Comprehensive Investigations of Transient Processes in Medium Voltage Distribution Networks with Long-Distance Power Transmission

Alexey A. Kuzmin, Ivan Ye. Naumkin, Leonid I. Sarin, Ayuurzana Erdenebileg, Altanduulga Bazarragcha

***Abstract*--The paper deals with the features of operation of medium voltage distribution networks with long-distance power transmission lines. In some cases, the length of transmission lines may exceed hundreds of kilometers. Power supply reliability of these lines determines power supply security of the region.**

The paper presents the results of field experiments of solid and arcing single phase-to-ground faults in an operating 35 kV network. Based on the results, a model for transient process simulation was developed using EMTP.

The paper gives information on the features of transient processes at single phase-to-ground faults in the long-distance transmission line with various neutral grounding conditions.

High overvoltage levels observed under normal operating conditions, compensation detuning occurring with ground fault point variation and other factors cause some features that should be considered when developing technical solutions of the network configuration.

Therefore, the paper presents the results of transient process investigations in the case of solid and arcing ground faults: the dependence of initiation of dangerous overvoltage levels along the transmission line was experimentally defined, studied and described; reliability of the neutral grounding system used in the network was evaluated. The protection area was experimentally identified for the neutral grounding system, including Petersen coils and resistors. The developed simulation model was used for determining the influence of network configuration on overvoltage levels.

***Keywords*: medium voltage distribution networks, long-distance transmission line, single phase-to-ground faults, Petersen coil, resistor.**

I. Introduction

THE power supply security in large-scale power systems depends largely on the system's operation stability in case of emergency. According to international statistics, single phase to ground faults are responsible for up to 80% of failures in 6–25 kV networks. Both field experience and dedicated studies show that phase to ground faults are usually accompanied by intermittent arcing that causes overvoltage throughout all components of the distribution network. As a result, short circuits caused by breakdown of impaired insulation occur at multiple locations [1].

It is generally accepted that, to reduce the failure rate, the system neutral is equipped with a Peterson coil. Capacitive current compensation devices are designed to reduce the current in the fault location. From the point of view of increasing the probability of arc extinction, the Peterson coil has to have resonant frequency tuning. A deviation from resonant frequency tuning is called compensation detuning.

The possibility of resonant neutral voltage stepup on the neutral is one of the main problems with resonant frequency tuning of the compensation current. If the Peterson coil is included in the network neutral, the diagram consists of an anti-resonant circuit where significant voltage build-ups in coil inductance are possible. In the case of resonant grounding and high reactor quality factor $q=X_r/R_r$, the voltage across the neutral resistor can be defined in a simple way, using $U_N \approx q \cdot U_{Nno\text{-}load}$. As the quality factor of the modern Petersen coil is rather high (50-100), some dangerous overvoltage can occur on the neutral point and, consequently, on the phases in the case of even small unbalance of the network with exact tuning of the Petersen coil (or if the Petersen coil tuning resonates).

In the case of fine resonance tuning, the residual current in the fault point is defined by high leakages and the higher harmonic current that is caused mainly by a nonlinear load which can also lead to overvoltage. In connection with that, the harmonic composition of the single phase-to-ground fault current is an important factor when choosing the neutral grounding mode.

To measure the neutral voltage in the normal mode and to prevent arc overvoltage, a combined mode of neutral grounding is used, where a high-value resistor is added in parallel with the reactor.

When selecting means for neutral grounding, a wide range of factors affecting the performance of said means should be taken into consideration, such as occurrence of harmonic distortions in the phase to ground current or influence of system state variables on the overvoltage level increase and so on [2–4]. Some results of comprehensive research focused on the influence that the neutral grounding mode has on transients occurring in case of phase to ground fault in a large-scale distribution network are presented in this paper.

In case of neutral grounding via Petersen coil, the arcing

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fault overvoltage values are lower and the overvoltage condition lasts for a relatively small period of time, not longer than half-wavelength, which is particularly important for insulation. Nevertheless, the advantage of resonant grounded systems as regards overvoltage suppression is minimized in case of compensation detuning to an extent greater than 5% deviation from the resonance value and practically brought to naught in case of compensation detuning to 20% and higher. In view of this, the task of maintaining the resonant tuning of the Petersen coil becomes particularly important. It could be possible that in large-scale distribution networks having long-distance lines a significant voltage drop occurs along the line resulting in decompensation in the case of ground fault at the point most distant from the main substation.

II. Subject of Research

A 35 kV network of Ulaanbaatar City Central Electricity Distribution Networks that supplies power for 10 regional substations with the total power of 14.7 MW situated within a radius of 140 km from the power supply center is studied in this paper. This network is fed from 35 kV busbars of Ulaanbaatar Combined Heat and Power (CHP) Plant No. 3. The total value of rated ground-fault capacitive current for the busbar section considered is 16 A. This network is provided with a Petersen coil ZROM-275/35 installed pursuant to regulatory requirements and a protective resistor RZ-3000-136-35 for overvoltage suppression. The network studied here is notable for significant length of particular lines, the longest of them extending over a distance of 140 km. The use of AS-50 (Aluminum and Steel) wire in this line results in a significant amount of line losses. While testing, the line was loaded to 20% of the rated power. The voltage drop along the line's length was then 1.15 kV.

The line consists of sections with single and double-circuit transmission poles without conductor transposition that results in voltage unbalance and, therefore, resonant voltage increase in case of the Petesen coil tuned to resonance. Neutral voltage was measured for this network in the normal operating mode with resonance and combined modes of neutral grounding.

III. Experimental Results

Neutral voltage was measured with the help of the end of the insulating rod (connected with the capacitance voltage divider (VD)) briefly touching the neutral point of the transformer neutral of the Petersen coil 35 kV busbar Section 1 network of Ulaanbaatar Combined Heat and Power (CHP) Plant No.3. To obtain reliable data about the value and harmonic composition of the voltage, the voltage signal at the lower arm of the voltage divider was oscillographed on the network neutral.

The voltage signal was oscillographed and the oscillograms were recorded using Yokohama DL750 digital oscillograph.

As a result of the measurements, the dependence of 50Hz neutral voltage on the Peterson coil current compensation was obtained. The data is given in Table I. Dependence of the harmonic distortion level on the compensation current is shown in Fig. 1. Both dependences are increasing; at the approach to the resonance value of the compensation current, the voltage level on the neutral increases.

TABLE I
NEUTRAL VOLTAGE, 50 HZ VALUES IN 35 KV BUSBAR SECTION 1 NETWORK OF ULAANBAATAR CHP PLANT NO. 3 MEASURED FOR PETERSEN COIL SWITCHED TO TAP POSITIONS 1-5

Neutral grounding mode	$U_{bias,pos.1}$, V	$U_{bias,pos.2}$, V	$U_{bias,pos.3}$, V	$U_{bias,pos.4}$, V	$U_{bias,pos.5}$, V
Resonant	139.790	205.290	229.310	255.560	348.570
Combined	95.112	95.112	121.010	83.962	125.510

The measurements have shown that neutral voltage reaches a value of 348.57 V in case of applying the resonant compensation tuning to the neutral grounded via Petersen coil, whereas the combined grounding approach imposes significant restriction on the growth of neutral displacement voltage so that neutral voltage reaches a much lower value of 125.51 V (reduced by 2.77).

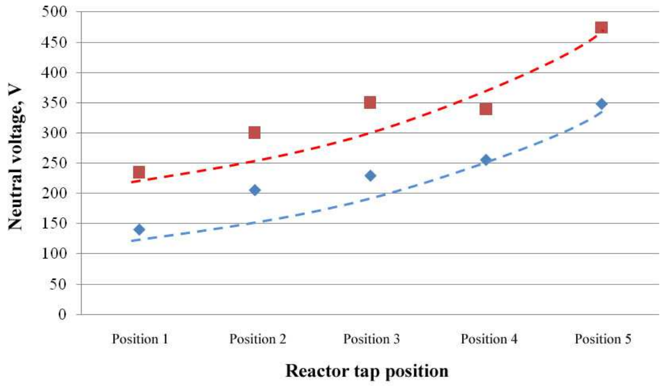

Fig. 1. Relationship between the neutral voltage and the compensation current values for 35 kV Busbar Section 1 network of Ulaanbaatar CHP Plant No. 3 (the neutral voltage with resonance neutral grounding – red colour, the neutral voltage with combined neutral grounding – blue colour)

The measured signals were processed using the Mathlab software package. As a result, the harmonic composition of the neutral voltage for resonance and combined modes of neutral grounding with different Petersen tuning were obtained.

TABLE II
HARMONIC DISTORTION OF NEUTRAL VOLTAGE IN 35 KV BUSBAR SECTION 1 NETWORK OF ULAANBAATAR CHP PLANT NO. 3 MEASURED FOR PETERSEN COIL SWITCHED TO TAP POSITIONS 1-5 WITH THE RESONANCE NEUTRAL GROUNDING

Harmonic number	$U_{bias,pos.1}$ V	$U_{bias,pos.2}$ V	$U_{bias,pos.3}$ V	$U_{bias,pos.4}$ V	$U_{bias,pos.5}$ V
3	5.918	8.571	11.913	9.480	11.713
4	4.423	6.060	4.261	2.547	1.007
9	6.585	5.606	2.205	4.904	9.153
18	**20.474**	**19.936**	**20.455**	**21.189**	**20.884**
21	6.551	4.126	3.465	4.974	3.320
24	5.386	5.563	6.999	6.896	3.059
Total harmonic distortion	28.427	29.399	30.586	30.848	33.393

Data for voltage harmonics exceeding 5V for the resonance mode and the combined mode of neutral grounding are given in Table II and Table III respectively.

TABLE III
TOTAL HARMONIC DISTORTION OF NEUTRAL VOLTAGE IN 35 KV BUSBAR SECTION 1 NETWORK OF ULAANBAATAR CHP PLANT NO. 3 MEASURED FOR PETERSEN COIL SWITCHED TO TAP POSITIONS 1-5 WITH THE COMBINED NEUTRAL GROUNDING

Harmonic number	$U_{bias,pos.1}$, V	$U_{bias,pos.2}$, V	$U_{bias,pos.3}$, V	$U_{bias,pos.4}$, V	$U_{bias,pos.5}$, V
2	2.158	2.158	6.841	2.833	6.324
3	7.164	7.164	13.735	9.107	8.866
5	3.109	3.109	5.147	2.901	1.816
6	4.002	4.002	5.885	3.526	1.800
18	**19.558**	**19.558**	**19.084**	**19.518**	**17.641**
24	5.584	5.584	5.511	6.818	7.552
Total harmonic distortion	27.398	27.398	30.169	27.996	27.779

In this research, a solid single phase-to-ground fault test has been carried out using the method of artifactual "direct" phase to ground short circuit with oscillography of ground fault current and phase voltages. This method is direct, it makes it possible to most reliably measure the factual values of single phase-to-ground faults and other values.

To study changes in transient processes in the case of moving away from the fault location, two observation points were set up. The first point was located in the fault location, the second one – at the distance of 140 km. There was a set of high voltage divider in each point. VD were connected to the busbars in the breaker compartment to the studied section with high-voltage wires. A digital storage oscillograph was connected to the VD low-voltage arm terminals vial a measuring cable to register phase voltage. The nominal range of operating frequencies with bandpass flatness of ±0.5dB is 20 - 2 10^6 Hz which ensures the required signal determination precision for further processing.

To oscillograph single phase-to-ground fault protection current, a current transformer (CT) was additionally included in the fault circuit; to oscillograph the Petersen coil current, a current transformer was also included in the ground network of the Petersen coil.

When making a short artifactual single phase "metal" fault-to-ground, current signals through the single phase-to-ground fault location via the Petersen coil, phase-to-ground voltage and the neutral voltage were oscillographed at the busbars.

The obtained values of 50Hz capacitance current and harmonic distortions are given in Table IV. The most prominent harmonic distortions are in the odd row: fifth, eleventh and thirteenth, as well as the second one, which testifies to possible existence of a 35 kV transformer with a "broken" coil flux guide in the distribution network. The measurement data showed significant undercompensation of ground fault current which is also confirmed by the curve form in Fig. 2.

TABLE IV
HARMONIC COMPOSITION OF CALCULATED SINGLE PHASE TO GROUND CURRENT FOR PETERSEN COIL TUNED TO RESONANCE IN 35 KV BUSBAR SECTION 1 NETWORK OF ULAANBAATAR CHP PLANT NO. 3

Harmonic number	I_{res}, A
1	14.910
2	0.226
3	0.111
5	0.294
7	0.101
11	0.172
13	0.172
Total harmonic distortion	0.480

A phase voltage transient oscillogram for post phase to ground fault condition (CH1_1 is for phase A (blue), CH1_2 for phase B (green), and CH1_1 for phase C (red) is shown in Fig. 2. After ground fault clearance, the recovered phase voltage had beats and reached a level of $1.86 \cdot U_{max}$. The transient period was 950 ms.

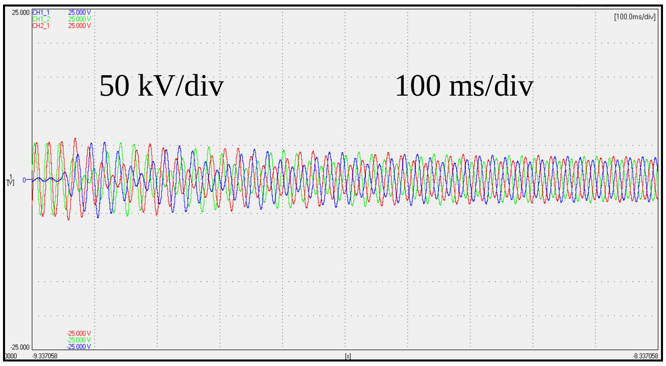

Fig. 2. Oscillography of phase voltages at the beginning of a long line in 35 kV Busbar Section 1 network of Ulaanbaatar CHP No. 3 (Petersen coil)

In order to estimate the effectiveness of combined neutral grounding, a test with parallel connection of a Petersen coil and a resistor has been carried out. Fig. 3 shows a phase voltage transient oscillogram. After ground fault clearance, the recovered phase voltage had no beats and reached a level of $1.65 \cdot U_{max}$. The transient period was 150 ms.

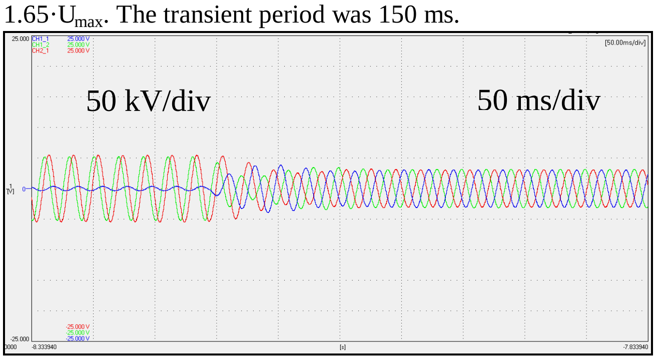

Fig. 3 – Oscillography of phase voltages at the beginning of a long line in 35 kV Busbar Section 1 network of Ulaanbaatar CHP No. 3 (Petersen coil+resistor)

The test data confirm the efficiency of using the impedance neutral grounding in the 35 kV network of Ulaanbaatar CHP No. 3. even in the case of significant network decompensation.

IV. TRANSIENTS IN DISTRIBUTION NETWORK

To investigate the effect of the neutral grounding facilities, the authors developed a mathematical model of a distribution network that included components listed below:

- Equivalent power source;
- Distribution network (cable and overhead lines);
- Power and voltage transformers;
- Substations (load centers).

The calculation scheme is shown in Fig. 4.

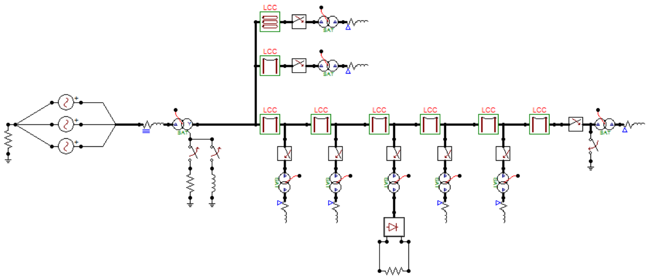

Fig. 4. Calculation scheme for the investigation of transients in the network in the event of a single-phase earth fault in 35 kV Busbar Section 1 network of Ulaanbaatar CHP No. 3.

As the most difficult loading case, the ground fault at the end of a long line has been selected. To substantiate the model's adequacy, the actual values of voltage drop along the line have been used as reference data. Then, a line load value equal to 80% of the rated power value was used for calculation. Raising the load resulted in a significant increase of voltage drop. According to calculation, the voltage drop value was 4.72 kV. If the coil tuned as per rated settings is located at the beginning of the line and a short-circuit condition occurs at the end, it results in considerable compensation detuning even if the coil is precisely tuned to resonance. The residual value of rated current is shown in Fig. 5.

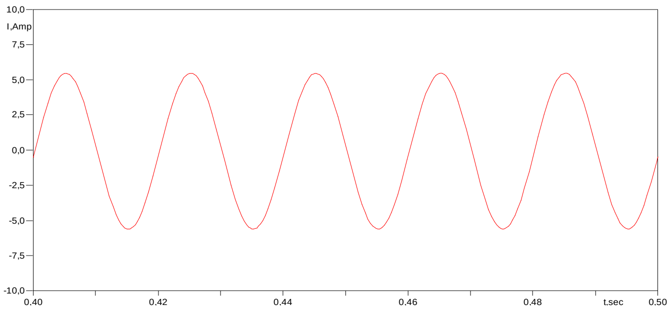

Fig. 5. Model-derived oscillography pattern of ground fault current at the end of the line for Petersen coil tuned to resonance in 35 kV Busbar 1 network of Ulaanbaatar CHP No. 3

In order to additionally specify the model parameters, nonlinear characteristics of power consumers have been taken into account. The technique and the algorithm for simulating loaded electrical devices with elements of electrical steel are described in some published papers [5-7].

As a result, a final network model describing the occurrence of ground fault in a network with resonant grounded neutral has been obtained. Fig. 6 shows a model-derived oscillogram for steady-state phase to ground fault current.

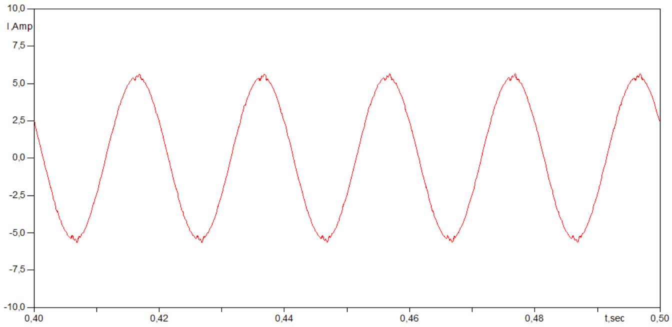

Fig. 6. Model-derived oscillography pattern of ground fault current at the end of the line for Petersen coil tuned to resonance in 35 kV Busbar Section 1 network of Ulaanbaatar CHP No. 3.

The frequency spectrum conforms to the field measurement data in terms of both quality and quantity (Table V).

TABLE V
HARMONIC COMPOSITION OF CALCULATED SINGLE PHASE TO GROUND CURRENT FOR PETERSEN COIL TUNED TO RESONANCE IN 35 KV BUSBAR SECTION 1 NETWORK OF ULAANBAATAR CHP PLANT NO. 3

Harmonic number	I_{res}, A
1	4.21
2	0.150
3	0.201
5	0.314
13	0.221
Total harmonic distortion	0.458

If the neutral and network grounding mode has certain parameters, a transient arises in case of ground fault (Fig. 7). The overvoltage value reaches $1.96 \cdot U_{amp}$ when the short-circuit condition arises and has its maximum at $1.84 \cdot U_{amp}$ after fault clearance. The transient period is 650 ms.

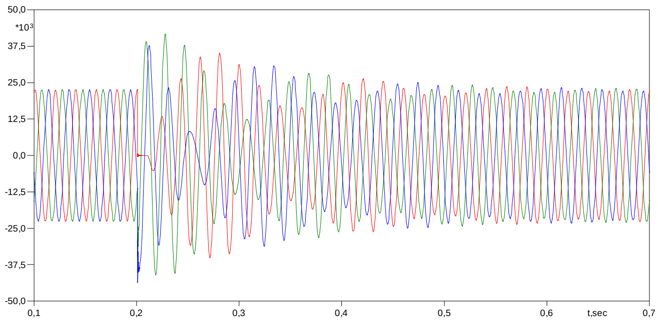

Fig. 7. Model-derived oscillograms of phase voltages at the beginning of a long line for resonant grounded neutral in 35 kV Busbar Section 1 network of Ulaanbaatar CHP No. 3

Fig. 8 shows a model-derived oscillogram for combined neutral grounding (the neutral includes an installed resistor RZ-3000-136-35). The overvoltage value reaches $1.93 \cdot U_{amp}$ when the short-circuit condition arises and has its maximum at $1.41 \cdot U_{amp}$ after fault clearance. The transient period is 40 ms.

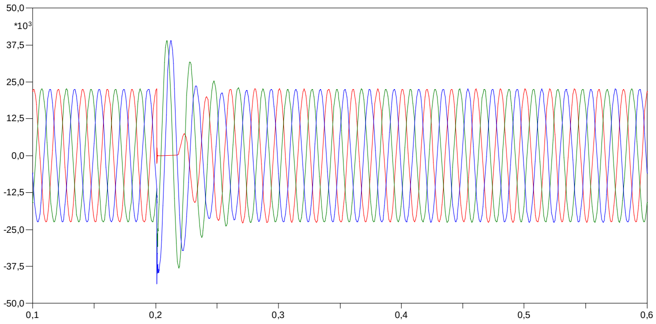

Fig. 8. Model-derived oscillograms of phase voltages at the beginning of a long line for combined neutral grounding in 35 kV Busbar Section 1 network of Ulaanbaatar CHP No. 3

V. Conclusions

The experimental studies of transients in case of single phase to ground faults (steady-state solid phase to ground in 35 kV Busbar 1 network of Ulaanbaatar CHP No. 3 for different neutral grounding modes) have shown that the combined neutral grounding via parallel-connected Petersen coils and resistors RZ-3000-136-35 or similar has the following effect:

- Normal operation voltage recovery rate reduction from 0.95 s to 0.15 s;
- Overvoltage reduction from 1.86U_{amp} to 1.65U_{amp};
- Resonance suppression in the network with Petersen coil;
- Limitation of neutral displacement voltage in the case Petersen coil is tuned to resonance.

Computer-aided investigation has shown that it is impossible to ensure precise resonant tuning for all cases of single phase to ground faults, particularly if the fault occurs at a considerable distance from the power supply center. The ground fault current has a significant residual value causing overvoltage. Compensation systems should be installed to provide for automatic compensation current control subject to distance to the ground fault location.

Results of experimental and theoretical investigation suggest that the combined neutral grounding method can be efficiently used on the 35 kV network of Ulaanbaatar CHP No.3.

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