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MATHEMATICAL MODEL OF PEDESTAL INSULATOR WITH INTERNAL REINFORCEMENT FOR INDOORS MOUNTING

Possible mechanisms of insulation fault formation in closed screened current conductors due to electric, mechanic and thermal factors have been analyzed. Mathematical model of pedestal insulator with inter reinforcement for indoors mounting is suggested.

Key words: *insulation, closed screen current conductors, mathematical model of insulator, asymmetric bodies of rotation, coaxial system, concentrators of mechanical stresses.*

Pedestal insulators with inner reinforcement are used in complex screened current conductors for connection of generator and transformer in a single unit of electric stations.

Reliability of current conductor insulation within the units must be not less than the reliability of generators and transformers insulation. Insulation of phase-wise current conductor insulation of ТКЭП-6/3200-125 type at Novodnistrovskay Hydroelectric Station, does not completely meet this requirements. Statistic data for insulators of ИОР-10-750ШУХЛ2 type faults are given in Table 1.

Table 1

Statistic data of insulators of ИОР-10-750ШУХЛ2 type

1	Total length of current conductor, m	Г1-Т1 140	Г2-Т2 125
2	Quantity of insulators in a phase, p-es.	130	85
3	Total quantity of insulators, p-es.	390	255
4	Total amount of current conductor of disconnections per year	13	3
5	Probability of damage per year of one insulator	0,0333	0,00118

Data, given in the Table, show low quality of pedestal insulators. Amount of insulators failures in current conductor Г1-Т1 is four times greater than in Г2-Т2.

Unit of phase –wise screened current conductor of ТКЭП-6/3200-125 type, (see Fig. 1), has individual aluminium coatings for each phase, the cross section of the coating is in the form of regular octagon of high rigidity. Phases of current conductor are placed in one horizontal plane. Tubular buses 2, 120 mm of diameter and thickness of 10 mm are fixed on pedestal insulators 5. Each insulator is fixed across the rubber spacer with bolt to a flange, which, in its turn, is fixed on coating 1 with four bolts.

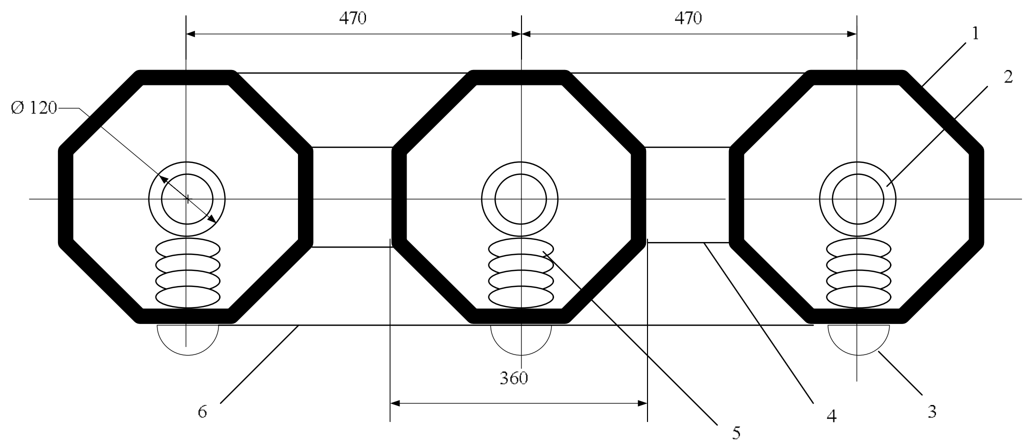

Fig. 1. Current conductor of ТЗМЭП-6-3150-128У1 type

Place of insulator fixing is closed by a cap 3 with rubber gasket. For reinforcement of places of insulators fixation bosses, made of aluminium alloy are welded from the inner part of screens.

Fixing of current conductors to metalwork structures is sliding (free), it is performed by means of steel clamps. Screens 1 of various phases of current conductors are connected by jumpers 4. Phase sheaths can be united by common sheath 6.

Such phase-wise current conductors are of large size, as compared with current conductors with common screen and their manufacture require more metal. Magnetic field of buses of these current conductor is compensated by magnetic fields of currents, induced in screens. That is why, mechanical loads, acting in case of short-circuit on buses and insulators are less here. As a result electrodynamic stability of phase-wise screened current conductors is higher, than that of current conductors with common screen.

It is known, that in case of short-circuit the temperature of aluminium and copper buses can reach the value of 200 ^{0}C and 300 ^{0}C correspondingly.

The construction of ИОР-10-750ШУХЛ2-type insulator, shown in Fig. 2, consists of three aligned cylinders: external- porcelain, intermediate- cement, internal -metal. Two first cylinders are thick-walled, and the internal cylinder consists of two solid cylindrical bodies, mode of non-magnetized grey cast iron of СЧ grade, divided by porcelain jumper of thickness.

Fixing of metal reinforcement to porcelain body by means of cement mortar is carried out by means of filling of circular cavity between reinforcement and porcelain body with Portland mortar, consisting of two parts of Portland cement and one part of the aggregate (fine river sand, washed off from clay substances or porcelain meal), mixed with water.

After solidification Portland cement mortar coalesces with the surface of porcelain and reinforcement and firmly unites them.

For preparation of the mortar Portland cement of the grade not less than 400 is used for pedestal rib, insulators of indoors mounting, rated 6 – 10 кV [1].

Ultimate strength of specimens of 40×40×160 mm^3 after solidification at compression σ_{com} > 40 MPa; at static bending σ_{ben} >5,5 MPa.

Temperature coefficient of linear expansion of cement mixture $TK_l = 10 \cdot 10^{-6}$.

Compaction of cement mixture after filling circular cavity between porcelain and reinforcement is achieved by short term vibration of the insulator or filling the cavity with cement mixture is performed under the pressure of 0,2 – 0,3 MPa, that is equivalent to fitting the cylinder into the cylinder tension.

Non- reinforced porcelain insulators do not decrease their mechanical strength under the impact of various cycles of temperature changes from +50 ^{0}C to –40 ^{0}C, as well as during lasting cooling up –60 ^{0}C.

While temperature changes of reinforced porcelain insulators in places of porcelain contact with reinforcement additional mechanical stresses appear, due to the difference of linear expansion coefficients of porcelain, cement mixture and metal reinforcement.

To decrease these additional stresses, porcelain surface and reinforcement, contacting with cement mixture are covered with the layer of compensating spreading, the thickness of the layer being 0,2 – 0,3 mm (asphalt-bituminous varnish БТ-99 or БТ-377). End faces of cement layer are covered with waterproof coating, for instance, enamal ПФ-115. It is worth remembering, that cement layer is destroyed under the impact of transformer oil.

Faults of pedestal insulators with inner reinforcement appear in the form of axial – radial cracks (fractures). In dry form electric resistance of the insulator with fractures is not decreased, but in case of high humidity, typical for hydroelectric stations microfilm of water is formed in the fracture on both surfaces of the fracture, including the porcelain jumper, where the length of leackage route does not exceed 25 mm.

In undamaged insulator ribbed external surface becomes humidified, this surface is of much longer length than the jumper and is calculated for normal level of insulation that is why the overlapping with operating voltage does not occur.

Average calculated humidity discharge intensity of electric field for porcelain is 2 – 2,5 кV/cm and remains the same for faulty and non-faulty insulators, that is why remaining level of insulation oh humidified surface of the jumper is 5 – 6 кV. That is why, the amount of failures of insulators in ТКЭП6/3200-125 does not decrease, not counting constant replacement of faulty insulators by new ones.

There are all reasons to think, that all the insulators of current conductors Г1-Т1 and Г2-Т2 have faults in the form of axial radial and being humidified, create routes for phase-wise short circuitings. Experimental tests of new insulators by” thermal shock”, carried out at the laboratory of engineering and electrophysics of high voltages of Vinnytsia National Technical University, testify that after passing of short-circuit current, rated for 31,5 кА along current conductor the temperature of internal reinforcement of insulators reaches 200 ^{0}C, as a result porcelain elements break, forming radial-axial cracks. These cracks reduce the length of leakage route along ribbed surface rill the value of jumper thickness (from 180 mm to 25 mm) i.e., 7.2 times. In dry form insulators with such faults keep up the remaining level of insulation at the level of not less than 30 kV. In case of humidification of the crack this level drastically drops to 5 – 6 kV, i.e., the route for new SFSC appears. As a result of this SFSC “thermal shock” influences on all insulators of the phase and last insulators, including new, installed instead of faulty ones break. Thus, we may assume, that all insulators of the given type, used in complex screened current conductors of Novodnistrovsky hydroelectric station are faulty: they have characteristic fault- radial-axial continual crack. The situation can be radically changed by immediate replacement of all the insulators of the given type of those insulators, where $\Omega < 2$, or $k < 0{,}57731$. Input control of such insulators should be performed, applying the technique, described in the given paper.

For theoretical studies, mathematical model of pedestal insulator with internal reinforcement is suggested, the given model has been developed by the specialists in the sphere of strength of materials [1]. While fitting of one cylinder into another with tension, circular stresses in the inner cylinder are compressing, and in the outer cylinder –they are stretching. Diagrams of mechanic stresses distribution, emerging after fitting, are shown in Fig. 2.

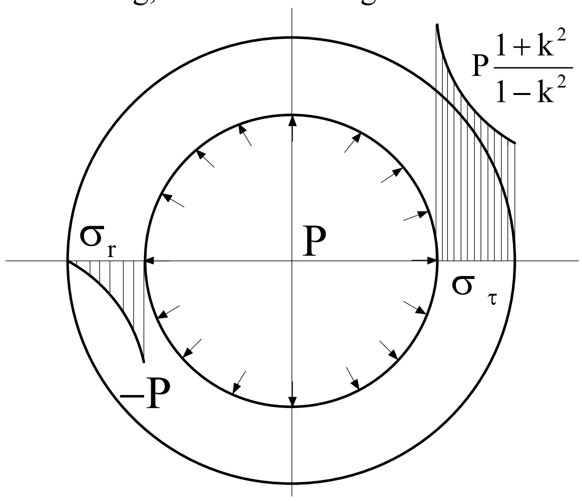

Fig. 2. Diagrams of mechanical stresses distribution in НОР insulator

Pedestal insulator, as compound cylinder while temperature change of inner cylinder due to ОКЗ in current conductor, creates in outer porcelain cylinder additionally stretching circular and compressing radial stresses (see Fig. 2). Theses stresses are described by the formula:

$$\sigma_r = \frac{r_1^2}{r_2^2 - r_1^2}\left(1 - \frac{r_2^2}{r^2}\right)p, \tag{1}$$

$$\sigma_\tau = \frac{r_1^2}{r_2^2 - r_1^2}\left(1 + \frac{r_2^2}{r^2}\right)p, \tag{2}$$

$$u = \frac{1-\mu}{E}\cdot\frac{r_1^2 p}{r_2^2 - r_1^2} r + \frac{1+\mu}{E}\cdot\frac{r_1^2 r_2^2}{r_2^2 - r_1^2} p \cdot \frac{1}{r}. \tag{3}$$

Stress σ_r is compressing everywhere, and σ_τ – is stretching. The greatest values of σ_r and σ_τ will be close to inner surface of cylinder if $r = r_1$:

$$\sigma_{r(r=r_1)} = -p; \tag{4}$$

$$\sigma_{\tau(r=r_1)} = \frac{1+k^2}{1-k^2}\cdot p, \tag{5}$$

where $k = r_1/r_2$.

Radial shift close to inner surface (increase of internal radius)

$$u = \frac{r_1}{E}\cdot\left(\frac{1+k^2}{1-k^2} + \mu\right)\cdot p. \tag{6}$$

It is known [1], that the cylinder with thick wall does not withstand internal pressure greater than $[\sigma]/2$. Substitution of this criterion in the formula (5) will give the relation

$$\sigma_{\tau_{crit}(r=r_1)} = \frac{1+k^2}{1-k^2}\cdot\frac{\sigma_{\tau_{crit}}}{2},$$

or $\frac{1+k^2}{1-k^2} \le 2$, and $k \le 0{,}57731$.

Stresses and shifts close to external surface of the cylinder at $r = r_2$:

$$\sigma_{r(r=r_2)} = 0; \tag{7}$$

$$\sigma_{\tau(r=r_2)} = \frac{2k^2}{1-k^2}\cdot p; \tag{8}$$

$$u_{r=r_2} = \frac{r_2}{E}\cdot\frac{2k^2}{1-k^2}\cdot p. \tag{9}$$

Diagrams of mechanical stresses, shown in Fig. 2, vary according to hyperbolic law. The most dangerous for destruction is the point, located near inner surface of porcelain insulator.

Circular stresses, resulted from internal pressure will be added to stresses, resulted from fitting in the porcelain and subtracted from them in the inner cylinder. Radial stresses from internal pressure and fitting pressure are summed up in both cylinders.

Summed up diagrams of stresses after pressure application have the form, shown in Fig. 2.

Characteristic feature here is jump in σ_τ diagram on the radius of cylinders contact. It is known [2], that porcelain has far less tensile strength, than comparison strength, that is why radial – axial cracks emerge due to internal pressure

$$p \le \frac{|\sigma_\tau|}{2},$$

as it is shown in [1].

Analysis of the formula (5) shows, that constructive parameter $\Omega = \frac{1+k^2}{1-k^2}$ is determining, for destruction conditions of porcelain body of pedestal insulator with internal reinforcement.

For determination of variations range of this parameter in modern insulators corresponding geometrical dimensions r_1, r_2, r_3 were measured.

Value of TK_l [2] for grey cast iron (constant) TK_{l1} = $12 \cdot 10^{-6}$ 1/grad of cement binder TK_{l2} = $12 \cdot 10^{-6}$ 1/grad allow to draw a conclusion, that cast iron and cement binder are uniform material, regarding this parameter. For condition in our problem it allows to pass to two-cylinder model of pedestal insulator, where the inner cylinder has the radius $r_{eq} = r_1 + r_2$, and outer cylinder r_3 - correspondingly.

For such model values $k = r_{eq}/ r_3$ are defined experimentally, the dependence Ω = f(k), presented graphically in Fig. 3 and in Table 2 has been constructed.

Table 2

k	0,95	0,9	0,85	0,8	0,75	0,7	0,65	0,6	0,55
Ω	19,5	9,5	6,2	4,55	3,57	2,9	2,46	2,12	1,86

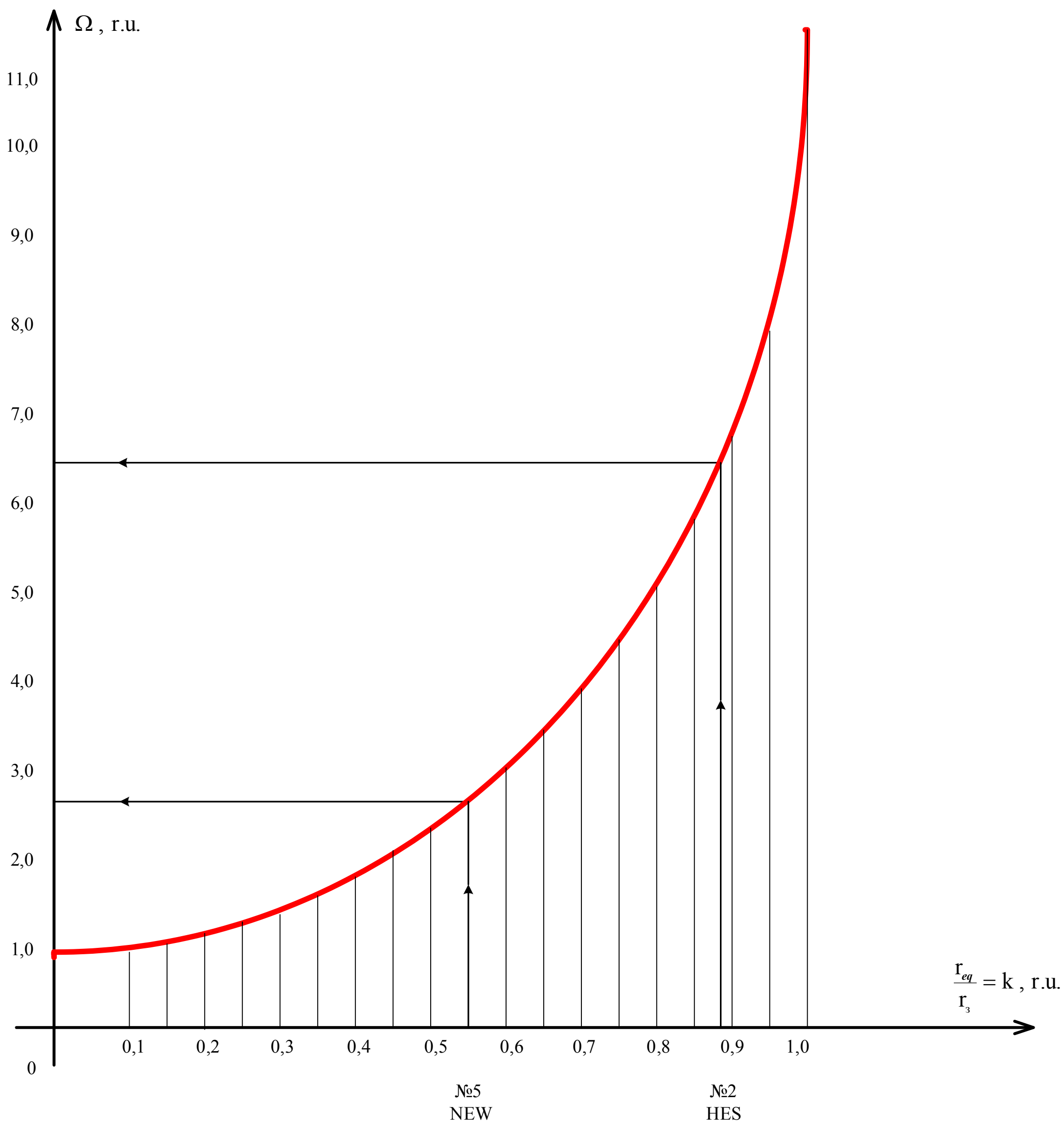

Fig. 3. Dependence Ω = f(k)

Internal pressure in the insulator emerges as a result of “thermal shock, that corresponds to conditions of SPSC current passage along current conductors.

It is known [3], that the temperature of aluminium and copper buses can increase in this process to 200 ^{0}C and 300 ^{0}C correspondingly.

During experimental research heating device with surface temperature 200 ^{0}C was applied to internal reinforcement of insulator for a short period of time.

However, temperature field in cylinders axially symmetric and constantly axial. In these conditions it may be considered, that the cross-sections remain flat and deformation σ_z = const. While heating insulators of ИОР-10-750ІІІУХЛ2 type with internal diameter $2r_1$ = 75 mm and external $2r_2$ = 90 mm to the temperature of internal surface T_1 = 200 ^{0}C, and external T_2 = 20 ^{0}C. Temperature stresses in porcelain can be defined, considering, that along the thickness of the wall temperature changes according to linear law.

In calculations we take such characteristics of porcelain:

$E = 0{,}5\cdot10^6$ kg/cm^2 – modules of elasticity;

$\alpha = 4{,}5\cdot10^{-6}$ – temperature coefficient of linear expansion;

$\mu = 0{,}3$ – Poisson’s ratio.

Excess of internal surface temperature relatively to external surface is 180 ^{0}C.

Let us define tangential and axial stresses near internal surface of porcelain cylinder by the formula

$$\sigma_{\tau(r=r_1)} = \sigma_{z(r=r_1)} = \frac{E\alpha T}{3(1-\mu)(r_2-r_1)}\left[3r_1 - \frac{2\left(r_2^3 - r_1^3\right)}{r_2^2 - r_1^2}\right]. \qquad (10)$$

For insulator of ИОР-10-750ІІІУХЛ2 type $\sigma_\tau = \sigma_z = -$ 684 kg/cm^2.

The results of the experiment of two types of insulator are presented in Table 2.

All the insulators of ИОР-10-750ІІІУХЛ2 type with Г1-Т1 and Г2-Т2 of Novovdnistrovsk Hydro accumulation electric station were broken by thermal shock, axial – radial cracks being formed along the total height of the insulators. The insulators of the second type ИОР-10-750 withstood the thermal shock without damage.

Thus, it was determined experimentally, that the parameter of similarity of insulators construction Ω is equivalent to gain factor of tangential stresses σ_τ on internal surface of porcelain cylinder and can serve as criterion for selection of reliable type of insulators for complex screened current conductor(CSC).

Conclusions

1. Insulators of ИОР-10-750ІІІУХЛ2 type in the process of operation break, forming axial – radial cracks along the total height, that leads to reduction of leakage route length on the surface of the insulators from 180 mm to 25 mm.

2. Process, considered in P 1. leads to destruction of porcelain jumper between internal reinforcement of current conductor and screen, as axial – radial cracks opens and forma instead of jumper open surface of jumper thickness length, i.e., 25 mm.

3. Remaining level of insulation at dry surface of the crack considerably exceed phase voltage of ТЗМЭП-6-3150-128У1 type current conductor.

4. Remaining level of insulation in case of crack surface humidification is 5 – 6 кV, that is less than phase voltage.

5. In case of conditions of P. 4 arc burning of SPESC along the height of the jumper leads to melting of amorphous component of porcelain, accompanied by formation of glass-like route (channel).

6. Thermal-physics tests of new insulators of ИОР-10-750ІІІУХЛ2 type resulted in cracking of all insulators, according to conditions of P. 1. Four cracks emerge, two very thin cracks (hair-like) go down, they stop at the level of jumper, and two other cracks, 0,1 – 0,18 mm of thickness –along

the radius and height.

7. Analogy of ИОР construction with thick walls coaxial cylinders is established, these cylinders are fitted with tension one into another.

8. On the base of conditions of P7 mathematical model of ИОР insulator has been constructed, the model enabled to suggest the criterion for geometrical relations of the construction $\Omega \leq 2$, or $k = r_1/r_2 \leq 0{,}6$ taking into account SPASC $p \leq \frac{|\sigma|}{2}$. Superposition of the values $k_1 = 0{,}6$ and $k_2 = 0{,}8$ on the curve $\Omega = f(k)$ shows that insulators of the second type ИОР-10-750IУХЛ2 must not break at thermal physical tests of new insulators, that was proved experimentally.

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