# Oscillography of Transient Processes at Physical Phase-to-ground Fault Modeling in Operational 6-35 kV Networks

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***Abstract*--The paper presents methods of accurate determination of single phase-to-ground currents, advantages and disadvantages of these methods, and general requirements to the measuring equipment used in oscillography of transient processes at single phase-to-ground faults. These methods have been tried in operational 6-35 kV networks for 8 years. Experimental investigations allow doing research of main parameters of a zero-sequence circuit. Using recorded oscillograms, we can analyze the character of transient processes, evaluate the efficiency of the compensation system, suppose the nature of processes, and determine overvoltage levels. Based on experimental investigations and calculations, recommendations on effective internal overvoltage protection at arcing ground faults can be proposed.**

***Index Terms*—single phase-to-ground fault, single phase-to-ground current, capacitance current, oscillography, oscillogram, transient process, higher harmonics**

## I. Introduction

AT the present time, in extensive 6-35 kV networks where capacitive currents exceed 10 A (or, in some cases, even 100 A) problems of neutral grounding conditions and Petersen coils application are of great importance. This is caused by: firstly, the absence of national standards regulated technical requirements to neutral grounding devices; secondly, operating conditions of networks that define frequency and rate of capacitive current change; thirdly, problems of inductive current control for Petersen coils at their possible simultaneous operation.

According to modern neutral grounding techniques, it is necessary to reduce capacitive currents at single phase-to-ground faults when these currents should be compensated, because actual values (e.g. 20 A for 10 kV networks and 30 A for 6 kV networks in accordance with PTE Russian engineering instructions on power stations and networks) are probably overestimated, since overvoltage levels at arcing in 6-35 kV networks are weakly dependent on capacitive current values in any cases. The accuracy of Petersen coil tuning under any operational conditions is a critical parameter determining overvoltage levels at ground faults. Possible detuning ratio of a Petersen coil should be determined. According to the latest investigations [1], detuning ratio should not exceed 1-2% that defines more stringent requirements to a Petersen coil autotune system.

There are no effective standard criteria for the determination of neutral grounding conditions in mixed networks where XLPE cables and mass-impregnated paper-insulated cables are in simultaneous operation.

When solving these problems, the presence of higher harmonics in a ground fault circuit (in a zero-sequence circuit) is not taken into account. The higher are these harmonics, the greater is capacitive current. Moreover, higher harmonics are not compensated by Petersen coils. Impacts of higher harmonics on electric strength and life time of insulation have not been studied in practice yet, but these impacts are supposed to be extremely negative. As early as 1950s-1960s, requirements on higher harmonic current compensation in zero-sequence circuits were developed [2] employing special high-voltage filters which have not been ever used in Russian practice. The applicability and possibility of installation of such devices in operational networks having high levels of harmonics in single phase-to-ground currents should be considered.

Apart from non-compensated capacitive current, ground-fault current contains active current which value depends on active leakages across network insulation. For normal cable insulation conditions, the value of active leakage current $I_G$ is chosen depending on active conductance of the network being equal to 5% of capacitive conductance. For aged cable insulation of urban networks, active conductance can be estimated as $Y_G \geq (0.1\text{-}0.15)\cdot Y_{\sum network}$. Actual values of leakages can be used as indirect diagnostic character for aging degree determination.

For evaluation of higher harmonics levels in a zero-sequence circuit, active and reactive component in a ground-fault current, determination of network response to single phase-to-ground faults, experiments on artificial solid single phase-to-ground faults (if necessary, arcing ground faults) should be done with the digital oscilloscopy of phase-to-ground voltages, single phase-to-ground currents, Petersen coil currents, and others.

## II. Oscillographic Methods and Process Data Recording System at Single Phase-to-ground Faults

Modern development of computer science and measurement technology allows the development of complex network analysis by artificial solid ground which comprises:

- digital oscilloscopy of phase-to-ground voltages and single phase-to-ground currents; after that obtained data can be mathematically processed by external software packages;
- measurements of capacitive currents at single phase-to-ground faults and their harmonic components for known network configuration;
- evaluation of the efficiency of the compensation system regarding to plunger or transductor reactors (Petersen coils), determination of actual detuning ratios in the network;
- analysis of the character of phase-to-ground voltages under normal operating conditions and in transient processes at ground faults, evaluation of network response to single phase-to-ground faults;
- indirect evaluation of high-voltage circuit breaker operability (these circuit breakers are used for feeder switching with voltage and current sensors connected).

The process data recording system for single phase-to-ground faults consists of digital oscilloscopes, voltage and current sensors, data cables, and special equipment for artificial phase grounding – a copper stranded conductor for the creation of artificial solid grounds or a spark gap for physical modelling of intermittent arcing. General connection diagram of measuring equipment is presented in [3].

In a special compartment prepared for artificial solid ground one phase is connected to a grounding device through a current sensor (current transducer). As a current sensor, a current transformer or a current transducer using the Hall effect can be employed. A current sensor should have linear amplitude-frequency characteristic (AFC) to provide desired frequency range for signal recording. According to expert evaluations [4], up to a steady-state value of single phase-to-ground current transient process frequency reaches 250-1000 Hz in overhead lines and 1500-3000 Hz in cable lines. Taking it into account, standard current transformers realizing signal recording in the frequency range of (20-5000) Hz or current transducers using the Hall effect and having linear conversion factor-frequency dependence in the frequency range of (0-150) kHz can be employed as current sensors. Accuracy rating of current transformers should be not more than 1.0, and their primary current should be close to maximum expectation single phase-to-ground current.

A signal from a current transformer secondary shunted by 0.1-1.0 Ohm resistance is transmitted via an instrument cable to an input of a digital storage oscilloscope used for single phase-to-ground current recording. Maximum permissible distortion level of instrument cables should not exceed 0.5%.

Using of standard voltage transformers for phase voltage recording is undesirable, especially in transient process recording at single phase-to-ground faults.

Analysis of experimental oscillograms recorded by digital oscilloscopes shows that the highest possible transient process frequencies at single phase-to-ground faults are equal to (10..50) kHz. Therefore, phase voltage recording should be done by special high-voltage dividers. Due to this fact, voltage divider parameters should be specified as follows:

- rated voltage is 10 or 35 kV;
- bandwidth is from 20 Hz to 2 MHz with AFC flatness of ± 0.5 dB and constant conversion factor in the full frequency range;
- load active resistance is not less than 1 MOhm;
- load capacitance is not more than 1.5 nF;
- dielectric loss tangent is not more than 0.002 at 25°C.

Signals from a low-voltage arm of voltage dividers connected to every phase are transmitted via an instrument cable to a digital storage oscilloscope. Voltage dividers are recommended to be connected to bus bars through an individual circuit breaker.

Modern digital oscilloscopes being generally PC-based oscilloscopes allow real-time signal displaying by using 10-16 independent 8-16 bit channels with (0.0001..20) V/div sensitivity in a bandwidth from 0 to tens GHz. Their buffers can store from several thousands to 50 million samples per channel (sampling rate). Input resistance of a digital oscilloscope should not exceed 0.95-1.0 MOhm.

For transient process recording at single phase-to-ground faults oscilloscopes having sampling rate not less than 50-100 kHz should be used. Oscilloscope triggering should be realized both at increasing part of the signal, and at decreasing part in standby, single and self-oscillating modes.

Multiple experiments of digital oscilloscopy of single phase-to-ground currents and phase-to-ground voltages in 6-35 kV networks show that:

- voltage and current sensors used for the conversion of voltages and currents at single phase-to-ground faults should have a linear AFC;
- more stringent requirements regarding bandwidths and voltage sensitivity should be imposed to digital signal recording systems.

Actual values of single phase-to-ground currents obtained by proposed methods and their further analysis can be used for corrected transient process modelling for the determination of network response to local disturbances (e.g. arc-overs to ground in cable networks).

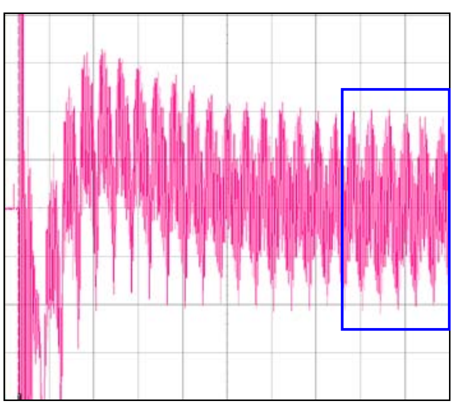
## III. Results of Experimental Investigations on Transient Processes at Single Phase-to-ground Faults and Higher Harmonic Analysis of a Ground-fault Current

By now, using modern digital technologies and measuring equipment we have carried out investigations on transient processes at single phase-to-ground faults in 6-35 kV networks of more than 40 power facilities including electric power plants (combined heat and power plants and hydro-electric power plants), Gazprom gas compressor stations, main substations of coal, metallurgical, petrochemical, and other industries.

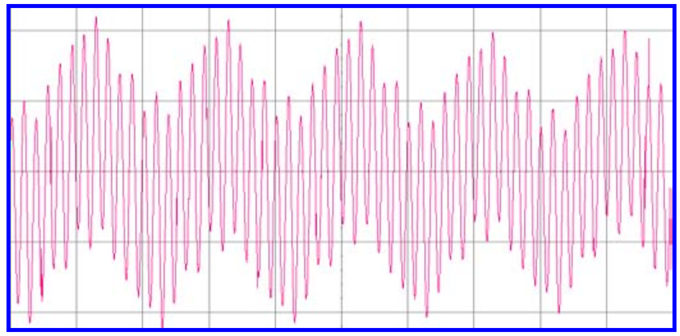
Consider some results of experimental investigations in the 6 kV main switchgear network of the high-capacity combined heat and power (CHP) plant which supplies some districts of the city with a population of more than 500 thousand people. Because of inadmissibility of undersupply of energy to customers, when recording capacitive current by artificial solid ground fault it was decided to determine a single phase-to-ground current with accurate tuning ratios for the full 6 kV main switchgear network. Sampling rate of a digital oscilloscope is 100 kHz.

Analysis of representative oscillograms of the current in a ground-fault place (see Fig. 1) shows that this current contains high-level harmonic components. The most visible higher harmonic is the 11th harmonic which exceeds fundamental frequency (i.e. residual 50 Hz current in a ground-fault place) more than 2.5 times.

High values of the residual current in the ground-fault place lead to the accident development caused by the transition of single phase-to-ground faults to multiplace faults and short circuits. It is known [2] that when the 50 Hz capacitive component is well-compensated, non-compensated current is almost fully (90-95%) determined by higher harmonics not taking into account active current components characterizing integral aging degree.



a)



b)

Fig. 1. Oscillograms of a steady-state ground-fault current in the 6 kV main switchgear network of the urban CHP plant with 80 A/div current sweep: a) original – 50 ms/div; b) expanded – 10 ms/div

Oscillograms at single phase-to-ground faults for the determination of harmonic composition and amplitudes of current harmonics were processed by MATLAB software. Active and reactive components of the residual current were determined: a fundamental frequency component is equal to 30.6 A which comprises a reactive component by Petersen coil being equal to 27.5 A, and an active component by active leakages across network insulation being equal to 14.3 A. Indirectly measured Petersen coil current is equal to 301 A, a capacitance current is equal to 273.5 A.

Harmonic analysis of recorded oscillograms at artificial solid ground fault shows that single phase-to-ground current contains high-level harmonics including the 11th harmonic being equal to 78.9 A (remind that residual current is equal to 30.6 A). The results of harmonic analysis at single phase-to-ground fault in the 6 kV network are presented in Table 1.

Table 1
Results of Amplitude-phase Harmonic Analysis at Single Phase-to-ground Fault in the 6 kV Network of the Urban CHP Plant

| Harmonics | *w*, rad/s | Initial phase, rad | Signal amplitude, A | Rms amplitude, A | Percentage of 50 Hz current, % |
|---|---|---|---|---|---|
| **1** | **314** | **2,492** | **43,78** | 30,96 | **100,0** |
| 2 | 628 | 0,428 | 0,252 | 0,178 | 0,6 |
| 3 | 942 | **-3,071** | **4,570** | 3,23 | 10,4 |
| 4 | 1256 | 1,243 | 0,392 | 0,277 | 0,9 |
| **5** | **1570** | **-3,005** | **9,680** | **6,85** | **22,1** |
| 6 | 1884 | 0,605 | 0,181 | 0,128 | 0,4 |
| 7 | 2198 | **-0,066** | **8,42** | 5,95 | 19,2 |
| 8 | 2512 | 2,793 | 0,408 | 0,288 | 0,9 |
| 9 | 2826 | **-0,288** | **3,44** | 2,43 | 7,9 |
| 10 | 3140 | 0,420 | 1,26 | 0,891 | 2,9 |
| **11** | **3454** | **2,929** | **111,6** | **78,91** | **254,8** |
| 12 | 3768 | -2,449 | 0,632 | 0,447 | 1,4 |
| 13 | 4082 | **-2,368** | **4,07** | 2,88 | 9,3 |

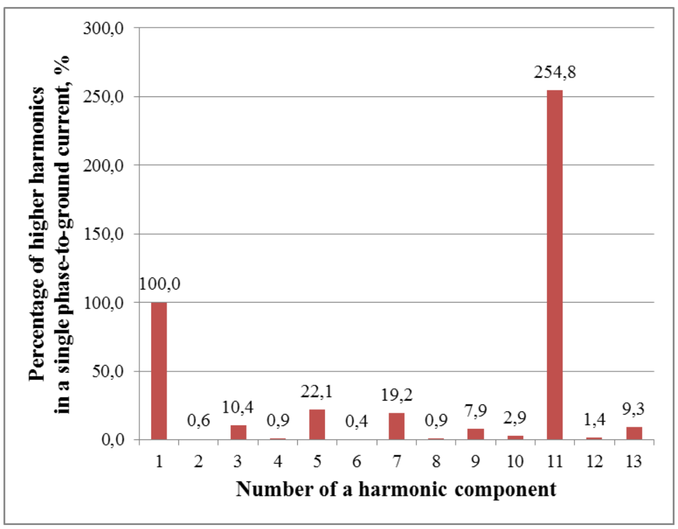
For integral estimation of higher harmonic currents, it is more convenient to estimate actual rms “distortion current” containing components of single phase-to-ground current components of known amplitudes according to the following equation:

$$I_{harm} = \sqrt{I_2^2 + I_3^2 + I_4^2 + ... + I_n^2}\ , \qquad (1)$$

where $n$ is a number of a harmonic component (start with the 2nd harmonic).

Using (1), calculated distortion current for odd and event harmonic components given in Table 1 is equal to 79.59 A. Contribution of even harmonics to the distortion of single phase-to-ground current is negligible that can be applied to most 6-35 kV networks.

According to Table 1, contribution of odd harmonic components (3rd, 5th, 7th, 9th, and 11th) to the total signal is significant. Influence of harmonic components more than 700 Hz (15th component and more) on the current amplitude is negligible. The histogram given in Fig. 2 shows the percentage of higher harmonics in a single phase-to-ground current.




a)

Fig. 2. Histograms of relative harmonic composition of single phase-to-ground current (a) and phase-to-ground voltage (b) in the 6 kV network of the urban CHP plant

The comparison between the harmonic composition of phase-to-ground voltages under normal operating conditions and the harmonic composition of unfaulted phase voltages at single phase-to-ground fault shows that in some cases an increase of the percentage of some harmonics can be observed. In investigated networks resonant step-up can be up to 10 times in comparison with normal operating conditions. Percentage of the 11th harmonic increases 1.4 times in comparison with the voltage of the same frequency under normal operating conditions (0.65% of the 50 Hz signal).

In other cases, experiments in the 10 kV network of the ferroalloy plant which supplies power ore-thermal furnaces having rated current of 1000 A show that some higher harmonics increase 3-9 times at single phase-to-ground faults in comparison with normal operating conditions, and 17-20 times in active smelting modes. Relative values of the 35th and 37th harmonics of 50 Hz single phase-to-ground current (its amplitude is 6.6 A) are 20% and 10.5%, respectively. They are changing during the period of single phase-to-ground fault (approximately, 2 s), as shown in Fig. 3.

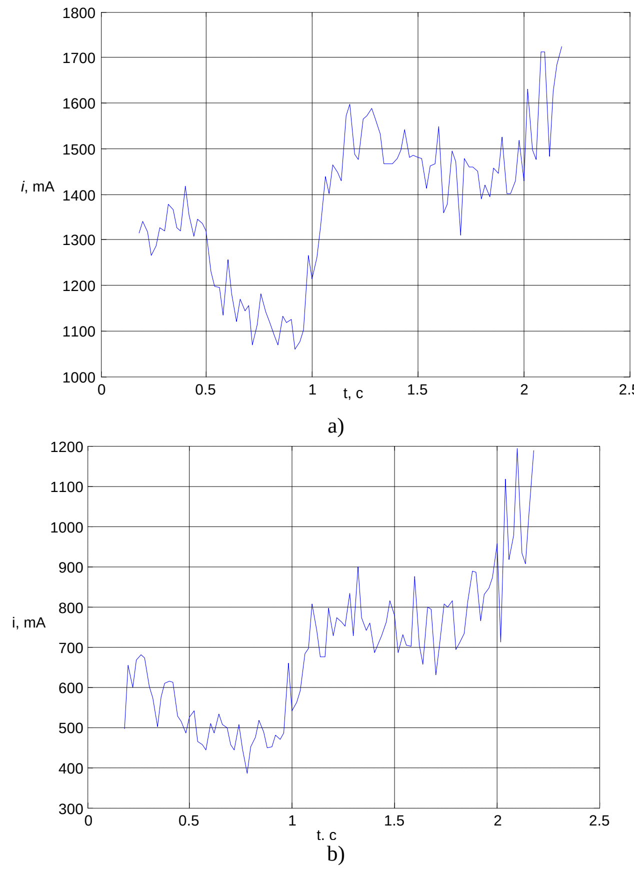



Fig. 3. Time changed process for the 35th (a) and 37th (b) harmonic amplitudes of single phase-to-ground current in the 10 kV network equipped with various ore-thermal furnaces

It shows that harmonic amplitudes of phase-to-ground voltages can increase during the period of ground fault (this period exceeds the experiment period) that may lead to overvoltages and further failures. Moreover, under resonant conditions at single phase-to-ground faults voltage harmonicity distortion coefficient increases 2-3 times taking into account that permissible coefficient is equal to 5% in accordance with [5]. Our investigations show that when capacitive current rises, a resonant range is shifted to a low frequency region.

Each zero-sequence circuit (it can be more than one depending on operating conditions) has its own resonant frequencies. Processes in system phases and in a system neutral at single phase-to-ground faults (both solid, and arcing ground faults) can be caused by subharmonic of ultraharmonic resonances. Resonant frequencies in a ground fault circuit are determined not only by system characteristics, but a ground fault place. High transient resistance in a ground fault place provides resonant process damping regardless of their frequency spectra. It determines unstable occurrence of higher harmonics in a single phase-to-ground current and possible change of their amplitudes at various ground fault experiments. Consequently, dangerous resonant processes can be eliminated by the connection of a resistor to a neutral of the network (this resistor will be an additive element to a zero-sequence circuit).

Percentage of several higher harmonics in a single phase-to-ground current for 6-35 kV networks is defined by the following parameters of devices connected to the ground circuit during a period of a ground fault:

a) conditions of a ground circuit (integrity of a circuit and correspondence of its ground resistances to rated values);
b) presence of specific non-linear power plants (e.g. steel, purifying, and ore-smelting furnaces; softstarters and frequency regulation devices of motors; harmonic filters; and others);
c) presence of Petersen coils in a system neutral, linearity of their current-voltage characteristics and methods of current compensation;
d) quantity and power of electrical machines (synchronous and asynchronous motors and generators).

## IV. Hypothesis on the Influence of Higher Harmonics on the Insulation Breakdown Voltage for Power Cables

Investigations on higher harmonics in a single phase-to-ground current are of a great interest for explanation of higher harmonic influence on the reliable operation of high-voltage network insulation. This problem has not been properly solved yet.

According to our investigations, combination of specific factors (e.g. insulation life time, direct voltage levels and periodicity of preventive tests, values of single phase-to-ground currents and their higher harmonics, overvoltage levels, and others) significantly effects on the rate of breakdown path carbonization (i.e. on decrease degree of insulation electric strength). The latter occurs according to an exponential law depending on the quantity of higher harmonics in a single phase-to-ground current. It can be applied to stator insulation of electrical machines and to cable insulation.

There is a direct dependence between levels of current $I_{harm}$ distorted by higher harmonics, arcing duration $T_{arc}$ at arcing ground faults, and electric strength recovery rate $V_{ESR}$ of an insulation gap:

$$V_{ESR} = f(\exp)(I_{harm},\ T_{arc},\ ...)\,. \qquad (2)$$

Equation (2) can be explained by neglecting influence of harmonic phases on insulation gap voltage.

Each harmonic component in a single phase-to-ground voltage causes certain voltage drop across an arc resistance being proportional to a current of this component. It results in additive increase of insulation gap voltage. This should lead to a decrease of an arcing gap electric strength and to an increase of restrike probability. The higher is harmonic composition of a single phase-to-ground current, the quicker is breakdown voltage reach. The breakdown voltage decreases after each breakdown. However, this hypothesis can be applied at high-value arc resistance caused by transient resistance in a ground-fault place.

It can be explained as follows. Average arc resistance at single phase-to-ground faults can be estimated in the range of (0.5..10) Ohm. This range can be limited to (2.8..6.5) Ohm for 6-10 kV cable networks [6]. Therefore, when even harmonic components with tens amperes (e.g. up to 100 A) are presented, voltage drops do not exceed (0.1..1.0) kV. If electric strength of insulation is close to critical ionization levels (e.g. 30 kV/mm – for mass-impregnated paper insulation, and 40 kV/mm – for XLPE insulation), contribution of higher harmonics to breakdown voltage can be estimated by relative values which is equal to 4.3% for mass-impregnated paper insulation and 7.5% for XLPE insulation. The proposed hypothesis can be applied to 6-10 kV cables with insulation thickness of 1.3 mm for mass-impregnated paper insulation and 3.0 mm for XLPE insulation.

The key conclusion of the proposed hypothesis is the necessity of numerical account of network insulation life time reducing (including cable insulation) if a single phase-to-ground current contains higher harmonics with amplitudes close to a reactive component of a ground fault power frequency current.

## V. Conclusions

1. Methods of digital oscillography and signal analysis at single phase-to-ground faults have been proposed and tested in operational networks; requirements to primary sensors have been developed. It was shown that experimental investigations of single phase-to-ground currents by digital oscillography allow determining actual active and reactive current components at power frequency or in the definite frequency range and giving recommendations on neutral grounding.
2. Because of the fact that recorded single phase-to-ground current contains active component in the frequency range up to 2 kHz, measuring current has never been purely reactive that is not taken into account during calculations. However, single phase-to-ground current circulating in a zero-sequence circuit contains higher harmonics in a wide frequency range (generally, from 25 Hz to 3.5 kHz). Harmonic component amplitude characteristics of current are defined by parameters of nonlinear magnetic shunts of power and instrument transformers and reactive loads. Phase of each harmonic randomly varies in time.
3. In networks equipped with Petersen coils, harmonic currents containing both reactive and active components and flowing in a ground-fault circuit are not compensated by Petersen coils. Because of this fact, it is rather difficult to tune a Petersen coil to a close-to-resonance mode and

keep the required tuning ratio at frequent changes in load conditions.

4. It is the first time the hypothesis of the influence of higher harmonics containing in ground-fault currents on the breakdown voltage of power cable insulation has been proposed. This hypothesis confirms the possibility of electric strength decrease for insulation of networks containing a great amount of higher harmonics.

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