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CONSTRUCTIVE COORDINATION OF INSULATION FAULT AND CUMULATIVE EFFECT RECEIVED FROM LIGHTNING IMPULSE STRING

The paper considers and researches the voltage breakdown process of circuit-breaker epoxy bushing and presented the mathematical model of the process of their damage. It was discovered that electrical breakdown channels in circuit-breaker epoxy bushing are the outcome of both, the constructive coordination of insulation fault and cumulative effect that is received from stray wave lightning impulse string.

Keywords*: circuit-breaker epoxy bushing, electrical damage, stray wave, impulse voltage, longitudinal insulation, lightning protector.*

Statistical materials of 750 kV circuit-breakers elements damageability, submitted by SWEPS repair service, testify that epoxy bushing of explosion chambers are damaged by electric through breakdown with formation of characteristic defects which are illustrated on photo. Mostly such damages arise in phases A or C which are connected to outermost phases of wires 750 kV PTL.

It is known, that with the greater probability lightning discharges strike the outermost phases of PTL at their horizontal arrangement. It occurs both as a result of breaks of a lightning through rope protection, and due to electromagnetic connection of the rope and wire in a dynamic mode, when on a rope there is an intensive pulse crown.

the above mentioned allows to assert, that initiators of epoxy bushing breakdowns in circuit-breakers are electromagnetic stray waves from a direct stroke place in PTL in the direction of substation. While the stray wave are moving to the substation, their amplitude is limited to a pulse level of line isolation, and they are deformed and fade due to influence of longitudinal and cross-section PTL parameters, therefore should not represent danger both for main and longitudinal isolation of transformers and reactors windings. The opposite effect is actually observed.

It is known [1], that through the primary channel of a lightning in a direct stroke place there can be up to 10-15 and more repeated main discharges without leader stage, therefore stray waves will run on substation with the packs of pulses.

It creates conditions for cumulative effect during the formation of electric breakdown of isolators.

Dangerous impulse voltage comes to the PTL switch from a natural source - lightning as aperiodic impulses of a microsecond range.

In relation to these impulses the switch under certain conditions - down time in autoreclosing cycle is the intensifier which will transform lightning voltage impulses to dangerous impulses both for own isolation, and for longitudinal isolation of transformers windings and shunt reactors. This is the results of analysis of its work with the help of electric equivalent circuits and mathematical models.

The electrical schematic diagram of switch VVB-750 kV is shown on fig. 1 which shows, that the phase of the switch has 16 individual breaks, each of them is shunt with two in parallel connected capacitors and has epoxy cast inputs.

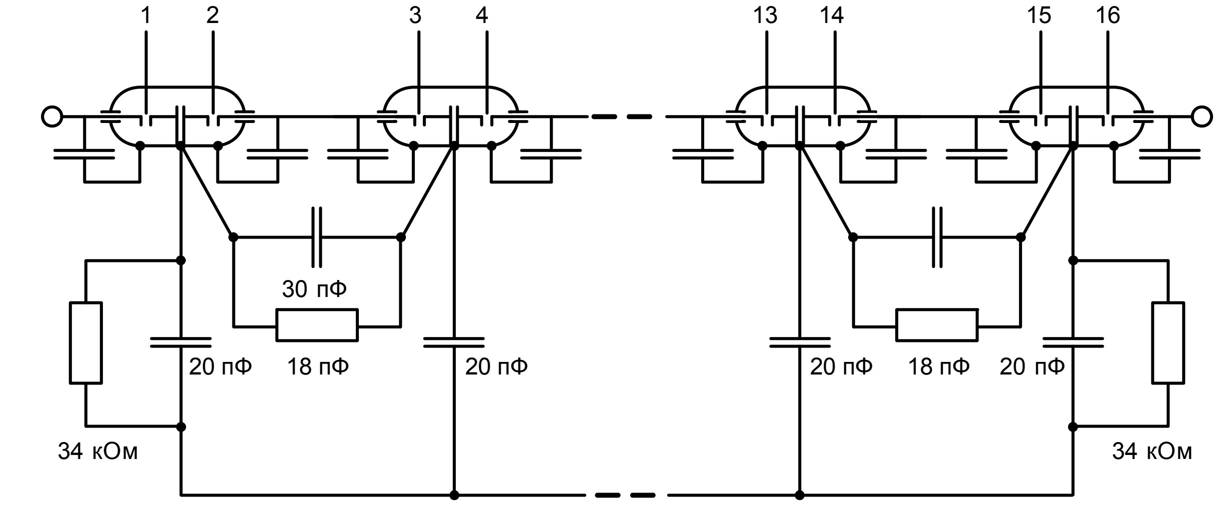

Fig. 1. Electrical schematic diagram of switch VVB-750 kV

The equivalent circuit of the switch for incoming impulse voltage of a lightning origin is shown on fig. 2.

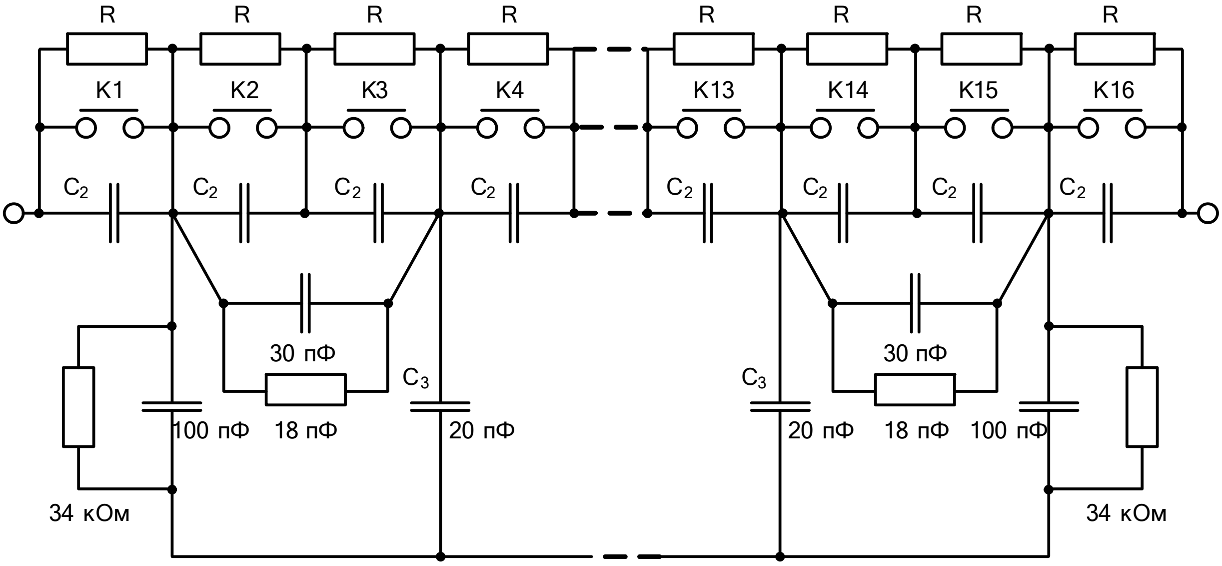

Fig. 2. The equivalent circuit of the switch for incoming impulse voltage of a lightning origin
C_2 – capacities between electrodes (longitudinal);
C_3 – electrode's capacities relatively to tank (ground) - crosscut; R – resistance of the outflow of isolating construction;
ρ – line's impedance.

Breakdown of intervals is simulated by short circuit of K keys. Resistances R are usually such big, that practically do not have influence on impulse process in the circuit.

Let $2\rho \cdot C_e << t_{зап.\min}$. $t_{зап.\min}$ - minimal delay time of breakdown; C_e – equivalent capacity of the switch relatively to bus and to linear poles; ρ – line's impedance. Front duration of a standard lightning impulse is usually longer than $t_{зап.\min}$, therefore the analysis of transient in the circuit fig. 4 can be carried out without taking into account the influence of line's impedance considering, that after breakdown of each key, on the rest not punched key the voltage has time to be steady-state according to a ratio of longitudinal C_2 and cross-section C_3 specific capacities.

In this case a settlement equivalent circuit it is possible to present as plural cell circuit of "m" elements (polythrone). The impulse voltage on electrodes of the switch after breakdown of intervals is distributed according to (1)

$$U_{K+1} = 2U_0 \frac{ch(m-k)\gamma}{ch(m-j)\gamma}, \tag{1}$$

$\gamma = \ln\left[1 + \frac{C_3}{2C_2}\left(1 + \sqrt{\frac{4C_2}{C_3} + 1}\right)\right]$; k – serial number of a key.

In case C_3/C_2 <2 the value γ can be defined by more simple expression:

$$\gamma = \ln\sqrt{\frac{C_3}{C_2}}.$$

The instantaneous electric potential can be defined on any key K by expression (1).

For example, for j=0, that is before breakdown of the first interval on it there will be instantaneous electric potential of form (2).

$$\Delta U_1 = U_1 - U_2 = 2U_0\left[1 - \frac{ch(m-1)\gamma}{ch(m\gamma)}\right]. \tag{2}$$

If $j >> 1$, and $m > 3$, then $\Delta U_1 = 2U[1 - \exp(-\gamma)]$.

Therefore, if $\gamma = 1$ on the first interval before breakdown will be $0{,}63\cdot 2U_0$ and K1 will be being broken at a big frequency rate of an overvoltage.

After breakdown of j intervals voltage swing on the k-th key will be

$$\Delta U_k = U_k - U_{k+1} = 4U_0 ch\frac{\gamma}{2}\frac{ch\left(m - k + \frac{1}{2}\right)\gamma}{ch(m-j)\gamma} \tag{3}$$

For our object - air circuit breaker VVB-750 kV we have such initial conditions: $m = 16$; $j = 3$; $m - j = 13$; $\gamma = 10$, therefore the voltage on an interval k+1=4 practically does not depend on γ and is equal to (4).

$$\Delta U_4 = 2U_0[1 - \exp(-10)] \approx 2U_0 \tag{4}$$

$U_0 \leq 1500$ кВ – an operate voltage of an aerial fuse RVMK-750. Therefore $\Delta U_4 \leq 3000$ kV, and rate of a voltage rise grows up to 10MV/μs at the front. At such rate of pulse rise the conditions for constructive coordination fault of any isolator along the pulse path and first of all of epoxy bushing of the circuit-breaker itself that results in through electric breakdown along a radial direction are created.

In experimental researches [3] it has been established, that through electric breakdowns of isolators by pulses with a sharp edge arose some times after the voltage applying.

Supplying isolator with the first voltage pulse when a rate of pulse rise is more than 1 MV/μs brings to spark overlapping over the surface in 0,1 μs. Falling edge of pulse is observed on oscillogram during this moment. Simultaneously the voltage is applied to insulation solid during this moment but high electric force (EF) lasts nanoseconds here. For this time there can be only a local partial breakdown deep into firm isolation at a depth of approximately $3\cdot 10^{-5}$ m. The further discharge process into the depth is stopped as a result of a voltage cutoff by overlapping and sharp decrease of electric force in a solid. Actually the thickness of insulating solid in this place is decreased to this depth. However occurrence of a microcrack which is filled with air, considerably deforms a pattern of the electric field and as a result EF is increased in tens times at the end of a crack from the following pulse of a voltage which by a principle of a baton push the channel further. The third - fourth pulses, as a rule, finish the electric breakdown. In process of moving of partial breakdown's channels in depth of insulation solid the coordinating factor from 1,6÷1,8 increases up to 1,0. Such isolator is already defective, and this multistage model of coordination fault, which takes into account cumulative effect of partial consecutive breakdowns, fully meets the experimental data [4].

Used in [4] oscillographic method of research of isolator's breakdown process basically not sensitive to origin and evolution of partial breakdowns for as overlapping of normal isolator shields revealing these processes on the oscillogram.

Sypplying of the penultimate pulse (concerning to a final effect) finishes the formation of the channel of through breakdown up to a stage of equal probabilities of the breakdown and overlapping, therefore the subsequent pulse affect on the defective isolator.

The pulse voltage with sharp edge results in only electric mechanism of breakdown of isolators.

The basic geometrical sizes of capillaries of the broken isolators are radius and length. The length of a capillary is determined by type of isolator and for epoxy bushing of circuit-breakers is up to 40 - 45 mm.

The radius of a capillary does not depend on type of isolator and varies in a narrow range of sizes 0,2÷0,3 mm. The geometrical sizes of cutoff craters do not depend on type of isolator and are determined by characteristics of the insulator. The sizes of cutoff craters which arise from both sides of the breakdown channel, were measured with the help of optical device MPB-2, with increase 24* and scale factor of 0,05 mm. Craters have the shape of cone with the big radius of 1,5÷5 mm, and smaller as a capillary has, that is 0,2÷0,3 mm.

On fig. 5 the schematic image of an integrated picture of defects in isolator after its pulse breakdown is given. The sites of epoxy compound which are directly adjoined to the channel of breakdown were collapsed up to fine structures, forming a crash zone. Here and further at the description of consequences of breakdown and destructions of isolators are used the terms used in the theory of destruction of firm substances by means of an explosive. It is not casual, because the mathematical models describing destruction of firm substances by explosion of an explosive, taking place in blast hole are similar to models of destruction of isolators after electric breakdown by pulses.

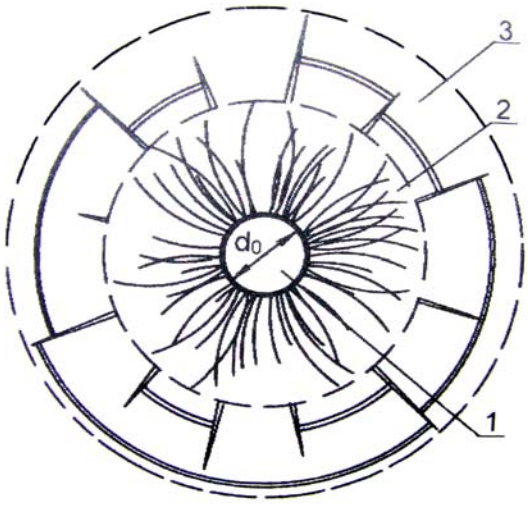

Fig. 3. The Schematic image of an integrated picture of defects in isolator after its pulse breakdown
1- channel of breakdown, 2- crash zone, 3- zone of radial and ring cracks

From peripheral areas of a crash zone in a direction of an external surface of isolator the chain of radial and ring cracks is formed. They form as a whole a crack zone. After primary breakdown of isolator these cracks are not opened, therefore are visually observed as hair-like [4]. Input and output cutoff craters appear after an azimuthal shock wave, coming up to a surface of isolator, is reflected from it (as boundary of two environments) owing to appearance of stretching mechanical pressure which destroy a mouth of the electric breakdown channel in the characteristic way. The subsequent experimental researches allowed to find out, that the digit gradient on a capillary does not exceed 10±1 kV/cm. It allows to predict a residual level of isolation of defective isolator. For instance epoxy bushing of the circuit-breaker has residual level Ubr.res = 10·4 = 40 kV.

Conclusions

1. Channels of electric breakdown in epoxy bushing of the circuit-breaker VVB-750 kV are consequence of the isolation constructive coordination fault and cumulative effect from a series of storm pulses from the stray waves coming on PTL 750 kV from direct stroke place of a lightning to central substation.
2. In relation to the stray waves of a storm origin the circuit-breakers works as the intensifiers that increases a steepness of pulse voltage in several times.
3. After the circuit-breaker the intensified pulses surge towards AT windings and reactors of cross-section compensation and form very dangerous gradients on the first turns and coils that can lead to electric breakdown of longitudinal isolation.
4. Lightning-protective aerial fuses do not have an influence on the escalated pulses steepness, that is do not protect longitudinal isolation of windings.

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