Transient Processes at Single Phase-to-Ground Faults in Combined Grounded Networks

Andrey Shirkovets, Anastasiya Vasilyeva, Andrey Telegin, and Leonid Sarin

Abstract--**This paper deals with the combined method of neutral grounding when a high-value resistor is continuously connected to a neutral in parallel with a Petersen coil. Monitoring of processes at single phase-to-ground faults was organized in the 6 kV network of the large-scale iron and steel plant. Within the investigation, more than 200 oscillograms of phase-to-ground voltages were analyzed. Based on recorded oscillograms, the comparison between processes at ground faults in the resonant grounded network (grounding through a Petersen coil) and in the combined grounded network (grounding through a high-value resistor in parallel with a Petersen coil) was done. Numerical values of dangerous for network insulation transient processes, frequency distributions of overvoltage levels, and arc durations were obtained by methods of statistical processing. Field experience of combined grounded networks shows that continuously operated neutral grounding resistors reduce the amount of emergency outages caused by ground faults 4-6 times and decrease undersupply of energy to customers; maximum overvoltage levels, arc duration, insulation breakdowns and multiplace faults also decrease.**

Index Terms--**Single phase-to-ground fault, combined grounding, high-value resistor, Petersen coil, transient process.**

I. Introduction

NEUTRAL grounding through a Petersen coil recommended by normative documents leads to capacitive current compensation at fault locations in medium voltage networks that provides conditions for self-quenching of arc and, in some cases, for overvoltage limitation. However, the danger of high overvoltages is not eliminated as in case of arcing ground faults under open-phase conditions which happen at nonsimultaneous operation or high voltage circuit breaker pole failures. The possibility of continuous overcompensation more than 5–10% that often exists in practice [1] is not considered in the paper. Induced overvoltages lead to the failures of motors, cables and voltage transformers due to insulation breakdowns.

To avoid this, high-value resistors are recommended to be connected to a neutral in parallel with a Petersen coil. Many organizations operating 6–35 kV networks have chosen this method of neutral grounding [2]–[5].

It should be noted that international manufacturers of Petersen coils and their control equipment (e.g. TRENCH in Austria and EGE in Czech Republic) use this method of neutral grounding in the following modified manner: a high-value resistor is connected in parallel with a Petersen coil only for the time of a ground fault (or a low-value resistor is connected to additional secondary winding of a Petersen coil). This modified method of neutral grounding can be explained by disadvantages of control equipment of Petersen coils. Most importantly, it does not decrease overvoltage levels in the case of ground faults. The method is only used for detection of a faulty feeder by relay protection. Therefore, we may consider that a kind of combined method of neutral grounding is practically used in Austria, Czech Republic, India and China.

Connecting a neutral to ground through a Petersen coil in parallel with a resistor results in reducing of free oscillations, suppression of beats and voltage reduction on the faulted phase. Overvoltage limitation at arcing ground faults leads to reducing of the number of insulation flashovers and the total number of faults. Almost full reduction of transitions of arcing ground faults to double-phase faults (i.e. short circuits) is observed. Since 1998, the combined method of neutral grounding is successfully used in various networks in Russia (more than 400 power facilities), including networks of iron and steel plants, distribution substations, and large CHP (Combined Heat and Power) networks [2].

Positive field experience of this method of neutral grounding can be evaluated through the monitoring of transient processes at single phase-to-ground faults recorded by special equipment. The monitoring system installed in the 6 kV network of Novokuznetsk Iron and Steel Plant allows collecting statistics on single phase-to-ground faults and analyzing comparatively transient processes in the electrical network which was operated with different methods of neutral grounding.

II. Object and Objectives

This study involves oscillograms of transient processes recorded by a special measuring system in the main switchgear of the 6 kV cable network of a CHP (Combined Heat and Power) Plant feeding a large Iron and Steel Plant (hereafter referred to as “NKMK”).

A set of three single-phase resistance-capacitance voltage dividers was installed to a voltage transformer compartment at bus bars. The voltage dividers are used as voltage sensors having voltage ratio K=2250 for signal transformation and linear amplitude-frequency characteristic in the frequency range of (0.025–200) kHz. For registration of transient processes, 4-channel PC-based digital oscilloscopes were used. During these investigations, maximum duration of registration of transient processes was 6.55 seconds with 20 kHz sampling rate.

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Oscillograms recorded in the 6 kV network of NKMK during one year were analyzed with regard to the overvoltage evaluation, overvoltage duration, and character of transient processes.

The diagram of the 6 kV network of the NKMK main switchgear is shown in Fig. 1.

Total capacitive current at single phase-to-ground faults is 136 A. Its compensation is provided by connection of ZROM-350/6 Petersen coils to the neutral of T1, T3 and T4 transformer windings; only two Petersen coils are in operation. Compensation current of ZROM No1 is 53.6 A. Compensation currents of ZROMs Nos3, 4 are 88 A and 87 A, respectively. Thus, total inductive current of a Petersen coil is (141.6…142.6) A, and overcompensation is (4.1…4.9)%.

However, implementation of compensation in 6 kV network of NKMK does not solve a problem of frequent faults of equipment insulation (cables and motors), including miltiplace faults, at single phase-to-ground faults. Consequently, for decreasing of equipment failures (generally, failures of power motors), power resistors were considered to be installed to a neutral of the network in parallel with every Petersen coil (the combined method of neutral grounding).

300-Ohm resistors rated for continuous maximum phase-to-ground voltage were put into operation in 2005.

7-year field experience of neutral grounding resistor operation in 6 kV networks shows that the combined method of neutral grounding allows efficient overvoltage limitation at single phase-to-ground arcing faults and improves the conditions of arc quenching.

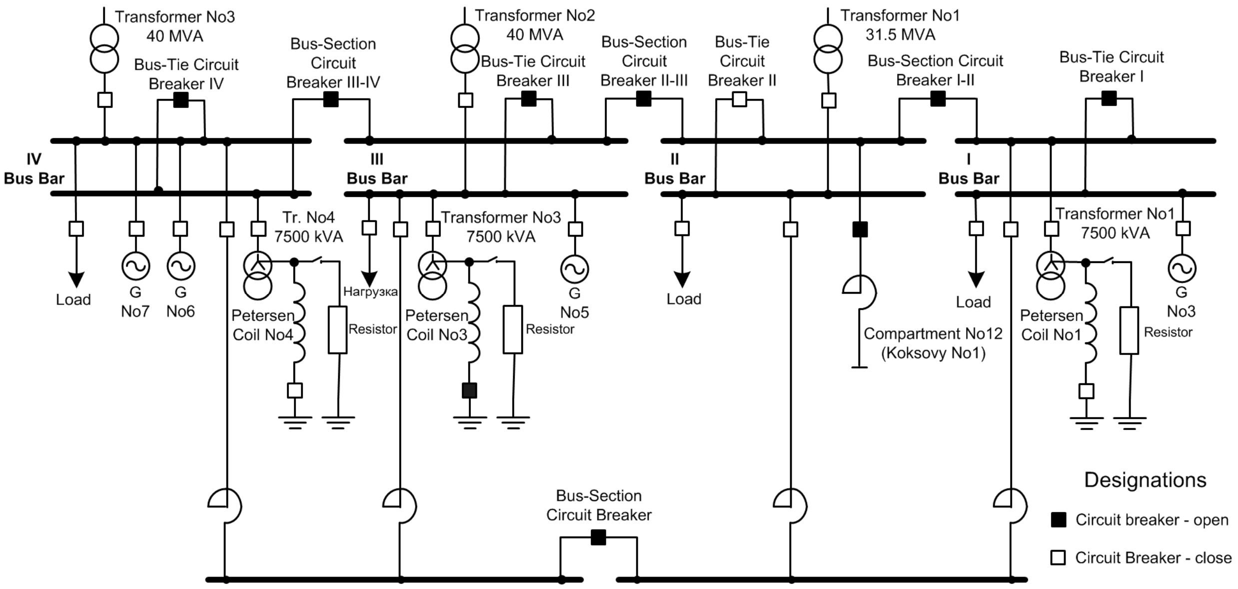


Fig. 1. Single line diagram of the Novokuznetsk Iron and Steel Plant 6 kV network where a neutral is connected to ground through a Petersen coil in parallel with a resistor.

The main aim of our investigation is to compare characteristics of transient processes at single phase-to-ground faults in the resonant grounded network (grounding through a Petersen coil) and in the combined grounded network (grounding through a high-value resistor in parallel with a Petersen coil). Using methods of statistical processing (239 oscillograms were processed) it was shown how characteristics of dangerous for network insulation transient processes change depending on the method of neutral grounding.

III. Statistics on Single Phase-to-ground Faults in 6 kV Network of NKMK

Overvoltages induced in cable networks at single phase-to-ground faults are dangerous not only because of their high levels, but because of the fact that they effect on reduced parts of the network many times and cause multiplace faults of network insulation with great damages and losses.

Information about the number of ground faults in the considered network obtained during the period of 22 December 2005 – 10 May 2008 is shown in Table I.

TABLE I
STATISTICS ON GROUND FAULTS IN THE 6 KV NETWORK OF NKMK

	Petersen coil	Petersen coil + Resistor
Total number of ground faults	98 (100%)	141 (100%)
Self-clearing faults, after the first breakdown	68 (69.4%)	127(90.1%)
Self-clearing faults, after the second (or more) breakdown	20 (20.4%)	14 (9.9%)
Faults leading to equipment power-off	10 (10.2%)	0

NOTE: Self-clearing fault is a short-time unstable ground fault with partial breakdown of insulation which does not cause non-cleared damages and feeder interruptions. Due to cable oil dribbling, breakdown channel pouring happens with further self-clearance of the fault. In most cases, this occurs at the beginning of the fault (usually after the first or the second breakdown of a cable phase).

At the moment of our investigations, 6 kV cable networks of NKMK have been operated not less than 25–30 years. Their cable sheaths are permanently exposed to chemical and electrochemical corrosion by acid soils at the premises of NKMK. Moreover, damageability of cable networks exceeds damageability of other network elements and approaches 10–12 cable network elements per 100 km per year.

Based on recorded voltage oscillograms at single phase-to-ground faults, investigations on overvoltage levels and arc durations were carried out.

According to Table I, the main part of ground faults (69.4%) is self-cleared without a resistor after the first breakdown. At the same time, about 10% of ground faults in a resonant grounded network lead to equipment power-off that cause power failures and undersupply of energy to customers.

Representative oscillograms of overvoltages in the 6 kV network of NKMK illustrated the character of transient processes with and without a resistor in a neutral are shown in Fig. 2.

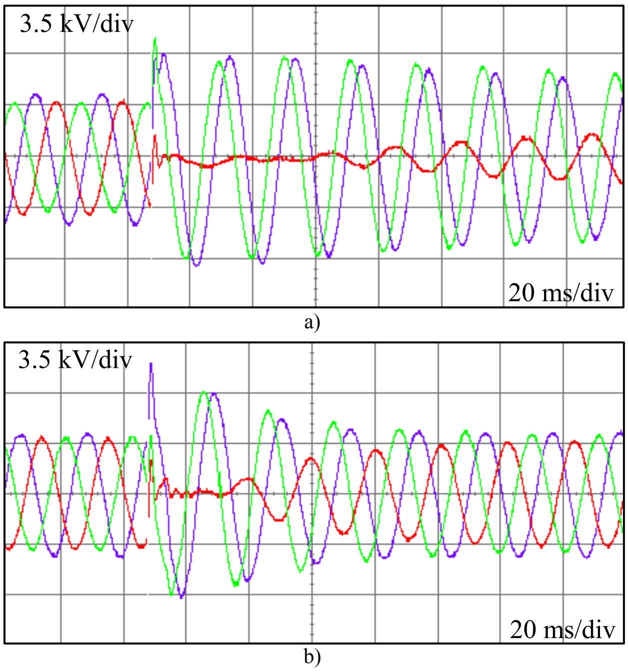


Fig. 2. Oscillograms of transient processes at single phase-to-ground faults in the 6 kV network of NKMK:
a) Petersen coil (without of a resistor);
b) Petersen coil + Resistor (in parallel).

Resistance neutral grounding not only reduces the number of single phase-to-ground faults with arc reignition (9.9% of total number of ground faults), but increases network reliability.

For the considered time interval, the number of single phase-to-ground faults when a resistor was connected to a neutral of the network increased. This fact is directly associated with seasonal increasing of cable network fault probability which depends on the combination of environmental factors, soil freezing, accumulation and development of existing defects, and increasing network loads.

It should be noted that when a resistor was connected to a neutral of the network there were no any power failures for customers as shown in Table I. A resistor connected to a neutral induces an active current at single phase-to-ground faults that is enough for selective operation of current protection which is immediately activated when ground-fault current occurs. Consequently, it reduces the time of detection and clearance of a faulty feeder.

IV. Overvoltages at Single Phase-to-Ground Faults

In resonant grounded networks at single phase-to-ground faults there is a possibility of dangerous overvoltages caused by intermittent arcing faults. Generally, cables of the main switchgear are exposed to overvoltages. In the 6 kV network of NKMK tap-changed Petersen coils are used. Changes in the power supply circuit caused by actions of operating personnel and relay operation can lead to overcompensation more than 10% which determines overvoltage levels at single phase-to-ground faults.

Moreover, at least two of three Petersen coils are operated in overcompensating mode; therefore, clearance of a ground fault frequently produces phase-to-ground voltage beats (i.e. superposition of steady-state power-frequency voltage and transient component having adjacent frequency). This case is characterized by voltage increase on a faulty phase up to (1.8..2.0) times the phase-to-ground voltage. It is observed in the analysis of recorded oscillograms.

Maximum overvoltage levels in the resonant grounded network are 2.7 times the phase-to-ground voltage; but according to Fig. 3 the occurrence probability of overvoltages more than 2.4 times the phase-to-ground voltage is 0.05 (5%).

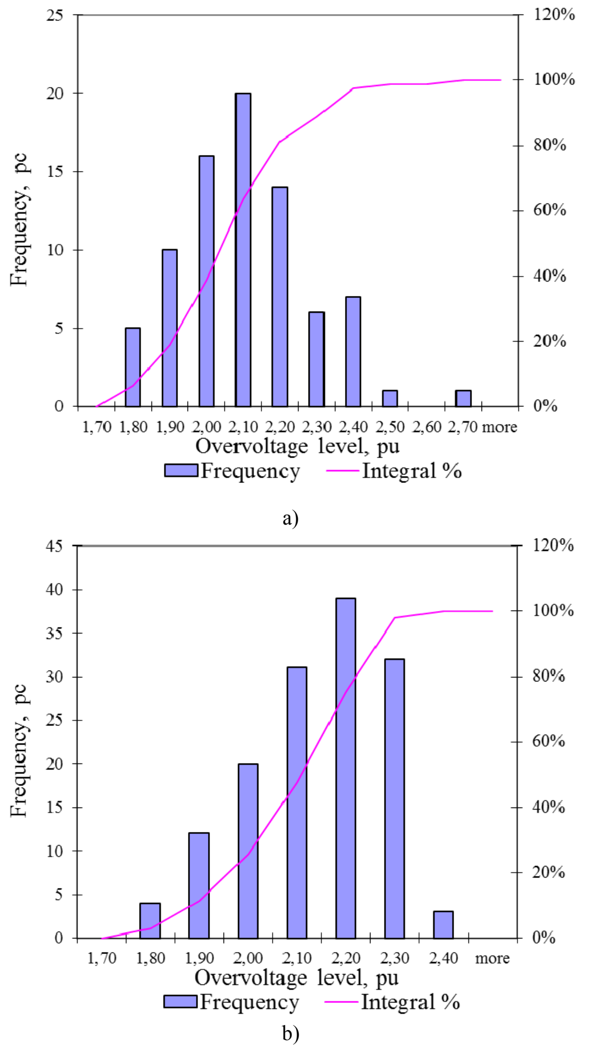


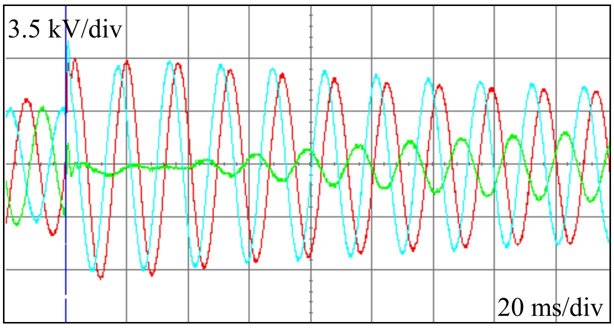
Fig. 3. Frequency distributions of overvoltage levels in the 6 kV network of NKMK (a – Petersen coil, b – Petersen coil + Resistor).

If a neutral of the network is grounded through a resistor connected in parallel with a Petersen coil, induced overvoltages does not exceed 2.3 times the phase-to-ground voltage with 0.95 probability. Both in Fig. 3a, and in Fig. 3b an integral distribution curve is sufficiently flattened in the range of (0.95...1.0), so the occurrence of maximum overvoltages in the combined grounded network (a resistor in parallel with a Petersen coil) is quite rare event.

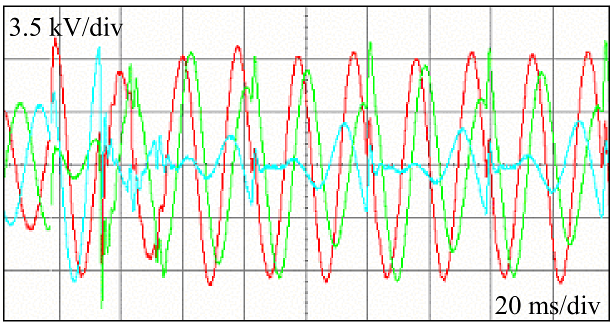
In accordance with recorded oscillograms, voltage recovery time of the faulty phase after arc extinction in the resonant grounded network (without a resistor) is 15–20 power-frequency periods (see Fig. 4a).

Moreover, multiple restrikes after 2–4 periods are observed on many recorded oscillograms (see the left part of Fig. 4b). Therefore, these breakdowns occur more frequently as opposed to classical concepts on the process of voltage recovery on the faulty phase given in [1], [6]. Overvoltages after restrikes before the transition of single phase-to-ground fault to steady solid single phase-to-ground fault causing equipment switching-off by relay protection can be higher than overvoltages after the first arc extinction. In the resonant grounded network (without a resistor), overvoltages with maximum levels 2.7 times the phase-to-ground voltage were recorded.

Analysis of recorded oscillograms shows that overvoltage levels, their durations and probability of restrikes in the combined grounded network (resistor + Petersen coil) are less than in the resonant grounded network (Petersen coil only).



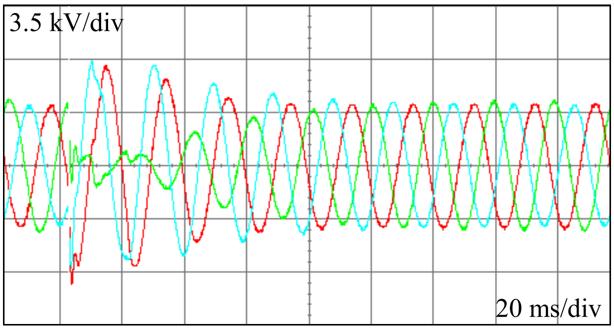
a)



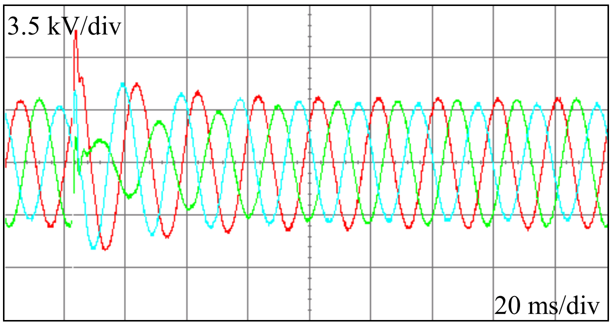
b)

Fig. 4. Oscillograms of phase-to-ground voltages at single phase-to-ground arcing faults in the 6 kV resonant grounded network (Petersen coil, without a resitor):
a) overvoltage ratio is 2.2 in pu;
b) overvoltage ratio is 2.35 in pu.

Representative oscillograms of phase-to-ground voltages for different feeders in the 6 kV combined grounded network of NKMK (a resistor in parallel with a Petersen coil) are shown in Fig. 5.



a)



b)

Fig. 5. Oscillograms of phase-to-ground voltages at single phase-to-ground arcing faults in the 6 kV combined grounded network (resistor + Petersen coil):
a) overvoltage ratio is 1.93 in pu;
b) overvoltage ratio is 2.14 in pu.

For the combined grounded network, reoccurrence of single phase-to-ground faults shows that for given resistance zero-sequence capacity has no time for full discharge (when neutral-to-ground voltage is equal to zero) for the period from arc self-quenching to the moment of reaching maximum voltage on the faulty phase which is close to the phase-to-ground voltage (1.05...1.1 times).

Therefore, when a resistor is connected in parallel with a Petersen coil to a neutral of the 6 kV network, all the attempts of restrikes and real breakdowns exist during one or two power-frequency periods after the first ground fault and do not lead to overvoltages more than initial overvoltages of (2.0…2.1) times the phase-to-ground voltage. Fig. 5 shows that voltage recovery time of the faulty phase does not exceed (3.0...3.5) power-frequency periods.

V. Investigations on Arc Duration in Networks Operated with Various Neutral Conditions

In the 6 kV cable network of NKMK many recorded overvoltages are caused by arcing in narrow channels at single phase-to-ground arcing faults. These arcs are characterized by forced longitudinal blast extinction and high deionization rates of arc space.

In the resonant grounded network (without a resistor) the probability of arc duration more than 100 ms is 0.95; so continuous arc duration (195 ms) is a quite rare event because an integral distribution curve is sufficiently flattened in the range of (0.95…1.0). In the combined grounded network arc duration is not more than 35 ms with 0.95 probability (see Fig. 6).

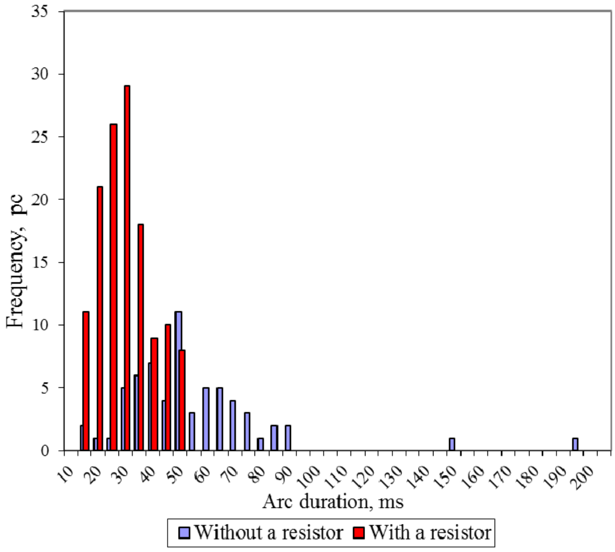


Fig. 6. Frequency distribution of arc durations.

The real process of arc duration is quite complex. This process is mainly determined by value and character of quasisteady ground-fault current (this current is not recorded in our investigation), and breakdown voltage of the faulty place after the arc extinction.

Arc duration and arc extinction conditions are determined by transient resistance and pressure in the place of arcing, a type of dielectric material, cooling rate, and others. Table II presents statistical characteristics of arc duration distribution at single arcing.

TABLE II
SIMPLE STATISTICAL CHARACTERISTICS OF ARC DURATIONS AT SINGLE PHASE-TO-GROUND ARCING FAULTS IN THE 6 KV NETWORK OF NKMK FOR THE PERIOD 23 DECEMBER 2004 – 22 DECEMBER 2005

Characteristic	Without a resistor	With a resistor
Mathematical expectation (mean), ms	50.2	17.5
Dispersion, ms^2	846	82.3
Root-mean-square deviation, ms	29.1	9.07
Maximum value, ms	195	38.0

In the combined grounded network arc duration is three times less than in the resonant grounded network. In accordance with recorded oscillograms, the probability of restrikes significantly decreases. Consequently, a resistor connected in parallel with a Petersen coil to a neutral of the network provides arc self-quenching, suppresses arc restrikes, and facilitates equipment insulation operation.

Fig. 7 shows oscillograms of phase-to-ground voltages at bus bars of NKMK with different arc durations and voltage recovering times. Here we can see that in the case of a Petersen coil connected to a neutral the process of voltage recovering on a faulty phase often breaks and arc restrikes occur.

According to classical concepts [1], arcing in a cable or in a cable terminal is accompanied by carbonization of a discharge channel. In the case of 30–150 A capacitance currents, time of transition of intermittent arcing ground faults into solid single phase-to-ground faults in mass-impregnated paper insulated cables is about 0.3–1.5 seconds.

However, statistical data obtained in 6–10 kV networks and oscillograms presented in Fig.7 show that these conditions are not always fulfilled. Duration of intermittent arcing ground fault with residual fault current of 10–15 A is from 0.04–0.06 s to tens of minutes. Eventually, this ground fault may not lead to phase insulation burning and the development of arc tracking between phase and ground. During a single phase-to-ground arcing fault in a cable network, the result of the second and further restrikes depending on energy release in the arc channel determines the possibility of local destructions and phase-to-phase insulation damages.

VI. REASONS FOR DECREASE OF ARC DURATION DUE TO FAULT CURRENT INCREASE CAUSED BY THE RESISTOR

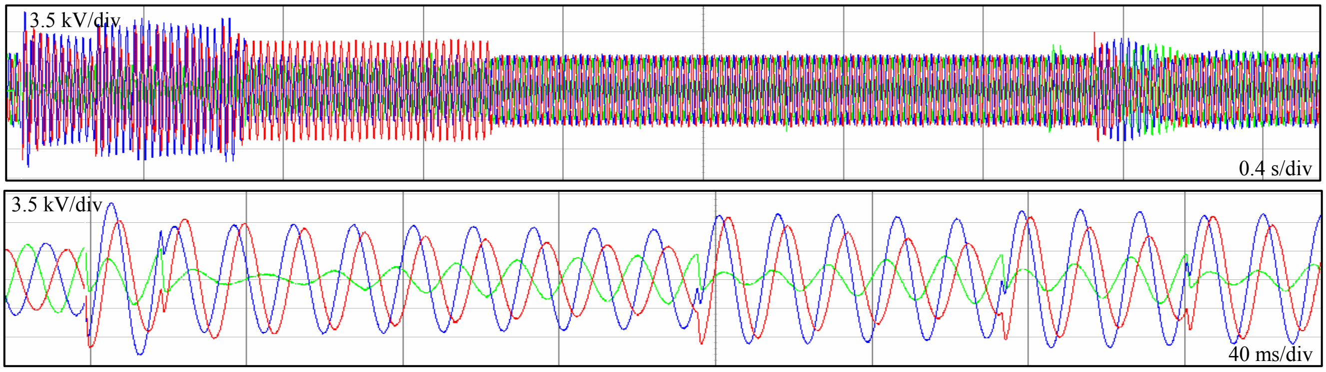
Depending on active component in arc current, as is shown above, self-quenching is possible to happen when fault current increases due to the resistor connected to the neutral of the network.

Decreasing of arc duration at arc current increasing can be explained as follows. Developed arc channel burns in a nozzle. It is a classic case of an ablation-controlled arc. Ablation is a process of removal of material from the surface of an object by vaporization or gas flow. Arc current increasing causes nozzle wall ablation increasing. This nozzle is located in polymer insulation of XPLE cable or in mass-impregnated paper insulation. After that, ablated nozzle wall material (i.e. evaporated and decomposed polymer or burned-out paper and cable oil) flows into the arc column. The temperature of ablated material is lower than the temperature of arc plasma in the arc channel, so ablated wall material acts as a coolant.

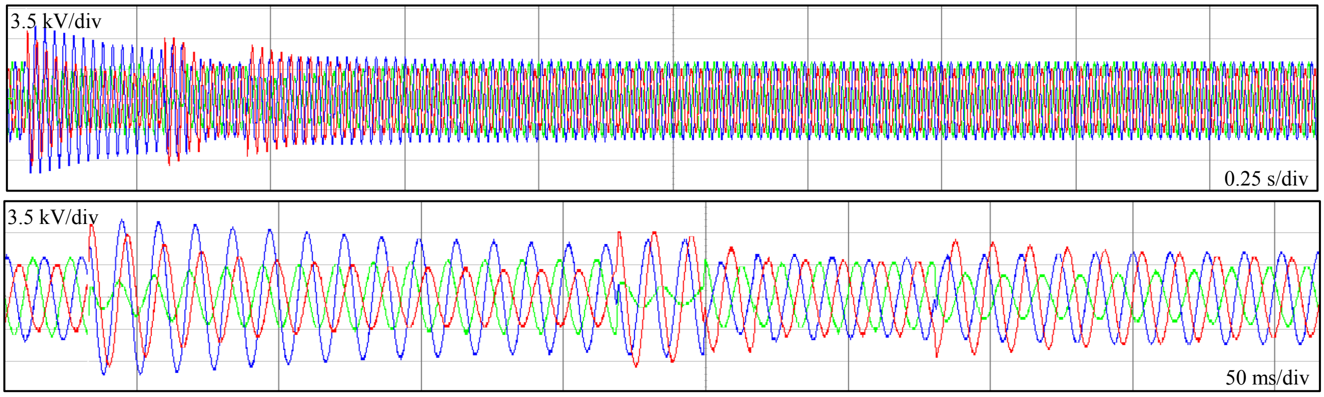
In addition, gas pressure and nozzle wall destruction rise significantly during ablation. Gas flow constricts an arc in radial direction. Temperature profile of arc column becomes sharper; conductivity at the boundary of arc column decreases due to the cooling by gas and ablated material. It causes that the current-carrying diameter of the arc diminishes that results in temperature rise in the center of the discharge channel. This means that the same current has to pass through the reduced section of arc column, thus higher electrical conductivity is required. Consequently, temperature rises in the center of the channel as the arc ‘response’ for cooling. Time constant of this thermal process is in the range of 10–100 μs.

Electrical conductivity increase of arc column and associated electrical conductance decrease (because conducting arc column is reduced in diameter) lead to dynamic arc resistance increase. It can result in arc quenching depending on ‘competition’ between two processes: arc cooling and arc channel expansion & recovering of electric strength and increasing of arc voltage. There is the possibility of self-regeneration of mass-impregnated paper insulation. As for polymer insulation, the probability of self-quenching of the arc at the discharge of polymer insulation (especially with feeding from cable current) is significantly low.

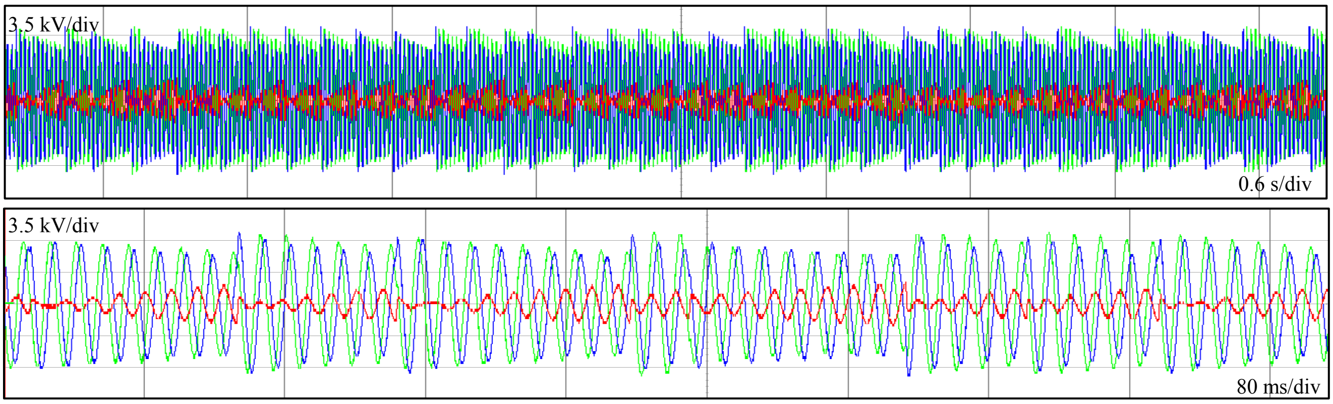
This explanation is quite simple and clarifies the reasons of the decrease of arc duration at single phase-to-ground faults that leads to the reduction of cable damage areas when current in the ground fault area increases.



a) transition of arcing ground fault into solid single phase-to-ground fault (duration 0.15s) with its further self-clearing and several restrikes after 0.32s



b) gradual voltage recovering on a faulty phase with restrikes (Petersen coil is tuned to a close-to-resonance mode)



c) intermittent arcing in a single phase of a cable with 40 minutes duration without a transition into steady solid single phase-to-ground fault

Fig. 7. Transient processes with arcing in the 6 kV resonant grounded cable network of NKMK.

VII. Conclusions

1. Maximum overvoltage levels at single phase-to-ground faults in the resonant grounded network are 2.7 times the phase-to-ground voltage; the occurrence probability of overvoltages more than 2.4 times the phase-to-ground voltage is 0.05. Maximum overvoltage levels at single phase-to-ground faults in the combined grounded network (high-value resistor in parallel with a Petersen coil) are not more than 2.35 times the phase-to-ground voltage; the occurrence probability of overvoltages more than 2.3 times the phase-to-ground voltage is 0.05.

2. In the resonant grounded network the probability of arc duration more than 100 ms is 0.95; in the combined grounded network arc duration is not more than 35 ms with 0.95 probability.

3. Character of arcing and arc extinction processes in combined grounded networks provides a decrease of overvoltage levels and a probability of the development of insulation defects.

4. In medium voltage resonant grounded networks the most dangerous faults are double-phase and multiplace faults. A resistor connected in parallel with a Petersen coil to a neutral of the network eliminates a possibility of voltage escalation on unfaulted phases and decreases a breakdown probability and multiplace fault occurence.

5. Conditions of discharge and arcing in combined cable insulation are different from traditional concepts used for the analysis of arcing and arc quenching. Particularly, the presence of active component in a single-phase-to-ground current causes the increase of oil evaporation rate and pressure in arcing area, providing quick arc quenching.

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IX. Biographies

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