Features of Arcing at Single-Phase Damages of Power Cable Insulation in Networks with Resistance in Neutral

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Abstract**-- The paper presents the results of qualification and quantification of influence of a resistive current in the circuit of a single phase-to-ground fault on the specific parameters of electromagnetic transients during single-phase damages of medium voltage power cable insulation. Expressions for the reference equivalent circuit are obtained by transformation of differential equations. Then, calculations were performed to quantify the influence of the ratio between resistive and capacitive current I_R/I_C on the damping factor and on the frequency of free oscillations during a single phase-to-ground fault transient in a cable network. Conditions of intermittent single-phase arcing transfer into stable arcing are studied for the case of neutral grounding through a resistor. Values are specified for such arcing fault parameters, as neutral voltage, phase of arc ignition and extinction, overvoltage level. It is shown, that the ratio I_R/I_C = 2.5..4.0 for XLPE-cable networks determines I_R value, that guarantees intermittent arcing transfer into stable arcing in 0.1–0.5s. Selective operation of simple relay protection against single phase-to-ground faults is also provided. As a rule, such value of a resistive current is generated by high-voltage resistors, and this current assures required sensitivity for simple current relays.**

Keywords**: grounding arc, resistive current, single-phase insulation damage, power cable, frequency of free oscillations, rate of damping, stability of arcing**

I. INTRODUCTION

A resistive component I_R of a fault current I_{SPGF} affects the rate of voltage recovery du_{rec}/dt at a faulty phase and the rate of dielectric strength growth de_{str}/dt during no-current period Δt. Short-time enhancement of a spark gap deionization in MIP-insulation is supposed to occur in the case of $I_R/I_C <$ 1.0–1.2 ratios. Discharging through the neutral is one of the reasons.

Arcing parameters at SPGF will change in the case of R_N resistor connected into the neutral in comparison with an ungrounded or compensated neutral. It is caused by changing of the rate of neutral voltage U_N decreasing after arc extinction:

$$u_N(t) = u_{NMAX} \cdot \exp(-\frac{t}{3R_N C_{ph}}), \qquad (1)$$

where u_{NMAX} = (0.5–1.2)u_{phMAX} – maximum neutral voltage, C_{ph} – phase capacity.

Maximum overvoltage level at unfaulted phases almost does not exceed the level, that occurs during the first arc ignition, if I_R = (0.7–1.2)I_C. Wolfgang Petersen proposed an expression in 1918, that determines the resistance value in order to limit overvoltage: R_N = (1.0–2.5)/3$\omega_{50}C_{ph}$, which complies with I_R = (1.0–0.4)I_C. To limit overvoltage I_R = (0.6–1.2)I_C ratio is used practically for neutral grounding through a high-ohmic resistor. Such overvoltage limiting effect determines necessity of resistive current being taken into account while investigating the conditions of single-phase arcing and arc extinction in power cable insulation.

Main purposes of current investigation are:

1. To calculate a probability of emergency tripping due to SPGF transfer into SC in a network with natural damping and damping by a resistor.
2. To define the influence of a resistance in a neutral on the frequency of free oscillations during arcing SPGF transient.
3. To assess overvoltage levels at arcing SPGF depending on the ratio between resistive current I_R and capacitive current of a network I_C, influence of I_R/I_C ratio on the damping process of free oscillations of special frequency – up to 10kHz – during SPGF.
4. To study the conditions of intermittent single-phase arcing transfer into stable arcing due to an additional resistive current flowing in a neutral of a network.

Efficiency of a neutral grounding device may be assessed in accordance with the quantity of single phase-to-ground fault (SPGF) transfers into phase-to-phase short circuits (SC). According to [1], 35% of such transfers are caused by the thermal effect of arcing, 65% – by overvoltage caused effect and by damages of other phases insulation or insulation in other points of a network. This is supposed to be valid for cable networks as well. Method of neutral grounding and type of cable insulation – polymer or mass-impregnated paper (MIP) – impacts significantly on the probability of fault development after SPGF. This probability may be evaluated as follows [2]:

– for a network with an ungrounded neutral $p = 1 - \exp(-I_{GF}/I_{lim})$,

– for a network with resistive neutral grounding $p = 1 - \exp(-I_{GF}/1.84 I_{lim})$,

where I_{GF} – varied value of a ground fault current, A,

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I_{lim} – standard limit value of a ground fault current, which allows continuous operation of a network under a ground fault (according to Russian Standards for 6.0/7.2kV networks I_{lim} = 30A, for 10/12kV networks – I_{lim} = 20A, for networks with rotating machines – I_{lim} = 5A).

Calculation of a probability of emergency tripping due to SPGF transfer into phase-to-phase SC for $I_C \leq 30$A values is presented in Fig. 1. It is assumed, that the proportion of a resistive current I_R in a total ground fault current does not influence the probability for the range from 0 to 30A. Fig. 1 shows, that the calculated probability $p \leq 0.05$ for I_{lim} = 20–30A only at $I_{GF} \leq$ 1.0–1.5A, and for I_{lim} = 5A at $I_{GF} \leq$ 0.5A. It means that SPGF transfer into SC is possible even in a short-cable network with some feeders of several tens of meters length. The highest probability corresponds to the networks, where continuous SPGF is not allowed in the case of more than 5A current.

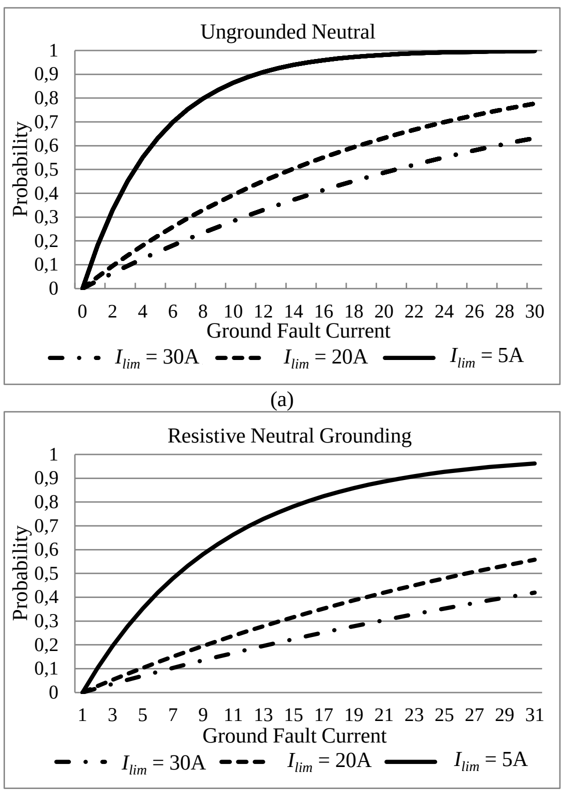

Fig. 1. Dependence of an emergency tripping probability on a ground fault current in the case of natural damping (a) and damping by resistor (b)

Minimum fault currents are presented below, which correspond to the probability p = 0.95 of SPGF transfer to SC. These currents are 15, 60 and 90A respectively for networks with an ungrounded neutral and 5, 20 and 30A limit currents; for networks with resistive neutral grounding these currents are 27.5, 110 and 165A respectively (45% higher). Additional calculations showed, that connection of a neutral grounding resistor leads to 28–45% decrease of the calculated probability of emergency tripping in a 6–10kV network with I_{lim} = 20–30A. This effect occurs in the same way for I_{lim} = 5A only in the case of $I_{GF} \leq$ 5–6A $\approx I_{lim}$.

It should be noted that the lower is ground fault current, the more significant is emergency tripping probability decrease due to a resistive current I_R. It corresponds to neutral grounding through a high-ohmic resistor. A resistor is chosen for such neutral grounding method to comply with $I_{GF} = \sqrt{2} I_C$ or $I_R = I_C$ condition in general case. Sometimes it is permitted to use $I_{GF} = \sqrt{3.25} I_C$ condition. Thus, I_R value should influence the probability. So, it may be concluded, that a range exists of ratios between resistive and capacitive (or resistive and residual) current I_R/I_C, which allows choosing the rated value of a resistor to solve the purpose – to decrease overvoltage and a probability of emergency tripping in the case of continuous SPGF; or to transfer SPGF into a stable arcing fault to be selectively cleared. This allows determining requirements for primary neutral grounding equipment, and also for a relay protection system against SPGF and its proper adjustment.

II. Influence of Neutral Resistance on Frequency of Free Oscillations and on Damping Rate of Transient

Inductance of a neutral grounding transformer (NGT) may be neglected in the case of neutral grounding through a high-ohmic resistor ($R_N \geq$ 300, 500, 2000Ω for 6, 10 and 35kV networks respectively). Leakage inductance of 100–840kVA NGT, which are used for neutral grounding through a low-ohmic resistor, leads to 5–15% limitation of I_R value (at $R \leq$ 150–200Ω). Inductance of a NGT influences the transients of 1–5kHz frequency and higher in the case under study, but this influence is insignificant in comparison with the influence of a supply transformer (over 10MVA).

According to the task description it is assumed, that unfaulted phases transients are equal and synchronous. The equivalent circuit is presented in Fig. 2 (R_T and L_T – resistance and inductance of a supply transformer).

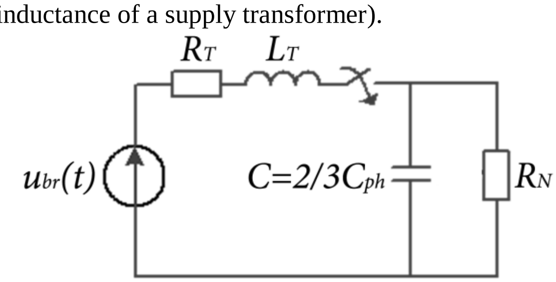

Fig. 2. Equivalent circuit of unfaulted phases during SPGF in a network with R_N resistance in a neutral

The transient in this equivalent circuit is defined in relation to a voltage at the capacitance by the following differential equation:

$$\frac{d^2 u_C}{dt^2} + \frac{du_C}{dt}\left(\frac{3}{2R_N C} + \frac{R_T}{L_T}\right) + \frac{u_C}{L_T C}\left(1 + \frac{R_T}{R_N}\right) = \frac{u_{br}}{L_T C}. \quad (2)$$

Resistance R_N of a resistor in a neutral and total capacitance of a network $C = 3C_{ph}$ may be defined as:

$$R_N = \frac{U_{ph}}{I_R}, \quad C = \frac{I_C}{U_{ph} \cdot \omega_{50}}, \quad (3)$$

where U_{ph} – phase voltage of a network; ω_{50} – angular frequency at 50Hz.

After transformation of (2) with (3) being taken into account:

$$\frac{d^2u_C}{dt^2}+\frac{du_C}{dt}2\delta\left(1+\frac{3I_R}{4\delta_*\omega_* I_C}\right)+\omega^2\left(1+\frac{2\delta_* I_R}{\omega_* I_C}\right)=\omega^2 u_{br}\,, \quad (4)$$

where $\delta=\frac{L_T}{2R_T}$, $\omega=\frac{1}{\sqrt{L_T C}}$, $\delta_*=\frac{\delta}{\omega}$, $\omega_*=\frac{\omega}{\omega_{50}}$.

The frequency of free oscillations during a transient for the equivalent circuit is defined as

$$\omega_0=\sqrt{\omega^2\left(1+\frac{2\delta_*}{\omega_*}\cdot\frac{I_R}{I_C}\right)^2-\delta^2\left(1+\frac{3}{4\omega_*\delta_*}\cdot\frac{I_R}{I_C}\right)^2}. \quad (5)$$

The damping factor for the equivalent circuit depends on resistive elements. Influence of R_N resistance on the damping process is critical:

$$\delta_R=\delta\left(1+\frac{3}{4\omega_*\delta_*}\cdot\frac{I_R}{I_C}\right). \quad (6)$$

Influence of a resistor in a neutral circuit on the rate of transient damping may be expressed in terms of I_R/I_C, as follows from (5) and (6). The higher is free oscillations frequency of the network ω_*, the lower is this influence (other things being equal). This is proved by calculations of free oscillations damping.

Specific values of ω and δ are assigned for the cable network under investigation to evaluate influence of I_R/I_C ratio on the damping of free oscillations according to (5) and (6): ω at f = 500–10000Hz and δ = 2772 s^{-1} for I_R/I_C = 0 [2]. Calculation results are shown in Table I.

In the case of an ungrounded neutral $I_R/I_C = 0$ and $\delta_R = \delta$. Neutral discharging during half of a period at 50Hz frequency is provided when $I_R/I_C \approx 1$. This leads to 8.5% increase of the damping ratio.

Resistive current relative value may increase under some conditions. For example, when some consumers are tripped off. Practically, it allows illustrating the influence of I_R/I_C ratio on the frequency and damping rate of the transient without reference to I_C of the network. That is why ω_0 and δ_R values are also calculated for I_R/I_C = 2; 3; 4 ratios.

TABLE I – INFLUENCE OF I_R/I_C RATIO ON THE DAMPING RATIO δ_R AND THE FREE OSCILLATIONS FREQUENCY ω_0 DURING A TRANSIENT AT SPGF IN A CABLE NETWORK

I_R/I_C		δ_R, s^{-1}	ω_0 at f, Hz, s^{-1}				
			500	1000	2000	5000	10000
			ω_* = 10	ω_* = 20	ω_* = 40	ω_* = 100	ω_* = 200
0		2772	1478	5639	12257	31293	62771
1		3008	2148	5830	12344	31327	62788
2		3243	2747	6019	12427	31360	62804
3		3479	3314	6206	12507	31390	62819
4		3714	3863	6391	12584	31419	62833
Parameter increment at $I_R/I_C = 0 \rightarrow I_R/I_C = 4$	s^{-1}	942	2385	752	327	126	62
	%	34	161	13.3	2.67	0.403	9.88·10^{-2}

Four times growth of a resistive current (from $I_R = I_C$ to $I_R = 4I_C$) results in damping ratio 23.5% increase, in comparison with an ungrounded neutral (I_R/I_C = 0) the increase is 34%, as shown in Table I. Growth of the specific frequency of transient from 500 to 1000Hz leads to relative increment ω_0 decreasing for all I_R/I_C ratios under investigation from 161% to 13.3%. Further 2–2.5 times growth of f (or its relative value ω_*) to 2, 5, 10kHz results in reduction of I_R/I_C ratio influence on the frequency of free oscillations ω_0: at f = 2kHz this influence is insignificant, at $f \geq$ 5kHz the influence is almost eliminated.

Thus, calculated influence of a neutral grounding resistor with I_R/I_C = 1–4 ratios on the transient frequency at free oscillations of zero-sequence circuit is hardly detectable, even in the case of inductance neglecting of the neutral grounding transformer. This also points to the fact, that fault current zero-crossing during first periods of unfaulted phases capacity charging is determined by the free component mostly. This is valid on the assumption of almost full discharge during no-current period ($I_R/I_C \approx 1$). Consequently, arc extinction may occur in these moments as well as in the case of an ungrounded neutral. That is why flowing of full current $I_{SPGF} = \sqrt{I_R^2+I_C^2}$ in the place of a fault should not lead to conditions worsening of arc extinction and probability increasing of restrikes in the case of $I_R/I_C \leq 1$. This is confirmed by the results of continuous recording in the 6kV cable network (see Fig. 3).

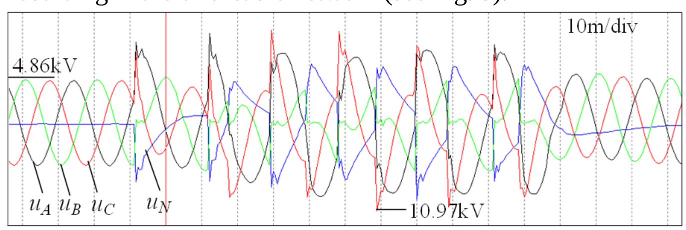

Fig. 3. Natural oscillogram of the self-cleared SPGF after 10 arcing breakdowns in the 6kV cable network with resistive neutral grounding; t_{SPGF} = 110ms, I_R/I_C = 0.36

It should be admitted, that influence of a neutral resistance on frequency parameters and amplitude parameters and on the “positive” result of an arcing fault in the case of I_R/I_C < 0.6 is significantly lower than in the case of $I_R/I_C \geq$ 0.6–1.0, in spite of an opportunity of arc self-extinction in a network with a resistor (Fig. 3). Consequently, probability of fault development differs insignificantly for the case of I_R/I_C < 0.6 and for the case of I_R/I_C = 0 other things being equal (see Fig. 4).

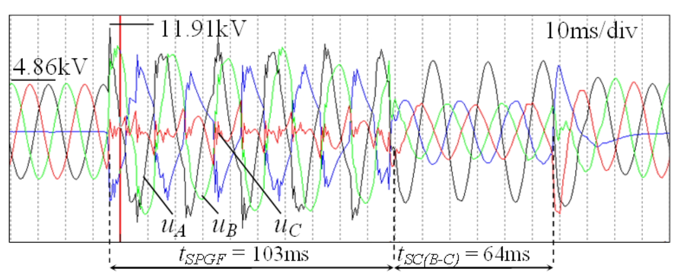

Fig. 4. Natural oscillogram of the arcing SPGF transferring into the phase-to-phase SC after 12 arcing breakdowns in the 6kV cable network with resistive neutral grounding, I_R/I_C = 0.49

III. Conditions of Intermittent Single-Phase Arcing Transfer into Stable Arcing

Below presented expressions [4] are used to define such arcing fault parameters, as u_N voltage, arc ignition ψ_{ign} and arc extinction phase ψ_{ext}, overvoltage level K_U for a network with a resistance in neutral.

Arc extinction phase, when voltage $u_N = u_{NMAX}$ and overvoltage level $K_U = K_{UMAX}$, is defined as

$$\psi_{ext} = \arcsin \frac{0.2\left(I_R/I_C\right)^2 - \sqrt{\left(I_R/I_C\right)^2 + 1}}{\left(I_R/I_C\right)^2 + 1}. \qquad (7)$$

Values of ψ_{ext} are shown in Fig. 5 for practically applicable I_R/I_C ratios.

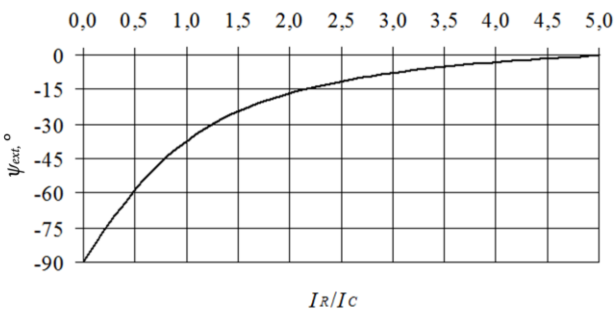

Fig. 5. Arc extinction phase (complying with $u_N = u_{NMAX}$ condition) versus I_R/I_C ratio dependence

Increase of current I_R flowing in the neutral results in decreasing of ψ_{ext} phase, which corresponds to maximum overvoltage K_{UMAX} level. As a rule, insulation breakdown occurs when $u \approx u_{MAX}$ ($\psi_{ign} \approx 90°$) independent on the neutral grounding method. Dependence of ψ_{ext} phase on I_R/I_C ratio (Fig. 4) confirms K_{UMAX} level significant decrease, when I_R/I_C ratio is increasing.

Arc ignition phase ψ_{ign}, which complies with $K_U = K_{UMAX}$ condition, does not depend on I_R/I_C ratio and equals ≈68°. Overvoltage in a cable network with resistive neutral grounding, with arc extinction phase ψ_{ext} being taken into account, may be defined based on (7) as:

$$K_U = 1.71 + \frac{(1-d)C_{ph}}{C_{ph} + C_{ph-ph}} \cdot \left[0.93 - \left(\sin\psi_{ext} - 0.2\right) \cdot \exp\left(-\frac{I_R}{I_C}\left(1.19 - \psi_{ext}\right)\right)\right], \qquad (8)$$

where $(1 - d)$ – ratio of free oscillations damping;

$C_{ph} \approx 3C_{ph\text{-}ph}$ – phase and phase-to-phase capacity of a network.

Dependence K_U (I_R/I_C) is shown in Fig. 6, obtained on the basis of (8) and with operation experience of medium voltage cable networks taken into account. Values d = 0.05–0.10 are typical for a wide range of cable networks. These values correspond to normal and reduced insulation of a network.

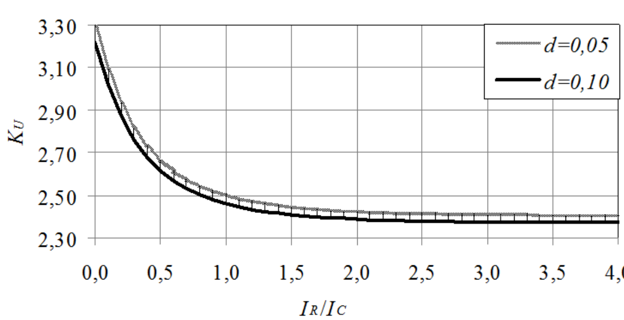

Fig. 6. Dependence of the overvoltage level at an arcing SPGF on I_R/I_C ratio in a cable network with resistive neutral grounding for different damping ratios d

As follows from Fig. 6, K_{UMAX} $(I_R/I_C = 0) > 3.0$. It is explained by the fact that overvoltage level calculated using (8) is valid for slightly reduced cable insulation. This calculation does not take additional damping into account of high-frequency transient due to resistive conductance of an insulation and additional resistance of a fault circuit. That is why 5–10% reducing of values obtained with (8) and shown in Fig. 6 is permitted to evaluate K_U level more correctly from engineering point of view. Effect of K_U level limiting due to further increase of I_R value becomes insignificant when $I_R/I_C \geq 2$. Thus, application of neutral grounding resistors with $I_R > 2I_C$ is intended to solve another practical issue – to transfer intermittent arcing into stable arcing and to provide selective operation of relay protection against SPGF.

Dependence of resistive neutral grounding on the features of an arcing ground fault and overvoltage levels, caused by this fault, was studied by N. N. Belyakov. The study was based on the 6kV network physical model: lumped capacities with grounding arc occurring in different insulation types, including MIP cable insulation [4]. It is shown, that arcing processes at I_R/I_C = 0.15–9.40, in spite of random nature of the parameters, are different. Arcing becomes stable, if $I_R/I_C > 3.5$. The rate of voltage growth at a spark gap 1.5–2 times increases compared with an ungrounded neutral, if arc extinguishes in the moment of $u \neq u_{phMAX}$.

Analysis of experimental data shows, that $I_R/I_C \geq$ 3.5–4.0 condition provides stable arcing at SPGF in networks with overhead lines, as well as with MIP cable lines. Expression I_R/I_C = 2.5–4.0 is proposed for 6–35kV networks with XLPE cables to define I_R value, which guarantees intermittent arcing transfer into stable arcing in t_{arc} = 0.1–0.5s and selective operation of simple current relays against SPGF. Such approach is stated in Russian Standard [5].

The results of natural experiments with the arcing fault current being recorded are presented below (Fig. 7). The experiments were carried out in the operated 10kV cable network of 110/10kV Ferrosplav substation. The results are shown to confirm I_R/I_C ratio experimentally, which provides arcing behavior changing at SPGF. The experiments were carried out using the spark gap with 1.2cm diameter ball-shaped copper electrodes, rotation speed was about 60.0rpm. Stable arcing was detected at I_R/I_C = 1.8–2.5, when two 10kV busbars were coupled, total capacitive current I_C = 9.9–13.6A, and two resistors with I_R = 25.1A were connected into the neutral points.

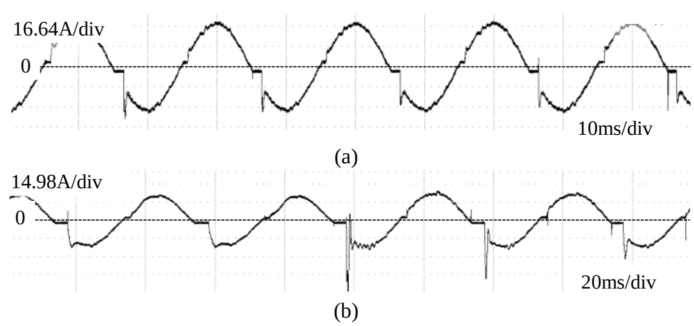

Fig. 7. Natural oscillograms of the stable arcing current at SPGF in the 10kV network with I_R/I_C = 1.8 (a), I_R/I_C = 2.5 (b)

On the basis of above presented statements, the following conditions for stable arcing in medium voltage cable networks are proposed:

$$\frac{I_R}{I_C} = \begin{cases} 4.0 \text{ at } I_C \le I_{stand}, \\ 4.0 - 2.5 \text{ at } I_{stand} < I_C < I_{lim}, \\ 2.5 \text{ at } I_C > I_{lim}. \end{cases} \quad (9)$$

where I_{st} – standard value of I_C, capacitive current compensation is needed if this value is exceeded according to the Russian Electrical Code;

I_{lim} = 60A for 6–10kV and I_{lim} = 30A for 35kV cable networks – limit value of SPGF current which provides an opportunity for arc self-extinction in a compensated network [6].

Proposed criterion (9) complies well with the results of experimental investigations.

The main reason of an arcing ground fault in a cable transfer into stable arcing is carbonization of an arcing channel with t_{arc} increase, independent on the method of neutral grounding. Energy release in an arcing channel is an important factor for the transfer process. According to our estimates, it accounts from several hundred to several units of kJ, depending on the consist of I_{SPGF}, arcing stage (ratio between t_{arc} and Δt), insulation type (conditions of arcing channel cooling) and other factors. It is obvious, that energy release in the place of a fault increases, if additional resistive current flows in the circuit of grounding fault. This measure will change the arcing behavior. Depending on the value of I_R, and with the rate of heat removal from the arcing channel being equal for equal type of insulation, it may lead to self-extinction of an arcing fault (most probably for I_R/I_C = 0.6–1.2 range), or to its development up to carbonized arcing channel occurrence (most probably for I_R/I_C > 2.5 range). Each variant is possible for MIP cable insulation. Self-extinction of SPGF in XLPE cable insulation is impossible theoretically.

Transfer of intermittent arcing into stable arcing due to neutral grounding resistors is intended to provide selective operation of a relay protection system against SPGF, decrease of fault duration to t_{SPGF} = (0.2–2.0)s (depending on the network topology, principles of relay protection and circuit breaker speed) and damage localization. Emergency feeder tripping (including cascade tripping), caused by SPGF transfer into SC, is prevented due to K_U level limitation.

IV. Conclusions

1. Calculated probability is presented of SPGF transfer into phase-to-phase SC for 6–10kV networks with an SPGF current to 30A. Effect of emergency tripping probability decrease due to resistive current I_R is more significant when SPGF currents are low. It is obvious, that in the case of continuing the operation of a network under SPGF, resistor connection into a neutral results in emergency tripping probability 28–45% decrease for 6–10kV networks with limit currents I_{lim} = 20–30A. The resistor value is chosen depending on the operating conditions of a network and principles of relay protection operation (tripping or alarming).
2. It is shown that calculated influence of neutral grounding through a resistor with I_R/I_C = 1–4 ratio on the transient frequency, caused by free oscillations of a zero-sequence circuit, is generally insignificant. After 5kHz this influence is eliminated. It is valid even in the case of inductance neglecting of a neutral transformer. Four times growth of a resistive current (from $I_R = I_C$ to $I_R = 4I_C$) results in damping ratio 23.5% increase, in comparison with an ungrounded neutral ($I_R/I_C = 0$) the increase is 34%.
3. Values were precised of such arcing fault parameters, as neutral voltage, phase of arc ignition and arc extinction and overvoltage level for a network with a resistance in the neutral. Dependence of overvoltage level on I_R/I_C ratio is obtained based on analytical expressions and on the medium voltage cable networks operation experience. The dependence is obtained for a wide range of cable networks with different damping ratios (for normal and reduced insulation of a network).
4. It is brought out that influence of a neutral grounding resistor on frequency parameters and amplitude parameters and on the probability of arc self-extinction in the case of I_R/I_C < 0.6 is insignificant. Great restrikes probability decrease due to arc self-extinction in MIP cable insulation is most likely at I_R/I_C = 0.6–1.2. Intermittent arcing transfer into stable arcing in a cable, independent on an insulation type, is observed in the range of I_R/I_C = 2.5–4.0, i.e. when operating a network with neutral grounding through a low-ohmic resistor.

V. References

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