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

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***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. 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

Processes in the 6 kV network of Novokuznetsk Iron and Steel Plant (hereafter referred to as “NKMK”) were recorded by a special measuring system from 23 December 2004 to 22 December 2005.

At the end of 2004 a set of voltage dividers was installed in a compartment connected to bus bars. The voltage dividers were used as voltage sensors in combination with digital storage oscilloscopes. A divider is rated for signal transformation in the frequency range of (0.025–200) kHz.

ACK-3117 PC-based Digital Oscilloscopes were used for the oscillography of phase-to-ground voltages. ACK-3117 allows signal displaying using 4 independent 8 bit resolution channels with high sensitivity (from 2 mV/div to 10 V/div) in the analog bandwidth of (0–100) MHz with a buffer having 131071 samples per channel (sampling rate). Such characteristics enable recording of processes having 6.55s lengths and 20 kHz sampling rate.

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.

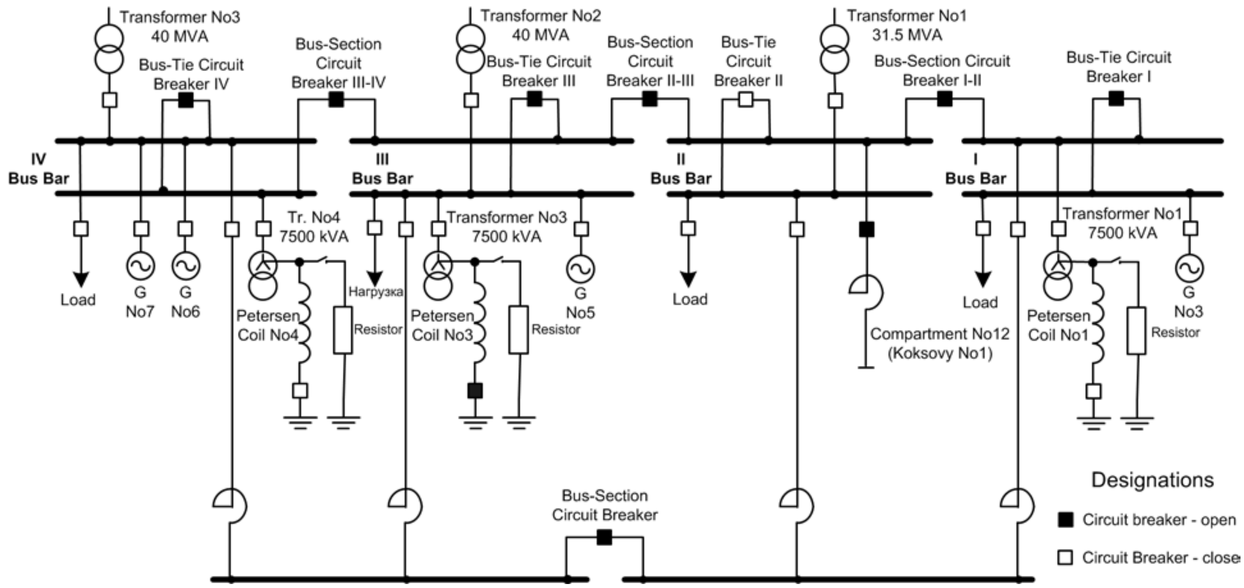


Fig. 1. Single line diagram of the Novokuznetsk Iron and Steel Plant 6 kV network where a neutral is connected to ground through a Petersen coil in parallel with a resistor

Total capacitive current at single phase-to-ground faults is 136 A. In accordance with PTE regulations of power stations and networks (Russian engineering instructions), capacitive current compensation should be employed when capacitive current is more than 30 A for 6 kV networks. Compensation is provided by connection of ZROM-350/6 Petersen coils (Nos 1, 3, 4) to the neutral of T1, T3 and T4 transformer windings; only two Petersen coils are in operation. ZROM No1 is operated in the 1st tap mode (compensation current is 53.6 A), ZROMs Nos3, 4 are operated in the 3rd tap mode (compensation currents 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)% that is less than 5% recommended by PTE regulations of power stations and networks (Russian engineering instructions).

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 RZ-300-40-6 were put into operation in September, 2005. Resistors RZ-300-40-6 consist of three parallel 900-Ohm resistive banks, each bank has 20 protective resistor elements. The resistor is rated for continuous maximum phase-to-ground voltage, thus it is not necessary to use relay protection and automatic equipment for its deenergization.

The combined method of neutral grounding allows efficient overvoltage limitation at single phase-to-ground faults and at arcing ground faults, and does not reduce speed of arc quenching. Active current induced by a resistor is enough for selective operation of current protection which can be adjusted for a signal or for tripping depending on required reliability and safety of power supply.

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 is shown in Table 1.

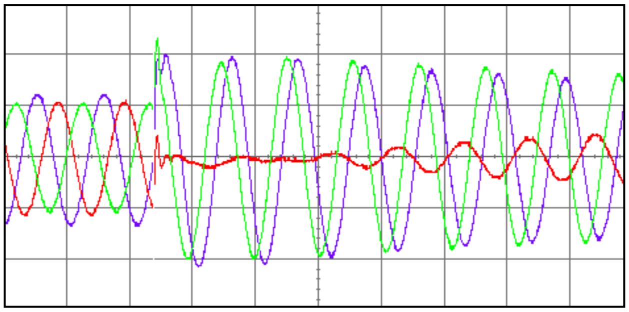
TABLE 1
STATISTICS ON GROUND FAULTS IN THE 6 KV NETWORK OF NKMK

	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

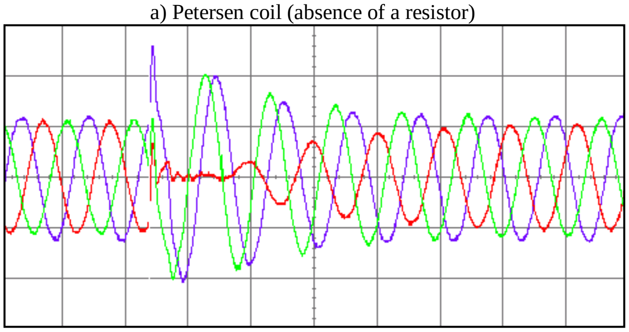
Based on recorded voltage oscillograms at single phase-to-ground faults, investigations on overvoltage levels and arc durations were carried out.

According to Table 1, 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 in the presence and in the absence of a resistor in a neutral are shown in Fig. 2.



a) Petersen coil (absence of a resistor)



b) Petersen coil + Resistor (in parallel)

Fig. 2. Oscillograms of transient processes at single phase-to-ground faults in the 6 kV network of NKMK

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.

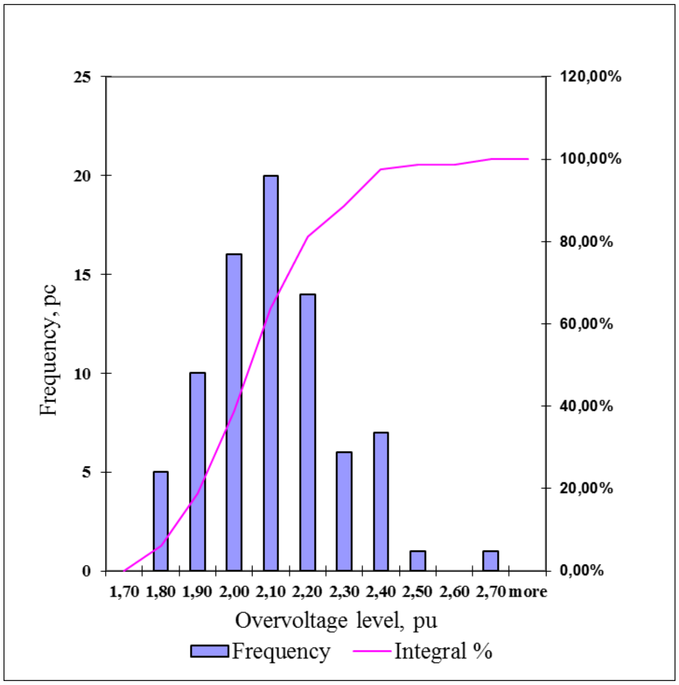
It should be noted that when a resistor was connected to a neutral of the network there were no any power failures for customers as shown in Table 1. A resistor connected to a neutral induces an active current at single phase-to-ground faults that is enough for selective operation of current protection 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

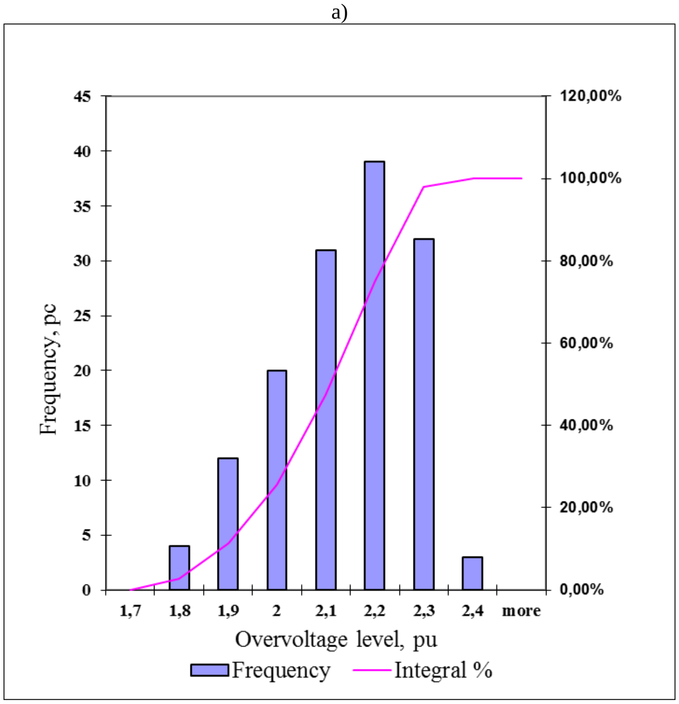
In resonant grounded networks at single phase-to-ground faults there is a possibility of dangerous overvoltages caused by intermittent arcing faults. Generally, cables of the main switchgear are exposed to overvoltages. As in majority of 6-35 kV networks, in the 6 kV network of NKMK tap-changed Petersen 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%).



a)



b)

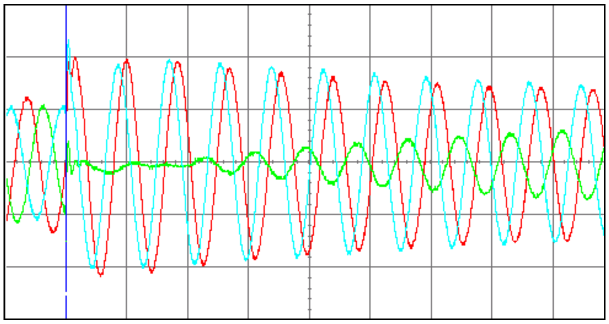
Fig. 3. Frequency distributions of overvoltage levels in the 6 kV network of NKMK (a – Petersen coil, b – Petersen coil + Resistor)

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.

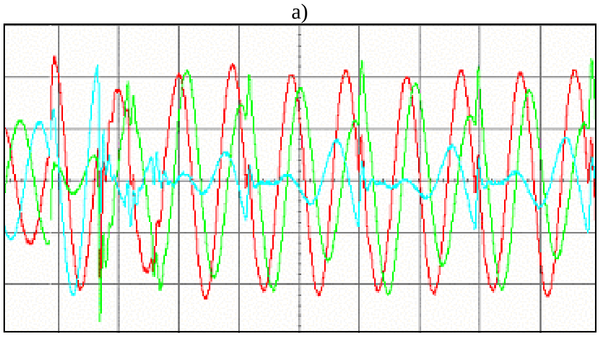
In accordance with recorded oscillograms, voltage recovery time of the faulty phase after arc extinction in the resonant grounded network (without a resistor) is 15-20 power-frequency periods (see Fig. 4a).

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], [3]. 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).



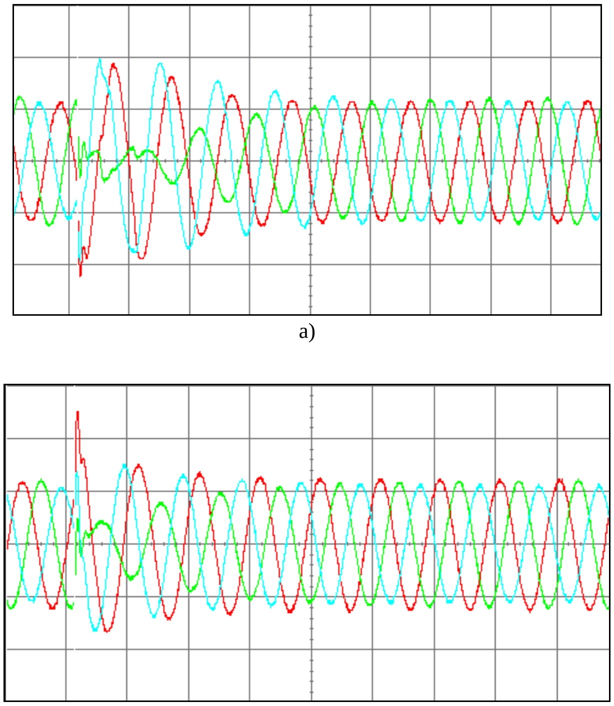
a)



b)

Fig. 4. Oscillograms of phase-to-ground voltages at single phase-to-ground arcing faults in the 6 kV resonant grounded network:
a) Feeder “CRP-3”, 25 September 2005, overvoltage ratio is 2.2 in pu;
b) Feeder “Prokatny-2”, 10 April 2005, 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:
a) Feeder “SPP-3”, 10 November 2005, overvoltage ratio is 1.93 in pu;
b) Feeder “CRP-1”, 13 December 2005, 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).

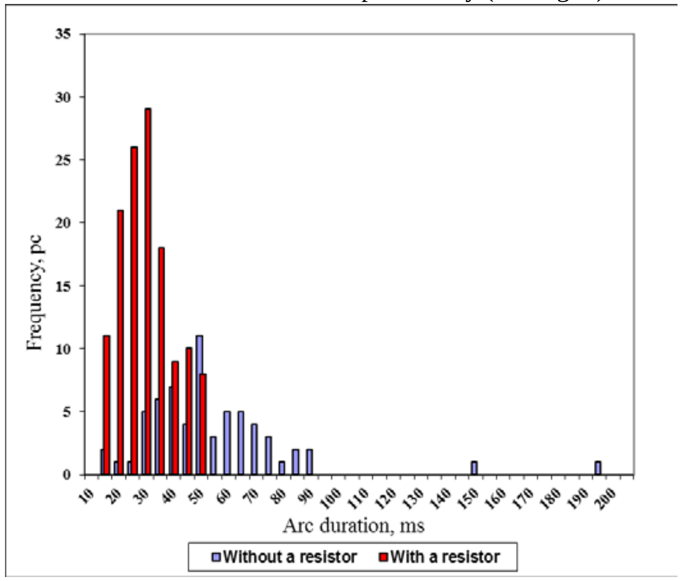


Fig. 6. Frequency distribution of arc durations

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 2 presents statistical characteristics of arc duration distribution at single arcing.

TABLE 2
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.

VI. 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.

VII. References

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VIII. Biographies

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Mikhail Ilinykh was born in 1960. He received Dipl.-Ing in electrical engineering from Novosibirsk State Technical University in 1982. He is currently working as Head of Research Department at LLC BOLID, Novosibirsk, Russian Federation, since 1998.