Control Engineering Practice 77 (2018) 213–224

Contents lists available at ScienceDirect

Control Engineering Practice

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

# Optimal scheduling of battery storage systems and thermal power plants for supply–demand balance

Masakazu Koike [a,*], Takayuki Ishizaki [b], Nacim Ramdani [c], Jun-ichi Imura [b]

[a] *Tokyo University of Marine Science and Technology 2-1-6, Echujima, Koutou-ku, Tokyo, 135-8533, Japan*
[b] *Tokyo Institute of Technology 2-12-1, Ookayama, Meguro-ku, Tokyo, 152-8552, Japan*
[c] *Univ. Orléans, INSA-CVL, PRISME, EA 4229, F45072, Orléans, France*

ARTICLE INFO

*Keywords:*
Photovoltaic power generation
Prediction uncertainty
Regulating capacity
Battery storage system
Optimal scheduling
Interval quadratic programming
**M**-matrix

ABSTRACT

This paper focuses on the day-ahead scheduling problem of generating power for thermal power plants and charging/discharging battery energy storage systems based on interval predictions of photovoltaic power. Our previous approach to this problem used the Jacobian of a solution with respect to the variation in demand. However, this study was limited in the sense that the output capacity constraints of thermal power plants were not taken into account. To overcome this problem, we introduce a virtual thermal plant and apply several properties of an **M**-matrix. To provide guidelines for the amount of power that should be generated, we determine the exact regulating capacity for each thermal power plant and a storage battery so as to maintain the supply–demand balance. The efficiency of the proposed method is verified numerically. We show that a brute-force Monte Carlo method cannot estimate the exact regulating capacity of the thermal power plants when the batteries effectively balance the supply and demand. Moreover, it is found that, unless their deterioration cost decreases significantly, storage batteries cannot be effectively utilized.

## 1. Introduction

In recent years, research on renewable energy has been brought to public attention to reduce damage to the earth. To use renewable energy sources efficiently, we need to improve performance of peripheral devices such as converters, inverters, storage batteries, and so on, and to consider the energy allocation problem into generators and storage batteries. There are found a lot of papers dedicated to improving peripheral devices. In Guo, Song, Yang, Wang, Liu, Rao, et al. (2018), Huang, Tang, Xin, Xiao, and Loh (2018), Liu, Vazquez, Wu, Marquez, Gao, and Franquelo (2017) and Yin, Tseng, Simanjorang, Liu, and Pou (2017), they aim to improve the performance of converters and inverters. In Vazquez, Lukic, Galvan, Franquelo, and Carrasco (2010), various storage batteries are classified in detail. On the other hand, in this paper, we focus on the energy allocation problem in Japan. In the near future, it is expected that a large number of photovoltaic (PV) power generating facilities and storage batteries will be introduced in Japan (Masuta & Yokoyama, 2012). For the efficient use of such renewable energy sources, it is crucial that thermal power plants and storage batteries can be used to cover the net-demand, which is defined as the total consumer load minus the PV-generated power. To properly control the power system using storage batteries and thermal power plants, the following steps are necessary. Step 1: First, on the previous day, the net-demand prediction should be used to determine the number of thermal power plants that should start generating power, known as the *unit commitment*. Step 2: To confirm whether the supply–demand balance can be maintained under this unit commitment, a scheduling problem concerning the storage batteries and thermal power plants should be solved on the previous day. Step 3: On the day of interest, based on the actual net-demand, the power generated by the thermal power plants and the charge/discharge (C/D) power from the storage batteries is determined within several hour-long intervals, a procedure known as *economy dispatch control*. Step 4: The generating power and C/D power are then determined within several minute-long intervals, a procedure known as *load frequency control*. Steps 1–4 have been established in cases where the net-demand can be entirely covered by thermal power plants. However, in situations where the net-demand is covered by both thermal power plants and storage batteries, these procedures must be modified appropriately. For example, several studies have considered Step 1 without the use of storage batteries (Damousis, Bakirtzis, & Dokopoulos, 2004; Meibom, Barth, Hasche, Brand, Weber,

* Corresponding author.
*E-mail addresses:* mkoike0@kaiyodai.ac.jp (M. Koike), ishizaki@sc.e.titech.ac.jp (T. Ishizaki), nacim.ramdani@univ-orleans.fr (N. Ramdani), imura@sc.e.titech.ac.jp (J. Imura).

https://doi.org/10.1016/j.conengprac.2018.05.008
Received 25 November 2017; Received in revised form 16 May 2018; Accepted 19 May 2018
0967-0661/© 2018 Elsevier Ltd. All rights reserved.

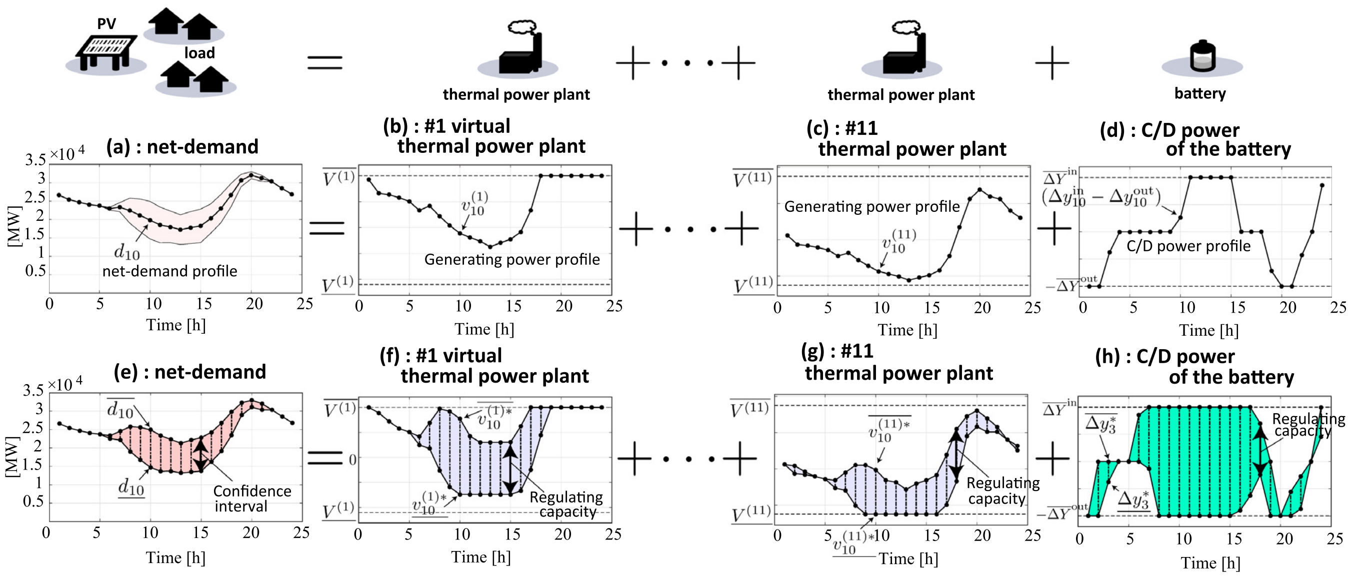


**Fig. 1.** Allocation problem.

& O'Malley, 2011). In contrast, research on Steps 2–4 has tended to assume the use of storage batteries. In terms of Step 2, an appropriate schedule can be determined by considering the uncertainty of PV and wind predictions using a stochastic method, e.g., chance constraints, scenario trees, and fuzzy modeling (Arun, Banerjee, & Bandyopadhyay, 2009; Liang & Liao, 2007; Sturt & Strbac, 2012; Su, Wang, & Roh, 2014). For Step 3, distributed algorithms and dynamic programming algorithms have been employed (Kim, Oh, & Ahn, 2015; Xiaoping, Ming, Jianghong, Pingping, & Yali, 2010). *Model predictive control* has been applied to address Step 4 (Liu, Zhang, & Lee, 2016). This paper focuses on the optimal scheduling problem of storage batteries and thermal power plants, which corresponds to Step 2. In particular, we deal with the allocation problem in which a predicted net-demand profile, namely a time trajectory of the net-demand, is dispatched into the generating power profile of thermal power plants and the battery C/D power profile; see Fig. 1(a), (b), (c), and (d).

Note that the predicted net-demand profile is uncertain because it depends on the predicted PV power generation. The explicit consideration of uncertainty in scheduling is a significant issue, and many studies have expressed the level of uncertainty through stochastic methods. In recent years, however, a method in which uncertainty is considered in terms of confidence intervals has attracted attention. To take uncertainty into account, this approach expresses the predicted net-demand as a confidence interval (Fonseca, Oozeki, Ohtake, & Ogimoto, 2014; Khosravi, Nahavandi, & Creighton, 2013). The objective of the present study is to identify the regulating capacity for each thermal power plant and storage battery so as to maintain the supply–demand balance under all possible net-demand profiles in the confidence interval; see Fig. 1(e), (f), (g), and (h). This type of problem can be formulated as an *interval quadratic programming problem*. Such problems are not always easy to solve because, to obtain the optimal solution set (which corresponds to the regulating capacity), they generally require the optimal solution to be calculated for an infinite number of grid points in the parameter space.

Several approaches can be applied to this type of problem (Bemporad, Morari, Dua, & Pistikopoulos, 2002; Hansen & Walster, 2003; Jaulin, 2001; TøNdel, Johansen, & Bemporad, 2003). In Bemporad et al. (2002); TøNdel et al. (2003), a parametric quadratic programming problem is handled by dividing the parameter space to produce an image of the optimal solution set. However, as the number of decision variables and constraint conditions increases, the computational load increases. Constraint propagation techniques and branch-and-bound algorithms, which are used in interval analysis, can also be applied to this kind of problem (Hansen & Walster, 2003; Jaulin, 2001). However, these methods often provide a conservative solution because certain variables will be overestimated.

A method focusing on the monotonicity of the solution with respect to the net-demand variation has been developed (Ishizaki, Koike, Ramdani, Ueda, Masuta, Oozeki, Sadamoto, & Imura, 2016). In this method, it is first examined whether the solution of the optimization problem is monotonic with respect to the net-demand variation. If so, an exact image of a solution set can be found efficiently through a finite number of operations, which correspond to solving parametric quadratic programming problems under a parameter set to an extreme point. In Ishizaki et al. (2016), we proposed a method for handling multiple thermal power plants, but this approach cannot take the upper and lower limits of the generated power at each thermal power plant into account. Thus, in some cases, this method gives an optimal generating power that is negative. In practical situations, thermal power plants cannot generate a negative power output; a limited output capacity is the best that can be achieved.

As an extension of this previous method, the approach described in this paper aims to obtain the exact regulating capacity of the optimal generating power for thermal power plants; based on this, the regulating capacity of the optimal C/D power for a storage battery is also derived. To obtain the range of the regulating capacity, it is necessary to investigate the Jacobian of an output function with respect to the optimal solution. As the Jacobian is too complex to analyze directly, two key ideas are employed. The first is to introduce a virtual thermal power plant whose output capacity constraint is not imposed. As a result, the Jacobian can be transformed into a simplified form (Koike, Ishizaki, Ramdani, & Imura, 2017). This allows the regulating capacity of the optimal generating power for thermal power plants to be determined. The second key idea for analysis is to divide the Jacobian into an **M**-matrix and a **Z**-matrix. This is the original idea described in this paper. Furthermore, using the properties of the **M**- and **Z**-matrices (Fiedler & Ptak, 1962), the regulating capacity of the optimal C/D power can be derived. We show how to find the range of the regulating capacity using an algorithm. Finally, we compare the results given by the method proposed in this paper with those of our preliminary model (Koike et al., 2017), in which the regulating capacity of the optimal generating power for the thermal power plants is derived under their own output capacity constraints. In the proposed method, the regulating capacity of the optimal C/D power for the battery is also given. With

Download English Version:

https://daneshyari.com/en/article/7110267

Download Persian Version:

https://daneshyari.com/article/7110267

Daneshyari.com