Economic evaluation of demand response in power systems with high wind power penetration

Javad Saebi and Mohammad Hossein Javidi
Department of Electrical Engineering, Ferdowsi University of Mashhad, Mashhad 9177948974, Iran

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The penetration of wind power generation is expected to increase in power systems, dramatically. The unpredictable nature of the wind generation poses an obstacle to high penetration of wind energy in the electric power systems. Demand response (DR) may be considered as an efficient approach to cope with the energy unbalances caused by the wind power intermittency. Fair mechanism for pricing of the DR may increase the demand-side participation which consequently facilitates wind power integration in the power systems. This paper focuses on the economic evaluation of the DR according to its potential for mitigating the wind power forecast error in the power system operation. Demand increase, similar to the demand curtailment, is considered as a DR resource and evaluated in this paper. For this purpose, first an insight is provided into the power system operation under the high wind power penetration with the aim of extracting the DR benefits. Based on the DR benefits, a mathematical model is developed to find the maximum monetary incentive for the DR that the system operator is willing to pay to the DR providers. In the proposed model, DR’s potential in reducing the cost of supplying load as well as its capability in reducing the cost of system reserve, start up and shut down of units, load shedding, and wind power spillage are considered. The results of the proposed evaluation method provide valuable information for both the system operator and demand response providers. The proposed method is implemented on an example and a realistic case study and discussions on results are presented. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4885176]

NOMENCLATURE

- $C_{RD}^{i,t}$: cost of downward spinning reserve of unit $i$ in period $t$ ($$/MW h$)
- $C_{RNS}^{i,t}$: cost of non-spinning reserve of unit $i$ in period $t$ ($$/MW h$)
- $C_{RU}^{i,t}$: cost of upward spinning reserve of unit $i$ in period $t$ ($$/MW h$)
- $C_{SD}^{i,t}$: shut-down cost of unit $i$ in period $t$ ($$)
- $C_{SU}^{i,t}$: start-up cost of unit $i$ in period $t$ ($$)
- $C_{VOLL}^{j,t}$: value of lost load for consumer $j$ in period $t$ ($$/MW h$)
- $C_{SP}^{q}$: cost of wind power generation spillage of producer $q$ ($$/MW h$)
- $C_{DA}^{t}$: availability cost for downward DR offered by demand-side in period $t$ ($$/MW h$)
- $C_{UА}^{t}$: availability cost for upward DR offered by demand-side in period $t$ ($$/MW h$)
- $L_{sh}^{j,t,w}$: load shedding of consumer $j$ in period $t$ and scenario $w$ (MW)
- $P_{W,q}$: average generation of wind producer $q$ during the scheduling time horizon (MW h)
- $P_{i}^{max}$: maximum power output of unit $i$ (MW)
- $P_{i}^{min}$: minimum power output of unit $i$ (MW)

**Author to whom correspondence should be addressed. Electronic mail: saebi.javad@stu.um.ac.ir. Tel.: +98 511 880 6077.**

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Increasing price of the fossil fuels and the environmental concerns are the main reasons that motivate governments to increase installed wind capacity in the electrical energy sector.
Due to intermittent nature of the wind power, higher penetration of the wind power leads to higher integration costs.\textsuperscript{1,2} To accommodate wind power volatilities, the flexibility of the power systems must be increased. Demand response (DR) increases power system flexibility by allowing very fast upward/downward changes in the demand. This potential can be interpreted as the ability to provide fast upward/downward reserves, facilitating the utilization of the wind power in the power system.\textsuperscript{3–7}

Basically, the DR is considered as the consumers’ ability to alter their normal consumption patterns in response to changes in the electricity prices or because of the incentive payments designed to resolve reliability issues.\textsuperscript{5} Note that the DR can be classified as either demand curtailment or demand increment. Furthermore, two types of the DR programs are introduced, including price-based and incentive-based DR. In the price-based DR, consumers respond to the energy prices by changing their common consumption patterns while in the incentive-based the consumers are paid for providing DR.

The role of the DR in the operation and planning of the power systems with high level of wind power integration has been investigated by many researchers. The effect of the price-based DR on the integration of the wind power has been analyzed in the literature.\textsuperscript{9–11} However, authors in Ref. \textsuperscript{10} demonstrated that delays in the consumers’ response to the price signals dramatically decrease the benefits of the demand response in mitigating wind uncertainty costs. The impact of the incentive-based DR in reducing the operational costs incurred by the wind power volatilities is investigated in many studies and researches.\textsuperscript{12–16} These researches have focused on scheduling the DR as a virtual resource. However, determining the real value of DR based on its potential for mitigating the operational costs incurred by the wind power forecast error is an issue that has not been pursued by the researchers. This provides valuable information for both the system operator and demand response providers (DRPs).

Knowing the real DR value, the system operator can better decide on the monetary incentives to the customers. On the other hand, discovering the real DR value is also useful to the demand response providers to offer their prices for providing the DR. This paper provides an insight into the system operation under the high wind penetration with the aim of determining DR’s benefits for mitigating wind power forecast errors. Then, a DR evaluation mechanism is proposed to fairly determine the monetary incentives paid to the DR-providing consumers by the system operators. In the proposed formulation, DR’s potentials for reducing the cost of supplying load as well as its capability in reducing the cost of system reserve, start up and shut down of units, load shedding, and wind power spillage are considered. The results of the proposed evaluation method provide valuable information for both the system operator and demand response providers.

The rest of this paper is organized as follows. In Sec. II, the structure of the energy/reserve market in the presence of the wind power is explained. Benefits and costs of the DR in power system operation under high wind integration have been discussed in Sec. III. Section IV presents the numerical simulations results and discussion. Validation of the proposed method is included in Sec. V. Finally, concluding remarks are drawn in Sec. VI.

II. ENERGY/RESERVE MARKET WITH HIGH WIND POWER PENETRATION

In order to accommodate with the wind power forecast errors, day-ahead scheduling needs to be modified in actual operation of the power system. To ensure energy balance in the real-time operation, sufficient reserve must be purchased in the energy/reserve market. Therefore, stochastic programming approaches have been implemented in literature to consider wind power generation scenarios in the energy/reserve market.\textsuperscript{17–22} In Ref. \textsuperscript{17}, a two-stage stochastic programming market-clearing model is proposed to determine the required reserves in the power systems with high penetration of the wind power. The first stage represents the electricity market and its constraints and in the second stage actual operation of the power system under a set of possible wind power generation scenarios is modeled. According to the considered scenarios for the wind production and the cost of procuring reserves, optimal energy, and reserve contracts are determined.
Figure 1 illustrates the scheme of the two-stage energy/reserve market considering wind power generation scenarios as proposed in Ref. 17. As shown in Figure 1, scheduled generation of the generating units and wind power producer is determined at the market stage. Required reserves is then determined based on the considered scenarios for the wind power generation. Next, in the stage of the actual operation condition the production of the units in the scenarios representing the most plausible realizations of the wind power is determined. Wind power spillage and load shedding may also be called for balancing the energy in the real-time operation conditions.

In this paper, output variables of the energy/reserve market are assumed to be known. To obtain output variables of the energy/reserve market, we used the methodology proposed in Ref. 17. These output variables include the following:
• Scheduled up-, down-, and non-spinning reserves for the conventional generating units in each time period
• Deployed up-, down-, and non-spinning reserves for the conventional generating units in each time period and wind power scenario
• Load shedding deployed for consumers in each time period and wind power scenario
• Wind power spillage for the wind power producers in each time period and wind power scenario
• Market clearing price in each time period and wind power scenario

III. ECONOMIC EVALUATION OF DR

In this section, a mathematical formulation is proposed to evaluate the potential of DR for mitigating the operational costs incurred by the wind power forecast error. It should be noted that the DR can be realized as either demand curtailment or demand increment. Both types of the DR programs can help reducing the operational costs of the power system under the penetration of the wind power. Therefore, in this paper, the demand increment (downward DR) as well as the demand curtailment (upward DR) is evaluated. For this purpose, an insight is provided into the operation of the power system in the presence of the wind power production with the aim of determining the benefits of upward and downward DRs.

A. Required DR

As mentioned earlier, the main purpose of this paper is to evaluate the DR based on its potential for reducing the effects of the wind power forecast error during operation of the power system. These undesirable effects can be classified as follows:

• Deviation of the production of the conventional units from the scheduled quantities. These deviations are foreseen in the energy/reserve market as spinning reserves.
• Startups of the generating units that may occur in some scenarios due to the low wind power generation. This effect is foreseen as non-spinning reserve.
• Involuntary load shedding that may occur in some scenarios due to the low wind power generation.
• Wind power spillage in some scenarios with high wind power generation.

The DR has the ability to reduce the abovementioned operational costs by allowing very fast upward/downward changes in the demand. Therefore, in order to determine the real value of the DR in power systems, its potential for alleviating each of the abovementioned effects should be evaluated. For this purpose, the total amount of the upward and downward DRs required for mitigating the effects of the wind power volatility on the power system operation is calculated using the results of the energy reserve market. Then, based on these quantities, the benefits of the DR are expressed in terms of the mathematical functions.

The total required upward DR ($T_{dU}^{t,w}$) is obtained using the results of energy/reserve market as the sum of the deployed upward reserve (spinning and non-spinning) and load shedding in time period $t$ and scenario $w$.

$$T_{dU}^{t,w} = \sum_i (r_{iU}^{t,w} + r_{iNS}^{t,w}) + \sum_j L_{jsh}^{t,j,w}, \quad (1)$$

where $r_{iU}^{t,w}$ and $r_{iNS}^{t,w}$ are, respectively, the deployed upward and non-spinning reserve by unit $i$ during period $t$ and scenario $w$ in the energy/reserve market. $L_{jsh}^{t,j,w}$ is load shedding of consumer $j$ during period $t$ and scenario $w$.

Similarly, the total required downward DR ($T_{dD}^{t,w}$) is obtained using the results of energy/reserve market as the sum of the deployed downward reserve and wind power spillage in time period $t$ and scenario $w$. 
\[ T_d^{D_i} = \sum_i r_{i,t,w}^{D_i} + \sum_q S_{,q,t,w}, \tag{2} \]

where \( r_{i,t,w}^{D_i} \) is the deployed downward spinning reserve by unit \( i \) during period \( t \) and scenario \( w \) in the energy/reserve market and \( S_{,q,t,w} \) is the wind power spillage of producer \( q \) during period \( t \) and scenario \( w \).

In the rest of this section, the benefits and costs of DR are provided.

B. DR benefits

1. Reduction in system reserves

The upward DR can reduce the scheduled upward reserves (spinning and non-spinning) by providing demand reduction. Similarly, the downward DR has the ability to reduce required downward reserve of the system through increase in the demand. If demand-side can provide the required DRs stated in Eqs. (1) and (2), the potential of the DR in reducing the scheduled reserve of the system can be interpreted in terms of the following benefit functions:

\[ \rho_{RU}(i,t) = C_{,i,t}^{RU} R_{i,t} \quad \forall i,t, \tag{3} \]
\[ \rho_{RD}(i,t) = C_{,i,t}^{RD} R_{i,t}^{D} \quad \forall i,t, \tag{4} \]
\[ \rho_{RNS}(i,t) = C_{,i,t}^{RNS} R_{i,t}^{NS} \quad \forall i,t, \tag{5} \]

where \( R_{i,t}^{U} \), \( R_{i,t}^{D} \), and \( R_{i,t}^{NS} \) are, respectively, the scheduled up-, down-, and non-spinning reserves for unit \( i \) during period \( t \) and scenario \( w \) in the energy/reserve market; \( C_{,i,t}^{RU} \), \( C_{,i,t}^{RD} \), and \( C_{,i,t}^{RNS} \) are, respectively, the costs of the up-, down-, and non-spinning reserves of unit \( i \) during period \( t \).

2. Reduction of unit start-up costs

In some scenarios with low wind production, one or more units may be required to start up due to the lack of generation. In such situations, if available upward DR in period \( t \) and scenario \( w \) during period \( t \) and scenario \( w \) for unit \( i \) is scheduled for the startup \( (r_{i,t,w}^{RU} \neq 0) \), is equal to/greater than the total required upward DR stated in Eq. (1), then the unit start-up can be prevented by the demand reduction. Therefore, the expected DR benefit function for reducing the start-up cost in each scenario of wind power can be mathematically expressed as

\[ \rho_{SU}(i,t,w) = \pi_w C_{,i}^{SU}, \quad \text{for} \{(i,t,w)|r_{i,t,w}^{RU} \neq 0\}, \tag{6} \]

where \( \pi_w \) is the probability of wind power scenario \( w \) and \( C_{,i}^{SU} \) is the start-up cost of unit \( i \) in period \( t \).

3. Reduction of unit shut-down costs

In scenarios with high wind production, one or more scheduled units may be required to be shut down. Suppose that \( P_{i,t}^{S} \) is the generation of the unit \( i \) in period \( t \) and \( P_{i,t,w}^{S} \) is the generation of the unit \( i \) in period \( t \) and scenario \( w \). If \( P_{i,t}^{S} \) is non-zero during the period \( t \) and \( P_{i,t,w}^{S} \) is zero, then it will be expected that unit \( i \) shut down in scenario \( w \). If the load recovery (downward DR) happens in such situations, it may prevent unit shutdown. We define \( r_{i,t,w}^{SD} \) equal to \( P_{i,t}^{S} \) for \( P_{i,t,w}^{S} = 0 \) and zero otherwise. Therefore, if the available downward DR in period \( t \) and scenario \( w \), where unit \( i \) is scheduled for the shutdown \( (r_{i,t,w}^{SD} \neq 0) \), is equal to/greater than the total required downward DR stated in Eq. (2), the expected DR benefit function for reducing shut-down cost can be calculated by

\[ \rho_{SD}(i,t,w) = \pi_w C_{,i,t}^{SD}, \quad \text{for} \{(i,t,w)|r_{i,t,w}^{SD} \neq 0\}, \tag{7} \]

where \( C_{,i,t}^{SD} \) is the shut-down cost of unit \( i \) in period \( t \).
4. Reduction of load shedding costs

Wind power volatility together with the technical limits of the conventional generators may cause involuntary load shedding in the actual operation conditions. The upward DR can reduce the cost of lost loads by voluntary reduction in the load. If the available upward DR in period $t$ and scenario $w$ is equal to/greater than the total required upward DR stated in Eq. (1), then the expected benefit of the DR for reducing the load shedding can be defined as

$$\rho_{LS}(j, t, w) = \pi_w \cdot C_{j}^{VOLL} \cdot L_{j, t, w}^{sh},$$

where $C_{j}^{VOLL}$ is the value of lost load (VOLL) for consumer $j$ in period $t$.

5. Reduction of wind power spillage

In some scenarios with high wind power generation, the wind power spillage may occur due to low electricity demand and/or some technical constraints of the generating units. In such circumstances, the downward DR can reduce the wind power spillage through load recovery and consequently increase the utilization of the wind power in operation of the power system. In case of reducing the wind power spillage, if the available downward DR in period $t$ and scenario $w$ is equal to/greater than the total required downward DR stated in Eq. (2), then the expected benefit of DR can be defined as follows:

$$\rho_{SP}(q, t, w) = \pi_w \cdot C_{SP}^{q} \cdot S_{q, t, w}.$$

In Eq. (9), $C_{SP}^{q}$ refers to the average benefit (AB) obtained through decreasing the total operation cost of the system when 1 MW h of wind power is injected at bus $q$. Such injection of the wind power into the power system results in lower expected cost of operation. However, due to this action the associated uncertainty costs will be increased. Therefore, $C_{SP}^{q}$ is equal to the AB minus the average uncertainty cost ($AUC_p$) caused by the injection of one additional MW h of wind power at bus $q$. In Eq. (10), $AB_p$, interpreted in $$/MW h, is a measure of the decrement in the expected cost as a result of injecting one additional MW h of the wind power into the network at bus $q$. This measure is defined as follows:

$$AB_p = \frac{EC^*_{p} - EC^*_{0}}{P_{W, q}},$$

where $EC^*_{p}$ and $EC^*_{0}$ are optimal values of the objective function of the energy/reserve market in Ref. 17 with and without wind power generation, respectively, and $P_{W, q}$ (in MW h) represents the average wind power production in the scheduling time horizon. Similarly, $AUC_p$ (in $$/MW h) can be interpreted as a measure of the equivalent deterministic cost of a wind generator producing the forecasted power, exactly. This measure is expressed as follows:

$$AUC_p = \frac{EC^*_{p} - EC^*_{0}}{P_{W, q}}.$$

In Eq. (11), $EC^*_{p}$ represents the optimal value the objective function of the energy/reserve market in Ref. 17 for the forecasted scenario only.

Finally, $C_{SP}^{q}$ can be calculated using Eq. (12).

$$C_{SP}^{q} = AB_p - AUC_p.$$

6. Reduction of the cost of meeting load

Change in the demand due to the DR leads to the change in the cost of meeting load. If the upward DR happens during peak hours with high energy prices and then this load
curtailment is recovered in off-peak hours, the DR results in the reduction of the cost of supplying load. The change in the cost of meeting load due to the upward and downward DRs can be mathematically stated as follows:

\[ \zeta^U (t, w) = \pi \eta^E Td^U_{t, w}, \]
\[ \zeta^D (t, w) = -\pi \eta^E Td^D_{t, w}, \]

where \( \zeta^U (\cdot) \) and \( \zeta^D (\cdot) \) are, respectively, the expected benefit function of upward and downward DRs due to its potential for reducing load meeting cost in period \( t \) and scenario \( w \). \( \eta^E_{t, w} \) is the energy price in real time operation conditions at period \( t \) and scenario \( w \).

C. DR costs

1. Availability payment

With the abovementioned benefits of the DR, the consumers must be paid for providing the DR. In this paper, DR is considered as a tool for compensation of the energy unbalances caused by wind power uncertainty in actual operation conditions. Therefore, an availability payment should be considered for the DR providers to have them on call during power system operation. In this paper, a fixed-rate upward/downward DR availability payment \( (C^U_{t, A}, C^D_{t, A}) \) is considered for the consumers who provide the DR. The availability payments paid to consumers for providing, respectively, upward and downward DRs in period \( t \) are defined by \( \eta^U_A (t) \) and \( \eta^D_A (t) \) as follows:

\[ \eta^U_A (t) = C^U_{t, A} TDR^U_t, \]
\[ \eta^D_A (t) = C^D_{t, A} TDR^D_t. \]

The consumer must be available for providing the upward and downward DRs, \( TDR^U_t \) and \( TDR^D_t \), respectively, at time period \( t \). These quantities are equal to the highest amount of the DR required to be deployed in all of the scenarios considered for the wind power generation at time period \( t \) and can be stated by Eqs. (17) and (18),

\[ TDR^U_t = \max_w \left( Td^U_{t, w} \right), \quad \forall j, t, \]
\[ TDR^D_t = \max_w \left( Td^D_{t, w} \right), \quad \forall j, t. \]

2. Deploying payment

If the DR is called in a scenario in actual operation condition, the providing consumers must be paid according to the price of the DR. The price of the upward and downward DRs in the actual operation condition are shown by \( \eta^U_{R, t, w} \) and \( \eta^D_{R, t, w} \), respectively. The expected payments for providing the upward and downward DRs in actual operation condition can be defined by \( \eta^U_R (t, w) \) and \( \eta^D_R (t, w) \), respectively, as follows:

\[ \eta^U_R (t, w) = \pi \eta^D_{U, t, w} Td^U_{t, w}, \]
\[ \eta^D_R (t, w) = \pi \eta^D_{D, t, w} Td^D_{t, w}. \]

D. Evaluation of upward DR

Considering the benefits and costs of the DR, explained in Subsections III B and III C, we can evaluate the upward DR based on its potential for reducing the operational costs incurred...
by the wind power uncertainty. The value of the upward DR is the maximum amount of $\lambda_{t,w}^{D,U}$ from system operator’s point of view. Upward DR has the ability of reducing the cost of the upward reserve (spinning and non-spinning), unit start-ups, load shedding, and supplying load. On the other hand, the consumers must be paid for providing the upward DR. Therefore, if the benefits of the upward DR are greater than or equal to its costs, calling the upward DR is considered beneficial by the system operator

$$
\sum_i \rho_{RU}(i,t) + \sum_i \rho_{RU}(i,t) + \sum_i \rho_{SU}(i,t,w) + \sum_j \rho_{LS}(j,t,w) + \delta^U(t,w) \geq \eta^U(t) + \eta^U(t,w). \quad (21)
$$

By substitution of Eqs. (1), (3), (5), (6), (8), (13), (15), and (19) into Eq. (21) and then solving for $\lambda_{t,w}^{D,U}$, the upper bound of the upward DR price will be obtained as follows:

$$
\lambda_{t,w}^{D,U} \leq \lambda_{t,w}^{E} + \frac{\sum_i \rho_{RU}(i,t) + \sum_i \rho_{RU}(i,t)}{\pi w Td_{t,w}^U} + \frac{\sum_{j \in J} \rho_{SU}(j,t,w) + \sum_{j \in J} \rho_{LS}(j,t,w)}{\pi w Td_{t,w}^U} - \frac{\lambda_{t,w}^{E}}{\pi w Td_{t,w}^U} = \lambda_{t,w}^{E} + \lambda_{t,w}^{B,U} \quad (22)
$$

The upper bound of the upward DR price, which is the value of upward DR, consists of two terms, including the energy price and $\lambda_{t,w}^{B,U}$. The $\lambda_{t,w}^{B,U}$ is the pure value of 1 MW of the upward DR during the operation of the power system. It should be noted that the aggregate value of the upward DR, $\lambda_{t,w}^{D,U}$, is the price of the demand curtailment as a virtual resource.

E. Evaluation of downward DR

Similar to the upward DR, the downward DR can be evaluated based on its potential for reducing the operational cost incurred by the wind power uncertainty. The value of the downward DR is defined as the maximum amount of $\lambda_{t,w}^{D,D}$ for the system operator’s point of view. The downward DR has the ability of reducing the cost of the downward reserve, unit shut-downs, wind power spillage, and supplying load. On the other hand, consumers must be paid for providing the downward DR. Hence, if the benefits of downward DR are greater than or equal to its costs, as expressed by Eq. (23), the system operator may be interested in calling the downward DR

$$
\sum_i \rho_{RD}(i,t) + \sum_i \rho_{RU}(i,t,w) + \sum_q \rho_{SP}(q,t,w) + \delta^D(t,w) \geq \eta^D(t) + \eta^D(t,w). \quad (23)
$$

By substitution of Eqs. (2), (4), (7), (9), (14), (16), and (20) into Eq. (23) and solving for $\lambda_{t,w}^{D,D}$, the upper bound of the downward DR price is obtained as follows:

$$
\lambda_{t,w}^{D,D} \leq -\lambda_{t,w}^{E} + \frac{\sum_i \rho_{RD}(i,t)}{\pi w Td_{t,w}^D} + \frac{\sum_{j \in J} \rho_{SU}(j,t,w) + \sum_{j \in J} \rho_{LS}(j,t,w)}{\pi w Td_{t,w}^D} - \frac{\lambda_{t,w}^{E}}{\pi w Td_{t,w}^D} = \lambda_{t,w}^{E} + \lambda_{t,w}^{B,D} \quad (24)
$$

The upper bound of the downward DR price, which is the value of downward DR, is composed of two terms, i.e., the energy price with negative sign and $\lambda_{t,w}^{B,D}$. The $\lambda_{t,w}^{B,D}$ is the pure value of 1 MW of the downward DR in the operation of the power system. It should be noted that if the
aggregate value of downward DR ($\lambda_{t,w}^{D,D}$) is negative ($\lambda_{t,w}^{B,D}$ is lower than the energy price) then its absolute value is equivalent to the price of the energy consumption for the consumers providing the downward DR. Otherwise, if $\lambda_{t,w}^{D,D}$ is positive, the pure downward DR value is greater than the price of energy and the consumers providing downward DR in such a situation will be paid $\lambda_{t,w}^{D,D}$ for their energy consumption.

IV. NUMERICAL STUDY

A. Six-bus test system

To investigate the proposed DR evaluation method, it is applied on a six-bus test system, shown in Figure 2. The test system includes three generation companies (GenCos) and a DRP. Since the main purpose of this paper is to find the value of deploying DR, we simply consider a fixed rate for the availability payment. The availability payment for the upward and downward DRs is assumed 1 $/MW h$. The time frame of the system operation is considered 24 h. The peak of load in this time frame is assumed 150 MW. The load profile is shown in Figure 3 and the data of the GenCos are presented in Table I.

![Six-bus test system](image)

FIG. 2. Six-bus test system.

![Load profile](image)

FIG. 3. Load profile.
The wind power producer is located at bus 5 in Figure 2 with the installed capacity of 20% of peak load. The data used for wind power generation forecast for the next 24 h are extracted from a summer day in Ireland power grid. To consider short-term wind power forecast error, a Beta distribution function is used around the forecasted value in each time period. Figure 3 illustrates a typical Beta distribution function. For the sake of simplicity, just three wind power scenarios are considered for each time period, including predicted (Pre), low, and high, with the probabilities of 0.5, 0.2, and 0.3, respectively. Figure 4 shows how these three scenarios are determined based on the Beta distribution function. For example, all the wind power generation scenarios within the lower bound of the Beta function and with the probability of 0.2 (i.e., \( \int_0^b \beta(x) \, dx = 0.2 \)) are considered as a single low scenario. Furthermore, the time horizon (24 h in this study) is divided into four periods, which can involve any of the three aforementioned wind power realization scenarios. The wind power scenarios for these periods are summarized in Table II.

In this paper, the CPLEX 10.1.1 under GAMS software has been employed to solve the mixed integer linear programming resulted from the energy/reserve market clearing in Ref. 17.

Figure 5 illustrates the value of the upward and downward DR in each hour of the scheduling time horizon and wind power generation scenario. The pure value of the DR (\( \lambda_{U,DR} \), \( \lambda_{D,DR} \)),

<table>
<thead>
<tr>
<th>Table I. Data of GenCos.</th>
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<tr>
<td>GenCo</td>
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<td>------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

FIG. 4. Beta distribution function.
market clearing price of the energy \( (\eta^E_{t,w}) \) and aggregate value of the DR \( (\eta^D_U, \eta^D_D) \) are depicted in Figure 5. The detailed results of the proposed DR evaluation for four sample hours of the scheduling time horizon are reported in Table III. In this table, the benefits of the DR and the system operators’ requirement for the DR are reported.

The results obtained from the DR evaluation in the power system with high wind power integration are as follows:

- The upward DR is required in scenarios with low wind power generation and its value is high in such situations.

<table>
<thead>
<tr>
<th>Period</th>
<th>Hours</th>
<th>Pre.</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1–6</td>
<td>8</td>
<td>6</td>
<td>12</td>
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<td>2</td>
<td>7–12</td>
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</tr>
<tr>
<td>4</td>
<td>19–24</td>
<td>20</td>
<td>12</td>
<td>25</td>
</tr>
</tbody>
</table>

*TABLE II. Wind power scenarios for six-bus test system.*

**FIG. 5.** DR evaluation in each of wind power scenarios during the scheduling time horizon.
• To cope with the wind power forecast error, the upward DR is not only required during the peak hours but also it may also be needed during some off-peak periods due to the wind power variations and technical constraints of the generating units. For instance, in Figure 5(c) the pure value of upward DR during off-peak periods is non-zero.

• The pure value of the upward DR has reached to 80% of the energy price for some hours and scenarios. For example, the pure value of the upward DR at hour 11 in the scenario low has been obtained as 65 $/MW h while the energy price is 80 $/MW h (Table III). In other words, 1 MW demand curtailment in such circumstance has an equivalent value of 145 $/MW h, which is the sum of the energy price and the pure upward DR value.

• In scenarios with high wind power generation, the need for the demand curtailment is low. Consequently, the pure values of upward DR in such conditions are low or zero (Figure 5(e)).

• According to Eqs. (22) and (24), the availability payment for the DR has a significant impact on replacing the scheduled reserve of the system with the DR.

• The system operator’s requirement for the downward reserve is tighter in the scenarios with high wind power generations. Consequently, the pure value of downward DR in such conditions is non-zero (Figure 5(f)).

• If the consumers recover their previously curtailed load due to the DR during the periods when the pure value of the downward DR is non-zero, they can enjoy the low energy price during such periods (aggregate value of downward DR).

• The downward DR has more value during off-peak periods and low wind power production scenarios.

• In the simulated case study, it was found that with the 24-h ahead wind power forecast error around 50%, the effects of the wind forecast error on the power system operation can be mitigated by the DR participation of 8.6%.

As shown in the investigated case, no wind power spillage and load shedding happens and its impact on the DR evaluation is not illustrated. The wind power volatility and technical constraints of the conventional units may lead to the unwanted load shedding and/or wind power spillage. To show these effects on the DR evaluation, two additional cases are considered (cases 1 and 2). In case 1, the wind power generation in scenario high of the 4th time period is increased to 45 MW. Increasing the wind power generation during this period with low load level brings about to the wind power spillage. In case 2, the wind power generation in scenario low of the 3rd time period is lowered to 5 MW and unit ramp rates is limited to 20MW/h. In this case, load shedding happens due to the low wind generation and unit ramp limits. Table IV reports the results of DR evaluation in these two additional cases at hours 24 and 18. As shown
in this table, in case 1 the pure value of the downward DR is even greater than the price of the energy at hour 24 and the aggregate value of downward DR is positive. In other words, the consumers who provide load recovery in such a condition will be paid 10 $/MW h for energy consumption. In case 2, as the upward DR can prevent the load shedding, the value of upward DR will be equal to the VOLL.

B. IEEE reliability test system (RTS) case study

In this subsection, the application of the proposed DR evaluation method on the IEEE reliability test system is presented. The data for the generators and loads have been extracted from Ref. 28. It is assumed that all generators provide spinning and non-spinning reserves at the rate of 25% and 20% of their highest marginal cost of energy production, respectively. The peak load during the scheduling period (24 h) is 2850 MW. All loads are considered as DR providers. It is assumed that a wind farm with the installed capacity of 20% of the peak load is connected to bus 7. Table V shows the scenarios of the wind power generation, obtained based on the method described in Sec. IV A.

The result of the proposed DR evaluation method on the test system is illustrated in Figure 6. The aggregate values of the upward and downward DRs during 24 h for each wind

<table>
<thead>
<tr>
<th>Case</th>
<th>Hour</th>
<th>Scenario</th>
<th>$\rho_{SP}$</th>
<th>$\rho_{LS}$</th>
<th>$\bar{x}_{w}^{U}$</th>
<th>$\bar{x}_{w}^{D}$</th>
<th>$\bar{x}_{w}^{U}$</th>
<th>$\bar{x}_{w}^{D}$</th>
<th>$\bar{x}_{w}^{U}$</th>
<th>$\bar{x}_{w}^{D}$</th>
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<td>0</td>
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<td>20</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>Low</td>
<td>0</td>
<td>200</td>
<td>70</td>
<td>1</td>
<td>1000</td>
<td>0</td>
<td>1070</td>
<td>-70</td>
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</table>

TABLE V. Results of DR evaluation in additional cases.

<table>
<thead>
<tr>
<th>Period</th>
<th>Hours</th>
<th>Wind power output (MW)</th>
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<tr>
<td></td>
<td></td>
<td>Pre.</td>
</tr>
<tr>
<td>1</td>
<td>1–6</td>
<td>205.20</td>
</tr>
<tr>
<td>2</td>
<td>7–12</td>
<td>364.80</td>
</tr>
<tr>
<td>3</td>
<td>13–18</td>
<td>570.0</td>
</tr>
<tr>
<td>4</td>
<td>19–24</td>
<td>342.0</td>
</tr>
</tbody>
</table>

FIG. 6. Results of implementing DR evaluation method on IEEE RTS.
power generation scenario are shown in this figure. As seen in Figure 6, the value of the upward DR in low wind power generation scenario is higher while the aggregate value of the downward DR is lower in high wind generation scenario. The results obtained from implementing the proposed method on the six-bus test system (Sec. IV A) are also confirmed in this case study (see Figure 6).

Furthermore, the effect of the wind power penetration level and variations on the proposed DR evaluation method is investigated. For this purpose, two cases for the wind power penetration level are considered, including 5% and 20% wind power penetration levels. In each case, two states of 5% and 15% are considered for the maximum variation of the wind power generation. The maximum variation of the wind power generation around the forecasted value can be used as a measure to show the wind power forecast error. The expected aggregate values of the upward and downward DRs for different cases of wind generation and variation are reported in Table VI. According to this table, the value of DR increases when the wind penetration and/or variation increase.

V. VALIDATION OF THE PROPOSED METHOD

To validate the proposed DR evaluation method, the energy/reserve market in Ref. 17 with the demand-side reserve offers is run for the two case studies of Sec. IV. In this analysis, two scenarios are considered for the price offered by the DR providers, as follows:

- **Scenario 1 with high DR prices**: The DR prices are assumed to be equal to the values obtained from the proposed method; i.e., upward and downward DR prices are $\lambda_{r,w}^E + \lambda_{r,w}^U$ and $\lambda_{r,w}^B,D$, respectively.
- **Scenario 2 with low DR prices**: The upward and downward DR prices are assumed $\lambda_{r,w}^E + 0.5 \times \lambda_{r,w}^U$ and $0.5 \times \lambda_{r,w}^B,D$, respectively.

A. Six-bus test system

The results of running the energy/reserve market on the six-bus test system with and without the DR offers are reported in Table VII. The results are obtained for two DR price

| TABLE VII. Results of the energy/reserve market with and without DR (six-bus test system). |
|-----------------------------------------------|---------------------------------|---------------------------------|
| Total scheduled upward spinning reserve (MW h) | Without DR | Scenario 1 | Scenario 2 |
| Total scheduled downward spinning reserve (MW h) | 34 | 6.50 | 0.5 |
| Total scheduled non-spinning reserve (MW h) | 138 | 144 | 144 |
| Total scheduled upward DR (MW h) | 45 | 22 | 0 |
| Total scheduled downward DR (MW h) | 0 | 50.50 | 77.50 |
| Reserve cost ($) | 2367 | 1910.25 | 1644.75 |
| Total operation costs ($) | 67 512 | 67 333.62 | 66 852.81 |
scenarios. As shown in Table VII, in scenario 1 while the DR price is assumed to be equal to the upper bound of the upward DR value in Eq. (22), but the upward DR is deployed in the energy/reserve market. As might be expected, since the upper limit of the DR prices are considered in this scenario, a small decrease in the operation cost is occurred compared to the case without the DR. According to Table VII, by using the results of the proposed evaluation method in the energy/reserve market with the DR offers, the operation and reserve costs are decreased compared to the case without the DR. Decrease in the DR prices in scenario 2 leads to the increase in the deployed upward DR up to 77.5 MW h. In this scenario, the operation cost decrement is higher than scenario 1. It should be noted that since the aggregate values of the downward DR are negative (see Table III), the downward DR is not deployed in this case study. However, if the load recovery constraints are considered in the energy/reserve market with the DR offers, the downward DR will be deployed during the hours that the pure value of the downward DR is non-zero.

In addition, the case of the wind power spillage in the energy/reserve market (Sec. IV) is investigated. According to Table IV, the pure value of the downward DR at hour 24 is higher than the energy price. Therefore, the aggregate value of downward DR is positive at this hour. The results of running the energy/reserve market with the DR offers in this case show that 8.55 MW of the downward DR is deployed at this hour to decrease the wind power spillage up to 21%.

B. IEEE RTS case study

To show the efficiency of the proposed DR evaluation method, the IEEE reliability test system\(^\text{27}\) is also employed. Based on the results of the DR evaluation, the energy reserve market with the DR offers is run for each DR price scenario, defined in Sec. IV. Table VIII shows the benefits obtained from incorporating the DR into the energy/reserve market based on the results of the proposed DR evaluation. As seen in this table, by the proposed DR evaluation method, the reserve cost, considered to cover the volatility of the wind power in real time, is decreased.

VI. CONCLUSION

In this paper, a mathematical model for economic evaluation of the demand response (DR) has been proposed. The main objective of this model was to find the real and fair value of the DR considering its abilities to mitigate the volatility effects of the wind power on power system operation. Demand increase, similar to the demand curtailment, was considered as a DR resource and evaluated in this paper. The proposed model was examined on two case studies and discussions on results were reported. The results of the proposed evaluation method provided valuable information for both the system operator and demand response providers. Furthermore, fair pricing of the DR as proposed in this paper leads to the increase in the demand-side participation which consequently facilitates integration of the wind power plants into the power systems.
APPENDIX: LOAD DATA

The DRP’s load profile of the six-bus test system is reported in Table IX.

<table>
<thead>
<tr>
<th>t (h)</th>
<th>Load (MW)</th>
<th>t (h)</th>
<th>Load (MW)</th>
<th>t (h)</th>
<th>Load (MW)</th>
</tr>
</thead>
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