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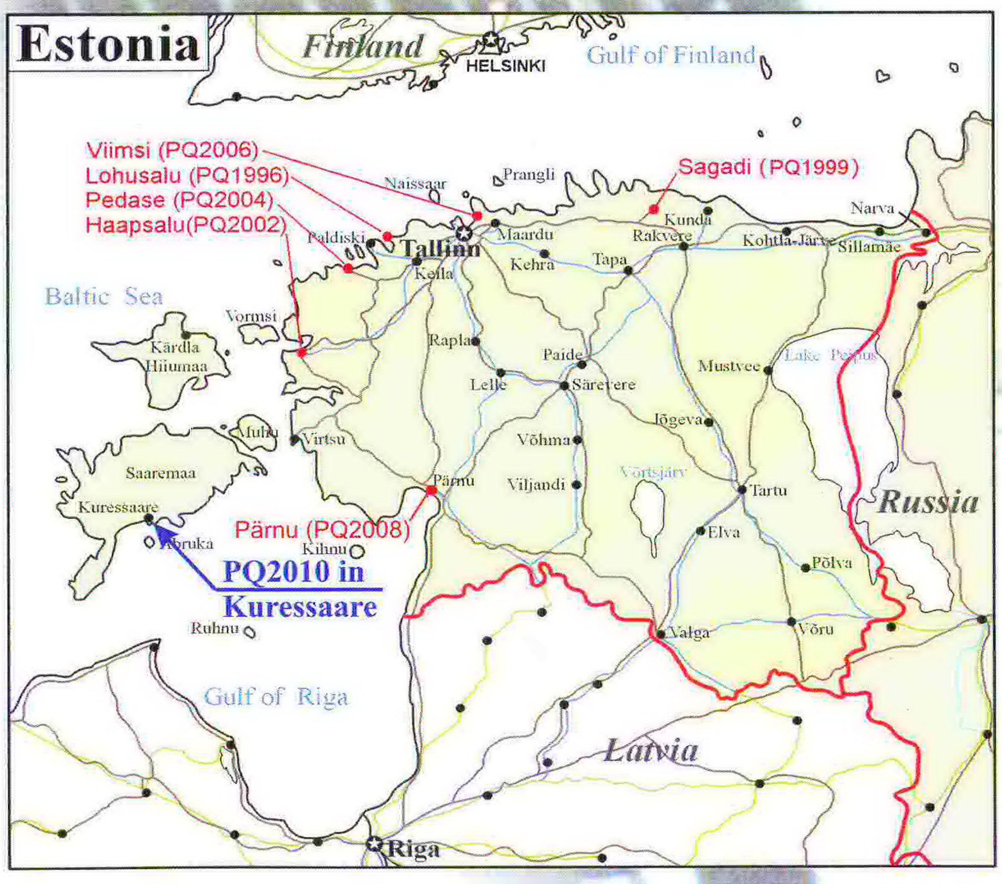
TALLINN UNIVERSITY OF TECHNOLOGY

Department of Fundamentals of Electrical Engineering and Electrical Machines

The 7th International Conference

2010 ELECTRIC POWER QUALITY AND SUPPLY RELIABILITY



CONFERENCE PROCEEDINGS

June 16...18, 2010
Kuressaare, ESTONIA

IEEE

Tallinn
2010

IEEE PES
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Part F – Supply Reliability in Distribution Networks – Earth Faults

Part G – Supply Reliability – Detection and Locating Faults

Experimental Investigations and Calculations in 6-35 kV Networks with Various Neutral Conditions

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ABSTRACT: Resonant grounded or ungrounded neutral system produces specific overvoltages, e.g. overvoltages at single line-to-ground arcing faults. Theoretical research and field experience show that reducing overvoltage levels at arcing ground faults and decreasing the number of ground faults without increasing of ground-fault currents can be reached by connecting the neutral of the transformer to ground through a high-value resistor. Determination of real capacitance current value in 6-35 kV network is urgent and needs accurate solution.

1. Introduction

6-35 kV distribution networks are the most extensive networks among high-voltage networks. In comparison with 110-1150 networks, they have various different circuit designs and used equipment. It is connected with their different areas of application, e.g. town mains, auxiliary networks of power plants, industrial plants, agricultural and mining industry. It is also influenced by the technological process of different consumers. Electric power supply continuity depends on reliability of 6-35 kV networks. Faults in 6-35 kV networks with continuous production process cause substantial (material) damages in the form of large-scale wastes (defective goods) and damages of production equipment. The main reason of most faults in 6-35 kV networks is internal overvoltages which occur during such electromagnetic transients as arc, ferroresonant and commutation transients [1].

In many cases, a high level of faults in 6-35 kV networks is caused by open-phase operating conditions including single line-to-ground faults which occur in 90% of all faults [1], [2]. Then, high-amplitude overvoltages, spreading over the interconnected grid, appear which are dangerous to equipment insulation because of their long duration. The level of overvoltages at arcing ground faults is largely defined by neutral conditions. Traditional use of circuits with insulated or resonant grounded (with a ground fault neutralizer) neutral in 6-35 kV networks in Russia in many cases seems to be not a very good strategy.

Neutral grounding with ground-fault neutralizers recommended by PUE regulations leads to compensation of capacitive currents at fault locations, providing conditions for self-quenching of arc and, in some cases, overvoltage limitation. However, there remains a danger of high overvoltage ratios at arcing ground faults in conjunction with open-phase conditions at nonsimultaneous operation or failed switch phases, or with improperly adjusted ground-fault neutralizers. In some cases, the used automatic tuning of ground fault neutralizer, because of inertial operation or permissible variation of controlled inductive current, can't eliminate high overvoltage ratios induced at arcing ground faults [3], [4]. At present, on the basis of solutions offered by surge protection manufacturers, sufficiently reliable protection against internal and lightning overvoltages can be developed for the purpose of reducing fault probability for critical equipment, that is illustrated in Fig. 1 by the typical power supply circuit of 110/35/10/6 kV electrical substation.

2. Oscillographic Methods for Single Phase-to-Ground Faults in 6-35 kV Networks

When the network is used for many years, it is rather difficult to calculate capacitance current at single phase-to-ground faults, especially when modernizing equipment and using new power cables with cross-linked polyethylene insulation (XLPE cables). Therefore, it is difficult to take into account a network configuration during calculations.

Test measurements of capacitance current at single phase-to-ground faults allow determining its precise value and giving recommendations of existing ground fault neutralizer adjustments and their new installations. In addition, measured values of capacitance current at single phase-to-ground faults can be used for overvoltage evaluation at single phase-to-ground arcing faults and development of their limitation methods. By now, some techniques of test measurements of capacitance current at single phase-to-ground faults have been studied and successfully used.

Proposed comprehensive approach to "direct" capacitance current measurements ("direct" means making an artificial single line-to-ground fault) includes the following:

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- Phase-to-ground voltages and currents at single phase-to-ground faults are measured by oscillograph, then data can be mathematically processed using external software;
- Capacitance current at fundamental frequency and its harmonic components are measured for the known network configuration;
- Behavior of phase-to-ground voltages under normal operating conditions and in transient processes of ground faults and their clearance is analyzed, so it allows evaluating of network response to single phase-to-ground faults.

Modern development of computer science and measurement technology allows development of a process data recording system at single phase-to-ground faults including phase-to-ground voltage and single phase-to-ground current signal recording with various amplification coefficients using analog-to-digital converters (ADC) and computers. This system consists of the following equipment:

- voltage and current sensors;
- communication cables (data cables);
- A-to-D cards and digital storage oscilloscopes (DSO);
- personal computer with dedicated software which allows data processing and analyzing.

Proposed circuit for measuring capacitance current at single phase-to-ground faults by artificial solid ground and phase-to-ground voltage registration is shown in Fig. 1 where connected equipment is marked with blue.

Experiments carried out in various 6-35 kV networks show that capacitance current at single phase-to-ground

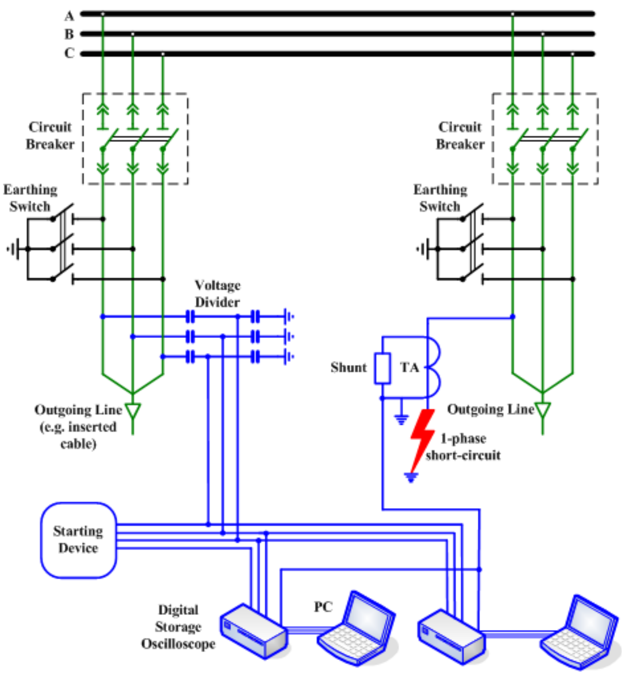

Fig. 1. Connection diagram of measuring equipment at capacitance current measurement and registration of transient process at single phase-to-ground fault

fault always carries a number of harmonic components (recorded by the oscillograph) in a wide frequency range, usually 25 Hz – 3,5 kHz. Odd harmonics from the 3rd to the 11th make a major contribution to the resultant signal. Moreover, percentage of each harmonic can be more than 50% of a ground-fault current. In many cases, odd harmonics are observed (e.g. 3, 5, 7, 11, ..., 35, 37) which values vary from 0.2% to 60%.

Figure 2 illustrates oscillograms of single phase-to-ground current at solid ground in 6 kV main switchgear resonant grounded network.

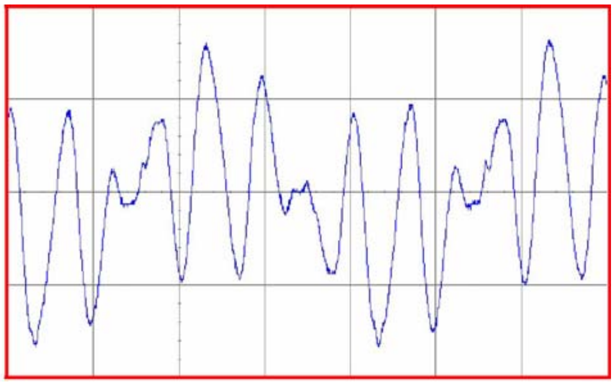

Fig. 2. The oscillogram of artificial solid ground current in 6 kV main switchgear (5 ms/div, 19.7 A/div)

It is analyzed that single phase-to-ground current of the first and the second sections of the main switchgear carries the 5th, 7th and 11th harmonics equal to 7.7 A, 12.2 A and 3.2 A, respectively. Therefore, the 7th harmonic exceeds 2.2 times the 1st harmonic and is not compensated by the ground fault neutralizer.

Ground fault neutralizer (GFN) adjustment is very common in power networks because GFN resonance adjustment cannot be kept by network operation, especially at frequent changes in load conditions.

Therefore, developed oscillographic methods for single phase-to-ground faults in 6-35 kV networks when recording phase-to-ground voltages and single phase-to-ground current by multichannel digital device allow determining overvoltage limits at ground faults and voltage harmonic composition under normal operating conditions and at single phase-to-ground faults. The nature of recorded processes and further analysis show the detuning ratio of the GFN in the resonant grounded network that helps to choose neutral conditions of the network.

2. Transient process investigations at arcing ground faults in 6-35 kV networks

The main purpose of the present study is to investigate transient processes at arcing ground faults in 6-35 kV networks and analyze neutral conditions effect to overvoltage levels.

The single line diagram of 110/35/10/6 kV electrical substation is shown in Fig. 3. 10 kV network is resonant grounded, 6 kV and 35 kV networks are ungrounded.

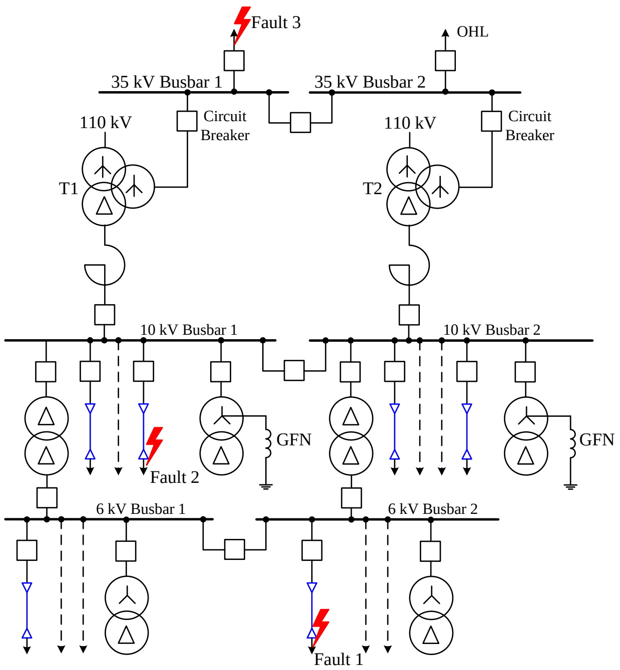

Fig. 3. Single line diagram of 110/35/10/6 kV electrical substation

Single line-to-ground arcing fault is considered to be the rated duty which occurs by turns in each voltage class network at the fault of one of their connections. The analysis of electromagnetic transients at arcing ground faults in 6-35 kV networks is carried out with the VMAES application suite intended for electromagnetic transient process calculation in power networks. The calculation model is composed of VMAES library elements.

Representative oscillograms of overvoltages in 6, 10 and 35 kV networks are shown in Figs. 4-6.

Oscillograms given below illustrate phase-to-ground and neutral-to-ground voltages at an arcing ground fault in Phase A (Phase A – black, Phase B – blue, Phase C – red, neutral-to-ground voltage – green; voltages are in kV, time is in seconds). The peak voltages are presented in the top-left corner of the diagram for the time interval given in the bottom of the diagram.

Therefore, calculations of transient processes at arcing ground faults in 6-35 kV networks demonstrate fault probability for equipment insulation at arcing ground faults with high overvoltage ratios 3.2-3.36 U. In 35 kV network with low ground-fault currents electro-magnetic transient processes are oscillating processes with developing steady ferroresonance. Inrush currents of 0.8-1.3 A are observed in the primary winding of a voltage transformer in 35 kV network. These currents exceed permissible current values in thermal stability of windings for a voltage transformer in the interval of 0.2…0.3 A [5].

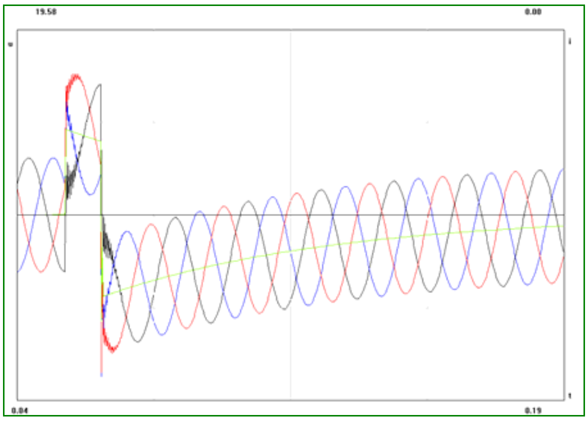

Fig. 4. Oscillogram of phase-to-ground and neutral-to-ground voltages at an arcing ground fault in 6 kV network with ungrounded neutral (I_{fault}=10.75 A)

overvoltage ratio is 3.32 in pu

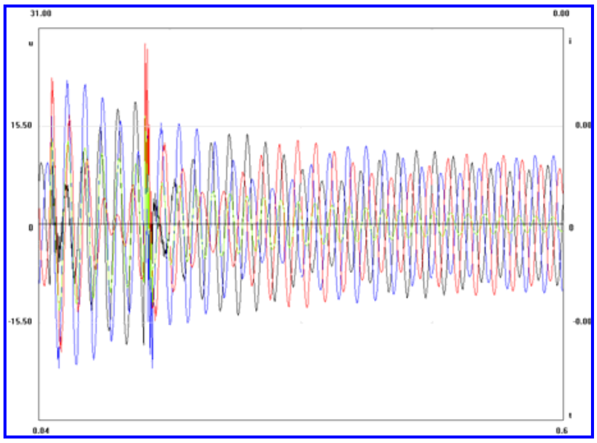

Fig. 5. Oscillogram of phase-to-ground and neutral-to-ground voltages at an arcing ground fault in 10 kV network with resonant grounded neutral through ground fault neutralizer (I_{fault} = 61.3 A, I_{GFN} = 77 A, overcompensation is 25%)

overvoltage ratio is 3.20 in pu

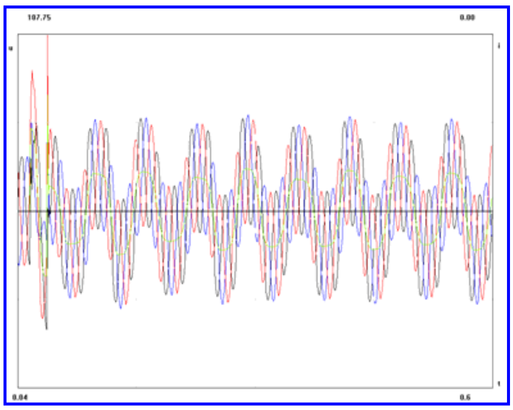

Fig. 6. Oscillogram of phase-to-ground and neutral-to-ground voltages at an arcing ground fault (Fault 3) in 35 kV network with ungrounded neutral (I_{fault} = 2.39 A)

overvoltage ratio is 3.26 in pu

3. Overvoltage limitation by connecting the neutral of the transformer to ground through a resistor in 6-35 kV networks

Theoretical research and field experience show that reducing overvoltage levels at arcing ground faults and decreasing the number of ground faults without increasing of ground-fault currents can be reached by connecting the neutral of the transformer to ground through a high-value resistor, as shown in Fig. 7.

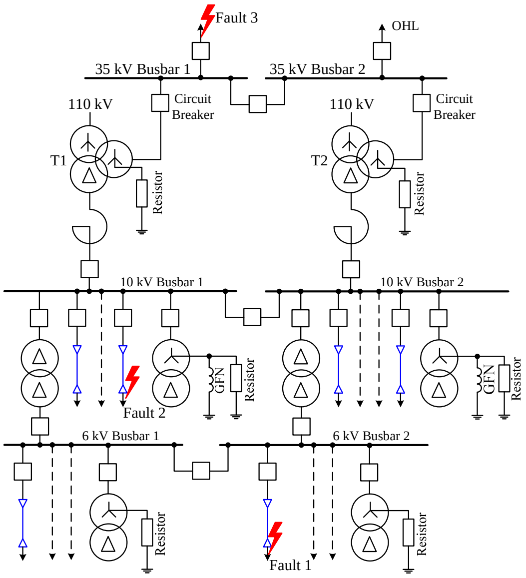

Fig. 7. Single line diagram of 110/35/10/6 kV electrical substation. The neutral of 6-35 kV network is connected to earth through a high-value resistor (in 10 kV network – resistor is connected in parallel with a ground fault neutralizer)

Overvoltage limitation at arcing ground faults in resistance-grounded system is reached by reducing of electric discharge time constant of sound (unfaulted) phase capacity during no-current condition and decreasing of neutral-to-ground voltage to the value when there is no voltage escalation at subsequent breakdowns on reduced insulation of the faulted phase, as shown in Figs. 8-10.

Therefore, calculations of transient processes at arcing ground faults in 6-35 kV networks demonstrate that high-value RZ resistor can efficiently limit overvoltages at arcing ground faults to the value of 2.4-2.5 U, eliminate ferroresonance phenomena and reduce inrush currents in primary windings of voltage transformers to values permissible by thermal stability of windings for voltage transformers. Connecting the neutral to ground through a ground fault neutralizer in parallel with a resistor results in reducing of free oscillations, suppression of beatings and voltage reduction on the faulted phase. In this case, the resistor support process transfer from oscillating to aperiodic. Overvoltage limitation at arcing ground faults lead to reducing of the number of insulation flashovers and the total number of faults. Almost full reduction of transferring of arcing ground fault to double-phase faults is observed.

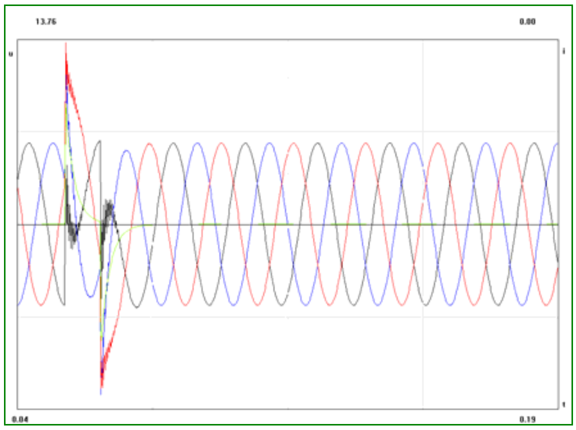

Fig. 8. Oscillogram of phase-to-ground and neutral-to-ground voltages at an arcing ground fault in 6 kV network with a neutral connected to ground through the 400-Ohm resistor

overvoltage ratio is 2.33 in pu

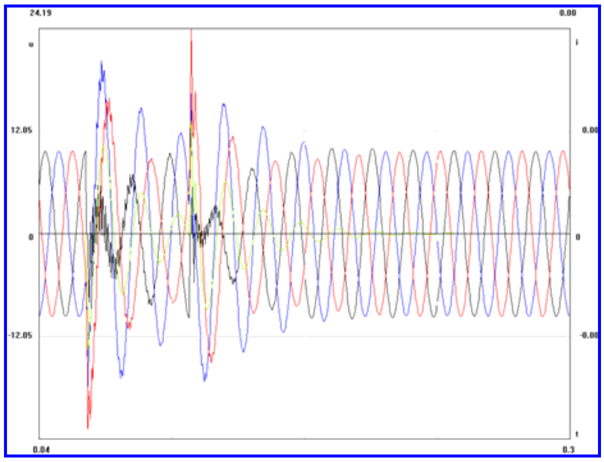

Fig. 9. Oscillogram of phase-to-ground and neutral-to-ground voltages at an arcing ground fault in 10 kV network with a neutral connected to ground through a ground fault neutralizer in parallel with a resistor

overvoltage ratio is 2.49 in pu

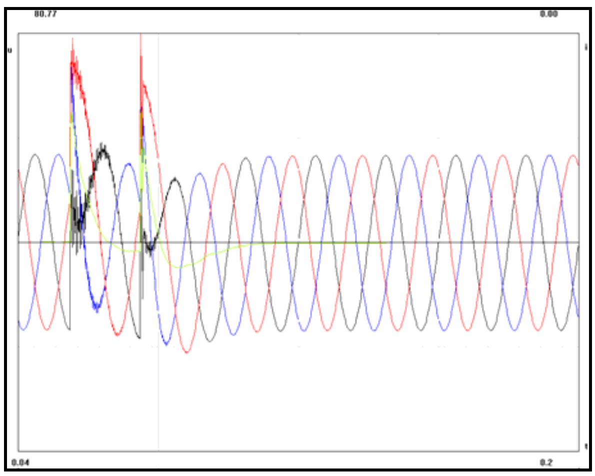

Fig. 10. Oscillogram of phase-to-ground and neutral-to-ground voltages at an arcing ground fault in 35 kV network with a neutral connected to ground through the 8000-Ohm resistor

overvoltage ratio is 2.44 in pu

Active current induced by the resistor is enough for current protection selectivity which can be adjusted for a signal or for tripping depending on required reliability and safety of power supply.

The resistor is rated for peak voltage for at least 6 hours, thus it is not necessary to use relay protection and automatic equipment for its deenergization.

4. Summary

Developed oscillographic methods for single phase-to-ground faults in 6-35 kV networks allow determining overvoltage limits at ground faults and voltage harmonic composition under normal operating conditions and at single phase-to-ground faults. The nature of recorded processes and further analysis of oscillograms show the detuning ratio of the ground fault neutralizer in the resonant grounded network that helps to choose neutral conditions of the network.

The neutral of the transformer can be connected to ground through a resistor or through a ground fault neutralizer in parallel with a resistor. These methods are the solution of the following problems:

1. *Significant overvoltage limitation at arcing ground faults and elimination of multiplace faults;*
2. *Bringing the neutral offset voltage to the permissible level under normal operating conditions in resonant grounded systems;*
3. *Elimination of resonance and ferroresonance processes and related damages of voltage transformers and other equipment;*
4. *Application of high-sensitivity selective relay protections against line-to-ground faults based on the current or phase principle.*

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