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DIAGNOSTICS OF LINE -STICK INSULATORS

The paper describes the possibility of applying method and means of infra-red equipment for detecting the damages in line-stick insulators at the early stage of their development. There had been researched the influence of dielectric losses of porcelain on the heat processes in insulators. It had been shown that the reveal of temperature anomaly, with the increase in temperature less than by 0,2 – 0,3 °C, by infra red equipment is possible during the increase of dielectric losses 20 – 30 times in comparison with the standard.

Key words: *insulation damage, dielectric losses, insulation heating.*

Introduction

Line-stick insulators (LSI) are widely used in electric installations with voltage of 110 – 750 кV. The experience in operating electric installations of distributing devices of electric power stations and substations with voltage of over 110 kV testifies that line-stick insulators are elements which undergo damages, especially if they are installed in disconnectors. The number of technological violations connected with destruction of LSI in electric power energy systems of Ukraine amounts to dozens each year [1]. Great number of failures stipulates for the necessity in improvement of LSI diagnostics quality.

In Ukraine, in accordance with the acting normative documents [2], the control over the technical state of LSI stipulates for control over the general state, measuring of insulation resistance, mechanical testing, LSI control by ultrasonic method, insulation diagnostics by means of infra red equipment [3], testing porcelain samples from technological parts during manufacture of insulators [4].

Control over the general state of LSI remains very actual, though the significant number of insulators is damaged without the visible cracks. Measuring the insulators resistance appeared to be of low efficiency, out of 20damaged insulators only one had the resistance, that did not satisfy the requirements [1]. Mechanical testing cannot be conducted on disconnectors and switchers with class of voltage over 220 kV [5]. The reveal of damaged insulators by means of infra red equipment is definitely perspective, but first, certain state of insulators is necessary to perform such test and second, it does not allow to state definitely their operational fitness, especially at the early stage of damage development [6]. The same concerns methods, based on registration of ultraviolet radiation. The method of fuchsin test under pressure [4], is the definite index of available open porosity. But this method is not suitable in practical application since it is not possible without the destruction of insulators. Method of ultrasonic structuremetrics does not have strict criteria for grading of insulators by the speed of distribution of ultrasonic waves.

The objective of the paper. Determination of diagnostics parameters for revealing mechanic damages of LSI at the early stage of their development by means of infra red equipment. The porcelain is known to be non-polar dielectric, that is the molecules have symmetric structure: centers of equivalent positive and negative charges coincide, therefore, during the absence, of external field, non-polar molecules do not have their own electric moment. The availability of the fault in the form of microscopic porosity [6] in the insulator may cause the moisture saturation in the internal volume of porcelain body. Water molecules are constant dipoles, which cause the sharp increase in dielectric losses, stipulated by the increase of dipole polarization intensity.

Tangent of the angle of dielectric losses is integral parameter, which takes into account the polarizational losses, losses of internal electric conductivity and loses due to drain of surface conductivity, and is determined by the value of shift of current vector in comparison with current vector in the ideal dielectric. Qualitative porcelain of line-stick insulators is characterized by the insignificant dielectric losses $tg\delta \le 0{,}025$ [7]. Total energy of dissipation, emitted in certain volume of the insulator and stipulated by the active component of polarizational current and electric conductivity, is calculated by the formula:

$$P_T = U^2 \cdot \omega \cdot C \cdot tg\delta, \tag{1}$$

where $\omega = 2 \cdot \pi \cdot f$ – is angle velocity of applied voltage , c^{-1}; U – is voltage applied to the insulator, кV; $tg\delta$ –is tangent of dielectric losses angle, when $f = 50Hz$, for quality porcelain [7] $tg\delta \le 0{,}025$; C – is insulator capacitance, μF.

Dissipation energy, emitted in the insulator in alternative electric field, is transformed into the thermal energy, causing the heating of insulator's porcelain. Differences in temperature between the insulator and air causes the heat exchange between the insulator porcelain and the environment – irreversible process of transferring heat energy in the space, stipulated for by the heterogeneous temperature field.

According to the second law of thermodynamics the heat is transferred to the direction of lower temperature. Volume of energy in relation to the surface unit, which is transferred due to heat conductivity, according to the Fourier law [8], is proportional to the temperature gradient and is determined as the density of thermal stream, where the sign minus points the direction of heat transfer.

$$q = -\lambda \cdot grad(T), \tag{2}$$

where q – is the density of thermal stream, W/m^2; λ – is factor of thermal conductivity, which characterizes the ability of the substance to conduct heat, for porcelain [7] $\lambda = 1{,}68$ W/(m·°K); $grad(T)$ – is temperature gradient, °K.

Analytical expression for density of thermal stream of connective heat exchange from the insulator's surface to the air is determined by the Newton's law [8]:

$$q_n = \alpha \cdot (T_p - T_a), \tag{3}$$

where q_d is the – density of thermal stream, transferred from the body surface to the air, W/m^2; α – is the factor of convective heat exchange, W/m^{2}·°K; T_p –is the temperature on insulator surface, °K; T_a – is air temperature, °K.

Coefficient of convective heat exchange α determines the thermal stream, which is transferred through the unit of insulator surface at temperature difference between the surface and the air 1°K.

As for the physical content α – is the value, inverse to the sum of thermal resistances in the system, through which the thermal stream is spread, and depends on air-dynamic conditions close to the surface, its sizes and form, heat capacity and physical properties of the air.

Heat transfer from the surface of solid body to the environment may be considered as the thermal conductivity through the thin layer of air, contacting the surface of solid body. According to the Newtons law of convective heat exchange (2) and heat conductivity of Fourier (3) the equation of heat exchange on the bounder between the insulator and air looks like:

$$-\lambda_n \cdot grad(T) = \alpha \cdot (T_p - T_a), \tag{4}$$

where λ_n – is coefficient of air heat conductivity, when $T = 300$ °K [2], $\lambda_n = 26{,}2 \cdot 10^{-3}$ W/(m·°K).

Temperature gradient of heat carrier in the left part of the equation (4) determines the density of heat stream, which is transferred by thermal conductivity through theoretically infinitely thin layer of the air, which is unmovable relating to the body surface. Coefficient of exchange α in the right part of the equation characterizes the intensity of convective heat exchange from the insulator's surface to the air by convection and thermal emission.

Let us consider the temperature field and thermal process inside the insulator. According to the first law of thermodynamics, the volume of heat, being lost by the body, may appear only due to the decrease in internal body energy per unit of time $\left(-\rho \cdot c_p \cdot \frac{\partial T}{\partial t}\right)$, as well as due to the impact of internal sources of heat, having power q_v. For the process which does not take into account the dependence of heat capacity on temperature, the following expressions is valid [9]:

$$dQ = \int_V (q_v - \rho \cdot c_p \cdot \frac{\partial T}{\partial t}) dt dV, \tag{5}$$

where q_v – is electric energy dissipation power in the unite of volume, W/m^3; c_p – is specific heat capacity of the material, for porcelain [7] at $T = 300$ °K $c_p = 750$ J(kg·°K); ρ – is material density, for porcelain [7] $\rho = 2500$ kg/m^3; V – is the volume of body, m^3; t – is time of acting of alternative electric field on the insulator, sec.; T – is the temperature of the porcelain °K.

Taking into account formulas (2) and (5), the equation of heat conductivity acquires the form (6), which establishes the connection of space and time temperature change inside the insulator, that is, the expresses the dependence of change in time of temperature of any point of the body on properties of field and dissipation of energy in the vicinity of this point.

$$\rho \cdot c_p \cdot \frac{\partial T}{\partial t} = grad(\lambda \cdot grad(T)) + q_v. \tag{6}$$

For further calculations, with some assumption as the absence of temperature fluctuations within for twenty four hours, change in wind speed, it is possible to consider that the process is steady state: achieving definite value, the temperature inside and on the surface of the insulator does not change in time, that is $\frac{\partial T}{\partial t} = 0$. Consequently, considering (4) we obtain:

$$grad(\lambda \cdot grad(T)) + q_v = 0. \tag{7}$$

To evaluate the heat exchange processes, we consider the insulator as the complete cylinder with the radius $R = d/2$, with equally distributed inner sources with the power of q_v, which is in the air environment. The ribbing of the side surface form is not taken into consideration and average insulator diameter d is accepted an average between the rib diameter and the diameter of intercostal part of insulator. The air acts as heat transfer agent – mobile environment which participates in heat exchange and intensifies it. Air temperature is T_n and convective heat exchange factor α.

If convective heat exchange of porcelain body of insulation to flanges is not taken into consideration, the temperature field inside the insulator will be one-dimensional $T = f(r)$. If isothermal surface is allocated at the distance r from the insulator axes, then, in the established mode, the heat, which is radiated in volume $V_r = \pi \cdot r^2 \cdot h$, will be transferred through the isothermal surface of the area $F_r = 2\pi \cdot r \cdot h$ due to heat conductivity.

Heat flow through the isothermal surface which is at the distance $r = R$ of the central vertical axes of the insulator, considering formula (2), may be presented as:

$$Q = -F \cdot \lambda(\partial T/\partial r) = -2\pi \cdot R \cdot h \cdot \lambda(\partial T/\partial r), \tag{8}$$

where Q – is the power of inner energy sources in insulator W; $F = 2 \cdot \pi \cdot R \cdot h$ – is insulator surface area m^2; λ – is the factor of porcelain heat conductivity, W/(m·°K).

In cylindric coordinate system when $\lambda = const$ for one-dimensional system equation (7) may be presented as [8]:

$$\frac{\partial}{\partial r}\left(r^n \partial T/\partial r\right)=\frac{-q_v \cdot r}{\lambda}, \tag{9}$$

where n – is exponent , the value of which depends on body form, for cylindric form $n=1$.

After the fist integration we get the expression:

$$T=-\frac{1}{2}\cdot r\cdot\frac{q_v}{\lambda}+\frac{C_1}{r}, \tag{10}$$

where C_1 – is integration constant.

Hence, when $r=0$, at symmetric conditions, $dT/dr=0$, consequently $C_1=0$.

After the repeated integration the equation (9) acquires the form:

$$T=-\frac{1}{4}\cdot r^2\cdot\frac{q_v}{\lambda}+C_1\cdot ln\,r+C_2, \tag{11}$$

where C_2 – is integration constant.

Let us consider the equation (4) for limiting conditions on the outer surface of insulator, that is, when $r=R$, and $(\partial T/\partial r)_p=-q_v\cdot R/2\lambda$ and $T=T_p=T_a-r^2\cdot q_v/4\lambda+C_2$:

$$-\lambda\cdot\left(\frac{\partial T}{\partial r}\right)_p=\alpha\cdot(T_p-T_a). \tag{12}$$

Let us substitute the limiting conditions in the formula (12) and find C_2:

$$C_2=T_p+\frac{1}{2}\cdot q_v\cdot R\cdot\left(\frac{1}{\alpha}+\frac{R}{2\lambda}\right). \tag{13}$$

We receive the temperature distribution inside the insulator, substituting the integration constant (13) into the expression (11):

$$T=T_p+q_v\cdot R/2\alpha+q_v\cdot\left(R^2-r^2\right)/4\lambda. \tag{14}$$

where T – is porcelain temperature at distance r from the vertical insulator axis, °K; T_n – is air temperature, °K; λ_{is} – insulator heat conductivity factor, W/(m·°K); q_v – is the power of electric energy dissipation in the volume unit, W/m^3; α is convective heat exchange factor, W/m^{2}·°K; R – is insulator radius, m.

On the insulator vertical axis, when $r=0$, temperature T is maximum, and the temperature on the porcelain surface when $r=R$, will be determined by equation:

$$T_p=T_a+q_v\cdot R/2\alpha, \tag{15}$$

where $T_ф$ – insulator surface temperature, °K.

Thus, considering (14) and (15), temperature field inside the insulator is described by the formula:

$$T=T_p+\frac{q_v}{4\lambda}\cdot R^2-\frac{q_v}{4\lambda}\cdot r^2. \tag{16}$$

Evaluation of heat exchange parameters is conducted for line -stick insulator of the ИОС-110-600 type with average diameter $d=0{,}2$ m and height $h=1{,}1$ m, which is of white glaze and is passed by air stream with temperature $T_p=300$ °K ($T_p=27$ °C) under normal atmospheric pressure.

Table 1

Tangent of angle of dielectric losses $tg\delta$.

Wind speed v, m/sec	Temperature excess of insulator surface over air temperature $(T_ф - T_n)$, °K							
	0,3	*0,5*	*1*	*2*	*3*	*4*	*5*	*10*
	Tangent of angle of dielectric losses $tg\delta$							
0,2	0,42	0,70	1,41	2,83	4,25	5,69	7,13	14,48
0,4	0,49	0,82	1,64	3,28	4,93	6,59	8,26	16,74
0,6	0,56	0,93	1,87	3,74	5,62	7,52	9,42	19,05
0,8	0,62	1,03	2,07	4,15	6,23	8,33	10,43	21,09
1	0,68	1,13	2,26	4,52	6,79	9,07	11,36	22,94
1,5	0,80	1,33	2,67	5,34	8,03	10,72	13,42	27,07
2	0,91	1,51	3,03	6,07	9,12	12,18	15,24	30,70
2,5	1,01	1,68	3,36	6,73	10,12	13,50	16,90	34,02
3	1,10	1,83	3,67	7,35	11,04	14,74	18,44	37,10
4	1,27	2,12	4,23	8,47	12,72	16,98	21,25	42,72
5	1,47	2,45	4,91	9,82	14,75	19,68	24,62	49,47

Dielectric losses, according to equation (1), are determined by values of the voltage U applied to the insulator, the own capacity of the insulator C and 00 tangent of dielectric losses angle.

For evaluation of dielectric losses we will assume that alternative voltage $U = 100kV$, is applied to insulator, when $f = 50Hz$, and insulator capacity $C = 1{,}2 \cdot 10^{-6} \mu F$.

Considering the above -mentioned assumption, the main factor, influencing the intensity of energy dissipation in the insulator, is the tangent of dielectric losses angle, which may be determined by the expression [10]:

$$tg\delta = \frac{\chi \cdot \lambda_n \cdot (\rho_n \cdot \upsilon \cdot d / \mu_n)^m \cdot \pi \cdot h \cdot (T_ф - T_n) + \varepsilon \cdot \sigma \cdot \pi \cdot d \cdot h \cdot (T_ф{}^4 - T_n{}^4)}{U^2 \cdot \omega \cdot C}, \qquad (17)$$

where χ and m – are factors, which depend on type of air stream and on insulator geometry; σ is Stephan-Bolzman constant, $\sigma = 5{,}669 \cdot 10^{-8}$ W/m^2·°K^4; d –is average diameter of the insulator.

With the help of equation (17) we receive the calculated values of $tg\delta$ (Table 1).

Thus, considering the accepted restrictions, even for insignificant insulator heating, at insignificant wind speed, it is necessary to increase $tg\delta$ 20 – 30 times, in comparison with quality porcelain, for which $tg\delta \le 0{,}025$.

Conclusions

1. The main reason for heating of line stick insulators are usually losses due to dipole polarization connected with porcelain moistening which cause the increase of in $tg\delta$.

2. To reveal temperature anomaly of insulator by means of infra red equipment it is necessary that the excess of temperature be not less than 0,2 – 0,3°K, that requires the increase of $tg\delta$ 20-30 times, in comparison with quality porcelain.

3. Heat emission from the insulator surface is conducted by forced convection and radiation, the convection begins to dominate over heat emission by radiation at wind speed of 0,5 m/sec. In real conditions the influence of natural convection in the process of convective heat exchange may be neglected.

REFERENCES

1. Лабзун М. П. Методи та засоби діагностування опорно-стрижневих ізоляторів: монографія / М. П. Лабзун, О. Є. Рубаненко, В. М. Кутін. – Вінниця, ВНТУ, 2010 – 323 с.

2. Норми випробування електрообладнання: СОУ-Н ЕЕ 20.302: 2007. – [Чинний з 15.04.07]. – Офіційне видання. – К.: ГРІФРЕ: Міністерство палива та енергетики України». 2007-11. 262 с. (Нормативний документ

Міністерство палива та енергетики України. Норма).

3. Технічне діагностування електрообладнання на контактних з'єднань електроустановок і повітряних ліній електропередач засобами інфрачервоної техніки: СОУ-Н ЕЕ 20.577: 2007. – [Чинний з 16.03.07].– Офіційне видання. – К.: ДП «НТКУ «АсЕлЕнерго». Міністерство палива та енергетики України, 2007. – 119 с.

4. ГОСТ 20419-83 «Материалы керамические электротехнические классификация и технические требования». – [Чинний з 01.01.85]. – М. ИПК. Издательство стандартов, 2002. – 8 с.

5. Кутін В. М. Система перевірки механічної міцності опорно-стрижневих ізоляторів роз'єднувачів і відокремлювачів / В. М. Кутін, С. В. Матвієнко // Вісник Кременчуцького державного політехнічного університету – 2004. – № 2 (35). – С. 109 – 111.

6. Шейкин А. А. Технологии оценки состояния фарфоровых изоляционных конструкций высоковольтных электроустановок / А. А. Шейкин, А. И. Таджибаев, Ю. А. Омельченко, М. А. Наделяев. – Санкт-Петербург, Петербургский энергетический институт повышения квалификации (ПЭИПК), 2004. – 110 с.

7. Григорьев И. С. Физические величины. Справочник / И. С. Григорьев, Е. З. Мейлихов. – М.: Атомиздат, 1991. – 1232 с.

8. Крутов В. И. Теплотехника. Учебник для втузов / В. И. Крутов. – М.: Машиностроение, 1986. – 432 с.

9. Уонг Х. Основные формулы и данные по теплообмену для инженеров. Справочник / Х. Уонг, – М.: Атомиздат, 1979. – 216 с.

10. Лабзун М. П. Діагностичні параметри теплових процесів в опорно-стрижневих ізоляторах при їх пошкодженнях / М. П. Лабзун, В. Л. Таловер'я, В. М. Кутін // Вісник Кременчуцького державного технічного університету – 2010. – № 3. – С. 100 – 104.

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