A Method for Calculating Power Supply Capacity of a High Voltage Distribution Network based on Power Supply Area Division

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Abstract: Starting from the application purpose of distribution network planning and the idea of solving a large-scale and complex problem through using a simple method, a practical method is proposed for calculating the power supply capacity of a high voltage distribution network based on power supply area division. Based on relatively independent power supply subareas, the power supply capacity of a high voltage distribution network is obtained by the direct accumulation of its subareas' power supply capacities. As part of that work, an approximate estimation formula is deduced, which can convert the allowable line voltage loss into a corresponding capacity constraint, so that the influence of voltage quality on power supply capacity can be concisely considered. Also, the approximate formulas are deduced for estimating the power supply capacities of typical high-voltage wiring modes, which are convenient for manual calculation or intervention. The example shows that the presented model and method are intuitive, simple, stable and effective, and are convenient for popularization and application in practice.

1 INTRODUCTION

The total supply capability (TSC) of a distribution network generally refers to the total load supply capacity of that network to meet the "N−1" safety criterion in a certain power supply area.

At present, the methods of calculating the power supply capacity of a distribution network are mainly divided into two categories. One is to model TSC as a non-linear programming problem (Xiao Jun, et.al, 2014; Fan T, et.al, 2013), in which the power flow-based power supply capacity model is generally adopted in order to improve the calculation accuracy with the upper and lower bounds of node voltages being involved. However, that method is complex and computational cost is large, and is mainly used for the power supply capacity calculation under actual operating condition. The other is to model TSC as a linear programming problem (Liu Hong, et.al, 2012; Zhai Guodong, et.al, 2018), which simplifies the calculation model without voltage constraints being considered, and is suitable for the power supply capacity calculation of future planning network with uncertainties in grid structures and loads. However, that method results in a big calculation error for the long lines with heavy loads (especially in the case of load transfer at "N-1") (Xiao Jun, et.al, 2014).

Aiming at engineering application, a simple thinking line is adopted in this paper to solve the calculation of power supply capacity of a large-scale complex distribution network. The power supply capacity of a high voltage distribution network is calculated by accumulating the power supply capacities of its subareas (or wiring modes). An approximate estimation formula is deduced for transforming the allowable voltage loss of a typical wiring mode into a corresponding line capacity, so that the voltage constraints can be approximately taken into account with the computational cost being increased slightly. Also, an approximate formula is derived to estimate the power supply capacity of a typical high voltage wiring mode, which is convenient for manual calculation or intervention.

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2 OVERALL THINKING LINE

Considering the relative independence of sub-areas, a simplified calculation method is presented to calculate the overall power supply capacity of a high voltage distribution network.

2.1 Area Division Based Power Supply Capacity Calculation

The power supply area division is to convert the calculation of overall power supply capacity of a high voltage distribution network from large to small and from complex to simple. The principle of power supply area division is that the power supply subareas are relatively independent in electricity (or power supply capacity), such as the typical high-voltage wiring modes of radiation wiring, loop wiring, T and π chain wiring, etc.

The calculation steps of power supply capacity are as follows. Firstly, the power supply area division of a high voltage distribution network is performed to obtain relatively independent subareas based on different wiring modes. Secondly, the approximate estimation is made for the power supply capacities of small-scale power supply subareas. Finally, the total power supply capacity is obtained by directly accumulating the power supply capacities of those power supply subareas.

2.2 Current and Voltage Constraints Based Allowable Line Capacity

Because there are a lot of uncertainties for network planning, the maximum allowable voltage losses of lines are used to approximately represent voltage constraints instead of the upper and lower limits of node voltages, and the maximum allowable line voltage losses are converted the corresponding allowable line capacities. The smaller value of the current and voltage-based capacities for a line is taken as the final capacity constraint of the line.

The current-based capacity for a line can be expressed as

$$S_{\mathrm{N},l} = \sqrt{3}U_{\mathrm{N}} I_{\max,l} \tag{1}$$

Where $S_{\mathrm{N},l}$ is the current-based allowable capacity of line l, U_{N} and $I_{\max,l}$ are respectively the rated line voltage and current of line l.

In this paper, the voltage-based capacity of a line means the line's maximum apparent power which does not result in the violation of maximum allowable line voltage loss. With the current and voltage constraints being satisfied, the final line capacity can be expressed as

$$S_{\mathrm{C},l} = \min\left\{S_{\mathrm{N},l}, S_{\mathrm{V},l}\right\} \tag{2}$$

Where $S_{\mathrm{V},l}$ is the capacity corresponding to the maximum allowable voltage loss of line l.

The voltage loss of line l can be approximately expressed as

$$\Delta U_l = \frac{S_l r_l L_l \cos\alpha}{U_{\mathrm{N}}}\left(1+\frac{x_l}{r_l}\tan\alpha\right) \tag{3}$$

Where Ll and $r_l + jx_l$ are respectively the length and the impedance per unit length of line l, and Sl and $\cos\alpha$ are respectively the apparent power and power factor of line l,.

Let ξ_0 be equal to $\cos\alpha\left(r_l + x_l\tan\alpha\right)/U_{\mathrm{N}}$. According to (3), the capacity corresponding to the maximum allowable voltage loss can be expressed as

$$S_{\mathrm{V},l} = \frac{\Delta U_{\max,l} U_{\mathrm{N}}}{L_l \xi_0} \tag{4}$$

Where $\Delta U_{\max,l}$ is the maximum allowable voltage loss of line l.

3 VOLTAGE LOSS BASED CAPACITY FORMULAS FOR TYPICAL WIRING MODES

According to the characteristics of high voltage lines, a simplified formula is derived to convert the allowable voltage loss into an equivalent capacity with the per unit length impedance being assumed to be the same for a wiring mode.

(1) Single-Line Single-Substation

For the wiring mode of single-line single-substation, the capacity corresponding to the maximum allowable voltage loss can be expressed as

$$S_{\mathrm{V},1} = \frac{\Delta U_{\max,l}}{\xi_0 L_1} \tag{5}$$

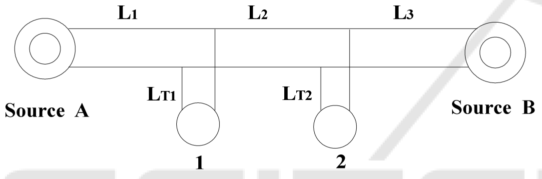
According to the relevant guidelines, the maximum allowable voltage deviation under abnormal conditions need to satisfy the requirement of ±10% (Wang Li, 2015) for a high voltage distribution network, i.e., the maximum allowable voltage loss under ideal conditions is no more than 20%, and in addition the maximum voltage loss under normal conditions is no more than 5%.

(2) Double-chain T-connected

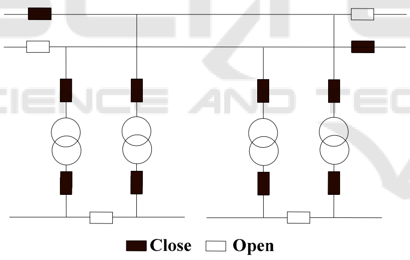
The wiring mode of double-chain T-connected and the normal operational states of its switches are shown in Figure 1. By taking the outage of power source B as an example, the formula for the voltage-based capacity of line L1 is deduced below.

Based on (3), the maximum voltage loss for the line of L1 and L2 can be expressed as

$$\Delta U_{\max,l} = \xi_0 \left[S_{\mathrm{T1}} L_1 + S_{\mathrm{T2}} \left(L_1 + L_2 + L_{\mathrm{T2}} \right) \right] \tag{6}$$



a. single line figure



b. wiring figure

Figure 1. Schematic diagram of double-chain and T-connected wiring.

Where ST1 and ST2 are the maximum allowable loads of substations 1 and 2 respectively.

Assuming that ST1 and ST2 are the same, the maximum allowable load ST2 can be obtained according to (6) as follows.

$$S_{\mathrm{T2}} = \frac{\Delta U_{\max,l}}{\xi_0 \left(2L_1 + L_2 + L_{\mathrm{T2}} \right)} \tag{7}$$

The voltage-based capacity of line L1 can be expressed as

Table 1. Summary of voltage -based capacity estimation formulas for typical wiring modes.

Connection Modes	Voltage-based Line Capacity Estimation Formula
Single-radiation single-substation	$S_{\mathrm{V},1} = \frac{\Delta U_{\max,l}}{\xi_0 L_1}$
Single-radiation double-substation	$S_{\mathrm{V},1} = \frac{2\Delta U_{\max,l}}{\xi_0 (2L_1 + L_2)}$
Double-radiation (Or Single-ring/chain) Single-substation	$S_{\mathrm{V},1} = \frac{\Delta U_{\max,l}}{\xi_0 L_1}$
Single-ring/ chain Double-substation	$S_{\mathrm{V},1} = \frac{2\Delta U_{\max,l}}{\xi_0 \left(2L_1 + L_2\right)}$ $S_{\mathrm{V},3} = \frac{2\Delta U_{\max,l}}{\xi_0 \left(L_2 + 2L_3\right)}$
Double-radiation π-connected Double-substation	$S_{\mathrm{V},1} = \frac{2\Delta U_{\max,l}}{\xi_0 \left(2L_1 + 0.5L_2\right)}$
Double-radiation T-connected Double-substation	$S_{\mathrm{V},1} = \frac{2\Delta U_{\max,l}}{\xi_0 \left(2L_1 + L_2 + L_{\mathrm{T2}}\right)}$
Double-chain T-connected Double-substation	$S_{\mathrm{V},1} = \frac{2\Delta U_{\max,l}}{\xi_0 \left(2L_1 + L_2 + L_{\mathrm{T2}}\right)}$ $S_{\mathrm{V},3} = \frac{2\Delta U_{\max,l}}{\xi_0 \left(L_2 + 2L_3 + L_{\mathrm{T1}}\right)}$
Double-ring/ chain T-connected Double-substation	$S_{\mathrm{V},1} = \frac{2\Delta U_{\max,l}}{\xi_0 \left(2L_1 + L_2\right)}$ $S_{\mathrm{V},3} = \frac{2\Delta U_{\max,l}}{\xi_0 \left(L_2 + 2L_3\right)}$
Double-chain T-connected Triple-substation	$S_{\mathrm{V},1} = \frac{3\Delta U_{\max,l}}{\xi_0 \left(3L_1 + 2L_2 + L_3 + L_{\mathrm{T3}}\right)}$ $S_{\mathrm{V},4} = \frac{3\Delta U_{\max,l}}{\xi_0 (L_2 + 2L_3 + 3L_4 + L_{\mathrm{T1}})}$
Triple-chain T-connected Double-substation	$S_{\mathrm{V},1} = \frac{2\Delta U_{\max,l}}{\xi_0 \left(2L_1 + L_2 + L_{\mathrm{T2}}\right)}$ $S_{\mathrm{V},3} = \frac{2\Delta U_{\max,l}}{\xi_0 \left(L_2 + 2L_3 + L_{\mathrm{T1}}\right)}$
Triple-chain T-connected Triple-substation	$S_{\mathrm{V},1} = \frac{3\Delta U_{\max,l}}{\xi_0 \left(3L_1 + 2L_2 + L_3 + L_{\mathrm{T3}}\right)}$ $S_{\mathrm{V},4} = \frac{3\Delta U_{\max,l}}{\xi_0 \left(L_2 + 2L_3 + 3L_4 + L_{\mathrm{T1}}\right)}$

$$S_{\mathrm{V},1} = S_{\mathrm{T}1} + S_{\mathrm{T}2} = \frac{2\Delta U_{\max,l}}{\xi_0\left(2L_1 + L_2 + L_{\mathrm{T}2}\right)} \tag{8}$$

Similar to the deduction of (8), if power supply source A is out of operation, the voltage-based capacity of line L3 can be expressed as

$$S_{\mathrm{V},3} = \frac{2\Delta U_{\max,l}}{\xi_0\left(L_2 + 2L_3 + L_{\mathrm{T}1}\right)} \tag{9}$$

(3) Summary of Voltage-Based Capacity Estimation Formulas for Typical Wiring Modes

Using the deduction process similar to the above, the voltage-based capacity estimation formulas for typical wiring modes can be obtained as shown in Table 1.

4 POWER SUPPLY CAPACITY CALCULATION OF A HIGH VOLTAGE DISTRIBUTION NETWORK

4.1 High Voltage Subareas

In this paper a high-voltage subarea is defined as the high-voltage local network whose high-voltage lines can support one another through the tie-switches, such as the typical wiring modes.

(1) Single-Line Single-Substation

Based on (2), the maximum allowable load of line L1 in the normal operation condition can be can be expressed as

$$S_{\mathrm{C},1} = \min\left\{S_{\mathrm{N},1}, S_{\mathrm{V},1}\right\} \tag{10}$$

Considering that the "N-1" safe power supply capacity is 0 for the wiring mode of a single line and a single substation, the power supply capacity in this case is defined as the maximum allowable load in the normal operation condition, and can be expressed as

$$C_{\mathrm{HTC}} = \min\left\{S_{\mathrm{C},1}, C_{\mathrm{Sub},1}\right\} \tag{11}$$

(2) Double-chain T-connected

In the wiring mode shown in Fig. 1, the capacity constraint of L2 are generally neglected when calculating the power supply capacity because the power flowing through L2 is smaller than that through L1 and L3. Therefore, based on (2), is the power supply for the series circuit of double-chain T-connected wiring mode can be approximately expressed as

Table 2. Summary of power supply capability estimation formulas for typical high voltage wiring modes.

Connection Modes	Power Supply Capacity C_{HTC}
Single-radiation single-substation	$\min\left\{S_{\mathrm{C},1}, C_{\mathrm{Sub},1}\right\}$
Single-radiation double-substation	$\min\left\{S_{\mathrm{C},1}, C_{\mathrm{Sub},1} + \min\left\{S_{\mathrm{C},2}, C_{\mathrm{Sub},2}\right\}\right\}$
Double-radiation (Or Single-ring/chain) Single-substation	$\min\left\{S_{\mathrm{C},1}, C_{\mathrm{Sub},1}\right\}$
Single-ring/ chain Double-substation	$\min\{S_{\mathrm{C},1}, S_{\mathrm{C},3}, C_{\mathrm{Sub},1} + \min\left(S_{\mathrm{C},2}, C_{\mathrm{Sub},2}\right), C_{\mathrm{Sub},2} + \min\left(S_{\mathrm{C},2}, C_{\mathrm{Sub},1}\right)\}$
Double-radiation π-connected Double-substation	$\min\{S_{\mathrm{C},1}, C_{\mathrm{Sub},1} + f_{\mathrm{hvm}}\left(2S_{\mathrm{C},2}, C_{\mathrm{Sub},2}\right)\}$
Double-radiation T-connected Double-substation	$\min\{S_{\mathrm{C},1}, \min\left(S_{\mathrm{C,T1}}, C_{\mathrm{Sub},1}\right) + \min\left(S_{\mathrm{C,T2}}, C_{\mathrm{Sub},2}\right)\}$
Double-chain T-connected Double-substation	$\min\{S_{\mathrm{C},1}, S_{\mathrm{C},3}, \min\left(S_{\mathrm{C,T1}}, C_{\mathrm{Sub},1}\right) + \min\left(S_{\mathrm{C,T2}}, C_{\mathrm{Sub},2}\right)\}$
Double-ring/ chain T-connected Double-substation	$C_{\mathrm{HTC1}} = \min\{\min\left(S_{\mathrm{C},1}, C_{\mathrm{Sub},1}\right) + C_{\mathrm{Sub},2}, \min\left(S_{\mathrm{C},3}, C_{\mathrm{Sub},2}\right) + C_{\mathrm{Sub},1}, \min[S_{\mathrm{C},1}, S_{\mathrm{C},3}, \frac{1}{2}\left(C_{\mathrm{Sub},1} + C_{\mathrm{Sub},2}\right)] + \frac{1}{2}\left(C_{\mathrm{Sub},1} + C_{\mathrm{Sub},2}\right)\}$
Double-chain T-connected Triple-substation	$\min\{S_{\mathrm{C},1}, S_{\mathrm{C},4}, \min\left(S_{\mathrm{C,T1}}, C_{\mathrm{Sub},1}\right) + \min\left(S_{\mathrm{C,T2}}, C_{\mathrm{Sub},2}\right) + \min\left(S_{\mathrm{C,T3}}, C_{\mathrm{Sub},3}\right)\}$
Triple-chain T-connected Double-substation	$\min\{2S_{\mathrm{C},1}, 2S_{\mathrm{C},3}, f_{\mathrm{hvm}}\left(2S_{\mathrm{C,T1}}, C_{\mathrm{Sub},1}\right) + f_{\mathrm{hvm}}\left(2S_{\mathrm{C,T2}}, C_{\mathrm{Sub},2}\right)\}$
Triple-chain T-connected Triple-substation	$\min\{2S_{\mathrm{C},1}, 2S_{\mathrm{C},4}, f_{\mathrm{hvm}}\left(2S_{\mathrm{C,T1}}, C_{\mathrm{Sub},1}\right) + f_{\mathrm{hvm}}\left(2S_{\mathrm{C,T2}}, C_{\mathrm{Sub},2}\right) + f_{\mathrm{hvm}}\left(2S_{\mathrm{C,T3}}, C_{\mathrm{Sub},3}\right)\}$

$$S_{\mathrm{CL}} = \min\left\{S_{\mathrm{V},1}, S_{\mathrm{N},1}, S_{\mathrm{V},3}, S_{\mathrm{N},3}\right\} \tag{12}$$

The power supply capacity for the T-connected circuit of double-chain T-connected wiring mode can be expressed as

$$S_{\mathrm{CT}} = \min\left\{S_{\mathrm{C,T1}}, S_{\mathrm{sub},1}\right\} + \min\left\{S_{\mathrm{C,T2}}, S_{\mathrm{sub},2}\right\} \tag{13}$$

The overall power supply capability can be expressed as

$$C_{\mathrm{HTC}} = \min\left\{S_{\mathrm{CL}}, S_{\mathrm{CT}}\right\} \tag{14}$$

(3) Summary of Power Supply Capacity Estimation Formulas for Typical Wiring Modes

By using the derivation process similar to the above, the power supply capacities of typical wiring modes can be obtained as shown in Table 2.

4.2 High Voltage Distribution Network

Based on the subareas of typical wiring modes, the overall power supply capacity calculation of a high-voltage distribution network can be expressed as

$$C_{\mathrm{HV}} = \sum_{i=1}^{N_{\mathrm{HTC}}} C_{\mathrm{HTC},i} \tag{15}$$

Where CHVC,i is the power supply capacity of subarea i and NHTC is the number of subareas.

5 EXAMPLE

(1) System Introduction

As shown in Fig. 2, the high-voltage distribution network includes three kinds of typical wiring modes, i.e., double-chain π-connected of substations A and B, single-line and single-substation of substation C and single-substation double-line of substation D. The conductor types of each 35kV high voltage lines are LGJ-400, and their current-based capacities are 51.23MVA, and their lengths are shown in Table 3. The known power supply capacities of substations A, B, C and D are 47.29 MVA, 52.42 MVA, 17.68 MVA and 40 MVA, respectively.

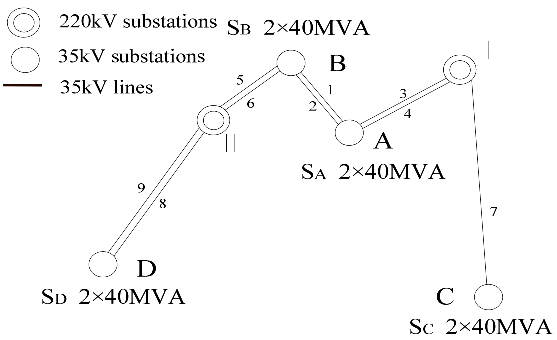


Figure 2. Schematic diagram of the high-voltage distribution network.

Table 3. HV line parameters.

Line Name	Line Length (km)	Line Name	Line Length (km)
1,2	6.3	7	24.8
3,4	9.2	8,9	35.2
5,6	7.5	/	/

(2) Power Supply Capacity of Subareas

According to Table 2, the power supply capacity of double-chain π-connected wiring mode is 98.52 MVA. The power supply capacity of single-line single-substation wiring mode is 11.12 MVA. The power supply capacity of single-substation double-line is 15.65 MVA.

Without considering voltage constraints, the power supply capacity of single-line single-substation is 32 MVA and that of single-substation double-line is 40 MVA.

(3) Overall Power Supply Capacity

According to (15), the overall power supply capacity is 125.29 MVA. Without considering voltage constraints, the power supply capacity is 170.52 MVA, which is 36.1% higher than that of 125.29 MVA with voltage constraints being considered.

6 CONCLUSIONS

The main conclusions are as follows:

(1) Based on the relatively independent power supply subareas (or wiring modes), a simplified method is proposed for calculating the power supply capacity of a high-voltage distribution network.

(2) The upper and lower limit constraints of node voltages are skillfully converted to the maximum allowable line voltage loss ones which are then transformed into line capacity ones. Thus, voltage

constraints can be automatically considered when the capacity constraints are taken into account, which simplifies the calculation process and solves the calculation error problem caused by neglecting voltage constraints.

(3)The approximate formulas are derived for estimating the power supply capacities of typical high-voltage wiring modes. These formulas are of practical value in engineering application.

(4) The proposed model and method are more realistic, intuitive, simple, fast, stable and effective, and easy to be popularized and applied in practice. As long as the basic idea and method in this paper are mastered, planners can use simple computing tools or even rely on manual work to complete specific tasks.

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