Investigation and Simulation of Ground Faults and Group Ferroresonance in 6 kV Industrial Cable Network with Involvement of Results of Transients Digital Recording

A. I. Shirkovets, A. Yu. Vasilyeva, A. A. Bazavluk, A. V. Telegin

***Abstract* -- Ground faults in the operating 6 kV cable network supplying a mining quarry are analyzed and classified. Specific features of the considered network are extremely alternating conditions of electric motors loading and a large number of electromagnetic voltage transformers (VTs). After continuous recording of transients, 246 oscillograms are processed (incl. 190 single-phase faults). An engineering assessment of group ferroresonance occurrence depending on the capacitive current value and the damping time of non-linear oscillations after grounding arc extinction is performed. An empiric dependence is determined according to the recorded transients, that allows evaluating the impedance in the place of a single-phase damage in a cable in the case of a stable single-phase fault with non-zero faulty phase voltage. A mathematical model of the 6 kV industrial network is developed using MAES software based on the real ground fault parameters. The model allows calculating transients taking into account special non-linear parameters of the elements in the circuit. The measures for ferroresonance prevention and mitigation based on the change of a VT design and optimization of a network design with additional damping are given. Results of the development and testing of new silicone liquid dielectric samples that can be used as power transformer and instrument transformer insulation are presented.**

***Keywords*: Phase-to-ground faults, group ferroresonance, cable network, transients recording, mathematical modeling, voltage transformers, fireproof liquid dielectrics**

I. Introduction

Single phase-to-ground faults (SPGF) of high-voltage insulation in networks of industrial plant are the main reason for generating nonlinear resonance oscillations. Under specific conditions, such oscillations may result in damages of electromagnetic voltage transformers (VT), voltage distortions and losses of relay protection signals for consumer feeders. Due to the presence of various VT types having different magnetizing curves at busbars of the primary substation and at busbars of secondary substations, there is a possibility of non-simultaneous saturation of VT magnetic cores under 25-30% higher voltage applied to VT primary windings. Although that condition is sometimes fulfilled when switching no-load busbars (having a capacitance of 0.08 – 0.10 μF) with ferroresonance at higher harmonics [1], the main reason for subharmonic ferroresonance occurrence with $n\cdot f$ frequency (n =1/2, 1/3,…) is magnetizing current inrushes caused by overvoltages at cycles of arc ignition and arc extinction. Importance of this problem is that industrial plants use 6-10 kV networks with an ungrounded neutral and electrical safety risks, especially in networks of mining and petrochemical plants having a large number of VTs used for power metering, protection and telemechanics.

Due to the variety of SPGF types in these networks, it is necessary to classify them according to the specific characteristic. One of such characteristics is duration of no-current conditions Δt which depends on the breakdown voltage (ionization rate of an arcing gap) and relation between the voltage recovery rate on the faulty phase and the rate of rise of electric strength across an arcing gap. These rates are functions of the ratio between active and reactive components of a SPGF current and the compensation detuning in the case of using Petersen coils.

Interrupted arcing and intermittent arcing are characterized by the duration of no-current conditions Δt = 10 – 40 ms and Δt = 160 – 200 ms respectively. Under real operating conditions of cable networks, a wide scatter of Δt is observed. It is caused by randomness of a breakdown moment and stochastic combinations of above mentioned parameters. Duration of arcing t_{ARC} for each breakdown can also be considered as a specific characteristic which differs for interrupted / intermittent arcing SPGF (t_{ARC} = 1 – 10 ms) and stable arcing SPGF (t_{ARC} > 20 ms). At the same time, stable ground faults in a cable network (which result, as a rule, in phase-to-phase insulation breakdown with emergency feeder interruptions) may differ by the voltage drop of a faulty phase $u_{FAULTY} \neq 0$ due to the presence of a ground fault impedance Z_{GF}. In turn, duration of non-linear oscillations of phase voltages after SPGF current interruption is an indirect characteristic of network stability to ferroresonance conditions. This duration may significantly vary depending on operating conditions.

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The main condition for the occurrence of ferroresonance processes (FRP) is the definite combination of phase-to-ground capacitances (or capacitive currents I_C), number and types of instrument VTs and active losses in the network. Ferroresonance oscillations may lead to relay pick up with $3U_0$-voltage signal (i.e. false operation of ground fault relay protection), including further possible actuation of relay protection devices for main power supply cables with disconnection of 6-10 kV busbars at primary substations.

The importance of the considered problems of analyzing real oscillograms from recording systems, developing verified simulation models and choosing measures for group ferroresonance elimination in industrial networks is proved by severe consequences of VT damages during operation and the need for reliable VT protection, without VT replacements for cast resin instrument VTs. To improve thermal stability and provide fire safety for voltage transformers, new noncombustible silicone dielectrics are proposed to be used.

II. Ground Fault Parameters and Network Stability to Ferroresonance

To obtain a real distribution of single phase-to-ground faults in an operating cable network, analysis of oscillograms from a recording system Parma installed at two primary substations with four 6 kV busbars having several secondary substations supplied electric drives of mining quarry consumers (e.g. machines, blasthole drills, excavators, and so on) is performed. The considered 6 kV network is designed with rubber cables and mass-impregnated paper-insulated cables with core sections of 70-120 mm^2. Each 6 kV busbar has from 6 to 12 voltage transformers of NTMI-6 or NTMK-6 type.

The simplified single-line diagram of the first considered primary substation is shown in Fig. 1. It involves two busbars with outgoing substations having a different number of voltage transformers. Busbar 1 has 12 VTs, Busbar 2 has 8 VTs. As for the second primary substation having the similar structure, it is different from the first one by the number of outgoing substations, that is the number of VTs (10 VTs – for Busbar 3, 9 VTs – for Busbar 4).

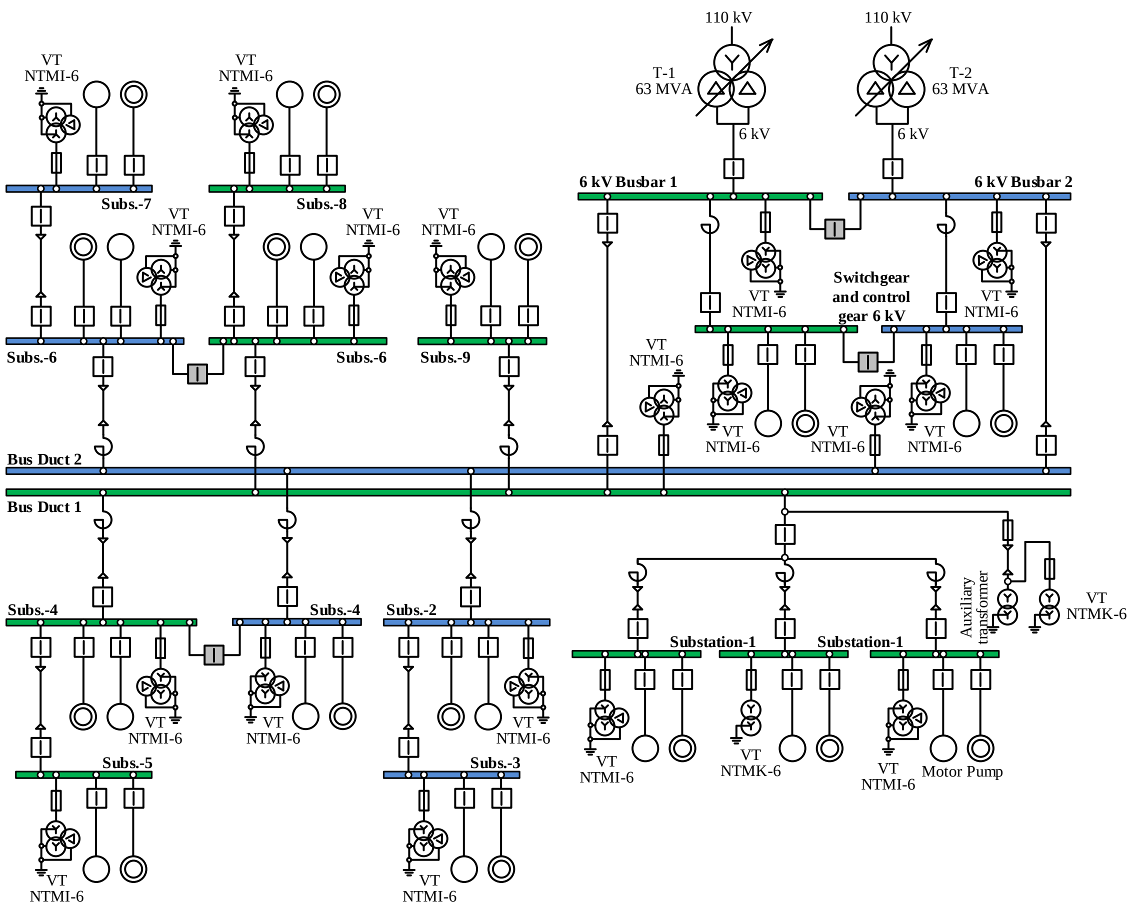
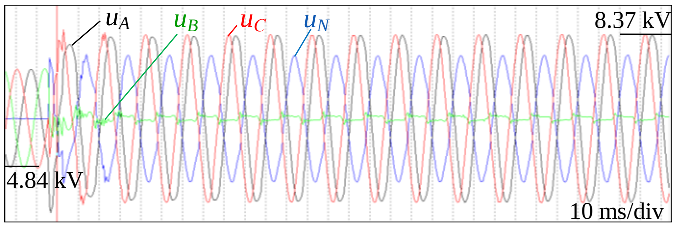


Fig. 1. Simplified single-line diagram of the first primary substation

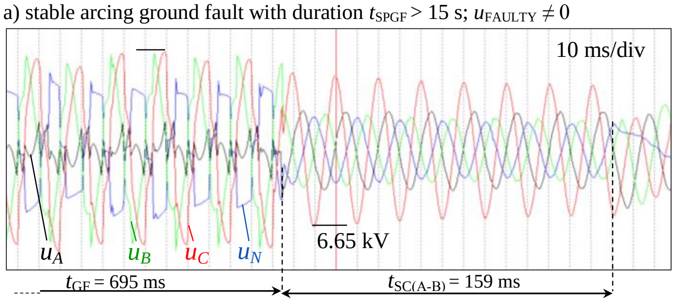
A wide variety of digital oscillograms of fault events were recorded by a recording system. Figure 2 shows only the most representative oscillograms.

Parameters of single phase-to-ground faults obtained during analysis of real oscillograms from a recording system for a half-year period are given in Table 1. A low sampling rate of recording systems Parma not exceeding 1 kHz per channel does not allow evaluating overvoltage levels correctly, because SPGF transient frequencies are usually in the range of 0.5 – 50 kHz.

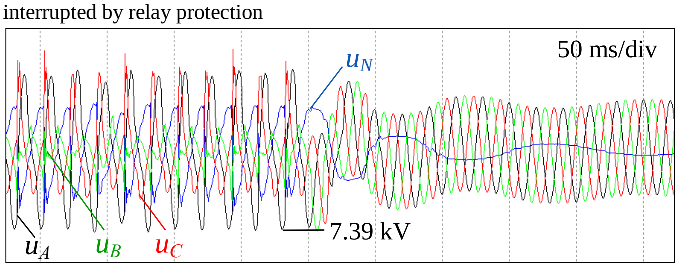
Analysis of a great variety of real oscillograms allows performing the following engineering assessment. FRP durations up to 80-100 ms in the case of self-damping phase-voltage oscillations after arc extinction with a capacitive current I_{Cmax} > 2.5…3.0 A per one VT with a grounded winding characterize a lower risk for ferroresonance occurrence in the network. These parameters are in good correspondence with investigations presented in [2] where the range of capacitances (at the upper limit of subharmonic ferroresonance conditions) for possible saturation of voltage transformers of NTMI-6 type are determined: C_{PHmax} = 0.47…0.83 μF (i.e. 1.55…2.74 A), that represents the family of weber-ampere characteristics and differ from the basic characteristic by ±30%.



a) stable arcing ground fault with duration t_{SPGF} > 15 s; $u_{FAULTY} \neq 0$



b) development of intermittent arcing ground fault into two-phase short circuit interrupted by relay protection



c) intermittent arcing ground fault, t_{SPGF} = 13.9 s, after interruption – decaying ferroresonance with duration of t_{FRP} = 340 ms

Fig. 2. Real oscillograms of phase voltages at arcing ground faults in the 6 kV cable network with ungrounded neutral, $I_{SPGF\ 50\ Hz}$ = 12 – 14 A

TABLE I
TIME PARAMETERS OF SINGLE PHASE-TO-GROUND FAULTS IN THE 6 KV NETWORK OF A MINING QUARRY WITH EVALUATION OF A RISK FOR FERRORESONANCE

Busbar 6 kV	Total SPGFs	Minimum SPGF duration, ms	Maximum SPGF duration, ms	FRP duration, s	FRP risk
1	32	66.0	658.0	0.37	medium
2	52	2.00	$91.5 \cdot 10^3$	0.22	medium
3	44	20.0	$1.047 \cdot 10^3$	1163	**high**
4	62	30.0	$610 \cdot 10^3$	0.45	medium

In the considered network, there is a capacitive current I_C = 1 – 2 A per each VT. In this case, frequent stable FRPs were observed at busbar 3. It is dangerous for electromagnetic VTs, because of overcurrents flowing in primary VT windings with current inrushes of I > 1 A which significantly exceed permissible currents with regard to thermal stability (0.1…0.3 A). Stable FRPs ($t_{FRP} \geq$ 1…2 s) cause burning and fusing of primary winding turns and may result in their mechanical destruction, particularly in cast resin transformers having poor heat-removal. As is noted during operation, cascade failures of voltage transformers in the case of group ferroresonance conditions occur not at the same time, with the time difference from several minutes to several months. It is explained by non-symmetrical magnetizing curves of different VTs in one-phase VT groups, routine switchings in the network, seasonal and weather changes of active insulation conductances and other reasons.

At busbars (1), (2) and (4), several unstable self-damping oscillations with t_{FRP} < 0.5 s were observed in 20…25% cases of arcing SPGFs. The risk for non-linear ferroresonance is evaluated as "medium". At six busbars of three other primary 6 kV substations, not considered at the present study, capacitive currents are in the range of 0.37…1.38 A. In that cases, there were both stable and decaying FRPs having 16 or 25 Hz frequencies in the most processes.

However, operating personnel of the power supply department did not face any troubles with failures and malfunctions of busbar VTs during the recording period that is explained by the following factors. Firstly, oil-insulated voltage transformers can withstand non-rated currents in primary windings for several minutes. It is due to low energy impact of inrush currents (particularly, at unstable arcing SPGF and decaying FRP) supported by good heat removal of oil insulation. Secondly, real operating regimes of industrial plant networks are connected with frequent switchings of electric motor loads and 6(10)/0.4 kV transformers. It means the change of VT saturation conditions due to the movement of an operating point along the hysteresis curve. With a high probability, it leads to breaking of non-linear oscillations during no-current conditions between arc ignitions and arc extinctions, that facilitates operation of oil-insulated VTs.

III. Classification of Ground Faults Based on Arcing Stability

Detailed analysis of 246 oscillograms for the four-busbar 6 kV network (busbars 1-4) for a half-year period showed that there were 190 single phase-to-ground faults ($n_{SPGF\Sigma}$ = 190), 17 of them (8.95%) developed into two-phase and three-phase short circuits with interruption of 6 kV feeders. Single phase-to-ground faults can be classified based on investigations of t_{ARC}, Δt, SPGF type (intermittent or stable), SPGF development (self-quenching of the arc, burning of phase-to-phase insulation), presence and stability of FRP. Classification of SPGFs with their parameters is presented in Table 2 for the considered network.

In the considered 6 kV networks, 49 (25.8%) of 190 (100%) SPGFs are characterized by relatively low fault impedances that can be shown from faulty phase voltage during a ground fault: $u_{FAULTY} \leq 0.1 u_{PHASE}$. Such ground fault may exist from 1.5…5.1 cycles to 24…34 cycles of 50 Hz. Maximum duration of these SPGFs (t_{SPGF} = 610 s) is observed in only one case and may be caused, probably, by arcing in the cable insulation.

In the case of u_{FAULTY} = (0.22 – 0.86)u_{PHASE}, 104 (54.7%)

of 190 (100%) SPGFs are classified as remote ground faults or faults through a high fault impedance. Non-zero faulty phase voltage are influenced by the following factors:

a) a ground fault current circuit from a fault place to busbars includes cable sheaths impedances (e.g. flexible power supply cables of walking excavators are often operated with damaged sheaths);

b) earthing conductor resistance is higher than permissible 10 Ohm due to, for example, insufficient conductivity of quarry soils;

c) arcing channel resistance at insulation breakdown during a ground fault is considered.

TABLE II
SPGF CLASSIFICATION BASED ON CONTINUOUS RECORDING OF PHASE VOLTAGES IN 6 KV NETWORKS OF A MINING QUARRY

Busbar 6 kV	Stable SPGFs, $u_{FAULTY} \leq 0,1u_{PH}$		Stable SPGFs, $u_{FAULTY} > 0,1\ u_{PH}$		Intermittent SPGFs		SPGF development into phase-to-phase short circuits	
	n_{SPGF}	t_{SPGF}, ms	n_{SPGF}	u_{FAULTY} / u_{PH}	n_{SPGF}	t_{SPGF}, ms	n_{SPGF}	t_{SPGF}, ms
1	9	103–480	17	0.33–0.86	2	147–219	4	66.0–658
2	6	48.0–685	39	0.38–0.80	2	$115–91.5 \cdot 10^3$	5	2.00–168
3	15	46.0–617	19	0.45–0.84	6	20.0–1047	4	140–340
4	19	$30.0–61 \cdot 10^3$	29	0.22–0.61	10	$39.0–15 \cdot 10^3$	4	200–3700

Known values of capacitive currents I_C = 12 – 14 A for each 6 kV busbar allow calculating a ground fault impedance during stable arcing as $Z_{GF} \approx U_{FAULTY}/I_C$. Assessment of Z_{GF} for the considered 6 kV network in the range of u_{FAULTY}/u_{PHASE} = 0…1 is given in Fig. 3.

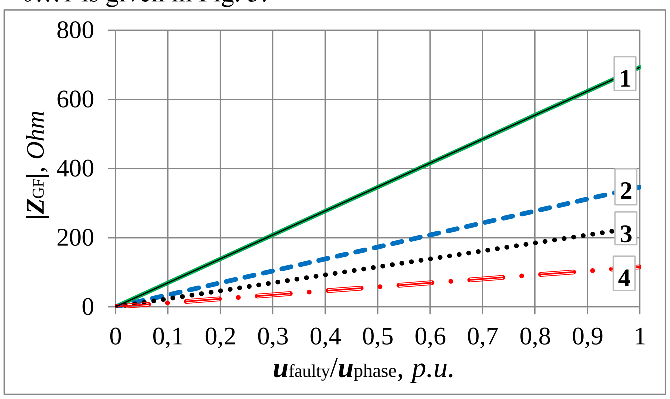


Fig. 3. Engineering assessment of a ground fault impedance at insulation breakdown during a stable arcing ground fault in the 6 kV network with different capacitive currents: 5 A (curve 1), 10 A (curve 2), 15 A (curve 3), 30 A (curve 4)

It can be shown that if active insulation conductances being equal to $(0.01…0.10)I_C$ are taken into account, it will lead to decreasing of Z_{GF} by not greater than 0.5%. The given dependence allows evaluating a ground fault impedance at stable SPGFs under different operating conditions of the 6 kV network characterized by non-zero faulty phase voltage.

IV. RESULTS OF MATHEMATICAL MODELING OF GROUP FERRORESONANCE

When simulating ferroresonance processes, it is very important to choose correct magnetizing curves of voltage transformers [3]. Unfortunately, weber-ampere (volt-ampere) characteristics are not included into VT technical data. It is preferred to use experimental results of VT magnetizing curve determination taking into account saturation process of a VT magnetic core. The present study involves the results of experimental measurements for a NTMI-6 voltage transformer [2, 4] using a conventional equivalent circuit with the following parameters: r_1 = 1.2 kOhm, L_μ = 1.8…2.5 H, L_{μ_satur} = 2.5…3.7 H, $\psi_{satur}/\psi_{rated}$ = 2, ψ_{max_rated} = 15.6 Wb, $i_{no\text{-}load\_rated}$ = 0.0065 A.

When modeling a weber-ampere VT characteristic, the following equation with empirically determined coefficients is used:

$$\psi = 0.0283*arctg(80000* i_\mu) + 7.726* i_\mu, \qquad (1)$$

where i_μ – magnetizing current.

A no-load VT is assumed for modeling. However, when a load of NTMI-6 (10) is more than 120 V·A, ferroresonance is successfully damped. Nevertheless, this assumption is adequate due to the following reasons: firstly, the number of VTs is large, and, secondly, the effect of damping of ferroresonance oscillations by secondary windings loading will be weak because of significant values of capacitances in the considered 6 kV network (I_C > 10 A at each busbars). The most common reason for generation of resonance processes in networks with voltage transformers is an arcing ground fault. This condition was used for ferroresonance modeling in the considered 6 kV industrial network. To simulate single-phase arcing, the model developed by W. Petersen was used in the paper. Active conductance of insulation was assumed to be 2…3% of capacitive conductance. Simulation was performed using the MAES software [5]. The value of power supply voltage has a significant impact on calculation results: increase or decrease of power supply voltage changes the range of FRP occurrence conditions by 10%.

Figures 4, 5 show representative calculated oscillograms of two cycles of a SPGF with ferroresonance oscillations occurring after the moment of arc extinction. Calculated amplitudes of VT primary currents are 10-15 times greater than permissible continuous currents.

Table 3 presents overvoltage levels (u_{PHmax}/u_{PH}) and VT primary currents (I_{VT}) depending on the network capacitance (in the form of a capacitive current I_C) with regard to the number of installed VTs at an arcing SPGF obtained from FRP modeling for the considered 6 kV cable network of a mining quarry. Stable FRP is marked with "+", while unstable FRP decaying for less than 100 ms is marked with "–".

TABLE III
RESULTS OF COMPUTER SIMULATION OF GROUP FERRORESONANCE IN THE INDUSTRIAL 6 KV CABLE NETWORK

I_C, A	Number of VTs, pc	u_{PHmax}/u_{PH}, pu	I_{VT}, A	FRP character
0.4	1	3.02	2.03	+
1.3	1	3.11	2.90	+
2.6	2	3.21	2.31	+

5.06	2	3.15	2.77	–
6.91	3	3.16	2.81	–
13.4	8	3.01	2.06	+
24.7	10	3.14	2.80	–

Calculations with the use of the developed model prove the results of oscillogram analysis: occurrence of group ferroresonance at arcing ground faults is possible with different capacitive currents (from percents to several amperes per one VT), depending on the parameters of weber-ampere VT characteristics (i.e. steel grade of a VT magnetic core) and active losses in the network.

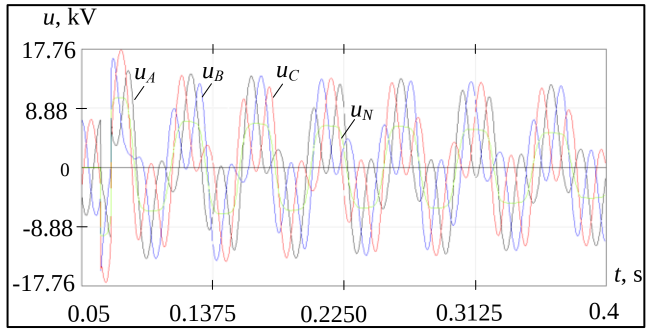
Development of ferroresonance, as a rule, is observed at subharmonic frequencies (16 or 25 Hz), at the industrial frequency or at higher harmonics (greater than 50 Hz). Required active power to break stable ferroresonance is reached even with the ratio between active and capacitive current of I_R/I_C = 0.1…0.2 or with a 25 Ohm resistor connected to an open-delta VT winding. Energy stored by a non-linear VT inductance for a given flux linkage is numerically equal to the square between the ordinate axis and a magnetizing curve. Thus, the lower a magnetizing curve in relation to the ordinate axis, the higher active losses are to be involved into a resonance circuit to break oscillations. Calculations show that the break of stable group ferroresonance in the considered 6 kV network is observed even with a 5...20 kOhm resistor connected to a neutral point: lower resistances eliminate non-linear oscillations, while higher values force FRP decaying for up to 100 ms after arc current interruption.

V. Mitigation and Prevention of Ferroresonance

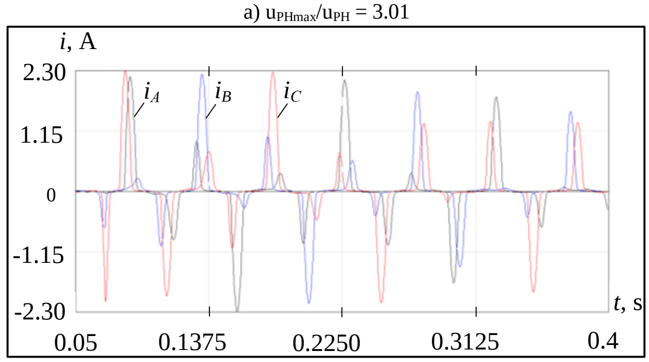
All types of ferroresonance in 6-10 kV networks, particularly those initiated by arcing SPGFs, are dangerous to develop fault events in the network. Surge overvoltages (u_{PHmax}/u_{PH} ≥ 2.5…3.0 pu) and temporary overvoltages (u_{PHmax}/u_{PH} ≥ 1.8….2.0 pu) may cause damages of voltage transformers and breakdowns in motor stator insulation and, less often, in cable insulation. It results in double-phase faults with feeder interruption that breaks ferroresonance conditions and protects voltage transformers in networks with an ungrounded neutral. In networks with neutral grounding through Petersen coils and resistors, VT damages are not observed, because there are no conditions for ferroresonance occurrence.

To protect electromagnetic voltage transformers against overcurrents and eliminate FRP occurrence conditions, it is possible to use the following network designs: grounding of VT primary windings through resistors, connection of resistors into a broken delta VT winding, connection of high-value resistors into phases between a power supply network and primary VT windings, using of anti-resonance electromagnetic VTs, using of capacitive VTs. However, these measures lead to degradation of metrological characteristics of voltage transformers and could not be versatile, because these measures influence on the consequences, not for the reasons.

Connection of a low-voltage resistor (5 – 25 Ohm, or, less frequent, 50 – 60 Ohm) into a broken delta VT winding results in the increase of magnetizing impedance during saturation. Thus, it is efficient in the cases of low capacitances to ground (i.e. with currents of $I_C \leq 0.013 - 0.08$ A) and does not have any effects with non-symmetric VT magnetizing curves (asymmetry of about 20%) [6]. Continuous operation of secondary low-voltage resistors of less than 25 Ohm are not usually used in practice. Taking into account that the range of change of a weber-ampere characteristic for an operable VT may reach 15 – 20% in relation to a standard magnetizing curve, it is concluded that using of secondary resistors is not suitable for VT protection against group ferroresonance in industrial networks with various VTs and high capacitive currents.

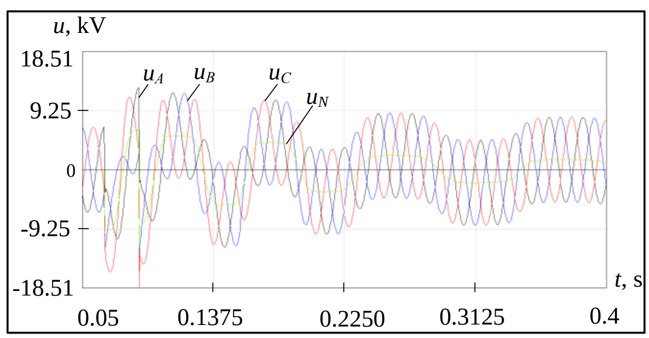


a) u_{PHmax}/u_{PH} = 3.01

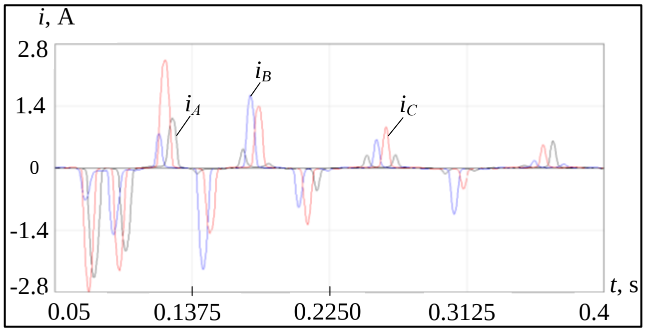


b) I_{max}=2.3 A

Fig. 4. Calculated oscillograms of phase voltages (a) and VT primary currents (b) during stable group ferroresonance in the 6 kV industrial network with ungrounded neutral (I_C = 13.4 A, 8 VTs)



a) u_{PHmax}/u_{PH} = 3.14



b) I_{max}=2.8 A

Fig. 5. Calculated oscillograms of phase voltages (a) and VT primary currents (b) during unstable group ferroresonance in the 6 kV industrial network with ungrounded neutral (I_C = 24.7 A, 10 VTs)

Ferroresonance can be eliminated by applying anti-resonance VTs which are not saturated at SPGFs [7]. It is provided by the following methods: partial using of structural steel having higher hysteresis losses in a magnetic core, using of a three-leg magnetic core with a short-circuited additional compensation winding, connection of an additional one-phase transformer with 300 – 600 kOhm reactances or a 800-1000 Ohm resistor between a neutral point and ground.

Efficiency of implementation for such VTs decreases if the considered network has measuring voltage transformers of different types, including saturable VTs. Unfortunately, damages of anti-resonance VTs at continuous arcing ground faults are not fully eliminated. Some of anti-resonance VTs may cause false ground fault detection [6]. To prevent ferroresonance and eliminate damages of electromagnetic VTs, neutral grounding (incl. neutral grounding through resistors) is used as a universal technical solution.

Calculations with the use of the 6 kV network model under conditions of I_C = 12 – 14 A with 8-10 VTs show that resistance being not greater than 5 kOhm is sufficient to break ferroresonance and eliminate non-linear oscillations. It was found that full elimination of non-linear oscillations may be obtained even with I_R/I_C = 0.2, while stable ferroresonance becomes decaying at $I_R/I_C \approx 0.1$. However, the main condition for choosing resistors is not ferroresonance elimination, but overvoltage suppression to the level of $u_{PHmax}/u_{PH} \leq 2.5$ pu. In the case of continuous operation at ground faults, resistors having active currents of $I_R = (0.6\ldots1.2)\ I_C$ are used [8]. When a ground fault should be disconnected by relay protection, resistors with active currents of $I_R \geq (3,5\ldots4,0) I_C$ are applied [8].

VI. Ensuring of Fire Safety for Voltage Transformers

Operational reliability of power and measuring transformers can be enhanced by the use of new synthetic liquid dielectrics of low flammability instead of mineral oil. The following liquid dielectrics can be used for this purpose: high molecular weight hydrocarbons (R-Temp®), silicone fluids (mainly, polydimethylsiloxanes as, for example, Powersil®Fluid TR 50), synthetic esters (Envirotemp® 200™, Midel 7131), natural esters derived from renewable vegetable oils (Envirotemp® FR3™). Such dielectric fluids are often used in power equipment manufacturing in Great Britain, USA, Canada, Japan. However, their universal implementation is limited by high prices and some restrictions on thermal operating conditions and environmental safety. At the same time, petroleum oils as transformer fluids are manufacturable and possess sufficient electric strength of 16…24 kV/mm and oxidation stability. On the other hand, these fluids have a relatively low flash point (145 °C) and high viscosity at low temperatures: solidification is observed even at -40…-45 °C.

Authors of the paper in cooperation with Boreskov Institute of Catalysis of the Siberian Branch of the Russian Academy of Sciences (Novosibirsk, Russia), Bolid LLC (Novosibirsk, Russia) and the specialized laboratory of Lomonosov Moscow State University of Fine Chemical Technologies (Moscow, Russia) developed and tested 96 samples of fireproof silicone dielectric fluid (SDF) which is intended to be used as an alternative solution to transformer oils for operation under low temperatures. All the test samples were in the form of colorless fluid with the main content according to a chromatogram: [*n-siloxane, m-decamethyl*], [*n-siloxane, m-siloxane or cyclo-k-siloxane*], and some other polymers with mass fractions of components in the range from 30 to 100% (with $n, m, k \leq 10$).

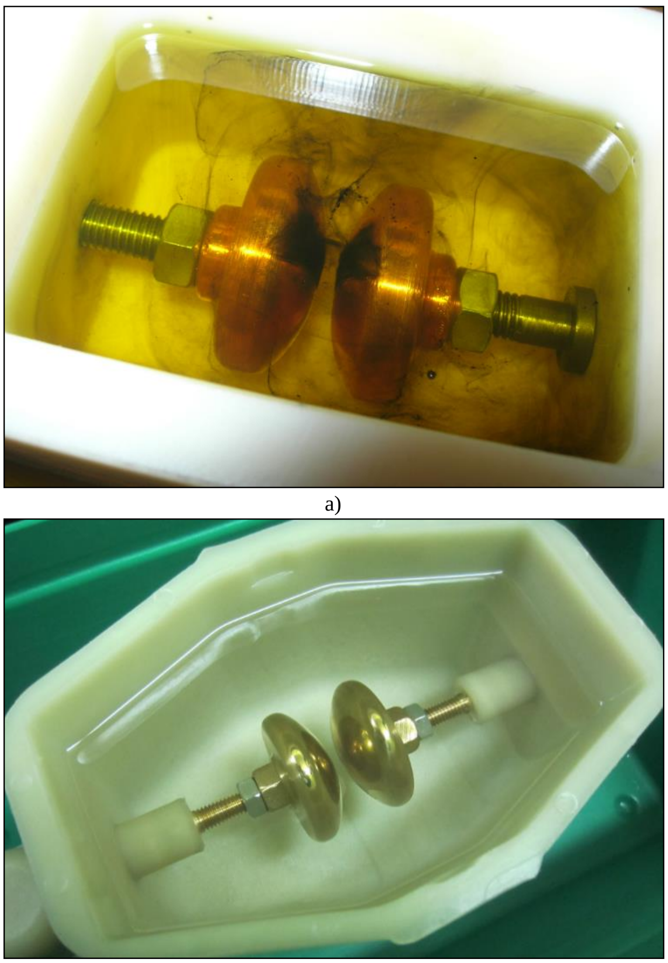
SDF samples were tested for toxicological safety and showed excellent results. SDF samples were certified for the IV class of hazard according the Russian standard GOST 12.1.007-76 [9]. Tests for influence on insulating materials (incl. polyamide, glass tape, resin, herringbone tape LE-30-46, insulating boards B-1, 4, 5, 6; insulating paper EKM-100, K-080, K-120; synthetic resin bonded paper laminate, plexiglas, and others) that are used in Russian 10 kV transformer showed that the developed SDF samples are chemically inert. Using coulometric titration by the Karl Fischer method, water content in SDF samples was determined (0.019…0.153 mg/g). Volume resistivity of SDF samples equals to approx. 1×10^9 Ohm·m, dissipation factor at 50 Hz and 70…90 °C amounts to $tg\delta$ = 0.02/0.07% (for new transformer oil according to IEC recommendations – $tg\delta \leq 0.5\%$ at 90 °C).

Fig. 6 presents photographs of a mineral oil sample and a SDF sample showing their condition after breakdown tests in a common spark gap. A spark gap consists of two brass electrodes placed in a porcelain 500 cm^3 vessel and separated by the 2.5mm-gap. Electrodes are disk-shaped of the 36mm-diameter with round edges. 50-Hz voltage was applied from the oil breakdown voltage test device AIM-90 with the sample temperature of 20±5 °C under the atmospheric pressure of 750 – 770 mm Hg. Values of breakdown voltage for the best SDF samples reached 59.0 – 67.3 kV at the first breakdown and 70.1 – 73.4 – at the second breakdown on the next day without sample replacement. Breakdown of new untreated mineral oil involved carbonaceous decomposition products. As for SDF samples, there were no any by-products at the first and the second breakdowns.

Flash points of the best SDF samples reached 170 °C. It is fair to note that the flash point for Envirotemp® FR3™ equals to 330 °C (but its solidification temperature is mere -25 °C).

Breakdown voltages for the developed SDF samples determined in the common spark gap described above proved to be comparable or even higher than for existing liquid dielectrics. Therefore, the developed silicone dielectric fluid can be a good alternative to existing dielectrics. For example, laboratory tests for samples of Midel 7131, Sofexil–TSJ and transformer oil T-1500 (without sample preparations, under the same initial conditions) showed breakdown voltages of 40.0, 40.7, 41.35 kV respectively.

Fig. 7 presents comparative results of kinematic viscosity measurements (1 cSt = 1 mm^2/s) for a mineral oil sample and a SDF sample. It indicates significant advantage of the developed SDF in the area of low temperatures. for example, measured kinematic viscosity at -20 °C for a SDF sample is 25 times lower than for a mineral oil sample (13.6 cSt vs 335 cSt), at -40 °C – 120 times lower (30.9 cSt vs 3750 cSt). It is of great importance for transformer equipment operation in North regions with low winter temperatures.


a)

b)

Fig. 6. Overview of liquid dielectrics after testing of a transformer oil sample (a) and a SDF sample (b) for breakdown voltage

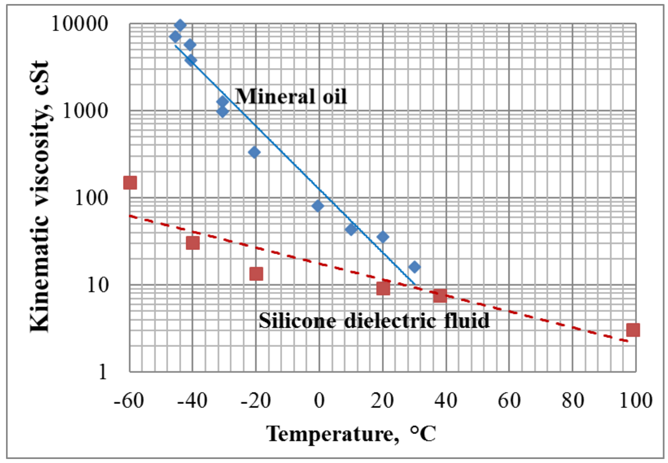


Fig. 7. Measured values of kinematic viscosity for mineral oil and silicone dielectric fluid

After performing all the test procedures for SDF, it can be a good alternative to existing liquid dielectrics [10]. According to requirements of National power grid company Rosseti PJSC, industrial implementation of silicone dielectric fluids requires positive results of investigations on SDF physicochemical properties during trial operation in a power transformer in two years. At present, developed SDFs are being improved in the field of temperature dependence of electric strength, increasing of a flash point, providing of chemical stability and biodegradability.

VII. Conclusions

1) Based on processing of real oscillograms, SPGF classification and SPGF parameters are presented for the operating 6 kV cable network of a mining quarry with 12...14 A currents and with 6...12 voltage transformers. 190 SPGFs were recorded in a half-year period: 10.5% of them were intermittent arcing SPGFs, 80.5% of them were stable SPGFs, while 8.95% developed into two-phase and three-phase short circuits with 6 kV feeder interruptions. Stable and decaying ferroresonance processes with durations from 0.22 s to 19 minutes were observed.
2) The possibility for occurrence and the character of a group FRP (i.e. stable or unstable) in the industrial 6 kV cable network are determined by combination of magnetizing curve parameters of various VTs, network capacitances to ground and active losses in the zero-sequence circuit. A capacitive current of more than 2.5...3.0 A per one electromagnetic VT characterizes that a network does not have any risks for occurrence of a stable FRP (regardless of a network design and the number of VTs).
3) A universal technique to suppress subharmonic ferroresonance in 6-10 kV industrial networks is the change of neutral grounding. Full elimination of non-linear oscillations may be obtained even with I_R/I_C = 0.2, while stable ferroresonance becomes decaying at $I_R/I_C \approx$ 0.1. To limit overvoltages at arcing ground faults, being the main reason for FRP generation, the value of a resistor should be at least 3...6 times lower (i.e. I_R/I_C = 0.3…1.2).

If having an emergency power supply, an optimal way of operation is quick automatic interruption of all the SPGFs.

4) Oil-insulated VTs, including VTs with anti-resonance construction, in comparison with cast resin VTs, provide better conditions of heat removal at overcurrent flowing in primary windings. It reduces the probability for fusing winding turns and for damages under continuous intermittent arcing and ferroresonance conditions.
5) To ensure fire safety of power and measuring transformers, it is possible to use noncombustible liquid dielectrics as insulating transformer fluids. These liquid dielectrics possess low kinematic viscosity (31…3.1 cSt in the range of -40…+100 °C), good electric strength (24…28 kV/mm) with possible increase at repeated breakdowns, low $tg\delta$ (0.07% at 90 °C). It is supported by the results of developments and field tests of silicone dielectric fluids.

VIII. References

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