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Information Parameters of Transient Electrical Values to Use for Earth-Fault Protection of Medium-Voltage Electrical Networks

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1 INTRODUCTION

Single-phase earth fault (SPEF) is common type of damage (70-90% of general number of electrical damages) at medium-voltage electrical networks (6-10kV), which can be ungrounded systems, resonant grounding by arc-suppression reactor (ASR) or high-resistance grounding systems. Also SPEF is frequently cause dangerous short-term interruption of supply and economic damage. Thus, power supply reliability significantly depends on engineering perfection (selectivity and stability functioning) of SPEF relay protection units.

Two common types of units are to be used as alarming or tripping protection against SPEF at above networks. They are based on the following principles:

- Monitoring of magnitudes and ratios of steady-state components of zero-sequence current and voltage (fundamental frequency, higher harmonics, «superimposed» current – artificial created high- or low-frequency components when a SPEF has occurred)
- Monitoring of magnitudes and ratios of transient electrical values to appear at the moment of isolation fault (first and following) from phase to earth.

For the first type of units electromagnetic transient currents and voltages are the noise that perverts magnitudes and ratios of monitored steady-state fault values and influences significantly dynamical stability of their functioning. For the second type of units electrical values of transient are the information signals.

The main information parameters of electrical values of SPEF transient, which influence significantly dynamical stability functioning of the above types units, are the following:

- amplitude and integral magnitudes of transient current and their ratios;
- frequency characteristic of transient currents and voltages (frequency spectrum, gain-frequency characteristic, power characteristic);

The main factors, which influence magnitudes and frequencies SPEF transient currents, are the following: total capacitive current I_{CS} , inductance of power source L_{PS} , remoteness place of SPEF from power source bus l_{SPEF} , system-grounding principle [1, 2].

Investigation and evaluation of parameters of SPEF transient electrical values of medium-voltage electrical networks are the key issue. Solution of this problem is necessary to rise engineering perfection of the relay protection against SPEF and first of all dynamical stability functioning in case of the most dangerous arcing intermittent earth-fault.

In order to determine magnitudes and evaluation range of possible changes in the information parameters of transient electrical values in case of SPEF and investigation of the affect of the above factors the following techniques can be used:

- analytic solution of SPEF transient equations;
- mathematical simulation of SPEF transient by computer.

Effectiveness of simulation by computer can be significantly improved if we sort out the main influence factors and their combinations by approximate analytic methods and determine their desired range of changes. Therefore, the best method for studying electromagnetic transients SPEF at 6-10 kV networks is a combination of analytical methods for solving the problem based on a simplified model of medium-voltage electrical network and method of simulation by computer that provides the perfection and the accuracy of the model.

2 MAIN PART

Analytical determination of magnitudes of information parameters of SPEF transient electrical values of the electrical 6-10 kV networks. Practically all known methods of implementation and execution of protection against SPEF are based on the use of zero-sequence current i_0 and voltage u_0 . Analytical solutions for the current i_0 and the zero-sequence voltage in case of SPEF can only be obtained for a simplified model of (equivalent circuit) electrical network. At the same time, the network model should take into account all the main factors influencing the shape and amplitude of free components and i_0 и u_0 . [1, 2] shows, that this requirement is sufficiently satisfies the equivalent circuit of a medium voltage electrical network in Fig. 1, taking into account the presence of the transient electrical values when SPEF two main frequency components: discharge (related with the discharge capacities fault phase) and charge (related to boosting charge capacities of fault-free phases).

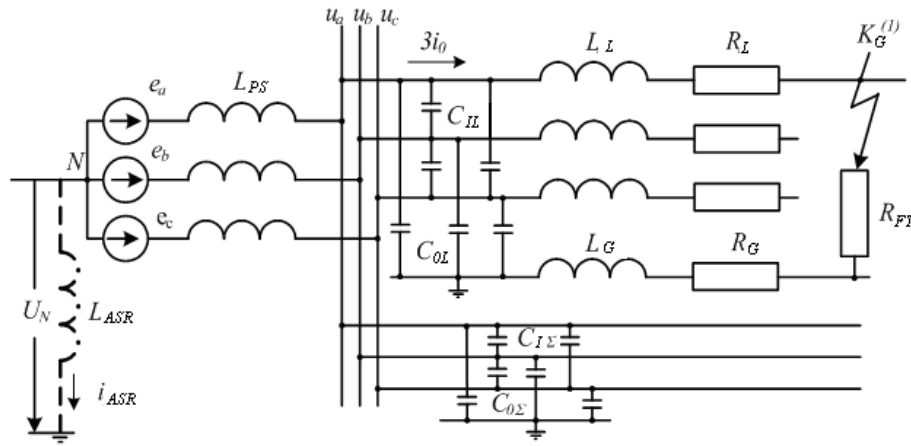


Fig. 1: Two-frequency equivalent circuit of a radial network of 6 - 10 kV for the analysis of SPEF transients

For the equivalent circuit network of Fig. 1, working with isolated neutral, the zero sequence voltage $u_0(t)$ the following equation can be obtained [1, 2]:

$$u_0(t) = u_{com} + u_{dch} + u_{ch} = U_m \sin(\omega t + \varphi) - U_m a_1 e^{-\delta_{dch} t} \left[\frac{\sqrt{\omega^2 \cos^2 \varphi + \omega_{dch}^2 \sin^2 \varphi}}{\omega_{dch}} \sin(\omega_{dch} t + \varphi_{dch}) - \frac{u_N(0)}{U_m} \cos \omega_{dch} t \right] - U_m a_2 e^{-\delta_{ch} t} \left[\frac{\sqrt{\omega^2 \cos^2 \varphi + \omega_{ch}^2 \sin^2 \varphi}}{\omega_{ch}} \sin(\omega_{ch} t + \varphi_{ch}) - \frac{u_N(0)}{U_m} \cos \omega_{ch} t \right]; \quad (1)$$

$$U_{mdch} = U_m a_1 \frac{\sqrt{\omega^2 \cos^2 \varphi + \omega_{dch}^2 \sin^2 \varphi}}{\omega_{dch}} \quad (2)$$

$$U_{mch} = U_m a_2 \frac{\sqrt{\omega^2 \cos^2 \varphi + \omega_{ch}^2 \sin^2 \varphi}}{\omega_{ch}} \quad (3)$$

where u_{com} – compelled component of transient voltage $u_0(t)$; u_{dch} - discharge component of the voltage $u_0(t)$; u_{ch} - charging voltage component of $u_0(t)$; U_m - amplitude component of the voltage of industrial

frequency on the damaged phase; $u_N(0)$ - voltage of bias neutral network at the time of the breakdown of insulation; ω_{dch} - frequency of discharging fluctuations, ω_{ch} - the frequency of charging fluctuations; δ_{dch} - damping constant discharging fluctuations; δ_{ch} - damping constant charging fluctuations;

$$\operatorname{tg} \varphi_{dch} = \frac{\omega_{dch} \sin \varphi}{\omega \cos \varphi + \delta_{dch} \sin \varphi}; \operatorname{tg} \varphi_{ch} = \frac{\omega_{ch} \sin \varphi}{\omega \cos \varphi + \delta_{ch} \sin \varphi}; a_1 = \frac{\omega_1^2 - \omega_{ch}^2}{\omega_{dch}^2 - \omega_{ch}^2}; a_2 = \frac{\omega_1^2 - \omega_{dch}^2}{\omega_{ch}^2 - \omega_{dch}^2}.$$

Frequency characteristics ω_{dch} , ω_{ch} and damping constants discharging δ_{dch} and δ_{ch} charging fluctuations are determined by the following equations [1, 2]:

$$\omega_{dch} = \frac{1}{\sqrt{2}} \sqrt{k_c \omega_1^2 + \omega_2^2 + \sqrt{k_c^2 \omega_1^4 + \omega_2^4 + (2k_c - 4) \omega_1^2 \omega_2^2}}; \quad (4)$$

$$\omega_{ch} = \frac{1}{\sqrt{2}} \sqrt{k_c \omega_1^2 + \omega_2^2 - \sqrt{k_c^2 \omega_1^4 + \omega_2^4 + (2k_c - 4) \omega_1^2 \omega_2^2}}; \quad (5)$$

$$\delta_{dch} = \alpha \cdot \frac{\omega_{dch}^2 - \omega_2^2}{2 \cdot (2\omega_{dch}^2 - \omega_2^2 - k_c \cdot \omega_1^2)}; \quad (6)$$

$$\delta_{ch} = \alpha \cdot \frac{\omega_{ch}^2 - \omega_2^2}{2 \cdot (2\omega_{ch}^2 - \omega_2^2 - k_c \cdot \omega_1^2)} \quad (7)$$

where $\alpha_1 = R_1/L_1$; $\omega_1^2 = 1/L_1 C_1$; $\omega_2^2 = 1/L_2 C_2$; $k_c = 1 + C_1/C_2$; $L_1 = 3L_L + L_G$; $C_1 = C_{0\Sigma} + C_{0L}$; $C_2 = C_{0\Sigma} + C_{0L}$; $R_1 = 3R_L + R_G + 3R_{FT}$; $L_2 = 2L_{PS}$; $C_2 = 0,5[C_{0\Sigma} + C_{0L} + 3(C_{I\Sigma} + C_{IL})]$.

Transient SPEF current in failure place for a network with isolated neutral is proportional to the derivative of voltage $u_0(t)$:

$$3i_0 = -3C_1 du_0/dt = i_{com} + i_{ch} + i_{dch} = 3C_{0\Sigma} U_m \cos(\omega t + \varphi) + I_{mdch} e^{-\delta_{dch} t} \cos(\omega_{dch} t + \theta_{dch}) + I_{mch} e^{-\delta_{ch} t} \cos(\omega_{ch} t + \theta_{ch}); \quad (8)$$

$$I_{mdch} = -3C_{0\Sigma} U_m \omega_{dch} a_1 \sqrt{\frac{\omega^2 \cos^2 \varphi + \omega_{dch}^2 \sin^2 \varphi}{\omega_{dch}^2 + \delta_{dch}^2}}; \quad (9)$$

$$I_{mch} = -3C_{0\Sigma} U_m \omega_{ch} a_2 \sqrt{\frac{\omega^2 \cos^2 \varphi + \omega_{ch}^2 \sin^2 \varphi}{\omega_{ch}^2 + \delta_{ch}^2}}, \quad (10)$$

where $\theta_{dch, ch} = \varphi_{dch, ch} + \operatorname{arctg} \frac{\delta_{dch, ch}}{\omega_{dch, ch}}$.

In compensated networks the ASR does not affect the amplitude and frequency of the discharge and charge components of the transient current due to its inertia, so the parameters of free components of the current and voltage can be approximately determined by (1) - (10).

In case of intermittent arc SPEF insulation breakdown after repeated breakdowns occur at greater voltages than the amplitude U_m , which leads to a proportional increase in the amplitudes of the discharge and charge components. Knowing the limiting value of voltage on the fault phase of the repeated breakdowns of insulation (e.g. [3]) by expressions (8) - (10) can define the components of the transient current and under intermittent arc SPEF.

Amplitude of the transient currents in case of SPEF. Amplitude of the discharge and charge components of the transient zero-sequence current were defined by equations (9), (10). Figure 2 shows transient current in case of SPEF and its components obtained by the above equations.

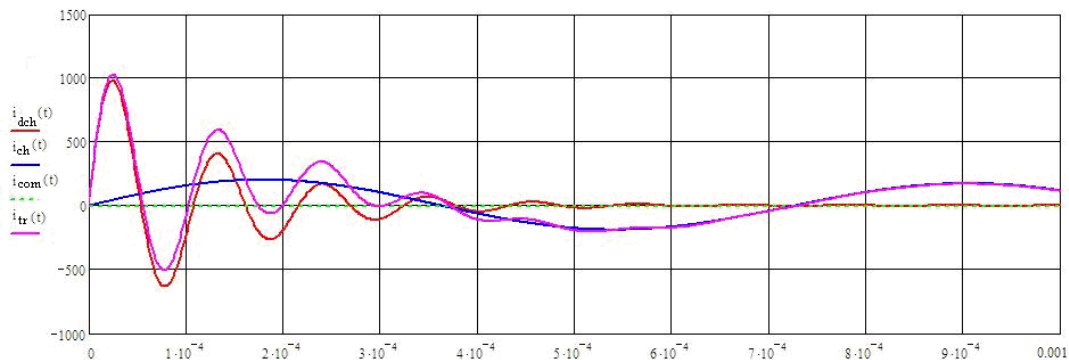


Fig. 2: Transient SPEF currents in the 6 kV network where $I_{C\Sigma} = 30$ A for the distance from SPEF place $l_{SPEF} = 1$ km and $\varphi = 90^\circ$: $i_{dch}(t)$ - discharging component, $i_{ch}(t)$ - charging component, $i_{com}(t)$ - compelled component; $i_{tr}(t)$ - total transient current

Fig. 2 shows that for small losses in the zero-sequence circuit 6 - 10 kV network, when the discharge component of the transient current $i_{dch}(t)$ in case of SPEF remains of oscillatory type, $I_{m dch} \gg I_{m ch}$ and amplitude of the total transient current $I_{m tr}$ are determined primarily by the $I_{m dch}$ and can be defined as the value of the current $3i_0$ at $t = t_m \approx 1/4f_{dch}$ according the equation (8).

The most significant effect on the amplitude of $I_{m ch}$ charge component of the transient current is the quantity of the total capacitive current network I_{CS} and inductance of the power supply (simply determined by the value of the current of three-phase short circuit on the buses). The most significant effect on the amplitude of the discharge component $I_{m dch}$ is the value of I_{CS} and inductance damaged line from the buses to the point of breakdown, that is, distance l_{SPEF} SPEF point of buses.

Calculations showed that when the total capacitive network current I_{CS} changes from 5 to 100 A, current three-phase short circuit at the power supply bus changes from 5 to 20 kA and the remoteness of SPEF from bus changes from 0,1 to 10 km the amplitude of the discharge current $I_{m dch}$ and total transient current I_m can vary from hundreds of amperes to ~3 kA, the amplitude of the charging current $I_{m ch}$ - up to ~1 kA.

The results obtained analytically by equations (1) - (10), were tested by computer simulation, taking into account the distributed nature of the parameters of the damaged line for identical design conditions (the parameters of the network and the damaged line): discrepancy between the results of analytical calculation and computer simulation does not exceed 5%.

Integral values of the transient current. Zero-sequence current protection (ZSCP) and directional zero-sequence current (DZSCP) protection responsive to the integral current and zero sequence voltage in the protected feeder were most widely used in electrical power networks 6 - 10 kV. ZSCP with measuring part on the basis of electromechanical and most versions of microprocessor ZSCP and DZSCP respond to the mean-square value of the controlled current. Half-period average value of controlled zero-sequence voltage and current can also be used in microelectronic and microprocessor implementations of ZSCP and DZSCP.

To study the dynamic stability of different versions of ZSCP, as well as some versions of directional current protection against SPEF (DZSCP) integral values of transient currents with a single breakdown in isolation and intermittent arc SPEF are of grate interest.

For a single insulation fault with suppression of grounding arc during the last free oscillations current passes through zero (the worst case of detuning conditions for the ZSCP against external SPEF) we can obtain the following (equations 9, 10):

$$I_{eff, sin gle} = \sqrt{\frac{1}{T_{dmp}} \int_0^{T_{dmp}} i_{tr}^2 dt} = \sqrt{\frac{1}{T_{dmp}} \int_0^{T_{dmp}} (i_{dch} + i_{ch})^2 dt} = \sqrt{\frac{1}{T_{dmp}} \int_0^{T_{dmp}} (I_{m dch} e^{-\delta_{dch} t} \cos(\omega_{dch} t + \theta_{dch}) + I_{m ch} e^{-\delta_{ch} t} \cos(\omega_{ch} t + \theta_{ch}))^2 dt}; \quad (11)$$

$$I_{hpa, sin gle} = \frac{1}{T_{dmp}} \int_0^{T_{dmp}} |i_{tr}| dt \approx \frac{1}{T_{dmp}} \int_0^{T_{dmp}} |i_{ch} + i_{dch}| dt = \frac{1}{T_{dmp}} \int_0^{T_{dmp}} |I_{m dch} e^{-\delta_{dch} t} \cos(\omega_{dch} t + \theta_{dch}) + I_{m ch} e^{-\delta_{ch} t} \cos(\omega_{ch} t + \theta_{ch})| dt; \quad (12)$$

$$I_{eff, sin gle} = \sqrt{\frac{2}{T_{50}} \int_0^{T_{50}/2} i_{tr}^2 dt} = \sqrt{\frac{2}{T_{50}} \int_0^{T_{50}/2} (i_{dch} + i_{ch})^2 dt} = \sqrt{\frac{2}{T_{50}} \int_0^{T_{50}/2} (I_{m dch} e^{-\delta_{dch} t} \cos(\omega_{dch} t + \theta_{dch}) + I_{m ch} e^{-\delta_{ch} t} \cos(\omega_{ch} t + \theta_{ch}))^2 dt}; \quad (13)$$

$$I_{hpa, sin gle} = \frac{2}{T_{50}} \int_0^{T_{50}/2} |i_{tr}| dt \approx \frac{1}{T_{dmp}} \int_0^{T_{dmp}} |i_{ch} + i_{dch}| dt = \frac{2}{T_{50}} \int_0^{T_{50}/2} |I_{m dch} e^{-\delta_{dch} t} \cos(\omega_{dch} t + \theta_{dch}) + I_{m ch} e^{-\delta_{ch} t} \cos(\omega_{ch} t + \theta_{ch})| dt, \quad (14)$$

where T_{dmp} - time for a complete damping of free components of the transition process in case of SPEF (may be taken as ~3 ... 5 ms [3]).

For the case when suppression of grounding arc is at the time of passing current of industrial frequency through zero (the theory of Peters and Slepian):

$$I_{eff, sin gle} = \sqrt{\frac{2}{T_{50}} \int_0^{T_{50}/2} i_{tr}^2 dt} = \sqrt{\frac{2}{T_{50}} \int_0^{T_{50}/2} (i_{dch} + i_{ch})^2 dt} = \sqrt{\frac{2}{T_{50}} \int_0^{T_{50}/2} (I_{m dch} e^{-\delta_{dch} t} \cos(\omega_{dch} t + \theta_{dch}) + I_{m ch} e^{-\delta_{ch} t} \cos(\omega_{ch} t + \theta_{ch}))^2 dt}; \quad (15)$$

$$I_{hpa, sin gle} = \frac{2}{T_{50}} \int_0^{T_{50}/2} |i_{tr}| dt \approx \frac{1}{T_{dmp}} \int_0^{T_{dmp}} |i_{ch} + i_{dch}| dt = \frac{2}{T_{50}} \int_0^{T_{50}/2} |I_{m dch} e^{-\delta_{dch} t} \cos(\omega_{dch} t + \theta_{dch}) + I_{m ch} e^{-\delta_{ch} t} \cos(\omega_{ch} t + \theta_{ch})| dt, \quad (16)$$

where $T_{50} = 20$ ms - the period of the current of industrial frequency.

Calculations based on expressions (11) and (12) show that the factor having the greatest influence on the integral values of the transient current with a single breakdown, is the total capacitive current network $I_{C\Sigma}$.

For intermittent arc SPEF according to the Petersen theory (Fig. 7) the amplitude of the transition current in repeated insulation failures in the limit may be increased 2,0 ... 2,5 times in comparison with the amplitude of the transient current during the first failure, and in an arc of intermittent SPEF according to the Peters and Slepian theory it may increase about 2 times.

Fig. 8 shows that for the arc intermittent SPEF root-mean-square (effective) and half-period average values controlled current protection can be increased 5 ... 15 times compared to established modes of fail, which leads to the need for significant coarsening series of performances ZSCP and limitation of their sensitivity and field possible applications [4].

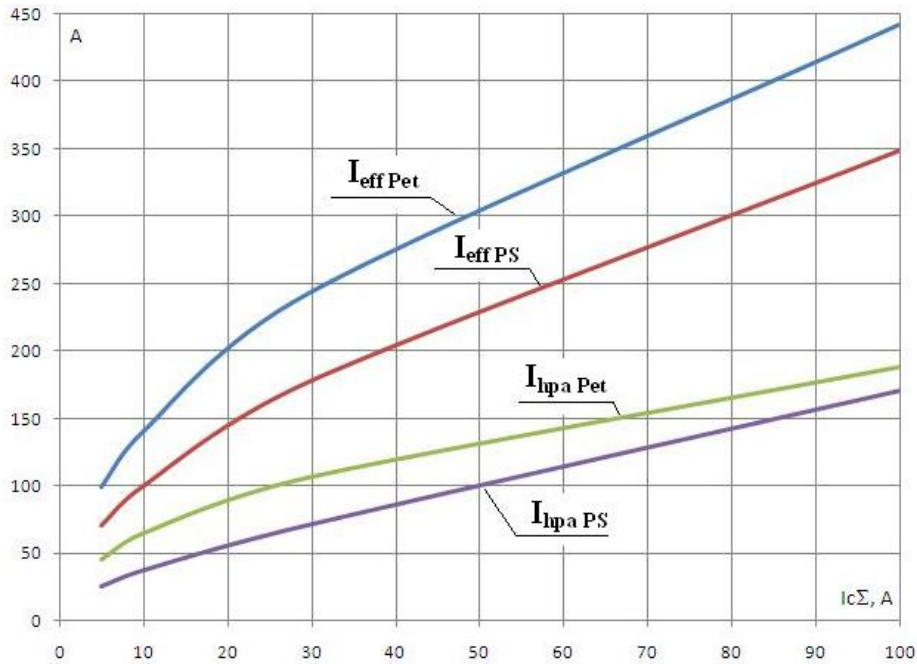


Fig. 3: Dependence of the root-mean-square (effective) and the half-period average transient currents values on the total capacitive current of 6 kV cable network in case of intermittent arc SPEF on the theory of Petersen, and Peters and Slepian ($I_{SPEF} = 1\ km$, $\varphi = 90^\circ$); $I_{eff\ Pet}$, $I_{hpa\ Pet}$ - effective and half-period average values for the quenching of the grounding arc at the time of transition through a zero free component of the current transition process (Petersen theory); $I_{eff\ PS}$, $I_{hpa\ PS}$ - the same with the grounding of the arc extinction at the time of transition through the zero of compelled component (Peters and Slepian theory)

Frequency of transition process currents. Frequency of the discharge i_{odch} and charge i_{och} components of the transitional process current can be determined by (4) and (5).

Analysis of the calculation results shows that the frequency of these components f_{dch} and f_{ch} depending on the electrical network parameters and SPEF position changes approximately within: $f_{dch} = 3000 \dots 30000\ Hz$ and $f_{ch} = 300 \dots 2000\ Hz$.

Effect of frequency filtering on the integral values of transient currents SPEF. It is possible to limit the impact of the transition process current in the sustainability of ZSCP in case of external arc intermittent SPEF by using lower input filters (LPF).

Calculations on the mathematical model shows that the use of low-pass filter with a cutoff frequency of 500 Hz helps to restrict half-period average value of the transient current in case of arc intermittent SPEF to values not exceeding the half-period average value of steady earth fault current, i.e. provides an effective detuning from the impact of the transition process current.

To obtain a similar effect for ZSCP based on the use of the root-mean-square (effective) values of the controlled current it is necessary to use low-pass filter with a cutoff frequency around 300 Hz.

Spectral characteristics of transient currents. Spectral density $\tilde{S}(\omega)$, its real $A(\omega)$ and imaginary $B(\omega)$ parts and the amplitude-frequency characteristic (AFC) of non-periodic signal $3i_0(t)$ is determined by the expression [5]:

$$\tilde{S}(\omega) = \int_0^{t_{obs}} 3i_0(t) e^{-j\omega t} dt = S(\omega) e^{-j\phi(\omega)} = A(\omega) - jB(\omega); \quad (17)$$

$$A(\omega) = \int_0^{t_{obs}} 3i_0(t) \cos \omega t dt; \quad (18)$$

$$B(\omega) = \int_0^{t_{obs}} 3i_0(t) \sin \omega t dt; \quad (19)$$

$$S(\omega) = \sqrt{A(\omega)^2 + B(\omega)^2}, \quad (20)$$

where t_{obs} is observation time of non-periodic signal, in this case it is the attenuation time of free components of the transition process in case of SPEF ($\sim 3 \dots 5$ ms [3]).

Relationship between the signal energy and its spectral characteristic is set by Parseval equation:

$$\tilde{A} = \int_0^{t_{obs}} [3i_0(t)]^2 dt = \frac{1}{2\pi} \int_0^{\infty} S(\omega)^2 d\omega, \quad (21)$$

where E is energy released by current when resistance is 1 Ohm.

Expression (18) - (21) using expressions (1) - (10) help to calculate the energy dependence of the current of transition process in case of SPEF E in the frequency range $f = 0 \dots 10000$ Hz by varying the total capacitive current of the network $I_{C\Sigma}$ within $5 \dots 100$ A, the distance of SPEF from the bus l_{SPEF} within $0,1 \dots 10$ km and the magnitude of the current three-phase short circuit on the buses $I_e^{(3)}$ within $5 \dots 20$ kA.

Calculations shows that most of energy (90%) of free components of the transition process current in case of SPEF in cable networks of 6 - 10 kV voltage is concentrated in the spectral range of upper frequency $f = 3-4$ kHz (for example, fig .4).

On the upper frequency of range a total capacitive current of network and inductance of supply (current value of three-phase short circuit on the bus of the source) have most significant influence. These results show that working frequency range can be limited by the upper frequency $f \leq 3-4$ kHz, without prejudice to the effectiveness of functioning for internal failure of the protection against SPEF, based on the use of electrical quantities of the transition process,. This allows us to simplify greatly the requirements for such protection against SPEF on microprocessor element basis.

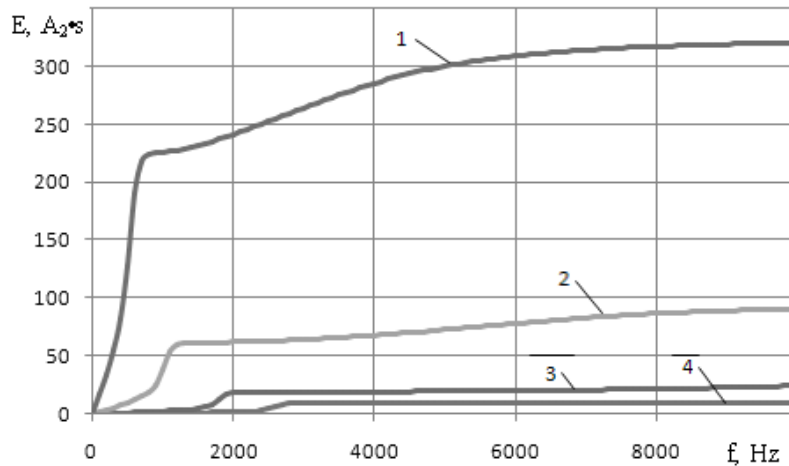


Fig. 4: Dependence of free components energy of the transient current of network with $U_{nom} = 6$ kV, $I_e^{(3)} = 10$ kA for $l_{SPEF} = 1$ km on the frequency for different values of the total capacitive current $I_{C\Sigma}$: 1 - $I_{C\Sigma} = 100$ A, 2 - $I_{C\Sigma} = 30$ A, 3 - $I_{C\Sigma} = 10$ A, 4 - $I_{C\Sigma} = 50$ A

3 CONCLUSIONS

1. Functioning of various versions of protection against SPEF for electrical networks of medium voltage is strongly influenced by values currents and voltages of electromagnetic transients (amplitude and integral values) and their ratio, the frequency characteristics of transient currents and voltages (frequency spectrum, amplitude-frequency characteristics, power characteristics), and phase relationships of electrical quantities of the transient.

2. Analytical expressions for estimate of basic information parameters of the transient current, such as amplitude and integral values, frequency of discharge and charge components, energy characteristics for a single insulation failure and intermittent arc SPEF according to the theory of Petersen and Peters and Slepian were obtained by solving the equations of the transient against SPEF for a simplified two-frequency equivalent circuit of 6 - 10 kV network.

3. Calculations shows that in the arc intermittent SPEF root-mean-square (effective) and half-period average values of current in fault location can be increased 10 ... 15 times compared to steady-state regime of SPEF. This leads to significant coarsening of the majority of ZSCP versions, limiting their sensitivity and the possible area of application.

4. Application of low-pass filter with a cutoff frequency of 300 Hz allows to limit the root-mean-square value of arc intermittent SPEF to values not exceeding the root-mean-square value of the steady-earth fault current, i.e. provides an effective detuning ZSCP with measuring part of current, which is reactive to an effective value of the controlled current from the effects of electromagnetic transients.

5. Most of energy (90%) of the current transient free components of SPEF in cable networks of 6 - 10 kV is concentrated in the spectral range of the upper frequency $f = 3-4$ kHz, which allows to limit the working frequency range and simplify the requirements for protection against SPEF, based on the use of transients, based on a microprocessor.

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