Effects of Demand Response Siting on High Wind Power Integration in a Transmission Constrained System

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Abstract: Demand Response is now an effective approach to integrate wind power as it could be flexibly deployed to follow the wind power generation. This paper presents a scheduling model with real time pricing (RTP). The effects of wind power location, transmission constraint and DR siting on wind power integration are discussed in this paper. Simulation on PJM-5 bus System indicted that transmission constraint plays a more important role than wind power location on DR distribution and operation cost. It is cost-effective to site wind power at load center and increasing demand elasticity of bus near to congested lines rather than other buses with a limited budget in a transmission constraint system.

Introduction

Increasing wind power resources impose challenges on system operation and the challenges mainly stem from unpredictability, steep ramping requirement, intra-hour variability of wind power and over-generation at middle night [1]. It requires more flexibility from conventional generators to adapt to the wind power availability. Since flexibility of supply side is restricted, Demand Response (DR) and energy storage are investigated as the major effective way to address the above challenges [2].

DR could be flexibly deployed to follow the wind power generation in a more economical way comparing with energy storage. In practical terms, DR can achieve load shifting/reduction and especially provide various ancillary services including regulation, spinning reserve, non-spinning reserve and ramping for integrating renewable energy [3]. Many works have demonstrated the feasibility of DR to accommodate wind power. However, few researches have focused on optimal DR distribution, especially considering the influence of transmission constraint and wind power location.

As the amount of power imported is restricted to transmission capacity, wind power location has a significant affection on the value of wind power except for wind power penetration and concentration [4]. In other words, network capability to accommodate, and transport the power coming from wind farm rather than wind power availability is one of the most influential factors in the value of wind power. Moreover, it will exaggerate the effect of wind power fluctuation when large-scale wind power injected in a single bus [5]. Transmission constraints can substantially limit renewable energy production, especially in system in which wind resources are sited away from load pockets. Since wind power location is an important factor for wind power integration as mentioned above, the effects of DR siting in a transmission constraint system need to be discussed.

Real time pricing (RTP) is an important DR program which can guide consumers to follow the situation of supply side using price signal. Price elasticity is a measure to indicate the quantity of responsive load in response to price change [6]. Consequently, the different elasticity siting which is regarded as DR siting will be discussed in this paper to analyze the effects of DR siting on wind power integration. It especially explores whether an optimal bus exists to improve the elasticity of
which would be more beneficial to system than other buses. This academic research work can be useful for ISO DR planning to choose optimal DR location in certain area under limited investing budget as increasing elasticity need extra investment.

Above all, a detailed optimal scheduling model with RTP was established to address the issues above. The key factors including wind farm location, transmission constraint and different DR siting were all considered in this model. Simulation is based on PJM 5-bus system with high wind penetration levels.

**Modeling Approach**

DR programs can be classified into Incentive-Based Programs (IBP) and Price-Based Program (PBP) [7]. RTP is one of PBPs in which customers are charged hourly fluctuating prices reflecting change in the supply side[8]. RTP allows customers to flexibly respond the operating status and retain overall control [9], and it has been convinced to be the most direct and efficient DR programs suitable for competitive electricity markets [10]. And price response behavior which is the key factor in the model considering DR can be characterized by price elasticity. This paper is focusing on the short-term price elasticity and own-price elasticity. And it assumes customers’ behavior is known by system operator without uncertainty, and the response is immediate.

**Objective Function**

A cost-minimizing approach is applied in this model. In objective function (1), the operation cost including generation cost, start-up cost and wind power curtailment cost is minimized. \( n \) is Index of conventional generators, \( n = 1, 2, \ldots, Ng \); \( \omega \) is index of wind generators, \( \omega = 1, 2, \ldots, W \); \( t \) is Index of time periods, \( t = 1, 2, \ldots, T \); \( p_{n,t} \) is output of conventional; \( \text{start\_cost}_{n,t} \) is start-up costs of conventional generator; \( \text{CC}_{\omega} \) is curtailment cost of wind generator of wind generator \( \omega \); \( \text{curt}_{\omega,t} \) is wind power curtailment.

\[
	ext{Min} \left[ \sum_{n=1}^{N_g} \sum_{t=1}^{T} f(p_{n,t}) + \sum_{n=1}^{N_g} \text{start\_cost}_{n,t} + \sum_{\omega=1}^{W} \sum_{t=1}^{T} \text{CC}_{\omega} \cdot \text{curt}_{\omega,t} \right]
\]

\( \sum_{n=1}^{N_g} \sum_{t=1}^{T} f(p_{n,t}) + \sum_{n=1}^{N_g} \text{start\_cost}_{n,t} + \sum_{\omega=1}^{W} \sum_{t=1}^{T} \text{CC}_{\omega} \cdot \text{curt}_{\omega,t} \) \quad (1)

**Constraints**

(1) power balance

\[
\sum_{n=1}^{N_g} p_{n,t} + \sum_{\omega=1}^{W} (\text{wind}_{\omega,t} - \text{curt}_{\omega,t}) - \sum_{j=1}^{J} B_{ij} (\theta_{i,t} - \theta_{j,t}) = \text{Load}_{i,t} + \text{dem}_{i,t}
\]

\( B_{ij} \) is line susceptance between bus \( i \) and \( j \); \( \theta_{i,t} \) is voltage angle of bus \( i \) at period \( t \); \( \text{dem}_{i,t} \) is responsive load of bus \( i \) at period \( t \); \( \text{Load}_{i,t} \) is initial inelastic demand level; \( \text{wind}_{\omega,t} \) is wind power injection.

(2) transmission constraint

\[
|B_{ij} (\theta_{i,t} - \theta_{j,t})| \leq TRC_{ij}
\]

\( TRC_{ij} \) is transmission capacity on line from \( i \) to \( j \).

(3) DR constraint

\[
\text{dem}_{i,t} = \varepsilon_i \cdot \text{Load}_{i,t} \left( \frac{\text{price}_{i,t}}{\text{price\_ref}} - 1 \right) \quad (4)
\]

\[
\text{dem}_{i,t} \leq \text{max \_Dflex}_i \quad (5)
\]
\[
price_{i,t} \geq \frac{\sum_{n=1}^{N_n} f(PMAX_n) + \sum_{n=1}^{N_n} \sum_{t=i}^{T} \text{start}_n \cos t_{i,t}}{\sum_{n=1}^{N_n} \text{PMAX}_n + T \sum_{n=1}^{N_n} \text{PMAX}_n}
\]

(6)

\[
\sum_{t} \text{dem}_{i,t} = 0
\]

(7)

\(\varepsilon_i\) is demand elasticity of bus \(i\); \(\text{price}_{\text{ref}}\) is reference price; \(\text{price}_{i,t}\) is RTP price of bus \(i\) at period \(t\); \(\text{maxDflex}_i\) is maximum responsive demand; \(\text{PMAX}_n\) is maximum generation output.

Equation (2) assures that system has power balance all the time, and \(n \in i\) means generator \(n\) connected to bus \(i\). Constraint (3) is transmission network constraint which limits the line flow no more than the transmission capacity. Equation (4) is responsive demand function based on demand elasticity and (5) restrict the responsive load is within the maximum of response. (6) forces price is not lower than average operation cost. Equation (7) ensures a decrease demand is recovered in other period which is regarded as a perfect load shifting [11]. Other constraints related to unit commitment can be found in [12].

**Case Study**

PJM5-bus system has been chosen for this case study. Wind farms will be added to this system at different locations. The analysis mainly compares the total operation cost under different wind farm location and various DR siting. The case study was solved by using CPLEX 12.1 and YALMIP under MATLAB.

**Data Assumption**

Fig.1 shows the configuration and key parameters of PJM5-bus system. There is a transmission constraint line 4->5 with capacity of 240MW. The load curve of different buses [13] are shown in Fig.2 and the peak-normalized overall profiles of wind power are shown in Fig.3. The wind power data from that of wind farms in Southern Californian [14]. Wind1 is the server condition with more output during valley load time and less output during peak load time, while Wind2 is more favorable to the system operation. The main parameters of this model can be obtained from [12].
Results and Discussion

(1) Wind Farm Location

The demand elasticity of each bus is the same in this part to analyze the effects of wind farm location. Bus1 and Bus4 which locate in generation and load center respectively were assumed to have wind unit installed.

TABLE I indicates that the total cost will reduce as demand elasticity increases, but the total cost of wind farm located at bus4 always lower than bus1 when transmission capacity is considered. Fig. 4 illustrates the transmission power flow in line 5->4 P45. When wind farm is located at Bus1, the transmission constrain is almost binding at all the time. As shown in Fig. 1, the generators at Bus1 and Bus5 are cheaper than those at other buses within the load center, so they are dispatched more. But when wind farm is located at Bus4, the load can be met locally and therefore P45 is much smaller. In addition, load will increase to integrate wind power during 1-8, so the flow in line 5->4 with DR is generally larger than that without DR.

Table 1. Total Cost Comparison of Various Wind Farm Location and εi (wind_max=3.5 p.u.).

<table>
<thead>
<tr>
<th></th>
<th>ε_i=0</th>
<th>ε_i=-0.1</th>
<th>ε_i=-0.2</th>
<th>ε_i=-0.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus1</td>
<td>17590.71</td>
<td>17519.28</td>
<td>17460.18</td>
<td>17442.78</td>
</tr>
<tr>
<td>Bus4</td>
<td>17371.07</td>
<td>17280.45</td>
<td>17202.91</td>
<td>17168.21</td>
</tr>
<tr>
<td>Wind2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus1</td>
<td>17332.76</td>
<td>17280.88</td>
<td>17246.76</td>
<td>17228.40</td>
</tr>
<tr>
<td>Bus4</td>
<td>17040.85</td>
<td>16870.54</td>
<td>16825.32</td>
<td>16783.88</td>
</tr>
</tbody>
</table>

Fig. 5 confirms that the cost difference between Bus1 and Bus4 gradually decreases to 0 as transmission capacity of line4-5 increases. Since the generation of conventional units and wind power could be imported to each bus without transmission constraint, the wind power location will not affect the total generation cost and the generation units will be dispatched only based on the cost.
Figure 5. Cost difference between bus1 and bus4 with various transmission capacity ($\varepsilon_i=-0.2$).

(2) DR Siting

The previous analysis is based on the assumption that all loads have equal $\varepsilon$ and it suggest that increasing demand elasticity could be cost-effective to system operation. Some investment will need, such as replacement electrical equipment, incentives, AMI installments and so on, to improve demand elasticity. The demand elasticity of every bus in the system cannot be increased once for all in some cases when budget is limited. So it needs to discuss the results of improving elasticity of one specific bus. That is whether there is a relatively optimal bus improving elasticity of which could be much better than the others and a co-relationship between optimal bus and wind farm location. It assumes the cost of increasing elasticity of every bus is the same, so the investment of which is not included in this model.

It assumes $\varepsilon_{\text{base}}$ as the initial elasticity of buses and $\varepsilon_{\text{increase}}$ as the increased elasticity. There are three elasticity siting scenarios discussed in this paper as shown in TABLE II. For example, S1 with $[\varepsilon_{\text{base}}=-0.1, \varepsilon_{\text{increase}}=-0.2]$ means one bus’s elasticity is -0.2, and elasticity of the other two buses is -0.1 which including the distribution of $[\varepsilon_2=-0.1, \varepsilon_3=-0.1, \varepsilon_4=-0.2]$, $[\varepsilon_2=-0.1, \varepsilon_3=-0.2, \varepsilon_4=-0.1]$ and $[\varepsilon_2=-0.2, \varepsilon_3=-0.1, \varepsilon_4=-0.1]$. Experiments have been done with various DR siting and only three typical cases are detailed described in this paper.

Table 2. Demand Elasticity Siting Scenarios.

<table>
<thead>
<tr>
<th></th>
<th>$\varepsilon_{\text{base}}$</th>
<th>$\varepsilon_{\text{increase}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>-0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>S2</td>
<td>-0.1</td>
<td>-0.3</td>
</tr>
<tr>
<td>S3</td>
<td>-0.2</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

Figure 6. Total Cost with Various Elasticity Siting Scenarios and Wind Power Location (wind_max=3.5 p.u.).

Fig.6 presents the total cost under various elasticity siting scenarios, and the x-axis of Fig.6 is the bus number with increased elasticity. In more specific terms, when $x=4$ in Fig.6 means the elasticity of Bus4 is equal to $\varepsilon_{\text{increase}}$ and that of Bus2 and Bus3 are both equal to $\varepsilon_{\text{base}}$. That is the elasticity of Bus4 is higher than that of other two buses. It is clear that increasing the elasticity of Bus4 is more cost-effective than Bus2 and Bus3 no matter where the wind farm is located as illustrated in Fig. 6a) and b).

Moreover, results of wind power decentralized injected to system is also calculated by author. When wind power located in each bus with conventional generator (Bus1, Bus3, Bus4 and Bus5 in
PJM5-bus system), the results confirm that there is no significant co-relationship between wind farm location and elasticity siting. Because of the limitation of length, detail results will not be shown here.

Conclusions

DR has now been proved an effective approach to deal with the challenges caused by high wind power penetration. This paper preliminary explores the effects of different DR siting on wind power integration in a transmission constraint system on the basis of previous research. Demand elasticity which is the measure of amount of a customer reacts to the price change is regarded as DR siting to realize the analysis in this paper. Effects of wind power location, various elasticity sting scenarios and transmission constraint are all considered in the paper. The simulation based on PJM5-bus system indicates that it will be cost-effective to locate wind power at load center in a transmission constraint system. There is no significant co-relationship between wind power location and DR siting. And it is more inclined to be beneficial to wind power integration when the elasticity of bus close to congestion line is improved in the case of a limited budget. This model could provide some useful reference for DR planning. The investment of increasing elasticity will be studied to investigate the optimal DR siting and sizing in the future research.

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References


