VOLTAGE AND REACTIVE POWER OPTIMAL CONTROL IN DISTRIBUTION NETWORKS WITH DISTRIBUTED GENERATION

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ABSTRACT

Distributed generation (DG) is gaining wide attention for the possible influences on the power system. Considering the effects of DG, the voltage and reactive power optimal control in distribution networks is modelled as a multi-objective combinational optimization. The objectives, voltage profiles, power losses and voltage variation, are evaluated by membership functions respectively, so that the satisfactions of different objectives can be compared. To facilitate the solving process, a compromised objective is formed by the weighted sum approach. The weightings of the objectives are calculated by fuzzy judgement matrix. The reactive tabu search algorithm is employed to get the solutions. Simulation results demonstrated that the proposed method is effective in improving the voltage profiles and all the other objectives as well.

INTRODUCTION

Voltage and reactive power (volt/var) optimal control aims to improve the voltage profiles and reduce active power losses by adjusting reactive power distribution. Generally, regulating means in distribution systems are transformer tap-changers, voltage regulators and shunt capacitors, which are both discrete variables. Conventionally volt/var problem is formed as a constrained combinatorial optimization problem to minimize the active power losses without voltage violation.

With the environmental consciousness and development of high-efficiency small generators, increasing number of distributed generators (DG) are embedded in distribution networks. The possible influences of DG on distribution networks are wide attention. The DG connection impacts many aspects of distribution network operating and planning. The detailed models of synchronous and induction machines for DG and their impacts on distribution networks are presented in [1]. Steady-state voltage profiles may be impaired for the DGs output and their influences on voltage regulation apparatus. The voltage rise problem caused by reverse power flow is introduced in [2], and the optional techniques that can alleviate the problem are compared in detail. The voltage variation caused by uncertain DG output should also be considered in volt/var optimal control. The worst situation happens on DG disconnection.

Voltage Profiles Assessment

The membership function is introduced to evaluate voltage profiles.

\[
F_v(V_i) = \begin{cases} 
\frac{L_{0,\text{upper}} - V_i}{L_{0,\text{upper}}} & \left( L_{0,\text{upper}} < V_i < L_{0,\text{upper}} \right) \\
\frac{V_i - L_{0,\text{lower}}}{L_{1,\text{lower}} - L_{0,\text{lower}}} & \left( L_{1,\text{lower}} < V_i < L_{1,\text{lower}} \right) \\
1 & \left( L_{1,\text{lower}} < V_i < L_{0,\text{upper}} \right) \\
0 & \text{(others)}
\end{cases}
\]

where \( V_i \) is the voltage of node \( i \); \( L_{0,\text{upper}} \) and \( L_{0,\text{lower}} \) are unacceptable voltage limits; \( L_{1,\text{upper}} \) and \( L_{1,\text{lower}} \) are power losses and voltage profiles, voltage variation and short circuit current are taken into consideration to evaluate the impact of DG [6].

A multi-objective optimization formulation is constructed for volt/var optimization in distribution network with DG embedded. The objectives include improving the voltage profiles, minimizing voltage variation due to DG disconnection and decreasing the active power losses. Regulating means are transformer tap-changers and shunt capacitors.

MODELING

Characteristics of volt/var optimal control with DG

The active power injection from DG affects the voltage significantly for the \( R/X \) ratio of branches tends to be high. But considering the uncertainty of DG and variation of its output, DG can not serve as a voltage regulating means.

The objective of voltage regulation is to maintain the customer’s voltage in permissible limits. In peak load conditions, the voltage drop is high. The network maintains voltage profiles without relaying on the output of DG. In valley load conditions, the reverse power flow may cause over-voltage. Several regulating means, including switching tap-changer and adjusting DG output, can be utilized to alleviate the over-voltage problem [2].

The voltage variation caused by uncertain DG output should also be considered in volt/var optimal control. The worst situation happens on DG disconnection.
acceptable voltage margins.

The membership function of the network voltage profiles is:

$$F_{vol} = \frac{1}{N} \sum_{i=1}^{N} F_v(V_i)$$  \hspace{1cm} (2)

where $N$ is the number of nodes; $V_i$ is the voltage of node $i$.

**Active Power Losses Assessment**

The active power losses are also scaled by a membership function to compare between the objectives. Different from evaluating voltage profiles, there is not a standard or reference value for active power losses reduction.

In this paper, the membership function for active power losses is determined by two parameters. $P_{l,ori}$ represents the active power losses before optimization, and the membership value for $P_{l,ori}$ is set 0.5. $P_{l,min}$ is the active power losses only caused by active power current, and its membership value is 1.[7]

The membership function of the active power losses is shown as Fig. 1.

$$F_{loss}(P_l)$$

Fig. 1. Membership function for active power losses assessment

The two parameters, $P_{l,ori}$ and $P_{l,min}$, are determined by the system structure and original operating conditions. Therefore, the assessment results of trial solutions under different operating conditions are comparable.

**Voltage variation assessment**

Voltage variation may be caused by the DG output changing. The DG influence on voltage variation is represented by the largest voltage difference in the worst situation, DG disconnection.

The satisfaction of voltage variation is defined as:

$$\Delta V = \text{Max}\left(\Delta V_i\right)$$

$$F_{AV} = \begin{cases} 
1 & \Delta V \leq L_i^{AV} \\
\frac{\Delta V - L_0^{AV}}{L_i^{AV} - L_0^{AV}} & L_i^{AV} < \Delta V < L_0^{AV} \\
0 & \Delta V \geq L_0^{AV} 
\end{cases}$$  \hspace{1cm} (3)

where $\Delta V_i$ is the voltage variation of node $i$ before and after DG disconnection; $L_i^{AV}$ is the acceptable variation margin; $L_0^{AV}$ is the unacceptable variation limits.

**Multi-objective optimization model**

Based on the fuzzy evaluation functions, the multi-objective volt/var optimization model is constructed to maximize the satisfactions of different objectives by adjusting transformer tap-changers and shunt capacitors. The objectives include voltage profiles, active power losses and voltage variation caused by DG disconnection. The multiobjective optimization model is represented as:

$$\min \max F_{vol} \hspace{1cm} \max F_{loss} \hspace{1cm} \max F_{AV}$$

$$\text{s.t. } T_k^{min} \leq T_k \leq T_k^{max}$$

$$0 \leq Q_j \leq Q_j^{max}$$

in which $F_{vol}$ is the membership function for voltage profiles; $F_{loss}$ is the membership function for active power losses; $F_{AV}$ is the membership function for voltage variation caused by DG disconnection; $T_k$ is the ratio of transformer $k$; $Q_j$ is the capacity of capacitors at node $j$. The restriction of power flow is not listed here.

**SOLUTION METHOD**

**Fuzzy judgement matrix method**

The weighted sum approach is utilized to facilitate the solving process. Generally, the weightings are decided according to the experiences. With the increase of objectives number, it is hard to decide the weightings.

The fuzzy judgement matrix is introduced to calculate the weightings.

The judgement matrix can be formed as:
\[
M = \begin{pmatrix}
1 & a_{i2} & \cdots & a_{in} \\
a_{j1} & 1 & \cdots & a_{jn} \\
\vdots & \vdots & \ddots & \vdots \\
a_{nj1} & a_{nj2} & \cdots & 1
\end{pmatrix}
\] (5)

\[
\alpha_{ij} = \frac{1}{\alpha_{ji}} (i, j = 1, \ldots, n)
\]
in which \( \alpha_{ij} \) represents the importance comparison between objective \( i \) and objective \( j \) with an integer from 1 to 9\(^8\).

The weighting for objective \( i \), \( w_i \), is calculated as:

\[
w_i = \frac{\pi_i}{\sum_{j=1}^{n} \pi_j}
\] (6)
in which

\[
\pi_j = \left( \prod_{j=1}^{n} \alpha_{ij} \right)^{1/n}
\] (7)

With the weighting calculated, the single-objective optimization problem can be formed.

**Reactive Tabu Search algorithm**

Reactive Tabu Search algorithm (RTS) is utilized to solve the constrained combinational optimization problem\(^9\). In conventional tabu search, the two searching strategies, diversification and intensification, are balanced by the length of tabu list, which is determined by experiences. The feedback mechanism is introduced in RTS to adjust the length of tabu list. Therefore, the two opposing strategies can be balanced according to characteristics of the problem and the optimization process. Therefore, compared with traditional TS, the RTS is more robust and effective.

**TEST RESULTS**

The proposed method is tested in a 33-bus distribution system (Fig.2). The parameters of on-load tap-changer, DG and shunt capacitors are shown in Table 1. In peak loads condition the source node voltage is 1.0 p.u.. In valley loads condition, the loads are one sixth of the peak loads, and the source node voltage is 1.03p.u..

**Table.1 Parameters of equipments**

<table>
<thead>
<tr>
<th>New-Added Apparatus</th>
<th>Position</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLTC</td>
<td>0#</td>
<td>1.0±0.0125×8</td>
</tr>
<tr>
<td>DG</td>
<td>55#</td>
<td>1000 kW 0 kVar</td>
</tr>
<tr>
<td></td>
<td>6#</td>
<td>800 kW 0 kVar</td>
</tr>
<tr>
<td></td>
<td>55#</td>
<td>150×4 kVar</td>
</tr>
<tr>
<td>Shunt capacitors</td>
<td>59#</td>
<td>150×2 kVar</td>
</tr>
<tr>
<td></td>
<td>4#</td>
<td>300×3+150×1 kVar</td>
</tr>
</tbody>
</table>

The fuzzy judgement matrix and weightings of objectives are shown in Table 2. The volt/var optimal control schemes for the peak and valley loads conditions are represented in Table 3, and the result comparisons in Table 4 and 5.

**Table.2 Fuzzy judgement matrix and weightings of objectives**

<table>
<thead>
<tr>
<th>Fv</th>
<th>FLoss</th>
<th>F(_\Delta v)</th>
<th>Wi</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3</td>
<td>1</td>
<td>1/3</td>
<td>0.6694</td>
</tr>
<tr>
<td>1/3</td>
<td>1/3</td>
<td>1</td>
<td>0.2426</td>
</tr>
<tr>
<td>1/7</td>
<td>1/3</td>
<td>1</td>
<td>0.0879</td>
</tr>
</tbody>
</table>

**Table.3 Optimal control schemes**

<table>
<thead>
<tr>
<th>Position</th>
<th>Peak Load</th>
<th>Valley Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLTC</td>
<td>0#</td>
<td>0.975</td>
</tr>
<tr>
<td></td>
<td>55#</td>
<td>600 kVar</td>
</tr>
<tr>
<td>Shunt Capacitors</td>
<td>59#</td>
<td>300 kVar</td>
</tr>
<tr>
<td></td>
<td>4#</td>
<td>1050 kVar</td>
</tr>
</tbody>
</table>

**Table.4 Optimization results in peak load condition**

<table>
<thead>
<tr>
<th>Before Optimization</th>
<th>After Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG Output ratio (%)</td>
<td>100 0 100 0</td>
</tr>
<tr>
<td>Max volt (p.u.)</td>
<td>1.00 1.00 1.026 1.026</td>
</tr>
<tr>
<td>Min volt (p.u.)</td>
<td>0.949 0.930 0.982 0.963</td>
</tr>
<tr>
<td>P(_l) (kW)</td>
<td>188.377 324.231 116.322 241.172</td>
</tr>
<tr>
<td>Max ΔV(p.u.)</td>
<td>0.01963 0.01891</td>
</tr>
</tbody>
</table>

**Table.5 Optimization results in valley load condition**

<table>
<thead>
<tr>
<th>Before Optimization</th>
<th>After Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG Output ratio (%)</td>
<td>100 0 100 0</td>
</tr>
<tr>
<td>Max volt (p.u.)</td>
<td>1.038 1.030 1.03 1.03</td>
</tr>
<tr>
<td>Min volt (p.u.)</td>
<td>1.030 1.019 1.005 0.996</td>
</tr>
<tr>
<td>P(_l) (kW)</td>
<td>10.912 7.720 9.741 6.377</td>
</tr>
<tr>
<td>Max ΔV(p.u.)</td>
<td>0.01728 0.01768</td>
</tr>
</tbody>
</table>

In peak load condition, the network relies on DG to maintain the voltage profiles before optimization. Some nodes endure under-voltage (0.93p.u.) when DG

![Diagram of the test distribution network](Fig.2)
disconnects. After optimization, conventional regulating means are adjusted to improve the voltage profiles. The voltages of all the nodes are eligible with or without DG output. The active power losses and voltage variation are also reduced.

In valley load condition, reverse power flow raises the voltage and power losses. After optimization, the over-voltage is alleviated, and the voltage profiles are improved. The power losses comparison shows that, the volt/var optimal control scheme decrease the power losses by reducing reactive power transferred. Although the maximum voltage variation increases very slightly, the integral satisfaction improved evidently.

CONCLUSION

The volt/var optimal control is modeled as a multiobjective optimization problem and solved by weighted-sum approach. The weightings are calculated by fuzzy judgement approach according to the importance comparison of every two objectives. Reactive tabu search is employed to find the solutions.

Simulation result shows the efficiency of the proposed method. The negative influences of DG in different operating conditions are lightened by adjusting the conventional volt/var regulation means.

REFERENCES


