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Energy Storage in Power System Operation: The Power Nodes Modeling Framework

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Abstract—A novel concept for system-level consideration of energy storage in power grids with dispatchable and non-dispatchable generators and loads is presented. Grid-relevant aspects such as power ratings, ramp-rate constraints, efficiencies, and storage capacities of the interconnected units are modeled, while technology-dependent and physical unit properties are abstracted from. This allows the modeling of a technologically diverse unit portfolio with a unified approach. The concept can be used for designing operation strategies for power systems, especially in the presence of non-dispatchable generation and significant storage capacities, as well as for the evaluation of operational performance in terms of energy efficiency, reliability, environmental impact, and cost. After introducing the modeling approach and a taxonomy of unit types, a simulation example is presented for illustration.

Index Terms—Power Nodes, Energy Storage, Dispatch, Balancing, Active Power Control, Curtailment, Load Management, Intermittent Generation

I. INTRODUCTION

ELECTRIC power is a real-time commodity, which means that both its provision and consumption occur instantaneously. Traditionally, controllable generation units provide the necessary flexibility to achieve a continuous balance between supply and demand. While the power balance is established through an arrangement of automatic controls, integral (e.g. hourly) amounts of energy are procured in energy markets based on predictions.

The combustion of fuels with chemically stored energy enables the flexible dispatch of generators. This process is mainly driven by spot market electricity prices and marginal electricity generation costs. In the 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 expected opportunity costs from expected future prices and available storage levels [1]. Thus, energy constraints – inherent to all kinds of energy storage – induce a different dispatch logic. Considering the ongoing large-scale deployment of intermittent renewable energy sources (RES) [2], energy storage is likely to become a dominant factor in future power systems [3].

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A. Energy Storage in Power Systems

All forms of energy storage, except for electro-mechanical energy storage inherent to AC power systems with rotating machines, depend on energy conversion processes which are based on a wide range of technologies [4]. In addition to reversible energy storage in the form of batteries, flywheels etc., 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 amounts of electric vehicles connected to the power system [5]–[8]. 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 [9], [10].

The economic value of energy storage is derived from the abilities to perform market-oriented dispatch and to act as a control resource in the framework of ancillary services. Especially in systems dominated by intermittent and inflexible generation capacity, flexibility is valuable [11]. However, current grid operation frameworks do not directly support and capitalize on the specific capabilities of energy storage. For instance, storage reserves are not conceptually considered in the traditional procurement of control reserves: Only power reserves are relevant, while the amount of energy required for control actions is not visible to the operator and is settled in post-operation.

B. Intermittent In-Feeds

Intermittent power in-feeds from wind turbines and photovoltaic arrays are predictable to a certain extent [12]. Nowadays, information on the predicted future power in-feed is included in the power plant day-ahead dispatch in areas with high RES penetration. Curtailment of intermittent power in-feed is usually only used as an emergency measure, not as a normal-operation control resource. Similarly, the unavoidable prediction errors are balanced via intra-day trading and conventional control reserves, not by the intermittent generation units themselves.

The utilization of on-line control measures for intermittent generation units, such as partial generation curtailment [13], [14], 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, i.e. wind force, which cannot be influenced. The challenge of systematically and consistently integrating such methods into power system operation and control constitutes another motivation for the present work.

C. Objective of this Work

The additional degrees of freedom that energy storage and an increased controllability of intermittent power infeeds provide can only be utilized if an appropriate control architecture is established. Many control architectures, often utilizing aggregation principles, have been proposed in this context, such as Virtual Power Plants [15], Cells [16], [17], or MicroGrids [18]. The impacts of energy storage are particularly relevant for dispatch problems because of the storage dynamics and associated inter-temporal constraints. Here, the control methodology of (distributed) Model Predictive Control is particularly suitable [19]–[21].

A comprehensive performance comparison of different control approaches constitutes a challenge in itself [22], [23]. This paper aims at developing an appropriate evaluation framework for addressing this challenge. The concept of “Power Nodes” is introduced to represent a variety of unit types in a unified framework for the assessment of energy-storage-based operation strategies for power systems. On the basis of instantaneous quantities in the storage model, a number of power and energy balances can be formulated that allow to evaluate the overall system performance. The objective is to consider all types of energy storage relevant for system operation.

The paper is structured as follows: Section II introduces the Power Nodes framework, while Section III explains the representation of common unit types as power nodes. The benefits of the developed concept are illustrated by a simple simulation example in Section IV, followed by conclusions in Section V.

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 “use-forms” of energy, respectively. The degrees of freedom necessary for fulfilling the power balance in the electric grid arise from the freedom that the supply- 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- or use-process including the associated energy conversion, 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, illustrated in Fig. 1. In the resulting enhanced model, the electro-mechanical domain of the electric grid is interfaced with the pre-grid Power Node domain, which represents conversion processes and an associated energy storage functionality. A third, external, domain is formed by the use and supply processes consuming energy from and feeding energy into the Power Node domain.

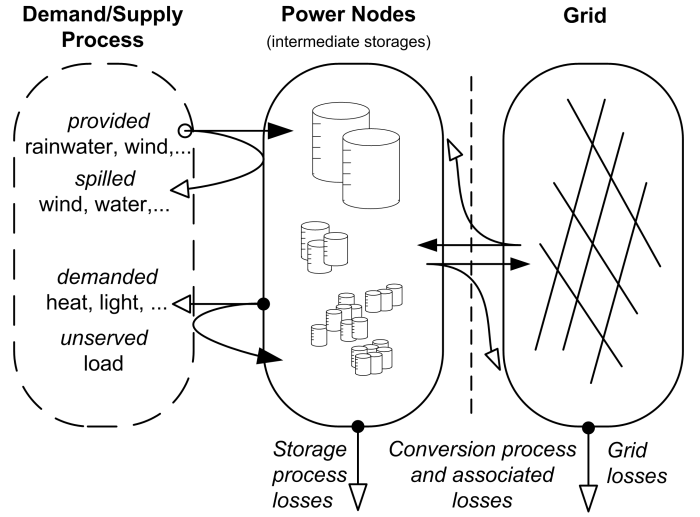


Fig. 1. Illustration of the three-domains concept. The Power Node- and Grid domains are model-internal domains and both are considered integral parts of the electric energy system. The domain of Demand/Supply processes is considered external, indicated by the dashed frame. Arrows indicate the energy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

For ensuring the consistency of the model, 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/reactive 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 Grid domain, while pre-grid 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 (cf. Section II-C).

All supply and demand processes are connected through 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, as is illustrated by straight and rounded arrows in Fig. 1. This enables the formalized representation 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 performance of the overall system, it is necessary to keep track of these losses and to account for the value associated with them. For this purpose, the balance terms formulated in Section II-E can be utilized.

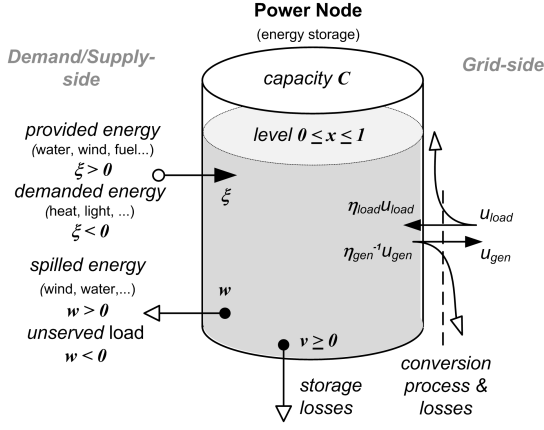


Fig. 2. Notation for a single power node.

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 a use and $\xi > 0$ a supply. The term $u_{\text{gen}} \geq 0$ describes a conversion corresponding to a power generation with efficiency η_{gen} , while $u_{\text{load}} \geq 0$ 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.

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

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

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 influence or not. Internal dependencies, such as a state-dependent physical loss term $v_i(x_i)$, are feasible. Charge/discharge efficiencies may be non-constant in the general case, 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 non-negative 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 non-negative. 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 with a simplified representation of the local dynamics.

Apart from the constraints listed here, there may be additional ones imposed on the variables, e.g. in order to define certain standard unit types with characteristic properties (cf. Section III). Generally speaking, the explicit mathematical form of a power node equation depends on the particular modeling case. Note that the labeling for the power node equation is based solely on a generic process perspective, providing technology-independent categories linked to the evaluation functions given in Section II-E.

2) *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 ambience due to a difference between the internal storage temperature and the ambient temperature. For this purpose, a linear dependence of v_i on the storage state x_i is assumed, and the efficiencies are assumed constant in order to eliminate nonlinearities:

$$\begin{aligned}
 C_i \dot{x}_i &= \eta_{\text{load},i} u_{\text{load},i} - \eta_{\text{gen},i}^{-1} u_{\text{gen},i} + \xi_i - w_i \\
 &\quad - a_i (x_i - x_{\text{ss},i}), \quad (2)
 \end{aligned}$$

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 ambience, and a_i is a non-negative loss coefficient.

3) *Modeling a Power Node without Storage:* Power nodes are also useful to represent processes independent of energy storage, such as conventional generation/load, as well as intermittent generation. 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

$$\xi_i - w_i = \eta_{\text{gen},i}^{-1} u_{\text{gen},i} - \eta_{\text{load},i} u_{\text{load},i}. \quad (3)$$

This equation is able to describe both externally driven processes and controllable power generation.

In the case of an externally driven supply/demand process $\xi_i = \xi_{\text{drv},i}(t)$, the supplied/required energy is either directly fed into/taken from the grid, or it is spilled/not served, accounted for by the waste term w_i . This model is particularly relevant for external supply and demand processes which are not directly controllable, while there may be a choice to curtail the process. Examples are

intermittent power generation ($\xi_{\text{drv},i}(t) \geq 0$) and classical load ($\xi_{\text{drv},i}(t) \leq 0$).

In the case of a fully controllable supply process such as a conventional generator, the grid-related variables $u_{\text{gen},i}$ or $u_{\text{load},i}$ are the controlled variables. The power exchange with the environment through ξ_i then accounts e.g. for primary energy usage.

C. Mapping from Power Nodes to Grid Domain

All electric load and generation units are represented by power nodes, i.e. no further injections and loads need to be accounted for. Consider a power grid composed of power nodes $i \in \mathcal{N} = \{1, \dots, N\}$, representing a number of single or aggregated units, and buses denoted by $m, n \in \mathcal{M} = \{1, \dots, M\}$. In order to map the N power nodes to the M buses in the grid model, power node indices are divided into sets \mathcal{N}_m associated with each bus; the following properties hold for \mathcal{N}_m : $\mathcal{N}_m \subseteq \mathcal{N}$, $\mathcal{N}_m \cap \mathcal{N}_n = \emptyset$ 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:

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

D. DC Grid Model with Power Nodes

The Power Systems literature in general offers many options to model a power system, depending on the questions of relevance to the study. In principle, the Power Nodes domain can be interfaced with many grid model types due to the clear separation from the electro-mechanical domain.

To illustrate the approach, this section formulates a network represented by linear DC power flow equations. The DC network representation is used for example in an active-power dispatch of a unit portfolio in a capacity-constrained transmission system. The DC power flow assumes small angle differences, a constant, flat voltage profile, and neglects the resistance of lines. While voltage angles are generally small, the critical assumptions are the flat voltage profile and the negligible resistance [24].

The power flow is governed by the following equations:

$$P_{\text{exch},m} = \sum_{\substack{n \in \mathcal{M} \\ n \neq m}} B_{mn} (\delta_m - \delta_n) \quad , \quad (5)$$

$$0 = \sum_{m=1}^M (P_{\text{netinj},m} - P_{\text{exch},m}) \quad , \quad (6)$$

where δ_m is the voltage angle at bus m , and $B_{mn} = 1/X_{mn}$ is the inverse of the line reactance.

The line flows may be subject to capacity constraints:

$$-P_{mn}^{\text{cap}} \leq B_{mn} (\delta_m - \delta_n) \leq P_{mn}^{\text{cap}} \quad . \quad (7)$$

The system frequency can be described by an aggregate inertia model:

$$H\dot{\omega} = \sum_{m=1}^M P_{\text{netinj},m} \quad , \quad (8)$$

where H is the aggregate inertia constant and ω is the angular frequency of the system.

E. System-Level Balance Formulations

In order to establish an accounting framework for the evaluation of operation and control strategies acting on an electrical grid interfaced with a set of power nodes, a number of balance terms can be formulated. These can be established in the form of instantaneous quantities in order to characterize the current operational state of the system, or as time-integrals of the former which serve to evaluate the system performance over a certain time span.

Note that the expressions stated here are considered examples, not a complete list of possible balance terms. The list can be extended with respect to the specified power and energy performance indicators and can also include technology-dependent weighting terms for monetary cost or environmental impact. Examples for instantaneous balance terms indicating the current system state are:

- Power supplied to grid: $P_{\text{gen}}^{\text{grid}}(t) = \sum_{i \in \mathcal{N}} u_{\text{gen},i}(t)$,
- Power consumed from grid: $P_{\text{load}}^{\text{grid}}(t) = \sum_{i \in \mathcal{N}} u_{\text{load},i}(t)$,
- Currently stored energy: $E_{\text{stored}}(t) = \sum_{i \in \mathcal{N}} C_i x_i(t)$,
- Power supply available: $\xi_{\text{supply}}^{\text{total}}(t) = \sum_{i \in \{i | \xi_i > 0\} \subset \mathcal{N}} \xi_i(t)$,
- Power demand: $\xi_{\text{demand}}^{\text{total}}(t) = \sum_{i \in \{i | \xi_i < 0\} \subset \mathcal{N}} \xi_i(t)$,
- Power supply curtailed: $w^+(t) = \sum_{i \in \{i | w_i > 0\} \subset \mathcal{N}} w_i$,
- Power demand not served: $w^-(t) = \sum_{i \in \{i | w_i < 0\} \subset \mathcal{N}} w_i$,
- 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 non-controllable non-buffered generation units would require a summation over the index $i \in \{i | C_i = 0 \wedge \xi_i = \xi_{\text{drv},i}(t) \geq 0 \wedge w_i = 0\} \subset \mathcal{N}$.

Based on line flows estimated by the DC model and the assumption $R \ll X$, grid losses may be approximated by:

$$P_{\text{loss}}^{\text{grid}}(t) = \sum_{m=1}^{M-1} \sum_{n=m+1}^M |G_{mn} (\delta_m(t) - \delta_n(t))| \quad , \quad (9)$$

with G_{mn} being the (m, n) -th element of the bus conductance matrix.

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

- Electric energy supplied to grid: $\int_{t_1}^{t_2} P_{\text{gen}}^{\text{grid}}(t) dt$,
- Primary energy supplied: $\int_{t_1}^{t_2} \xi_{\text{supply}}^{\text{total}}(t) dt$,
- Primary energy curtailed: $\int_{t_1}^{t_2} w^+(t) dt$,
- Energy conversion losses: $\int_{t_1}^{t_2} P_{\text{loss}}(t) dt$.

III. CHARACTERIZATION OF UNIT TYPES

In this section, we provide a taxonomy of unit types that can be modeled using the Power Nodes framework. A “unit” in this context is an arbitrary generation, load, or storage device, or a group of aggregated devices. The type distinction is established by a set of constraints on the variables 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), providing a classification of units with different operational properties. First, a set of unit properties is established, then a number of possible combinations of these properties are listed, providing a link between the modeling framework and real units found in power systems.

A. Unit Properties

Table I establishes a set of basic properties defining the operational behavior of a unit modeled as a power node. The particular choice of constraints is explained in the following:

- The power node variables $u_{\text{gen},i}$ and $u_{\text{load},i}$ determine whether a power node is injecting power into or consuming power from the grid. A pure generation process would imply that $u_{\text{load},i} = 0$ at all times, while a pure load cannot inject power, expressed by $u_{\text{gen},i} = 0$. In a bi-directional conversion system, both variables can assume non-zero values. In this case, it must be further distinguished whether both conversions can happen at the same time (e.g. in a storage with two separate conversion units, such as a pumped hydro plant with independent turbine and pump), or whether one of the variables must always be zero (e.g. in an inverter-connected battery storage).
- The storage capacity C_i determines whether a unit is modeled with ($C_i > 0$) or without energy storage capabilities ($C_i = 0$).
- The sign of the external process variable ξ_i determines whether a supply process ($\xi_i > 0$) or demand process ($\xi_i < 0$) is considered. If no external process is considered, $\xi_i = 0$ holds.
- Constraints on ξ_i and w_i determine the controllability of a unit. In case ξ_i is driven by an external signal $\xi_i = \xi_{\text{drv},i}(t)$, e.g. induced by an intermittent supply, the unit may either be regarded as non-controllable (no curtailment possible: $w_i = 0$), or curtailable (no further constraint on w_i). Units are considered controllable if ξ_i is not externally driven. In this case, $w_i = 0$ can be assumed because the curtailment of a directly controllable process would be unnecessary¹.
- The storage associated with a power node is considered lossless if $v_i = 0$, and lossy otherwise.
- The grid variables $u_{\text{gen},i}$ and $u_{\text{load},i}$ may be rate-constrained, which is reflected in continuous time by

¹Note that more detailed sets of constraints may be established for the power node variables in order to model particular units. In this case, it may be practical to allow for a non-zero w_i even in the presence of a (partly) controllable ξ_i .

TABLE I
UNIT PROPERTIES DETERMINED 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	$C_i = 0$	Non-buffered unit
	$C_i > 0$	Buffered unit
ξ_i	$\xi_i = 0$	No external process
	$\xi_i \geq 0$	Supply process
	$\xi_i \leq 0$	Demand process
ξ_i, w_i	$\xi_i = \xi_{\text{drv},i}(t) \wedge w_i = 0$	Non-controllable
	$\xi_i = \xi_{\text{drv},i}(t)$	Curtailable
	ξ_i arbitrary, $w_i = 0$	Controllable
v_i	$v_i = 0$	Lossless storage
	$v_i > 0$	Lossy storage
$\dot{u}_{\text{gen},i}$	$\dot{u}_{\text{gen},i}^{\min} \leq \dot{u}_{\text{gen},i} \leq \dot{u}_{\text{gen},i}^{\max}$	Ramp-rate-constr. gen.
$\dot{u}_{\text{load},i}$	$\dot{u}_{\text{load},i}^{\min} \leq \dot{u}_{\text{load},i} \leq \dot{u}_{\text{load},i}^{\max}$	Ramp-rate-constr. load

an upper and lower bound on their derivatives. This serves to model physical limitations on the rate of change of a power conversion process, e.g. due to the amount of thermal stress on power plant components.

B. Property Combinations for Common Unit Types

Based on the unit properties described above, standard unit types can be defined, as presented in Table II. The unit category is followed by the set of defining power node variable constraints, as well as a unit example corresponding to each category. Note that, from a combinatorial point of view, more combinations of the constraints listed in Table I are possible. However, many of these have been eliminated because they are not meaningful from a physical or operational point of view.

IV. SIMULATION EXAMPLE: MANAGEMENT OF INTERMITTENT POWER IN-FEED

The case of managing an intermittent power in-feed to the grid is considered in order to illustrate the utilization of the Power Nodes framework together with a Model Predictive Control strategy. This simple example consists of five power nodes connected to a single grid bus:

- 1) A storage unit with capacity C_1 and without external process ($\xi_1 = 0$),
- 2) An intermittent generation unit that can be curtailed, here a wind farm ($C_2 = 0$, $\xi_2 = \xi_{\text{drv},2}(t) \geq 0$),
- 3) A conventional generation unit ($C_3 = 0$, ξ_3 controllable, $w_3 = 0$),
- 4) A thermal load with thermal energy storage capacity C_4 , lossless ($v_4 = 0$), with constant demand ($\xi_4 = \xi_{\text{drv},4} = \text{const} < 0$),
- 5) A conventional load without buffer that can be curtailed if necessary ($\xi_4 = \xi_{\text{drv},5}(t) < 0$).

The power node equations are based on the affine specialization (2) of the power node equation (1). As nodes 2, 3,

TABLE II
UNIT TYPE DEFINITIONS, RESULTING POWER NODE CONSTRAINTS, AND REAL-WORLD EXAMPLES

Unit type	$u_{\text{gen},i}, u_{\text{load},i}$	C_i	ξ_i	w_i	Example
Buffered load w/controllable demand	$u_{\text{gen},i} = 0$	$C_i > 0$	$\xi_i \leq 0$	$w_i = 0$	Non-time-critical thermal process
Buffered load w/non-controllable demand	$u_{\text{gen},i} = 0$	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \leq 0$	$w_i = 0$	Residential water heating
Buffered load w/curtailable demand	$u_{\text{gen},i} = 0$	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \leq 0$	–	Res. water heating w/shedding relay
Non-buffered load w/controllable demand	$u_{\text{gen},i} = 0$	$C_i = 0$	$\xi_i \leq 0$	$w_i = 0$	Non-time-critical production process
Non-buffered load w/non-contr. demand	$u_{\text{gen},i} = 0$	$C_i = 0$	$\xi_i = \xi_{\text{drv},i}(t) \leq 0$	$w_i = 0$	Conventional load
Non-buffered load w/curtailable demand	$u_{\text{gen},i} = 0$	$C_i = 0$	$\xi_i = \xi_{\text{drv},i}(t) \leq 0$	–	Conventional load w/shedding relay
Buffered gen. w/controllable supply	$u_{\text{load},i} = 0$	$C_i > 0$	$\xi_i \geq 0$	$w_i = 0$	Electricity-led CHP w/heat storage
Buffered gen. w/non-controllable supply	$u_{\text{load},i} = 0$	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \geq 0$	$w_i = 0$	PV/battery system
Buffered gen. w/curtailable supply	$u_{\text{load},i} = 0$	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \geq 0$	–	PV/battery system w/shedding relay
Non-buffered gen. w/controllable supply	$u_{\text{load},i} = 0$	$C_i = 0$	$\xi_i \geq 0$	$w_i = 0$	Fossil-fuel power plant
Non-buffered gen. w/non-contr. supply	$u_{\text{load},i} = 0$	$C_i = 0$	$\xi_i = \xi_{\text{drv},i}(t) \geq 0$	$w_i = 0$	PV system
Non-buffered gen. w/curtailable supply	$u_{\text{load},i} = 0$	$C_i = 0$	$\xi_i = \xi_{\text{drv},i}(t) \geq 0$	–	PV system w/shedding relay
Storage w/o external process	–	$C_i > 0$	$\xi_i = 0$	$w_i = 0$	Pumped hydro w/o inflow/outflow
Storage w/controllable supply	–	$C_i > 0$	$\xi_i \geq 0$	$w_i = 0$	Pumped hydro w/inflow control
Storage w/non-controllable supply	–	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \geq 0$	$w_i = 0$	Pumped hydro w/stochastic inflow
Storage w/curtailable supply	–	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \geq 0$	–	Pumped hydro w/inflow bypass
Storage w/controllable demand	–	$C_i > 0$	$\xi_i \leq 0$	$w_i = 0$	Pumped hydro w/controlled irrigation
Storage w/non-controllable demand	–	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \leq 0$	$w_i = 0$	Pumped hydro w/fresh water system
Storage w/curtailable demand	–	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \leq 0$	–	Pumped hydro w/blockable irrigation

and 5 contain no inherent storage, they are based on the reduced model (3). Thus, the set of power node equations for this problem is

$$C_1 \dot{x}_1 = \eta_{\text{load},1} u_{\text{load},1} - \eta_{\text{gen},1}^{-1} u_{\text{gen},1} \quad (10)$$

$$\xi_2 - w_2 = \eta_{\text{gen},2}^{-1} u_{\text{gen},2} \quad (11)$$

$$\xi_3 = \eta_{\text{gen},3}^{-1} u_{\text{gen},3} \quad (12)$$

$$C_4 \dot{x}_4 = \eta_{\text{load},4} u_{\text{load},4} + \xi_4 \quad (13)$$

$$\xi_5 - w_5 = -\eta_{\text{load},5} u_{\text{load},5} \quad (14)$$

All principal constraints set forth in (1) hold. The numerical values of parameters and constraints are summarized in Table III. All power quantities are expressed in MW, all energy quantities in MWh.

TABLE III
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Storage capacities			
C_1	40 MWh	C_4	20 MWh
Power ratings			
$P_{\text{rated},1}$	1 MW	$P_{\text{rated},2}$	2.5 MW
$P_{\text{rated},3}$	1.5 MW	$P_{\text{rated},4}$	1 MW
$P_{\text{rated},5}$	1.5 MW		
Grid variable constraints			
$u_{\text{load},1}^{\min}$	0	$u_{\text{load},1}^{\max}$	$P_{\text{rated},1}$
$u_{\text{gen},1}^{\min}$	0	$u_{\text{gen},1}^{\max}$	$P_{\text{rated},1}$
$u_{\text{gen},2}^{\min}$	0	$u_{\text{gen},2}^{\max}$	$P_{\text{rated},2}$
$u_{\text{gen},3}^{\min}$	$0.26 \cdot P_{\text{rated},3}$	$u_{\text{gen},3}^{\max}$	$P_{\text{rated},3}$
$u_{\text{load},4}^{\min}$	$0.5 \cdot P_{\text{rated},4}$	$u_{\text{load},4}^{\max}$	$1.5 \cdot P_{\text{rated},4}$
$u_{\text{load},5}^{\min}$	0	$u_{\text{load},5}^{\max}$	$P_{\text{rated},5}$
Efficiencies			
$\eta_{\text{load},1}$	0.8	$\eta_{\text{gen},1}$	0.9
$\eta_{\text{gen},2}$	1	$\eta_{\text{gen},3}$	0.4
$\eta_{\text{load},4}$	1	$\eta_{\text{load},5}$	1
MPC parameters			
Q	$\text{diag}([0, 3])$		
x_{ref}	$\text{diag}([0, 0.5])$		
R	$\text{diag}([1, 1, 0, 20, 0, 0, 0, 0, 5000, 0, 0, 0])$		
δR	$\text{diag}([0, 0, 0, 0, 50, 0, 0, 0, 0, 0, 0, 0])$		
N_{opt}	16		

In accordance with the unit properties established in Section III, the additional constraints on these power node equations are:

$$0 = u_{\text{gen},1} u_{\text{load},1} \quad (15)$$

$$\xi_2 = \xi_{\text{drv},2}(t) \geq 0 \quad (16)$$

$$\xi_4 = \xi_{\text{drv},4} = \text{const} < 0 \quad (17)$$

$$\xi_5 = \xi_{\text{drv},5}(t) \leq 0 \quad (18)$$

The power balance of the single bus system is

$$\sum_{i=\{1,2,3\}} u_{\text{gen},i} - \sum_{i=\{1,4,5\}} u_{\text{load},i} = 0 \quad (19)$$

The operational goal for this example is to balance storage conversion losses and thermal load setpoint deviations against wind curtailments in order to avoid unnecessary generator ramping and load shedding. A Model Predictive Control strategy is utilized for choosing optimal values for the controllable inputs of the units while maintaining the power balance in the system. This scheme respects all of the above defined constraints on power input/output, as well as on the states of charge of the storage units.

For practical implementation, vectors of decision variables are formed, which are

$$x = [x_1, x_2]^T \quad (20)$$

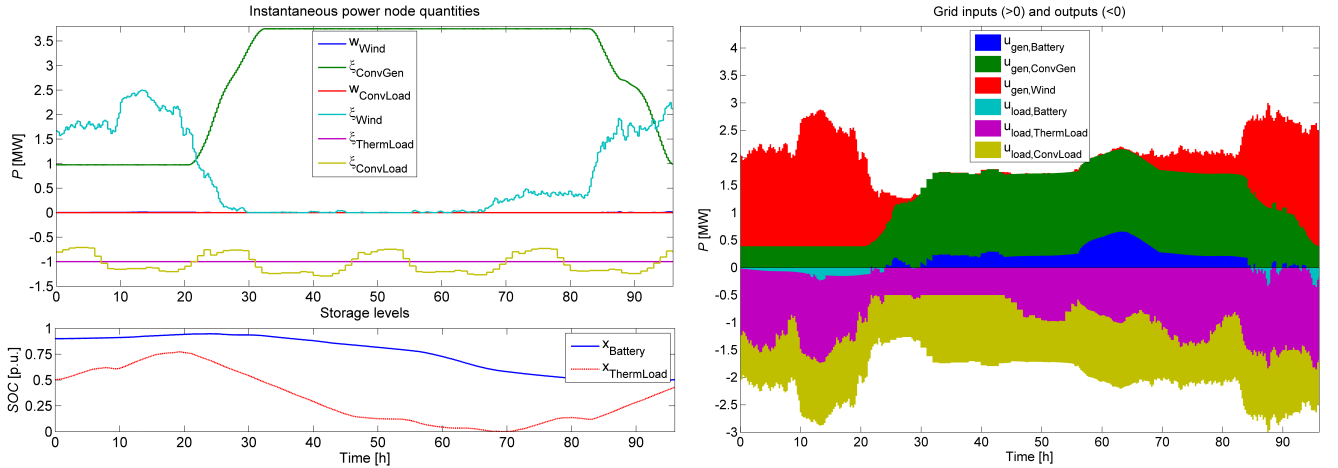
$$u = [u_{\text{gen},1}, u_{\text{load},1}, u_{\text{gen},2}, w_2, u_{\text{gen},3}, \xi_3, \dots \quad (21)$$

$$u_{\text{load},4}, u_{\text{load},5}, w_5, \xi_2, \xi_4, \xi_5]^T \quad (22)$$

The cost function in time step k is defined as

$$J_k = \sum_{l=k}^{l=k+N-1} (x_l - x_{\text{ref},l})^T Q (x_l - x_{\text{ref},l}) + u_l^T R u_l + \delta u_l^T \delta R \delta u_l \quad (23)$$

with x_{ref} being a reference value for the state variables, and the derived variable δu being the difference of the input vectors between two time steps ($\delta u_l = u_l - u_{l-1}$).



(a) Instantaneous power node quantities and storage energy levels.
Fig. 3. Power node quantities, energy storage levels, and grid power balance.

TABLE IV
BALANCE TERMS FOR SIMULATION EXAMPLE

Balance term	Value [MWh]
Electricity consumed by loads	194.7968
Electricity consumed by battery	3.2907
Electricity supplied by conv. gen.	108.4607
Electricity supplied by wind turbine	72.9727
Electricity supplied by battery	16.6541
Prim. energy supplied by wind	73.1373
Prim. energy supplied by conv. gen.	271.1517
Use energy demanded by load	-196.1315
Wind energy curtailed	0.16454
Load demand not served	-0.0033

The diagonal weight matrices Q , R , and δR serve to individually penalize the optimization variables (cf. Table III). One sampling interval k has a duration of 15 min. The receding horizon N_{opt} is chosen as 16 (4 hours) with the assumption of perfect prediction. YALMIP [25] has been used for the implementation of the MPC setup.

The setup is tested for the case of an intermittent wind power in-feed, $\xi_2 = \xi_{\text{drv},2}(t)$, over a time-period of four days. Note that the wind power in-feed time series is obtained from actual measurements from a single location. Consequently, the intermittency is more significant than in the case of aggregated wind in-feeds in transmission grids covering larger areas, and one can hardly assume any reliably available wind power (capacity credit).

Fig. 3 depicts the results of the balancing simulation. The internal power node variables (instantaneous power values and energy storage levels) are shown on the left side in Fig. 3-(a), while all grid-related variables u_{gen} , u_{load} are summarized in Fig. 3-(b). It can be observed that shorter-term fluctuations are mainly balanced by actuation of the battery storage and the thermal load. Wind curtailment is small because of the relatively conservative system sizing, while load curtailment is kept at zero at (almost) all times. The weight on $\delta u_{\text{gen},3}$ causes the conventional generator to ramp up and down relatively smoothly even in the presence of steep wind ramps. Some corresponding balance terms are presented in Table IV.

Note that the used controller parameters shown in the lower section of Table III have been obtained by manual

tuning in order to achieve the desired system behavior. They do not represent real monetary costs, e.g. incurred by electricity generation, generator ramping, or load curtailments. Relating the controller parameterization and the balance terms from Section II-E to an energy economics framework (e.g. in the form of unit commitment and optimal power flow) is beyond the scope of this paper and will be subject to future work.

V. CONCLUSION & OUTLOOK

In this paper, a flexible and comprehensive modeling framework for generic energy storage 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. The newly introduced power nodes have been defined as a representation of units connected to electricity grids which exhibit associated storage properties and different degrees of dispatchability. The straight-forward practical applicability of the approach has been demonstrated by simulations of a small wind energy balancing example.

Further research will address the formulation of a framework to represent different control structures for flexible reconfiguration and experimentation with alternative control strategies and architectures. Also 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.

Highly interesting research opportunities include the application of the presented framework to the operation of power systems with a high penetration of a diverse portfolio of renewable energy generation units facilitated by an equally diverse portfolio of storage types. 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 towards a more holistic operation concept that integrates intermittent generation, flexible demand and energy-constrained storage.

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