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BRANCHED CIRCUIT OF 6 kV OPERATION WITH INSULATED NEUTRAL UNDER PHASE-TO-EARTH FAULT

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Line-to-earth faults which occur in branched circuit 6-10 kV with insulated neutral are the most spread type of failure. Overvoltage under line-to-earth faults leads to the failure of electric equipment and extra expenses. Mathematical models considering branched circuit parameters changes are developed. The mathematical model considering linear arms' active resistances of a branched circuit is studied. It was found that these resistances can be neglected under transient processes evaluation while arcing. The analysis based on the mathematical model considering branched circuit phase insulation was performed. Calculations show that these parameters do not affect overvoltage level significantly. Different cases of voltage level calculation in circuit phases under arcing and voltage recovery process with different circuit parameters and earth circuit resistance values are considered. It was found that overvoltage levels depend on earth circuit resistance value, arc blowout moment and voltage value of secondary initiations. Earth circuit resistance value is determined by the number of high-frequency current zeros and correspondingly determines transient processes' character. The highest overvoltage levels can exceed fourfold values.

Key words: line-to-earth faults, substitution circuit, mathematical modeling, overvoltage level.

РОБОТА РОЗПОДІЛЬЧИХ МЕРЕЖ 6–10 кВ З ІЗОЛЬОВАНОЮ НЕЙТРАЛЛЮ ПРИ ЗАМИКАННІ ФАЗИ НА ЗЕМЛЮ

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У розподільчих мережах 6–10 кВ з ізольованою нейтраллю однофазні замикання на землю є переважним видом ушкоджень. Перенапруги, які виникають при однофазних замиканнях на землю, негативно впливають на роботу електрообладнання, призводять до додаткових витрат. Для оцінки характеру перехідних процесів розроблено математичні моделі, що найбільш повно враховують зміни параметрів розподільчих мереж. Розглянуто математичну модель з урахуванням активних опорів поздовжніх гілок розподільчої мережі та встановлено, що при оцінці перехідних процесів під час горіння дуги цими опорами можна знехтувати. Проведено дослідження на математичній моделі, в якій враховані провідності ізоляції фаз розподільчої мережі. Чисельна оцінка показує, що дані параметри суттєво не впливають на рівень перенапруг. Розглянуто приклади розрахунку рівнів напруг у фазах мережі при горінні дуги та в процесі відновлення напруги за різними параметрами мережі та значеннями опору кола замикання на землю. Встановлено, що рівні перенапруг залежать від величини опору кола замикання на землю, моменту гасіння дуги й величини напруг повторних запалень. Значення опору кола замикання на землю визначає кількість високочастотних переходів струму однофазного замикання на землю через нульове значення й тим самим визначає характер розвитку перехідних процесів. Найбільші рівні перенапруг у розподільних мережах можуть перевищувати чотирикратні значення.

Ключові слова: однофазні замикання на землю, схема заміщення, математичне моделювання, рівень пере-напруг.

PROBLEM STATEMENT. Line-to-earth faults which occur in branched circuit 6–10 kV with insulated neutral are the most spread type of failure and make more than 75 % of total amount of failures [1]. Overvoltage while line-to-earth faults declines electric durability of cables' insulation, provokes their fault and multiplace breakdown. It leads to the failure of electric equipment, long-lasting stoppage of manufacturing equipment, extra expenses on its restoration, and finally, to the reduction of enterprise's output.

Overvoltage level decline in 6–10 kV branched circuit under line-to-earth faults due to determination of rational ways of their reduction is an important issue.

Efficiency and reliability increase of 6–10 kV branched circuit with insulated neutral under line-to-earth faults is an important task.

Prominent scientists, such as Petersan, Peters and Slyapin, M.M. Belyakova, F.A. Likhachova, L.Yu. Dudareva, I.S. Samoilovich, M.P. Dergilyova dedicated their works to overvoltage decrease under arc earth faults [1–5]. However, earth circuit impact on overvoltage level under line-to-earth faults was not considered in those works. It restricted overvoltage development forecast as well as determination of the measures to be taken for their minimization and circuit efficiency increase.

Existing mathematical models of transient processes under line-to-earth faults in branched circuits are too simplified where single-phase substitution circuit is used, or too complicated considering insignificant parameters which almost do not affect overvoltage development [6–9]. Most of the models did not consider earth circuit resistance value or considered it as invariable which restricted their use for other branched circuits [10–13].

Due to transient arc line-to-earth faults can be considered as a switch which earths failed phase through resistance equal to a constant earth circuit resistance value.

For proper estimation of transient processes' character and rational ways of overvoltage reduction under line-to-earth faults in branched circuits it is required to develop mathematical models that would consider changes of branched circuits' parameters and to study transient processes thoroughly taking into account different parameters' impact.

The aim of the work analysis and reduction of overvoltage levels in 6–10 kV branched circuits under line-to-earth faults.

EXPERIMENTAL PART AND RESULTS OBTAINED. Following acceptances were made while mathematical models development: three-phase circuit of mains to be considered as symmetrical for all operational modes; do not consider saturation of magnet systems (except magnet systems of voltage transformers) to believe inductive resistance of all circuit elements being stable and current independent; neglect magnetizing currents of transformers; express divided parameters as lumped ones.

We shall consider mathematical model comprising linear arms' active resistances. The Figure 1 shows a substitution circuit with linear arms' active resistances.

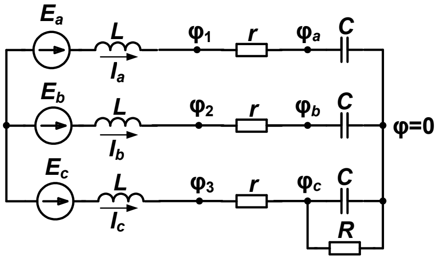


Figure 1 – Substitution circuit with linear arms' active resistances

Secular equation of a system

$$\left[p^3+\left(\frac{r}{L}+\frac{1}{RC}\right)p^2+\frac{1}{LC}\left(1+\frac{r}{R}\right)p+\frac{1}{3RLC^2}\right]\times \qquad (1)$$
$$\times\left(p^2+\frac{r}{L}p+\frac{1}{LC}\right)=0.$$

Notations used $r_* = r/\rho$, $R_* = R/\rho$, $\rho=\sqrt{L/C}$, root equations are proportional to natural vibration frequency $\omega_0 = 1/\sqrt{LC}$, equation in relative values:

$$p^3+\left(r_*+\frac{1}{R_*}\right)p^2+\left(1+\frac{r_*}{R_*}\right)p+\frac{1}{3R_*}=0; \qquad (2)$$
$$p^2+r_*p+1=0.$$

Resistance value r is insignificant in real branched circuit: from particles to several Ohm units. Solution to equation (1) is one real root and two complex conjugate roots: p_1 and $p_{2,3}=\delta_{1*}\pm\omega_{\kappa 1*}j$.

Taking the data into account it is evident that linear resistances of real mains (r_* =0,005–0,015) do not affect p_{1*} and ω_{k1*} values under any R_*.values. Another pair of complex conjugate roots (solution to equation 2) does not depend on earth circuit resistance value but depends on r resistance: $p_{4,5}=\delta_{2*}\pm\omega_{\kappa 2*}j$, where $\delta_{2*}=-r_*/2$; $\omega_{\kappa 2*}=\sqrt{1-r_*^2/4}$.

Neglecting comparatively small amplitude values of periodic components the law of phase potentials alteration is set

$$\varphi_{cв}(t)=A_1e^{pt}+A_2e^{\delta_1 t}\sin\left(\omega_{\kappa 1}t+\nu_1\right). \qquad (3)$$

Obtained voltages in phases are shown in Fig. 2.

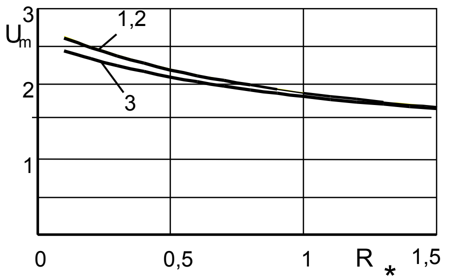


Figure 2 – Maximal voltages in leading phase up to a moment of line-to-earth current zero:
1 – r_*=0; 2 – r_*=0,01; 3 – r_*=0,1

It was found that active resistance of linear arms is equal to 0.01 in relative values (*r.v.*) for one cycle period under earth circuit small resistance (R_*<0,2) reduces overvoltage level during arcing in leading phase by (0.29–0.76) %, and under voltage recovery in failed phase reduces maximal voltage in this phase by (3.24–3.71) %. Therefore, linear arms' active resistances can be neglected while transient processes investigating. Investigation based on mathematical model considering conductance of phase insulation was performed (Fig. 3).

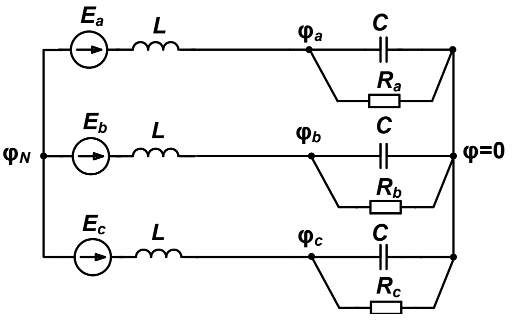


Figure 3 – Substitution circuit of mains supply considering conductance of phase insulation

When $G_{П*}$ is a conductance of failed phase ($G_{П*} = 1/R_*$), G_{H*} is a conductance of healthy phase the equation will be as follows:

$$\left[p^3 + \left(G_{П*} + G_{H*}\right)p^2 + \left(1 + G_{П*}G_{H*}\right)p + \left(G_{П*} + 2G_{H*}\right)/3\right] \times \\ \times \left(p^2 + G_{H*}p + 1\right) = 0. \tag{4}$$

As $G_{П*} >> G_{H*}$, and G_{H*} value can be neglected p_{1*}, $p_{2,3*}$ roots for small R

($0 \le R_* \le 1/3\sqrt{3}$) are equal to: $p_{1*} \approx -\dfrac{1}{R_*}$; $\delta_{1*} \approx \dfrac{R_*}{3}$;

$\omega_{k1*} \approx \dfrac{1}{\sqrt{3}}$.

Thus, active conductance of healthy phases does not affect transient processes while arcing.

During voltage recovery secular equation is expressed by three factors

$$\left(p + G_{\acute{I}*}\right)\left(p^2 + G_{\acute{I}*}p + 1\right)\left(p^2 + G_{\acute{I}*}p + 1\right) = 0, \tag{5}$$

its roots are $p_{1*} = -G_{H*}$; $\delta_{1*} = \delta_{2*} = -\dfrac{G_{H*}}{2}$;

$\omega_{k1*} = \omega_{k2*} = \sqrt{1 - G_{H*}^2 / 4}$.

Aperiodic component attenuates during voltage recovery. It was calculated that neutral shift voltage aperiodicaly declines to 0.97–0.98 from the level that was correspondent to arc blowout moment in circuits with active current up to 5 %.

A simplified substitution circuit was taken for transient processes investigation (Fig. 4).

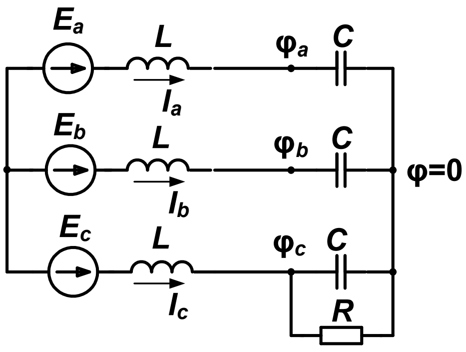


Figure 4 – Substitution circuit
under line-to-earth faults

The analysis of branched circuit mathematical models shows that earth circuit resistance varies within 200 Ohm and affects transient processes under line-to-earth fault. While transient processes under line-to-earth fault investigating linear arms' resistance and insulation conductance of healthy phase can be neglected as overvoltage level in circuit with them being taken into account reduces not more than by 1 %. Insulation resistance does not recover to the initial level and its value should be accepted on the models as the value of half-period industrial frequency aperiodic component attenuation equal to 0.95. Three-phase substitution circuit considering earth circuit resistance can be used for transient processes in mains.

Substitution circuit is described by secular equation system (Fig. 4):

$$\left.\begin{aligned}
&C\frac{d\varphi_a}{dt} + \frac{1}{L}\int\varphi_a dt - \frac{1}{L}\int\varphi_N dt = \frac{1}{L}\int e_a dt;\\
&C\frac{d\varphi_b}{dt} + \frac{1}{L}\int\varphi_b dt - \frac{1}{L}\int\varphi_N dt = \frac{1}{L}\int e_b dt;\\
&C\frac{d\varphi_c}{dt} + \frac{1}{L}\int\varphi_c dt + \frac{1}{R}\varphi_c - \frac{1}{L}\int\varphi_N dt = \frac{1}{L}\int e_c dt;\\
&\frac{3}{L}\int\varphi_N dt - \frac{1}{L}\int\varphi_a dt - \frac{1}{L}\int\varphi_b dt - \frac{1}{L}\int\varphi_c dt = -\frac{1}{L}\int(e_a + e_b + e_c)dt.
\end{aligned}\right\} \tag{6}$$

Secular equation of this system in relative values

$$p^3 + \frac{1}{R_*}p^2 + p + \frac{1}{3R_*} = 0. \tag{7}$$

Equation (7) is general and independent from L, C parameters of substitution circuit. That is why roots' value and transient processes' character will depend only on value R_*: p_*, $p_{2,3*} = \delta_* \pm \omega_{k*}j$,

where $p_* = -\dfrac{1}{3R_*}\left(1 - \alpha_* - \beta_*\right)$; $\delta_* = -\dfrac{1}{3R_*}\left(1 + \dfrac{\alpha_*}{2} + \dfrac{\beta_*}{2}\right)$;

$$\omega_{k*} = \frac{1}{2\sqrt{3}R_*}\left(\alpha_* - \beta_*\right);\ \alpha_* = \sqrt[3]{-1 + 3\sqrt{3}R_*^2\sqrt{R_*^2 + \frac{1}{3R_*} - 1}};$$

$$\beta_* = \sqrt[3]{-1 - 3\sqrt{3}R_*^2\sqrt{R_*^2 + \frac{1}{3R_*} - 1}}.$$

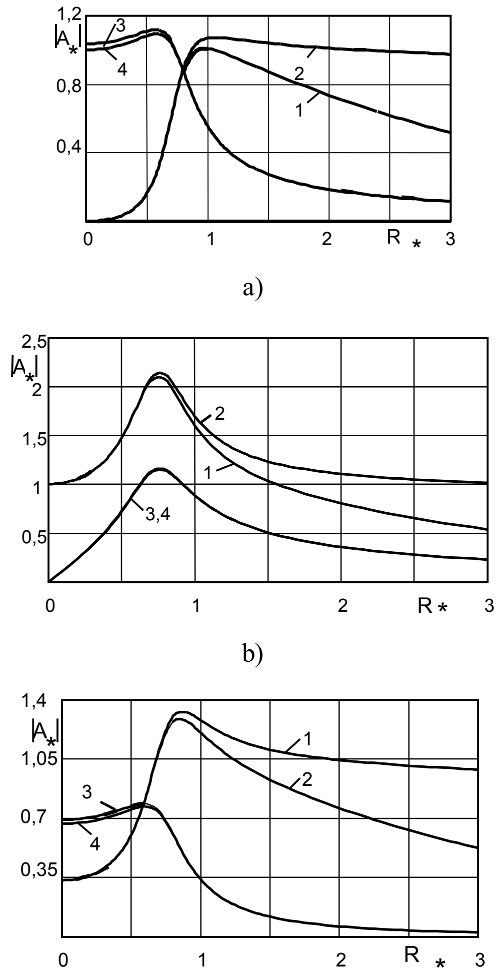
Free component of transient process has two components: aperiodic $A_1e^{p_1t}$ and periodic $A_2e^{\delta t}\sin\left(\omega_k t + \nu\right)$ (Fig. 5).

Amplitudes of voltage free components in phases and neutral depend on line-to-earth fault moment (overlap angle ψ_k) which determines primary conditions of overvoltage start. Amplitudes obtain the biggest values when faults occur in moments when voltage of failed phases reaches its maximal values.

Failed phase voltage under line-to-earth fault alters by law

$$u(t) = \varphi_\infty\sin\left(\omega t + \psi_\infty\right) + A_1e^{pt} + A_2e^{\delta t}\sin\left(\omega_k t + \nu\right). \tag{8}$$

Depending on value of R_* resistance, transient processes can have one or several current zeros for circuit half-period $\left(T_c/2\right)$. There are such $\tilde{R}_*$ values that are the boundaries between one and two high frequency current zeros.



a)

b)

c)

Figure 5 – a chart of free components amplitude dependence of phase voltage from R_*:
a – healthy, d – failed, c – neutral;
1 – $A_1 = f(R_*)$, f_0=450 Hz ; 2 – $A_1 = f(R_*)$, f_0=2250 Hz Hz ; 3 – $A_2 = f(R_*)$, f_0=450 Hz ;
4 – $A_2 = f(R_*)$, f_0=2250 Hz

The important parameters before current zero are t_{i} – arcing time; k_δ – periodic component attenuation moment, $k_\delta = e^{\delta t_i}$; $i_i^{'} = di/dt$ – current zero speed alteration; t_{m} – time moment of maximal voltage value of healthy phase. Current zero time t_{i} is defined through the equation (9):

$$\varphi_\infty \sin(\omega t + \psi) + A_1 e^{pt} + A_2 e^{\delta t} \sin(\omega_k t + \nu) = 0 . \qquad (9)$$

$i_i^{'}$ value is defined through the equation (10):

$$i_i^{'} = \frac{1}{R}[\varphi_\infty \omega \cos(\omega t_i + \psi) + pA_1 e^{pt_i} + \\ +\delta A_2 e^{\delta t_i} \sin(\omega_k t_i + \nu) + \omega_k A_2 e^{\delta t_i} \cos(\omega_k t_i + \nu)]. \qquad (10)$$

Amplitude values A_1, A_2 depend on R_* and defined:

$$A_1 = \frac{\varphi_0^{''} - 2\delta\varphi_0^{''} + \omega_0^2 \varphi_0}{\omega_0^2}; \qquad A_2 = \frac{-\varphi_o p\delta + 2\delta\varphi_0^{''} - \varphi_0^{''}}{\omega_0^2 \sin\nu};$$

$$tg\nu = \frac{2\delta\varphi_0^{'} - p\delta\varphi_0 - \varphi_0^{''}}{\omega_0\left(p\varphi_0 + \varphi_0^{'}\right)},$$

where φ_0, $\varphi_0^{'}$, $\varphi_0^{''}$ are free values and their derivatives for corresponding potentials before recovery moment.

Free components of voltage in transient process under line-to-earth fault have periodic and aperiodic components the value and level of their attenuation are determined by earth circuit resistance and arc initiation moment. The greatest amplitude values are seen when arc initiation occurs in failed phase under maximal voltage level. Aperiodic components attenuate fast under small R_*, and periodic under $R_* = \sqrt{3}/2$. Overvoltage level under line-to-earth fault depends on earth circuit resistance value. The higher R_* the less overvoltage level is.

Different overvoltage levels are theoretically possible in branched circuits under line-to-earth faults: $(3{,}9 \div 4{,}17)U_{\text{ф}}$, $2U_m$, $7U_{\text{ф}}$ [1, 2, 14].

It was accepted that initial earth fault occurs under maximal voltage in failed phase and blowout under first or next current zeroes while line-to-earth faults modeling in branched circuit. Repeating initiations in several primary cycles occur under stable voltage of repeating initiations.

There are those $\tilde{R}_*$, who are outside it between one- and two high-frequency current zeros [15].

We shall consider several examples of voltage calculation in failed phase under different circuit parameters and earth circuit values.

1. Circuit parameters: L=0,05 Hn; $C = 2{,}5 \cdot 10^{-6}$ Ф; $R_* = 0{,}1$; $\psi_\kappa = 150^0$ (ψ_κ – overlap angel). Voltage (r.v.) alters by law:

$$u(t) = 3{,}4 \cdot 10^{-2}\, sin\left(314t - 3{,}42 \cdot 10^{-2}\right) - 1{,}013 e^{-28095t} = \\ -0{,}12 e^{-94{,}6t}\, sin(1636t - 0{,}12).$$

Dependence $u_* = f(t)$ is shown in Fig. 6,a.

2. Circuit parameters: L=0,01 Hn; $C = 0{,}5 \cdot 10^{-6}$ Ф; $R_* = 2{,}0$; $\psi_\kappa = 150^0$. Voltage (r.v.) alters by law:

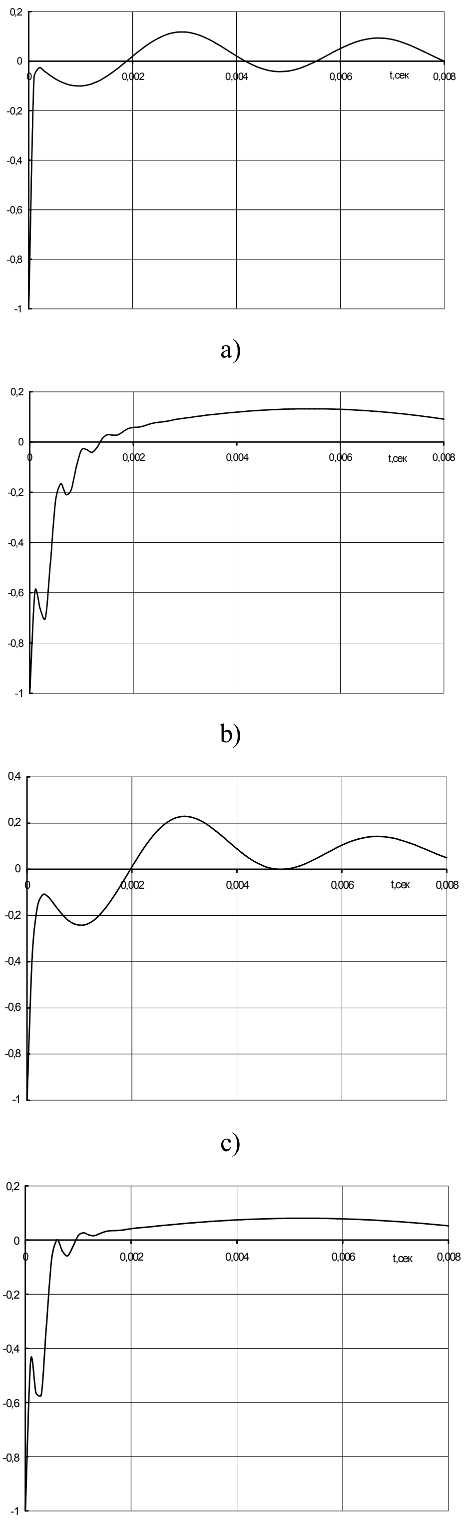
$$u(t) = 0{,}13\, sin(314t + 6{,}15) - 1{,}11 e^{-2500t} + \\ +0{,}358 e^{-2286t}\, sin(13540t - 0{,}35).$$

Dependence $u_* = f(t)$ is shown in Fig. 6,b.

3. Circuit parameters: L=0,05 Hn; $C = 2{,}5 \cdot 10^{-6}$ Ф; $R_* = 0{,}28$; $\psi_\kappa = 150^0$. Voltage (r.v.) alters by law:

$$u(t) = 9{,}53 \cdot 10^{-2}\, sin(314t - 0{,}09) - 1{,}11 e^{-9560t} - \\ -0{,}36 e^{-271t}\, sin(1657t - 0{,}35).$$

Dependence $u_* = f(t)$ is shown in Fig. 6,c.



a)

b)

c)

d)

Figure 6 – Charts of voltage alteration in failed phase under arcing: a) vibration mode in failed phase; b) non-vibration mode in failed phase with one high-frequency current zero; c) boundary between vibration and non-vibration mode ($di/dt=0$ under second current zero);

d) boundary between vibration and non-vibration mode ($di/dt=0$ before first current zero)

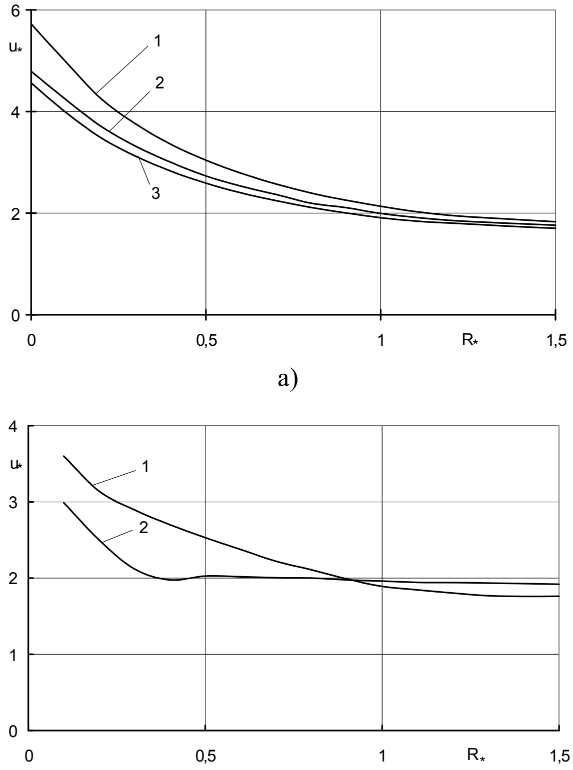
4. Circuit parameters: L=0,01 Hn; $C=0,5\cdot10^{-6}$ Ф; $R_*=1,216$; $\psi_к=150^0$. Voltage (r.v.) alters by law:

$$u(t)=8,1\cdot10^{-2}\,sin(314t+6,2)-1,41e^{-4626t}+$$
$$+0,67e^{-3502t}\,sin(12463t+0,67).$$

Dependence $u_*=f(t)$ is shown in Fig. 6,c.

Analysis showed that after 3–5 cycles of “arcing-recovery” overvoltage rise stops with earth circuit resistance value $R_*=\sqrt{3}/2$. If arc does not attenuate under first current zero but burns quite long, before blowout moment under certain n current zero transient process attenuates much faster and overvoltage levels will be lower under small R_*

Maximal overvoltage depending on R_* with arcing time $t=T_c/2$ is expressed in mathematical model (Fig. 7).

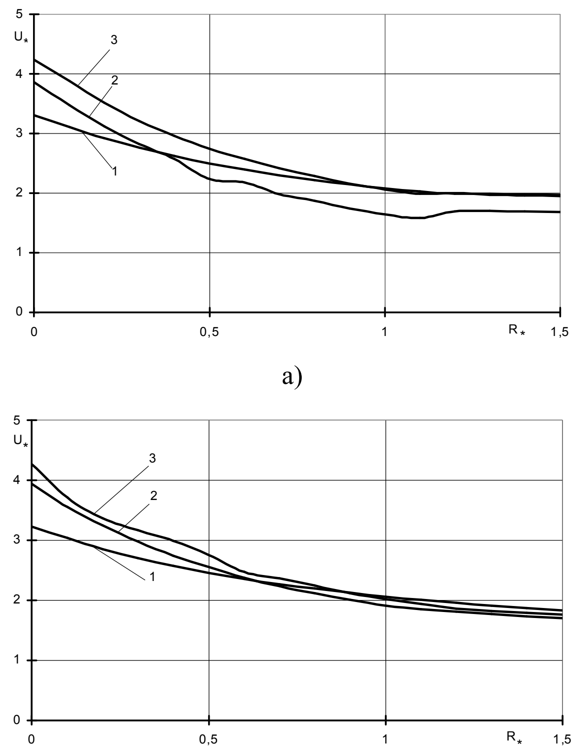


a)

b)

Figure 7 – Dependence of maximal overvoltage on R_*:
a) blowout after first current zero, under f_0=450 Hz;
1 – in failed phase under recovery; 2 – in leading phase under recovery; 3 – in leading phase under arcing;
b) arcing length $\approx T_c/2$ under f_0=450 Hz; 1 – in failed phase under arcing; 2 – in failed phase under recovery

The investigation states that there are different types of transient processes with different overvoltage levels in real circuits. Calculated value of maximal overvoltage equality is 4.266–3.861, Fig. 8.



a)

b)

Figure 8 – Charts of overvoltage dependence on R_*: a) under f_0=2250 Hz; b) under f_0=450 Hz; 1 – in failed phase under recovery; 2, 3 – in leading phase under arcing and recovery

Calculated overvoltage levels are maximal under $R_* \to 0$: in leading phase under arcing – 4.56, in leading phase under recovery – 4.89, in failed phase under recovery – 5.87.

CONCLUSIONS. The developed mathematical model of 6–10 kV branched circuit through mathematical apparatus enabled us to appreciate the value and impact of earth circuit on transient processes character and overvoltage levels while line-to-earth faults.

When R_* increases, overvoltage level decreases. Maximal overvoltage levels in branched circuits appear under small earth circuit resistance and can exceed fourfold value (3.86–4.27). It was found that overvoltage levels depend on earth circuit resistance value, arc blowout moment and voltage value of secondary initiations.

Earth circuit resistance value is determined by the number of high-frequency current zeros and correspondingly determines transient processes' character.

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РАБОТА РАСПРЕДЕЛИТЕЛЬНЫХ СЕТЕЙ 6–10 кВ С ИЗОЛИРОВАННОЙ НЕЙТРАЛЬЮ ПРИ ЗАМЫКАНИИ ФАЗЫ НА ЗЕМЛЮ

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В распределительных сетях 6–10 кВ с изолированной нейтралью однофазные замыкания на землю являются подавляющим видом повреждений. Перенапряжения, возникающие при этом, негативно влияют на работу электрооборудования, приводят к дополнительным расходам. Для оценки характера переходных процессов разработаны математические модели, которые наиболее полно учитывают изменения параметров распределительных сетей. Рассмотрена математическая модель с учетом активных сопротивлений продольных веток распределительной сети и установлено, что при оценке переходных процессов при горении дуги этими сопротивлениями можно пренебречь. Проведено исследование на математической модели, в которой учтены проводимости изоляции фаз распределительной сети. Численная оценка показывает, что данные параметры существенно не влияют на уровень перенапряжений. Рассмотрены примеры расчета уровней напряжений в фазах сети при горении дуги и в процессе восстановления напряжения при различных параметрах сети и значениях сопротивления цепи замыкания на землю. Установлено, что уровни перенапряжений зависят от величины сопротивления цепи замыкания на землю, момента гашения дуги и величины напряжений повторных зажиганий. Значение сопротивления цепи замыкания на землю определяет количество высокочастотных переходов тока однофазного замыкания на землю через нулевое значение и тем самым определяет характер развития переходных процессов. Наибольшие уровни перенапряжений в распределительных сетях могут превышать четырехкратные значения.

Ключевые слова: однофазные замыкания на землю, схема замещения, математическое моделирование, уровень перенапряжений.

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