Demand response power system optimization in presence of renewable energy sources

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Abstract. *This paper optimizes the price-based demand response of a large customer in a power system with stochastic production and classical fuel-supplied power plants. The implemented method of optimization, under uncertainty, is helpful to model both the utility functions for the consumers and their technical limitations. The consumers exposed to price-based demand can reduce their cost for electricity procurement by modifying their behavior, possibly shifting their consumption during the day to periods with low electricity prices. The demand is considered elastic to electricity price if the consumer is willing and capable to buy various amounts of energy at different price levels, the demand function being represented as purchasing bidding blocks. The demand response is seen also by the scientific literature as a possible source of the needed flexibility of modern power systems, while the flexibility of conventional generation technologies is restricted by technical constraints, such as ramp rates. This paper shows how wind power generation affects short term operation of the electricity system. Fluctuations in the amount of wind power fed into the grid require, without storage capacities, compensating changes in the output of flexible generators or in the consumers' behavior. In the presented case study, we show the minimization of the overall costs in presence of stochastic wind power production. For highlighting the variability degree of production from renewable sources, four scenarios of production were formulated, with different probabilities of occurrence. The contribution brought by the paper is represented by the optimization model for demand-response of a large customer in a power system with fossil fueled generators and intermittent renewable energy sources. The consumer can reduce the power system costs by modifying his demand. The demand function is represented as purchasing bidding blocks for the possible price forecasted realizations. The consumer benefit function is modelled as a piecewise linear function.*

Keywords: electricity market, demand response, renewable energy**.**

Introduction and Literature Review

The increase of renewable energy sources share in a whole country production can have an important influence on the operating performances of the power system, their level depending on:

- the operating characteristics of the sources and their produced power;
- the characteristics of the electrical network where these sources are connected;
- the operating characteristics of the classical units within the system.

In agreement with the international regulations, the network operators must allow the access of all customers to the public grid, among them also the producers from renewable energy sources. The advantageous economic conditions that European Union offered to investors in renewable energy sources determined their massive development in the last decade in Europe. The important advantages that these renewable energy sources offer, like cleaner energy production, varied mix of energy sources, reduced costs of primary input energy for wind and solar installations, as well as the non-exhaustive character, makes them important for the future development of society (Golovanov et.al. 2015). The structure of energy production is determined by the electricity market operation, by the decisions for operation of the existing units (maintenance, development, outage), by the future investments in classical units, and in particular by the development of renewable energy sources (in particular wind and solar systems). This structure influences the possibility to future integrate the renewable energy sources to cover the demand profile and the necessity to have cross-border exchange agreements and balancing of the production and consumption at power system level, possibility to ensure primary, secondary and tertiary reserve.

The liberalization of the electricity market had the objective to improve the customers' security of supply through a competition among the power producers and electrical energy suppliers. The electricity market represents all transactions of purchasing and selling of electrical energy in a determined area, creating and organizing the regulation procedures to fulfil the buying and selling contracts (Dumbrava et al., 2004; Shahidehpour et al., 2002). The competitive environment determines effective cost management and providing incentives in order to reduce costs and efficient use of resources (Harris 2006; Kirschen and Strbac 2004). The competition is necessary but requires clear rules on energy trades, on rights/obligations of the competitors, on trading mechanisms and payment obligations (Zhong et al., 2015).

The goal of the power system optimized operation is to minimize the fuel consumption or the operating cost of the whole system through the determination of the power output of each generating unit subject to the system load demands constraints and renewable sources intermittent production. In a typical power system, multiple generators are implemented to provide enough total output to balance the total consumer demand. Each of these generators can have a unique cost-per-hour characteristic for its output operating range. Considering the electricity markets with interconnected thermal power plants of imposed operating regime (nuclear power plant), the demand profile and cross-border export contracts, the constraints associated with hydro power plants operation, and the necessity to respect the merit order for each characteristic time interval of the electricity market, the power produced at each moment by the renewable energy sources, to balance the system demand can be determined. The constraints imposed to local injected powers are determined by the transfer capacity of the area network lines, and the capacity to evacuate/use the generated power. In addition, constraints imposed by the admitted power quality levels at the point of common coupling can exist in practice.

The investigation of power system operation with volatile renewable energy sources and the involved power system reserve for preserving safe operation was conducted in (Ortega-Vazquez and Kirschen, 2009; Ortega-Vazquez and Kirschen, 2010). The requested reserve under forecast errors in wind production and load demand was optimally

determined by minimizing the socio-economic costs of load disconnection. The stochastic optimization problem for market clearing considering forecast errors was formulated and analyzed in. The reserve requirements in power systems with high wind power integration, computed based on a probabilistic method, such that to ensure a specific level of reliability was carried on in (Meibom et al., 2011). An optimized operation must account for unit commitment and economic dispatch of power generation units and storage systems facing the renewable sources uncertainties, load forecasting and demand-response such that to achieve secure operation minimizing the operational costs (Wu et al., 2015; Bouffard et al., 2005a). Demand response strategies can boost the secure operation of the power system by mitigating the supply-demand balance uncertainties, and benefiting as much as possible of the clean renewable energy sources (Bouffard et al., 2005b; Albadi and El-Saadany, 2008). The stochastic character of renewable energy sources and the increasing penetration rate of these sources within the existing power systems require adopting measures and incentives for demand flexibility (Gatsis and Giannakis, 2013; Tavakoli Bina and Ahmadi, 2015).

In this paper, the optimization model for demand-response of a large customer in a power system with fossil fueled generators and intermittent renewable energy sources is formulated and implemented. The consumer can reduce the power system costs by modifying his demand. The demand function is represented as purchasing bidding blocks for the possible price forecasted realizations. The consumer benefit function is modelled as a piecewise linear function.

The electricity market in Romania

On the electricity market, the electricity is acquired by suppliers from producers or other suppliers, for further selling or for their own use, and also by the network operators to balance their own energy consumption. On the wholesale electricity market, the transactions are carried on by electrical energy producers, suppliers and network operators. The transactions on the wholesale electricity market consist in purchasing or selling electrical energy, transport services, green certificates, and ancillary services.
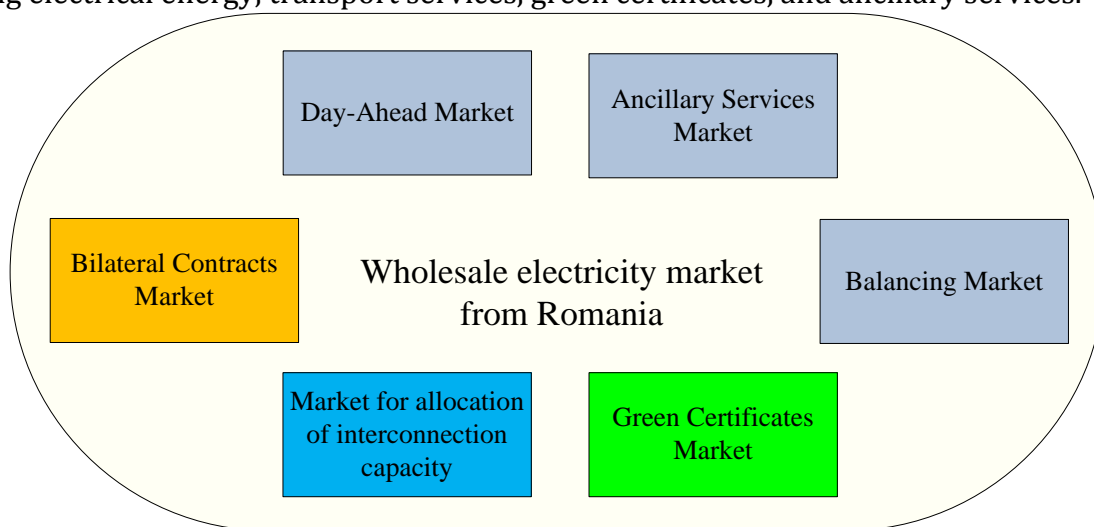

Figure 1. **The main components of the electricity market in Romania**

Source: Authors' own results.

Spot Market

The spot market is a component of wholesale electricity market where hourly transactions occur, with delivery in the consecutive day. The spot market is operational in Romania since 2005, representing a centralized market for purchasing and selling electrical energy for short term. The participation in this market is allowed to all entities licensed by the national commercial operator for the spot market.

The licensed entities are:
- electrical energy producers;
- electrical energy suppliers;
- network operators who can become participants in the spot market and may participate in this market only if they carry out the operations explicitly established in the commercial code.

Network operators are not allowed to trade on the spot market for benefit obtaining. Moreover, excluding electricity sales by the transmission system operator to compensate the unplanned exchanges with other operators, he has not the right to sell electricity on the spot market.

On spot market, independent markets are occurring on each delivery hour, at constant power during the analyzed trading horizon.

The delivery day comprises 24 consecutive trading hours, the first trading period starting from 00:00 on the delivery day. Exceptions are the days corresponding to passing from summer to winter time when the delivery day has 25 intervals, and from winter to summer time when the delivery day has 23 intervals.

Bilateral Contracts Market

The licensed entities, can establish bilateral transactions with electrical energy, including electricity export/import agreements, in agreement with the existing regulations of the electricity market operation.

The bilateral contracts for purchasing/ selling electricity can be:
- Bilateral contracts with minimal agreement established by the regulating authority;
- Deregulated contracts, where the agreement is determined through direct negotiation between the involved parts, in compliance with the regulating requirements of the commercial code.

Intra-day market

The intra-day market offers, to the entities participating on this market, a supplementary functional instrument to hourly achieve, for the delivery day, the adjusting on their own agreement portfolios for achieving a balance between the bilateral contract portfolio, the demand forecast and the technical availability of the producing units. The excess or deficit of electrical energy can be adjusted by selling or purchasing it from the intra-day market.

A key condition that a licensed entity must fulfil for registering to the intra-day market is to establish with the transmission system operator an assuming agreement for balancing responsibility or the proof of transferring this balancing responsibility to another entity responsible with balancing.

Balancing market

The liberalization of the electricity market in Romania automatically involved the intensification of transactions with electricity market on various markets, and the participants could not fulfil the assumed obligations for purchasing/selling due to the differences between production, consumed or traded quantities and the planned ones. These differences influence the secure, stable and at standardized parameters operation of the power system, that led to the evolution of mechanisms required to balance in real time the generation and demand.

Due to these cases, in 2005 the balancing electricity market was created. Through this market, to achieve the secure and stable operation of the power system, the transmission system operator carry on balancing actions, identifying the requirements for regulation at generation or consumption and acquiring balancing energy which will be injected/extracted from the power system by the participants at the balancing market. The balancing energy is acquired through contracts established on another component of the wholesale market, i.e. ancillary services market, between the producers/consumers qualified for delivering each type of ancillary service and the transmission system operator. The balancing energy is used for equilibrating a production deficit by increasing the generation of dispatchable units or by downward demand response, and a production excess through generation reduction of a dispatchable units or by upward demand response. All participants on the wholesale electricity market interconnected to the power system (producers, suppliers, network operators, large consumers) are obliged to have financial responsibility for the produced unbalances through variations between scheduled and actual productions or between the scheduled and realized trades.

The balancing electrical energy is physically delivered in the delivery day, at the interconnection point with the power system, by the dispatchable unit or consumer, when the power system operator requires the balancing actions to be fulfilled.

The balancing energy is the quantity that can be made available to the power system operator by a dispatchable unit or a dispatchable consumer in a certain time period. The reunion of many participants within a single balance responsible party allows the reciprocal compensation of individual unbalances and distribution of costs and benefits among its participants. This can be achieved through adoption within the balance responsible party of a method generally accepted for internal allocation of costs or benefits determined by net unbalances of the balance responsible party. Thus, the balance responsible party is an entity composed of more participants on electricity market, such that to optimize the costs associated with differences between forecasts and real production/consumption of its components.

Mathematical model

In addition, congestions in the transmission network can occur during periods of high production from renewable energy sources that can lead to important modifications of the power flows within the electrical system.

A mathematical model that optimizes the costs associated with the operation of the power system on the day-ahead market is proposed. The model accounts also for the balancing operations determined by the intermittent production of renewable energy sources

(Bouffard et al., 2005b; Albadi and El-Saadany, 2008). The objective of the optimization problem is minimizing the power system operation costs:

$$[\text{MIN}] \quad C = \sum_{s \in S} \pi_s \cdot \left[\begin{array}{l} \sum_{k \in K} \left(a_k \cdot P_{k,s} + C_k^u \cdot R_{k,s}^u + C_k^d \cdot R_{k,s}^d \right) + \\ \sum_{l \in L} v_l^{LOL} \cdot L_{l,s}^{shed} + \sum_{d \in D} C_{dem,d,s} \cdot \Delta P_{dem,d,s} \end{array} \right] \quad (1)$$

where π_s is the probability of the scenario production s of the renewable energy source s from the set S of all possible scenarios, a_k is the fuel cost of power plant k (m.u./MWh), $P_{k,s}$ is the scheduled output power of power plant k in each scenario s (MW), C_k^u and C_k^d are the offer costs for upward reserve, respectively downward reserve, deployed by unit k (m.u./MWh), $R_{k,s}^u$, $R_{k,s}^d$ are the scheduled upward reserve capacity, respectively downward reserve capacity, for the power plant k (MW), v_l^{LOL} is the penalty cost of load shedding (m.u./MWh), $L_{l,s}^{shed}$ is the load shedding imposed to load l and scenario s, and $C_{dem,d} \cdot \Delta P_{dem,d}$ is the revenue associated to the demand variation block $\Delta P_{dem,b}$.

The constraints of the model are presented by each bus balance equation and capacity constraints:
- bus balance equations between production and consumption

$$\sum_{k \in K} P_{k,s,n} + \sum_{r \in R} WT_{r,s,n} - \sum_{l \in L} L_{l,s,n} + \sum_{d \in D} \Delta P_{dem,d,s,n} = \sum_{b \in B} PF_{b,s,n}, \quad \forall n \in Buses, \forall s \quad (2)$$

where $WT_{r,s}$ is the wind turbine r production from the set of all wind turbines R in each scenario s (MW), and $PF_{b,s}$ is the power flow between the various buses of the network.
- capacity constraints

$$PF_b \leq PF_b^{\max}, \forall b \in Branch$$

$$P_k + R_k^U \leq P_k^{\max}, \forall k \in K$$

$$P_k - R_k^D \geq 0, \forall k \in K \quad (3)$$

$$WT_r \leq WT^{\max}, \forall r \in R$$

where PF^{max} is the maximum allowed power flow in each branch b, P^{max} is the maximum produced power of the classical generators, and WT^{max} is the maximum produced power of wind generators.
- load shedding limit

$$0 \leq L_{l,s}^{shed} \leq L_t \quad l \in L, s \in S \quad (4)$$

Case study

The case study is applied on a 6 bus test system with classical generators, 2 wind turbines and two loads, illustrated in Figure 2. The power of the classical generators can vary between 0 and 100 MW, with a cost of 100 u.m./MW for G1–G3 and 150 u.m./MW for G4–G6 (table 1). The reactance of the transmission lines is 0.12 p.u. on a 100 MVA base. The maximum power flow capacity is 75 MW, except for the line between buses 3 and 4 which is

50 MW. The load demand at each bus is 100 MW. The wind power plants output scenarios and probability of each scenario are reported in table 2. The probabilities of each considered scenario are $\pi_1 = 20\%$, $\pi_2 = 30\%$, $\pi_3 = 20\%$, and $\pi_4 = 30\%$. The demand blocks are reported in table 3.

Table 1. *Generator data*

Generator	Pg MIN (MW)	Pg MAX (MW)	a (m.u./MWh)
G1, G2, G3	0	100	100
G4, G5, G6	0	100	150

Source: Authors' own results.

Table 2. *Wind power scenarios [MW]*

WT 1	10	5	0	10
WT 6	10	5	0	0

Source: Authors' own results.

Table 3. *Demand blocks*

	Block 1 [MW]	Block 1 [m.u./MW]	Block 2 [MW]	Block 2 [m.u./MW]	Block 3 [MW]	Block 3 [m.u./MW]
L3	10	150	15	100	20	50
L4	25	300	30	250	35	100

Source: Authors' own results.

The obtained optimization results are illustrated in figures 3 and 4, showing the demand blocks required in each scenario at bus 3, respectively at bus 4. The wind turbine productions at bus 1 is 6.5 MW and at bus 6 is 3.5 MW. The classical generators are producing 45 MW at bus 1, 53.5 MW at bus 2, 90 MW at bus 4, and 1.5 MW at bus 5.
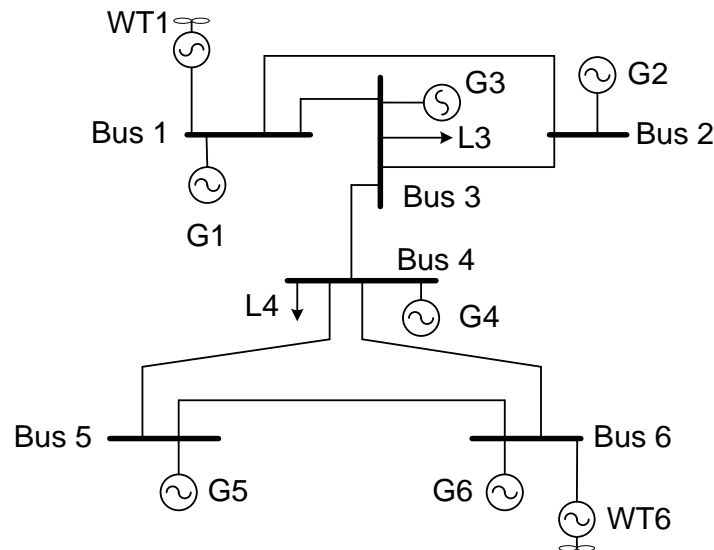

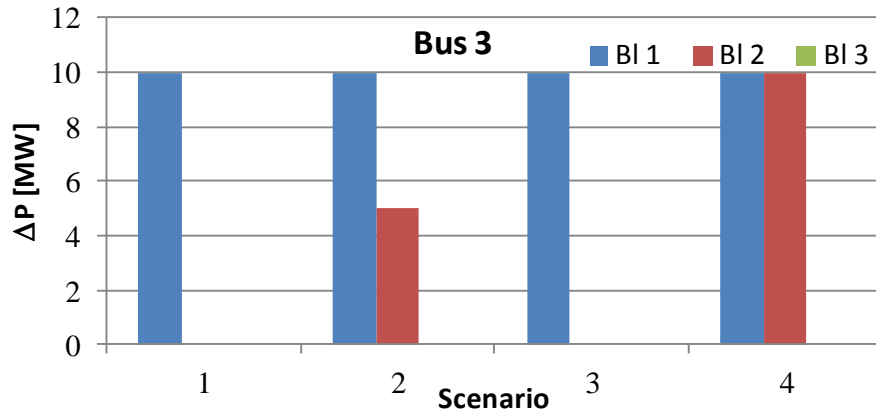*Figure 2.* **Test system with 6 buses**

Source: Authors' own results.

Figure 3. *Obtained optimization results for demand L3 in each scenario*

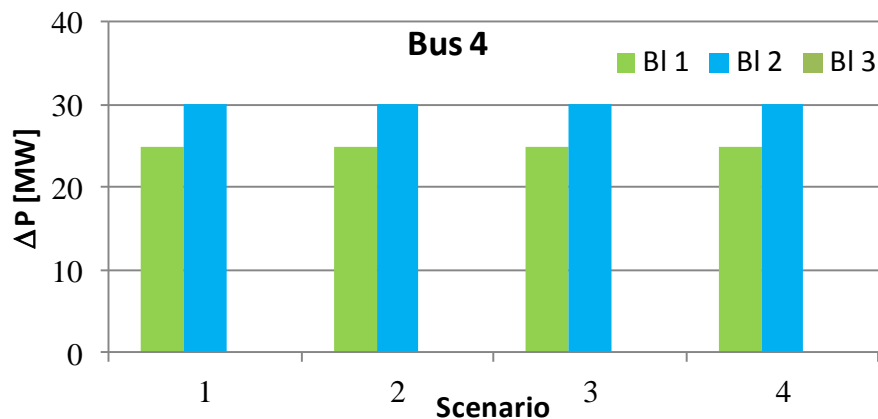Source: Authors' own results.

Figure 4. *Obtained optimization results for demand L4 in each scenario.*

Source: Authors' own results.

Conclusions

In this paper, we proposed a model to optimize the operation of a price-based demand customer in a power system with intermittent sources and fueled units. The loads within the power system have adjustable demand blocks, reduce their costs for electricity procurement by modifying their behavior, possibly shifting their consumption during the day to periods with low electricity prices. In the presented case study, we have tried to show the minimization of the overall costs in presence of stochastic wind power production.

For highlighting the variability degree of production from renewable sources, four scenarios of production were formulated, with different probabilities of occurrence.
The electrical production, registered in these scenarios, is consumed by the customers from the test electrical network. However, there were cases when not the entire production from renewable energy sources can be used due to the system constraints on power flows.
Future researches will deal with minimizing the electrical production from renewable sources which cannot be used, increasing the integration share of electrical production from RES into the power system.

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