Electrical Power and Energy Systems 72 (2015) 155–164

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Analyzing operational flexibility of electric power systems

Andreas Ulbig *, Göran Andersson

Power Systems Laboratory, ETH Zurich, Switzerland

ARTICLE INFO

Article history:
Received 1 February 2015
Accepted 16 February 2015
Available online 18 March 2015

Keywords:
Operational flexibility
Power system analysis
Grid integration of Renewable Energy Sources (RES)

ABSTRACT

Operational flexibility is an important property of electric power systems and plays a crucial role for the transition of today's power systems, many of them based on fossil fuels, towards power systems that can efficiently accommodate high shares of variable Renewable Energy Sources (RES). The availability of sufficient operational flexibility is a necessary prerequisite for the effective grid integration of large shares of fluctuating power feed-in from variable RES, especially wind power and Photovoltaics (PV).

This paper establishes the necessary framework for quantifying and visualizing the technically available operational flexibility of individual power system units and ensembles thereof. Necessary metrics for defining power system operational flexibility, namely the power ramp-rate, power and energy capability of generators, loads and storage devices, are presented. The flexibility properties of different power system unit types, e.g. load, generation and storage units that are non-controllable, curtailable or fully controllable are qualitatively analyzed and compared to each other. Quantitative results and flexibility visualizations are presented for intuitive power system examples.

An outlook for the usage of the here proposed methods in power system control centers is given.

Introduction

This paper presents a novel approach for analyzing the available operational flexibility of a given power system. In the context of this paper we mean by this the combined available operational flexibility that an ensemble of – potentially very diverse – power system units in a geographically confined grid zone can provide in each time-step during the operational planning, given load demand and Renewable Energy Sources (RES) forecast information, as well as in real-time in case of a contingency. Operational flexibility is essential for mitigating disturbances in a power system such as outages or forecast deviations of either power feed-in, i.e. fluctuating electricity generation from wind turbines or solar units, or power out-feed, i.e. fluctuating load demand. Metrics for assessing the technical operational flexibility of power systems, i.e. power ramp-rate (ρ), power capacity (π), energy capacity (ϵ) and ramp duration (δ) have been proposed by Makarov et al. in [1] and their meaning further discussed by the authors in [2]. In this paper we establish the necessary framework for quantifying and visualizing the technically available operational flexibility of individual power system units and ensembles thereof. The functional modeling of all power system units is accomplished using the Power Nodes modeling framework introduced in [3,4]. The flexibility properties of different power system unit types, e.g. load, generation and storage units that are non-controllable, curtailable or fully controllable are qualitatively analyzed and compared to each other. Quantitative results as well as flexibility visualizations of the here proposed flexibility assessment framework are presented for intuitive benchmark power systems.

The remainder of this paper is organized as follows: Section 'Operational flexibility in power systems' discusses operational flexibility and its role in power system operation. It also introduces necessary metrics for operational flexibility. Section 'Modeling of operational flexibility' explains how operational flexibility can be modeled using the Power Nodes modeling framework. This is followed by Section 'Analyzing operational flexibility', which illustrates how operational flexibility can be quantified and analyzed for individual power system units as well as for ensembles of power system units. Finally, a conclusion and a summary of the contributions are given in Section 'Conclusion'.

Operational flexibility in power systems

Operational flexibility is an important property of electric power systems and essential for mitigating disturbances in a power system such as outages or forecast deviations of either power feed-in, i.e. from wind turbines or Photovoltaics (PV) units, or power out-feed, i.e. load demand. The availability of sufficient

---

* Corresponding author.
E-mail addresses: ulbig@eeh.ee.ethz.ch (A. Ulbig), andersson@eeh.ee.ethz.ch (G. Andersson).

http://dx.doi.org/10.1016/j.ijepes.2015.02.028

operational flexibility is a necessary prerequisite for the effective grid integration of large shares of fluctuating power feed-in from variable RES.

Increasing need for operational flexibility

In recent years power system dispatch optimization and real-time operation have become more and more driven by several major trends, which notably include.

(1) Wide-spread deployment of variable RES, i.e. wind turbines and PV units, that has led to significant relative and absolute shares of power generation, which is highly fluctuating and neither perfectly predictable nor fully controllable. Variable RES power feed-in causes non-deterministic power imbalances and power flow changes on all grid levels [5,6].
(2) Growing power market activity that has led to operational concerns of its own, i.e. deterministic frequency deviations caused by transient power imbalances due to more frequent changes in the now market-driven operating set-point schedules of power plants as well as more volatile (cross-border) power flow patterns [7].
(3) The emergence of a *smart grid* vision as a driver for change in power system operation [8]. Using the reference framework of control theory, the term *smart grid* can be understood as the sum of all efforts that improve observability and controllability over individual power system processes, i.e. power feed-in to the grid and power out-feed from the grid as well as power flows on the demand/supply side, happening on all voltage levels of the electricity grid. An improved observability and controllability of individual power system units should, eventually, also lead to an improved observability and controllability of the entire power system and the processes happening therein.

Altogether, these developments constitute a major paradigm shift for the management of power systems. Operating power systems optimally in this more complex environment requires a more detailed assessment of *available* operational flexibility at every point in time for effectively mitigating the outlined system disturbances.

Sources of operational flexibility

Different sources of power system flexibility exist as is illustrated in Fig. 1. Operational flexibility can be obtained on the generation-side in the form of dynamically fast responding conventional power plants, e.g. gas- or oil-fueled turbines or rather flexible modern coal-fired power plants and on the demand-side by means of adapting the load demand curve to better absorb fluctuating RES power feed-in. In addition to this, RES power feed-in can also be curtailed or, in more general terms, modulated below its given time-variant maximum output level. Furthermore, stationary storage capacities, e.g. hydro storage, Compressed Air Energy Storage (CAES), stationary Battery Energy Storage System (BESS) or fly-wheels, as well as time-variant storage capacities, e.g. the aggregated battery capacity of electric vehicle fleets, are well-suited for providing different types of operational flexibility.

Operational flexibility can also be obtained from other grid zones via the electricity grid's tie-lines in case that the available operational flexibility in one's own grid zone is not sufficient or more expensive. Readily available power import and export capacity, nowadays facilitated by more and more integrated national and international power markets, is used in daily power system operation to a certain degree as a *slack bus* for fulfilling the active power balance and mitigating power flow problems of individual grid zones by tapping into the flexibility potential of other grid zones. For power system operation, importing needed power in certain situations and exporting undesirable power feed-in in other situations to neighboring grid zones is for the time being probably the most convenient and cheapest measure for increasing operational flexibility. However, power import/export can only be performed within the limits given by the agreed line transfer capacities between the grid zones. In the European context this corresponds to the Net Transfer Capacity (NTC) values [9], which are a rather conservative measure of available grid electricity transfer capacity. This discussion also extends to physical line constraints of the grid topology within a grid zone, which may effectively limit the delivery, i.e. the physical transport, of operational flexibility, i.e. active power, between individual bus nodes (confer [10,11]).

Definitions of operational flexibility

The term operational flexibility in power systems is often not properly defined. In a power systems context, the term *flexibility* may refer to very different things ranging from the quick response times of generation units, e.g. gas turbines, to the degree of efficiency or robustness of a given power market setup. The topic is receiving wide attention [1,2,14,6,12,13]. In the remainder of this paper the focus is solely on the technical aspects of operational flexibility (Definition 1).

Definition 1 (*Operational flexibility in power systems*). Operational flexibility is the technical ability of a power system unit to modulate electrical power feed-in to the grid and/or power out-feed from the grid over time.

This means the technical ability of a grid operator to modulate the power in-flow/outflow on a global scale, i.e. for achieving power balance, and within a grid topology, i.e. to control power flows via the modulation of power injections and outtakes at specific grid nodes.

Classification of operational flexibility

In liberalized power systems, operational flexibility is traded in the form of *energy products* via power markets, i.e. day-ahead and intra-day spot markets, as well as *control reserve products*, i.e. primary/secondary/tertiary frequency control reserves, from Ancillary Services (AS) markets.

A classification of operational flexibility in resources and reserves, inspired by established classification system for natural resources, e.g. crude oil, natural gas and coal [15], is presented in the following. The categories for classifying *available operational flexibility* are:

- *Potential Flexibility Resources*, i.e the flexibility resources exist *physically* and could be used. The necessary controllability, and also observability, over the power system units is lacking.
- *Actual Flexibility Resources*, i.e. the part of the potential flexibility resources that can in fact be used because controllability, and also observability, over the power system units exists.
- *Flexibility Reserves*, i.e. the part of the actual flexibility resources can be used economically.
- *Market-Available Flexibility Reserves*, i.e. the part of the flexibility reserves that can be procured from power or Ancillary Services markets. Constraints due to AS product *structuring* may limit the amount of operational flexibility that can in fact be procured in practice.

The procurement of the market-available operational flexibility reserves is accomplished via the market auctioning of the so-called