

Research on Improvement Plan of Low-voltage Area Line Loss Calculation

RUAN Bo¹, LI Yu², ZHANG Bu-han², SU Fu-wen²

(1. *Economy & Technology Research Institute of State Grid Hubei Electric Power Company, Wuhan Hubei 430077, China;*

2. *Huazhong University of Science and Technology, Wuhan Hubei 430074, China)*

(Abstract) With the development of smart distribution grid, metering devices for low voltage distribution network is getting better and better, which lays the foundation for the accurate calculation of theoretical line loss. Firstly, this article points out existing problem of commonly used calculation methods--equivalent resistance method for low-voltage area theoretical line loss. Secondly, under the premise of adequate configuration of the metering devices, this article puts forward two kinds of theoretical calculation methods of low voltage area line loss, which are improved equivalent resistance method by using the head end of three phase current and the improved back/forward sweep method based on equivalent resistance. At last, the proposed plan is applied to the actual low voltage area, which verifies the feasibility of the plan.

Key Words: line loss; low-voltage area; equivalent resistance method; three-phase unbalance;

1 Introduction

Line loss rate is not only the important reference index for production and operation of power company, but also the comprehensive reflection of planning, design, production, operation, management of power system and enterprise economic level^(1,2).

Considering the present situation of line loss management, many power supply companies put forward a lot of control measures for line losses reduction.⁽³⁻⁶⁾ The line loss management of low-voltage area⁽⁷⁻⁸⁾ is difficult due to complicated structure and incomplete data of low-voltage area.

2 Summary of line loss management

Line loss means the power energy loss caused by the electricity on the distribution line transforms into thermal energy, management line loss and statistical line loss. The relationship among three losses is shown in formula (1-1); Line loss rate is the percentage of power loss divided by power supply. Generally the line loss rate can be classified into actual line loss rate and theoretical line loss rate, the calculation methods are shown in formula (1-2) and (1-3)⁽⁹⁻¹⁰⁾.

$$\text{Actual line loss rate} = \text{statistical power line loss} / \text{power supply} \times 100\% \quad (1-2)$$

$$\text{Theoretical line loss} = \text{theoretical line loss of power/power supply} \times 100\% \quad (1-3)$$

Statistical line loss is the difference between actual power supply and powers sales calculated by residual method in accordance with the power meter reading; Management line loss is equal to the difference between statistical line loss and theoretical line loss, including line loss caused by lots of uncertain factors, so the management line loss also called unknown loss.

3 Existing calculation method for low-voltage area

The low-voltage distribution network of 0.4 kV and below has two characteristics: First, the way and structure of power supply is complex, mainly three-phase four-line and single-phase two-line; Second, the power load varies greatly, and the meter and device are not complete so that the complete operating records and materials are lacked. So it is tough to accurately calculate the theoretical line loss of low-voltage distribution network.⁽¹²⁾

a) Assumptions of existing calculation method for low-voltage area

- (1) Assuming that the load power factor of user side is equal to the load power factor of head end in the station area.
- (2) Assuming that the load curve of user side is similar to the load curve of head end in the station area.
- (3) Assuming that the voltage of each node is equal to the voltage of head end in distribution feeder, ignoring the influence of the line voltage drop on the line loss.

b) Existing calculation method of equivalent resistance

The basic idea of equivalent resistance method: the power energy loss caused by each branch current flows through the resistance is equal to the power energy loss caused by the outlet current flows through the equivalent resistance. The formula for calculating the equivalent resistance is as follows:

$$R_{eq} = \frac{\sum_{j=1}^{m_j} N_j A_{j,\Sigma}^2 R_j}{(\sum_{i=1}^m A_i)^2} (\Omega) \quad (2-1)$$

In the formula (2-1), $A_{j,\Sigma}$ is the sum of power meter reading of low-voltage user in a certain line, kWh; A_i is the sum of power meter reading of all users in the station area, kWh; R_j is a resistance in the calculated line, $R_j = r_{0j} L_j, \Omega$; N_j is a structure constant of the calculated line, the constant will be 6 if the line is single-phase single-wire, and the constant will be 1 if the line is three-phase four-line.

c) Power energy loss calculation

The formula for calculating the power loss of the distribution network in low-voltage area is as follows:

$$\Delta A_k = 3 I_{T,rms}^2 R_{eq} T \times 10^{-3} (\text{kWh}) \quad (2-2)$$

In the formula (2-2), $I_{T,rms}$ is the root mean square value of head end current of distribution network in period T; the T normally takes a day of 24 hours.

d) Modified coefficient of equivalent resistance method

Assuming that the daily active power supply and reactive power supply are respectively A_P and A_Q , the average operating line voltage is V_l , the current records of 24 hours are I_t ($t=1, 2, \dots, 24$) in the distribution line on representative day. If the A_P and A_Q are divided into each hour in accordance with the graph of load current, the daily active power and reactive power of distribution line outlet are:

$$P_t = A_P \cdot \frac{I_t}{I_\Sigma} (\text{kW}) \quad (2-3)$$

$$Q_t = A_Q \cdot \frac{I_t}{I_\Sigma} (\text{kVar})$$

Therein:

$$I_\Sigma = \sum_{t=1}^{24} I_t (\text{A}) \quad (2-4)$$

The hourly calculated current of the distribution line outlet is

$$I_t' = \frac{\sqrt{P_t^2 + Q_t^2}}{\sqrt{3}V_l} = \frac{\sqrt{A_P^2 + A_Q^2}}{\sqrt{3}V_l I_\Sigma} \cdot I_t (\text{A}) \quad (2-5)$$

So the modified coefficient of equivalent resistance method is

$$k = \frac{I_t'}{I_t} = \frac{\sqrt{A_P^2 + A_Q^2}}{\sqrt{3}V_l I_\Sigma} \quad (2-6)$$

Due to the variable line loss ΔA_k (sum of the line loss and the copper loss of distribution network transformer) of distribution network is directly proportional to the square of load current, the modified formula of variable line loss is

$$\Delta A_k' = k^2 \cdot \Delta A_k = \frac{A_P^2 + A_Q^2}{3(V_l I_\Sigma)^2} \Delta A_k (\text{kWh}) \quad (2-7)$$

References (11) and (16) considered the influence of unbalanced three-phase current on line loss, the value of power energy loss would be corrected by three-phase unbalance coefficient k_{ub} . First introducing the unbalance factor of current β_ϕ , the formula is

$$\beta_\phi = (I_\phi - I_{av}) / I_{av} \quad (2-8)$$

Where, I_ϕ is three-phase current; $I_{av} = \frac{1}{3}(I_A + I_B + I_C)$ (A).

If the resistance of neutral line and phase line are R in three-phase four-wire line, power factors of each phase are the same, the power loss of phase line is

$$\begin{aligned} \Delta P_\phi = & ((1 + \beta_A)^2 + (1 + \beta_B)^2 \\ & + (1 + \beta_C)^2) I_{av}^2 R \text{ (W)} \end{aligned} \quad (2-9)$$

Because of $\beta_A + \beta_B + \beta_C = 0$, $\Delta P_\phi = (3 + \beta_A^2 + \beta_B^2 + \beta_C^2) I_{av}^2 R$ (W)

Null line current:

$$\begin{aligned} I_N = & (1 + \beta_A) I_{av} + (1 + \beta_B) \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2} \right) I_{av} \\ & + (1 + \beta_C) \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2} \right) I_{av} \text{ (A)} \end{aligned} \quad (2-10)$$

The loss of null line is

$$\begin{aligned} \Delta P_N = & \left(\beta_A - \frac{\beta_B}{2} - \frac{\beta_C}{2} \right)^2 \\ & + \left(\frac{\sqrt{3}}{2} \beta_C - \frac{\sqrt{3}}{2} \beta_B \right)^2 I_{av}^2 R \text{ (W)} \end{aligned} \quad (2-11)$$

Total losses:

$$\begin{aligned} \Delta P = & \Delta P_\phi + \Delta P_N = (3 + 2(\beta_A^2 + \beta_B^2 + \beta_C^2) \\ & - \beta_A \beta_B - \beta_B \beta_C - \beta_C \beta_A) I_{av}^2 R \text{ (W)} \end{aligned} \quad (2-12)$$

The three-phase unbalance coefficient is

$$\begin{aligned} K_{ub} = & \frac{\Delta P_\phi + \Delta P_N}{\Delta P_\phi} = \\ & \frac{3 + 2(\beta_A^2 + \beta_B^2 + \beta_C^2) - \beta_A \beta_B - \beta_B \beta_C - \beta_C \beta_A}{3 + \beta_A^2 + \beta_B^2 + \beta_C^2} \end{aligned} \quad (2-13)$$

In case of unbalanced three-phase current, the power energy loss is

$$\Delta A'_k = k_{ub} \Delta A_k \text{ (kWh)} \quad (2-14)$$

Using current correction coefficient k from formula (2-3) to formula (2-7) to correct and figure out the line loss:

$$\begin{aligned} \Delta A'_k = & k_{ub} k^2 \cdot \Delta A_k \\ = & k_{ub} \frac{A_p^2 + A_Q^2}{3(V_a I_\Sigma)^2} \Delta A_k \text{ (kWh)} \end{aligned} \quad (2-15)$$

4 Improvement plan of Line Loss of Low-voltage Area

- (1) In accordance with the three-phase unbalance degree k_{ub} , the three-phase unbalance degree of each day is a fixed value;
- (2) Ignored the influence of voltage drop along wire and other factors on line loss.

a) The improved equivalent resistance method of using three-phase current of head end

The improved equivalent resistance method of using three-phase current of head end adopts 24-hour three-phase current of station area outlet to reflect three-phase current unbalance and load fluctuation:

$$\Delta A_k = (I_a^2 R_a + I_b^2 R_b + I_c^2 R_c + I_0^2 R_0) \times T \times 10^{-3} \text{ (kWh)} \quad (3-1)$$

Where, the current of null line is equal to the vector sum of three-phase current, the expression is

$$\dot{I}_0 = \dot{I}_a + \dot{I}_b + \dot{I}_c \text{ (A)} \quad (3-2)$$

If the resistance value of three-phase phase line R_a , R_b , R_c are equal to the resistance value of neutral line R_0 , which are all equivalent resistance R_{eq} , the formula (3-1) can be simplified as:

$$\Delta A_k = (I_a^2 + I_b^2 + I_c^2 + |\dot{I}_a + \dot{I}_b + \dot{I}_c|^2) R_{eq} \times T \times 10^{-3} \text{ (kWh)} \quad (3-3)$$

In the calculation, assuming that the phase angle differences among phase A, B and C, under the condition of unbalanced load, are 120° , so after knowing the three-phase current amplitude, the expression of \dot{I}_a , \dot{I}_b , \dot{I}_c can be obtained, thus the value of current of null line \dot{I}_0 is obtained. Equivalent resistance is obtained from formula (2-1).

Using correction coefficient from formula (3-3) to formula (3-7) to correct and figure out the line loss, the ultimate theoretical calculation result of electricity of line loss is

$$\Delta A_k' = k^2 \cdot \Delta A_k = \frac{A_p^2 + A_Q^2}{3(V_a I_\Sigma)^2} \times \Delta A_k \text{ (kWh)} \quad (3-4)$$

b) The improved equivalent resistance method based on back/forward sweep.

There are too many assumptions in the original equivalent resistance method. Great error will be made when the actual assumptions deviate from the theoretical assumptions.

i. Process of back/forward sweep method

Take the circuit as single-phase circuit for power flow calculation, all data are converted into per-unit value. The specific principles of calculation are as follows:

(1) Set the initial values of nodes voltage: $\dot{U}_i(c) = 1$; $i=1,2,3, \dots, n$, n is the number of nodes; c is the number of cycles.

(2) Inputting the current into the node that calculated by formula (3-1)

$$\dot{I}_i = A_i (1 - j \tan \varphi_i) / \sqrt{3} \dot{U}_{i(c)} T \text{ (p.u.)} \quad (3-5)$$

In the formula, \dot{I}_i is the average current (complex number) of node; A_i is the active electrical degree of node (user) measured in period T , normally it is of daily active electricity, the value of T is 24; φ_i is load power factor angle of node. $\dot{U}_{i(c)}$ is the voltage of node i , c is number of cycle, if $c=0$, the $\dot{U}_{i(c)}$ is the initial voltage value before performing iteration calculation, it normally is $i+j0$; during the process of back/forward sweep, voltage of each node will be varied.

(3) Calculating the current of each branch from the foot branch: figure out current $I_{ij(c)}$ ("i" is the parent node) of each branch from the foot branch to each sub branch:

$$\dot{I}_{ij(c)} = \frac{A_i (1 - j \tan \varphi_i)}{\sqrt{3} \dot{U}_{i(c)} T} + \sum_{k=1}^m \dot{I}_{jk(c)} \text{ (p.u.)} \quad (3-6)$$

Where, m is the collection of all sub-branches which are directly connected to the node j , $\dot{I}_{jk(c)}$ is the current of corresponding branch. If the power factors of the head end of station area side and user side are same.

(4) Sweeping forward to figure out node voltage: sweeping from the first branch to following branches to figure out voltage of each node:

$$\dot{U}_j(c+1) = \dot{U}_i(c+1) - \dot{I}_{ij(c)} Z_{ij} \text{ (p.u.)} \quad (3-7)$$

Where, “j” is the parent node, “i” is the sub node, Z_{ij} is the impedance between branch i and j .

(5) Calculating the correction value of voltage amplitude of each load node:

$$\Delta U_j(c+1) = \left| \dot{U}_i(c+1) \right| - \left| \dot{U}_i(c) \right| \text{ (p.u.)} \quad (3-8)$$

(6) Calculating the maximum correction value of each node. $\left| \Delta U_j(c+1) \right|$

(7) Convergence criteria:

$$\max \left| \Delta U_j(c+1) \right| < \varepsilon \quad (3-9)$$

Where, ε is the accuracy of calculation, if the maximum correction value of voltage is greater than accuracy of calculation, the cycle ends and the calculation result is obtained; if not, repeat step (2) - (7) until the requirement of (5) is met.

ii. Calculation of equivalent resistance and line loss of station area

The current of each line, power of head end and terminal end and voltage of each node can be calculated by back/forward sweep method for power flow. The method can directly figure out the line loss. Converting all values into actual value for next calculation, the expression for hourly line loss of station area is

$$\begin{aligned} \Delta P &= \sum_{l=1}^m \left[\frac{(P_{jl}^2 + Q_{jl}^2)}{V_j^2} \right] R_l \\ &= \left[\frac{(P_{\Sigma}^2 + Q_{\Sigma}^2)}{V_s^2} \right] R_{eq} \text{ (kW)} \end{aligned} \quad (3-10)$$

Where, P_{jl} and Q_{jl} is respectively active power and reactive power of terminal end of the “T” branch, V_j is the voltage of terminal end node of the “T” branch, R_l is the resistance of branch l ; P_{Σ} and Q_{Σ} is the power of root node of outlet of station area, V_s is the voltage of the root node of outlet of station area. According to the formula (3-6), the equivalent resistance of station area is

$$R_{eq} = \frac{\sum_{l=1}^m \left[\frac{(P_{jl}^2 + Q_{jl}^2)}{V_j^2} \right] R_l}{\left[\frac{(P_{\Sigma}^2 + Q_{\Sigma}^2)}{V_s^2} \right]} \text{ (}\Omega\text{)} \quad (3-11)$$

Comparing back/forward sweep method and original method, the former considers the influence of voltage drop along the line on line loss, therefore the result is more accurate by using back/forward sweep method. Put the equivalent resistance R_{eq} into the formula (3-3) which considering the influence of load fluctuation and three-phase unbalance on line loss, and obtain the line loss of distribution lines by using formula (3-4).

5 Case study

a) Structure and parameters of station area

A network structure diagram of 0.4 kV station area is shown in Fig. 2, determining the calculation sequence by There are total 15 nodes and branches and 9 users; the daily power supply is 141.12kWh, the daily power sales is 136.59kWh, and the daily power loss is 4.53kWh (including the estimated meter loss of 1.300 kWh), the statistic lien loss is 3.21%, the power factor is 0.9, there are two types of the wires, LGJ-25 and BLV-16. In Fig. 2, the line $l_{3,4}$, $l_{8,9}$, $l_{10,12}$ and $l_{13,15}$ are single-phase one-wire, and the rest of lines are three-phase four-wire.

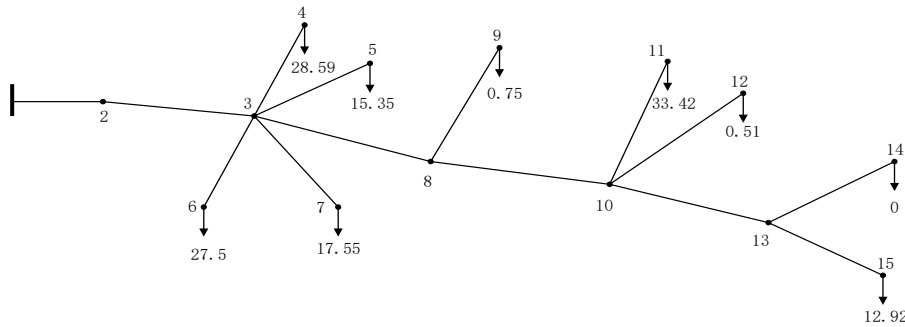


Fig. 2 Network structure diagram of the station area

b) Calculation of improvement plan

The result of theoretical line loss of the station area by applying improved method is shown in Tab. 2.

Tab. 2 The calculation results of theoretical line loss

Calculation method		Equivalent resistance/ Ω	Line loss/kWh	Meter loss/kWh	Total loss/kWh	Line loss rate	
Original method	Equivalent resistance method	0.155	1.748	1.300	3.048	2.16%	
Improve methods	Metho d One	The improved equivalent resistance method of using three-phase current of head end	0.155	2.109	1.300	3.409	2.42%
	Metho d Two	The improved equivalent resistance method based on back/forward sweep.	0.183	2.490	1.300	3.790	2.69%

The improved equivalent resistance method based on back/forward sweep needs more information, such as network structure and load power factors of each node.

6 Conclusion

This paper provides two improvement plan according to the equivalent resistance method based on original calculation method for line loss of low-voltage area, the improved equivalent resistance method of using three-phase current of head end and the improved equivalent resistance method based on back/forward sweep. These two improvement plans are applied to calculate the theoretical line loss of low-voltage area of 0.4kV power supply station, and the results are compared with the result calculated by the original method. The result shows that the effect of these two improvement plans are significant. In accordance with existing data and accuracy requirements, there are options for the calculation line loss of low voltage distribution network: if the data is complete, the improved equivalent resistance method based on back/forward sweep is selected to accurately calculate the line loss; if the data is incomplete, the improved equivalent resistance method of using three-phase

current of head end will be considered to estimate the line loss.

References

- (1) Sun Ruifeng. Power Loss Calculation Method for Distribution Network(J). Northeast Electric Power Technology, 2010, 31(2):34-36.
- (2) Wang Tao, Zhang Jianmin, Li Xiaoping. Calculation and Evaluation of Scheduled Loss Ratio(J). Central China Electric Power, 2003, 16(1):5-7.
- (3) Zhao Jihong. The Line Loss Management of Power System in 10kV Network(J). Rural Electrification, 1999(11):39-42.
- (4) Han F, Yin M, Jun L I, et al. Discussions on Related Issues of Smart Grid Development in China(J). Power System Technology, 2009, 33(15):47-53.
- (5) He Jian, Ding Lvna. Development and Application of the Visual Theoretically Calculating Software for the Distribution Network's Flow Loss(J). Zhejiang Electric Power, 2002, 21(3):6-9.
- (6) Tai H, Hogain E O. Behind the buzz (In My View)(J). IEEE Power & Energy Magazine, 2009, 7(2):96-92.
- (7) Lu Yang, Zhou Hongguang, Lan Caijin. Analysis of Improved Distribution Network's Line Loss Calculation Method(J). Electrical Engineering, 2013(1):98-100.
- (8) Ding Xinhai. Research on Power Loss Calculation Method for Distribution Network(D). Wuhan University of Hydraulic and Electric Engineering Wuhan University, 1997.
- (9) Yang Yaojie. Study on the Manage Model of Low-voltage Public Transformer District(D). Zhengzhou University, 2004.
- (10) Tan Yafeng, Li Yunlong, Sang Chuanchuan. Analysis of Line Loss Management of Urban Power Supply Bureau(J). Guangxi Electric Power, 2016(14):37-39.