2017 International Conference on Energy, Power and Environmental Engineering (ICEPEE 2017)
ISBN: 978-1-60595-456-1

Operating Reserve Allocation Methods Relative to Energy Unit Commitment

Ivan PAVIĆ[1*], Matea FILIPOVIĆ[1], Igor KUZLE[1] and Yong-qian LIU[2]

[1]University of Zagreb, Faculty of Electrical Engineering and Computing, Unska 3, 10000 Zagreb, Croatia

[2]School of Renewable Energy, North China Electric Power University, Beijing 102206, China
*Corresponding author

Keywords: Operating reserves, energy and reserve co-optimization, power system balancing, wind power.

Abstract. The most distinguished global trend in power systems development in the last decade is by far rapid growth of power generating facilities driven by renewable energy resources. In theory, their primary energy source is a free natural resource such as wind or solar radiation, therefore, their integration should lead to lower marginal costs at wholesale level and therefore lower retail electricity prices payed by end-consumers. The problem lies in their non-dispatchable and stochastic nature. Inability to be dispatched in accordance to power system real-time conditions means that they cannot be committed in the time of need for the power system, i.e., they are unable to provide balancing reserves. Stochasticity of their generation leads to greater need for flexible units capable of changing their operating point, i.e. the greater need for operating reserve units. One can conclude, when the share of renewable energy sources increases, the share of units capable of operating reserves provision decreases, but at the same time the operating reserve requirements increase.

Possibilities to solve mentioned problem and to bolster further renewable energy sources integration range from integration of a new flexible conventional units (such as gas power plants), or an energy storage technologies, to usage of renewable units for operating reserves provision despite their lost opportunity cost occurrence. When observing operating reserve's adequacy, it is very important to evaluate the way how it is allocated. With efficient reserve allocation method, the need for additional investments in power system flexibility are deferred and mitigated. This paper provides an insight into different ways of reserve allocation and how does it affect total operating costs of the power system.

Introduction

Power systems of today are huge systems covering vast geographical areas consisting of numerous interconnected subsystems such as generating facilities, transmission and distribution elements supplying billions of end-customers devices. Power systems often include grids and other facilities located in adjacent countries and one of the biggest in the world is ENTSO-E (European Network of Transmission System Operators) which represents 43 electricity transmission system operators (TSOs) from 36 countries across Europe. ENTSO-E totaled in 2015. With generating capacity of 1030 GW, annual consumption of 3278 TWh and winter peak load of 528 GW [1].

Power systems have unique feature where generation of a product must be equal to its consumption in each time of a day, otherwise the system would collapse. In conventional way of power system operation, power generation is dispatchable and controllable whereas consumption is stochastic and uncontrollable. Hence, to sustain generation-consumption equilibrium power system operators should predict consumption and accordingly dispatch generation, i.e., the generation follows consumption. The generation of each kWh from conventional units incur costs and require primary resource (coal, oil, gas, water inflow) procurement planning. Therefore, units should be scheduled for electricity generation prior to the real-time supply requirements. But, the consumption cannot be predicted with 100% accuracy. Apart from already allocated capacity for covering of the deterministic consumption curve, additional capacity to cover all consumption mispredictions should

be available, it should be reserved. Apart from inability to accurately forecast consumption, reserves are also needed to cover unexpected generation or network elements failures

Reserves can be divided into several groups: capacity reserve, network reserve and operating reserve. Capacity reserve, together with other capacity remuneration mechanisms [2], is additional capacity withheld from unit commitment in normal operating condition in order to provide long-term generation capacity adequacy for rare, scarcity periods. It is allocated to cover long-term stochastics of power system operation [3]. Network reserve is capacity withheld from unit commitment in order to solve grid congestions and to secure uniform wholesale price in the whole transmission area [4]. Network reserve is an opposite method of congestion management to LMP pricing commonly used in the US [5]. Mentioned reserves are out the scope of this paper.

To balance system in shorter time scales, system operators use operating or balancing reserves. Operating reserves are usually divided into three main subgroups: primary, secondary and tertiary reserve [6]. Primary reserve is allocated for maintaining the system frequency at the nominal level, it solves small and often system disturbances. Secondary reserve is allocated for frequency and interchange restoration to rated values and for the release of primary reserve capacity, it solves larger and less often generation-consumption mismatches. Tertiary reserve is allocated for release of the secondary reserve and for covering of large and seldom failures and forecast errors by direct changes in unit commitment. Due to simplicity, this paper will observe all operating reserves as one reserved capacity by simply referring to it as *reserve*.

High integration of renewable energy sources (RES) into power system make changes to basic system operations. The stochasticity and uncontrollability is no longer only on consumption side, but it also passes to generation side. Higher amount of unpredictability and variability in power system directly means higher reserve requirements. Higher reserve requirements mean higher requirements for flexible and dispatchable units. But at the same time, higher RES integration entails total capacity decrease of those units. To bolster further RES integration without fossil-fueled generation units, system operators must find a new way to provide necessary flexibility. RES generation forecasting methods should be improved as much as possible to decrease impact on reserve requirements increase [7]. Necessary flexibility provision can be achieved by energy storage integration, but that kind of technology is still too expensive to be used just as reserve provider. Other way could be usage of novel technologies from consumption side and to provide reserve by demand response or by electric vehicles which could be understood as both energy storage and demand response [8]. Authors in [9] proposed using RES generating facilities for reserve provision but due to high lost opportunity cost other methods have shown to be more favorable [10].

The key to the problem could also be proper operating reserve allocation method. This paper will compare different reserve allocation methods to find the most favorable one. The general idea is to use same power system and analyze which method yields lowest costs for different reserve requirement policies and different share of RES integration. Next Section will present mathematical models used for evaluation, then results will be displayed and discussed. Last Section will conclude and highlight the most important findings.

Model

In every power system, organized either as liberalized market or centralized monopoly, there is a method how to schedule both units for energy generation and for reserve provision by minimizing the cost and maximizing the reliability. Different methods exist today. US power and reserve markets are managed by the same institution (regional transmission operator) which opens the door for co-optimized unit commitment method where energy and reserve providers are simultaneously scheduled on a day-ahead or intraday basis [11]. In Europe, power markets are operated by power exchanges (e.g., in Denmark NordPool [12]) while reserve markets are operated by transmission system operators (e.g., in Denmark Energinet.dk). Therefore, energy and reserve is allocated separately. Usually, reserves are allocated some time before unit commitment of energy therefore units should anticipate their possibility to participate in power market and to be within market

clearing price (MCP). Those who estimate that cost of their electricity generation is higher than MCP will try to compete at reserve market if their technical constraints allow them. This method can be named forward reserve auctions. Another method is to organize reserve auctions after closure of energy market, so those who have spare capacity can compete for reserve provision. This kind of method is usually called balancing market. In this paper we will not try to mimic energy and reserve markets but algorithms for total cost minimization of both energy and reserve provision. Therefore three different algorithms will be defined: co-optimized energy and reserve allocation, first-energy-then-reserve allocation or a priori reserve allocation algorithm (balancing market) and first-reserve-then-power allocation or a posteriori reserve allocation algorithm (forward reserve auctions). Due to simplicity and comparability of the results all algorithms will simulate day-ahead allocation of resources with one hour time step. All algorithms are made as mixed integer linear programs and all simulations are carried out by FICO Xpress optimizer.

The considered power system is composed of thermal power plants capable of providing reserve and wind power plants whose generation is based on historical data and the do not provide reserve. The reserve can be provided by online units if there is spare capacity or by fast startup and fast shut-down of gas turbines for upward and downward reserve, respectively. Constraints for all algorithm are the same but the used in a different way, i.e. with different objective function and different sequence. All constraints are listed in the following:

$$\sum_{i=1}^{N_i} M_{i,b}^{TG} \cdot g_{t,i}^{TG} + \sum_{w=1}^{N_w} M_{w,b}^{WG} \cdot g_{t,w}^{WG} + \sum_{l=1}^{N_l} M_{l,b}^{TL} \cdot f_{t,l}^{TL} = \sum_{d}^{N_d} M_{d,b}^{PD} \cdot D_{t,d}, \qquad \forall t \in [1, N_t], b \in [1, N_b] \tag{1}$$

$$f_{t,l}^{TL} = B_l^{TL} \cdot \sum_{b=1}^{N_b} M_{l,b}^{TL} \cdot \Theta_{t,b}^{TB}, \quad \forall t \in [1, N_t], l \in [1, N_l] \tag{2}$$

$$-F_l^{MX} \le f_{t,l}^{TL} \le F_l^{MX}, \quad \forall t \in [1, N_t], l \in [1, N_l] \tag{3}$$

$$\Theta_{t,b}^{TB} = 0, \quad \forall t \in [1, N_t], b \equiv b^{REF} \tag{4}$$

$$-\pi \le \Theta_{t,b}^{TB} \le \pi, \quad \forall t \in [1, N_t], b \in [1, N_b] \setminus b^{REF} \tag{5}$$

$$g_{t,w}^{WG} \le W_{t,w}, \quad \forall t \in [1, N_t], w \in [1, N_w] \tag{6}$$

$$x_{t,i}^{SU} - x_{t,i}^{SD} = x_{t,i}^{ON} - x_{t-1,i}^{ON}, \quad \forall t \in (1, N_t] \tag{7}$$

$$x_{t,i}^{SU} + x_{t,i}^{SD} \le 1, \quad \forall t \in (1, N_t] \tag{8}$$

$$x_{t,i}^{ON} = X_i^{ON_0}, \quad \forall t \in [1, T_i^{UP_0} + T_i^{DN_0}] \tag{9}$$

$$\sum_{\tau=t-T_i^{UP}+1}^{t} x_{\tau,i}^{SU} \le x_{t,i}^{ON}, \quad \forall t \in [T_i^{UP}, N_t] \tag{10}$$

$$\sum_{\tau=t-T_i^{DN}+1}^{t} x_{\tau,i}^{SD} \le 1 - x_{t,i}^{ON}, \quad \forall t \in [T_i^{DN}, N_t] \tag{11}$$

$$y_{t,i,j}^{SU} \le \sum_{\tau=T_{i,j}^{SU}}^{T_{i,j+1}^{SU}-1} x_{t-\tau,i}^{SD}, \quad \forall t \in \left[T_{i,j+1}^{SU}, N_t\right], j \in [1, N_j) \tag{12}$$

$$\sum_{j=1}^{N_j} y_{t,i,j}^{SU} = x_{t,i}^{SU}, \quad \forall t \in [1, N_t], j \in \left[1, N_j\right] \tag{13}$$

$$g_{t,i}^{TG} = \sum_{k=1}^{N_k} g_{t,i,k}^{IN}, \quad \forall t \in [1, N_t], i \in [1, N_i] \tag{14}$$

$$g_{t,i,k}^{IN} \le G_{i,k}^{IN} \cdot x_{t,i}^{ON}, \quad \forall t \in [1, N_t], i \in [1, N_i], k \in [1, N_k] \tag{15}$$

$$g_{t,i}^{TG} \le G_i^{MX} \cdot x_{t,i}^{ON}, \quad \forall t \in [1, N_t], i \in [1, N_i] \tag{16}$$

$$g_{t,i}^{TG} \geq G_i^{MN} \cdot x_{t,i}^{ON}, \quad \forall t \in [1, N_t], i \in [1, N_i] \tag{17}$$

$$g_{t,i}^{TG} - g_{t-1,i}^{TG} \leq A_i^{UP} \cdot x_{t-1,i}^{ON} + G_i^{MN} \cdot x_{t,i}^{SU}, \quad \forall t \in (1, N_t], i \in [1, N_i] \tag{18}$$

$$-g_{t,i}^{TG} + g_{t-1,i}^{TG} \leq A_i^{DN} \cdot x_{t,i}^{ON} + G_i^{MN} \cdot x_{t,i}^{SU}, \quad \forall t \in (1, N_t], i \in [1, N_i] \tag{19}$$

$$\sum_{i=1}^{N_i} \left(r_{t,i}^{UP\_ON} + r_{t,i}^{UP\_OFF} \right) = R_t^{UP}, \quad \forall t \in [1, N_t] \tag{20}$$

$$\sum_{i=1}^{N_i} \left(r_{t,i}^{DN\_ON} + r_{t,i}^{DN\_OFF} \right) = R_t^{DN}, \quad \forall t \in [1, N_t] \tag{21}$$

$$r_{t,i}^{UP\_ON} \leq G_i^{MX} \cdot x_{t,i}^{ON} - g_{t,i}^{TG}, \qquad \forall t \in [1, N_t], i \in [1, N_i] \tag{22}$$

$$r_{t,i}^{DN\_ON} \leq g_{t,i}^{TG} - G_i^{MN} \cdot x_{t,i}^{ON}, \qquad \forall t \in [1, N_t], i \in [1, N_i] \tag{23}$$

$$r_{t,i}^{UP\_ON} \leq A_i^{UP} \cdot x_{t,i}^{ON}, \qquad \forall t \in [1, N_t], i \in [1, N_i] \tag{24}$$

$$r_{t,i}^{DN\_ON} \leq A_i^{DN} \cdot x_{t,i}^{ON}, \qquad \forall t \in [1, N_t], i \in [1, N_i] \tag{25}$$

$$r_{t,i}^{UP\_OFF} \geq G_i^{MN} \cdot x_{t,i}^{SU\_RO}, \qquad x_{t,i}^{ON} \leq 0 \,\&\, T_i^{UP} \leq 1 \,\&\, T_i^{DN} \leq 1, \;\; \forall t \in [1, N_t], i \in [1, N_i] \tag{26}$$

$$r_{t,i}^{UP\_OFF} \leq G_i^{MX} \cdot x_{t,i}^{SU\_RO}, \qquad x_{t,i}^{ON} \leq 0 \,\&\, T_i^{UP} \leq 1 \,\&\, T_i^{DN} \leq 1, \;\; \forall t \in [1, N_t], i \in [1, N_i] \tag{27}$$

$$r_{t,i}^{UP\_OFF} \leq A_i^{UP} \cdot x_{t,i}^{SU\_RO}, \;\; x_{t,i}^{ON} \leq 0 \,\&\, T_i^{UP} \leq 1 \,\&\, T_i^{DN} \leq 1, \qquad \forall t \in [1, N_t], i \in [1, N_i] \tag{28}$$

$$r_{t,i}^{DN\_OFF} \leq g_{t,i}^{TG}, \;\; x_{t,i}^{ON} \geq 1 \,\&\, T_i^{UP} \leq 1 \,\&\, T_i^{DN} \leq 1, \qquad \forall t \in [1, N_t], i \in [1, N_i] \tag{29}$$

$$r_{t,i}^{DN\_OFF} \geq G_i^{MN} \cdot x_{t,i}^{SD\_RO}, \;\; x_{t,i}^{ON} \geq 1 \,\&\, T_i^{UP} \leq 1 \,\&\, T_i^{DN} \leq 1, \qquad \forall t \in [1, N_t], i \in [1, N_i] \tag{30}$$

$$r_{t,i}^{DN\_OFF} \leq A_i^{DN} \cdot x_{t,i}^{SD\_RO}, \;\; x_{t,i}^{ON} \geq 1 \,\&\, T_i^{UP} \leq 1 \,\&\, T_i^{DN} \leq 1, \qquad \forall t \in [1, N_t], i \in [1, N_i] \tag{31}$$

Eq. 1-5 model DC power flow in transmission grid. Eq. 6 defines the maximum power generation of wind power plants. Eqs. 6-12 are referring to binary logic of thermal power plants. Eq. 14-19 represent technical constraints of thermal power plants concerning power generation. Eq. 20-21 define total reserve requirements, while Eq. 22-25 and Eq. 26-31 represent technical constraints of thermal power plants concerning online and offline reserve provision, respectively. Additional explanation of proposed constraints can be find in [13]. Costs can be incurred to energy allocation as in Eq. 32 which is composed of: Start-Up (each time unit is started up), Shut-Down (each time unit is shut), No-Load (each period when unit is online) and INcremental (fuel cost, for each kWh of generated energy). Costs can also be incurred by reserve provision as in Eq. 33: Reserve Up of ONline units, Reserve DowN of ONline units, Reserve Up of OFFline (unit can be started up in a short period) units and Reserve DowN of OFFline units (unit is online but can be shut down in a short period).

$$c_{t,i}^{Energy} = c_{t,i}^{SU} + c_{t,i}^{SD} + c_{t,i}^{NL} + c_{t,i}^{IN} \tag{32}$$

$$c_{t,i}^{Reserve} = c_{t,i}^{RU\_ON} + c_{t,i}^{RD\_ON} + c_{t,i}^{RU\_OFF} + c_{t,i}^{RD\_OFF} \tag{33}$$

Co-optimization. Co-optimized algorithm at the same allocates both energy and reserve. Hence all equations mentioned above (Eq. 1-31) are included and joint together by one objective function:

$$min\, c^{Co-opt} = \sum_{t=1}^{N_t} \sum_{i=1}^{N_i} \left(c_{t,i}^{Energy} + c_{t,i}^{Reserve} \right), \tag{34}$$

A priori. A priori algorithm includes two optimizations: first one finds least cost solution for energy scheduling by including Eq. 1-19 and using Eq. 35 as objective function, then second algorithm use variables $g_{t,i}^{TG}$ and $x_{t,i}^{ON}$ as input parameters and including Eq. 20-31 and Eq. 36 as objective function finds least cost solution for reserve provision.

$$min\, c^{A\,priori-energy} = \sum_{t=1}^{N_t} \sum_{i=1}^{N_i} \left(c_{t,i}^{Energy} \right), \tag{35}$$

$$min\ c^{A\ priori-reserve} = \sum_{t=1}^{N_t}\sum_{i=1}^{N_i}(c_{t,i}^{Reserve}), \tag{36}$$

A posteriori. A posteriori algorithm includes three optimizations. First one has been used for estimation of possible outcomes in energy market where all units which estimate they will be used as base-load units do not offer up reserve, while units which estimate that they will be used for load following offer part of their capacity as up reserve. All units which estimate that they will be beneath MCP offer part of their capacity for down reserve provision. This optimization includes all equations (Eq. 1-31) as constraints but only have Eq. 35 as objective function. Second optimization uses estimated generation level (modified $g_{t,i}^{TG}$) from first optimization and minimizes just reserve costs (as in Eq. 36) using Eq. 20-31. Third optimization objective function finds least cost solution for energy provision with constraints Eq. 1-20 and objective function Eq. 35. Constraints Eq. 16-17 are modified to Eq. 37-38 in order to facilitate already allocated reserve capacity. Variables $r_{t,i}^{UP_ON}$and $r_{t,i}^{DN\_ON}$ from second optimization are used as input parameters for third optimization.

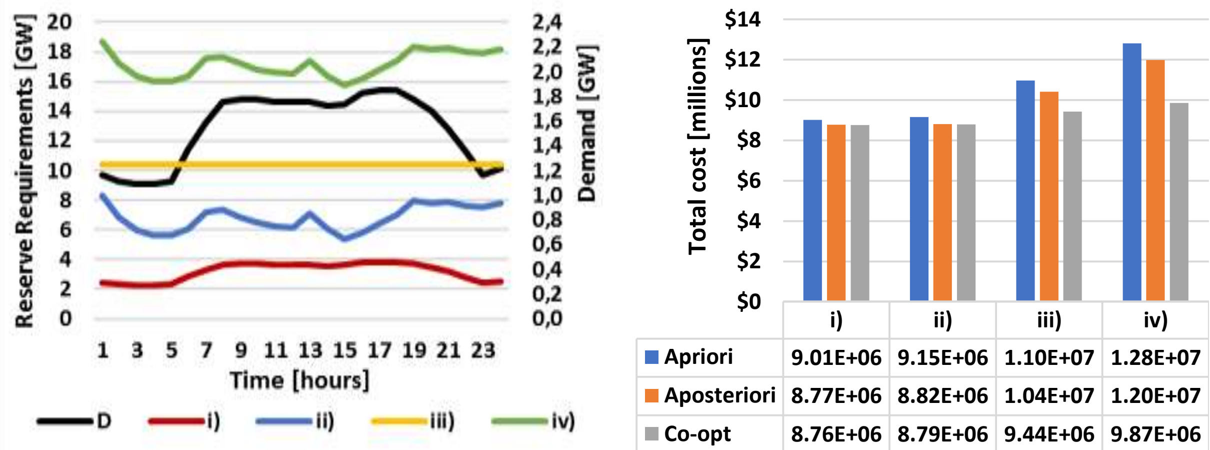
$$g_{t,i}^{TG} \leq G_i^{MX} \cdot x_{t,i}^{ON} - r_{t,i}^{UP\_ON}, \quad \forall t \in [1, N_t], i \in [1, N_i] \tag{37}$$

$$g_{t,i}^{TG} \geq G_i^{MN} \cdot x_{t,i}^{ON} + r_{t,i}^{DN\_ON}, \quad \forall t \in [1, N_t], i \in [1, N_i] \tag{38}$$

Results

All input data used for case studies bellow has been taken from ISO-NE power market, and ISO-NE 8 bus power system has been used as transmission grid [14]. First case study considers different reserve policies, while second consider different wind integration levels. Observed total costs are objective function from co-opt algorithm, sum of objective functions from a priori algorithm and sum of objective functions of second and third optimization of a posteriori algorithm.

Different Reserve Policies. Considered reserve policies (Fig. 1a): *i*) demand uncertainty, 3% of hourly load; *ii*) demand and wind uncertainty, 3% of hourly load + 5% of hourly wind forecast; *iii*) largest hourly contingency; *iv*) demand, wind uncertainty and largest contingency, 3% of hourly load + 5% of hourly wind forecast + largest contingency. D represents daily demand. It can be seen from Fig. 2b that with higher reserve requirements total cost rise for all algorithms, but the lowest rise is for co-opt algorithm and the highest is for a priori.



	i)	ii)	iii)	iv)
Apriori	9.01E+06	9.15E+06	1.10E+07	1.28E+07
Aposteriori	8.77E+06	8.82E+06	1.04E+07	1.20E+07
Co-opt	8.76E+06	8.79E+06	9.44E+06	9.87E+06

Figure 1. a) Reserve requirements for different reserve policies b) Results for different reserve policies.

Different Wind Power Integration. Considered wind integration levels are (Fig. 2a): historic records displayed as 1xW, doubled historic records 2xW, four time higher then historic records 4xW and eight times higher than historic records 8xW. W represents daily wind profile. It can be seen from Fig. 2b that higher wind penetration decreases total cost with co-opt algorithm and a posteriori (they decrease more for co-opt algorithm) but for a priori algorithm the total costs are increasing.

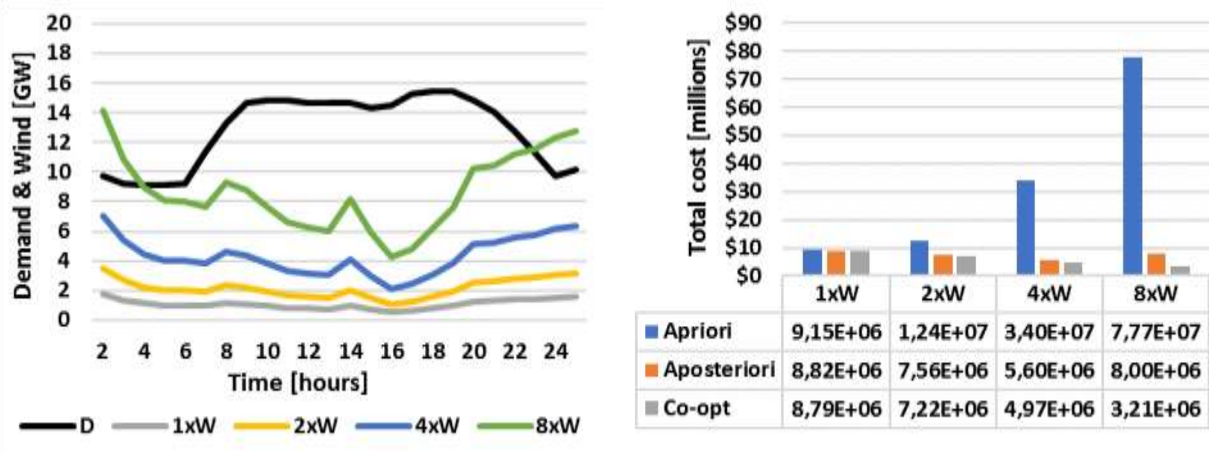


Figure 2. a) Historic wind generation curves for different wind levels b) Results for different wind levels.

Summary

The paper presented three algorithms for reserve allocation problem solving: energy and reserve co-optimization, first-energy-then-reserve allocation or a priori reserve allocation algorithm and first-reserve-then-power allocation or a posteriori reserve allocation algorithm. It demonstrated clear benefits of the co-optimized algorithm over all others. The a priori algorithm is the most expensive one for end-customers for each of the observed test cases. It is also the one which cannot easily adopt to higher reliability margin and higher RES integration. The least expensive one and the most adoptable one is co-opt algorithm, while a posteriori is a little bit more inflexible.

Acknowledgement

This research was financially supported by been supported by the Croatia-China Cooperation in Science and Technology project (2016-2017) under the name “BIL-IRES-8 – Instigation of Research and Innovation Partnership on Renewable Energy, Energy Efficiency and Sustainable Energy Solutions for Cities” and by Croatian Environmental Protection and Energy Efficiency Fund under the project “uGRIP – microgrid Positioning”.

References

[1] ENTSO_E, “Electricity without borders European Network of Transmission System Operators,” 2016.

[2] KU Leuven Energy Institute, “El Fact sheet Capacity Mechanisms.”

[3] ENTSO-E, “Mid-Term Adequacy Forecast,” 2016.

[4] “Germany’s new power market design | Clean Energy Wire.” [Online]. Available: https://www.cleanenergywire.org/factsheets/germanys-new-power-market-design. [Accessed: 10-Apr-2017].

[5] E. Hausman, R. Fagan, D. White, K. Takahashi, and A. Napoleon, “LMP Electricity Markets: Market Operations, Market Power, and Value for Consumers,” 2006.

[6] Z. Zhou, T. Levin, and G. Conzelmann, “Survey of U . S . Ancillary Services Markets,” Chicago, 2016.

[7] J. Yan, F. Li, Y. Liu, and C. Gu, “Novel Cost Model for Balancing Wind Power Forecasting Uncertainty,” IEEE Trans. Energy Convers., vol. 32, no. 1, pp. 318-329, Mar. 2017.

[8] I. Pavić, T. Capuder, and I. Kuzle, "Value of flexible electric vehicles in providing spinning reserve services," Appl. Energy, vol. 157, pp. 60-74, Nov. 2015.

[9] M. A. Ortega-Vazuqez, D. S. Kirschen, and Y. Dvorkin, "Wind generation as a reserve provider," IET Gener. Transm. Distrib., vol. 9, no. 8, pp. 779-787, May 2015.

[10] I. Pavic, T. Capuder, and I. Kuzle, "Low carbon technologies as providers of operational flexibility in future power systems," Appl. Energy, vol. 168, pp. 724-738, 2016.

[11] FERC, "Energy Primer," Washington DC, 2015.

[12] "Nord Pool." [Online]. Available: http://www.nordpoolspot.com/. [Accessed: 05-Oct-2016].

[13] H. Pandzic, T. Qiu, and D. S. Kirschen, "Comparison of State-of-the-Art Transmission Constrained Unit Commitment Formulations," in IEEE Power and Energy Society General Meeting (PES), 2013, pp. 1-5.

[14] D. Krishnamurthy, S. Member, W. Li, and S. Member, "An 8-Zone Test System Based on ISO New England Data : Development and Application," IEEE Trans. Power Syst., vol. 31, no. 1, pp. 234-246, 2016.