2} \xi^{\text{total}}_{\text{supply}}(t)\, dt.$$
3) Primary energy curtailed
$$\int_{t_1}^{t_2} w^{+}(t)\, dt.$$
4) Energy conversion losses
$$\int_{t_1}^{t_2} P_{\text{loss}}(t)\, dt.$$

The calculated power and energy quantities can be combined with time-specific cost, or energy-specific, and fuel-specific emissions information, characterizing the scenario in this important larger context.

III. Decomposition of Power Node Equations for Multistage Operation

This section presents a decomposition of the affine power node equation (Section II-B3) for consideration of the contributions of different planning and operation stages: day-ahead planning, intraday rescheduling and real-time operation. Unit commitment and long-term planning issues are not addressed here. Given a representation of units as power nodes, the following three stages are considered:

1) *day-ahead dispatch*: an operating point schedule for the controllable variables, established once a day, on the basis of operation cost and predictions for uncertain variables;
2) *intraday rescheduling*: alteration of the operating point schedule, several updates a day;
3) *real-time operation*: realization of continuous system behavior, formulated as relative changes to the

operating point schedules determined in previous stages.

The degrees of freedom related to each of the decision and control problems shall be modeled separately. The actual power node model variables are therefore decomposed into three fractions, consisting of scheduled values (sch), schedule updates as deviations from the scheduled values (upd), thus formulating the real-time (rt) behavior as a deviation from the planned baseline

$$\aleph = \aleph^{\mathrm{sch}} + \Delta\aleph^{\mathrm{upd}} + \Delta\aleph^{\mathrm{rt}} \tag{5}$$

with $\aleph = \{u_{\mathrm{gen}},\ u_{\mathrm{load}},\ \xi,\ w\}$ as the actual power node variables. Physical storage loss (v) is dealt with separately.

A. Decomposition of Power Node Equation

The decomposition of the power node equation and constraints is based on the analogous decomposition of the storage state variable

$$x = x^{\mathrm{sch}} + \Delta x^{\mathrm{upd}} + \Delta x^{\mathrm{rt}} \quad \text{and} \tag{6}$$

$$\dot{x} = \dot{x}^{\mathrm{sch}} + \Delta \dot{x}^{\mathrm{upd}} + \Delta \dot{x}^{\mathrm{rt}}. \tag{7}$$

The goal is to formulate separate power node dynamics for each of the fractions, such that in superposition they constitute the original power node equation. As condition for superposition, the differential equation has to be linear. This decomposition is thus not applicable for the general case (1), but it can be shown to hold for the affine case (3). If a coordinate translation $\hat{x} = x - x_{\mathrm{ss}}$ is applied to the affine model (3), the result is as follows:

$$C_i\, \dot{\hat{x}}_i = \eta_{\mathrm{load},i}\, u_{\mathrm{load},i} - \eta_{\mathrm{gen},i}^{-1}\, u_{\mathrm{gen},i} + \xi_i - w_i - a_i\, \hat{x}_i. \tag{8}$$

The power node equation is linear in $\hat{\square}$-coordinates, enabling the application of the superposition principle. For the decomposition of $\hat{x}$, the offset x_{ss} can be associated with any of the fractions of x in (6). We choose $\hat{x}^{\mathrm{sch}} = x^{\mathrm{sch}} - x_{\mathrm{ss}}$, and consequently $\Delta\hat{x}^{\mathrm{upd}} = \Delta x^{\mathrm{upd}}$ and $\Delta\hat{x}^{\mathrm{rt}} = \Delta x^{\mathrm{rt}}$. The original coordinates can thus be employed to denote the three related power node formulations.

1) Power node equation for the scheduling problem

$$C_i\, \dot{x}_i^{\mathrm{sch}} = \eta_{\mathrm{load},i}\, u_{\mathrm{load},i}^{\mathrm{sch}} - \eta_{\mathrm{gen},i}^{-1}\, u_{\mathrm{gen},i}^{\mathrm{sch}} + \xi_i^{\mathrm{sch}} - w_i^{\mathrm{sch}} - a_i\,(x_i^{\mathrm{sch}} - x_{\mathrm{ss},i}). \tag{9}$$

2) Schedule update equation, formulated as a deviation

$$C_i\, \Delta\dot{x}_i^{\mathrm{upd}} = \eta_{\mathrm{load},i}\, \Delta u_{\mathrm{load},i}^{\mathrm{upd}} - \eta_{\mathrm{gen},i}^{-1}\, \Delta u_{\mathrm{gen},i}^{\mathrm{upd}} + \Delta\xi_i^{\mathrm{upd}} - \Delta w_i^{\mathrm{upd}} - a_i\, \Delta x_i^{\mathrm{upd}}. \tag{10}$$

3) Real-time balancing and control (power node) dynamics, formulated as the difference between realization and schedule: $\Delta\aleph^{\mathrm{rt}} = \aleph(t) - (\aleph^{\mathrm{sch}} + \Delta\aleph^{\mathrm{upd}})$

$$C_i\, \Delta\dot{x}_i^{\mathrm{rt}} = \eta_{\mathrm{load},i}\, \Delta u_{\mathrm{load},i}^{\mathrm{rt}} - \eta_{\mathrm{gen},i}^{-1}\, \Delta u_{\mathrm{gen},i}^{\mathrm{rt}} + \Delta\xi_i^{\mathrm{rt}} - \Delta w_i^{\mathrm{rt}} - a_i\, \Delta x_i^{\mathrm{rt}}. \tag{11}$$

TABLE II
DIRECTIONALITY OF CONTROL RESERVE PROVISION

	Positive Reserve	Negative Reserve
Generation	$\Delta u_{\mathrm{gen},i}^{\mathrm{rt}} \nearrow \Rightarrow \Delta x_i^{\mathrm{rt}} \searrow$	$\Delta u_{\mathrm{gen},i}^{\mathrm{rt}} \searrow \Rightarrow \Delta x_i^{\mathrm{rt}} \nearrow$
Load	$\Delta u_{\mathrm{load},i}^{\mathrm{rt}} \searrow \Rightarrow \Delta x_i^{\mathrm{rt}} \searrow$	$\Delta u_{\mathrm{load},i}^{\mathrm{rt}} \nearrow \Rightarrow \Delta x_i^{\mathrm{rt}} \nearrow$

The continuous power balance in the grid is established by an arrangement of reactive control structures and operator interventions. Real-time imbalances are caused by continuous variation of load and intermittent generation, forecast errors, and unplanned outages of conventional generation, but also by uncoordinated ramping between scheduled operating points. For a given operation strategy, the $\Delta\aleph^{\mathrm{rt}}$-formulation may provide feedback about the quality of schedules established by the planning stages [15].

B. Constraints Coordination and Reserve Allocation

The power node constraints (a)–(f) in (1) have been formulated as "physical" limitations of the unit operation ranges. The multistage formulation requires a coordination of constraints between the stages that is compliant with those original power node constraints. For the real-time control of power systems, e.g., for load frequency control provision, power capacity is reserved for activation when imbalances occur[2]

$$-\Delta u_{\mathrm{gen}}^{\mathrm{rt,neg}} \le \Delta u_{\mathrm{gen}}^{\mathrm{rt}} \le \Delta u_{\mathrm{gen}}^{\mathrm{rt,pos}} \tag{12}$$

$$-\Delta u_{\mathrm{load}}^{\mathrm{rt,pos}} \le \Delta u_{\mathrm{load}}^{\mathrm{rt}} \le \Delta u_{\mathrm{load}}^{\mathrm{rt,neg}} \tag{13}$$

where (rt, pos) and (rt, neg) indicate constraints associated with the provision of positive/negative control reserves.

Nowadays it is not common in power system operation to deliver control reserves through units with energy constraints relevant on the time-scale of the reserve provision. Pumped hydro power plants, which are naturally energy-constrained by their water reservoir, usually have sufficient storage capacity to securely deliver the contracted control reserves without risk of depletion or overflow of their storage. This is different in the case of reserve provision by controllable thermal loads, small-scale combined-heat-and-power units, or plug-in hybrid electric vehicles, which have a significantly smaller capacity to store energy in proportion to their power capacity. Here, it may be necessary to also reserve a storage control band

$$-\Delta x^{\mathrm{rt,pos}} \le \Delta x^{\mathrm{rt}} \le \Delta x^{\mathrm{rt,neg}}. \tag{14}$$

The nomenclature of $\Delta x^{\mathrm{rt,pos}}$ for the lower and $\Delta x^{\mathrm{rt,neg}}$ for the upper bound is due to positive and negative reserves being formulated from a grid perspective, whereas x is from a power node perspective. The implications of reserve provision by energy-constrained generation and load units are summarized in Table II.

Control reserves are security-critical and are typically procured with considerable lead-time. This requirement of availability calls for the reservation of a control band to be taken

[2]In the following, the subindex i is dropped for compact notation.

into account in the day-ahead-*scheduling* stage of the power node operation

$$\Delta x^{\mathrm{rt,pos}} \leq x^{\mathrm{sch}} \leq 1 - \Delta x^{\mathrm{rt,neg}}$$
$$0 \leq u_{\mathrm{gen}}^{\min} + \Delta u_{\mathrm{gen}}^{\mathrm{rt,neg}} \leq u_{\mathrm{gen}}^{\mathrm{sch}} \leq u_{\mathrm{gen}}^{\max} - \Delta u_{\mathrm{gen}}^{\mathrm{rt,pos}}$$
$$0 \leq u_{\mathrm{load}}^{\min} + \Delta u_{\mathrm{load}}^{\mathrm{rt,pos}} \leq u_{\mathrm{load}}^{\mathrm{sch}} \leq u_{\mathrm{load}}^{\max} - \Delta u_{\mathrm{load}}^{\mathrm{rt,neg}}.$$

For the schedule-*update*, the above absolute constraints are then formulated relative to the pre-planned trajectory

$$\Delta x^{\mathrm{rt,pos}} - x^{\mathrm{sch}} \leq \Delta x^{\mathrm{upd}} \leq 1 - \Delta x^{\mathrm{rt,neg}} - x^{\mathrm{sch}}$$
$$u_{\mathrm{gen}}^{\min} + u_{\mathrm{gen}}^{\mathrm{rt,neg}} - u_{\mathrm{gen}}^{\mathrm{sch}} \leq \Delta u_{\mathrm{gen}}^{\mathrm{upd}} \leq u_{\mathrm{gen}}^{\max} - u_{\mathrm{gen}}^{\mathrm{rt,pos}} - u_{\mathrm{gen}}^{\mathrm{sch}}$$
$$u_{\mathrm{load}}^{\min} + u_{\mathrm{load}}^{\mathrm{rt,pos}} - u_{\mathrm{load}}^{\mathrm{sch}} \leq \Delta u_{\mathrm{load}}^{\mathrm{upd}} \leq u_{\mathrm{load}}^{\max} - u_{\mathrm{load}}^{\mathrm{rt,neg}} - u_{\mathrm{load}}^{\mathrm{sch}}.$$

The constraints ensure that trajectories scheduled in one stage do not influence the feasibility of trajectories formulated in another stage with respect to the original power node constraints.

All other constraints (d)–(f) in (1) can be transformed accordingly. Note that the nonlinear constraint (d) can be easily recasted as a linear constraint, as $\xi(t) \neq 0\ \forall\, t$ for most processes. Additional ramping-constraints can be formulated entirely analogously.

IV. Dispatch and Real-Time Simulation Environment

Planning activities are aimed at establishing the best possible use of available resources. This objective can be formulated as minimizing the cost of system operation, while maintaining power system security constraints. In real-time operation, these schedules define the baseline of expectations for the actual events. Here, the primary objective is to maintain a secure operating state in spite of unexpected variations and events—optimality becomes a secondary objective. Today, the schedules for operation planning are usually an outcome of market operations, facilitating the coordination of multiple actors. In the perspective of a system operator, an economic dispatch approximates the outcome of market operations [34].

A perfect dispatch would require perfect information about the actual operating conditions, which is not available in advance. In particular, uncertainty in the prediction of load or wind power induces a mismatch between scheduled and actual energy turnover. In analogy to the multistage formulation of the power node equation, the simulation environment is composed of three stages.

1) *Day-ahead dispatch*: daily multiperiod optimization for a complete day, with optimization horizon of several days; generates the baseline operating point schedule for the controllable variables and storage states, utilizing predictions of the uncertain variables with a time-lag of half a day; the optimization result can be interpreted to reflect a market outcome.
2) *Intraday rescheduling*: receding horizon optimization, executed regularly, e.g., hourly, utilizing predictions with a short time-lag as well as the day-ahead baseline controllable variables and storage levels; results in a new operating point schedule for controllable variables; the result reflects the intraday market outcome.
3) *Real-time operation*: simulation of continuous system behavior with high time-resolution; utilizes the operating point schedule for the controllable variables and actual values of uncertain variables, enhanced by characteristic power fluctuations; here, power system operation structures are modeled.

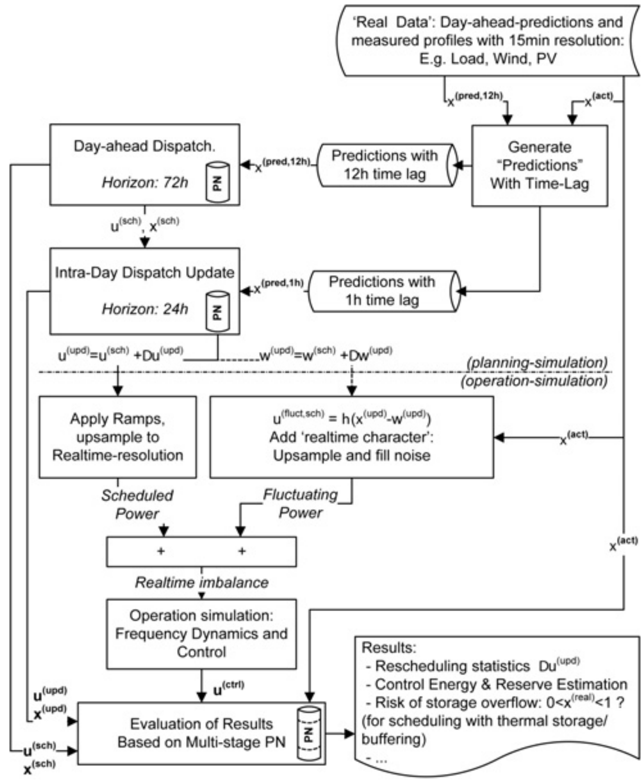

Fig. 3. Flow diagram of the simulation environment. The (PN) symbols indicate that the respective internal model and data formatting are based on the PowerNode formalization.

The implementation used here consists of two parts: a dispatch strategy based on in-feed and load predictions utilized in an MPC approach, and a simulation of the actual load and in-feed realizations including power system frequency dynamics and control. Both parts are combined in the case study in Section V. The flow diagram in Fig. 3 illustrates the structure of the simulation environment.

A. MPC-Based Planning

A multiperiod optimization is required in the presence of inter-temporal constraints. In particular the presence of energy storage requires the explicit consideration of dynamic states in the planning environment. MPC-based optimization provides these features. MPC combines a receding horizon optimization with a periodic observation of actual state variables of the plant. This emulates a closed-loop-like behavior, which enables the controller to deal with unanticipated disturbances. Within the power nodes approach, the state of the "plant" is the set of state-of-charge variables $\boldsymbol{x}_i$ of the storages, and external

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predictions for in-feeds and loads are considered up to the optimization horizon.[3]

The main simulation parameters of the two stages for day-ahead scheduling and update are as follows:

1) the optimization frequency, e.g., daily, hourly, and so on;
2) the sampling time and the look-ahead horizon;
3) available predictions at the time of carrying out the optimization, e.g., 24 h ahead wind forecast with 15 min time resolution;
4) the time lag between the execution of the optimization and the realization, in liberalized settings given by the gate closure time of the energy exchange.

The details of the multistage optimization are given as follows.

1) *Cost Functions:* For compact cost function formulation, we define the state and input variable vectors

$$\boldsymbol{x} = [x_1, \ldots, x_n]^{\mathrm{T}} \tag{15}$$

$$\boldsymbol{u} = [u_{\text{gen},1}, \ldots, u_{\text{gen},N}, u_{\text{load},1}, \ldots, u_{\text{load},N}, \xi_1, \ldots, \xi_N, w_1, \ldots w_N]^{\mathrm{T}} \tag{16}$$

$$\boldsymbol{\delta u}_k = \boldsymbol{u}_k - \boldsymbol{u}_{k-1} \tag{17}$$

where $\boldsymbol{x}^{\text{ref}}$ and $\boldsymbol{u}^{\text{ref}}$ are reference values for state and input variable vectors. We consider the following cost function for the day-ahead dispatch:

$$J_k = \sum_{l=k}^{k+N_{\text{opt}}-1} \left((\boldsymbol{x}_l - \boldsymbol{x}_l^{\text{ref}})^{\mathrm{T}}\, \boldsymbol{Q}\, (\boldsymbol{x}_l - \boldsymbol{x}_l^{\text{ref}}) + \boldsymbol{q}^{\mathrm{T}} (\boldsymbol{x}_l - \boldsymbol{x}_l^{\text{ref}}) \right) + \sum_{l=k}^{k+N_{\text{opt}}-1} \left((\boldsymbol{u}_l - \boldsymbol{u}_l^{\text{ref}})^{\mathrm{T}}\, \boldsymbol{R}\, (\boldsymbol{u}_l - \boldsymbol{u}_l^{\text{ref}}) + \boldsymbol{r}^{\mathrm{T}} (\boldsymbol{u}_l - \boldsymbol{u}_l^{\text{ref}}) \right) + \sum_{l=k}^{k+N_{\text{opt}}-1} \left(\boldsymbol{\delta u}_l^{\mathrm{T}}\, \boldsymbol{\delta R}\, \boldsymbol{\delta u}_l \right). \tag{18}$$

The individual terms in the cost function are as follows. The first line penalizes a deviation of the state from a desired target value. Penalizing state deviation is only meaningful in cases when actual financial costs are incurred by the deviation, or when the state shall be kept in the vicinity of a certain level, e.g., in order to reduce the risk of a storage depletion or overflow. The second line penalizes all instantaneous quantities except for the physical loss term v. This includes mainly generator cost functions (linear and/or quadratic terms) for fuel cost and operation and maintenance, and penalties for curtailments of load and generation (the latter is only relevant when actual compensation payments have to be made, e.g., for RES curtailments). The last line represents ramping costs incurred by working point changes. This is particularly relevant for thermal generation processes where thermal stress is an important factor for unit lifetime.

The cost function can be reformulated to also accommodate a receding horizon problem for the dispatch update. Note that the variables for day-ahead dispatch and intraday update are indexed with (sch) and (upd), respectively.

[3]Although the nature of the given problem is stochastic, a deterministic dispatch based on the available predictions is chosen here for simplicity. This can be extended in order to better represent the stochasticity of the underlying processes by: 1) a stochastic programming approach, or 2) a Monte Carlo scenario-based optimization.

2) *Day-Ahead dispatch:*

a) *Available predictions and timing:* The day-ahead dispatch is usually settled around noon of the day preceding actual operation. One day in advance, predictions of the load and fluctuating RES in-feed are still rather inaccurate. Due to the time lag between execution of the prediction and implementation, the full length of the available prediction, e.g., 72 h cannot be exploited. The effectively available prediction is shortened by this.

b) *Cost function:* The penalization used for the day-ahead dispatch should normally be based on the marginal cost that is incurred by system operation, provided that the goal of the dispatch is least-cost operation.

3) *Intraday Update:*

a) *Available predictions and timing:* Intraday predictions are usually more accurate and have a shorter forecast horizon, e.g., 4–12 h. Due to the market gate-closure, there is also a time lag between prediction and execution, e.g., of 1 h. This leads to a reduction in accuracy of the forecast because it is already 1 h old when it is executed, and a current measurement of the real values cannot be employed directly for the upcoming period.

b) *Cost function:* For the intraday update, the penalization should also include the marginal cost of system operation. Additionally, terms can be included which penalize the deviation from the original schedule. The main reasons for this are transaction costs for intraday rescheduling, as well as costs due to the deviation from the scheduled storage operation, which was determined to be optimal by a longer-term optimization.

B. Operation Simulation

The two planning stages result in a schedule for the dispatchable generation, formulated on the basis of expectations of fluctuating consumption and power generation. Simulating the realization of schedules in real-time means that additional information has to be added to the available signals. In operation-time, schedules for dispatchable generation are realized in form of ramping between the schedule-levels. But fluctuating power does not follow the prediction. Given a realization of the fluctuating power with a low time resolution, the energy content will be correct for that resolution, but the continuous fluctuation of the signal needs to be added. The system dynamics and control structures then react to the deviations between scheduled and actual values in continuous time.

1) *Upsampling:* For the simulation of realtime-operation, the scheduled and recorded power profiles with a low time resolution (Δt_{disp}) are upsampled to a higher resolution (Δt_{rt}). Here the ramping and fluctuating character of different processes is emulated.

a) *Ramping of scheduled power:* According to [4], the transition between schedule levels shall occur with a 10 min long ramp, starting 5 min before and ending 5 min after the schedule time. In the present model, this is realized on the basis of 15 min schedules.

b) *Emulation of wind power and load behavior:* Wind power fluctuation and load behavior in real-time are best understood as stochastic processes. The recorded profiles present the energy content for a 15 min resolution. The fluctuation module emulates the real-time fluctuation by: 1) spline-interpolation through interval midpoints; 2) adding a combination of white noise with time-lag filters; and 3) rescaling the resulting signal to the energy content given by the profiles. The parameters of white noise and time-lag filters have been tuned heuristically to match the fluctuation width for an estimated average wind farm size using data from [35]. The noise is then scaled by a factor of $1/\sqrt{N}$, e.g., [36], modeling the smoothing of uncorrelated power fluctuations from wind farms at different sites. The load noise is modeled as white noise and scaled roughly according to literature values [37].

2) *Frequency Control Simulation:* The present real-time module emulates the behavior of a secondary (area) controller in the ENTSO-E Regional Group Continental Europe. Primary (droop) frequency control in the face of instantaneous fluctuations is performed by the whole synchronous region. As a result, only slower fluctuations are visible in the control actions of the individual area controller. At present, no tertiary control actions and operator interventions are modeled. Other types of control structures may be embedded in this block by simply exchanging the real-time simulation module.

C. *Evaluation of Multistage Signals*

The present simulation environment translates a scenario definition and a control structure into virtual operation data. The operation data includes time series of all control variables and allows the evaluation of the given control scenario. This data serves as a basis to define measures for evaluating the performance of the respective control and operation structures. Are incentives given by power markets and grid codes aligned with control needs? Are control actions effective or are control resources wasted? What is the energy content of control actions?

The data generated allows the study of: 1) different control structures under same parameterizations of the dispatch framework; 2) alterations of the dispatch parameters, e.g., gate closures, with a fixed control structure; and 3) the study of varying energy scenarios and with load and generation mixes. In addition to the energy accounting functions introduced in [17] and Section II-E, the present multistage formulation allows indicators for evaluating control performance characteristics, for example the following:

a) control energy requirements per time-scale;
b) reserve requirements estimation;
c) rescheduling statistics $\Delta u^{(\mathrm{upd})}$.

Data generated from multistage evaluation allows the study of other operation-relevant features than the dispatch simulation alone. If the operation stages are well-modeled, this data reproduces the characteristic behavior of actual system operation. Evaluation can be performed by comparison to actual operation data. However, within the scope of this paper, only a simple case is presented.

V. EXEMPLARY STUDY CASE

As a study case, a simulation of a hypothetical control area within the ENTSO-E Regional Group Continental Europe is studied. The exemplary setup consists of four power nodes connected to a single grid bus:

1) a conventional load without buffer, not curtailable ($\xi_1 = \xi_{\mathrm{drv},1}(t) < 0$);
2) an intermittent generation unit that can be curtailed, here the aggregated wind of a region ($C_2 = 0$, $\xi_2 = \xi_{\mathrm{drv},2}(t) \geq 0$);
3) conventional generation aggregated in one unit ($C_3 = 0$, ξ_3 controllable, $w_3 = 0$);
4) a storage unit with capacity C_4 and without external process ($\xi_4 = 0$) emulating the pumped hydro capacity in that region.

TABLE III
SIMULATION PARAMETERS

Storage Capacities			
C_1,C_2,C_3	0 GWh	C_4	480 GWh
Power Ratings			
$P_{\mathrm{rated},1}$	60.2 GW	$P_{\mathrm{rated},2}$	90 GW
$P_{\mathrm{rated},3}$	60.2 GW	$P_{\mathrm{rated},4}$	60 GW
Grid Variable Constraints			
Efficiencies			
$\eta_{\mathrm{gen},3}$	0.45		
$\eta_{\mathrm{gen},4}$	0.9	$\eta_{\mathrm{load},4}$	0.85

The set of power node equations given here is based on (1). As power nodes 1–3 contain no inherent storage, they use the reduced model (2). The problem set is thus

$$\xi_1 = -\eta_{\mathrm{load},1}\, u_{\mathrm{load},1} \tag{19}$$
$$\xi_2 - w_2 = \eta_{\mathrm{gen},2}^{-1}\, u_{\mathrm{gen},2} \tag{20}$$
$$\xi_3 = \eta_{\mathrm{gen},3}^{-1}\, u_{\mathrm{gen},3} \tag{21}$$
$$C_4\, \dot{x}_4 = \eta_{\mathrm{load},4}\, u_{\mathrm{load},4} - \eta_{\mathrm{gen},4}^{-1}\, u_{\mathrm{gen},4}. \tag{22}$$

The numerical values of the scenario parameters and power node constraints are summarized in Table III.

The setup is tested for the case of one year, sampled in 15 min intervals, with a wind energy contribution of up to 40% of the total load. Fig. 4 illustrates the result of a day-ahead dispatch for an excerpt of 16 days. The result of the corresponding intraday redispatch exhibits some differences, notably the significant curtailment of wind power in-feed around the fifth day, as shown in Fig. 5. The internal evaluation of the predictive dispatch is given in Table IV. Note that the actual performance of the dispatch will deviate strongly, given that it is subject to large forecast errors.

A 14 h excerpt of the real-time simulation is provided in Fig. 6, showing trajectories of fluctuating and dispatched power (lower plot), as well as control signals and balancing power (upper plot). The real-time imbalance results from summing up dispatched and fluctuating power. Here dispatched power is the sum of conventional plus hydro storage schedules with 10 min ramps applied, and fluctuating power is load minus wind power. The resulting imbalance is the disturbance signal for the grid frequency dynamics and frequency control cascade. The continuous decrease in scheduled generation, observable in the lower plot from 4 h onward, is a result of increasing wind power generation. Significant imbalances can be

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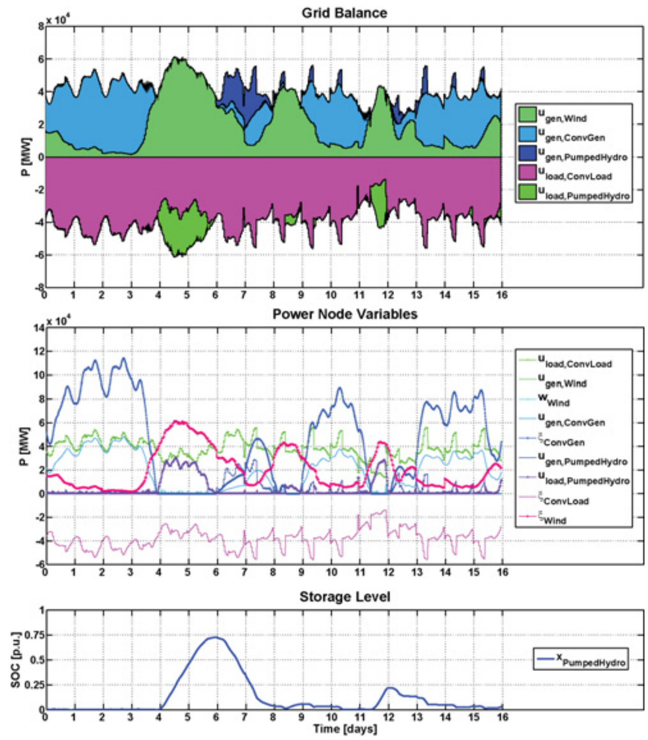

Fig. 4. Dispatch based on day-ahead predictions.

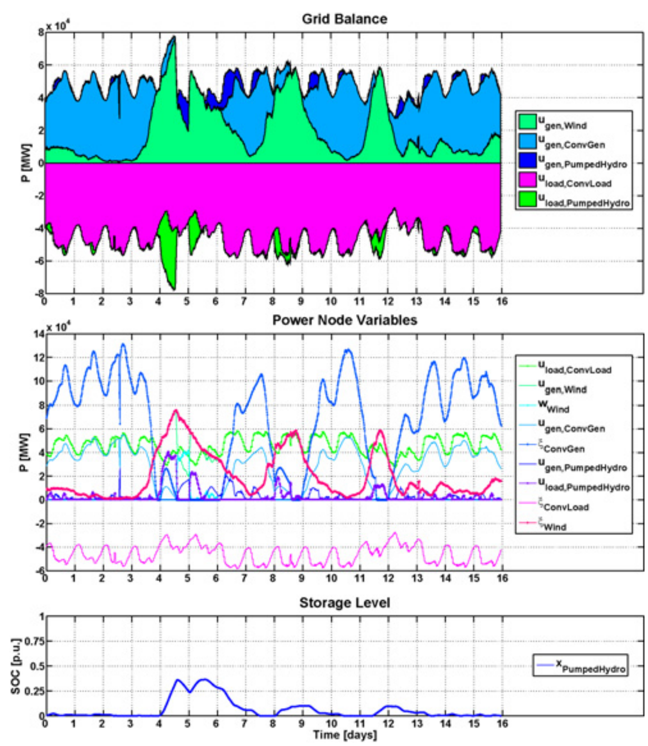

Fig. 5. Redispatch based on intraday prediction updates.

observed with an hourly pattern, which results from the hourly resolution of energy markets and load forecasting. The secondary control power (black line in upper plot) follows minute-to-minute fluctuations, hourly trends are clearly visible.

An important aspect in the evaluation of energy storage for power system operation is that the time sequence of control

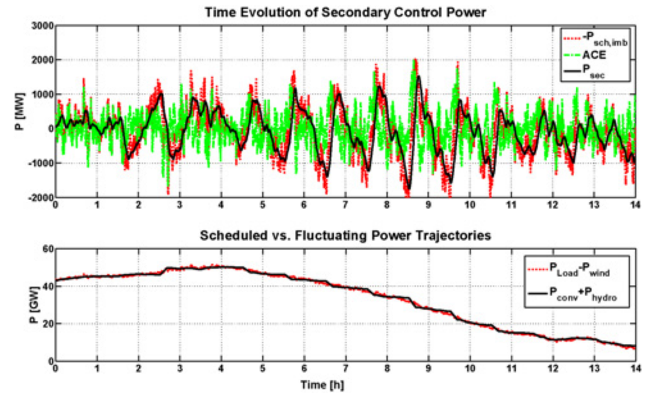

Fig. 6. Excerpt of real-time simulation of control areas.

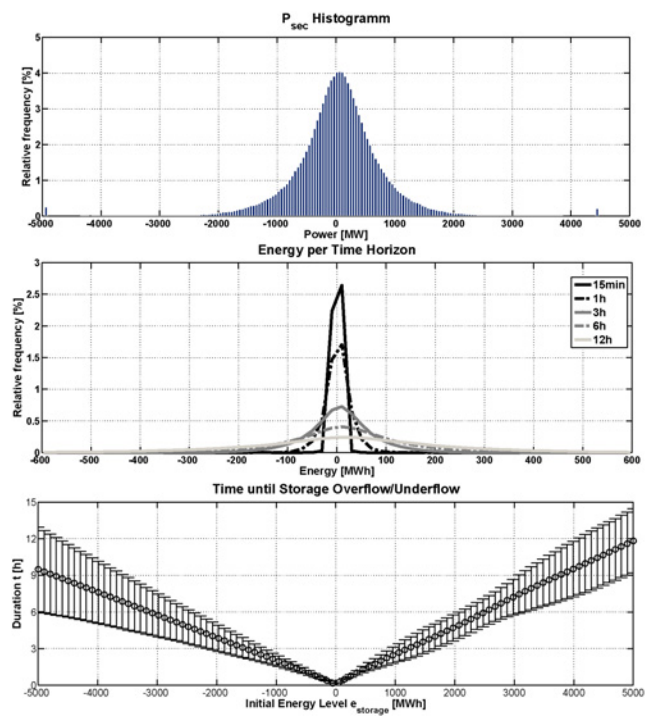

Fig. 7. Three analyses of the secondary control power signal.

signals matters more than in conventional power systems. The present framework generates these time series with a high time-resolution. This data can be utilized to generate statistics characterizing the resource utilization for a given resource mix and control framework. Fig. 7 suggests exemplary graphs evaluating the present study case. The topmost plot presents a power histogram which is a classical method for the study of control reserve needs (the relative frequency in this "historic" data corresponds to a likelihood for the given power value). As observed from this plot, the modeled fluctuations and prediction errors induce significant utilization of the secondary reserve, even though plant outages have not been included in this simulation. The histogram shows a minor positive bias for small fluctuations. The other two diagrams serve the investigation of energy volumes in the time-sequence. The distributions presented in the middle plot show a likelihood distribution for how much energy reserve units provide/consume offering secondary reserve for a given time period (15 min, 1 h, 3 h,

TABLE IV
BALANCE TERMS FOR SIMULATION EXAMPLE

Balance Term [TWh]	Int. Dispatch	Int. Update
Energy consumed by load	355.87	361.53
Energy supplied by conv. gen.	207.71	224.79
Energy supplied by wind power	151.64	141.15
Energy supplied by hydro storage	13.42	18.24
Energy consumed by hydro storage	16.90	22.64
Wind energy curtailed	0.53	3.90
Load demand not served	0	0

6 h, 12 h). The energy values have been computed as time integrals for the given time horizons, with varying initial times. The somewhat expected results indicate that for the 15 min horizon less than ±50 MWh and for the 1 h horizon less than ±100 MWh of energy are required. It can be seen that after 12 h, the energy-values become quite uncertain, just indicating the slight positive bias seen already in the power histogram. The second energy diagram evaluates the data strategically from an energy-storage perspective. For how long could a given energy storage(-level) provide a specific (either positive or negative) regulating power service? Given the available power signal, the time for which the service could be provided has been computed for each initial energy level. By computing the time for varying initial times, a distribution of service-time could be calculated for each energy level. The plot provides mean and standard deviation for the charging/discharging time (assuming a Gaussian distribution of the statistic) of the various energy levels. As a decision-support, this diagram may be read the other way around: charging a cluster of batteries with 200 MWh by continuously providing 10% of the total negative reserve will take about 5±1 h.

The generated data can then be used to feed investigations of control requirements that result from these scenarios. In addition to this identification of quantitative requirements, also the effect of different regulation services can be estimated in this framework.

VI. CONCLUSION AND OUTLOOK

A flexible and comprehensive modeling framework for generic energy storage and different degrees of dispatchability in power systems has been presented. The model architecture is designed such that it can integrate with existing power system analysis tools such as power flow computations and dynamic frequency simulations.

It has been shown how the power node equation can be decomposed into a baseline scheduling model, a schedule update model, and a real-time control model, which in superposition account for the entire affine power node dynamics. While the baseline model accounts for the basic dispatch, e.g., in day-ahead planning, the update model is a valuable tool to consider updated predictions of intermittent units closer to real-time operation. The balance terms associated with the power node equations can be used to evaluate the effect of updated predictions on unit and reserve utilization. The real-time model accounts for disturbances and control actions at the time of realization, e.g., the provision of load frequency control around a baseline trajectory. In contrast to (computationally less expensive) implicit approaches, the explicit modeling allows the synthesis of system-behavior: by integration of knowledge about characteristic real-time behavior, e.g., of load, wind or PV, it enables parametric scaling. Future energy scenarios are typically computed on a highly aggregated level, which makes it difficult to anticipate the implications for power system operation. With the presented modeling environment, operation-data can be generated out of relatively simple scenario specifications. This formulation is particularly attractive when the introduction of new ancillary services in a changing external environment is to be studied. The multistage formulation is also useful to analyze how provision of control services by energy-constrained units should be combined with scheduling requirements. Some examples for the evaluation criteria of real-time control structures have been presented.

The formulation of concrete power node equations for common units in power systems, such as different types of generation units, storage technologies and clusters of thermostatically controlled loads will broaden the support for applications. Ongoing research addresses the formulation of representations for control structures enabling flexible reconfiguration and experimentation with alternative control strategies and architectures. Further analysis of both existing and newly proposed power system operation concepts will support the adaptation of power system operation to the challenges ahead, such as the challenge of power systems with 100% RES.

In traditional operation concepts, intermittent generation is seen predominantly as a disturbance. The presented framework is aimed at facilitating the shift from the traditional operation paradigm of controllable generation and fluctuating demand toward an understanding of operation that integrates conventional, as well as noncontrollable and partially controllable intermittent generation, flexible demand and energy storage.

ACKNOWLEDGMENT

The authors would like to thank P. Jonas for the strong commitment to his masters thesis, which was related to this paper.

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