Impacts of Stochastic Demand Response Resource Scheduling on Large Scale Wind Power Integration

E. Heydarian-Forushani, M.E. H. Golshan
Isfahan University of Technology
Isfahan, Iran
e.heydarian@ec.iut.ac.ir, hgolshan@cc.iut.ac.ir

M. Shafie-khah, J.P.S. Catalão
Univ. Beira Interior, Covilhã, Portugal, and
INESC-ID, IST, Univ. Lisbon, Lisbon, Portugal
miadreza@ubi.pt; catalao@ubi.pt

***Abstract*—Alongside significant advantages which come through large scale integration of wind power into the grid, it imposes some essential challenges on Independent System Operators (ISOs) performance. The stochastic nature of wind power causes technical and economic impacts on power system operation. As one of the highly-flexible and low-cost solutions, demand response (DR) resources are expected to be helpful for reducing integration problems. In this regard, this paper proposes a stochastic energy and reserve scheduling framework that includes DR resources.The proposed market clearing formulation contains network constraints and considers economical, technical and environmental aspects. In order to investigate the role of DR in the improvement of wind power integration, a new index is proposed in the paper. The IEEE-RTS is selected as a test system to illustrate the effectiveness of the proposed stochastic scheduling model in wind integration.**

***Index Terms*—Wind integration, demand response, stochastic programming, system reliability index, emission constraint.**

I. Nomenclature

Indices

i	Index of generating units
n, n'	Index of buses
s	Index of wind power scenarios

Variables

C_{its}^{A}	Cost due to the change in start-up plan of unit *i*
CSU_{it}	Start-up cost of unit *i* in time *t*
D_{nts}^{C}	Power consumed by the load of bus *n*
$f_{ts}^{n,n'}$	Power flow through line (n, n')
L_{nts}^{shed}	Involuntary load shedding of load of bus *n*
P_{it}	Scheduled power of unit *i* in time *t*
P_{dts}^{DRP}	Power output of DRP *d* in time *t* and scenario *s*
P_{its}^{G}	Power output of unit *i* in time *t* and scenario *s*
P_{Git}^{m}	Power scheduled from *m-th* block of energy
P_{t}^{wind}	Scheduled wind power in time *t*
r_{Gits}^{m}	Reserve deployed from the *m-th* block of energy
r_{its}^{NS}	Non-spinning reserve deployed by unit *i*
$r_{its}^{U/D}$	Spinning reserve up/down deployed by unit *i*
r_{dts}^{U}	Reserve up deployed by DRP *d*
RNS_{it}	Non-spinning reserve scheduled for unit *i*
RU_{it}, RD_{it}	Spinning reserve up and down scheduled
RU_{dt}	Spinning reserve up scheduled for DRP *d*
S_{ts}^{W}	Wind power spillage in time *t* and scenario *s*
z_{it}	Binary variable representing commitment status
θ_{nts}	Voltage angle at node n in time *t* and scenario *s*

Parameters

c_{dt}^{r}	Offer cost of spinning reserve up of DRP *d*
D_{nt}	Demand of load which is connected to bus *n*
$P_{i}^{\max/\min}$	Maximum/Minimum power output of unit *i*
SC_{t}	Spillage cost of wind power in time *t*
$VOLL_{nt}$	Value of lost load for load connected to bus *n*
$X_{n,n'}, f_{n,n'}^{\max}$	Reactance and maximum capacity of line (n, n')
π_{Git}^{m}	Marginal cost of *m-th* block of offered energy
$\pi_{it}^{RD}, \pi_{it}^{RU}$	Offer cost of spinning reserve down/up of unit *i*
π_{it}^{RNS}	Offer cost of non-spinning reserve of unit *i*
π_{it}^{SU}	Start-up offer cost of unit *i* in time *t*
ρ_{s}	Probability of wind power scenario *s*
τ	Spinning reserve market lead time

II. Introduction

As worldwide concern for environmental issues is growing, renewable energy resource integration will be more and more a crucial problem in future power systems. Among the renewable energy resources, wind power generation holds the first rank in terms of use and importance. However, the uncertain nature of wind power and its high investment costs have created several barriers and may lead to prevent its large scale grid integration.

Nevertheless, many power systems have started changing their energy generation portfolios to include significant amount of wind power in their outlook. As an example, it is expected that 20% of the total energy consumption in U. S. comes from wind power generation by 2030 [1]. The main question is how ISOs can overcome the negative impacts of wind power intermittency and facilitate its large scale grid integration. Various options that can facilitate the integration of wind power are discussed and compared in [2].

The large scale integration of wind power needs more flexible power system and it may impose some additional cost to system operation. Therefore, highly flexible and low cost solutions are sought. The option that has the highest flexibility and the lowest cost is demand response (DR) resources. These resources allow system operators to compensate wind power fluctuations.

Different solutions for facilitating large scale integration of wind power are listed in [3]. Also, it analyses the possible impact of demand side management (DSM) and DR with the aim of enabling integration of intermittent resources in Portugal. Demand side resources are proposed as an energy resource that can form part of the power system plant mix and contribute to the flexible operation of power system in [4]. The obtained results represent that demand side resources can contribute to efficient and flexible operation of systems with high penetration of wind power. A new concept of flexible load following the wind farm output power is presented in [5], where several objectives have been optimized through a two-stage approach and the system load curve is accommodated due to the wind farm output power. In [6], a DR program which helps to integrate wind power by reshaping the load of the system is proposed. The proposed method considers a fix and deterministic pattern for wind generation. Reference [7] presents a stochastic model for the hourly scheduling of optimal reserves by considering wind and load forecast errors. The effect of DR is considered as means of mitigating transmission violations when uncertainties are considered. The operation of an electric system with high wind penetration is modeled by means of a unit commitment problem in [8]. In [9], a stochastic model of the demand-side reserve provision is presented by considering electricity and reserve markets with high penetration of wind power.

This paper proposes a two-stage stochastic programming framework which considers DR resources participation in wholesale market with the aim of wind power integration. The stochastic nature of wind power is modeled using a scenario generation technique. Furthermore, a comprehensive decision making framework is designed from ISO perspective, which includes economical, technical and environmental issues related to wind power integration. At the same time, DR resources are considered in addition to conventional units for enhancing the system flexibility and reducing the operation costs. Moreover, energy, up and down spinning reserves, and non-spinning reserves are scheduled simultaneously in a stochastic way. The rest of the paper is organized as follows: the uncertainty characteristics related to wind generation and DR resource participation in wholesale market are discussed in section III. Section IV describes and formulates the proposed model including energy and reserve market clearing procedure and network constraints. The numerical studies are given in section V. Finally, section VI concludes the paper.

III. Wind Energy and DR Models

A. Wind energy

Wind power production relies on wind speed that varies randomly according to time. Accurate probability distribution function (PDF) of wind speed is non-stationary and no discernible actual PDF can be adjusted to it; yet, most of the former researches (e.g. [10]) have used Weibull distribution in order to model the wind speed. The PDF of wind speed is represented by (1), where c>0 and k>0 are referred to as scale factor and shape factor, respectively.

$$f_v(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^{k}\right] \tag{1}$$

In our work, Swift Current wind data is utilized [11]. The PDF is split into S_N scenarios. The probability of i-th scenario can be obtained as follows:

$$prob_i = \int_{WS_i}^{WS_{i+1}} f_v(V) \quad dV\,, \qquad i = 1,2,...,S \tag{2}$$

where WS_i is the wind speed of i-th scenario. The power generated, P_{GW}, corresponding to a specific wind speed, WS_i, can be obtained through (3). In (3), A, B, and C are constants that can be calculated according to [10].

$$P_{GW} = \begin{cases} 0 & 0 \le WS_i \le V_c \;\; or \;\; WS_i \ge V_{c0} \\ P_r\left(A + B \cdot WS_i + C \cdot WS_i^2\right) & V_c \le WS_i \le V_r \\ P_r & V_r \le WS_i \le V_{co} \end{cases} \tag{3}$$

In (3), V_c, V_{c0}, and V_{cr} represent the cut-in speed, cut-out speed and rated speed, respectively. Also P_r is the rated power of wind generation. Different realizations of the wind power generation are modeled by usage of the scenario generation process based on Roulette Wheel Mechanism (RWM). At first, the distribution function is separated into several class intervals. Afterwards, each interval will be related to a certain probability achieved by the PDF. Consequently, due to the various intervals and the mentioned probabilities, RWM is utilized to generate hourly scenarios, as in [12].

B. DR resource in wholesale market

DR comprises some reactions taken by end-use customers to decrease the electricity consumption due to increase in the price of electricity. There are several papers addressing the benefits of DR, which is highly underutilized in electricity markets [13]-[14]. Ref. [15] has assessed DR benefits in seven categories: economic; environmental; pricing; market efficiency; customer services; lower cost electric system and services; risk management and reliability.

In order to improve DR benefits, a player called Demand Response Provider (DRP) is proposed to take part in the electricity market. The DRPs' task is to aggregate and manage customers' responses. DRPs are allowed to operate as conventional units and permitted to submit their price-quantity offers in day-ahead energy and reserve market. The DRP's offered price-quantity is shown in Fig. 1. The DRP quantities are labeled as q_d^k with the associated cost of c_d^k. A representation of the DRPs' price-quantity is shown in (4)-(8).

$$DR_{dt} = \sum_{k=1}^{NQ_d} q_{dt}^k \tag{4}$$

$$CDRP_{dt} = \sum_{k=1}^{NQ_d} c_{dt}^k . q_{dt}^k \tag{5}$$

$$q_{dt}^k \le q_{dt}^{k,\max} \tag{6}$$

$$DR_{dt} \le DR_{dt}^{\max} \tag{7}$$

where DR_{dt} is the total amount of power of DRP d that is traded in the wholesale market in period t, and $DR_{dt}^{\max}$ is the maximum offered capacity of DRP d in period t. Equation (6) limits the maximum achievable DR in each quantity block. The maximum amount of DR that DRP d can provide in each hour is represented by (7).

IV. Problem Formulation

The proposed method which is schematically shown in Fig. 2 uses a two-stage stochastic programming approach to consider the stochastic nature of wind generation.

The market clearing procedure and its constraints are given in the first stage. This stage includes the startup cost, energy, spinning and non-spinning reserves scheduling cost of supply side and demand side. The second stage is related to wind power scenario realization and includes network constraints and limitations. This stage includes the cost associated with start-up and shut-down plan adjustment of generating units, the costs resulting from the actual deployment of reserves by generating units and DRPs, and the cost associated with involuntary load shedding and wind power spillage.

The objective function to be minimized is the expected cost (EC) of the system as (8). The market equilibrium constraint is given by (9). Equation (10) indicates the unit production and DRP capacity limits. Spinning and non-spinning scheduled reserve limits are represented by (11)-(13). Equations (14)–(15) are related to spinning reserve market lead time, where RUR_i and RUR_i refer to ramp up and ramp down rates of generation units. The start-up cost of units is shown in (16). The mathematical formulation of constraints related to minimum up/down time and generation unit ramp rates is omitted for simplicity. Other constraints which are related to scenario realizations are presented in (17)–(21). The DC load flow equation is given by (17). Equation (18) represents the power balance at each bus. Equation (21) shows the capacity limit of transmission lines. Also, involuntary load shedding and wind curtailment limits are presented in (20) and (21), respectively. The parameter P_{ts}^{W} is related to actual wind generation in scenario s.

$$\begin{aligned} EC = &\sum_{t=1}^{T}\Bigg\{\sum_{i=1}^{I}\left(CSU_{it} + \sum_{m=1}^{M}\pi_{Git}^{m}P_{Git}^{m}\right) + \sum_{d=1}^{NDRP}\left(\sum_{k=1}^{NQ_d} c_{dt}^{k}.q_{dt}^{k}\right) \\ &+ \sum_{i=1}^{I}\left(\pi_{it}^{RU}RU_{it} + \pi_{it}^{RD}RD_{it} + \pi_{it}^{RNS}RNS_{it}\right) \\ &+ \sum_{d=1}^{NDRP} c_{dt}^{r}.RU_{dt}\Bigg\} \\ &+ \sum_{t=1}^{T}\sum_{s=1}^{S_N}\rho_s\Bigg\{\sum_{i=1}^{I}\left(C_{its}^{A} + \sum_{m=1}^{M}\pi_{Git}^{m}r_{Gits}^{m}\right) + \sum_{d=1}^{NDRP}\left(\sum_{k=1}^{NQ_d} c_{dt}^{k}.r_{dts}^{k}\right) \\ &+ \sum_{n=1}^{N}\left(VOLL_{nt}L_{nts}^{shed}\right) + \left(SC_t S_{ts}^{W}\right)\Bigg\} \end{aligned} \tag{8}$$

$$\sum_{i=1}^{I} P_{it} + \sum_{d=1}^{NDRP}\sum_{k=1}^{NQ_d} q_{dt}^{k} + P_t^{wind} = \sum_{n=1}^{N} D_{nt} \tag{9}$$

$$P_i^{\min} z_{it} \le P_{it} \le P_i^{\max} z_{it}, \qquad \sum_{k=1}^{NQ_d} q_{dt}^{k} + RU_{dt} \le DR_{dt}^{\max} \tag{10}$$

$$0 \le RU_{it} \le \left(P_i^{\max} - P_{it}\right) z_{it} \tag{11}$$

$$0 \le RD_{it} \le \left(P_{it} - P_i^{\min}\right) z_{it} \tag{12}$$

$$0 \le RNS_{it} \le P_i^{\max}\left(1 - z_{it}\right) \tag{13}$$

$$RU_{it} \le \tau \cdot RUR_i \tag{14}$$

$$RD_{it} \le \tau \cdot RDR_i \tag{15}$$

$$CSU_{it} \ge \pi_{it}^{SU}\left(z_{it} - z_{i,t-1}\right), \qquad CSU_{it} \ge 0 \tag{16}$$

$$f_{ts}^{n,n'} = \left(\theta_{nts} - \theta_{n'ts}\right)/X_{n,n'} \tag{17}$$

$$\begin{aligned} &\sum_{i\in n} P_{its}^{G} + \sum_{d\in n} P_{dts}^{DRP} - \sum_{L\in n}\left(D_{nts}^{C} - L_{nts}^{shed}\right) + \left(P_{ts}^{W} - S_{ts}^{W} \,\middle|\, n = wind\_bus\right) \\ &- \sum_{n':(n,n')} f_{ts}^{n,n'} = 0 \end{aligned} \tag{18}$$

$$-f_{\max}^{n,n'} \le f_{ts}^{n,n'} \le f_{\max}^{n,n'} \tag{19}$$

$$0 \le L_{nts}^{shed} \le D_{nts}^{C} \tag{20}$$

$$0 \le S_{ts}^{W} \le P_{ts}^{W} \tag{21}$$

For the sake of conciseness, the constraints related to unit generation limit in scenarios are not shown in this part. It should be noted that the amount of reserve in each scenario must be lower than the amount of scheduling reserves in the first-stage. The subsequent constraints are linking constraints. The power generated by units and the power consumed by each load is decomposed as it is illustrated in (22) and (23). These constraints are considered for DRPs in a similar way which is not mentioned here. Equations (24)–(26) are the representation of supply side deployed reserves into blocks. Equations (24)-(26) should be rewritten for DRPs in a similar manner. These equations are not expressed here because of duplicity. The start-up cost adjustment is given in (27).

$$P_{its}^{G} = P_{it} + r_{its}^{U} + r_{its}^{NS} - r_{its}^{D} \tag{22}$$

$$D_{nts}^{C} = D_{nt} - \sum_{k=1}^{NQ_d} q_{dt}^{k}\big|_{d\in n} - r_{dts}^{U}\big|_{d\in n} \tag{23}$$

$$r_{itk}^{U} + r_{itk}^{NS} - r_{itk}^{D} = \sum_{m=1}^{NM} r_{Gitk}^{m} \tag{24}$$

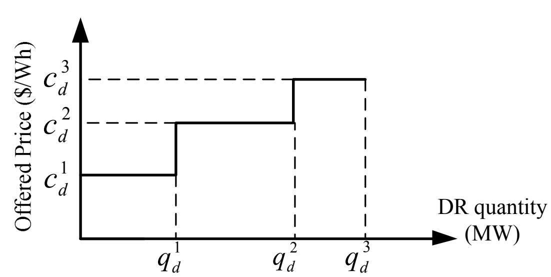

Fig. 1. Typical price-quantity offer of a DRP.

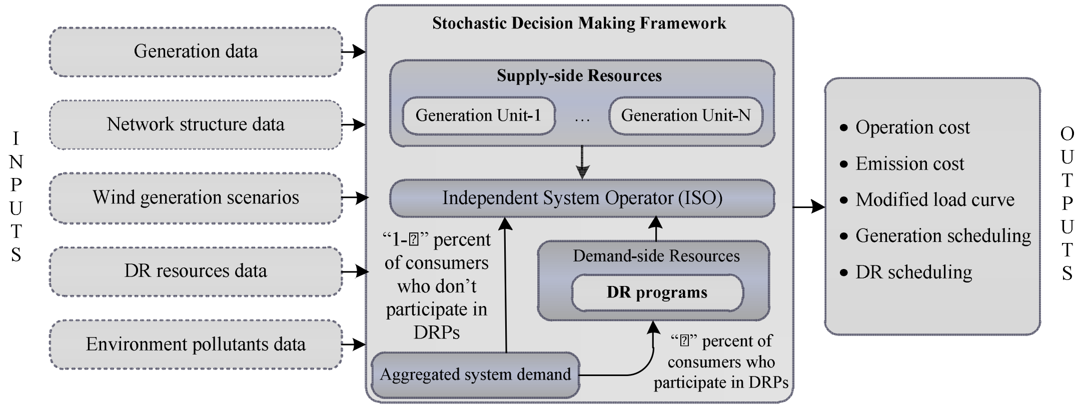

Fig. 2. Schematic of the proposed approach.

$$r_{Gitk}^{m} \le P_{Git}^{m,\max} - P_{Git}^{m} \tag{25}$$

$$r_{Gitk}^{m} \ge -P_{Git}^{m} \tag{26}$$

$$C_{its}^{A} = CSU_{its} - CSU_{it} \tag{27}$$

The constraint related to the reliability index, $EENS$, is given by (28). The pollutant emission constraints are shown in (29) and (30). The parameters $PC_{it}^{NO_x}$ and $PC_{it}^{SO_2}$ show the pollution coefficients.

$$EENS = \sum_{n=1}^{N}\sum_{t=1}^{T}\sum_{s=1}^{S_N}\rho_s L_{nts}^{shed} \tag{28}$$

$$EM_{NO_x} = \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{s=1}^{S_N}\sum_{m=1}^{M}\rho_s . P_{its}^{G} . PC_{it}^{NO_x} \tag{29}$$

$$EM_{SO_2} = \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{s=1}^{S_N}\sum_{m=1}^{M}\rho_s . P_{its}^{G} . PC_{it}^{SO_2} \tag{30}$$

V. Numerical Studies

The IEEE-RTS test system is selected [16] in order to validate the proposed model. A 775 MW wind farm is located in bus 22 instead of hydro units in order to establish a 20% wind power penetration. It is assumed that each generation unit bids at its marginal cost according to linearized cost curves of generation units in three blocks. The generation units offer capacity cost of up/down spinning reserve and non-spinning reserve at rates of 40% and 20% of their highest incremental cost of energy, respectively. Peak load of the system is assumed to be 2850 MW. Involuntary load sheding cost is considered to be 2000 $/MWh in all buses. The wind power curtailment cost is also assumed to be 2000 $/MWh. The NO_x and SO_2 pollution coefficients of generation units are extracted from [17].

It is assumed that one DRP is found in each of the 17 load buses. The load curve is divided into three intervals, low load period (1:00-9:00), off-peak period (10:00-19:00), and peak period (20:00-24:00). The DRPs' price-quantity offers for off-peak periods are presented in Table I. These offered prices are multiplied by 1.1 and 0.9 for peak and low load periods, respectively.

The offered cost of DRPs for up spinning reserve is assumed to be 40% of their highest cost of energy. Also, ten scenarios are considered for wind generation after proper scenario reduction using K-Means method.

Several case studies are designed on the test system, given in Table II. In the first four case studies, DR resources are not considered. In Case1, system operation is evaluated without considering any constraint for the system reliability and emission cap. In Case2 and Case3, reliability constraint and emission cap are considered, respectively. In Case4, both the reliability and emission constraints are considered. The last four case studies are dual of the four former cases while DR resources are also allowed to participate in energy and up spinning reserve markets.

Table III represents in detail the costs of IEEE-RTS associated with eight case studies. The obtained results of Table III imply that if the reliability and emission constraints are considered for ISO operation, ISOs are imposed with more costs in comparison with Case1 (base case) that has no constraints. The pollutant emission has been indicated in Fig. 3 for the mentioned case studies. In Case1, total pollutant emission is 392.968 ton and the reliability index, EENS, is equal to 7.658. The maximum expected cost of the system is assigned to Case4 which includes both reliability and emission cap constraints. Comparison of Case1 and Case2 (and also Case5 and Case6) indicates that by inducing restrict reliability constraints enforces ISOs to procure more amounts of reserve in order to compensate wind power variations.

DR resource utilization decreases significantly the expected cost of system operation. Furthermore, DR resource possesses environmental benefits in addition to economic aspects. In this situation, the emission constraint induces no limitation on ISO scheduling procedure. The obtained results of Case6 and Case8 are similar for this reason.

TABLE I
A Typical DRP Offer in Wholesale Market

k	1	2	3
q_{dt}^{k} (Percent of total response)	%25	%75	%100
c_{dt}^{k}	12	14	16

TABLE II
CASE STUDIES DEFINITION

Case No.	DR Enrolment (%)	Reliability Constraint (MWh)	Emission Constraint (ton)
1	0	No	No
2	0	$EENS \leq 2$	No
3	0	No	≤ 380
4	0	$EENS \leq 2$	≤ 380
5	10	No	No
6	10	$EENS \leq 2$	No
7	10	No	≤ 380
8	10	$EENS \leq 2$	≤ 380

The impact of DR utilization on scheduled wind power is studied for different case studies. The hourly scheduled wind power with and without DR enrolment has been illustrated in Fig. 4. Fig. 4(a) indicates that 10% DR enrolment can increase the scheduled wind power in most of hours. As it can be seen, the increase in some hours (e.g. hours 1, 7- 9, 14, 21 and 22) is more than 100%. The impact of DR utilization on scheduled wind power for a desirable level of system reliability is indicated in Fig. 4(b). In this context, Case2 and Case6 are compared. It can be seen that DR facilitates considerably the integration of wind power. With considering the desirable level of system reliability, the effect of DR enrolment is less than the one without reliability constraints. The impact of DR enrolment on a system by considering the emission constraints has been indicated in Fig.4(c). As it can be observed, the integration of wind power can be increased by DR enrolment especially between hours 1 and 3 when the system base-load can be increased by load shifting effect of DR. Fig. 4(d) compares Case4 and Case8 in order to investigate the effect of DR utilization in a system considering both the reliability and the emission constraints. As it can be seen, DR can enable significantly the integration of wind power.

The scheduled DR in different case studies has been illustrated in Fig. 5. As it can be seen, in Case5 the highest amount of DR has been scheduled. In this context, Case5 has followed by Case7. Case6 and Case8 that considered reliability constraints have the lowest amount of scheduled DR. It can be concluded that, system reliability is more effective constraints to limit the amount of DR utilization than emission constraints.

In order to further investigate the role of DR in wind power integration, the so-called Integrated Wind Average Benefit (IWAB) is given as a new index in this paper, defined as:

$$IWAB = \sum_{t=1}^{T} \left[(EC_t^0 - EC_t^*) \Big/ P_t^{wind} \right] \quad (\$/MWh) \tag{31}$$

This new index represents the average benefit that comes through 1 MWh wind power injection to the system. In (31), EC_t^0 is the optimal value of the objective function in hour t without wind power generation and is equal to 788560 \$. EC_t^* is the optimal value of the objective function in hour t in a specified case study considering wind power generation. The index is calculated for the case studies and the results are presented in Fig. 6. In the first four case studies, where DR is not used, IWAB index has a low value (even negative in Case2 and Case4), meaning that wind power integration imposes an additional cost to the system.

However, in last four cases, all obtained values are positive and much greater than the previous ones. Hence, it can be concluded that DR utilization greatly facilitates wind power integration and significantly reduces system operation costs.

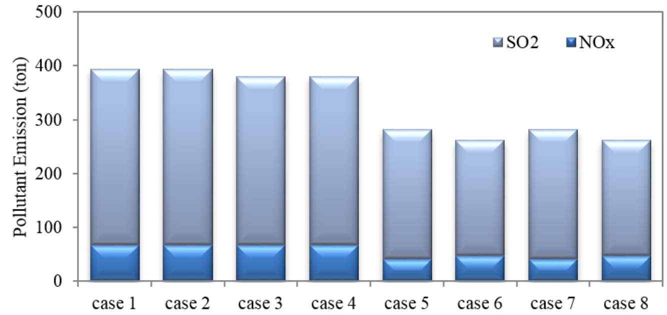

Fig. 3. Pollutant emission in different case studies.

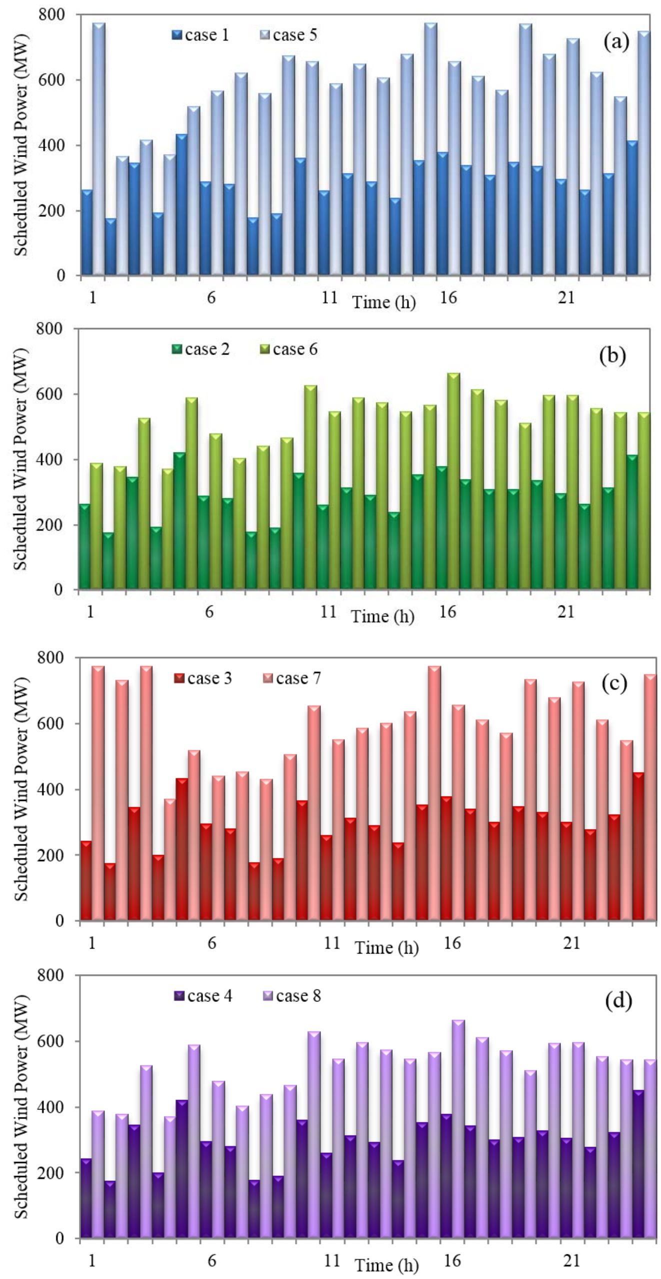

Fig. 4. Impact of DR on scheduled wind power.

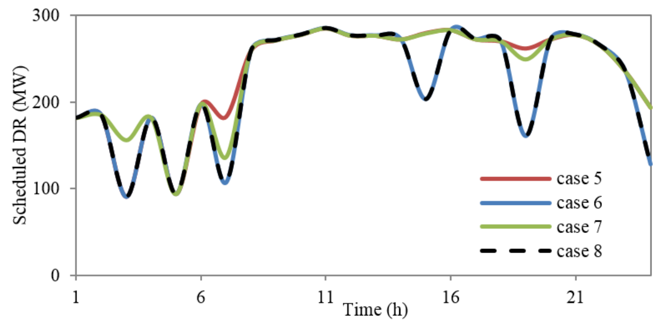

Fig. 5. Amount of scheduled DR in different case studies.

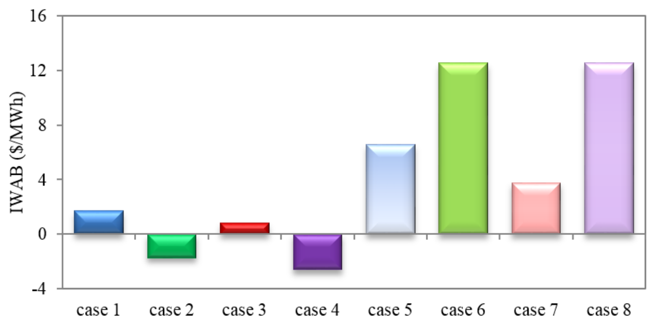

Fig. 6. IWAB measure for different case studies.

VI. Conclusion

This paper proposed a two-stage stochastic programming model with application to wind power integration. Since the integration of wind power needs more system flexibility, DR resources are considered as a highly flexible and low-cost resource to participate in the wholesale market. In addition to economic evaluation, several case studies were designed in order to include environmental and system reliability aspects. The obtained results demonstrate that DR utilization can significantly decrease the operation cost and reduce pollutant emission. Also, the role of DR in the improvement of wind power integration under a desirable reliability level was thoroughly investigated. Finally, a new index was proposed that shows in an innovative way the average system operation cost reduction that comes through an additional MWh of wind power injection into the grid. The results show the positive impact of DR utilization on increasing wind power benefits.

Acknowledgment

The work of Miadreza Shafie-khah and João P. S. Catalão was supported by FEDER funds (European Union) through COMPETE and by Portuguese funds through FCT, under Projects FCOMP-01-0124-FEDER-020282 (Ref. PTDC/EEA-EEL/118519/2010) and UID/CEC/50021/2013, and also by the EU Seventh Framework Programme FP7/2007-2013 under grant agreement no. 309048.

References

[1] 20%Wind Energy by 2030: Increasing Wind Energy's Contribution to US Electricity Supply, US DOE Report, Jul. 2008.

[2] B. M. Nickell, "Wind Dispatchability and Storage Interconnected Grid Perspective, presentation for the U.S. Department of Energy Wind and Hydropower Program," 2008.

[3] P. S. Moura, and A. T. de Almeida, "The role of demand-side management in the grid integration of wind power," *Applied Energy*, vol. 87, pp. 2581-2588, 2010.

[4] A. Keane, A. Tuohy, P. Meibom, E. Denny, et al, "Demand side resource operation on the Irish power system with high wind power penetration," *Energy Policy*, vol. 39, pp. 2925-2934, 2011.

[5] M. Parsa Moghaddam, P. T. Baboli, E. Alishahi, and F. Lotfifard, "Flexible load following the wind power generation," in *Proc. IEEE International Energy Conference*, Bahrain, 2010.

[6] M. Parvania, and M. Fotuhi-Firuzabad, "Integrating load reduction into wholesale energy market with application to wind power integration", *IEEE Systems Journal*, vol. 6, pp. 35-45, 2012.

[7] C. Shahin, M. Shahidehpour, and I. Erkmen, "Allocation of hourly reserve versus demand response for security-constrained scheduling of stochastic wind energy," *IEEE Trans. Sustainable Energy*, vol. 4, pp. 219-228, Jan. 2013.

[8] K. Dietrich, J. M. Latorre, L. Olmos, and A. Ramos, "Demand response in an isolated system with high wind integration," *IEEE Trans. Power Syst.*, vol. 27, pp. 20–29, 2012.

[9] B. Kladnik, G. Artac, A. F. Gubina, T. Stokelj, and R. Golob, "Demand-Side Participation in System Reserve Provision in a Stochastic Market Model with High Wind Penetration," Powercon 2012, pp. 1-6, 2012.

[10] R. Karki, P. Hu, and R. Billinton, "A simplified wind power generation model for reliability evaluation," *IEEE Trans. Energy Convers*; vol. 21, pp. 533-540, 2006.

[11] Canada's National Climate Archive [online], 2006. Available: http://www.cli mate.weatheroffice.ec.gc.ca.

[12] T. Niknam, R. Azizipanah-Abarghooee, and M.R. Narimani, "An efficient scenario-based stochastic programming framework for multi-objective optimal micro-grid operation," *Applied Energy*, vol. 99, pp. 455-470, 2012.

[13] S. Chua-Liang, and D. Kirschen, "Quantifying the Effect of Demand Response on Electricity Markets," *IEEE Trans. Power Syst.*, vol. 24, pp. 1199-1207, 2009.

[14] R. Walawalkar, S. Fernands, N. Thakur, and K.R. Chevva, "Evolution and current status of demand response (DR) in electricity markets: Insights from PJM and NYISO," *Energy*, vol. 35, pp. 1553-1560, 2010.

[15] J. Aghaei, and M. I. Alizadeh, "Demand response in smart electricity grids equipped with renewable energy sources: A review," *Renew. Sustain. Energy Reviews*, vol. 18, pp. 64-72, 2013.

[16] C. Wang, and M. Shahidehpour, "Effects of ramp-rate limits on unit commitment and economic dispatch," *IEEE Trans. Power Syst.*, vol. 8, pp. 1341-1350, 1993.

[17] M. Behrangrad, H. Sugihara, and T. Funaki, "Effect of optimal spinning reserve requirement on system pollution emission considering reserve supplying demand response in the electricity market," *Applied Energy*, vol. 88, pp. 2548-2558, 2011.

TABLE III
System Costs in Details

Case	Total Cost ($)	Energy Cost ($)	Reserve Scheduling Cost ($)	DR Scheduling Cost ($)	Load Shedding Cost ($)	Wind Curtailment Cost ($)
1	776240	663220	38724.67	0	15315.13	58980.20
2	801020	663200	38767.06	0	4000.00	95052.94
3	782420	669550	38574.67	0	15315.13	58980.20
4	807310	669630	38627.06	0	4000.00	95052.94
5	691350	412580	24437.26	78987.71	78631.82	96713.21
6	629210	511680	29226.24	74912.75	0	13391.00
7	733170	411350	25891.12	79027.57	193080.00	23821.31
8	629210	511680	29226.24	74912.75	0	13391.00