Study on Influence of Voltage Deviation on Loss of Low Voltage Distribution Network

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Abstract. Voltage deviation is one of the important power quality problems. Studying its impact on the power loss of low voltage distribution network is of great significance for the development of loss reduction measures and the realization of economic operation of power grid. The calculation models of transformer and line loss considering voltage deviation are derived firstly. The influence of voltage deviation on iron loss and copper loss of transformer and line loss under different load types are analysed in depth. The relationships between voltage deviation and additional loss of low voltage distribution network are obtained. The simulation verifications are carried out in PSCAD/EMTDC, which prove the accuracy and effectiveness of the calculation models.

1. Introduction
Voltage deviation is one of the important power quality problems affecting the loss of low voltage distribution network [1-3]. In the low voltage distribution network, the impedance of the transformer and the line, the high load rate and the unreasonable grid structure result in the serious and widespread voltage deviation [4-6]. According to statistics [7], the loss of the distribution part is 2.3 times that of the generation and transmission part and the power loss of the low voltage distribution network accounts for about four-fifths of the total distribution network loss, which brings huge economic losses and energy waste to the power industry and the whole society. With the lean management and service of the grid integrated energy service to the user side [8], it is urgent to analyze the impact of various power quality problems on the loss of the low voltage distribution network, so as to carry out targeted energy-saving improvement to improve power quality and realize the economic operation of the grid.

At present, the research on the additional loss of low voltage distribution network caused by power quality problems is still in its infancy at home and abroad. [9-10] propose a network loss calculation model that takes into account harmonics, and only analyze the influence of harmonics on the additional loss of low voltage distribution network. The influence of three-phase unbalance on additional losses of distribution transformers with different wiring group is studied in [11]. [12] proposes a three-phase unbalance function formula and analyzes the influence of three-phase unbalance on the additional losses of the line; In [13], the distribution of three-phase unbalanced loss increment caused by the load imbalance in power system has been studied; [14] has obtained the conclusion that the additional loss caused by the imbalance and the harmonics is greater than the sum of the additional losses when they exist alone; In [15], a decoupling method for composite power quality disturbance is proposed, which
decouples the additional loss into the sum of the three-phase unbalanced additional loss and the harmonic additional loss. The above literatures mainly focus on the effects of three-phase unbalance and harmonic power quality problems on the additional loss of low voltage distribution network. Voltage deviation is the traditional primary constrained power quality problem. The existing researches mainly focus on the hazards of excessive voltage deviation to the service life of the electrical equipment and the safe and stable operation of the power grid [1], and there is no literature to conduct in-depth research on the impact of voltage deviation on the additional loss of low voltage distribution network.

Therefore, based on the equivalent circuit of low voltage distribution network, the calculation models of transformer and line loss considering voltage deviation are derived in this paper. The influence of voltage deviation on transformer iron loss and the influence of voltage deviation on transformer copper loss and line loss under different load types are analyzed in depth. The relationships between voltage deviation and additional loss of low voltage distribution network are obtained. The simulation verifications are carried out in PSCAD/EMTDC, which prove the accuracy and effectiveness of the calculation models.

2. Mechanism Analysis of Influence of Voltage Deviation on Network Loss

2.1. Equivalent circuit model of low voltage distribution network

The equivalent circuit model in the low voltage distribution network is shown in Fig. 1. The voltage deviation of the transformer outlet and the line end are calculated as follows

\[
\beta_1 = \frac{U_1 - U_N}{U_N} \times 100\% \tag{1}
\]

\[
\beta_2 = \frac{U_2 - U_N}{U_N} \times 100\% \tag{2}
\]

Where \(\beta_1\) is the transformer outlet voltage deviation, \(\beta_2\) is the voltage deviation at the end of the line, \(U_1\) is the actual voltage at the transformer outlet (kV), \(U_2\) is the actual voltage at the end of the line (kV), and \(U_N\) is the nominal voltage of the power system (kV).

![Figure 1. Equivalent circuit diagram of low voltage distribution network.](image)

Low voltage distribution network losses mainly include transformer iron loss, transformer copper loss and line loss. In this paper, the copper loss of the transformer and line loss are collectively referred to as copper loss. The effects of voltage deviation on transformer iron loss and copper loss are studied separately in the following.

2.2. The influence of voltage deviation on transformer iron loss

The relationship between voltage deviation and transformer iron loss is

\[
P_{fe} = \left(\frac{U_1}{U_{TN}}\right)^2 P_0 = \left(\frac{U_N}{U_{TN}}\right)^2 (\beta_1 + 1)^2 P_0 \tag{3}
\]
Where \( P_{fe} \) is the actual iron loss of the transformer (MW), \( P_0 \) is the rated iron loss of the transformer (MW), and \( U_{TN} \) is the rated voltage on the low side of transformer (kV).

The additional loss of transformer iron loss caused by voltage deviation is

\[
\Delta P_{fe} = \left( \beta_1^2 + 2\beta_1 \right) \left( \frac{U_N}{U_{TN}} \right)^2 P_0
\]

It can be seen from equation (4) that the additional iron loss of the transformer is related to the voltage deviation and the rated iron loss. When the voltage deviation is constant, the greater the rated iron loss of the transformer is, the greater the additional iron loss of the transformer will be. When the voltage deviation is positive, the additional iron loss of the transformer is nonlinearly positively correlated with the absolute value of the voltage deviation; otherwise, the additional loss of the transformer is nonlinearly negatively correlated with the absolute value of the voltage deviation.

2.3. The influence of voltage deviation on transformer copper loss

When the access load types in the system are different, the voltage deviation has different effects on copper loss. Therefore, the effects of voltage deviation on copper loss of low voltage distribution network are analyzed when the system is connected to different load types. Due to the short distance and low voltage of the 380V low voltage distribution network, and the fundamental-to-ground capacitance and the phase-to-phase capacitance shunt are small and negligible, so the following analysis applies to both overhead lines and cables.

(1) Constant power load

As shown in Figure 1, when the load type in the system is only constant power load, the copper loss in the distribution network is

\[
P_C = \frac{P^2 + Q^2}{U_2^2} R_C = \frac{P^2 + Q^2}{\left( \beta_2 + 1 \right)^2 U_N^2} R_C
\]

Where \( P_C \) is copper loss (MW), \( P \) is the equivalent load active power at the end of the line (MW), \( Q \) is the equivalent load reactive power at the end of the line (Mvar), and \( R_C \) is the total resistance of the high and low voltage windings of the transformer or line resistance (Ω).

Load rate

\[
L = \sqrt{\frac{P^2 + Q^2}{S_N}} \times 100\%
\]

Where \( L \) is the load rate and \( S_N \) is the rated capacity of the low voltage distribution network (the rated capacity of the transformer).

Bringing the formula (6) into the equation (5), the additional copper loss caused by the voltage deviation can be obtained as

\[
\Delta P_C = -\frac{\left( \beta_2^2 + 2\beta_2 \right) S_N^2 L^2}{\left( \beta_2 + 1 \right)^2 U_N^2} R_C
\]

It can be seen from equation (7) that when only constant power load is connected to the system, the additional copper loss is related to the voltage deviation, the load rate, and the \( R_C \). When the voltage
deviation is constant, the higher the load rate is, the larger the transformer resistance or the line resistance is, and the larger the absolute value of additional copper loss will be. When the voltage deviation is positive, the additional copper loss is negatively correlated with the absolute value of the voltage deviation; otherwise, the additional copper loss is positively correlated with the absolute value of the voltage deviation.

(2) Constant impedance load

When the load type connected to the system is only constant impedance load, the copper loss in the distribution network is

\[ P_C = \frac{U_N^2}{Z_f^2} R_C = \left(\frac{\beta_2 + 1}{2}\right)^2 \frac{U_N^2}{Z_f^2} R_C \]  

(8)

Where \( Z_f \) is the impedance of the load (\( \Omega \)).

The additional copper loss caused by the voltage deviation is

\[ \Delta P_C = \left(\frac{\beta_2^2 + 2\beta_2}{2}\right) \frac{U_N^2}{Z_f^2} R_C \]  

(9)

It can be seen from equation (9) that when only a constant impedance load is connected to the system, the additional copper loss is related to the voltage deviation, the load impedance, and \( R_C \). When the voltage deviation is constant, the smaller the load impedance is, the larger the transformer resistance or the line resistance is, and the larger the absolute value of the additional copper loss will be. When the voltage deviation is positive, the additional copper loss is positively correlated with the absolute value of the voltage deviation; otherwise, the additional copper loss is negatively correlated with the absolute value of the voltage deviation.

(3) Constant current load

When the load type connected to the system is only constant current load, the copper loss in the distribution network is

\[ P_C = I^2 R_C \]  

(10)

Where \( I \) is the load current (kA).

It can be seen from equation (10) that when only a constant current load is connected to the system, the copper loss is independent of the voltage deviation.

(4) Integrated load

When the type of load connected to the system is integrated load, the copper loss in the distribution network is

\[ P_C = \sum \left( F_{Zp} (\beta_2 + 1) + F_{Ip} (\beta_2 + 1) + F_{Pp} \right) P_0^2 + \sum \left( F_{Zq} (\beta_2 + 1) + F_{Iq} (\beta_2 + 1) + F_{Pq} \right) Q_0^2 \]  

\[ \left( \beta_2 + 1 \right)^2 \frac{U_N^2}{Z_f^2} R_C \]  

(11)

In equation (11), \( F_{Zp} \) (\( F_{Zq} \)), \( F_{Ip} \) (\( F_{Iq} \)), and \( F_{Pp} \) (\( F_{Pq} \)) are the active (reactive) proportional coefficient of three types of load: constant impedance (Z), constant current (I), and constant power (P). \( P_0 \) is the active power of the load at the rated voltage, and \( Q_0 \) is the reactive power of the load at the rated voltage. The additional copper loss caused by the voltage deviation is
It can be known from equation (12) that when the integrated load is connected to the system, other factors are unchanged, and the influence of the voltage deviation on the additional copper loss of the low voltage distribution network is related to the ZIP load proportional coefficients.

As can be seen from the foregoing, the constant current load has no effect on the additional copper loss caused by the voltage deviation. It can be seen from equation (12) that when the relationship between the ratio of the constant impedance load to the constant power load and the voltage deviation is as shown in Fig. 2, the additional copper loss is zero.

![Figure 2. The relationship between the ratio of constant impedance load to constant power load and voltage deviation in the connected system when the additional copper loss is 0](image)

It can be seen from Fig. 2 with integrated load when the voltage deviation is between -10% and 10%, the ratio of the constant impedance load to the constant power load is between 1.11 and 0.91, that is, when the size of the constant impedance load is basically same to that of the constant power load, the voltage deviation has little effect on the additional copper loss of the low voltage distribution network.

Assume that the load rate is high, the transformer iron loss can be neglected, and the load type and size can be adjusted. When the power supply node voltage in normal operation of the system is mainly positive deviation, adjusting the ratio of constant impedance load to constant power load below the curve of Fig. 2 can reduce the network loss. When the power supply node voltage in normal operation of the system is mainly negative deviation, adjusting the ratio of constant impedance load to constant power load above the curve of Fig. 2 can reduce the network loss. That is to say, the appropriate voltage operation level within the allowable range of voltage deviation can be selected according to the load type ratio of the power supply node to reduce the network loss.

3. Simulation Verification

According to the circuit diagram shown in Fig. 1, a simulation test platform is built in PSCAD/EMTDC for simulation verification. The power supply voltage is 10kV, and the transformer parameters are shown in Table 1. The line model is JKLYJ-150, the length is 100m, the resistance is 0.03Ω, and the reactance is 0.0382Ω. The load rate of the system is about 30%. By changing the transformer tap, the transformer ratio is adjusted to 11:0.4, 10:0.4, and 9:0.4. And the accuracy and effectiveness of the loss model are...
verified under the condition that the access load type is constant power load, constant impedance load, constant current load and comprehensive load, respectively.

| Table 1. Transformer parameters |
|--------------------------------|
| Type | Ratio | Rated capacity | Wiring group | No-load loss | Load loss |
| S13  | 10:0.4 | 100kVA | Dyn11 | 106W | 1020W |

(1) Constant power load
The load type is constant power type, with rated active power of 27kW and rated reactive power of 13kvar. Simulation calculation is conducted, and the results are shown in Table 2. The variations of calculated additional iron loss in transformer and additional copper loss with voltage deviation are shown in Fig. 3.

![Figure 3](image1.png)

**Figure 3.** Relationship between additional loss and voltage deviation (constant power load)

As can be seen from Fig. 3, when the access load type is constant power type and the load rate is 30%, the voltage deviation has the greatest impact on the line additional loss, followed by the additional copper loss of the transformer, and the additional iron loss of the transformer.

(2) Constant impedance load
The access load type is set to constant impedance type, and the impedance value is 1.574Ω. The simulation calculation is performed, and the results are shown in Table 2. The variations of calculated additional iron loss in transformer and additional copper loss with voltage deviation are shown in Fig. 4.

![Figure 4](image2.png)

**Figure 4.** Relationship between additional loss and voltage deviation (constant impedance load)

It can be seen from Fig. 4 when the load type is constant impedance and the load rate is about 30%, the order of the influence of voltage deviation on additional copper loss in transformer, additional iron loss in transformer and line additional loss is consistent with Fig. 3, and the change range is basically
the same, but the change trend of additional copper loss is contrary to Fig. 3. These are consistent with the results of the previous analysis.

(3) Constant current load

The access load type is set to constant current type, and its current is 0.13634kA. The simulation calculation is performed, and the results are shown in Table 2. The copper loss is independent of the voltage deviation, and the variation of calculated additional iron loss in transformer with voltage deviation is shown in Fig. 5.

![Figure 5. Relationship between the additional iron loss and voltage deviation of transformer (constant current load)](image)

(4) Integrated load

The access load type is set to integrated type, with the active power of 27kW and the reactive power of 13kvar at the rated voltage, and the active power and reactive power proportions of the three types of ZIP load are 0.25, 0.55 and 0.2 [16], respectively. The simulation calculation is performed, and the results are shown in Table 2. The variations of calculated additional iron loss in transformer and additional copper loss with voltage deviation are shown in Fig. 6.

![Figure 6. Relationship between additional loss and voltage deviation of low voltage distribution network (integrated load)](image)

Since the constant current load is relatively high and the ratios of constant impedance load and constant power load are similar in the integrated load, it can be observed that the variation ranges of additional copper loss in transformer and line additional loss with voltage deviation in Fig. 6 are smaller than those in Fig. 3 and Fig. 4, which are consistent with the conclusions obtained in the previous analysis.

As can be seen from Table 2, the errors between the calculated values of the network loss calculation model considering voltage deviation and the simulation results are less than 5%. Therefore, the accuracy and effectiveness of the calculation model with voltage deviation are verified.
### Table 2. Simulation results of connected to different load types

| Load type          | Transformer ratio | Voltage deviation (%) | Transformer loss | Line loss |
|--------------------|-------------------|-----------------------|------------------|----------|
|                    |                   |                       | Calculated value (kW) | Measured value (kW) | Error (%) | Calculated value (kW) | Measured value (kW) | Error (%) |
|                    |                   |                       | iron loss | copper loss | Combined |                   |                   |           |
| Constant power load| 11:0.4            | -1.4                 | 13.9       | -5        | 0.07     | 12.3            | 1.312           | 1.332      | 1.50      |
|                    |                   |                       | 0.08       | 0.96      | 1.062    | 1.106           | 3.98            | 3.98       |
|                    |                   |                       | 0.12       | 0.74      | 0.869    | 0.873           | 0.46            | 0.46       |
| Constant impedance load| 11:0.4       | -12.6                | 11.0       | -5        | 0.08     | 0.75             | 0.835           | 0.870      | 4.00      |
|                    |                   |                       | 0.09       | 0.91      | 1.015    | 1.042           | 2.50            | 2.50       |
|                    |                   |                       | 0.12       | 1.11      | 1.241    | 1.290           | 3.80            | 3.80       |
| Constant current load| 11:0.4       | -13.5                | 12.1       | 1         | 0.08     | 0.91             | 0.991           | 1.024      | 3.20      |
|                    |                   |                       | 0.09       | 0.91      | 1.009    | 1.047           | 3.60            | 3.60       |
|                    |                   |                       | 0.12       | 0.91      | 1.034    | 1.079           | 4.10            | 4.10       |
| Integrated load    | 11:0.4            | -13.5                | 12.1       | 1         | 0.08     | 0.90             | 0.989           | 1.028      | 3.70      |
|                    |                   |                       | 0.09       | 0.91      | 1.010    | 1.054           | 4.10            | 4.10       |
|                    |                   |                       | 0.12       | 0.92      | 1.049    | 1.089           | 3.60            | 3.60       |

4. Conclusion
This paper deduces the power loss models of transformers and lines in a low voltage distribution network considering voltage deviation, and deeply analyzes the influence of voltage deviations on transformer iron loss and on transformer copper loss and line loss under different load types. The simulations in PSCAD/EMTDC are carried out to prove the accuracy and effectiveness of the derived calculation models. It is of great significance to analyze the loss of low voltage distribution network, formulate loss reduction measures and carry out energy-saving transformation in a targeted way, so as to improve the power quality of users and realize the economic operation of the grid.
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References
[1] X. Xiao. Power quality analysis and control [M]. Beijing: China electric power press, 2004.
[2] Otcenasova. A, Bolf. A, Altus. J, et al. The Influence of Power Quality Indices on Active Power Losses in a Local Distribution Grid [J]. Energies, 2019, 12 (7).
[3] H. Chen, X. Liu, X. Chen, et al. Identification of Key Energy-consumption Sectors and Loss Reduction Plan for Distribution Networks [J]. Power Capacitor & Reactive Power Compensation, 2016, 37 (06): 40 - 45.
[4] Z. Su, M. Ze, C. Kong, et al. Research on Calculation Method of Distribution network Line Loss Based on Influence Factors of Line Loss [J]. Electrotechnical Application, 2013, 32(S2): 413 - 416.
[5] W. Yang, B. Wang, Z. Cheng, et al. Optimized Decision Approach of Loss Reduction Plan for Medium- and Low-Voltage Urban Distribution Networks [J]. Power System Technology, 2014, 38 (09): 2598 - 2604.
[6] Y. Zhang, M. Zhang. Feasible Methods to Improve the Voltage Quality of Distribution Network [J]. Power Capacitor & Reactive Power Compensation, 2015, 36 (01): 26 - 29.
[7] X. Liu. Research on loss reduction of distribution network of qinglong power supply company [D]. Baoding: north China electric power university, 2011.
[8] Y. Wang, Y. Li, J. Ye, et al. Research on Development Model of Power Demand Side Management during Electric Power System Reform [J]. Electric Power, 2016, 49 (S1): 75 - 81+88.
[9] C. Wei, Q. Li, J. Jiang. Quantification Calculation and Modeling Simulation of Distribution Network Losses Considering Harmonic Factor [J]. Journal of Zhengzhou University (Engineering Science), 2018, 39 (01): 53 - 58+66.
[10] M. Jawad G, Hossein M. Impact of Harmonics on Power Quality and Losses in Power Distribution Systems [J]. International Journal of Electrical and Computer Engineering, 2015, 7 (1): 166 - 174.
[11] Z. Yan, X. Lei, J. He, et al. Study on the influence of three-phase unbalance on distribution transformer loss [J]. Electrical Measurement & Instrumentation, 2017, 54 (16): 43 - 49.
[12] Z. Zhu, F. Ye. Improved Method for Theoretical Line Loss Calculation of Low-voltage Distribution Network [J]. Electrical Measurement & Instrumentation, 2012, 49 (11): 6-10+70.
[13] C. Xu, H. Li, C. Feng, et al. Distribution of Additional Loss in Unbalanced Power System[J]. Water Resources and Power, 2016, 34 (08): 189 - 193.
[14] C. Feng, C. Xu, H. Li, et al. Analysis of the Influence of Three-phase Current Unbalance and Harmonics on Grid Loss [J]. Electrotechnical Application, 2016, 35 (13): 47 - 52.
[15] L. Jiang, J. Meng, J. Zhang, et al. Decoupling analysis of additional loss of key equipment in low voltage distribution network under complex power quality disturbance [J]. Electrical Measurement & Instrumentation, 1-10 [2019-08-16]. http://kns.cnki.net/kcms/detail/23.1202.TH.20190805.1523.006.html.
[16] Z. Gao, J. Jia, Q. Wang. Foundation and Application of Grid Synthesis Load Model [J]. Hebei Electric Power, 2011, 30 (06): 6 - 9.