Study on the Accommodation of Photovoltaic Power Considering Network Reconfiguration and Demand Response

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\textbf{Keywords:} photovoltaic (PV); accommodation; distribution network reconfiguration; demand response (DR); particle swarm optimization algorithm.

\textbf{Abstract.} The penetration rate of photovoltaic (PV) is increasing, but its volatility and intermittent characteristics constrain the accommodation power of PV in the distribution network. This paper firstly constructs a mathematical model of distribution network reconfiguration, and finds the optimal switch combination of the distribution network with the maximum PV accommodation power as the fitness function. Then it takes the control loads (thermostatically controlled loads, TCLs) and the transferable loads based on the demand response (DR) to establish the multi-objective optimal scheduling model. The model considers the largest accommodation power of PV and the lowest operating cost of the distribution network. The particle swarm optimization algorithm is used to compare the PV accommodation before and after considering the DR. The simulation results show that the method improves the PV accommodation power, reduces the purchase of electricity from the grid and decreases the operating costs of the distribution network.

\textbf{Introduction}

Among a variety of renewable energy sources, PV is one of the major sources of distributed renewable energy\textsuperscript{[1]} that has no supply limitations and is predicted to become the biggest contributor to electricity generation by 2040 \textsuperscript{[2]}. This provides more power from renewable energy sources but cause adverse effects as well in the distribution grid like voltage limit violation at point of common coupling, frequency disturbances, grid stability issues etc\textsuperscript{[3]}. A review of recent papers indicates that the interest is mainly focused on the PV output characterisation, voltage quality issues caused by the intermittent nature of PV, impacts of voltage issues in LV distribution networks, and a topology study of different mitigation techniques to alleviate voltage problems\textsuperscript{[4-7]}. For the increasing penetration of PVs, the greatest problem is PV power curtailment. With the advanced construction of smart grid in china, the level of information interaction between demand side and grid is increasing\textsuperscript{[8]}. To improve the flexibility of power system by using DR is possible. The role of DR was studied in reducing power system operating costs in \textsuperscript{[9]}. The authors in paper \textsuperscript{[10]} take energy storage technology and DR into power generation scheduling optimisation and analyse its ability to enhance the accommodation of wind power. On the basis of different ways of participating in power system scheduling, paper \textsuperscript{[11]} use the DR project to improve the utilisation of wind power. Literature\textsuperscript{[12]} propose the reconfiguration of distribution network considering variation of load to reduce power losses and improve voltage profile in the standard 33 bus. The authors in paper \textsuperscript{[13]} consder the demand response and reconfiguration in distribution network to integrate and model the uncertainties of renewable production. A methods considering Demand response measures and its quantitative effects to increase the accommodation of renewable energy is proposed in \textsuperscript{[14]}, but it only consider the transferable loads.

Based on the above researches\textsuperscript{[8-14]}, this paper makes a study on the accommodation power of PV considering network reconfiguration and DR. The DR is not only consider the transferable loads but also the controllable loads(air conditioners). It firstly finds the optimal switch combination of the distribution network with the maximum PV consumption power as the fitness function. Secondly, it
establishes the multi-objective optimal scheduling model with the largest accommodation of PV and
the lowest operating cost of the distribution network based on the DR. The simulation results show
that the method proposed in this paper improves the PV accommodation power.

Network reconfiguration for promoting the accommodation power of PV

The objective function of distribution network reconfiguration

The objective function is the max accommodation power of PV:

$$\max R = \sum_{i=1}^{n} P_{PV_i}.$$  \hspace{1cm} (1)

Where, $P_{PV_i}$ is the PV power accessing in distribution network at node $i$, $n$ is the number of PV nodes.

The constraints of distribution network reconfiguration

The constraints consist of the node voltage, branch current and power balance constraint.

$$P_i = U\sum_{j=1}^{N} U_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij})$$

$$Q_i = U\sum_{j=1}^{N} U_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}).$$  \hspace{1cm} (2)

Where, $P_i$ and $Q_i$ are the active power and the reactive power at node $i$ respectively; $U_i$ and $U_j$ are the
voltage of node $i$ and node $j$ respectively; $G_{ij}$, $B_{ij}$, $\delta_{ij}$, $\theta_{ij}$ are the conductance, admittance and phase
difference of the branch formed by node $i$ and $j$; $V_i$ is voltage amplitude of node $i$; $V_{imax}$ and $V_{imin}$ are the upper and lower limits of the voltage amplitude respectively. $I_i$ is current amplitude of node $i$, $I_{imax}$
and $I_{imin}$ are the upper and lower limits of the current amplitude of the node $i$ respectively.

Demand response model

The model of controllable load

1) Approximate aggregated power of TCLs

We adopt a commonly-used second-order ETP model to describe the thermal behavior of an
individual AC in residential buildings. The discrete differential equation is expressed as:

$$d\theta(t)/dt = -1/CR \cdot [\theta(t) - \theta_a(t) + m(t)R_P]$$

$$m(t) = \begin{cases} 
0, & \text{off} \\
\theta(t) \leq \theta_a \\
1, & \text{on} \\
\theta(t) > \theta_a 
\end{cases}.$$  \hspace{1cm} (3)

Where, $\theta(t)$ and $\theta_a(t)$ are the indoor temperature and the ambient temperature at time $t$; $C$ is the air
thermal capacity; $P_a = \eta P$, where $P$ is the rated power of TCL and $\eta$ is the energy efficiency ratio; $m(t)$
is switch state of TCL. Where, $\theta$ and $\theta_a$ indicates the upper and lower limit of indoor temperature.

The turn-on time $\tau_{on}$ and turn-off time $\tau_{off}$ of a TCL can be derived from (3). By inequality
transformation, we can obtain the upper and lower limit of the aggregated power of N TCLs:

$$P_{d agg} = \sum_{i=1}^{N} \frac{\theta_a - \theta_{set,d} + \delta_i}{\eta R_i} / 2, \quad P_{u agg} = \sum_{i=1}^{N} \frac{\theta_a - \theta_{set,d} - \delta_i}{\eta R_i} / 2.$$  \hspace{1cm} (4)
The estimated value of aggregated TCLs can be expressed by any value in the interval \([P_{agg}^d, P_{agg}^u]\):

\[
\beta_{agg}^o = \alpha P_{agg}^d + (1-\alpha) P_{agg}^u .
\]  

(5)

Where, \(\alpha\) is the constant in interval \([0,1]\).

**Controllable capacity of TCLs**

The controllable capacity of TCLs can be assessed by controllability \(C\), acceptability \(A\) and curtailment \(S\).

The controllable capacity of TCLs is:

\[
L_{ct,i} = \beta_{agg}^{se} - \beta_{agg}^u .
\]  

(6)

Where, \(\beta_{agg}^{se}\) and \(\beta_{agg}^u\) are the baseline power and mean power of TCLs during the DR event in period \(h\) respectively.

The controlled loads in DR will receive certain fee compensation. The compensation fee is:

\[
C^C = \sum_{i=1}^{N} \rho |L_{ct,i}| .
\]  

(7)

Where, \(\rho\) is the compensation coefficient. When \(P_{P,i} \geq L_{ct,i}, L_{c,i} \geq 0\); when \(P_{P,i} < L_{ct,i}, L_{c,i} = 0\).

**The model of transferable load**

Active transferred load will get some compensation fees:

\[
C^T = \sum_{i=1}^{N} \rho L_{in,i} = \sum_{i=1}^{N} \rho L_{out,i} .
\]  

(8)

When \(P_{P,i} \geq L_{ct,i}, L_{in,i} \geq 0, L_{out,i} = 0\); when \(P_{P,i} < L_{ct,i}, L_{in,i} = 0, L_{out,i} \geq 0\). Where, \(P_{P,i}\) is PV power output at time \(t\), \(L_{ct}\) is the total power of load at time \(t\).

**Collaborative control strategy**

1) Objective function

\[
\min f = \left[ -\sum_{i=1}^{N} P_{L,i} + \varepsilon \sum_{i=1}^{N} (e P_{N,i} + \rho L_{in,i} + \rho L_{ct,i}) \right] .
\]  

(9)

Where, \(N\) is the total scheduling time; \(P_{L,i}\) is the PV output consumed by the loads at time \(t\); \(P_{N,i}\) is the amount of electricity that needs to be purchased from the grid at time \(t\). \(\varepsilon\) is a penalty coefficient.

When \(P_{P,i} \geq L_{ct,i}, P_{L,i} = L_{ct,i}\); when \(P_{P,i} < L_{ct,i}, P_{L,i} = P_{P,i}\):

\[
L_{ct} = L_{ct}^o - L_{out,i} + L_{in,i} + L_{c,i} .
\]  

(10)

When \(P_{P,i} \geq L_{ct,i}, P_{N,i} = 0\); when \(P_{P,i} < L_{ct,i}, P_{N,i} = L_{ct} - P_{P,i}\). \(L_{ct}^o\) is the original load power consumption.
2) Constraints

\[ P_{v,j} + P_{i,j} = L_{i}^{i} - L_{out,i} + L_{in,i} + L_{c,j} \]

\[ P_{v,j} \leq P_{v,j} \leq P_{v,j}^{\text{max}} \]

\[ 0 \leq L_{in,i} \leq L_{in}^{\text{max}} \]

\[ 0 \leq L_{out,i} \leq L_{out}^{\text{max}} \]

\[ \sum_{i=1}^{N} L_{in,i} = \sum_{i=1}^{N} L_{out,i} \]

\[ 0 \leq P_{v,j} \leq P_{v,j}^{\text{max}} \]  

(11)

Simulation analysis

IEEE 33-bus is taken as an example in this paper, and the model is shown in Fig.2. PV would be connected to node 24 with the installed capacity of 10MW. The initial combination of contact switches is \([33, 34, 35, 36, 37]\). Particle swarm size \(M = 50\), iteration time \(T_{\text{max}} = 300\), learning factor \(c_1 = 0.02\); \(c_2 = 2\); \(\omega = 0.5\). TCLs participated in DR are connected to node 8, 24, 25 and 30.

Fig. 2 IEEE 33-bus distribution system

It can be assumed that the load parameters of 500 ACs obey uniform distribution in the interval shown in Table 1 and the highest ambient temperature is 35\(^\circ\)C. The estimated value of the aggregated power of 500 ACs is \([870.05, 961.80]\) kW. As the adjustment amount of the set temperature changes, the aggregated power and the controllable capacity percentage are shown in Table 2. The relevant parameters of demand response are shown in Table 3.

### Table 1. The parameters range of ACs

<table>
<thead>
<tr>
<th>parameter</th>
<th>range</th>
<th>parameter</th>
<th>range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R )</td>
<td>([1.5, 2.5])</td>
<td>( \theta_{\text{set}} )</td>
<td>([24, 26])</td>
</tr>
<tr>
<td>( C )</td>
<td>([1.5, 2.5])</td>
<td>( \delta )</td>
<td>([1])</td>
</tr>
<tr>
<td>( P_{c} )</td>
<td>([16, 20])</td>
<td>( \eta )</td>
<td>([2.6, 3])</td>
</tr>
</tbody>
</table>

### Table 2. The aggregated power under different adjustment amount of temperature set value

<table>
<thead>
<tr>
<th>( \Delta t )</th>
<th>-0.5</th>
<th>-1</th>
<th>-1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{agg,h}^{\text{PV}} ) (kW)</td>
<td>962.38</td>
<td>1011.03</td>
<td>1056.84</td>
</tr>
<tr>
<td>( s_h )</td>
<td>-5.07%</td>
<td>-10.38%</td>
<td>-15.38%</td>
</tr>
<tr>
<td>( \Delta t )</td>
<td>-2</td>
<td>-2.5</td>
<td>-3</td>
</tr>
<tr>
<td>( P_{agg,h}^{\text{PV}} ) (kW)</td>
<td>1094.23</td>
<td>1143.95</td>
<td>1194.76</td>
</tr>
<tr>
<td>( s_h )</td>
<td>-19.47%</td>
<td>-24.89%</td>
<td>-30.44%</td>
</tr>
</tbody>
</table>

### Table 3. The parameters of demand response

<table>
<thead>
<tr>
<th>Transferable loads</th>
<th>( L_{\text{in}}^{\text{max}} )/MW</th>
<th>( L_{\text{out}}^{\text{max}} )/MW</th>
<th>( \rho )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controllable loads</td>
<td>( \Delta t )</td>
<td>-0.5</td>
<td>-1</td>
</tr>
<tr>
<td>power/kW</td>
<td>46.45</td>
<td>95.1</td>
<td>140.91</td>
</tr>
</tbody>
</table>
The dynamic reconfiguration method of distribution network to improve the accommodation power of PV is shown in Table 4. PVs with the power of 0MW and 2.6MW are connected to the switch combination of [7,14,9,32,37] (combination one) and [20,12,35,28,22] (combination two) respectively. The voltage of each node of different switch combination is shown in Fig. 3.

<table>
<thead>
<tr>
<th>PV output power /MW</th>
<th>Disconnected switch combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>P=0</td>
<td>7,14,9,32,37</td>
</tr>
<tr>
<td>P≤1.8</td>
<td>33,34,35,36,37</td>
</tr>
<tr>
<td>1.8&lt;P≤2.6</td>
<td>20,12,35,28,22</td>
</tr>
</tbody>
</table>

In order to study the impact of DR on PV accommodation power, two scenarios with DR and without DR were established. Table 5 shows the optimal dispatching results in different scenarios. Table 6 shows the condition of load transfer and load control in a period of dispatching.

<table>
<thead>
<tr>
<th>Scenario No.</th>
<th>Max power/MW</th>
<th>Min power/MW</th>
<th>Power purchase/MW</th>
<th>Purchasing fee/yuan</th>
<th>PV accommodation/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.1</td>
<td>-5.22</td>
<td>49.08</td>
<td>29448</td>
<td>60.1%</td>
</tr>
<tr>
<td>2</td>
<td>4.975</td>
<td>-4.676</td>
<td>44.855</td>
<td>26913</td>
<td>66.3%</td>
</tr>
</tbody>
</table>

The load curve and PV output without and with the demand response being added are shown in Fig. 5. It can be seen from the figure that after the demand response being introduced, PV accommodation power is increased.

**Conclusions**

In this paper, for the purpose of increasing PV accommodation power, it combines the distribution network reconstruction to find the optimal switch combination and the demand response, and then analyses the PV accommodation power with and without the demand response being added. The following conclusions are drawn:

1) In the environment of large-scale PV accessing distribution network, the proposed reconfiguration of distribution network is feasible to improve the PV accommodation power;
2) The addition of demand response further increases the PV accommodation rate of the distribution network, reduces the purchase of electricity from the large grid, and decreases the cost of distribution network operation.

Acknowledgements

This work was financially supported by the Shanghai talent development fund(2018004), State Grid Corporation of China (1806-00513)

References


