ANALYSIS OF OVERVOLTAGES OCCURRING AT GROUNDING FAULTS IN A MEDIUM VOLTAGE NETWORK DEPENDING ON THE NEUTRAL TREATMENT

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Abstract - The importance of the system earthing in electrical station 110kV/MV is much known, ways to treat the neutral directly affecting the behavior of the system regarding the maximum level of earth-fault currents and of the overvoltages that can occur. In this paper the authors present considerations of the isolated and resistor treated neutral systems and make an analysis of the overvoltages that appear when the neutral is isolated comparing to the situation when it is treated by resistor. In the last part of the analysis the conclusions are presented.

Keywords: neutral treatment, medium voltage networks, single phase-to-ground fault, phase overvoltage.

1. INTRODUCTION

These days the global trend for the companies that activates in electrical field is to improve the power distribution and security service acording with [1]. No doubt the most serious concerns of the parties involved in the process, are to made significant efforts to increase the reliability and stability of the electrical power systems.

Otherwise, the current operating philosophy of free energy markets imposed, after a period of increasing the quality level, a reduction in the costs related to the electricity distribution process by increasing productivity. Under these circumstances, serious pressure has been generated to reduce global costs.

The earthing system plays a very important role in an electrical network. For network operators and end users, avoiding damage to equipment, providing a safe operating environment for personnel and continuity of supply are major drivers behind implementing reliable fault mitigation schemes [2].

Fault current and transient over-voltage events can be costly in terms of network availability, equipment costs and compromised safety.

Interruption of electricity supply, considerable damage to equipment at the fault point, premature ageing of equipment at other points on the system and a heightened safety risk to personnel are all possible consequences of fault situations [2].

In general, several methods of earthing the neutral points of electrical systems are used:

1. The neutral entirely isolate;
2. The neutral earthed by a resistor
3. The neutral earthed by a suppression coil;
4. Solidly earth the neutral point (direct earthing).

According to the IEC norms [3] (for insulation coordination) the particularities associated to each neutral earthing arrangement are defined as following:

- network with isolated neutral – is a network whose neutral has no link specially made to the earth;
- network earthed by a resistor or suppression coil – is that network which have the neutral point linked to the earth by a resistor or coil; its inductance can be adjusted to closely match the network phase-earth capacitances, depending on the system configuration, so that the resultant earth-fault current is small.
- network directly earthed - is a network whose neutral point is directly linked to the earth (or via an low- value impedance, which reduces the transient oscillations and allows the flowing of a current big enough for protection selectivity)[4].

2. "BRIDGE GRANT" PROJECTS KNOWLEDGE TRANSFER

Knowledge transfer known in literature as the movement of know-how or technical knowledge from one organization to another, is considered to be one of the most important components of the strategic plan of the University of Craiova / INCESA research institute.

INCESA (Research Hub of Applied Sciences, University of Craiova) is a young organization; it already counts an important number of collaborations with the local and regional business environment. Consequently, it is developing a management strategy that approaches the knowledge transfer (KT) to the industry as a recurrent event [5].

One of the University of Craiova / INCESA's projects financed by national grants and based on a partnership with the regional power distribution company – Oltenia energy distribution – project "Intelligent solutions for neutral grounding in 110/MV distribution substations for increasing of the energy efficiency, personnel security and reliability of power users' supply" [6], has as one of the main objectives analysis of the main methods of neutral treatment and its implications concerning safe operating environment for the network & personnel and continuity of the power supply.

The regional power distribution operator delivers power energy for 7 counties in the Oltenia region, being committed to supplying all of it's over 1,400,000 clients with high quality electricity (over 3.5 million people).

Oltenia Energy Distribution (referred to as DEO) ensures through its own network (110kV, 20kV, 6kV and 0.4 kV) the power supply of industrial, domestic and service consumers.

The rapid expansion of DEO activities and units, doubled by the permanent objective of network reliability improvement and smart concept implementation shape its policy regarding the staff professional development and expertise.

Following these trends, DEO is perfectly aware of the importance of having highly qualified employees. One of the strategies used by DEO is the development and integration to partnerships with the local academic and research environment.

3. NETWORKS WITH NEUTRAL TREATED BY RESISTOR

The earthing solution of the neutral treatment for medium voltage networks (MV) through a resistor is used for the 110 kV / MV stations, Fig.1.

This method of neutral treatment is applied to electrical networks where total earthing current which flows have values above 10A and also have, over other treatment methods options, advantages such as [7]:

- reducing the insulation demands of electrical equipment by eliminating relatively fast long-term overvoltages;
- reducing the major risk of electric shocks by decreasing the effective values for the pitch voltages and their duration;
- grounding is in fact a one-phase short-circuit detected by the protection system that commands and controls a rapid disconnection, the short-circuit current that appears together with the fault moment has moderate values;

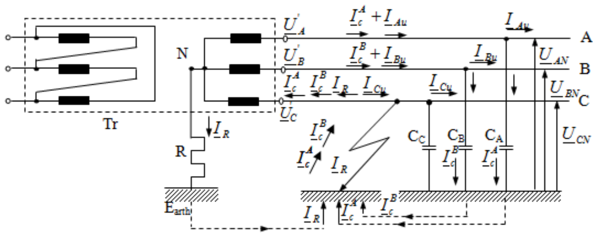


Fig. 1 - Grounding the neutral of a three-phase network by resistor – fault regime

In the picture there are:

● currents $\underline{I}_{Au}$, $\underline{I}_{Bu}$, $\underline{I}_{Cu}$ - which are the phase currents absorbed by users.

● $\underline{I}_c^A$, $\underline{I}_c^B$ - the capacitive currents which flows through the capacities of phases A and B - healthy phases;

● $\underline{U}_{AN}$, $\underline{U}_{BN}$, $\underline{U}_{CN}$ - the phase voltages;

Net earthing on a single phase in fact means that we have zero defect resistance and so $\underline{U}_{CN} = 0$ (Fig.2.);

In order not to have high potential values for neutral point of the network on the one hand, and to limit the single-phase fault current value on the MV bus bar to 300 A on the other hand, appropriate resistors values must be chosen.

The diagram of voltages and currents for net grounding is presented in Fig.2:

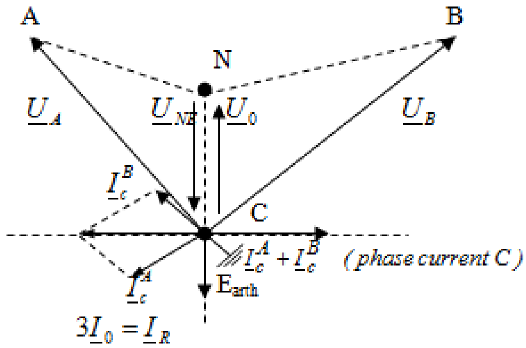


Fig. 2 - Phasoric diagram for a three-phase network with neutral grounding by resistor

where ● $\underline{U}_A, \underline{U}_B$ - are the voltages of healthy phases during the earthing;

$$\underline{U}_A = \underline{U}_B = \sqrt{3}U_f \qquad (1)$$

● $\underline{U}_{NE}$ - is the neutral displacement voltage;

$$\underline{U}_{NE} = \underline{I}_R \cdot R \qquad (2)$$

● $\underline{U}_0$ - is the homopolar voltage - equal to the phase one in case of net grounding.

Particularly, the current through the grounding site Ip has the value given by the relationship:

$$\underline{I}_p = \underline{I}_c^A + \underline{I}_c^B + \underline{I}_R \qquad (3)$$

$$\underline{U}_{NE} = -\underline{U}_0 \qquad (4)$$

Thus, the relationship of the residual current on the fault line will be given by the relationship:

$$3\underline{I}_0 = \underline{I}_R \qquad (5)$$

which is only valid if we have a single line connected on the medium voltage bus-bar.

Parts of the main advantages of treating the neutral with resistor that can be mentioned are:
- reducing transient overvoltage insulation stresses for electrical equipments and network;
- simple network operation and mentenance;
- fast depreciation of free oscillations occurring in the transient processes which accompanying short circuits with arc;
- lower costs for operation than in the case of using suppression coils [12].

As a disadvantage it can mention the increase of the disconnections number compared to the isolated neutral network.

Also earthing the neutral by resistor is the most usual method that is able to limit the earth-fault current to those values considered safe for the integrity of the system, but allowing simultaneously the selective operation of the protection system by using ordinary installation [4].

4. NETWORKS WITH ISOLATED NEUTRAL

The isolated neutral networks are MV networks with earth-fault currents within 10 A.

For normal operation (symmetrical network before fault), voltages on A, B and C are equal to the service voltage per phase, and the homopolar voltage U_0 is 0 [11]. As for the currents through A, B and C - I_{Au}, I_{Bu} and I_{Cu} in turn, are equal to the phase current value and their sum is 0. The capacities of the analyzed network phases are also equal $C_A = C_B = C_C$; and $\underline{Y}_A = \underline{Y}_B = \underline{Y}_C = j\omega C_\Sigma$.

(where C_Σ - the phase capacity of the entire galvanically connected network, in [μF])

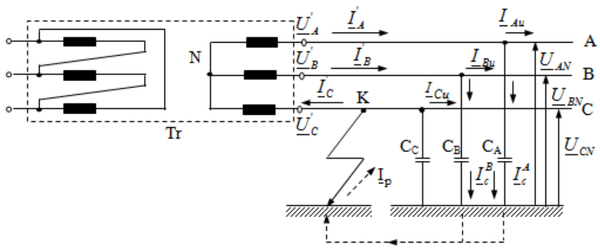


Fig. 3 - Three-phase network with isolated neutral – fault regime

$$\underline{I}_A' = \underline{I}_C^A + \underline{I}_{Au}$$

$$\underline{I}_B' = \underline{I}_C^B + \underline{I}_{Bu} \qquad (6)$$

$$\underline{I}_C' = \underline{I}_p + \underline{I}_{Cu}$$

where • $\underline{I}_{Au}$, $\underline{I}_{Bu}$, $\underline{I}_{Cu}$ are the phase currents absorbed by the users;

• $\underline{I}_A'$, $\underline{I}_B'$, $\underline{I}_C'$ - are the total currents through phases A, B and C during grounding;

• $\underline{I}_c^A$, $\underline{I}_c^B$ - are the capacitive currents of healthy phases A and B during grounding;

• $\underline{U}_{AN}$, $\underline{U}_{BN}$, $\underline{U}_{CN}$ - are the voltages of the phases at the site in the fault regime;

• $\underline{U}_A'$, $\underline{U}_B'$, $\underline{U}_C'$ - are the voltage values on the MV bus bar.

In the case of the net grounding of a phase (C) in point K (Fig.3.) [8] the following calculation conditions for the fault current can be used:

$$\underline{Y}_C = \infty; \quad \underline{U}_{CN} = 0 \qquad (7)$$

$$\underline{I}_p = \underline{I}_c^B + \underline{I}_c^A \qquad (8)$$

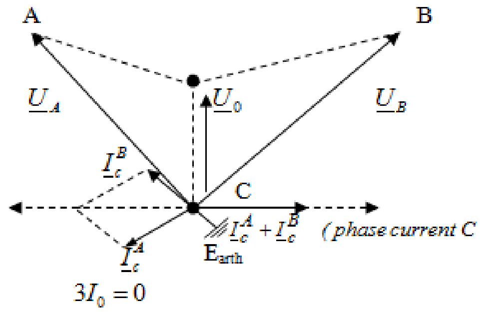


Fig. 4 - Phasoric diagram for a three-phase network – isolated neutral

Taking into account the previous relationships, the value of the fault current can be obtained as:

$$\underline{I}_p = j\omega \cdot 3C_\Sigma \cdot U_f \qquad (9)$$

Thus, if we have only one line in operation on the station's MV bus-bar, it is no longer possible to eliminate grounding with homopolar current protections and a homopolar voltage protection will be required.

The main advantage of isolated neutral networks in the case of single phase earthing is to ensure continuity in the electricity supply to consumers on the one hand and selective triggering of the fault line on the other.

Disadvantages includes things like: overstressing the insulation of the healthy phases, which involves considerable costs for increasing the level of insulation of the network phases to the earth; important interference in telecommunication circuits; amplifying the overvoltages of the healthy phases in case of an event with arcing pulses - intermittent defects; important values for dangerous voltages for humans near the fault location.

Note: for the drawing of the phasoric diagrams presented above or agreed upon the following: the capacitive currents running towards the line are offset before the voltage generating them (about 90 degrees); the capacitive currents running from the line to the bar are in phase opposition to the previous ones; the current through the resistor is in phase with the voltage that generates it (U_{NE}).

5. CASE STUDY

Samples for comparative analysis of events (overvoltages) occurring at grounding depending on the neutral treatment (with neutral treated by the resistor, respectively with the isolated neutral) were performed in a DEO transformation station 110/20 kV Stoina located in Gorj County. This station consists of a 110 kV bar divided into two sections connected by a longitudinal coupler, being equipped with two power transformers called T1 - 110/20 kV transformer with an apparent power of 16 MVA and a group of Yo D-11 connections; and T2 - 110/20 kV transformer with an apparent power of 10 MVA and a group of Yo D-11 connections.

On medium voltage level, the station is made up of 2 bus bars, the connection between them being realized by a transverse coupling. They feed 5 starting cells named: Coltesti; Totea; Slămneşti; Compresoare; Stejari.

The station also has two transformers for internal services with nominal power of 100kVA, Yzo5, $u_{SC}\%$ = 4%, I_{np}/I_{ns}=3A/144,5A and resistors with nominal voltage of 20 kV/11,55 kV, a current of 600/300A, and a resistance of 38-8 Ohm. Neutral treatment is done in two ways by resistor or isolated neutral.

Samples – earthing - were carried out at the terminal block of the second phase belonging to the line LES 20 kV (to the pillar No. 1) by mounting a short-circuit cable with its connection to the pole earth inlet (grounding) as the scheme from Fig.5. shows.

Thus, the line LEA 20 kV Slamnesti own capacitive current is the capacitive current of the 20 kV line LES at the output of the station (appreciatively 0,79 A).

This value was calculated from [9], considering the relation:

$$I_{cp/l} = I_{cs/l} \cdot l_l = 2,406 \cdot 0,328 = 0,79 \text{ [A]} \qquad (10)$$

where $I_{cs/l}$ is the specific capacitive current - [A/km], and l_l is the length of the LES line - [m] .The values were taken for a cable A2YSY with a section of 120 mm^2 [9].

Line LEA 20 kV Slamnesti, before the start of the samples was cut to pillar No. 2, at the exit of the station through the opening of the cutter separator, and the rest of the line was fed from the same station by closing the loop separator with the line 20 kV LEA Coltesti.

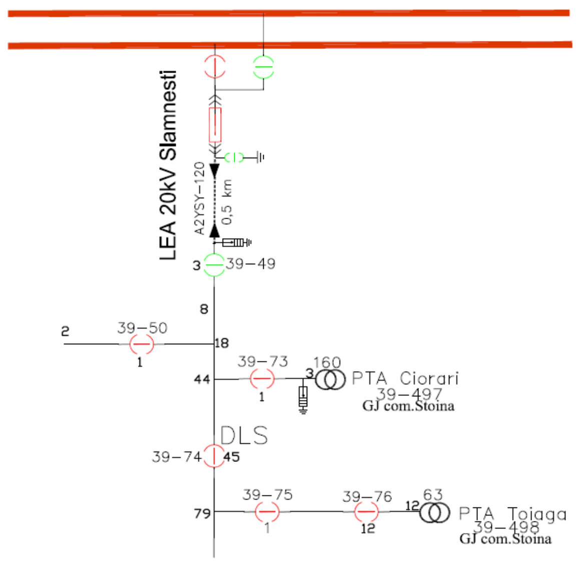


Fig. 5 - Power supply line LEA 20 kV Slamnesti

Description of samples for comparative analysis:

- ***Sample 1*** - with neutral achieved through by BPN and treated with 36 ohm resistance, the 20 kV switch from the 20 kV LEA Slamnesti was connected to a willing earthing on second phase; the line triggered by homopolar current protection; extracts from the protection relay were retrieved in order to analyze the transient regime (duration, phase overvoltage);
- ***Sample 2*** - with the isolated neutral (BPN out of operation), the 20kV circuit breaker was connected to 20kV LEA Slamnesti feeder on a dummy earthquake at the second phase; the line triggered by targeted homopolar protection; extracts from the protection relay were retrieved in order to analyze the transient regime (duration, phase overvoltage);

The records for the two samples were taken from SIPROTEC 7SJ82 - overcurrent protection which has specifically been designed for a cost-effective and compact protection of feeders and lines in medium-voltage and high-voltage systems. With its flexibility and the powerful DIGSI 5 engineering tool, SIPROTEC 7SJ82 offers future-oriented system solutions with high investment security and low operating costs.

The main applications of the 7SJ82 are [10]: detection of ground faults in isolated or arc-suppression-coil ground power systems in star, ring, or meshed arrangement; backup protection for differential protection devices of all kind for lines, transformers, generators, motors, and bus-bars; arc protection; overvoltage and undervoltage protection; frequency protection and frequency change protection for load shedding applications; power protection, configurable as active or reactive power protection; protection functions for capacitor banks, such as over-current, overload, current unbalance, peak overvoltage, or differential protection.

a) Neutral treated by resistor – sample 1

In the oscillograms taken during the grounding (Fig.6) on LES 20 kV Slamnesti - the following parameters are observed:

VaA - phase voltage A; VbB - phase B voltage; VcC - phase voltage C;

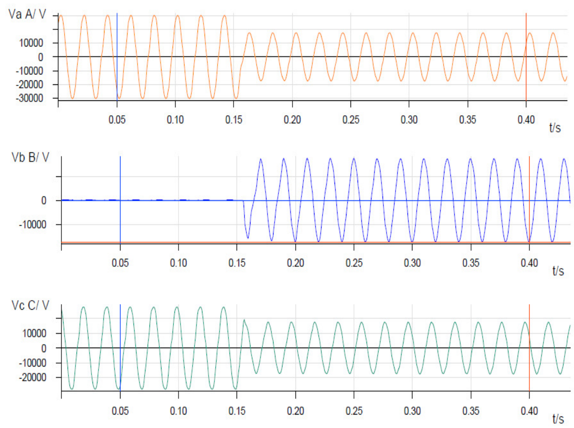


Fig. 6 - Phase voltages A, B, C.

At the same time we can observe (Fig.7.) the moment when the homopolar protection is triggered.

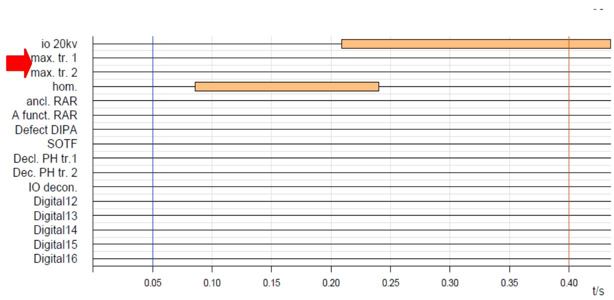
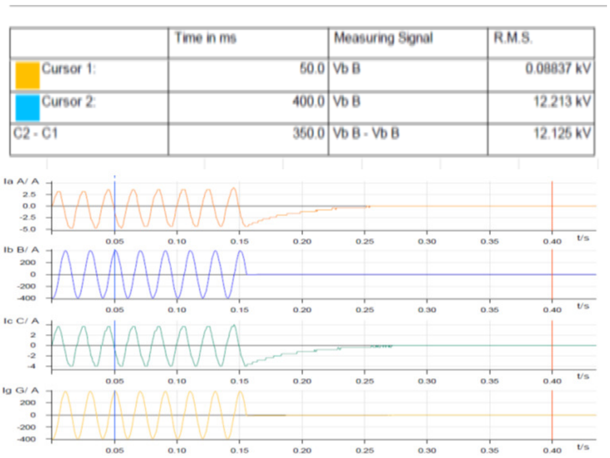


Fig. 7 - Triggering of the homopolar protection

Later (Fig.8.), the values of the currents are observed by the line phases and the residual current, the cursor 1 being positioned at time t=0.05 s



	Time in ms	Measuring Signal	R.M.S.
Cursor 1:	50.0	Vb B	0.08837 kV
Cursor 2:	400.0	Vb B	12.213 kV
C2 - C1	350.0	Vb B - Vb B	12.125 kV

Fig. 8 - Line phases and the residual current at 0.05 s

where:● IaA - current through Phase A of the LEA 20 kV Slamnesti;

● IbB - current through Phase B of the LEA 20 kV Slamnesti;

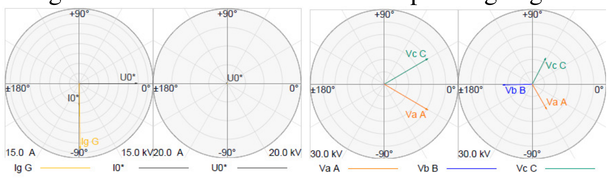
● IcC - current through Phase C of the LEA 20 kV Slamnesti;

● IgG - residual current in the LEA 20 kV Slamnesti, current obtained from the homopolar sequence filter.

Corresponding to the measured values table, shown in the figure below, we have the values (Fig.9.):

● Io* - the homopolar current calculated by the oscillogram viewing software from the three phase currents;

● Uo* - the homopolar voltage calculated by the oscillogram viewing software from the three phase voltages. Also it can be seen the corresponding angles.



Cursor 1: 50.0 ms

Measuring Signal	R.M.S.	Value	Phase	Extremum	5.Harmon.
Ia A	244.95 mA	166.62 mA	39.4°	-400.00 mA	8.6%
Ib B	13.418 A	13.370 A	-69.5°	18.800 A	4.3%
Ic C	223.61 mA	149.96 mA	50.6°	-400.00 mA	24.5%
Ig G	13.211 A	13.167 A	-66.8°	18.800 A	4.5%
Va A	20.437 kV	20.431 kV	-8.1°	28.704 kV	2.0%
Vb B	0.04986 kV	0.04537 kV	22.5°	0.03200 kV	30.7%
Vc C	20.464 kV	20.459 kV	52.6°	28.648 kV	1.9%
I0*	4.4145 A	4.4145 A	-68.3°		
U0*	11.780 kV	11.780 kV	22.3°		

Fig. 9 - Values for Io *, Uo * and corresponding angles

After t = 0.150 ms from the moment of the circuit breaker LEA 20 kV Slamnesti connection on earthing to the ground, visible in the voltage diagram shown above, the homopolar current protection implemented in the 7SJ82 relay gave the trigger command, and after analyzing the oscillograms, when t = 50 ms since the connection was done, the following significant significant values were read:

● currents on the three phases: IaA=3A; IbB= 278.83A; IcC=2.72A;

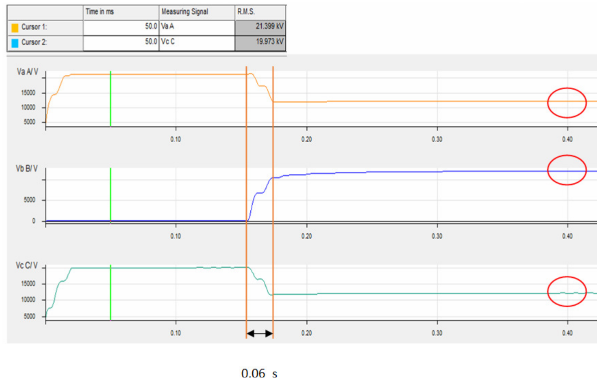
● residual current obtained from the homopolar sequence filter (IgG =IaA+IbB+IcC - vector sum) IgG = 276.72A;

● voltages on the three phases: VaA=21,399kV; VbB=0.088kV (grounded phase); VcC=19.97kV; phase shift (VaA, VcC) = 61.8 degrees;

● voltage on Vo*=11.83kV [Vo*= (VaA+VbB+ VcC)/3];

● phase angle between (Vo *, IgG) = 173.2 degrees.

From the overvoltages point of view, the during the earth leakage of LES 20 kV Slăneşti, the neutral being treated by the resistor, the oscillogram corresponding to the phase voltages (effective values) was analyzed (Fig.10.).



	Time in ms	Measuring Signal	R.M.S.
Cursor 1:	50.0	Va A	21.399 kV
Cursor 2:	50.0	Vc C	19.973 kV

Fig. 10 - Phase overvoltages A, B, C (R.M.S.).

After triggering the grounding line, the following effective values (at t = 400 ms from the moment of connection) were recorded in terms of phase voltage values: ●VaA=12,22kV; ●VbB=12.21 kV; ●VcC=12,20 kV symmetric and balanced voltage system;

Regarding the duration of the transient regime after the triggering of the earthing, the following conclusions can be drawn up until the moment of stabilization of the phase voltages: duration of the regime is maximum 60 ms; the voltages of the healthy phases decrease rapidly to VaA= 12.22kV and VcC=12,20 kV, the phase voltage set to ground rapidly increases to VbB = 12,21 kV, without to highlight voltage oscillations;

b) Isolated neutral– sample 2

The LEA 20 kV Slamnesti remained in the same configuration from the previous test, with the same grounding and the same place, and the three-phase artificial neutral coil was decommissioned, so the neutral of the station became isolated from the ground.

In the oscillograms taken during earthing on LES 20 kV Slamnesti - the neutral being isolated, the variance of the voltage parameters was observed (Fig.11.), where VaA- phase voltage A; VbB-phase B voltage; VcC-phase voltage C;

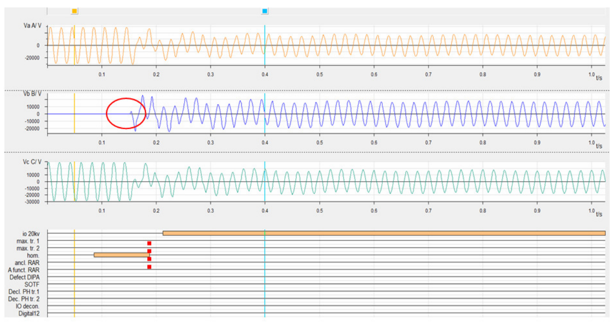


Fig. 11 - Phase voltages A, B, C.

The values of the phase currents (effective values) are shown in the following oscillogram (Fig.12.), where:

- IaA - current through Phase A of the 20 kV line Slamnesti;
- IbB - current through Phase B of the 20 kV line Slamnesti;
- IcC - current through Phase C of the 20 kV line Slamnesti;
- IgG -residual current of the 20 kV line Slamnesti, current obtained from the homopolar sequence filter;

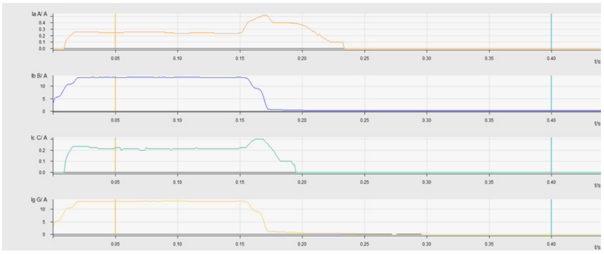


Fig. 12 - Values for current on phases A, B, C (R.M.S.) and the residual one

After t=0.150 ms from the connection of the 20 kV Slamnesti circuit breaker to the grounding as described above, the direct current homopolar protection implemented in the 7SJ82 relay gave the triggering command. After analyzing the oscillograms (after t=50 ms from the time of connection), the following significant values are read out below (Fig.13.):

- currents on the three phases:

IaA = 0.24A; IbB = 13.418A; IcC = 0.223A;

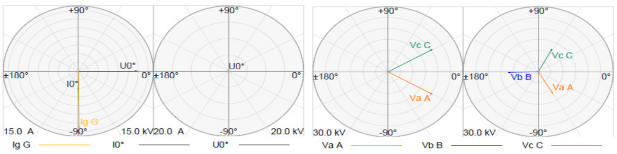
- residual current obtained from the homopolar sequence filter (IgG =IaA+IbB+IcC-vector sum):

IgG = 13.211A;

- voltages on the three phases:

VaA=20.437kV; VbB=0.049kV (ground phase); VcC =20.464kV;

- phase shift (VaA, VcC) = 60.6 degrees;
- Vo*=11.78 kV [Vo*=(VaA+VbB+VcC)/3]
- phase angle between (Vo*, IgG) = - 89 degrees;



Cursor 1: 50.0 ms

Measuring Signal	R.M.S.	Value	Phase	Extremum	5.Harmon.
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I0*	4.4145 A	4.4145 A	-68.3°		
U0*	11.780 kV	11.780 kV	22.3°		

Fig. 13 - Values for currents and voltages on the three phases system

Also, considering the current flow on the defective line during earthing, the total capacitive current of the station was calculated by the vector phase deflection (IbB) with the other two phase currents (IaA and IcC), resulting in a current capacitive total station about 14A.

After triggering the grounding line, the following effective values (at t=400ms from the moment of connection) were recorded in terms of phase voltage values: VaA=11.9 kV; VbB=12.19 kV; VcC=12,16 kV symmetric and balanced voltage system.

Regarding the duration of the transient regime after the triggering of the earthing, the following conclusions can be drawn up until the moment of stabilization of the phase voltages:

- the maximum duration of the regime is 400 ms;
- the voltages of the three phases record the oscillations leading to maximum values as follows (Fig.14.):
  - VaA = 14.7 kV (at t = 20 ms from the moment of triggering);
  - VbB = 15.6 kV (at t = 30 ms from the trigger time)
- phase with defect - triggered;
  - VcC = 15.2 kV (at t = 40 ms from the time of triggering);

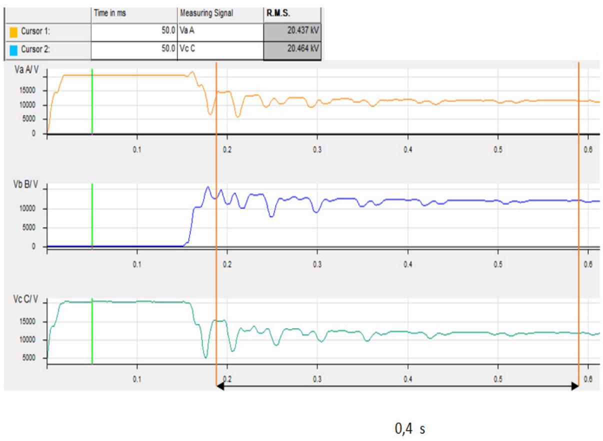

Fig. 14 - Values for voltages on the three phases A,B,C (R.M.S.)

5. CONCLUSION

From the tests result few main conclusions as:

- Existence of overvoltages on smaller healthy phases when the neutral is treated by the resistor compared to the situation where the same neutral is isolated;
- After triggering the grounding line (LEA 20 kV Slamnesti), if the neutral is isolated we have a transient regime with large oscillations related to the phase voltages, oscillations having maximum instantaneous values of 20.4 kV, compared to the situation in which the neutral is treated by resistor, in which case the voltages of the healthy phases decrease rapidly without oscillations at the phase voltage of 12.2 kV and the phase of the faulty faults rapidly increase to the phase voltage of 12.2 kV;
- After triggering the grounding line (LEA 20 kV Slamnesti), the duration of the transient regime is very high (t=0.4s) in the case of the isolated neutral, compared to the situation where the neutral is treated by the resistor, the situation where the transient regime lasts about 0.06s;
- Through these samples, the total capacitive current of the Stoina station (Ic=14A) was determined in order to dimension the extinguishing coil for the passage to the neutral treated by the extinguishing coil;

ACKNOWLEDGMENT

This work was supported by a grant of the Romanian National Authority for Scientific Research and Innovation, CNCS/CCCDI – UEFISCDI, project number PN-III-P2-2.1- BG-2016-0202, within PNCDI III”.

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