The Calculation Method of Ice Melting Schemes' Relay Protection Settings and Clarification of the Ice Deposition Control Method on Steel Lightning Protection Wires

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Abstract. The method of current values calculation of overcurrent and undercurrent relay protections included in the complex of relay protection of ice melting schemes by alternating current on steel lightning protection wires of overhead transmission lines is analysed. A comparison with the generally accepted method, called the element-by-element method, is made. The element-by-element method is based on using the parameters of all the elements included in the ice melting scheme to calculate the maximum and minimum melting currents, from which the corresponding protections must be adjusted. These parameters have a significant variation, especially the active and internal reactive resistances of steel lightning protection wires at alternating current, what increases the calculation error. The proposed method, called the recalculation method, is based on the use of the trial melting mode parameters, carried out annually in the autumn season on lightning protection wires, with a duration up to 2 minutes. In difference to the usual practice, the trial melting has to be carried out 2 times with different currents. According to the parameters of the mode the settings of relay protection are recalculated using the given methods. The methodological and additional errors of the new method are estimated, that shows proposed method advantage. The parameters of the trial melting mode can be used to specify the methodology for remote control of ice formation (the length of the ice formation zone).

1. Introduction
The relay protection complex (RP) of ice melting schemes (SIM) on lightning protection wires/ground wires (GW) of overhead transmission lines (OTL) includes overcurrent protection (OCP) against short circuits (SC) and undercurrent protection (UCP) against GW breakage without SC or with ground fault with high transient impedance [1-3].

The setting of the OCP is selecting by the condition of adjustment from the maximum melting current:

\[ I_{OCP} = K_{res} \cdot I_{max} \]  

where \( K_{res} \) – reserve factor, \( I_{max} \) – maximal current.

UCP setting is selecting by the condition of adjustment from the minimum melting current:
The method uses not the calculation of circuit parameters, but recalculation by the trial melting mode based on measurements of the electrical characteristics of the GW sample. This solution does not require previous measurements of the electrical characteristics of the GW sample from each OTL, but is based on measurements of the trial melting mode parameters.

The authors offer another method of determining the maximum and minimum AC melting currents on steel lighting protection wires, based on the using of experimental data measured during trial melting. The method uses not the calculation of circuit parameters, but recalculation by the trial melting mode parameters: voltage $U_{melt}$, current $I_{melt}$, active $P_{melt}$ and reactive $Q_{melt}$ powers. The feature of the method involves the necessary to carry out a test melting not once, but twice in a row, with two different positions of the supply on-load tap-changing transformer (OLTC transformer). This solution does not require previous measurements of the electrical characteristics of the GW sample from each OTL, but is based on measurements of the trial melting mode parameters.

The method was reported at the XLI session of the conference "Cybernetics of Energy Systems" in Novocherkassk [13].

\[
I_{UCP} = I_{\min} / (K_{res} \cdot K_{ret})
\]  

(2)

where $I_{\min}$ is the minimum current, $K_{ret} > 1$ is the undercurrent relay return factor. The reserve factor $K_{res}$ is determined by the calculation errors of $I_{\max}$, $I_{\min}$ and usually greater than 1,1÷1,2.

Calculation of the melting current, including the possible maximum and minimum values, is performed taking into account the equivalent EMF $E_{eq} = E_{PS}$ and the power supply impedance ($R_{PS}, X_{PS}$), the resistance of the melting circuit elements: ground wires ($R_{GW}, X_{GW}$), earth $R_{E}$, grounding equipment $R_{GE}$ by the formula (3) for the "ground wire-ground" scheme:

\[
I_{melt} = \frac{E_{eq}}{\left[\left(R_{PS} + R_{GW} + R_{E} + R_{GE}\right)^2 + (X_{PS} + X_{GW})^2\right]^{\frac{1}{2}}}
\]  

(3)

All parameters included in (3) can be varied within certain limits and are subject to calculation.

The feature of the alternating current calculation method for steel lightning protection wires is the non-linear dependence of the active resistance $R_{GW}$ and internal inductive reactance $X_{GW\text{int}}$ from the current $I_{melt}$, which have a maximum [4-12].

As found in [3], these dependencies differ significantly both for different GW brands, and for GW of the same brand with different operating life and operating conditions. If these dependencies are known, the calculation of $I_{melt}$ is carried out with element-by-element method according to (3) by the iterative process. The calculation is done as follows: the initial value is defining (zero iteration) $I_{melt}^{(0)}$, then determine the parameters $R_{GW}\left(I_{melt}^{(0)}\right)$ and $X_{GW\text{int}}\left(I_{melt}^{(0)}\right)$; by (3) calculating the first iteration of the current $I_{melt}^{(1)}$, after calculating $R_{GW}\left(I_{melt}^{(1)}\right)$ and $X_{GW\text{int}}\left(I_{melt}^{(1)}\right)$, and again – the second iteration by (3) – $I_{melt}^{(2)}$.

The process converges at all initial values $I_{melt}^{(0)}$, since for all ground wires the dependence of the active and reactive components of the voltage decrease on the wire increases monotonically with increasing current [3].

When carrying out calculations using the element-by-element method, it is necessary to define the resistances included in formula (3), which have an indefinite value. In addition to the fact that $R_{GW}$ and $X_{GW\text{int}}$ depend on the melting current, $R_{GW}$ depends on the environmental temperature, $R_{E}$ and $R_{GE}$ depend on the properties of the soil, its humidity and temperature, which is also determined by the current weather conditions.

The uncertainty in determining of the ice melting scheme elements impedances on steel lighting protection wires leads to the need to overestimate $I_{\max}$ and, therefore, the overcurrent protection setting, i.e., to increase the insensitivity zone, as well as to underestimate $I_{\min}$ and, therefore, the undercurrent protection setting. Such determining of the settings reduces the sensitivity to breakage of GW with ground-fault.

The authors offer another method of determining the maximum and minimum AC melting currents on steel lighting protection wires, based on the using of experimental data measured during trial melting. The method uses not the calculation of circuit parameters, but recalculation by the trial melting mode parameters: voltage $U_{melt}$, current $I_{melt}$, active $P_{melt}$ and reactive $Q_{melt}$ powers. The feature of the method involves the necessary to carry out a test melting not once, but twice in a row, with two different positions of the supply on-load tap-changing transformer (OLTC transformer). This solution does not require previous measurements of the electrical characteristics of the GW sample from each OTL, but is based on measurements of the trial melting mode parameters.

The method was reported at the XLI session of the conference "Cybernetics of Energy Systems" in Novocherkassk [13].
2. Recalculation method by trial melting mode parameters

2.1. Trial melting
In accordance with the Requirements of the Russian Energy Ministry for ice melting on wires and lightning protection wires of power lines [1] and Instructions of operating organizations before the start of the ice season, trial melting should be carried out on all lightning protection wires of OTL. During the trial melting the air temperature can be significantly higher than 0ºC, and the time of the trial melting is limited (up to 2 minutes).

Registration of the trial melting mode parameters on the GW allows by recalculation to determine the parameters of real melts under different weather conditions. It also allows taking into account wire temperature and nonlinear dependences on current of active and internal inductive resistances of steel GWs during ice melting. These parameters are used for selection of GW's relay protection settings of ice melting schemes.

The clarification of the RP settings increases the technical perfection and efficiency of its operation.

2.2. Trial melting measurements
In order to account for the possible non-linearity of the GW resistances, measurements have to be made at the two positions of the melting transformer on-load tap-changer (OLTC). It is preferable that these positions differ as much as possible in the operating range. In this case the following parameters should be measured: \( E_1, U_1, I_1, \phi_1 \) and \( E_2, U_2, I_2, \phi_2 \), where \( E_1, E_2 \) – power supply (PS) voltages when the GW is disconnected; \( U_1, U_2 \) – the same with the cable included in the SIM; \( I_1, I_2 \) – GW current values; \( \phi_1, \phi_2 \) – phase angles (usually closer to 20 el. degrees), and it is also necessary to fix the air temperature \( \vartheta_{air} \), that is equal to the temperature of the GW when it is switched on for a short time. To finding \( \phi_1 \) and \( \phi_2 \) it is possible to use active and reactive power measurements.

These data are used to calculate the impedances:

\[
R_1 = \left( \frac{U_1}{I_1} \right) \cdot \cos \phi_1; \quad x_1 = \left( \frac{U_1}{I_1} \right) \cdot \sin \phi_1
\]

\[
R_2 = \left( \frac{U_2}{I_2} \right) \cdot \cos \phi_2; \quad x_2 = \left( \frac{U_2}{I_2} \right) \cdot \sin \phi_2
\]

If the impedances at currents \( I_1 \) and \( I_2 \) are different, a non-linear dependence on current takes place. To evaluate the nonlinearity quantitatively, the nonlinearity coefficients \( \beta_a \) and \( \beta_r \), which have the meaning of differential active and reactive resistances in the current range \( I_1 \div I_2 \), should be calculated and used:

\[
\beta_a = \frac{U_2 \cos \phi_2 - U_1 \cos \phi_1}{I_2 - I_1} = \frac{I_2 R_a - I_1 R_a}{\Delta I}
\]

\[
\beta_r = \frac{U_2 \sin \phi_2 - U_1 \sin \phi_1}{I_2 - I_1} = \frac{I_2 x_2 - I_1 x_2}{\Delta I}
\]

where \( \Delta U_a \) and \( \Delta U_r \) are variations of active and reactive voltages.

Due to the monotonicity of the dependences \( U_a(I) \) and \( U_r(I) \), the obtained values of \( \beta_a \) and \( \beta_r \) can be used at \( I > I_2 \) and \( I < I_1 \) (\( I_2 \) > \( I_1 \)).

According to the measurement results, it is possible to estimate the resistance of the power supply at the first and second trial meltings:

\[
Z_{PS1} \approx x_{PS1} \approx \left( E_1 - U_1 \right) / \left( I_1 \sin \phi_1 \right)
\]

\[
Z_{PS2} \approx x_{PS2} \approx \left( E_2 - U_2 \right) / \left( I_2 \sin \phi_2 \right)
\]

and compare them with the previously calculated values.
2.3. The maximum melting current calculation
Melting current has the maximum value $I_{\text{max}}$ at the moment of switching on the SIM with a PS having the maximum EMF $E_{\text{PS, max}} = E_{\text{eq}}$ and minimum impedances $R_{\text{PS, max}}, x_{\text{PS, max}}$ at the minimum, actually possible, air (and wire) temperature $\vartheta_{\text{air, min}} < 0^\circ\text{C}$. (Note – indices (max) and (min) in brackets mean mode, not resistance value)

The GW resistances at the maximum current are determined by considering the differential resistances constancy in the range of currents from $I_2$ to $I_{\text{max}}$, therefore

$$R_{\text{(max)}} = \left[ U_{\text{eq}} + \beta_1 (I_{\text{max}} - I_2) \right] / I_{\text{max}}$$
$$x_{\text{(max)}} = \left[ U_{\text{eq}} + \beta_1 (I_{\text{max}} - I_2) \right] / I_{\text{max}}$$

where (max) in brackets means the maximum current mode, not the resistance value.

The decrease of the active GW resistance at the minimum, actually possible, air temperature $\vartheta_{\text{air, min}} < 0$, is determined with the correction $R_{\text{(max)}}$ by (4):

$$R_{\text{GW, (max)}} = R_{\text{(max)}} \left( 1 + \alpha_0 \vartheta_{\text{air, min}} \right) \left( 1 + \alpha_0 \vartheta_{\text{air}} \right)$$

where $\vartheta_{\text{air}}$ is the temperature of the air (wires) during the trial melting; $\alpha_0$ – the temperature coefficient of steel GW active resistance of various brands (can be accepted as $\alpha_0 = 0,00455 \, 1/\circ\text{C}$ in the real temperature range of $\vartheta_{\text{GW}}$ [10]).

Since $R_{\text{(max)}}, R_{\text{GW, (max)}}, x_{\text{(max)}}$ depend on the required current $I_{\text{max}}$, the calculation takes 1÷2 iterations. $R_2$ and $x_2$ are taken as initial values (zero iteration).

The calculation formula in the general case has the following view

$$I_{\text{max}}(k+1) = E_{\text{PS, max}} \sqrt{ \left( R_{\text{PS, (max)}} + R_{\text{GW, (max, (k))}} \right)^2 + \left( x_{\text{PS, (max)}} + x_{\text{GW, (max, (k))}} \right)^2 }^{\frac{1}{2}}$$

The iteration ends at $I_{\text{max}} \approx I_{\text{max}}(k+1) = I_{\text{max}}(k)$.

2.4. The minimum melting current calculation
Melting current has the smallest value at the end of the melting and the clearance of the ice formation from the ground wires, when the PS has the following parameters $E_{\text{PS, min}}, R_{\text{PS, (min)}}, x_{\text{PS, (min)}}$, and when the temperature and the active resistance of the ground wires became maximum. The influence of the difference between $I_{\text{min}}$ and $I_1$ (during trial melting) on the resistances $R_{\text{(min)}}, R_{\text{GW, (min)}}, x_{\text{(min)}}$ is taken into account by assuming that the differential resistances in the range of currents from $I_1$ to $I_{\text{min}}$ are constant, as in the previous calculation. But there is a difference, consisting in the requirement to determine the maximum temperature of the GW without ice, under the worst cooling conditions ($\vartheta_{\text{air, (min)}} = 0^\circ\text{C}$, wind speed along the transmission line $v_{\text{w, (min)}} = 2 \, \text{m/s}$), at the current $I_{\text{min}}$ that should be calculated.

For this application, it is possible to determine the temperature of the GW, $^\circ\text{C}$, in a simplified way:

$$\vartheta_{\text{GW}} = 90 \left( I_{\text{min}} / I_{\text{m.p}} \right)^2$$

where 90$^\circ\text{C}$ is the maximum long-term permissible temperature of the GW; $I_{\text{m.p}}$ is the maximum permissible current under the worst cooling conditions (can be determined by the calculation tables [11]).

The calculation formulas:

$$I_{\text{min}}(k+1) = E_{\text{PS, min}} \sqrt{ \left( R_{\text{PS, (min)}} + R_{\text{GW, (min, (k))}} \right)^2 + \left( x_{\text{PS, (min)}} + x_{\text{GW, (min, (k))}} \right)^2 }^{\frac{1}{2}}$$

where
As the zero approximation \((k = 0)\) \(I_{\text{min}} = I_1\) is taken. The calculation is finished when \(I_{\text{min}} = I_{\text{min}(k+1)} \approx I_{\text{min}(k)}\).

2.5. Errors of the recalculation method

The method of recalculation according to the parameters of the trial melting mode contains two types of errors: the main and the additional one. The main error is methodical, caused by linearization of nonlinear dependence of melting current on the applied power supply voltage. This is due to the replacement of the nonlinear of active and internal inductive steel GW impedances with constant differential values, defined during test melting. The additional error is a result of the difference in weather conditions during the trial melting in autumn and during the real ice melting in the autumn-winter period.

The research has shown that the methodical error of currents recalculation does not exceed 6%. For this purpose, it is necessary to ensure the interval between the equivalent EMF at two measurements during the trial melting \(\Delta E_{\text{eq}} \geq 0,1(E_2 - E_1)_{\text{max}}\).

The errors are equal and significantly less than the largest at \(E_{\text{eq},1}\) in the middle of the interval \(E_{\text{min}} + E_{\text{max}}\). The maximum value of the sum of methodical and additional errors does not exceed 7%. This error is compensated in the formulas for RP setting definitions (1) and (2) by the reserve coefficient \(K_{\text{res}} = 1,1\).

3. Using the trial melting mode parameters and recalculation method to control ice formation on steel lightning protection wires

In [14] a method of remote control of ice formation (determining the length of the ice zone and the end of ice melting by alternating current pulses) was proposed. This method is based on fixing the change in the OTL active resistance caused by wire heating on the ice-free section and depending on the temperature and the length of this section. Application of the proposed method for steel lightning protection wires is complicated by the necessary to take into account the AC current value influence on the wire active resistance.

To compensate for this influence, it is proposed to use differential active resistance of the melting scheme \(\beta_a\), determined experimentally during the trial melting (annually trials) at two values of current by the formula (4).

When the current in the GW changes from \(I_0\) to \(I_1\) (decline of the current’s pulse), the current-dependent increase in the active component of the voltage decline on the GW:

\[
\Delta U_{\text{GW}}(I) = (I_0 - I_1)\beta_a
\]

and the increment of the active resistance, depending on the current will be equal

\[
\Delta R(I) = \Delta U_{\text{GW}}(I)/I_1 = \left(\frac{I_0}{I_1} - 1\right) \cdot \beta_a
\]

Therefore, the required increment of the active resistance, taking into account the correction:

\[
\Delta R = \Delta R_{\text{GW}} - \Delta R(I)
\]

The increment \(\Delta R\) should be used when determining the relative length of the ice formation during melting current pulses and to stop melting when the length of the ice formation becomes equal to zero.
4. Conclusion
The analysis of the calculation methods of AC ice melting schemes relay protection settings on steel lightning protection wires has shown the advantage and admissibility of using the recalculation method proposed by the authors according to the trial melting mode parameters in comparison with the traditional element-by-element method.

Specification of the relay protection settings provides an improvement in the efficiency of its functioning.

The use of the recalculation methods allows to correct the results of the ice formation length remote control during ice melting by alternating current on the steel lightning protection wires.

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