

Cable Overheating Risk Warning Method Based on Impedance Parameter Estimation in Distribution Network

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Abstract. Cable overheating will lead to the cable insulation level reducing, speed up the cable insulation aging, even easy to cause short circuit faults. Cable overheating risk identification and warning is necessary for distribution network operators. Cable overheating risk warning method based on impedance parameter estimation is proposed in the paper to improve the safety and reliability operation of distribution network. Firstly, cable impedance estimation model is established by using least square method based on the data from distribution SCADA system to improve the impedance parameter estimation accuracy. Secondly, calculate the threshold value of cable impedance based on the historical data and the forecast value of cable impedance based on the forecasting data in future from distribution SCADA system. Thirdly, establish risks warning rules library of cable overheating, calculate the cable impedance forecast value and analysis the change rate of impedance, and then warn the overheating risk of cable line based on the overheating risk warning rules library according to the variation relationship between impedance and line temperature rise. Overheating risk warning method is simulated in the paper. The simulation results shows that the method can identify the impedance and forecast the temperature rise of cable line in distribution network accurately. The result of overheating risk warning can provide decision basis for operation maintenance and repair.

1. Introduction

Power cable is indispensable equipment in power system which account for more and more in urban distribution network. With the development of economic and the increasing load, the operating equipment of power cable is becoming more and more complex [1-3]. When the cable temperature exceeds the rated value because of overload or increasing contact resistance of cable connector, the internal insulation dielectric strength of cable line will decline and the cable insulation aging will accelerate fast [4-5]. If the insulation aging is serious, the insulation material will melt, and then lead to short circuit, even result to explosions and fires [6-8]. It will bring great harm to the operation of distribution network and the safety to operator [9]. Therefore, it is necessary to find an effective and practical method to diagnosis whether power cable is overheating timely and accurately before the cable temperature exceeding the rated value so that the operator can take some effective measures to prevent overheating.

At present, the operating temperature of cable conductor cannot be measured directly so that the temperature rise of cable could not perceive accurately by using traditional temperature measurement method [10-13]. Actually, there is a linear relationship between cable temperature and resistance of cable [14]. The higher the cable temperature is, the bigger the cable resistance is [15]. Therefore, a



new overheating risk early warning method which based on the impedance parameter online estimation is provided in the paper. The resistance of cable is calculated online by multi-state measurement voltage, current, reactive power and active power data from SCADA system. Then the cable resistance change rule is analyzed and the future resistance is calculated based on the grey forecasting theory. At last, according to the relationship between impedance and temperature rise of cable line and the resistance rated value, the overheating risk can be diagnosed accurately in the paper.

2. Overheating Risk Early Warning of Cble Line Based on Impedance Parameters Estimation

2.1. Impedance Parameter Estimation

The impedance parameters of cable line are estimated based on multi-period SCADA system measurement voltage and current data. Traditional π equivalent circuit model is used in the paper. Suppose the reference direction of the power and current which flow into the cable line is positive. The equivalent circuit model is shown in Figure 1. Where, 1 and 2 is the beginning node and the end node respectively. \dot{I} is the current phasor, \dot{U} is the voltage phasor, R is the resistance of cable, X is the reactance of cable, and B is the susceptance of cable.

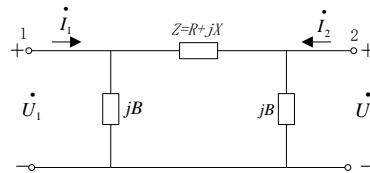


Figure 1. π equivalent circuit model

Firstly, multi-period SCADA system measurement equation of cable is established. Where, the parameters such as resistance, reactance and the ground capacitance are state variable in the equation. Second, taking the estimated value of the cable parameters as the sample and taking the variance coefficient threshold of the random sample as the convergence criterion, calculate the mean value of the cable parameters iteratively. The calculation results are regarded as the parameter estimation value.

Based on the multi-period measurement data of SCADA system and the measurement equation, the cable parameters are estimated as following steps:

(a) Calculate the estimated value of cable parameters in k period

The equations of voltage magnitude, active power and reactive power measurement data of cable line in k period time is as follows:

$$(4P_{2(k)}^2 + 4Q_{2(k)}^2 + 4Q_{2(k)}B_{(k)}U_{2(k)}^2 + B_{(k)}^2U_{2(k)}^4)R_{(k)} - 4U_{2(k)}^2(P_{1(k)} + P_{2(k)}) = 0 \quad (1)$$

$$(4P_{2(k)}^2 + 4Q_{2(k)}^2 + 4Q_{2(k)}B_{(k)}U_{2(k)}^2 + B_{(k)}^2U_{2(k)}^4)X_{(k)} - 4U_{2(k)}^2(Q_{1(k)} + Q_{2(k)}) - 2B_{(k)}(U_{1(k)}^2 + U_{2(k)}^2)U_{2(k)}^2 = 0 \quad (2)$$

$$\begin{aligned} & [2U_{2(k)}^2 - 2P_{2(k)}R_{(k)} - (2Q_{2(k)} + B_{(k)}U_{2(k)}^2)X_{(k)}]^2 + \\ & [2P_{2(k)}X_{(k)} - (2Q_{2(k)} + B_{(k)}U_{2(k)}^2)R_{(k)}]^2 - 4U_{1(k)}^2U_{2(k)}^2 = 0 \end{aligned} \quad (3)$$

The estimated value of cable parameters in k period time can be solved by using Newton method.

(b) Calculate the mean value of the estimated value of cable parameters

The mean value calculation formula of the estimated value of cable parameters in a long period time N is shown as follows:

$$\bar{R} = \frac{1}{N} \sum_{k=1}^N R_{(k)} \quad (4)$$

$$\bar{X} = \frac{1}{N} \sum_{k=1}^N X_{(k)} \quad (5)$$

$$\bar{B} = \frac{1}{N} \sum_{k=1}^N B_{(k)} \quad (6)$$

Where, \bar{R} , \bar{X} , \bar{B} is the mean value of the resistance estimation value, the reactance estimation value, and the susceptance estimation value respectively.

Suppose R , X , B is represented by a . The variance coefficient of mean value of cable parameter estimated value η_a is shown as:

$$\eta_a = \frac{\sqrt{\frac{1}{N(N-1)} \sum_{k=1}^N (a_{(k)} - \bar{a})^2}}{\bar{a}} \quad (7)$$

$$\eta_2 = \max(\eta_a) \quad (8)$$

Where, η_a is the variance coefficient of \bar{R} , \bar{X} , \bar{B} . η_2 is the maximum value of η_R, η_X, η_B .

When η_2 is less than the convergence precision ε_2 of parameter estimation, calculate and output \bar{R} , \bar{X} , \bar{B} which are the correct estimated value of parameters.

2.2. Resistance Forecasting Based on the Grey Prediction Theory

Grey prediction is to find and master the situation changes law of the system by the processing of the original data and grey prediction model and make a scientific quantitative forecast to the future situation of the system. By dealing with a series of original historical data and looking for the change law of the system, a new data sequence which can reflect the strong regularity can be generated by the grey prediction model. Then the corresponding grey differential equation model is established so as to predict the development station in future. In this way, we can predict the characteristic value of a certain time in the future.

The grey model $GM(1,1)$ can be defined as follows:

$$x^{(0)}(k) + az^{(1)}(k) = b \quad (9)$$

Where

$$z^{(1)}(k) = 0.5x^{(1)}(k) + 0.5x^{(1)}(k-1) \quad (10)$$

$x^{(1)}(k)$ is the primary accumulation of $x^{(0)}(k)$.

The defined equation of $GM(1,1)$ is close to the whitening differential equation of $GM(1,1)$ which is shown as follows:

$$\frac{dx^{(1)}}{dt} + ax^{(1)} = b \quad (11)$$

The value of a and b can be determined by formula (11).

The specific steps of modeling and forecasting by $GM(1,1)$ are as follows:

Step 1: Obtain original data sequence $x^{(0)}(k)$.

$$x^{(0)}(k) = (x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(n)) \quad (12)$$

The forecasting data sequence $x^{(1)}(k)$ is the primary accumulating generating of primitive data sequence $x^{(0)}(k)$, that is:

$$x^{(1)}(k) = \sum_{m=1}^k x^{(0)}(m) \quad (13)$$

Step 2: Substitute $k=1,2,3,\dots,n$ into equation (9), and the matrix equation group can be obtained as follows:

$$\begin{bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(n) \end{bmatrix} = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -z^{(1)}(n) & 1 \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} \quad (14)$$

Suppose: $Y_n = [x^{(0)}(2), x^{(0)}(3), \dots, x^{(0)}(n-1), x^{(0)}(n)]^T$

$$B = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -z^{(1)}(n) & 1 \end{bmatrix} = \begin{bmatrix} -0.5(x^{(1)}(1) + x^{(1)}(2)) & 1 \\ -0.5(x^{(1)}(2) + x^{(1)}(3)) & 1 \\ \vdots & \vdots \\ -0.5(x^{(1)}(n-1) + x^{(1)}(n)) & 1 \end{bmatrix} \quad (15)$$

Step 3: Solve the grey parameter \mathcal{G} by using the least square method.

$$\mathcal{G} = [a, b]^T, \quad \mathcal{G} = (B^T B)^{-1} B^T Y_n \quad (16)$$

Step 4: Substitute a and b into the whitening differential equation of $GM(1,1)$.

$$\hat{x}^{(1)}(k+1) = (x^{(0)}(1) - b/a)e^{-ak} + b/a \quad (17)$$

Step 5: The prediction value $\hat{x}^{(0)}(k+1)$ can be obtained by the following formula:

$$\hat{x}^{(0)}(k+1) = \hat{x}^{(1)}(k+1) - x^{(1)}(k) \quad (18)$$

Step 6: Test the precision of the model by using the relative residuals formula:

$$e^{(0)}(k) = \left[x^{(0)}(k) - \hat{x}^{(0)}(k) \right] / [x^{(0)}(k)] \times 100\% \quad (19)$$

If the test is not qualified, establish the residuals $GM(1,1)$ model to modify the original model.

2.3. Overheating Risk Early Warning Based on Resistance Estimated Value

Cable overheating will lead to the cable insulation level reducing, speed up the cable insulation aging, even easy to cause short circuit faults. Cable overheating risk identification and warning is necessary for distribution network operators. Cable overheating risk warning method based on impedance parameter estimation is proposed in the paper to improve the safety and reliability operation of distribution network.

The overheating risk warning step is as follows:

Step 1: Obtain $n \times m$ group voltage, current, active power and reactive power measurement datas of A,B,C three phase of cable line from SCADA system in a history period time of T_1, T_2, \dots, T_n .

Step 2: Calculate the impedance parameter estimated values Z_1, Z_2, \dots, Z_n of cable line by using the measurement datas.

Step 3: Calculate the mean value of impedance parameters sequence $\overline{Z_1}, \overline{Z_2}, \dots, \overline{Z_n}$ as the original sequence of the GM(1,1).

Step 4: Calculate the prediction value of impedance parameters based on the grey prediction model.

Step 5: Compare the forecasting resistance value to the raltaed value predetermined. Use the risk mechanism preestablished to diagnose whether the cable operates in overheating situation.

Step 6: If the cable operates in normal situation, return to step 2.

Step 7: If the cable operates in overheating situation, the risk warning information will be given, and return to step 2 to continue overheating risk diagnose.

3. Case Study

In order to verify the validity of overheating risk warning method proposed in the paper, choose a 10 kV cable line with 10km length which has measuring device installed on both ends for case study. The basic parameters of the cable line are shown in Table 1.

Table 1. The Basic Parameters of the Cable Line

Temperature (°C)	Rated voltage (kV)	Cross section (mm)	Resistance (Ω/km)	Reactance (Ω/km)	Buried allowable load flow (A)
20	10kV	240	0.090	0.086	455

3.1. Impedance Parameter Estimation Simulation

The measurement datas of the first time period obtained from SCADA system are shown in Table 2.

Table 2. The Measurement Datas of the First Time Period Obtained from SCADA System

U1 (Kv)	P1 (kW)	Q1 (kvar)	U2 (kV)	P2 (kW)	Q2 (kvar)
9.91	951.46	277.51	9.90	948.69	276.70

Obtain the measurement datas of the first m time periods and calculate mean value of the impedance estimated value by using the parameter estimation method proposed in the paper. Take the measurement datas of the first 100 time periods for example, the simulation results are shown as follows:

$$\overline{R} = \frac{1}{100} \sum_{k=1}^{100} R_{(k)} = 1.05\Omega \quad (20)$$

$$\overline{X} = \frac{1}{100} \sum_{k=1}^{100} X_{(k)} = 0.98\Omega \quad (21)$$

Suppose that m=100, 500, 800, 1000, the parameters estimation results of different time period are shown in Table 3.

Table 3. The Parameters Estimation Results of Different Time Period

m	Mean value of the impedance estimated value (Ω)	Impedance real value (Ω)	Error (%)
100	1.05+j0.98	0.9+j0.86	15.5%
500	0.94+j0.83	0.9+j0.86	3.5%
800	0.92+j0.88	0.9+j0.86	2%
1000	0.92+j0.85	0.9+j0.86	1.5%

The cable parameter estimation results show that the estimation error is within the limit of 3%. The amount of measurement data has certain impact on the estimation result. The greater the amount of data is, the more accurate the calculation results are. When the amount of measurement data reaches a certain number such as more than 800, a small amount of bad data has little effect on the calculation

results; while, when the amount of measurement data has not reached a certain size, the bad data has a great impact on the calculation results.

In the paper, we obtain twenty times 800 group measurement datas to estimate the impedance parameter, and the simulation results are shown in Table 4.

Table 4. Twenty Times Estimation Results

n	Mean value of resistanc parameter estimation (Ω)	Mean value of reactance parameter estimation (Ω)
1	0.892302	0.852302
2	0.892236	0.852236
3	0.895504	0.855504
4	0.897075	0.857075
5	0.903908	0.863908
6	0.885092	0.845092
7	0.909259	0.869259
8	0.921695	0.881695
9	0.903091	0.863091
10	0.902786	0.862786
11	0.893093	0.853093
12	0.893071	0.853071
13	0.900192	0.860192
14	0.895633	0.855633
15	0.901019	0.861019
16	0.904125	0.864125
17	0.895141	0.855141
18	0.905612	0.865612
19	0.899739	0.859739
20	0.902028	0.862028

3.2. Grey Prediction of Resistance Parameter

In order to make the grey prediction model established in the paper more close to the actual physical model of impedance change rule, the number of historical data obtained from SCADA systme has great impact on the predicted results of impedance. It is not the lager number of historical data, the more accurate the prediction results are. If the number of historical data is larger, the prediction results will not be accurate by the impact of the old data. If the number of historical data is less, the prediction results will not be accurate by the impact of the irregular changes of the historical data. Simulation result in Figure shows that the grey prediction model which established by using the latest nine historical data in the paper not only reflect the change law of the historical data, but also can not be affected by the irregular change of old historical data.

In order to verify the validity of the grey prediction model proposed in the paper, use the first 10 group data in Table 4 as the input data of the grey prediction model and caculate the prediction value of the resistance. Take the second 10 group data in Table 4 as the real value of resistance and analyze the grey prediction model validity. The results are shown in Table 5.

Table 5. Prediction Results

n	Real value of R (Ω)	Predicted value of R (Ω)	Average error (%)
1	0.893093	1.007389	4.02%
2	0.893071	0.886063	

3	0.900192	0.92191
4	0.895633	0.930357
5	0.901019	0.888107
6	0.904125	0.82960
7	0.895141	0.838525
8	0.905612	0.876596
9	0.899739	0.838749
10	0.902028	0.945538

It can be seen from Table 5 that grey prediction model has a good prediction effect. To some extent, the grey prediction model can reduce the irregular change of the historical data. The grey prediction model has higher prediction accuracy and the prediction average accuracy is about 95% and also can reflect the change trend of impedance parameters better.

3.3. Overheating Risk Warning Criterion of Cable Line

Obtain a large number of measurement data of cable line which operate in overload state. Usually, overload of cable line will lead to the overheat risk.

Actually, there is a linear relationship between the temperature rise caused by overheating and the resistance of cable conductor.

$$R_T = R_{20}[1 + \alpha(T - 20)] \quad (22)$$

Where, R_{20} is the conductor resistance under temperature 20 °C. T is the temperature of cable line.

α is the coefficient between conductor resistance and temperature. Generally, the coefficient of copper conductor is 0.00393 and the coefficient of aluminum conductor is 0.00403. The maximum rated temperature of the cable conductor is 90 °C in GB12706.3-9. Therefore, the maximum resistance allowable $R_{T_{\max}}$ of cable line can be deduced by formula (22).

Obtain historical sequence $(R_{t_1}, R_{t_2}, \dots, R_{t_k}, R_{t_n})$ of resistance parameter estimated mean value in history time period $(t_1, t_2, \dots, t_k, t_n)$ and the prediction sequence $(R_{t_{n+1}}, R_{t_{n+2}}, \dots, R_{t_{n+k}}, R_{t_{n+m}})$ in the future time $(t_{n+1}, t_{n+2}, \dots, t_{n+k}, t_{n+m})$. Calculate the mean value $\overline{R_H}$ of historical sequence and the mean value $\overline{R_F}$ of the prediction sequence. The overheating risk mechanism is shown as follows:

If $\overline{R_H} < R_{T_{\max}}$, $\overline{R_F} < R_{T_{\max}}$, then the cable line is operating in normal station.

If $\overline{R_H} > R_{T_{\max}}$, $\overline{R_F} < R_{T_{\max}}$, then the cable line is operating in overheat station.

If $\overline{R_H} < R_{T_{\max}}$, $\overline{R_F} > R_{T_{\max}}$, then the cable line is operating in overheat station.

If $\overline{R_H} > R_{T_{\max}}$, $\overline{R_F} > R_{T_{\max}}$, then the cable line is operating in normal station.

4. Conclusion

An overheating risk warning method of cable line based on impedance parameter estimation and prediction is proposed in the paper. This method can be used to diagnose whether the cable line is in the overheating operating station by the variation of the real time impedance of cable line during a certain period. The impedance parameter estimation method based on multi-period time SCADA measurement data is discussed in the paper. Simulation results show that the estimation method is valid and the accuracy of estimation result is related to the number of the measurement data. The larger the number of measurement data is, the more accurate the estimated results are. Then, the grey prediction model is used to forecast the resistance of the cable line. The simulation results show that the grey prediction model has higher prediction accuracy and the prediction average accuracy is about

95%. The overheating risk warning mechanism is proposed in the paper in order to provide more efficient advice to operator.

The overheating risk warning method based on impedance parameter estimation and prediction has advantages of good practicability, simple calculation, and easy operation. It can provide a reference for the operation and maintenance of the cable line to the operators.

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