ON-LINE CONTROL OF CABLE ELECTRIC LINES. DIAGNOSIS OF MV UNDERGROUND NETWORKS. TESTS IN SITU.

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INTRODUCTION

Maintenance is the total sum of means and activities that require to check, test, maintain, follow-up the operation and to establish the operation state of a system, in this specific instance, the Medium Voltage Underground Network – MVUN. Therefore, we may distinguish the following classes :

- *Preventive maintenance (systematic activities)*
- *Corrective maintenance (conditioned activities)*
- *Predictive maintenance (diagnosis activities)*
- *Combined maintenance*
  - *Preventive-corrective*
  - *Predictive-corrective*

Maintenance has evolved as a concept in recent years, and so did maintenance of M.V.U.N. Maintenance activities are, basically, supported by appropriate and precise records an equipment, its specific features and performance over time. Predictive activities aim at measuring parameters that may provide information on the state of the MVUN. Analysis of how these parameters evolve in time may point to the instant when preventive action is required, in order to avoid faults that may lead to an interruption of electricity supply to consumers. In Romania's specific circumstances - where MVUN have been erected using cables of various producers and inadequate quality there came up the urgent need of reporting their technical state, in view of developing a long - range strategy.

Practical experience will be shown with the aid of ON-LINE control system and diagnosis devices for cable electric lines.

Measurements were carried out on MVUN erected with foreign and Romanian made synthetic extruded cables of 12/20 kV as well as the first findings on MVUN erected with PVC or paper - insulated cables of 6/10 to 12/20 kV.

ON-LINE CONTROL OF CABLE ELECTRIC LINES

The disconnection (non-operation) time during the operational life of a Cable Electric Line - CEL - is conditioned by the following operations, activities and/or unused time :

- Failure occurrence and period of time until the faulty CEL is found and separated ;
- Unused time from faulty CEL identification until repair is done to it ;
- Period of time of the fault pre-location and point-location;
- Period of time of accessories execution at the fault spot;
- Testing period after execution of accessories.

These periods can be reduced, and the ones where technological procedures can be applied are :

- Finding out the faulty CEL ;
- The CEL which reached its operational limit is found and marked
- The CEL with faulty is found and marked simultaneously with the occurrence of the failure.

Reduction being obtained through implementation of a new concept and CEL control system, namely the ON-LINE control.

The principle of method

The method consists in measuring-controlling the conduction current through the insulation system of a CEL, figure 1.

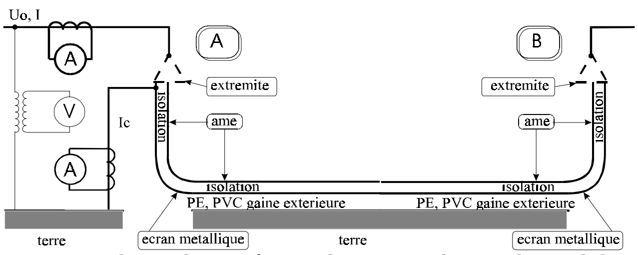

Figure 1. Fundamental circuit for one-phase CEL with one end grounded Screen

But the fundamentals of this concept require following conditions and can be applied only to the CEL which are to be manufactured-therefore to the new ones and to those having an extruded protection sheath.

According to this concept, as follows :

- only CEL which has introduced the new method, to put in the service
- CEL having an extruded protection sheath
- CEL having an metallic screen over phase
- CEL don't have metallic screen grounded in joints.

According to their construction CEL are, as follows :

- One-Phase Cables - OPC - with metallic screen grounded only to one end and to both ends
- Three-phase cables - TPC - with metallic screen grounded only to one end and to both ends

According to the operational regime, as follows :

- Normal operational regime
- Failure regime
  - in the cable insulation and/or in the protection sheath
  - of conductors or metallic screen.

Fulfilled control characteristics

- the CEL with faulty insulation or sheath, or conductor, or screen, is found and marked pre-warning being provided for :
  - the failure spot is pre-located
  - the CEL which reached its operational limit is found and marked

Paper show the stage of experiments in situ and in laboratory. The improvement and optimisation possibilities are practically countless.

One-Phase Cables with Metallic Screen Grounded Only to One End

When the CEL in figure 1 is energised, respectively in operation, in end A a conduction current is recorded which is directly proportional to the insulation impedance of the cable.

Current I_c value will depend on cable insulation state, directly proportional to the period of time since CEL has been in operation (energised), [1-2] ; respectively, it will be in accordance with the state of insulation, respectively insulation impedance, Z_c, which changes in time :

$$I_{c(t(} = \frac{U_0}{Z_{c(t)}} \quad (1)$$

To obtained this diagram the accurate value of the operational voltage U_0, is required which is obtained from the voltage transformer.

The gauges in point A are recording the conduction current through the cable insulation and they allow the on-line control of the CEL for the following instances.

Normal operational regime. The diagram the time-dependent conduction current is similar to that in figure 2.

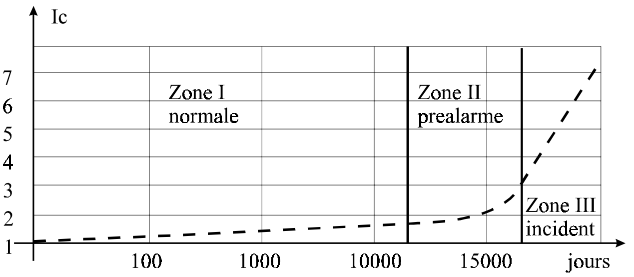

Figure 2. Diagram conduction current which on the operational period

Zone I - variation of current is directly proportional to the time, the ageing being normal ;

Zone II - insulation ageing is speeding up, this being the pre-alarm period in view of CEL interruption according to plan and of respective cable analysis;

Zone III -failure occurrence is certain, in which case if the CEL operation is not under control, failure may occur at any time.

In this case the fulfilled control characteristics is:

- *the CEL which reached its operational limit is found and marked*

Failure regime - failure of the protection sheath. In this case see figure 3 - the control gauges will signal a sudden drop of the conduction current because part of it will return to the source through the ground.

The protection sheath is not electrically stressed (zero differential of potential), therefore there will be no passing zone from normal to failure, but only two instances, namely :

- normal - proper sheath ;
- failure - contact with the ground which might occur because of :
  - cracks in the protection sheath due its ageing;
  - external factors : mechanical ones, digging, building, etc., or chemical corrosion of the sheath.

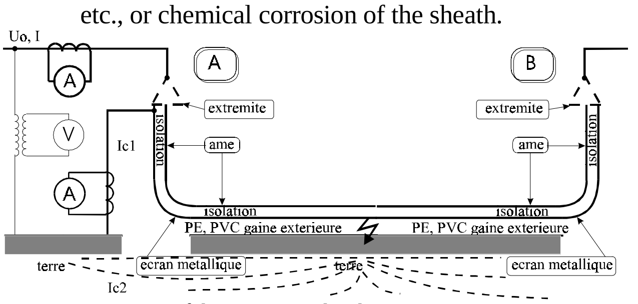

Figure 3. Damaging of the protection sheath

The conduction current I_c value will be directly proportional to the distance up to the failure point. There is detailed calculation model for the values of the currents which circulate through the cable metallic screen and through ground.

In this case the fulfilled control characteristics is

- *the CEL with faulty protection sheath is found and marked simultaneously with the occurrence of the failure ;*
- *the failure spot is pre-located.*

Failure regime - failure in the cable insulation

According to figure 4, in this case the control instrumentation will signal a sudden rise of the conduction current up to very high values, and of the short-circuit current as well.

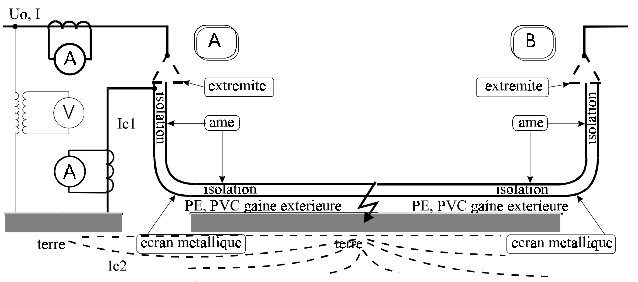

Figure 4. Damaging of the cable insulation

There will be two instances in this case, namely:

- Failure of the cable insulation only - only the cable insulation is impaired while the protection sheath remains untouched, in which case the whole of the short-circuit current passes through the control gauges.
- Failure of both the cable insulation and protection sheath. There are two failure cases :
  - The protection sheath is intact - the cable insulation has been damaged because of a manufacturing flaw. The control tools will record at first a very high, short

time current value, following which this value drops suddenly below the value of normal operating regime

- Both the sheath and insulation are simultaneously damaged. In this case damage can occur because of an external factor. There is a sudden drop of the conduction current simultaneous with the occurrence of a short-circuit current on the cable conductor.

In this case the fulfilled control characteristics is

- *the CEL with faulty insulation is found and marked pre-warning being provided for :*
  - *insulation damage, or*
  - *insulation damage followed by sheath damage, or*
  - *insulation and sheath damage - probably an external factor.*

For Three-Phase Cables with Metallic Screen Grounded to One End is similar of figure 1, but in this case conductor has three phases, presents an energised CEL in operation, in which case at end A no conduction current is recorded if the insulation on the three phases are identical. In fact, impedance are not perfectly identical, consequently neither the ageing will be identical onto the three phases simultaneously, so a conduction current will be recorded.
From now on all principles are repeated similarly to CEL with one-phase cable.

One-Phase Cables with Metallic Screen Grounded to Both Ends

Figure 5 shows an energised CEL in operation where theoretically equal conduction currents proportional to the CEL insulation impedance are measured to the both ends, A and B.

$$I_{cA(t)} - I_{cB(t)} = \frac{U_0}{2 * Z_{c(t)}} \quad (2)$$

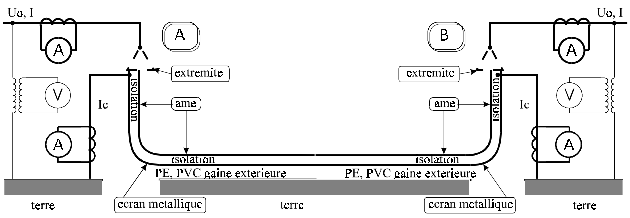

Figure 5. Circuit for one-phase CEL with both ends grounded screen

All the other principles presented in first case are similar. Particular emphasis is on the more accurate pre-location in case of protection sheath failure.
The same particular emphasis is laid on the more accurate pre-location performed in case of protection sheath failure.

For Three-Phase Cables with Metallic Screen Grounded to Both Ends the fundamental diagram is similar to One-Phase Cables with Metallic Screen Grounded to One End, respectively all the arguments presented above hold true.
The same particular emphasis is laid on the more accurate pre-location performed in case of protection sheath failure.

DIAGNOSIS OF MV UNDERBROUND NETWORKS

In this moment, there are many research groups in this area because the problem is very actual. So, in the bibliography list there are presented the titles of the works on this problem. There are mentioned too the methods used by the research groups in order to define effective and optimal technologies for the technical evaluation of an electric cable line.
The destructive methods [17-22] for the cable evaluation “in situ” are made by prelevating cable samples and bringing them into the labs for the analysis by infrared spectroscopy analysis, dielectric strength in steps with microscopically diagnosis, X-rays analysis, determination of the mass transfer from the semiconductive to the insulation layers, determination of the surface conductivity of the insulation material or the dielectric surface analysis
The most part of undistructive methods are in searching now [23-27] such as damped waves test, AC with sinus very low frequency test, AC with step cosinus very low frequency test, partial discharges initiation test, measurement of tag δ at different frequencies, from very low frequency to 50 Hz, measurement of the returned voltage, measurement of the partial discharges, measurements of the isothermal relaxation current, measurements of the depolarisation current or already known the AC resonance test, measurement of the capacitance, the 50 Hz AC test or the DC test.
It is obviously the necessity of using special test methods, others than AC, DC and - in the last time - VLF tests.
In this moment there are solutions such as partial discharges test, measurement of tag δ at low frequency and 50 Hz, the isothermal relaxation current analysis, the returned voltage analysis. The partial discharges analysis in situ needs special conditions, often unobtainable, and very high costs. The measurements of tag δ needs high levels of voltage in order to obtain good results. The isothermal relaxation current and returned voltage analysis are accessible methods, and, adding the levels of PC performances, they are easy to use methods, with possibilities for quick processing and evaluation, in situ.

Measurement principle

The conduction and polarisation phenomena of the insulator materials are shown by the discharged voltage U_d and returned voltage U_a curves. If on the insulation it is applied a loading voltage a long time t_{inc} - see the figure 6a. and then the power supply is turned off, the electric load of the electrodes will be discharged through the insulation resistance of the insulator material. If the voltage variation is recorded (with an electrostatic voltmeter), the curve of autodischarged voltage will be obtained, like in figure 6b .
If the charging time is long enough for polarisation development, then the initial gradient of autodischarging curve M_a will be proportional with the insulation conductivity:

$$M_a = k_m * \gamma * \frac{U}{\varepsilon_0} \quad (3)$$

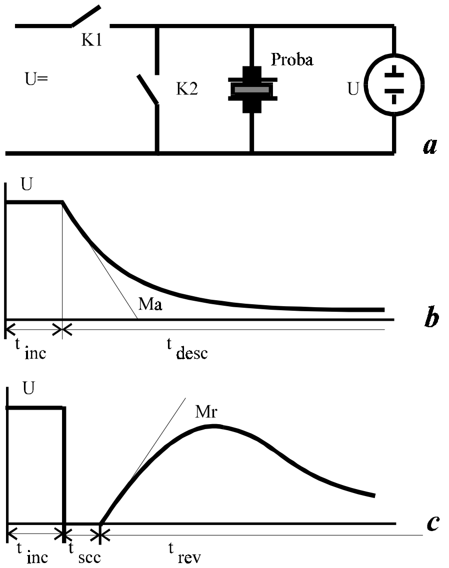

Figure 6. The discharging and returning phenomena ***a*** – the test scheme, ***b*** –the discharging voltage variation , ***c*** – the returned voltage variation

where :

k_m - an experimental determined constant of the material

γ - electrical conductivity

U - charging voltage

ε_0 - the vacuum permittivity

If after a long charging the insulation is short-circuited for a time t_{sc}, after taking off the short-circuit, on the electrodes will appear a returned voltage - figure 6c. The initial gradient of the returned voltage curve M_r is in interdependence with the polarisation phenomena of the insulator material and its value is proportional with the polarisation conductivity β, which defines the polarisation current like:

$$M_r = k_{me} * \beta * \frac{U}{\varepsilon_0} \qquad (4)$$

The two methods: isothermal relaxation current analysis and returned voltage analysis was used for the electric cable lines diagnosis on the existing network in Romania.

The isothermal relaxation current analysis method is based on the fact that the polymer store up into the dipoles an electric load at a level of energy specific to its structure. During the polarisation process, using a little supply of DC (1 kV) the different areas with small imperfections of the dielectric are “charged”. When the cable is suddenly discharged, the electric loads are released and a small current through the discharge resistance can be observed.

The different levels of energy of these areas is generating during the discharging waves with different time constants. Usually, damaged polymers, for example PE (typical case for water treeing) have a particular level of energy that can be separate from the normal current of PE. The damaged polymer leave a “mark” on the relaxation current, mark that can be isolated of the other sources and give a clear indication on the cable dielectric ageing or depreciation. This method is for PE or XLPE insulation.

The returned voltage analysis method is based on the fact that the polymer store up into the dipoles an electric load at a level and form specific to its structure. During the polarisation process, using a supply of DC (2 U_0 kV) the different areas with imperfections of the dielectric are “charged”. When the cable is suddenly discharged, the electric loads are released and a returned voltage can be observed.

The different levels of returned voltage with different time for maximal level, and decrease/increase curve show the stage of insulation system of CEL. This method can by use for PVC, PE, XLPE or paper insulation of cables.

TESTS IN SITU

With the equipment mentioned for ON-LINE control, there were made experiments in situ in order to create a data base for analysis the results and taking the appropriate decisions. There were made at four CEL on the ELECTRICA SA utilities and the results will be presented on slides.

In 1997 and 1998 the values of conduction currents were measured to 12/20 kV one-phase, 30 m long cables with normal PE insulation and XLPE - cables which were tested to accelerated ageing on the institute's stands.

The tests accelerated ageing consist of tests for accessories, according to standard RENEL 70. Sequence of tests was :

- measuring the conduction current through the insulation, before ageing
- high voltage alternating current test, short time, 1 min
- high voltage alternating current test, long time, 4 h
- 60 heating cycles :
  - 5 h heating until the conductor reaches a temperature 5 ^{0}C above the maximum rated temperature
  - 3 h natural cooling in air
- measuring the conduction current through the insulation, each 5 cycles

The measurements confirmed the base theoretical.

In 1998, 4 CEL of 12/20 kV with one-phase cable and PE/XLPE insulation will be selected and control and recording instrumentation for the conduction current values was installed to the end of each CEL.

The experimental data obtained will provide relevant conclusions on the method applicability.

The on-line control technology might be developed on at least two directions : computerisation of the conduction current measurement system in order to:

- compare the shape of the conduction current through insulation with the initial shape of voltage and/or current on the conductor, see figures 1 and 5
- process the current shape with a view to determine the level of partial discharges
- store the recorded data, etc.,

and second completion of the system described in F. Rodrigues (3), but in this case, investments are significant and they must be justified for the voltage of the CEL to won it is applied.

With the equipment mentioned for diagnosis CEL, there were made experiments in situ in order to create a structure of data specific Romanian cables. There were made more one hundred measurements on the CEL of ELECTRICA

SA utilities and the important results will be presented on slides.

Tests with the isothermal relaxation current method were made in measurements conditions:

- energising voltage - 1 kV
- energising time - 30 min
- short-circuit time - 5 sec
- measurement time - 30 min

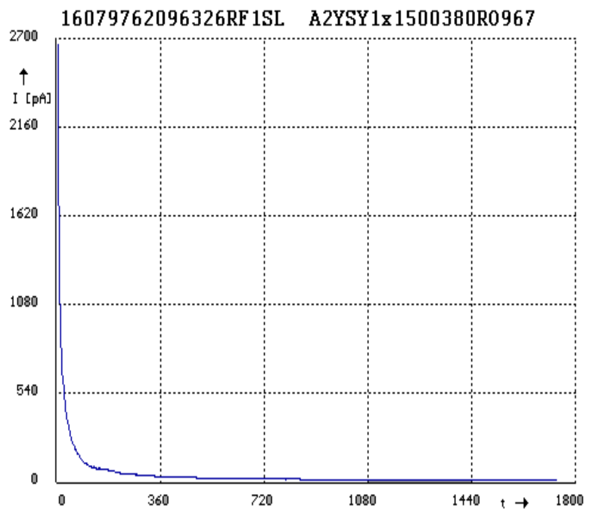

Figure 7. The isothermal current relaxation of an CEL 12/20 kV, SLOBOZIA, PE insulation, 620 m

and with the returned voltage method were made in measurements conditions :

- energising voltage – 2 U_0 kV
- energising time – min 5 min, depended of length cable
- short-circuit time - 2 sec
- measurement time – min 10 min, depended of length cable

There were made measurements on representative cable electric lines at ELECTRICA SA utilities, like those :

a) Bucharest - CEL - U_0/U - 12/20 kV, type of cable A2YSY, A2XSY, NAHKBA, manufacturers - ICME Bucharest – Romania, SIEMENS – Germania, KWO – Germania
CEL – U_0/U – 6/10 kV, type ACYAbY, manufacturer - ICME Bucharest – Romania

b) Brasov - CEL - U_0/U - 12/20 kV, type of cable A2YSY, manufacturer - ICME Bucharest – Romania

c) Slobozia - CEL - U_0/U - 12/20 kV, type of cable A2YSY, manufacturer - ICME Bucharest – Romania see figure 7 & 8

d) Giurgiu - CEL - U_0/U - 12/20 kV, type of cable A2YSY, manufacturer - ICME Bucharest – Romania see figure 9

The diagrams will be presented on slides.

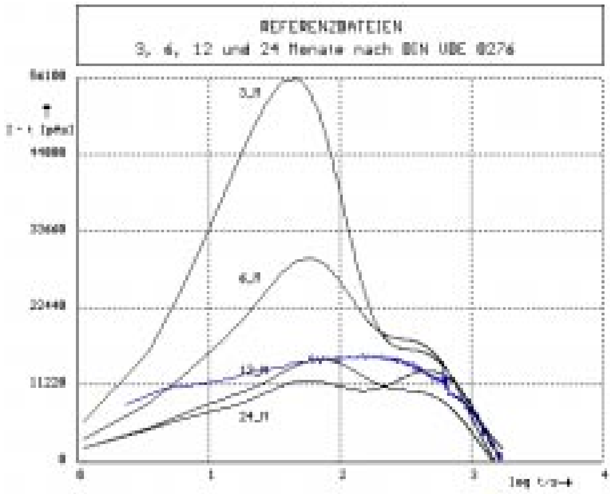

Figure 8. The loading in proportion with Ig(t), of an CEL 12/20 kV, SLOBOZIA, PE insulation, 620 m

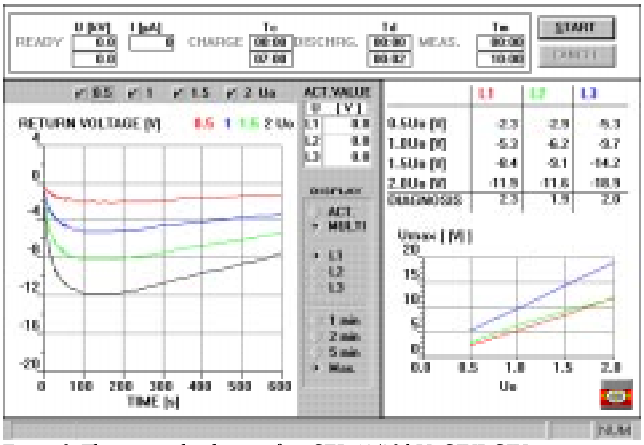

Figure 9. The returned voltages of an CEL 12/20 kV, GIURGIU, PE insulation, 250 m

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