

Real-Time Three-Phase Line Loss Calculation for Distribution Network Based on Electric Characteristic Measuring Terminal

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Abstract—Line loss rate is an important economic index of distribution network. In the paper, a new real-time three-phase line loss calculation method based on characteristic measurement is proposed for calculating the line loss of distribution network. The state characteristics of distribution network is measured by the new smart metering terminal, such that the change state of the electric load can be described in a simple way, relieving the pressure in transmitting and processing the large amount of real-time measurement data, while the calculating accuracy of the line loss of distribution network is ensured. The loop current method is used to calculate the three-phase line loss of distribution network, respectively, depending not on the topology and parameters of the distribution network. The effect of three-phase unbalance and distributed generation problems also can be considered effectively. The proposed method is applied to a practical distribution network, the results show its feasibility and effectiveness fully.

Keywords—distribution network; real-time line loss calculation; characteristic measurement; loop current method; three-phase unbalance; distributed generation

I. INTRODUCTION

Line loss rate is not only an important economic index to evaluate the operation state of power systems, but also a reference to its planning, operation and technological innovation. Since the distribution network in China had not been paid enough attention in the past years, its line loss rate is comparing higher than the transmission network [1].

Nowadays, much research has been done on the calculation of theoretical line loss of distribution network. The existing methods include the root-mean-square current method, average current method, maximum current method, equivalence resistance method and so on [2-3]. These methods just need a small amount of measurements, which are easy to be obtained via the coulomb meter, thus they are widely used in the practical engineering. However, these methods are proposed based on some idealized assumptions ignoring the difference of voltages, phase angles and load change shapes of distribution network. Thus, the results calculated by these methods have large errors in most cases. It is found in some practical applications that the calculation errors of these methods are even up to -23 % ~ 29 % [4].

In order to improve the accuracy, the line loss is also calculated based on the power flow methods, among which the

forward and backward substitution method and Newton-Raphson method are the most concerned ones. The forward and backward substitution method with good convergence is suitable to calculate the line loss of radial distribution network. However, it is difficult in dealing with the distribution network with looped structure [5]. The Newton-Raphson method performs well in calculating the line loss of distribution network with looped structure, but its convergence is sensitive to the initial value [6-7]. Due to the long-range radiation of distribution network, the true value always deviates from the initial value largely, making the Newton-Raphson method be not convergent [8].

In order to solve these problems, the power flow methods are improved from different aspects [9]. However, these improved methods are dependent on the fixed network structure and accurate line parameters. In the practical operation process, the structure of distribution network is changed some times. The line parameters also can't be measured accurately for the complicated factors such as the changing of climate [10].

In the paper, a new real-time three-phase line loss calculation method is proposed. The characteristic measuring technology combined with the loop current method is used to calculate the three-phase line loss of distribution network, respectively. The effect of three-phase unbalance, changing network structure and distributed generation integration all can be considered effectively by the proposed method.

II. LINE LOSS CALCULATION BASED ON LOOP CURRENT METHOD

A. Line Loss Calculation of Distribution Network

According to loop current method, a loop can be seen as a path from the first end feeder to a terminal branch, and the power loss of this loop can be calculated by multiplying its voltage with current.

As shown in Figure I, where the distribution network has N branches, it can form N loops with the common first end feeder and each terminal branch, respectively. The branch current can be regarded as the loop current, and the voltage difference between two ends can be regarded as the loop voltage. Then the power loss can be calculated as

$$\Delta P_{i,m} = U_{s,m} I_{i,m} \cos(\alpha_{s,m} - \theta_{i,m}) - U_{i,m} I_{i,m} \cos(\alpha_{i,m} - \theta_{i,m}) \quad (1)$$

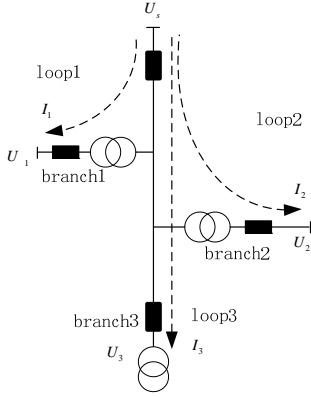


FIGURE I. BASIC PRINCIPLE OF LINE LOSS BASED ON LOOP CURRENT METHOD

where $\Delta P_{i,m}$ is power loss of loop i ; $U_{s,m}$ and $\alpha_{s,m}$ are the m phase voltage amplitude and angle of the first end feeder, respectively; $U_{i,m}$ and $\alpha_{i,m}$ are the m phase voltage amplitude and angle of branch i , respectively; $I_{i,m}$ and $\theta_{i,m}$ are the m phase current amplitude and angle of branch i , respectively.

The line loss $\Delta W_{i,m}$ in period T can be calculated as

$$\Delta W_{i,m} = \int_0^T [U_{s,m} I_{i,m} \cos(\alpha_{s,m} - \theta_{i,m}) - U_{i,m} I_{i,m} \cos(\alpha_{i,m} - \theta_{i,m})] dt \quad (2)$$

In order to measure the characteristics conveniently, the voltage and current phasor are changed into the algebraic form. Then the line loss $\Delta W_{i,m}$ in period T can be calculated as

$$\Delta W_{i,m} = \int_0^T (U_{s,m}^p I_{i,m}^p + U_{s,m}^q I_{i,m}^q - U_{i,m}^p I_{i,m}^p - U_{i,m}^q I_{i,m}^q) dt \quad (3)$$

where $U_{s,m}^p$ and $U_{s,m}^q$ are the real part and image part of m phase voltage of the first end feeder, respectively; $U_{i,m}^p$ and $U_{i,m}^q$ are the real part and image part of m phase voltage of branch i , respectively; $I_{i,m}^p$, $I_{i,m}^q$ are the real part and image part of m phase current of branch i , respectively.

According to the principle of superposition, the total line loss is equal to the sum of each loop line loss. Thus the total line loss ΔW can be calculated as

$$\Delta W = \sum_{i=1}^N \sum_{m=1}^3 \Delta W_{i,m} \quad (4)$$

where ΔW is the total line loss of distribution network.

In the above method, the three-phase unbalance problem can be solved effectively as the line loss of each phase is

calculated, respectively. The topological structure and parameter values are also omitted in the calculation process. Therefore, it is suitable to be applied in the distribution network where the topological structure changes some times and its true parameter values are unknown.

B. Line Loss Calculation Including Distributed Generation

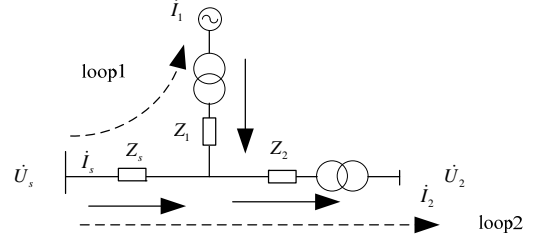


FIGURE II. BASIC PRINCIPLE OF LINE LOSS OF DISTRIBUTION NETWORK INCLUDING DISTRIBUTED GENERATION

The proposed method is also suitable to calculate the line loss including the distributed generation. Take Figure II as example, the distributed generation and load are connected in loop 1 and loop 2, respectively. The positive direction of current is defined as the direction from the first end feeder to each branch. According to Kirchhoff's law, the current phasor can be calculated as

$$\dot{I}_s = \dot{I}_1 + \dot{I}_2 \quad (5)$$

where \dot{I}_s , \dot{I}_1 and \dot{I}_2 are current phasors of the first end feeder, branch 1 and branch 2, respectively.

The total line loss W in period T can be calculated as

$$W' = \int_0^T (I_1^2 R_1 + I_2^2 R_2 + I_s^2 R_s) dt \quad (6)$$

where R_s , R_1 and R_2 are the resistances of the first end feeder, branch 1 and branch 2, respectively.

According to (3), the total loss can be calculated as

$$\begin{aligned} W &= \int_0^T \sum_{i=1}^2 (U_s^p I_i^p + U_s^q I_i^q - U_i^p I_i^p - U_i^q I_i^q) dt \\ &= \int_0^T \sum_{i=1}^2 [(U_s^p - U_i^p) I_i^p + (U_s^q - U_i^q) I_i^q] dt \\ &= \int_0^T \sum_{i=1}^2 [(I_s^p R_s - I_i^p X_s + I_i^p R_i - I_i^q X_i) I_i^p + \\ &\quad (I_s^p X_s + I_s^q R_s + I_i^p X_i + I_i^q R_i) I_i^q] dt \\ &= \int_0^T (I_1^2 R_1 + I_2^2 R_2 + I_s^2 R_s - I_s^p I_s^q X_s + I_s^q I_s^p X_s) dt \\ &= \int_0^T (I_1^2 R_1 + I_2^2 R_2 + I_s^2 R_s) dt \end{aligned} \quad (7)$$

It shows that the line loss calculation result based on the loop current method is as the same as (6). Thus, the loop

current method is also suitable to the line loss calculation of including distributed generation.

III. LINE LOSS CHARACTERISTIC MEASUREMENT

A. Line Loss Characteristics

In (3), the line loss can be calculated in discrete form as

$$\Delta W_{i,m} = \sum_{k=1}^M (U_{s,m,k}^p I_{i,m,k}^p + U_{s,m,k}^q I_{i,m,k}^q - U_{i,m,k}^p I_{i,m,k}^p - U_{i,m,k}^q I_{i,m,k}^q) \Delta T_k \quad (8)$$

where $U_{s,m,k}^p$ and $U_{s,m,k}^q$ are the real part and image part of m phase voltage of the first end feeder in period k ; $U_{i,m,k}^p$ and $U_{i,m,k}^q$ are the real part and image part of m phase voltage of branch i in period k ; $I_{i,m,k}^p, I_{i,m,k}^q$ are the real part and image part of m phase current of branch i in period k ; ΔT_k is the time interval in period k ; M is the total number of periods.

Equation (8) shows that the shorter the time interval is, the higher the calculation accuracy will be. But considering the communication limit of the distribution network, it is impossible to transmit the measurement in a very short interval. A more feasible approach is to measure the line loss characteristics, which represent the line loss fully, in an appropriate interval, and then transmit them into the master station for the accurate line loss calculation.

In the root-mean-square current method, the line loss is calculated by the mean square root of current in one period. It can be proved that the mean square root of current in a period is equal to the effect of actual current when the line loss is calculated. In this sense, the root mean square of current is a good characteristic for line loss calculation. But the traditional root mean square method can only process the effective value of current other than that in the algebraic form. Thus, it is necessary to propose the new line loss characteristics based on the root-mean-square current method.

For each branch of distribution network, a smart metering terminal can be set to measure the line loss characteristics. First, translate the phase current into the algebraic form as

$$I_{i,m,k}^p = I_{i,m,k} \cos(\theta_{i,m,k}) \quad (9)$$

$$I_{i,m,k}^q = I_{i,m,k} \sin(\theta_{i,m,k}) \quad (10)$$

Then the current characteristics can be calculated as

$$\tilde{I}_{i,m,k}^p = \sqrt{\frac{\int I_{i,m,k}^p{}^2 dt}{T}} \quad (11)$$

$$\tilde{I}_{i,m,k}^q = \sqrt{\frac{\int I_{i,m,k}^q{}^2 dt}{T}} \quad (12)$$

where $\tilde{I}_{i,m,k}^p$ and $\tilde{I}_{i,m,k}^q$ are the real part and image part of m phase current of branch i in period k , respectively.

Similarly, the voltage characteristics can be calculated as

$$U_{i,m,k}^p = U_{i,m,k} \cos(\theta_{i,m,k}) \quad (13)$$

$$U_{i,m,k}^q = U_{i,m,k} \sin(\theta_{i,m,k}) \quad (14)$$

$$\tilde{U}_{i,m,k}^p = \sqrt{\frac{\int U_{i,m,k}^p{}^2 dt}{T}} \quad (15)$$

$$\tilde{U}_{i,m,k}^q = \sqrt{\frac{\int U_{i,m,k}^q{}^2 dt}{T}} \quad (16)$$

where $\tilde{U}_{i,m,k}^p$ and $\tilde{U}_{i,m,k}^q$ are real part and image part of the m phase voltage of branch i in period k , respectively.

When the line loss characteristics in (11), (12), (15) and (16) are obtained, they can be substituted into (8) for the calculation of line loss.

B. Phase Change of Characteristics in Both Sides of Transformer

The transformers are generally classified into the special and public ones. For the special transformer, whose loss is taken charged by the users, its loss should not be taken into calculation. Since the measuring terminals of special transformer are generally installed in the high-voltage side, the characteristics can be used directly for the calculation of line loss. However, for the public transformer whose measuring terminals are installed in low-voltage side, its characteristics measured in the low-voltage side have to be translated into the high-voltage side for the calculation of line loss in 10kV.

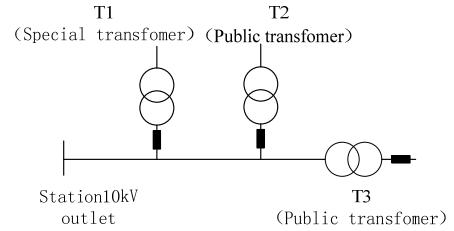


FIGURE III. INSTALLATION LOCATION OF METERING TERMINALS OF DIFFERENT TYPES OF TRANSFORMERS

Considering the three-phase unbalance problem of distribution network, the symmetrical component method is applied to decompose the characteristics in low-voltage side into different sequence components as

$$\begin{bmatrix} \tilde{U}_{i,a,k}^1 \\ \tilde{U}_{i,a,k}^2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} \tilde{U}_{i,a,k} \\ \tilde{U}_{i,b,k} \\ \tilde{U}_{i,c,k} \end{bmatrix} \quad (17)$$

$$\begin{bmatrix} \tilde{I}_{i,a,k}^1 \\ \tilde{I}_{i,a,k}^2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} \tilde{I}_{i,a,k} \\ \tilde{I}_{i,b,k} \\ \tilde{I}_{i,c,k} \end{bmatrix} \quad (18)$$

where $\alpha = e^{j120^\circ}$; $\tilde{U}_{i,a,k}^1$ and $\tilde{U}_{i,a,k}^2$ are the positive-sequence and negative-sequence component of A phase voltage characteristics, respectively; $\tilde{I}_{i,a,k}^1$ and $\tilde{I}_{i,a,k}^2$ are the positive-sequence component and negative-sequence component of A phase current characteristics, respectively; $\tilde{U}_{i,a,k}$, $\tilde{U}_{i,b,k}$ and $\tilde{U}_{i,c,k}$ are the A, B and C phase voltage characteristics of the public transformer in the low-voltage side, respectively; $\tilde{I}_{i,a,k}$, $\tilde{I}_{i,b,k}$ and $\tilde{I}_{i,c,k}$ are the A, B and C three-phase current characteristics of public transformer in the low-voltage side, respectively.

In general, the public transformers possess the D/Y₀-11 connection structure. According to the transformer ratio and phase variation of each sequence current, the characteristics in the high-voltage side can be calculated as

$$\begin{bmatrix} \tilde{U}_{i,A,k} \\ \tilde{U}_{i,B,k} \\ \tilde{U}_{i,C,k} \end{bmatrix} = K \begin{bmatrix} \tilde{U}_{i,a,k}^1 & \tilde{U}_{i,a,k}^2 \\ \alpha^2 \tilde{U}_{i,a,k}^1 & \alpha \tilde{U}_{i,a,k}^2 \\ \alpha \tilde{U}_{i,a,k}^1 & \alpha^2 \tilde{U}_{i,a,k}^2 \end{bmatrix} \begin{bmatrix} e^{j30^\circ} \\ e^{-j30^\circ} \end{bmatrix} \quad (19)$$

$$\begin{bmatrix} \tilde{I}_{i,A,k} \\ \tilde{I}_{i,B,k} \\ \tilde{I}_{i,C,k} \end{bmatrix} = K \begin{bmatrix} \tilde{I}_{i,a,k}^1 & \tilde{I}_{i,a,k}^2 \\ \alpha^2 \tilde{I}_{i,a,k}^1 & \alpha \tilde{I}_{i,a,k}^2 \\ \alpha \tilde{I}_{i,a,k}^1 & \alpha^2 \tilde{I}_{i,a,k}^2 \end{bmatrix} \begin{bmatrix} e^{j30^\circ} \\ e^{-j30^\circ} \end{bmatrix} \quad (20)$$

where $\tilde{U}_{i,a,k}$, $\tilde{U}_{i,b,k}$ and $\tilde{U}_{i,c,k}$ are the A, B and C phase voltage characteristics of the public transformer high-voltage side, respectively; $\tilde{I}_{i,a,k}$, $\tilde{I}_{i,b,k}$ and $\tilde{I}_{i,c,k}$ are the A, B and C phase current characteristics of the public transformer in high-voltage side, respectively.

IV. TEST ANALYSIS

A. Test Analysis of Pilot 1

The proposed method is applied to a real distribution network in Dongguan, Guangdong, whose network structure is shown in Figure IV. The equivalent resistance method, which is the major line loss calculation method in China Southern Power Grid Company Limited, is also used for the comparing its effectiveness with the proposed method. When the proposed method is applied, the time interval is set to be 15 minutes. The calculation results are shown in Figure 4 and Tab. I-III.

Figure V shows the real-time line loss of pilot 1 in a typical day. It can be seen that the line loss increases gradually from 7 o'clock, and then stay in a large value from 9 to 17 o'clock. The reason is that the loads in pilot 1 are mainly the small processing factories which consume mainly the electric

power during the day time, thus the line loss of this pilot at these times is relatively large.

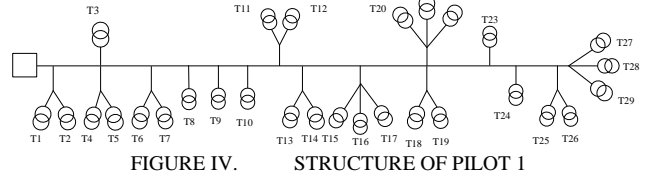


FIGURE IV. STRUCTURE OF PILOT 1

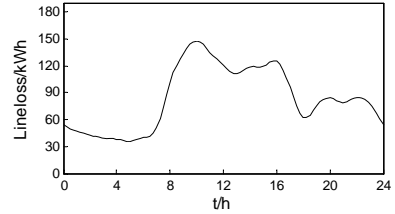


FIGURE V. CALCULATION RESULTS OF REAL-TIME LINE LOSS DURING THE TYPICAL DAY IN PILOT 1

TABLE I. CALCULATION RESULT OF LINE LOSS OF EACH LOOP IN PILOT 1

Loop	Loss	Loop	Loss	Loop	Loss
loop1	241.1708	loop11	562.6290	loop21	13.7974
loop2	155.4010	loop12	24.7449	loop22	4.9946
loop3	37.5871	loop13	101.1405	loop23	25.1765
loop4	61.8677	loop14	22.9689	loop24	26.4538
loop5	72.3295	loop15	3.73189	loop25	55.054
loop6	156.7959	loop16	50.2675	loop26	30.1814
loop7	38.4249	loop17	15.7338	loop27	16.3542
loop8	139.3663	loop18	49.9786	loop28	10.8543
loop9	71.0575	loop19	5.0040	loop29	18.2546
loop10	77.2643	loop20	2.0538		

(unit:KWH)

As shown in Table I-III, calculation results of the line loss provided by various methods are relatively small. The reason is that the power loss of the large number of special transformers is not included in the calculation of line loss of distribution network. When the calculation results of various methods are compared, it can be seen that the calculation results of the proposed method and the statistical line loss are close. Their relative deviation is only 5.45%. However, the relative deviation between the equivalent resistance method and the statistical line loss is 65.3%. This certifies the effectiveness of the proposed method in some extent.

TABLE II. CALCULATION RESULTS OF THE PROPOSED METHOD IN PILOT 1

Project	Total loss	A phase	B phase	C phase
line loss value	2110.6377	684.5334	760.4336	665.6687

(UNIT:kWh)

TABLE III. CALCULATION RESULTS OF DIFFERENT METHODS IN PILOT 1

Method	The method of equivalent resistance	Statistical line loss	The proposed method
line loss rate	1.69%	4.87%	4.6044%

B. Test Analysis of Pilot 2

The proposed method is used in another pilot including the distribution generations in Dongguan. Its structure is shown in the Figure VII, where T18, T19 and T20 are connected to the distributed generation. Select a typical day, and calculate the line loss by the proposed method and the equivalent resistance method, respectively. The real-time line loss is shown in Figure 7. The line loss value of each loop, each phase and the total line loss are shown in Table IV - V. The results provided by various methods are shown in the Table VI.

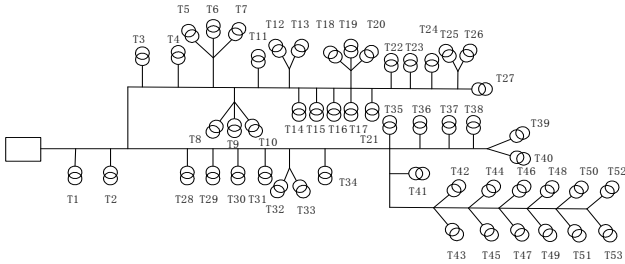


FIGURE VI. STRUCTURE OF PILOT 1

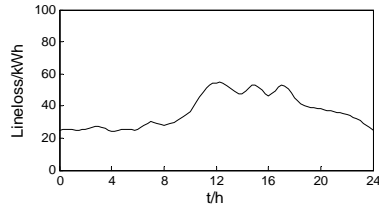


FIGURE VII. CALCULATION RESULTS OF REAL TIME LINE LOSS DURING THE TYPICAL DAY IN PILOT 2

It can be found that, the relative deviation between the equivalent resistance method and the statistical line loss is 25.46%, while relative deviation between the proposed method and the statistical line loss is 7.53%. Thus the proposed method is more suitable to calculate the line loss of distribution network including the distributed generations.

TABLE IV. CALCULATION RESULT OF LINE LOSS OF EACH LOOP IN PILOT 2

Loop	Loss	Loop	Loss	Loop	Loss
loop1	47.6621	loop19	-30.7173	loop37	32.6563
loop2	4.3117	loop20	-5.3944	loop38	20.1001
loop3	13.3312	loop21	7.4261	loop39	10.3580
loop4	28.1072	loop22	64.7861	loop40	25.6212
loop5	13.1453	loop23	76.8067	loop41	9.0686
loop6	9.3116	loop24	62.5157	loop42	11.0932
loop7	3.6143	loop25	44.2165	loop43	24.0056
loop8	16.6288	loop26	8.4729	loop44	8.7373
loop9	12.3217	loop27	6.6838	loop45	30.0599
loop10	85.2622	loop28	4.2814	loop46	12.5702
loop11	86.1164	loop29	2.7841	loop47	13.5282
loop12	7.4437	loop30	5.6842	loop48	72.3427
loop13	4.7193	loop31	72.5294	loop49	15.9137
loop14	24.3202	loop32	3.9007	loop50	21.2246
loop15	12.7484	loop33	28.3387	loop51	29.3955
loop16	8.4928	loop34	31.6356	loop52	22.1839
loop17	5.4343	loop35	25.2015	loop53	13.2262
loop18	-14.3579	loop36	32.4061		

(UNIT:kWh)

TABLE V. CALCULATION RESULTS OF THE PROPOSED METHOD IN PILOT 2

Project	Total loss	A phase	B phase	C phase
loss	2110.6337	684.5354	760.4336	665.6687

(UNIT:kWh)

TABLE VI. CALCULATION RESULTS OF DIFFERENT METHODS IN PILOT 2

Method	The method of equivalent resistance	Statistical line loss	The method of loop current
line loss rate	1.69%	4.87%	4.6044%

(UNIT:kWh)

V. CONCLUSIONS

A real-time three-phase line loss calculation method for distribution network based on characteristic measurement is proposed in this paper. Then it is applied in the real distribution network in Dongguan, Guangdong. The main conclusions are as follows:

- (1)The proposed method is able to calculate the three-phase real-time line loss of distribution network accurately when the three phases are unbalance;
- (2)The proposed method can describe the impact of distributed generations on the line loss fully, and calculate the line loss of distribution network accurately not matter the distributed generations are included or not;
- (3)The proposed method can be applied conveniently, depending not on the topology and parameters of the distribution network.

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