Integral Arc Models at Single Phase-to-Ground Faults and Special Characteristics of Arcing in Power Cable Insulation

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Abstract--**The paper presents the results of experimental investigations and calculations of arcing at ground faults in distribution networks up to 35 kV. It is shown that an additional active component in single phase-to-ground current caused by a high-voltage resistor connected to a neutral leads to the change of the following arcing ground fault parameters: voltage recovery rate on the faulty phase after arc quenching, conditions of arcing and arc quenching depending on the insulation material (mass-impregnated paper insulation, polymeric insulation), probability of restrikes. Special features of main stages of arcing ground fault are presented. Integral models of arcing based on conductivity, current and voltage functions for ablation controlled arcs in power cable insulation are proposed.**

Index Terms--**Arcing, single phase-to-ground fault, power cable insulation, integral models.**

I. Introduction

THE process of arcing at single phase-to-ground faults influencing on overvoltage levels and arc durations is rather complicated. It depends on ground fault location, electric strength recovery rate of an insulation gap, insulation purity and insulation defects, time of arc ignition and other factors. In mass-impregnated paper insulated cables arc burns in enclosed insulation area. If, at some time, the rate of electric strength recovery exceeds the rate of insulation gap voltage growth, faulty conditions may be self-cleared. It happens due to cable oil dribbling and breakdown channel pouring. Adequate time (i.e. tens of seconds and more) of no-current for channel pouring is a necessary condition for that situation. In cross-linked polyethylene (XLPE) insulation and in ethylene propylene-rubber (EPR) insulation the phenomenon of self-recovery of solid insulation cannot occur that provides fundamentally different character of prestrike conditions and features of electric breakdown and arcing.

At present, there are no any adequate models of electric breakdown and arcing in power cable insulation. When solving the problem of the development of these models, we need to consider disadvantages of existing hypotheses developed by Petersen (in 1916) and Peters & Slepian (in 1923) [1] which are now widely used for analyzing of arcing in power cable insulation that is not exactly correct.

Firstly, overvoltage levels and no-current durations are influenced by not only the parameters of a zero-sequence circuit but also the ratio of active and reactive components of a fault current (parameter I_R/I_C).

Secondly, insulation damage level significantly impacts on the time between serial arc ignitions. Insulation damage level highly varies depending on breakdown conditions and characterizing the transition of an intermittent arcing fault into a steady fault. During the development of single phase-to-ground arcing fault, overvoltage level decreases to some 'boundary' level. Further restrikes will occur at this overvoltage 'boundary' level. Based on field experience, this level does not exceed $(2.4 – 2.6)U_0$ where U_0 is phase-to-ground voltage.

Thirdly, the results of further restrikes at intermittent arcing caused by arcing ground fault in a cable terminal are determined by various factors. These factors are random values except main parameters of a zero-sequence circuit. Therefore, an ideal arc model should represent stochastic nature of main variable arc parameters, such as arc current, voltage recovery rate and growth rate of electric strength of an insulation gap after arc quenching.

Intermittent arc is an arc which is ignited and quenched every half-period or every period of power frequency. Interrupted arc is typical for real cable breakdown conditions. An interval between its ignitions and extinctions varies randomly from 0.02 seconds to tens periods of 50 (60) Hz power frequency.

Solving of the multi-factor task of the development of an adequate model of electric breakdown and arcing in power cable insulation should be supported by the analysis of real oscillograms recorded in operational networks. In common case, the solution of this task is complicated since it always depends on initial conditions and practically possesses a number of assumptions. Integral models of arcing in various types of power cable insulation based on one or several parameters of a transient process are proposed below.

Integral models of arc discharge are easy to use, because when modeling a transient process we can use only one parameter of this process taking into account its non-linear variation in time. Resistance of arc column is an example of such parameter. In addition, it is necessary to compare values of arc resistance R_{arc} and insulation resistance R_{ins} during different stages of breakdown, because the development of a breakdown channel is accompanied by gradual decrease of R_{ins} and the transition of R_{ins} into R_{arc}. Then, integral models of electric breakdown and arcing should be supported by mathematical models based on differential equations including heat balance equations.

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II. MAIN STAGES OF ARC BREAKDOWN DEVELOPMENT AND EVALUATION OF ARC RESISTANCE IN MASS-IMPREGNATED PAPER-INSULATED POWER CABLES

It is known that each arc burning in cable insulation is an ablation-controlled arc (*ablation is a process of removal of material from the surface of an object by vaporization or gas flow*). This means that before quenching an arc is cooled; its temperature profile is changed due to evaporated and decomposed polymer particles (in the case of XLPE or EPR cables) and burned-out paper and cable oil particles (in the case of mass-impregnated paper insulated cables) flowing into the arc column.

We emphasize that in our investigations the arc resistance is equal to the resistance of an arc breakdown channel. This assumption is permissible because of the following reasons:

a) energy release in the arc channel is determined not only by conductivity of the arc column but also by resistance of channel walls and burning paper particles and evaporating oil during arcing;
b) power released in the breakdown channel is transferred into radiation, heating of insulation walls locating in the boundary of the arc and the destruction of insulation;
c) for calculations of power and energy released in the arc which burns in the enclosed channel, we use values of arc current and equivalent resistance of arc channel, or voltage across an insulation gap. It is evident that this voltage is applied not to the arc column but to the whole breakdown channel.

Arc energy is evaluated based on the analysis of oscillograms of arcing faults in power cables. Obtained values vary from 500 J to 1000 J.

Known data on insulation resistances for mass-impregnated paper-insulated power cables shows that R_{ins} is influenced by many factors: duration, levels and frequency of transient processes during internal overvoltages, temperature field distribution in cable insulation, moisturizing level and gas content, level of dielectric breakdown for mass-impregnated paper insulation due to thermal-oxidative breakdown and others. Prestrike conditions always conform to reduced cable insulation (hundreds of kΩ or, less frequently, several MΩ).

It is evident that breakdown channel resistance is a non-linear function of time due to rising of channel dimensions and changing of insulation structure at the boundary of the channel. The development of arc breakdown in mass-impregnated paper insulation can be divided into the following three stages.

The first stage represents self-clearing non-periodical insulation breakdowns which last from one hour to several days. It is supported by experimental investigations [2], [3]. On the first stage the resistance of the channel changes stepwise: from the values conforming to the reduced insulation (field experience shows 100 – 200 kΩ) to the values of 1.0 – 10 Ω depending on breakdown channel dimensions and oil viscosity. Single phase-to-ground fault is possible to be self-cleared before reaching critical dimensions of the breakdown channel with the rise of the resistance at the fault place up to $10^4 – 10^5$ Ω.

However, insulation area where fault is self-cleared is potentially non-cleared-fault area which certainly causes feeder disconnection and faulty cable replacement.

The second stage represents series of continuous impulse breakdowns. Self-recovery of insulation in that case is not possible because quick ionization of the breakdown channel and the development of the stable breakdown path cause decomposition of oil flowing to the place of the breakdown and formation of a gas bubble (mainly H_2). Due to pressure rise, periodical arc quenching occurs with the formation of gas bubbles. Arc resistance exponentially decreases on this stage (e.g. from 1.0 – 10 Ω to $10^{-1} – 10^{-3}$ Ω) that leads to the carbonization of the breakdown channel.

The third stage represents stable arcing with current distorted by high harmonics, impulses and dips. Current curve is close to sine curve. Arc resistance changes weakly; it is determined by high conductivity of carbonized breakdown channel ($10^3 – 10^4$ siemenses). Arc channel can be presented as metallic hollow conductor having round cross section. Its length is equal to the distance between a cable core and a cable sheath, while its wall thickness is equal to insulating layer burned-out in the radial arcing channel.

III. INTEGRAL MODEL OF ARC BREAKDOWN AND ARCING IN MASS-IMPREGNATED PAPER-INSULATED POWER CABLES

The model of electric breakdown and arcing based of non-linear resistance changing during arcing fault development in mass-impregnated paper insulation can be presented in graphical form. Changing of insulation resistances and voltage breakdown can also be illustrated graphically.

Based on the mechanism of the development of arcing fault in mass-impregnated paper-insulated cables introduced in section II, the process of breakdown development and further arcing is adequately described by an integral model on the basis of non-linear insulation resistance R_{ins} and arc resistance R_{arc} (see Fig. 1). Here, insulation breakdown voltage U_{br} having the same form is also presented.

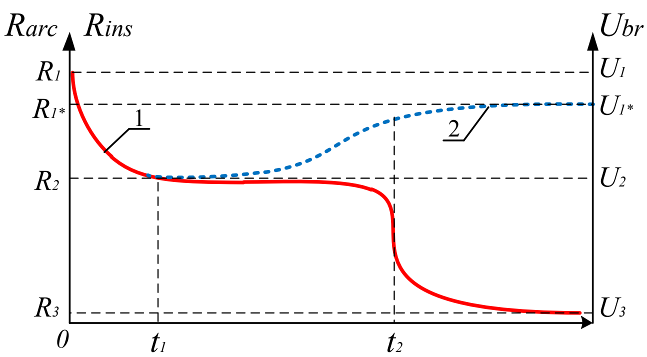


Fig. 1. Change of arc resistance (i.e. resistance of the arcing channel) and breakdown voltage for mass-impregnated paper-insulated cables during the development of arcing ground fault: 1 – development of non-cleared fault, 2 – breakdown channel pouring and self-recovery of insulation.

Fig. 1 can be explained as follows.

Interval $(0 – t_1)$ represents the first stage of arc breakdown (i.e. self-clearing non-periodical insulation breakdowns). Insulation resistance exponentially decreases from R_1 = 100 – 200 kΩ to R_2 = 1.0 – 10 Ω. Breakdown voltage also decreases, from $U_1 = nU_0$ (where $n >> 1$) to $U_2 = (0.8 – 0.9)U_0$. These values are supported by oscillograms obtained in 6–10 kV networks during the period of five years. Moreover, our experiments [3] show that breakdowns occur at different moments with various probabilities: at the maximum of voltage on the faulty phase (15% of breakdowns), before the maximum of voltage (34% of breakdowns), and after the maximum of voltage (51% of breakdowns).

Interval ($t_1 – t_2$) represents the second stage of arc breakdown (i.e. series of continuous impulse breakdowns) where possibility of further development of arcing fault is determined. Breakdown channel pouring happens due to cable oil dribbling with a verified experimental probability of 0.80 – 0.85; curve 1 passes into curve 2, breakdown voltage is recovered up to $U_{1*} = kU_0$ (where k = 2 – 4), and resistance becomes $R_{1*} = 10^4 – 10^5$ Ω. However, further development of breakdown and growth of breakdown channel are possible to happen with a probability of 0.15 – 0.20. Initial growth of restriking voltage is associated with the increase of gas release in the breakdown channel (i.e. passing into curve 2), while decrease of restriking voltage is caused by gradual expansion of the breakdown channel due to the destruction of insulation and channel carbonization (i.e. curve 1 at $t > t_1$).

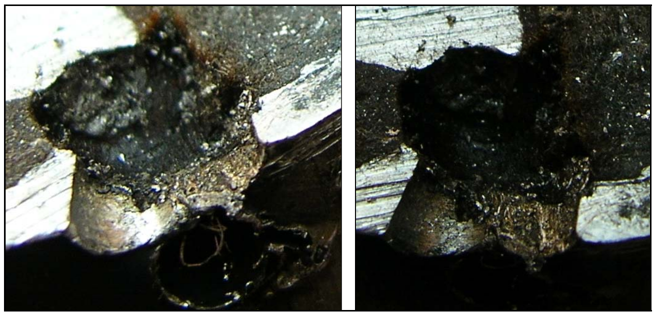
At the moment t_2 (*beginning of the third stage of arc breakdown*), strong impulse breakdown occurs with further decrease of voltage U_{br} to the values of $U_3 = (0.1 – 0.7)U_0$. The rise of the number of breakdowns results in further decrease of breakdown voltage U_{br}. Then, during the period of seconds or even minutes the arcing channel is developing; after that, serial impulse breakdowns pass into continuous arcing, and arc resistance reaches its minimum values of $R_3 = 10^{-1} – 10^{-3}$ Ω.

Values of arc resistance R_{arc} can be analyzed on the basis of arc dynamic current-voltage characteristics plotted for some interval of arcing. In accordance with obtained experimental results, arc resistance R_{arc} can be assumed to be in the range of $10^{-1} – 10^{-3}$ Ω depending on the stage of arcing and the character of the breakdown development (taking into account the possibility of self-clearance of arcing ground fault).

During a number of experiments and investigations on artificial arcing ground faults in operational networks, we found out mismatch between a place of an artificial fault (i.e. an artificial insulation defect like 'an artificial pinhole') and a place of real radial breakdown between a sector cable core and a grounded cable sheath as shown in Fig. 2. In this case, we evaluated the breakdown channel dimensions. The length of an arcing channel is about 3.5 – 4.0 mm (while the thickness of insulation between a core and a sheath is 2.95 mm). The diameter of a channel is from 2.0 mm at the beginning of a channel, near a cable core, to 3 – 4 mm at the end of a channel. Depending on arc power and arc duration, the dimensions of a breakdown channel can increase.

Oil decomposition and carbonization of mass-impregnated paper associated with arcing cause emission of H_2 (hydrogen), corrosive CO (carbon oxide) and CO_2 (carbon dioxide). Breakdown channel walls are covered with soot, asphaltenes and solid X-wax that verified by chemical analysis of faulty cables.

a)



b)

Fig. 2. Mismatch between a place of an artificial fault (i.e. an artificial insulation defect) and a place of real radial breakdown between a sector cable core and a grounded cable sheath (fig. a) and the result of arcing in a mass-impregnated paper-insulated cable (fig. b) during experiments and investigations on arcing ground faults in the operational 6 kV network.

IV. Analysis of Arc Breakdown Development in XLPE and EPR Power Cables

Based on the results of experimental investigations on artificial arcing ground faults in a single-phase XPLE cable in the operational 6–10 kV networks supported by real oscillograms, the model of arc breakdown development in solid polymeric insulation is proposed. On the basis of special features of insulation, the development of arc breakdown in XLPE or EPR insulation can be divided into the following four stages.

The first stage represents the prestrike conditions in close regions of possible partial discharges (PD). It is characterized by serial combination of internal defects (main channels of electrochemical treeings) with high-level of PDs. PDs characterize degraded and pre-fault conditions of a XPLE cable. It is a *development of the channel direction* of a radial breakdown in the medium between a cable core and a metal cable screen. Based on the results of PD investigations, it is shown that levels of quasi-charges exceed $1.05 \cdot 10^4$ pC (picocoulomb) and PD initiation voltage is less than or equal to U_0 [4]. Heating of insulation in the regions of inclusions and defects is insignificant and does not exceed 90 °C which is the permissible operating temperature for XLPE and EPR cables.

Duration of the first stage depends on service conditions (e.g. amplitude-frequency characteristics of internal overvoltages, rate of microdefect growth, load currents) and varies from several hours to 1 year.

The second stage represents the occurrence of microarcs (i.e. creeping surface discharges) at the walls of developing breakdown channel. The breakdown channel is the potential direction of arc discharge as solid interlayers of XPLE or EPR insulation in gas medium (caused by PD burning by-products, such as C_2H_2, C_2H_4, H_2 and others) with suspended particles of decomposed polyethylene in the form of conducting carbon compounds. This stage is associated with rapid ionization of a gas mixture in a breakdown channel (breakdown channel now is a combination of «microtubes» (i.e. very small channels where breakdown processes are in progress)) and gradual decrease of PD initiation voltage for each 'microtube' to the values of 30-50% of U_0. During these processes, increasing mechanical stresses in channel walls cause wall cracking that reduces the rate of breakdown channel development in radial direction and widens the channel. If water treeings are included into the breakdown channel during its development from one electrode to another (i.e. depending on the path of breakdown: from a core or from a screen), water is transformed into a gas form because temperature inside inclusions reaches 100 – 120ºC (rarely 130 – 150ºC).

Possible *duration of the second stage* varies from several minutes to several hours. The rise of the second stage duration due to the rise of dielectric losses and intensive micro discharges results in local overheating of insulation up to 140 – 160 ºC with barely visible decrease of electric strength of an insulation gap (no more than 5 – 10%).

The third stage represents the destruction of gas-liquid interlayers in polymer depth and the combination of «microtubes» into a single integrated channel. This channel is a cylindrical channel with variable cross-section and height close to cable insulation thickness. Arc breakdown in this cylindrical channel is developed in two ways.

The first way is more intensive. It is characterized by formation of a 'network' of creeping surface discharges which stretch in height along the developed cylindrical channel depending on the rate of local destruction of XLPE insulation with formation of conducting carbon compounds. This way provides a sufficient ionization rate for the development of volume discharge in the channel. Heating of XPLE caused by creeping discharges leads to local overheating of insulation and to the development of local heat breakdown.

The second way is influenced by volume discharge in the cylindrical channel filled by gas mixture. This way is supported by mechanisms of gas-filled gap breakdown with inhomogeneous electromagnetic field. Degree of nonuniformity for this field depends on PD initiation voltage, PD distribution equability, conductivity and density of gas mixture in different parts of the channel, etc. In this process, unstable local corona discharges are possible to occur (especially, being very close to electrodes) with initial voltage of $(0{,}1 – 0{,}9)U_0$.

The higher is the coefficient of nonuniformity of electromagnetic field (which is approximately equal to the ratio of radiuses of curvature for a cable core and a cable screen), the greater is the breakdown voltage related to the initial breakdown voltage. Provided that there is irreversibility of complete insulation breakdown (this is always observed in solid polymeric insulation, because electric strength of such insulation cannot be recovered even in the case of PDs), the possibility of complete insulation breakdown increases with increasing electromagnetic field strength E_{str} caused by external factors (i.e. switching of cable networks with reduced insulation by a vacuum circuit-breaker, occurrence of arcing ground faults in other points of a network and others) [5].

Possible *duration of the third stage* varies from several seconds to fractions of seconds.

The fourth stage represents the completion of arc breakdown. Due to increasing ionization rate and rapid growth of discharges in the channel, temperature rises sharply up to 400–500 °C in several milliseconds. With further heating of the breakdown channel, temperature rises up to 800–1200 °C, while temperature in the center of the channel is higher 2–4 times. After that, an arc is ignited. It is a low-temperature plasma. At that time, it is evident that electric strength E_{str} of a faulty part of insulation sharply drops to zero. Regardless of the electrode where the main streamer in the breakdown channel begins, another streamer is developing from the opposite electrode in the time of 10^{-4} seconds (or even less) before the complete breakdown of XLPE.

The fourth stage of the breakdown can be considered as two serial processes having different times of life: a) process of arc ignition; b) process of arcing. As each thermal process, these processes have time constants τ. According to preliminary estimations, time constant for the process of arc development in the channel is $\tau \approx 10 – 100$ µs.

Total arc duration t_{arc} in XLPE or EPR insulation is determined by not the physical properties of insulation, but by the parameters of the electrical network where cables are operated. Field experience shows that arc duration of $t_{arc} \leq$ 1 min corresponds to the time of the transition of single phase-to-ground fault into phase-to-phase short circuit with its further interruption. On the other hand, if each single phase-to-ground fault in the network must be interrupted, arc duration is determined by ground relay operating time (maximum delay time is no more than 0.4 – 0.5 seconds) and overall interrupting time of a circuit-breaker (for modern vacuum circuit-breakers interrupting time is not more than 0.1 seconds). Thus, arc duration $t_{arc} \leq 0.5 – 0.6$ seconds. It is evident that each fault in XLPE or EPR cables should be interrupted with minimum time delay due to the fact that these kinds of insulation cannot be self-recovered.

V. Integral Model of Arc Breakdown and Arcing in XLPE and EPR Power Cables

The process of electric breakdown of polymeric cable insulation is illustrated in Fig. 3. Representative curves of electric strength E_{str} and insulation resistance R_{ins} changing with time (see red curves in Fig. 3, Y-axes are from the left) are power functions which approach asymptotically to X-axis and Y-axes. On the contrary, temperature curves (see blue curves in Fig. 3, Y-axes are from the right) represent exponential functions of insulation heating during insulation breakdown development.

Numerical values of R_{ins} and E_{str} are marked on left Y-axes. They represent conditions of XLPE and EPR insulation:

a) for new undamaged cable insulation: $R_{ins} = 10^{12} – 10^{13}$ Ω, $E_{str50(60)Hz} = 30 – 40$ kV/mm. Insulation resistance values are obtained during diagnostic experiments on 10 kV XPLE cables. Electric strength values are verified by investigations carried out in Russian and international scientific test laboratories;
b) for reduced cable insulation where prestrike conditions are developing: $R_{ins} = 10^8 – 10^9$ Ω, $E_{str50(60)Hz}$ =

14 – 22 kV/mm. These values are verified by endurance tests with the evaluation of 'residual' electric strength according to [6];

c) for damaged cable insulation (by electric breakdown, non-self-recovered insulation): $R_{ins} = R_{arc} = 10^{-1} - 10^{-3}\ \Omega$, $E_{str50(60)Hz} = 0$.

Using the same time axis, insulation temperature curves T_{ins} are plotted. They illustrate insulation temperature before breakdown at 480 °C with further transformation into arc column temperature for low-temperature plasma (arc temperature in the center of the arcing channel $T_{arc} \approx 3000 - 4000$ °C) which does not significantly influence on arcing channel resistance. Temperature values in the range of 90 – 480 °C are obtained during our laboratory investigations on destructive testing of XLPE cables in heating furnaces.

We emphasize that curves given in Fig. 3 related to different Y-axes (i.e. red and blue curves) should not be compared with each other: for example, temperature rise does not cause electric strength E_{str} increase, and vice versa.

Based on experimental investigations presented in IEEE 400-2001 [7], we can compare curves of R_{ins}, E_{str}, T_{ins} (T_{arc}) with the rate of breakdown channel development V_{br} for polymeric XLPE and EPR insulation using known ratios K_U of power frequency voltage U_0.

Just for showing the strong dependence of parameters on V_{br}, curves having various curvatures are plotted in Fig. 3. Curves 1 and 1* correspond to $V_{br} = 175 - 611$ mm/h with $K_U = 4U_0$. Curves 2 and 2* correspond to $V_{br} = 2.2 - 5.9$ mm/h with $K_U = 3U_0$; Curves 3 and 3* correspond to $V_{br} = 1.7 - 2.4$ mm/h with $K_U = 2U_0$. Therefore, interval $t_1 - t_2$ for the curves given in Fig. 3 is significantly different and depends on cable insulation thickness.

When exposing to overvoltages of (2 – 4)U_0, the rate of breakdown channel development increases that is supported by [8]. So operating point can move to the next curve as is shown in Fig. 3 (A → B → C). For example, according to investigations of KEMA Testing and Certification Center (Netherlands), the rise of applied voltage frequency from 50 Hz to 500 Hz leads to the rapid destruction of insulation up to 6 – 8 times. It is expected that when applying voltages having frequencies in the range from hundreds Hz to several MHz, the degradation rate of polymeric insulation may increase 10 – 12 times or even more.

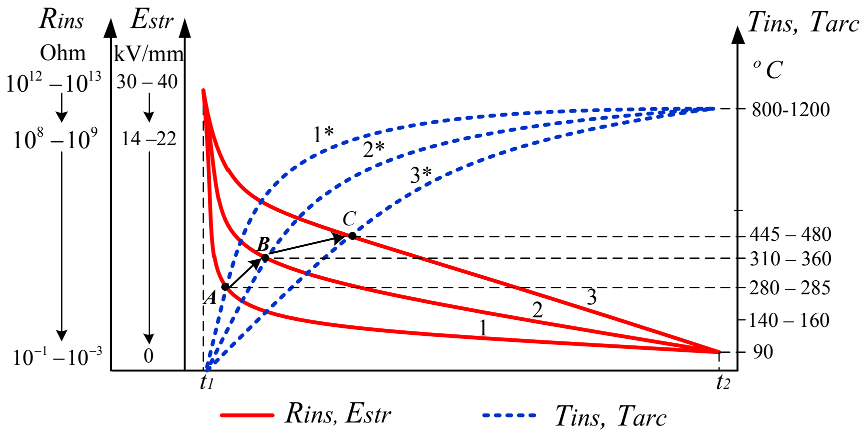


Fig. 3. Development of insulation breakdown for XLPE and EPR cables with time (R_{ins} – insulation resistance, E_{str} – electric strength, T_{ins} – insulation temperature, T_{arc} – arc column temperature) depending on different rates of breakdown channel development and applied 50 Hz voltage.

Our experimental investigations on polymer-insulated cables also confirm negative impacts of high harmonics and high-frequency overvoltages on XLPE and EPR insulation. Fig. 4 illustrates a breakdown channel in XLPE insulation of power cables which were operated during 1.5 years in the network equipped with variable-frequency electric drives being often switched by vacuum circuit-breakers. During laboratory overvoltage tests we found out that electric strength E_{str} of cable insulation decreases from putting into operation to 2.0 – 2.8 times in comparison with initial values (for different cable sections).

Calculations on breakdown channel dimensions for XLPE cables (see Fig. 4) shows that the channel diameter varies from 0.5 – 1.0 mm to 2 – 3 mm, and electric breakdown was developing in radial direction. Moreover, visual estimation of the breakdown channel and the analysis of arcing by-products allow describing of ablated products. Gases formed during the breakdown consist of organic hydrocarbon compounds (e.g. orange-red flame during arcing), carbon dioxide CO_2 and water vapours. Breakdown channel walls are covered with wax-like substances mixed with soot.

Fig. 4. Electric breakdowns of insulation in radial direction for 10 kV XLPE cables with short-time (up to 1 min) application of 50 Hz test voltage of 35–50 kV

VI. Development of Arc Model for Cable Insulation Based on Differential Heat Balance Equation

Papers of a number of scientists (e.g. G. Schwarz, A. Hohreiner, A. Avdonin, and others) show that arc parameters are functions of circuit conditions such as conductivity, current and voltage. These functions can be studied in relation to the development of the model of breakdown and arcing in cable insulation.

Conductivity of arc channel as is shown above is inversely proportional, with some assumptions, to the resistance of the arc burning in enclosed volume of cable insulation. *Arc current* is determined as a vector sum of currents in the self-capacitances of the equipment to ground which can be easily calculated with known network parameters and of the equipment connected to the neutral of the network. *Arc voltage* is more complex parameter which is difficult to calculate. It depends on qualitative characteristics (e.g. degree of insulation destruction in specified period of time, the character of arcing (interrupted arc or intermittent arc), external disturbances in the network) and quantitative characteristics (e.g. durations of no-current conditions, the ration of active and reactive components in the ground fault place) of arcing ground fault.

When developing a model, we use the heat balance equation for the arc channel and exponential function of arc conductivity depending on heat content inside the arc channel:

$$\frac{1}{g}\frac{dg}{dt}=\frac{P_0}{Q_0}\frac{\sqrt{4\pi}}{\sqrt{S}}\left(\frac{U\,I}{P_0 l\sqrt{4\pi S}}-1\right)-\frac{1}{l}\frac{dl}{dt}\left(1+\ln\frac{g\,l}{\sigma_0 S}\right)+ \\ +\frac{1}{S}\frac{dS}{dt}\left(1-\ln\frac{g\,l}{\sigma_0 S}\right) \qquad (1)$$

where g – arc conductivity, U – arc voltage, I – arc current, l – arc length, S – arc cross-sectional area.

The model described by equation (1) includes three unknown parameters – P_0, Q_0, σ_0. P_0 is heat removal from the arc surface due to axial convection and direct heat transfer, W/m^2. Q_0 is quantity of heat, J/m^3 (when Q_0 quantity of heat is removed from the arc column, arc conductivity decreases e = 2.7 times). σ_0 is a coefficient characterizing linear conductivity, S/m. Parameters P_0, Q_0, σ_0 are determined by experiments and assumed to be constant.

For a number of methods of arc stabilization in space, arc cross-sectional area and arc length should be considered to be constant values. But we study an ablation-controlled arc which is characterized by removal of material from the surface of a breakdown channel walls burned by an arc. Therefore, in any cases and under any conditions, arc cross-sectional area cannot be assumed as a constant parameter ($S \neq const$). Now, we should assume conditions under which arc length may be constant ($l = const$).

Firstly, the maximum arc length with its radial development is considered to be equal to thickness of cable insulation (i.e. shortest distance between a cable core and a cable sheath) or exceeds it several times. Arc lengths in XLPE and EPR cables almost always equal to cable insulation thickness (e.g. for 6 – 10 kV cables arc lengths are equal to 3.0 – 4.0 mm; for 20 kV cables – 5.5 mm; for 35 kV cables – 8.5 – 9.0 mm). For mass-impregnated paper-insulated cables arc length exceeds thickness of insulation (between a cable core and a cable sheath) 3 – 5 times and may reach 15 – 40 mm or even more, depending on rated cable voltage. It can be explained by the fact that the breakdown of mass-impregnated paper insulation is developed in curved path formed by combination of PDs at oil layers and destructed paper areas.

Secondly, an arc before its quenching and faulty feeder disconnection burns in enclosed volume that leads to the widening of the channel and to the occurrence of impact pressures on the reduced cable sheath.

Taking into account all the assumptions, the ablation-controlled arc model (1) with variable cross-sectional area and constant arc length $l = const$ will be transformed into the following:

$$\frac{1}{g}\frac{dg}{dt}=\frac{P_0}{Q_0}\frac{\sqrt{4\pi}}{\sqrt{S}}\left(\frac{U\,I}{P_0 l\sqrt{4\pi S}}-1\right)+\frac{1}{S}\frac{dS}{dt}\left(1-\ln\frac{g\,l}{\sigma_0 S}\right) \qquad (2)$$

Parameters of the arc model (2) with variable cross-sectional area can be determined by oscillograms of arc current and arc voltage on the faulty phase during arcing obtained from experimental investigations on arcing in the cable network. Function $S(t)$ can be defined analytically based on above-mentioned principles when developing the parameters of arcing ground faults and integral models of breakdown. In general, the change of breakdown channel cross-sectional area with time is determined by the following equation:

$$S(t) = A \cdot e^{-t/\tau} \qquad (3)$$

where A – coefficient of proportionality depending on the type of insulation and degree of degradation of insulation before the breakdown (determined by diagnostic tests); τ – time constant of arcing which is determined by the analysis of oscillograms of real arcing ground faults in cable networks and does not usually overcomes several milliseconds. Maximum linear dimensions of arc breakdown channels for cable insulation, as mentioned above, are usually known. It should be noted that function $S(t)$ may be defined on the basis of the change of arc column temperature. In that case, we need to solve the associated differential equation.

VII. Conclusions

1. Based on oscillographic investigations of many years, time characteristics of electric breakdown and arcing in power cables are presented. This process usually consists of three or four stages for each type of insulation. The complete breakdown of dielectric is preceded by a long process of decreasing of electric strength of an insulation gap 2 – 3 times and more accompanying by reducing of insulation resistance 10^2 – 10^4 times. Arc ignition and arcing associated with ground fault complete this process.

2. Total arc duration t_{arc} depends on the type of insulation and the parameters of the electrical network. For mass-impregnated paper-insulated cables, arc duration t_{arc} may vary from 10 – 20 milliseconds to several hours. For XLPE cables, arc duration t_{arc} does not exceed 0.5 – 0.6 seconds; but if the ground fault is not cleared, it

may reach approximately one minute. This is supported by long-term observations during cable operation and by the analysis of associated oscillograms.

3. Based on the classical theory of electric breakdown of solid and combined dielectrics, integral models of breakdown and arcing in different types of insulation are developed and presented in the graphical form for the first time.

4. It is shown that integral parameters of arc breakdown are associated with the rate of channel development which depends on physical properties of insulation and duration and amplitude-frequency characteristics of internal overvoltages. When applying 50 (60) Hz voltage of (2 – 4)U_0 to XLPE and EPR insulation, this rate of channel development determines the parameters of changing of insulation resistance, insulation electric strength and insulation temperature during arc breakdown and arcing.

5. Developing theory of arcing in enclosed volume of cable insulation, we proposed the differential equation of heat balance. This equation for an arc column with a variable cross section is to be solved for the determination of arc model parameters using recorded oscillograms of arc current and voltage on the faulty phase at arcing ground faults in the particular electrical network.

VIII. References

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IX. Biographies

Andrey Shirkovets was born in 1983. He received M.Sc. in electrical engineering from Novosibirsk State Technical University in 2006. Now, he is completing his PhD thesis in the field of arcing in cable insulation. He is currently working as Principal Engineer of Research Department at LLC BOLID, Novosibirsk, Russian Federation, since 2006.