Estimation of Induced EMF Value in Ground Wire During Ice-Melting Procedure

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***Abstract*—The TL (transmission lines) and the GW (ground wires) ice covering represents a danger to the power systems' operation. When the ice-melting procedure using rectifiers is conducted, accidents due to the induced EMF in the GW from the TL currents are possible. In this paper the induced EMF values are calculated for different TL operation modes, different positional TL relationship and different ice-melting diagrams. In addition, a methodology of the induced EMF value calculation in the GW is described, a comparison of the EMF values for different TL operation modes and different ice-melting diagrams is made, and possible dangers during the ice-melting procedures are noted. Ways to improve the calculation methodology are listed.**

Keywords*—*ice melting; wire ice covering; ground wire; rectifier; induced EMF

I. INTRODUCTION

The ice covering represents a huge danger to the power systems' operation. It can lead to the wires breakage and even to the towers destruction. In December 2001, the ice covering brought to the damage of TL (transmission lines) of total length 2500 km in Sochi. In early 2008, a severe ice storm occurred in Southern China, which caused at least 7541 TL above 10 kV and 859 substations above 35 kV to be out of service [1].

One of the ways to prevent these adverse events is an ice melting, which is the heating of the wires with an electric current. This leads either to the ice melting on the TL and the GW (ground wires), or the prevention of ice covering. The GW are usually connected to the towers using spark gaps so the current does not flow through towers to the grounding conductor.

The GW ice covering is considered to be the most dangerous case, because the fall of the GW may lead to the multiple-phase short circuits. The TL wires when operating, are heated with a flowing current. If the heat generated is not enough, there is often a possibility to change the power system operation mode to increase the current flowing (e.g. lowing the voltage while keeping the same electric power amount transported or the increasing of the latter) through the wires of the needed TL. The process of the GW ice covering is easier than the TL wire ice covering. Hence, even if the current value is enough to prevent the TL ice covering the possibility of the ice melting on the GW should be provided.

In some cases, the preventing heating is enough to avert the GW ice covering. The preventing heating of the GW is recommended when the air temperature is near zero ^{0}C and when the wind speed is 1-2 m/s [2]. DC is used more often than AC for the ice-melting procedures because the possibility of choosing the heating current is very limited if using AC [3]. The simplest ice-melting diagram called "GW-ground" is given in Fig. 1. The typical diagrams are given in Table I.

II. PURPOSE OF WORK

It is desirable to conduct the GW ice-melting procedure without powering down the TL. The currents in the wires of the TL, located on the same tower as the GW, and the currents of the neighboring TL induce the EMF in the ice-melting loop (Fig. 1). This can lead to the rectifier's breakdown while engaging as well as while operating. The aim of this paper is an estimation of the EMF value induced in the ice-melting loop under different conditions (such as different TL operation modes, different TL types and different ice-melting diagrams) and the development of an application to estimate the induced EMF value.

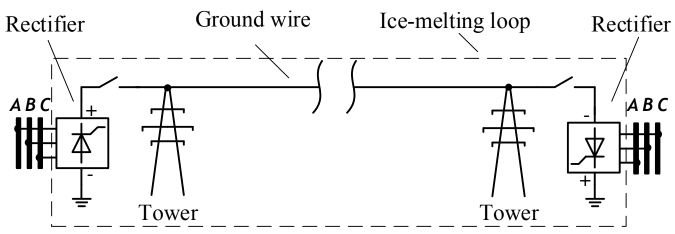
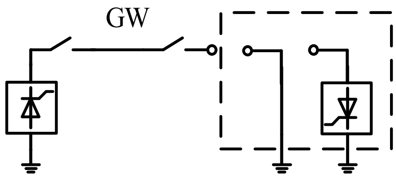
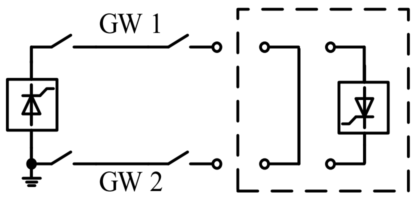


Fig. 1. "GW–ground" ice-melting diagram.

TABLE I. ICE-MELTING CIRCUIT DIAGRAMS

Name of the diagram	Diagrams
GW-ground	
GW 1,2	

III. INDUCED EMF CALCULATION METHOD

The induced EMF value in the ice-melting loop is determined by a magnetic flux Φ (which is created with the TL currents) through the surface whose boundary is the ice-melting loop [4]. The most significant factors, which determine the values of magnetic flux and EMF, are currents' values, their phase lags, and distance between the ice-melting loop and the TL wires. The calculation method rests on the following assumptions:

1) The TL currents form the balanced three-phase system;
2) because the currents' phase lags of all TL are not defined, we consider that the currents of the same phase index of the different circuits and of different towers have the same phase lag;
3) all TL wires and GW are rectilinear (we neglect the wires' deflection);
4) the ice-melting loop "GW-ground" from Table I is created with the GW and a ground surface below it.

With these assumptions, the induced EMF value can be calculated analytically. In case of using the ice-melting diagram "GW-ground" (Fig. 2), the magnetic flux through the surface of its loop can be calculated [4]:

$$\dot{\Phi}_B = \left(\dot{A}_1 - \dot{A}_2\right)\cdot l = \left(\frac{\mu_0}{2\pi}\sum_{k=1}^{3}\dot{I}_k \ln r_k^{(1)} - \frac{\mu_0}{2\pi}\sum_{k=1}^{3}\dot{I}_k \ln r_k^{(2)}\right)\cdot l \quad (1)$$

where l is the length of the parallel TL and GW; A_1, A_2 are the vector potential values on the GW and the ground respectively; $r_k^{(1)}$, $r_k^{(2)}$ ($k = 1,2,3$) are shown on Fig. 2.

The induced EMF value:

$$E = \left|\dot{E}\right| = \left|-j\omega\cdot\dot{\Phi}_B\right| = \omega\cdot\Phi_B \quad (2)$$

$$\omega = 2\pi\cdot f = 314 \text{ rad/s} \quad (3)$$

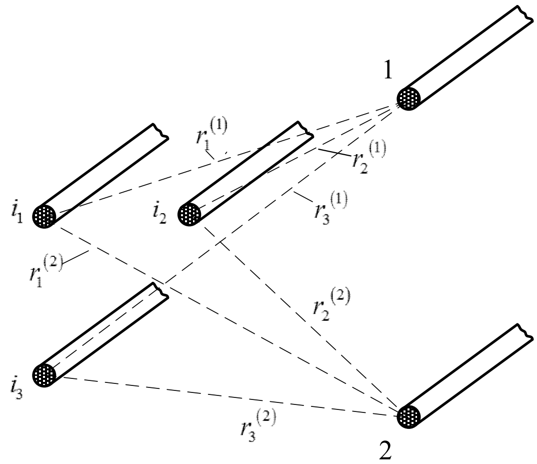


Fig. 2. Positional relationship of TL wires and GW using "GW-ground" ice-melting diagram. 1 – GW, 2 – ground.

The RMS EMF value calculated in (2) is a result of the effect from one circuit of the TL. After that, we can calculate the influence from the other TL circuit and, taking into consideration the assumption 2, sum both reactions. The result will be obviously the majoring one.

IV. CALCULATION RESULTS

The calculations were made using the application developed specifically for the present paper that includes:

- the TL map;
- the TL data such as types of GW, wires and towers as well as a transposition data;
- the nominal currents, voltages and electric power transported through TL.

Fig. 3(a) represents a map of a power system span in Moscow Oblast. TL 1, which is located on the same tower as GW in question, is located near TL 2, 3 and 4. All of them operate in nominal modes. Fig. 3(a) also contains the information of the nominal currents' values. Fig. 3(b) represents the tower dimensions.

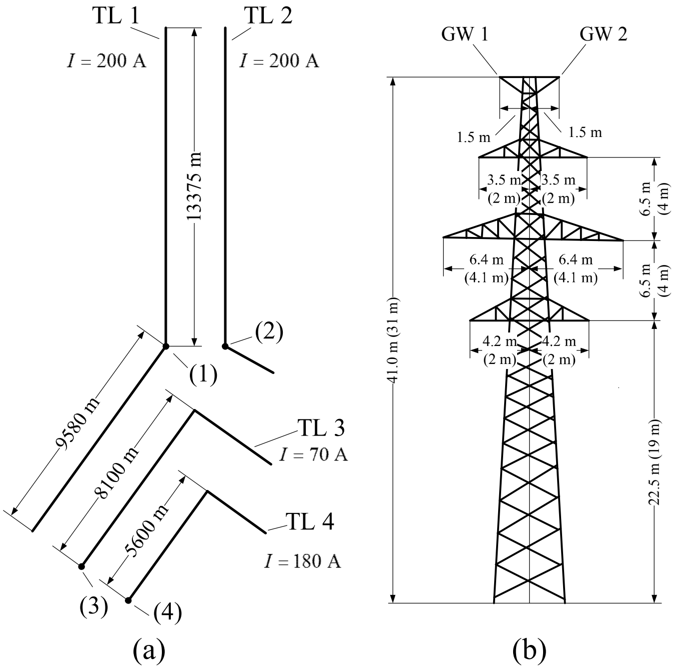


Fig. 3. Calculation data. (a) The map of a power system span. TL 1, TL 2, TL 4 – double-circuit TL 220 kV, TL 3 – double-circuit TL 110 kV. (b) The dimension of the towers used. The dimensions for 110 kV towers are given within brackets.

The minimum distance allowed between the wires of neighboring 220 kV towers is 7 meters [5]. We consider that all towers are located in such a way that this condition is met for all TL.

The calculations for two ice-melting diagrams from Table I are represented in Table II.

TABLE II. CALCULATION RESULTS

№	Ice melting diagram	Induced EMF value (RMS), kV				
		TL 1	*TL 2*	*TL 3*	*TL 4*	*Total*
1	GW-ground	0.416	0.070	0.013	0.013	0.512
2	GW 1,2	0.158	0.010	0.0015	0.0014	0.171
3	GW-ground	0.756	0.162	0.026	0.031	0.975
4	GW-ground	21.7	<0.1	<0.1	<0.1	21.7
5	GW 1,2	0.551	<0.1	<0.1	<0.1	0.551
6	GW-ground	0.416	9.45	<0.1	<0.1	9.87
7	GW 1,2	0.158	2.13	<0.1	<0.1	2.29
8	GW-ground	0.416	<0.1	1.74	<0.1	2.16
9	GW 1,2	0.158	<0.1	0.482	<0.1	0.640
10	GW-ground	0.416	<0.1	<0.1	1.67	2.09
11	GW 1,2	0.158	<0.1	<0.1	0.475	0.633

The rows 1-3 of Table II correspond to the nominal currents values of all TL according to Fig. 3(a). In cases 1, 2 phases' positions correspond to Fig. 4(a), in case 3 – Fig. 4(b).

The biggest EMF value does not exceed 1 kV. Nevertheless, such voltage levels represent a danger during the rectifier commutation and may be the reason of rectifier's breakdown while powering up. Such events were recorded to occur.

Rows 4-10 correspond to cases when one-phase short circuits occur in different TL (omitting assumption 2). The phase arrangement corresponds to Fig. 4(a). The circuit which contains index 1 in phase names (A_1, B_1, C_1) hereinafter is called "circuit 1".

4,5 – short circuit in spot (1) on Fig. 3(a), the current in circuit 1 of TL 1 is 6.14 kA, all other currents are nominal;

5,6 – short circuit in spot (2) on Fig. 3(a), the current in circuit 1 of TL 2 is 6.15 kA, all other currents are nominal;

7,8 – short circuit in spot (3) on Fig. 3(a), the current in circuit 1 of TL 3 is 2.80 kA, all other currents are nominal;

9,10 – short circuit in spot (4) on Fig. 3(a), the current in circuit 1 of TL 4 is 5.22 kA, all other currents are nominal.

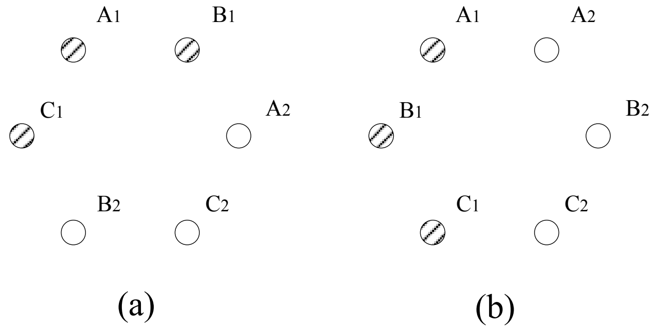


Fig. 4. Variants of phases' disposition. (a) The first variant. (b) The second variant.

For every TL operation mode the induced EMF value for the ice-melting diagram "GW-ground" is greater than for "GW 1,2". It is explained by both bigger loop surface area and its disposition to TL wires.

In case of short circuit in any TL the biggest contribution to the total induced EMF value is made with its currents, as expected. When the short circuit happens, the induced EMF value is 4-40 (depending on the specific TL where the short circuit occurs) times greater than under nominal conditions. The maximum EMF value obtained is 21.7 kV. Short-time voltage of such level will break the rectifier. Thus when analyzing the reasons of the equipment breakdown it is reasonable to check the logs of the power system protection functioning.

V. DISCUSSION

The current generated by a rectifier contains a higher harmonics. They can be limited with a reactor. However, it is not used when the ice-melting procedure is conducted because of its huge size. That is why ice-melting loop creates opposite influence to the TL wires. The amplitude of higher harmonics is not major, but because induced EMF values are directly proportional to the frequency, they may be considerable. The calculation results of these induced voltages made with described methodology before are represented in Table III. Calculations were made for the loops "A-B" and "A-C" for TL 1 and TL 2.

TABLE III. INDUCED EMF VALUES IN TL WIRES FROM ICE-MELTING LOOP

Harmonic number	Ice melting diagram	I, A	f, Hz	Induced EMF (RMS), V / Induced EMF (RMS), V/km			
				TL 1		TL 2	
				A-B	A-C	A-B	A-C
6	GW-ground	14	300	122 / 5.32	195 / 8.51	15.8 / 1.18	45.3 / 3.39
12	GW-ground	8	600	136 / 5.94	223 / 9.72	18.1 / 1.35	51.8 / 3.87
18	GW-ground	6	900	153 / 6.68	251 / 10.9	20.3 / 1.52	58.3 / 4.36
6	GW 1,2	14	300	16.5 / 0.719	24.7 / 1.08	2.93 / 0.219	6.05 / 0.452
12	GW 1,2	8	600	18.9 / 0.821	28.3 / 1.23	3.35 / 0.250	6.91 / 0.517
18	GW 1,2	6	900	21.2 / 0.924	31.8 / 1.39	3.76 / 0.281	7.78 / 0.582

Calculating induced EMF value for the ice-melting diagram "GW-ground" in the present paper we considered that a loop in which the EMF is induced is bounded by GW and a ground below it. Accounting for real current density distribution in the ground may be conducted using methods described in [6], [7]. This correction will lead to the decrease of induced EMF values calculated.

VI. CONCLUSIONS

When ice-melting procedure using rectifiers is going to be conducted, the induced EMF in GW from currents of neighboring TL should be taken into account. The average induced EMF value from one TL in ice-melting loop is 20 V/km (ice-melting diagram "GW-ground", the double-circuit TL 220 kV is located on the same tower as the GW).

The danger of inducing high EMF values in "GW 1,2" ice-melting diagram is significantly less than in the "GW-ground" loop.

When the ice-melting procedure is conducted, a short circuit current in any TL, which is parallel to the GW, induces EMF enough to damage a rectifier.

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