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How to model the cycling ability of thermal units in power systems

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ABSTRACT

For thermal units in power systems, the importance of quick load changes increases along with the share of volatile renewable feed-in. An adequate representation of the cycling abilities of thermal units is therefore important in energy system modeling. Five different model techniques used in the literature to describe the cycling ability of thermal generation units are applied in the optimizing energy system model PERSEUS-NET-TS. The model calculates the dispatch of German generation units while restrictions of the transmission grid are considered. Differences in the cumulated dispatch of coal, lignite, and gas combined-cycle units in Germany due to the different modeling techniques are analyzed based on the PERSEUS-NET-TS results as well as the resulting dispatch of two exemplary single generation units. While the cumulated dispatch for Germany does not show any major differences for coal and lignite units, the cumulated dispatch of gas units differs slightly depending on the approach. Moreover, the dispatch of individual generation units may differ significantly. Even though the real commissioning strategies are not publicly known, it could be identified that the mostly applied modeling approaches based on technical restrictions increase computing time unnecessarily and that cost based approaches reduce on/off cycling more.

1. Introduction

In power systems with an increasing amount of feed-in by volatile RES (renewable energy sources), there is a growing importance of quick load changes for the remaining fossil-fueled generation units [1]. Adjusting the unit output in order to meet the residual demand at any time, i.e. cycling, is important for a secure electricity supply [1]. An adequate representation of the cycling or load-changing abilities of fossil-fueled thermal units is therefore increasingly important in optimizing energy system models. For technical reasons, gas turbines (typical peak load units), for example, can cope better with load changes than most coal or, especially, lignite generating units (typical base load units). The start-up or ramping rate of thermal generation units is generally limited by thermal stress and resulting pressure differences [2]. Additionally, costs induced by load changes have to be considered. Load changes or cycling lead to increasing maintenance and repair costs due to creep and fatigue [3]. Emissions also increase through cycling. Especially during the start-up phase, additional costs and emissions occur [4]. According to Schröder et al. [2], there are three reasons for additional costs: Firstly, the additional fuel and manpower needed during the start-up phase. Secondly, an increased depreciation of the generation unit, and thirdly, higher fuel consumption due to a lower efficiency during the ramping phase. Modeling start-up costs may significantly improve the results of production cost models and makes them more realistic [5]. Costs for load changes while running also exist, but are significantly lower [6]. They are, among other things, due to abrasion and differ for all generation units because of the fuel type, different materials, outdated power plant design, operation, maintenance, and repair history [7]. Another technical restriction is the minimum power (i.e. minimum generation when running). It is not possible to operate at a level below that limit due to technical restrictions such as insufficient temperatures and/or excessive emissions [8]. To avoid putting too much thermal stress on the material, ramping rates are often specified for different generation units.

Different ways of modeling the cycling ability of thermal units for optimizing energy system models are described in the literature. Consideration of the minimum power (e.g. Ref. [9]) is

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comparatively easy to implement but comes with the cost of needing binary variables and thus with a mixed-integer calculation. One rather common way of mapping unit cycling in unit commitment, respectively dispatch models is by a combination of the minimum power with a minimum up-time and a minimum down time (e.g. Ref. [5] or [10]). Similar approaches introduce further constraints such as minimum cycle time [11] or limited ramping rates and start-up costs [12]. Hundt et al. [13] give technology-specific values for these constraints but argue that minimum up- and down-times are no purely technical but rather economic restrictions. Their application shall prevent the modeled generation units from performing too many load changes. However, as stated before, in optimizing models, this approach has the disadvantage of needing binary variables that lead to a mixed-integer problem. Accordingly, the calculation time of the considered optimization problem may rise tremendously. This makes it difficult to apply these modeling techniques if calculation time is crucial, as for example in stochastic models [14]. In that case, a linear description of the cycling abilities of thermal units is preferable. One linear description is the application of costs to any positive or negative load change (e.g. Ref. [15]). Yet another approach is the use of a linear description of start-up costs [16]. These costs only apply to positive load changes below the minimum power. Above the minimum power, there are no costs applied to further positive or negative load changes. Thus, the generation might rather remain at the minimum power for a few hours than be reduced below it and cause costs when generation is increased again later. The implementation of ramping rates in energy system models is also applied (e.g. Ref. [17]). Norouzi et al. [18] even consider dynamic ramp-rates and ramp-down limits. De Jonghe et al. [19] give technology-specific values and apply an illustrative example. Some recent studies include even more constraints [20], e.g. combine these ramping rates with minimum up- and down-times, and start-up costs (differing in accordance with warm or cold start) [21] as well as cold start time (e.g. Ref. [22]). However, modeling these in dispatching energy system models seems only useful with a time resolution that is finer than hourly [23].

So far, no comprehensive comparison of different approaches to modeling these flexibility constraints is given in the literature (or even a comparison with results neglecting these constraints). In order to understand the resulting inflictions, in this paper differences in the unit commitment are analyzed by applying five different approaches to depict the cycling ability of thermal units within the deterministic energy system model PERSEUS-NET-TS [24]. The following approaches are considered:

M1	Minimum power
M2	Minimum power in combination with minimum up- and down-time
M3	Costs on all load changes
M4	Costs on positive load changes below the minimum power (start-up costs)
M5	Combination of start-up costs and costs on all load changes
M0	No consideration of any cycling costs or restrictions

The resulting unit dispatches based on these approaches are compared to each other and to a model run where restrictions and costs of load-changing are totally neglected (M0). Consequently, in the next section, an overview of the optimization model PERSEUS-NET-TS is given. The third section focuses on the integration of the different ways of mapping the cycling ability. In Section 4, the resulting dispatches of the thermal units (lignite, coal, combined-cycle gas turbines (CCGT), and gas turbines) are compared to each other and to a dispatch without considering any restrictions of the cycling ability. A conclusion is given in the last section (5).

2. The energy system model PERSEUS-NET-TS

The optimizing energy system model PERSEUS-NET-TS [24] is used to evaluate the advantages and drawbacks of the five different approaches to modeling the cycling ability. In principle, the myopic model is able to calculate the investment and dispatch plans for thermal generation plants in the German energy system up to 2040. Starting with the base year 2012, at least every fifth year is calculated and thereby represented through an hourly mapping of one week for each season (672 h). For the task of analyzing how the cycling ability is modeled best, only the dispatch of existing generation units of the first period (i.e. 2012) is considered in this paper. Therefore, only equations and parameters relevant to calculating the dispatch of the generation units in the first period are described here and not those relevant to the commissioning of new generation units.

The model maps the German energy system and includes a nodal pricing approach based on a DC calculation of the German transmission grid. Over 440 nodes and over 500 lines (360 and 220 kV) are considered with their technical characteristics (see Fig. 1). About 260 large generation units (>100 MW) are depicted individually and allocated at their specific grid nodes. Smaller generation units are accumulated for each grid node. The driving force of the model is the exogenously given demand that has to be satisfied at each considered hour and each grid node whilst the system-relevant expenditures are minimized (see Fig. 2). This can either be done by electricity generation in the generation units assigned to that grid node or by electricity transfer via the transmission grid.

The PERSEUS-NET-TS model is structured as a graph in which so-called producers ($pd \in PD$)[1] form the nodes and flows of different energy carriers ($ec \in EC$) form the edges in between ($FS_{pd,\ pd',ec,t}$ (hourly flow level) and $FL_{pd,\ pd',ec,t}$ (yearly flow level)). Accordingly, different flows may connect the producers. Consequently, the grid nodes of the transmission grid are modeled as producers that may be connected to each other through electricity flows. Producers may have different (generation) units ($u \in U$) assigned to them. These units may then have different processes ($pc \in PC$). Imports from outside the system boundaries are the sources of the graph ($ip \in IP \subset PD$) and correspond to fuel purchases of some producers. Exports are the sinks of the graph ($ep \in EP \subset PD$) and correspond to electricity demand processes.

The expenditures in the objective function (cf. Equation (1)) are composed of costs related to energy carriers, electricity generation processes, and generation units. The energy carrier-related costs are the costs for fuel supply ($C^{Fuel}_{ip,pd,ec,t}$) times the level of the fuel import flow to the considered producer $FL_{ip,\ pd,ec,t}$. Fuel costs for thermal units already include additional costs for CO_2 emissions and are based on [25]. Variable costs ($C^{Var}_{pc,t}$) for electricity generation ($PL_{pc,t}$) are considered for each generation process as well as, if applicable, some kind of cycling costs ($C^{LC}_{pc,t,s-1,s}$) from one time slice to the next ($s \in S$). Additionally, fixed costs ($C^{Fix}_{u,t}$) for existing generation units ($Cap^{Tot}_{u,t}$) and investments ($C^{Inv}_{u,t}$) in new generation units ($Cap^{New}_{u,t}$) are considered. As for 2012 the existing power plant portfolio is known and no further capacities are needed for satisfying the electricity demand, $Cap^{New}_{u,t}$ equals zero for the following analyses. Consequently, the costs related to the existence of units are not decision-relevant in this context.

[1] A complete nomenclature can be found in the appendix.