Research on Economical Power Supply Radius and Transformer Capacity for Substations in Distribution Network

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Abstract. In order to improve the capacity factor of transformer and reduce the investment of substation, optimization is applied to reasonable transformer combination matched with economical power supply radius. In this paper, based on the principle of minimizing overall annual expenditure charged upon unit area in the power supply district, the optimization model was built. The satisfactory result in optimum option radius was obtained. Through the backward substitution method, suitable transformer combination was worked out. The method and calculation proposed in this paper provide effective references to the power grid planning.

Introduction

Distribution network is growing more and more complicated. The rationality of its structure determines its stability and future development. The method of calculating power supply radius only based on the limits of power quality is unable to meet the requirements of the distribution network’s economy. At present, most of the studies about power supply radius optimization are based on the minimum annual cost of unit area and the constraint of the technical indicators [1].

Reference [2], from a planning perspective, built an optimization model of minimum total cost per unit area, took the substation outlets into account, the investments and the operating costs, selected the best substation capacity, the optimal number of transformer and the best power supply radius. But before optimization, the economical capacity of transformer substation was unknown, the number and model of the main transformer were uncertain. Reference [3] used linear fitting between the investment costs of the main transformer and its capacity, and took its energy loss as a fixed mean value. This approach leads to errors in the calculation of the best power supply radius. In addition, many studies have not deeply discussed whether the results of the substation economical capacity model is feasible or not.

This paper builds the optimization model of the substation’s economical power supply radius based upon minimum overall cost per unit area in the power supply district with different load densities. The economical capacity of the 110/10kV transformer is estimated by fitting the unknown quantity based on the common parameters. Different configurations for the transformers are compared according to the estimated economical capacity. On this basis, economical power supply radius and the best capacity of main transformer under different load densities are obtained.

The Optimization Model of the Substation Economical Power Supply Radius

Assumptions

This section will adopt optimization algorithm to establish the economical capacity and the power supply radius model. During the process of modeling, basic assumptions are the following.
(1) Power supply area is approximated that the load density is uniform in the target grid area, power supply area is circular, and the substation is in the center.
(2) The dynamic investment is unconsidered, construction cost is counted as annual equal investment, and the operation cost in a certain year is taken as one-time injection.
(3) The lengths of the substation outlet feeders which is associated with the substation wiring are equal.

The Objective Function

The objective function based on minimum cost per unit area:

\[ \text{min} F = \frac{(Z_1+Z_2)/Y+(C_1+C_2+C_3)/\pi R^2}{\rho}. \]  

(1)

The cost includes: the investment of substation \( Z_1 \), the investment of outlet feeders \( Z_2 \), the operation cost of substation and feeders \( C_1 \), energy loss of outlet feeders \( C_2 \) and energy loss of transformers \( C_3 \).

(1) The investment of substation

The investment of substation can be represented as [4]:

\[ Z_1 = a_1 + b_1 S. \]  

(2)

\( a_1 \) is the fixed part of the investment of substation which has nothing to do with the choice of electrical equipment (\( RMB \)). \( b_1 \) is the correlation cost between the capacity and cost (\( RMB/MVA \)).

(2) The investment of outlet feeders

According to the power line economical transmission capacity, confirming the average load \( P \) of 10kV transmission line, the length is \( L=DR \), the investment of outlet feeders can be represented as:

\[ Z_2 = M(a_2 + b_2 L). \]  

(3)

\( M = \pi R^2 \sigma / P \), \( \sigma (MV/km^2) \) is average load density, \( a_2 \) is the fixed part of the outlet feeders (\( RMB/km \)), \( b_2 \) is the correlation cost between the length and cost (\( RMB/km \)).

(3) The fixed part of the operation cost of substation and feeders

The fixed part of the operation cost of substation and feeders mainly includes the repair and maintenance cost, which is generally proportional to the total investment. It can be represented as:

\[ C_1 = H_1 Z_1 + H_2 Z_2. \]  

(4)

\( H_1 \) and \( H_2 \) are the modulus related to the annual operation cost and the total investment.

(4) The annual energy loss of outlet feeders \( C_2 \)

Assuming the load is evenly distributed along the feeder line, at this point, the entire line current is not equal anywhere. Therefore, by using the integral method, we can obtain the total loss of power for each line, the formula is:

\[ C_2 = C_0 M \Delta P = C_0 M \pi \int_0^R 3\rho^2 \Delta \rho dr = 3C_0 M \pi \int_0^R \rho \left( \frac{R^2 - r^2}{\sqrt{3U \cos \phi}} \right)^2 dr / 10^3. \]  

(5)

In the formula, \( U_N \) is rated volt, \( \rho \) is wire resistance per unit length(\( \Omega/km \)), \( \tau \) is maximum load loss hours (\( h \)), \( C_0 \) is the price of electricity (\( RMB \)), \( \cos \phi \) is power factor.

(5) The annual energy loss of transformers \( C_3 \)

\[ C_3 = C_0 [\Delta P_{\text{no}} + \Delta P_{\text{lo}}(1/K_c \cos \phi)^2]. \]  

(6)

\( \Delta P_{\text{no}} \) is the transformer no-load loss (\( kW \)), \( \Delta P_{\text{lo}} \) is the transformer load loss (\( kW \)), \( t \) is the transformer annual operating hours.

(6) The cost per unit area of the supply area \( F \)

Assuming the effective investment years is \( Y \), the annual depreciation expense for investment is \((Z_1+Z_2)/Y\). The total sum of investment and operation cost of each substation and distribution area is:

\[ F = \frac{(Z_1+Z_2)/Y+(C_1+C_2+C_3)}{\rho}. \]  

(7)
The cost per unit area of the supply area is:

\[ F = \frac{(Z_1+Z_2)\sqrt{Y+(C_1+C_2+C_3)})}{\pi R^2}. \]  

(8)

When the cost is minimal, the value of the supply radius is equal to the optimal economical radius. Then check the optimal economical radius through calculating the voltage drop of transmission line.

**Station Transformers Capacity Estimation and Configuration**

According to the model in section I, the optimal power supply radius and substation economical capacity can be obtained in a certain load density. However, these are ideally calculated values, transformer capacity errors exist, furthermore, the rated capacity of the transformer has a fixed standard, which can’t be a haphazard selection. In many cases, transformer configuration cannot be matched with the substation optimal power supply radius.

For this reason, the following will introduce how to match the optimal power supply radius with the transformer configuration.

According to the Eq. 8, transformer economical capacity can be estimated while the power supply radius is optimal. According to this economical capacity, the appropriate transformers can be configured out. The transformer parameters then be taken back to the optimization model for verification. Specific steps are as follows:

1. According to the model in section I, calculate the optimal power supply radius and substation economical capacity in a certain load density.
2. Select four transformers, the rated capacity of which are 31.5 MVA, 40 MVA, 50 MVA, 63 MVA. The number of main transformers in one substation is 2 or 3. Make freely combination by using these transformers, select the combination which total capacity is more than or close to the economical capacity. The configuration scheme may be one or more.
   a) When there is only one feasible configuration scheme, take the parameters of the transformers used in the configuration into the optimal model in B of section I, calculate the optimal power supply radius in this case, and verify the radius with various constraints. Then the configuration of the transformers which matches the optimal radius under a certain load density is completed.
   b) When there are many feasible configurations schemes, select 2 or more combinations that the total capacity is more than or close to the economical capacity, take each transformer configuration into the optimal model in section I compare the annual investment per unit area of each transformer configuration scheme.

**The Example Analysis**

**Parameter**

1. Parameters of 110/10kV transformers
   This section mainly analyzes the common 110/10kV transformers with the rated capacities are 31.5 MVA, 40 MVA, 50 MVA, 63 MVA. As is mentioned in references [5-8], transformers with different capacities are greatly different in economical and technical parameters, which mainly reflect the substation economical capacity model, including investment of substations, loss of unit capacity, investment of outlets. Fit these types of transformer parameters [9].

   The relationship between the no-load loss fitted by linear regression and its capacity:

   \[ \Delta P_0 = a_0 + b_0 S. \]  

   (9)

   \[ a_0 = 8.1021, \quad b_0 = 0.0005. \]

   The relationship between the load loss fitted by linear regression and its capacity:

   \[ \Delta P_K = a_K + b_K S. \]  

   (10)

   \[ a_K = 33.27, \quad b_K = 0.0026. \]

2. Economical load of the substation 10kV transmission lines
Types of transmission lines used in 10kV distribution network are generally determined by unified planning of distribution network. The economical current density is used to determine the average load of feeder lines.

The calculation formula of transmission economical capacity for transmission lines is:

\[ P = \sqrt{3} U \cos \phi I_J \]  \hspace{1cm} (11)

The calculation formula of economical load current for transmission lines is:

\[ I_J = A_L J_I \]  \hspace{1cm} (12)

In the formula: \( I_J \) is economical load current (A), \( A_L \) is cross-sectional area of power line (mm\(^2\)), \( J_I \) is economical current density of power line (A/mm\(^2\)).

The common type of cable used in 10kV distribution network is YJV\(_{22}3\times240\), the data value of \( J_I \) is 1.05 (A/mm\(^2\)), then calculate \( P = 3.928 MW \).

### Table 1. Parameters of 110/10 kV transformers.

<table>
<thead>
<tr>
<th>type</th>
<th>rated capacity (kVA)</th>
<th>loss(kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>no-load</td>
</tr>
<tr>
<td>SF11-31500/110</td>
<td>31500</td>
<td>24.6</td>
</tr>
<tr>
<td>SF11-40000/110</td>
<td>40000</td>
<td>29.4</td>
</tr>
<tr>
<td>SF11-50000/110</td>
<td>50000</td>
<td>35.2</td>
</tr>
<tr>
<td>SF11-63000/110</td>
<td>63000</td>
<td>41.6</td>
</tr>
</tbody>
</table>

(3) Other parameter settings

Taking 10kV double-wound transformer as the research object, according to the literature[5,7] and general situation of distribution network, set the configuration as follows: \( \cos \phi = 0.9 \), \( D = 1.3 \), \( Y = 10 \), \( H_1 = H_2 = 8\% \), \( C_0 = 0.6 \text{ RMB/kWh} \), \( \tau = 4000 \), \( \tau_N = 4000 \), \( K_R = 2 \), \( U = 10kV \), \( b_2 = 86.3 \text{ RMB/km} \), \( \rho = 0.08 \Omega/km \).

### The Optimal Substation Economical Capacity under Different Load Density

According to the Eq.8, put the data in A of section III into it, set different values to the area load density, then the substation economical capacity under various load density can be calculated.

According to the above estimated economical capacity of the transformer, the appropriate configuration is selected, the cost per unit area of different transformer configuration is calculated and compared, as is shown in Table 3.

It can be observed through Table 3, in the power supply area which has different load densities and power supply radius, that as the optimal power supply area is smaller, the load density becomes larger and the annual cost per unit area becomes greater. Under the condition of same load density, to meet the premise capacity-load ratio the annual cost per unit area of different transformer configurations is different. The results can provide a reference to the distribution network planning.

### Table 2. Estimated economical capacity under different load density.

<table>
<thead>
<tr>
<th>load density (MW/km(^2))</th>
<th>economical capacity (MW)</th>
<th>power supply radius (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>52.4969</td>
<td>2.57</td>
</tr>
<tr>
<td>3</td>
<td>66.1420</td>
<td>2.04</td>
</tr>
<tr>
<td>5</td>
<td>78.4200</td>
<td>1.72</td>
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<tr>
<td>7</td>
<td>87.7275</td>
<td>1.54</td>
</tr>
<tr>
<td>9</td>
<td>95.3932</td>
<td>1.41</td>
</tr>
<tr>
<td>11</td>
<td>101.9923</td>
<td>1.32</td>
</tr>
<tr>
<td>13</td>
<td>107.8329</td>
<td>1.25</td>
</tr>
<tr>
<td>15</td>
<td>113.1012</td>
<td>1.19</td>
</tr>
</tbody>
</table>
Table 3. Comparison of power supply radius and transformer configuration under different load density.

<table>
<thead>
<tr>
<th>Load density (MW/km²)</th>
<th>Economical capacity (estimation) (MVA)</th>
<th>Transformer configuration</th>
<th>Economical capacity (MVA)</th>
<th>Power supply radius (km)</th>
<th>Cost per unit area (RMB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>52.4969</td>
<td>2*31.5 MVA</td>
<td>60.2130</td>
<td>2.7595</td>
<td>81.4935</td>
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<tr>
<td></td>
<td></td>
<td>1*63 MVA</td>
<td>67.3702</td>
<td>2.9189</td>
<td>86.2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2*40 MVA</td>
<td>63.4230</td>
<td>2.8321</td>
<td>83.6371</td>
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<tr>
<td>3</td>
<td>66.1420</td>
<td>3*31.5 MVA</td>
<td>75.8636</td>
<td>2.1833</td>
<td>135.0996</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2*40 MVA</td>
<td>79.9080</td>
<td>2.2407</td>
<td>138.6503</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3*31.5 MVA</td>
<td>89.9463</td>
<td>1.8411</td>
<td>197.6409</td>
</tr>
<tr>
<td>5</td>
<td>78.4200</td>
<td>2*50 MVA</td>
<td>96.5785</td>
<td>1.9077</td>
<td>204.7951</td>
</tr>
<tr>
<td>7</td>
<td>87.7275</td>
<td>3*40 MVA</td>
<td>105.9862</td>
<td>1.6903</td>
<td>261.6047</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2*63 MVA</td>
<td>109.0786</td>
<td>1.7421</td>
<td>269.6228</td>
</tr>
<tr>
<td>9</td>
<td>95.3932</td>
<td>3*50 MVA</td>
<td>117.4819</td>
<td>1.5718</td>
<td>320.2405</td>
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<tr>
<td></td>
<td></td>
<td>3*63 MVA</td>
<td>122.4198</td>
<td>1.6046</td>
<td>326.9064</td>
</tr>
<tr>
<td>11</td>
<td>101.9923</td>
<td>3*50 MVA</td>
<td>125.6091</td>
<td>1.4653</td>
<td>372.1917</td>
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<tr>
<td></td>
<td></td>
<td>3*63 MVA</td>
<td>130.8886</td>
<td>1.4958</td>
<td>379.9360</td>
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<tr>
<td>13</td>
<td>107.8329</td>
<td>3*50 MVA</td>
<td>132.8021</td>
<td>1.3815</td>
<td>421.9222</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3*63 MVA</td>
<td>138.3838</td>
<td>1.4102</td>
<td>430.6749</td>
</tr>
<tr>
<td>15</td>
<td>113.1012</td>
<td>3*63 MVA</td>
<td>145.1447</td>
<td>1.3548</td>
<td>484.7850</td>
</tr>
</tbody>
</table>

Summary

Based on the construction and operation parameters of transformer substations and transmission lines, from the perspective of the economics, the substation power supply radius optimization model is established in this paper, which depends on the optimization theory to ensure the accuracy of the model. The substation economical capacity and optimal power supply radius in different load density are discussed. The method provides an effective reference to the planning of distribution network.

Applying the established optimization model and taking the 110 kV substation into account, the statistics of construction and operation parameters of transformer with 4 kinds rated capacities are analyzed, quantitative suggestions for the configuration of transformer under different load density are provided as well. Analysis and calculation results show that in the supply area with different load density and power supply radius, the annual cost per unit area becomes greater as the load density of optimal power supply area being larger. With the condition of same load density, to meet the premise capacity-load ratio, the annual cost per unit area of different transformer configurations is different. Accordingly, in order to realize the economical optimal planning of distribution network, it is necessary to choose suitable transformers capacity matched with optimal power supply radius.

References


