Study on the Influence of Aging and High Impedance Faults on Line Loss of 10kV Distribution Line

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Abstract. With the rapid development of economy in China, the distribution network structure of China tends to be complicated. The overhead line is affected by environmental factors so that aging and high impedance faults occur, which increases the line loss and is not conducive to reliable and economic operation of the power system. In order to analyse the influence of aging and high impedance fault on the line loss of distribution network, this paper firstly establishes the mathematical model of the aging of 10kV distribution line, in which the impedance variation of each type of line with different operating years is obtained based on the actual measurement data. Then, the high-impedance grounding additional loss model under different grounding medium is established by experimental statistics. Finally, taking a distribution network as an example, the equivalent resistance method is utilized to calculate and analyse the influence of aging and ground faults on the distribution network loss. The results of the example show that on the one hand, the line loss of the distribution network increases exponentially with the operating period, and the line loss rate of the line with a long operating period easily exceeds the line loss standard; on the other hand, the high impedance fault will greatly increase the line loss rate for distribution network of smaller scale.

1. Introduction

With the gradual improvement in economy and comprehensive national strength of China, the situation of power system has gradually changed from a general lack of electricity to sufficient power supply. Under such a background, improving the efficiency of transmission and distribution systems and reducing various types of losses are important tasks for energy conservation and emission reduction. The distribution network occupies a major part of the entire power system due to its long line length, complex structure and wide distribution area. Moreover, there is large difference in the operation of various distribution networks, and the distribution network loss contributes the main part of the loss of entire power system. Therefore, it is very important to study the source of distribution network loss and propose reduction measures for various types of loss.

The research on distribution line loss in European and American countries started early and adopted various research methods. Reference [1] provides in-depth analysis of active and reactive power distribution in power network, and summarizes a method for reducing line loss by solving reactive power. It is proposed in [2] to utilize the unified power flow controller (UPFC) to control the current and voltage of the operating grid, so that the power line operates at the optimal state, thereby
reducing the line loss. In reference [3], the distribution coefficient of power network flow is used to distribute the power line loss, and the calculation model is analyzed.

In the development of power grids in China, there has always been a phenomenon that transmission is valued while distribution is ignored, which causes that the construction of distribution system is far behind the transmission system in China. The traditional statistical line loss calculation methods mainly include the average current method, the RMS current method, the maximum load loss hour method, the loss factor method [4], etc. Because the calculation principle of traditional theoretical line loss is simple and easy, it has been widely applied in the field of distribution network line loss in China. But the considered influence factors are relatively limited and the impact of aging and high impedance fault (HIF) on the distribution network loss is not studied in depth in the traditional theoretical line loss. On the one hand, the results from the existing research [5] show that the aging of overhead transmission line has a significant impact on the line impedance. On the other hand, HIF are different from metallic ground faults [6]. The fault currents of HIF are relatively small and difficult to be identified, which continuously discharge to ground so that considerable magnitude loss will be produced. Therefore, it is very important for the research on network loss to study the aging and HIF of the distribution network.

Based on the above content, firstly, through fitting method, the aging mathematical model of 10kV distribution line is established on the basis of experimental data. Then, the high-impedance grounding additional loss model under different grounding medium is established by experimental statistics. Finally, the equivalent resistance method is used to calculate and analyze the influence of aging and ground faults on the distribution network loss.

2. Mathematical model of line aging

2.1. Equivalent model of line

Since the length of the 10kV line is usually within 100km, its equivalent circuit can ignore the influence of the distributed parameter, and can be expressed by the concentrated parameter in (1):

\[
R = r \cdot l \\
X = x \cdot l \\
G = g \cdot l \\
B = b \cdot l
\]

(1)

where \( R \) is the total resistance, \( r \) is the unit length resistance, \( X \) is the total reactance, \( x \) is the unit length reactance, \( G \) is the conductance, \( g \) is the unit length conductance, \( B \) is the susceptance, and \( b \) is the unit length susceptance.

![Figure 1. Equivalent circuit of line.](image)

Normally, there will be no corona on 10kV lines, and its insulator leakage is low, thus it can be assumed that \( G = 0 \). In addition, the line susceptance has little effect on the circuit calculation when the voltage level is not high, thus it can be assumed that \( X = 0 \). The line can be equivalent to the \( \Pi \) type circuit shown in figure 1, where \( Z = R + jX \). Based on this, the line is equivalent to a total impedance \( Z \) in series.

2.2. Line aging model based on actual measurement

In order to analyse the relationship between line resistance and aging and line operating time, several models commonly used in 10kV distribution lines are selected as experimental objects for resistance testing: LJ-150, LGJ-185, LGJJ-185, LGJQ-300. Each line is tested with a test sample with the
operation time of 2-22 years and the length of 10 m. For a more intuitive and significant change in resistance, the test sample resistance is converted to a length of 100 km, as shown in Table 1. For a more visual display, the resistance change data of Table 1 is plotted in figure 2.

| Years | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 |
|-------|---|---|---|---|----|----|----|----|----|----|----|
| LJ-150| 21| 21.2| 21.4| 21.5| 21.8| 22 | 22.3| 22.6| 22.8| 23.1| 23.3|
| LGJ-185| 17| 17.1| 17.2| 17.2| 17.3| 17.5| 17.7| 18  | 18.2| 18.3| 18.4|
| LGJJ-185| 17| 17| 17.1| 17.2| 17.2| 17.3| 17.4| 17.5| 17.5| 17.6| 17.6|
| LGJQ-300| 11| 11.1| 11.2| 11.3| 11.5| 11.9| 12.1| 12.3| 12.4| 12.6| 12.8|

Figure 2. Resistance curve of 100km line during aging process.

As can be seen in figure 2, the resistance of the four lines has hardly changed within four years of operation, then began to increase slowly, and increased more and more rapidly after 10 years. After 15 years of operation, the increase of resistance has further accelerated. It can be seen that the resistance curve basically follow exponential growth, so the resistance curve is fitted by the exponential function shown in (2):

$$R(t) = Ae^{mt} + B$$

where $A$, $m$ and $B$ are fitting parameters.

Four resistance curves are fitted by curve fitting tool in MATLAB. The fitting results are shown in (3), the fitting confidence of which is more than 95%. The fitting curves are shown in figure 3.

$$R_{LJ-150}(t) = 1.533e^{0.044t} + 19.38$$
$$R_{LJ-380}(t) = 0.662e^{0.055t} + 16.26$$
$$R_{LGJJ-185}(t) = 2.445e^{0.011t} + 14.50$$
$$R_{LGJQ-300}(t) = 2.089e^{0.039t} + 8.7789$$

3. Mathematical model of HIF
In the distribution network, up to 80% of faults are single-phase ground faults. When overhead lines are in contact with branches, cement, sand, animals, etc., the grounding resistance is as high as several hundred ohms or thousands of ohms, becoming a HIF, accounting for about 5% of the total number of faults. The most obvious feature of HIF is that the fault current is small, and the current at the fault
point may be only 10% or even lower of the load current during normal operation of the system \[7\].

The research experimental data shows that the typical values of different types of HIF currents are between 0-75 A, and the specific values are shown in Table 2 \[7\].

| Medium                  | Current/A |
|-------------------------|-----------|
| Cement and sand         | 5         |
| Wet sand                | 15        |
| Dry turf                | 20        |
| Dry grass               | 25        |
| Wet turf                | 40        |
| Wet grass               | 50        |
| Reinforced concrete     | 75        |

Because the location of HIF in the distribution network has strong uncertainty, and the value of the grounding resistance varies greatly under different grounding medium, it is difficult to establish an exact equivalent resistance model. The grounding resistance of HIF is relatively large, so the short-circuit current is usually stable. Therefore, the fault point of HIF can be equivalent to a constant resistance, and its power loss can be expressed by (4) as an additional loss of line loss.

\[
P_{HIF} = U \cdot I_{HIF}
\]  

(4)

where \(P_{HIF}\) is the high-impedance grounding loss power, \(I_{HIF}\) is the fault current value, and \(U\) is the rated voltage.

The typical additional losses generated by each of the above types of HIF at a rated voltage of 10 kV are shown in Table 3.

| Medium                  | Loss/kW |
|-------------------------|---------|
| Cement and sand         | 50      |
| Wet sand                | 150     |
| Dry turf                | 200     |
| Dry grass               | 250     |
| Wet turf                | 400     |
| Wet grass               | 500     |
| Reinforced concrete     | 750     |

4. Equivalent resistance method for line loss calculation of distribution network

The equivalent resistance method approximately calculate the variable line loss \[8\] and its theoretical basis is the average current method. The equivalent resistance method regards the variable loss of the distribution network as the loss caused by the average current at the head of the line passing through the sum of equivalent resistance of the line and the distribution transformer \(R_{eq} = R_{LZL} + R_{LZB}\), and the equivalent resistance model of distribution lines is shown in figure 4.

![Figure 4. Equivalent resistance model.](image)
The calculation of line equivalent resistance is based on the plotted line diagram and the actual copying electricity on the secondary side of distribution transformer. It is calculated from the end to the head of the line, from the branch to the trunk, which is the order of increasing the line electricity quantity, and the common expression is as follows [9]:

\[
R_{DZ,L} = \frac{\sum_{j=1}^{n} \left( A_{b,j} \right)^2 R_j \Sigma}{\left( \sum_{i=1}^{m} A_{b,i} \right)^2}
\]  

(5)

where \( A_{b,j} \) is the sum of actual copying electricity on the secondary side of distribution transformer for line \( j \) power supply, \( n \) is the total segment number for line segmentation, \( A_{b,i} \) is the actual copying electricity on the secondary side of distribution transformer, \( m \) is the number of transformers on the whole line, \( R_j \) is calculation resistance of line wire for section \( j \): \( R_j = r_j L \), \( r_j \) is unit length resistance and \( L \) is the length of the line.

Similarly, the general formula for calculating the total equivalent resistance of transformer winding is [9]:

\[
R_{DZ,B} = \frac{\sum_{i=1}^{m} \left( A_{b,i} \right)^2 R_{B,i}}{\left( \sum_{i=1}^{m} A_{b,i} \right)^2}
\]  

(6)

where \( R_{B,i} \) is the equivalent resistance of the \( i \)-th distribution transformer winding to the primary side, which is calculated by the following formula:

\[
R_{B,i} = \Delta P_{k,i} \left( \frac{U_{1N}}{S_{e,i}} \right)^2 \times 10^5
\]  

(7)

where \( \Delta P_{k,i} \) is the rated short-circuit loss power of the \( i \)-th distribution transformer, \( S_{e,i} \) is the rated capacity of the \( i \)-th distribution transformer, and \( U_{1N} \) is the rated voltage for primary side of distribution transformer.

This paper mainly analyzes the loss of the distribution line, and believes that the loss of the distribution transformer remains unchanged with time.

5. Example analysis of impact of aging and faults on line loss

5.1. Impact of aging on line loss

Taking a 10kV small-scale distribution system as an example, its power grid structure is shown in figure 5, which contains 10 distribution transformers and 12 lines. The total capacity of the transformers is 490 kVA, and the average power factor of the lines is 0.75.
Figure 5. Example distribution network system.

The 100km resistance fitting formula in (3) is converted into a resistivity changing formula so that the resistance of each line at different years can be obtained corresponding to the length of each line. By substituting the resistance value of each line into the equivalent resistance method, the line loss and line loss rate of different years can be obtained, as shown in Table 4, and the data of Table 4 is plotted in figure 6.

Table 4. Line loss and line loss rate.

(a) Line loss.

| Years | Load rate(%) | 2     | 4     | 6     | 8     | 10    | 12    | 14    | 16    | 18    | 20    | 22    |
|-------|-------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 20    |             | 94.93 | 95.25 | 95.58 | 95.75 | 96.24 | 96.57 | 97.06 | 97.54 | 97.85 | 98.37 | 99.03 |
| 40    |             | 234.4 | 235.6 | 236.9 | 237.5 | 239.4 | 240.7 | 242.6 | 244.4 | 245.6 | 247.6 | 250.1 |
| 60    |             | 484.3 | 487.1 | 490.2 | 491.7 | 496.0 | 499.0 | 503.4 | 507.7 | 510.5 | 515.1 | 521.0 |
| 80    |             | 800.1 | 805.2 | 810.2 | 812.7 | 820.3 | 825.3 | 832.9 | 840.4 | 845.1 | 853.1 | 863.2 |

(b) Line loss rate.

| Years | Load rate(%) | 2     | 4     | 6     | 8     | 10    | 12    | 14    | 16    | 18    | 20    | 22    |
|-------|-------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 20    |             | 0.0527| 0.0529| 0.0531| 0.0532| 0.0535| 0.0537| 0.0539| 0.0542| 0.0544| 0.0547| 0.0550|
| 40    |             | 0.0664| 0.0668| 0.0672| 0.0673| 0.0679| 0.0682| 0.0688| 0.0693| 0.0696| 0.0702| 0.0709|
| 60    |             | 0.0900| 0.0906| 0.0911| 0.0914| 0.0922| 0.0928| 0.0936| 0.0944| 0.0949| 0.0958| 0.0968|
| 80    |             | 0.1131| 0.1141| 0.1148| 0.1152| 0.1163| 0.1170| 0.1181| 0.1191| 0.1198| 0.1209| 0.1223|
It can be seen from the calculation results that both the total line loss and the line loss rate increase exponentially with the operating period. The loss brought by aging is relatively in the distribution network with operation time of less than 10 years. However, when the operation time exceeds 10 years, the increase of the line loss is significant, so the line exceeding 10 years is the focus of the loss reduction management. Moreover, for the case where the load rate is low, the increase of the line loss rate is higher than that of the case where the load rate is high, so the increased line loss due to aging of the low load distribution network is more significant.

5.2. Impact of HIF on line loss
Since HIF usually occurs in a large-scale distribution network, the main feeder F4 in the improved IEEE-RBTS Bus6 test system is taken as an example [10], as shown in figure 7, including 1 bus and 26 feeder sections. It is distributed in three types of areas: township, rural and mountainous area. The fault mediums that may occur in each area is shown in Table 5. The daily average load of the distribution network is 4.815 MW.

Figure 6. Changing curve of line loss and line loss curve.

(a) Line loss changing curve                 (b) Line loss rate changing curve

Figure 7. Example network of HIF loss.
Table 5. Typical losses of various types of HIF.

| Area          | Fault medium                           |
|---------------|----------------------------------------|
| township      | Reinforced concrete, cement, dry turf, dry grass |
| rural         | Reinforced concrete, wet sand, cement   |
| mountainous   | Dry turf, dry grass, wet turf, wet grass |

Because the location and grounding medium of HIF are uncertain, and multiple ground faults may occur at the same time, in order to simulate the influence of HIF on line loss in different scenarios, several scenarios are randomly generated by the method of Monte Carlo sampling fault components in the distribution network reliability assessment.

Step 1: The simulation time and fault time are initialized respectively: \( H = 0 \), \( TTF = 0 \).

Step 2: The \( TTF \) (Time to Fault) and \( TTR \) (Time to Repair) of all components are generated, which are sequentially arranged to form operation time sequence of each component in the total simulation time:

\[
\begin{aligned}
TTF_i &= -\ln \sigma / \lambda_i \\
TTR_i &= -\ln \sigma / \mu_i
\end{aligned}
\]  

(8)

where \( \lambda_i \) and \( \mu_i \) are the outage rate and the repair rate of component \( i \), respectively, and \( \sigma \) is a random number between \((0, 1)\) which obeys uniform distribution.

Step 3: Combining the operation status sequence of each component, identify one or several components with the smallest \( TTF \) as fault components.

Monte Carlo simulation sampling method was used 7 times to sample the fault location as well as the fault medium. The ground loss of the sample was calculated according to the data in Table 3, and the ground loss rate was calculated. The results are shown in Table 6.

Table 6. Typical losses of various types of HIF.

| Fault line number | Grounding loss (kW) | HIF loss (%) |
|-------------------|----------------------|--------------|
| 1, 8, 21          | 1150                 | 23.88        |
| 5, 10, 17         | 750                  | 15.57        |
| 3, 8               | 250                  | 5.192        |
| 4, 11              | 1000                 | 20.76        |
| 7                  | 50                   | 1.038        |
| 9, 19, 20, 26     | 1050                 | 21.81        |
| 6                  | 750                  | 15.57        |

It can be seen from the calculation results that for a distribution network with a considerable scale, when there are multiple HIFs in the distribution network, grounding loss of hundreds or even thousands of kilowatts will be generated. For the distribution network with an average daily load of several megawatts, the loss rate will exceed 10%. Moreover, when the self-generated losses of lines are considered as well, the total loss will far exceed the line loss standard. Therefore, when a HIF occurs in the distribution network, its continuous and uninterrupted discharging to the ground will cause a large power loss, and its huge continuous heating will bring great hidden danger to the surrounding area of lines. In terms of both economy and safety, it is very important to detect and handle HIF in time.

6. Conclusion

On the one hand, this paper establishes the aging model of distribution network line based on the measured aging data of distribution lines. On the other hand, the loss model of HIF is established on
the basis of experimental statistics, and the influence of aging and HIF on distribution network line loss is analysed by an example. The following conclusions are drawn:

1) The resistance value of distribution lines increases exponentially with the operating years of lines, causing that the total line loss and line loss rate also increase exponentially with operating years.

2) The loss growth brought by aging of distribution network with low load rate is significantly higher than that of high load line, so low load line is also the focus of distribution network loss reduction.

3) The loss caused by HIF is continuous. For small-scale distribution network, the line loss rate will increase greatly after HIF occurs, so as to exceed the line loss standard.

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