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SOLVING EMC PROBLEMS IN THE DESIGN OF NEW HV TEST LABORATORY

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SUMMARY

The paper deals with solving electromagnetic compatibility (EMC) problems in the design of a new, case study, industrial high voltage test laboratory, intended to be used for testing of transformers and other apparatus up to 550 kV rated voltage. Modern high voltage test facilities are equipped, apart from primary test devices like AC, DC and impulse voltage generators etc., also with sophisticated numerical measuring instruments and informatics technology. Since such devices are sensitive to transient overvoltages, the highest degree of EMC is to be secured. This can be achieved by proper earthing and screening of test laboratory, what shall be designed in a way to satisfy all requirements conditioned by building lightning protection, personal protection and system earthing, avoiding electromagnetic compatibility disturbances at the same time. One of the main tasks is solving electromagnetic compatibility problems caused by outdoor electromagnetic disturbances originating from various unknown sources. Those disturbances and interferences may seriously influence measuring accuracy and readings of test devices, what consequently leads to false results. The stated is especially relating to partial discharge measurements. As to avoid such disturbances, the laboratory shall be completely screened with a net forming optimally designed Faraday cage. On the other hand, at high voltage tests with impulse voltages, especially with chopped tail waves, steep transient overvoltages may be generated. As a consequence, high transient potential differences between particular points along the earth electrode may occur, what can even lead to flashovers between parts of it. Therefore is of utmost importance to provide proper earthing and low inductance current return path for impulse high voltage test equipment where high frequency transients are to be anticipated. Improper earthing and bonding may result, apart from mentioned flashovers, in severe induced voltages in secondary cables with consequential influence on test results, possible destruction of measuring instruments and hazardous touch voltages for personnel. For analyzing transient potential differences, it is important to model, with maximum accuracy, impulse test circuit (impulse generator, chopping spark gap, voltage divider, Faraday cage, fundament earth electrode, earthing strips, earthing rods etc.). Magnitude of transient potential difference between particular points is proportional to earth electrode inductance, i.e. low inductance of earth electrode will result in decrease of transient potential difference.

KEYWORDS

EMC - Earthing - Bonding - Transient - Disturbance - Testing - Measuring.

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1. INTRODUCTION

Problems of electromagnetic compatibility (EMC) can be very often met in operation of high voltage open-air [1] and gas insulated substations [2]. Very similar problem of EMC exists in high voltage test laboratory where primary system consists of test apparatus and circuits that generate electro-magnetic interferences (EMI). The secondary systems consisting of all the apparatus and circuits for measurement, control and protection should be designed to function satisfactory in EMI conditions.

The paper describes a new industrial HV laboratory and foreseen methods of earthing, bonding and equipotential bonding, aiming to achieve security for personnel and suppression of EMC disturbances. The analysis of possible EMC problems is performed by EMTP-ATP modeling of earth electrode and impulse generator and simulating test with the lightning impulse chopped on the tail, the front time duration T_1 = 1,2 μs ± 30% and time to chopping T_c = 4 μs. Based on the obtained results, using analytical method [3], the verification and analysis of induced voltages developed at the ends of metal conduits for measuring cables, for the cases of conduit earthing at one end only and at both ends, had been performed.

2. DESCRIPTION OF TEST LABORATORY

Internal dimensions of the laboratory are: 30×35×25 m (w×ℓ×h). In order to provide required level of protection against external electromagnetic and noise interferences that might cause partial discharge and noise measurement errors, the high – voltage laboratory is constructed with a double wall with 1400 mm wide air space. As to additionally block an electromagnetic component of external influence, inner sheets of outside wall cladding are mutually galvanically joined.

The laboratory is equipped with one test input for voltage up to 110 kV, one test input for voltage up to 36 kV, two test inputs 12 kV and two low voltage test inputs (0 … 750 V). The power supply is provided by three generators, one of which with 200 Hz output, and rotating transformer. Test inputs 110 kV and 36 kV are supplied through outdoor HV switchyard with three-coil test transformer 12/4/(40 ... 80) kV and capacitor bank 92 Mvar.

The laboratory will be used, beside for other standardized tests, also for dielectric tests with standard lightning impulses and lightning impulses chopped on tail. Those tests are performed with negative polarity voltages with a view to avoid erratic flashovers in the external insulation and test circuit, since they, under laboratory conditions, present lower insulation stress. Utmost potential danger for insulation originates from chopped on tail impulse wave with front time T_1 = 1,2 μs ± 30% and time to chopping T_c = 2 … 6 μs. Connection scheme of impulse voltage test circuit is presented in Fig. 1 [4].

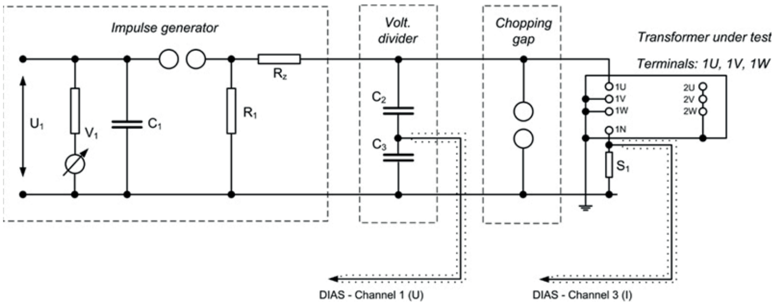

Figure 1. Connection scheme of impulse voltage test circuit

3. EARTHING AND EQUIPOTENTIAL BONDING

Laboratory earthing system is executed in a way to protect life and property in case of supply power system (50 Hz) faults (short circuits) and transient phenomena (lightning, transients resulting from impulse tests). The stated is achieved by equipotential bonding and preventing the unallowed potential rise of earthed metal parts, i.e. transient potential differences between different points of the laboratory earthing system and transfer of earth potential rise to external installations. Analyzed transient phenomena of the order of MHz are characterized with inductive earth electrode resistance, i.e. impulse earth resistance.

The laboratory earthing system consists of grid made of Fe/Zn 40×4 mm strips laid in the building foundations, concrete casted, and eight deep – driven copper earth rods, length 10 m each, equally distributed over laboratory ground plan surface [5]. It is galvanic connected with the earthing system of outdoor HV switchgear dedicated for power supply of test inputs, as well as with the surrounding industrial area earthing system.

Inside the laboratory floor a copper net, being part of its electromagnetic screen is laid. The net is made of metal plate, cut with slots and expanded, with diamond pattern meshes 10 × 5 mm, approx. 2 mm thick. Together with the net inside the inner wall and under the ceiling, made of spot - welded tinned steel wire ∅ 1 mm, with square meshes 10 × 10 mm, and the net inside the glass of test laboratory control room, it forms the Faraday cage (Fig. 2). The floor net is used as earth return for HF transient currents at execution of lightning impulse tests. All segments of nets inside the floor and the walls are mutually continuously soldered. The Faraday cage net is fixed to a grid of wooden slats mounted on a steel construction using screws made of rigid insulation material. Such executed net, galvanic connected to the laboratory earthing, represents an electromagnetic screen which effectively damps magnetic component of disturbances.

Figure 2. Faraday cage

All penetrations through the inner wall (e.g. door – posts, gate, bushing sealing flanges, electric cabinets, MV switch panels etc.) are integrated in the screening system by continuous galvanic connection with Faraday cage net along the entire perimeter.

Above-ground connections to lightning protection installation and metal construction connected thereto are executed via insulated spark gaps. Galvanic connection of Faraday cage and lightning protection installation and metal building construction is executed inside the ground, through foundation earthing grid and earth rods.

Faraday cage net is connected to foundation earth electrode via eight deep – driven copper earth rods. Galvanic connection of earth rods and copper floor net is executed through the copper plate welded to the net with silver solder along the perimeter. At the top of each earth rod, an earth plate electrode is welded, with connection points for earthing test objects and measuring equipment (Fig. 3.). Apart from the described, another 19 auxiliary plate electrodes for the same purpose are foreseen within the laboratory.

Test, measuring and power cables are run through steel conduits laid immediately below the earthed copper net in the laboratory floor. Conduits end in cable connection boxes which are galvanically connected to electromagnetic screen (Faraday cage) by continuous welding along the entire perimeter (Fig. 4). Steel conduits are the same way galvanically connected to cable boxes at both ends.

The test laboratory will be protected against external electromagnetic disturbances, that might cause errors at partial discharges measurements, by means of Faraday cage. Targeted damping [6] of the

Figure 3. Earth plate electrode

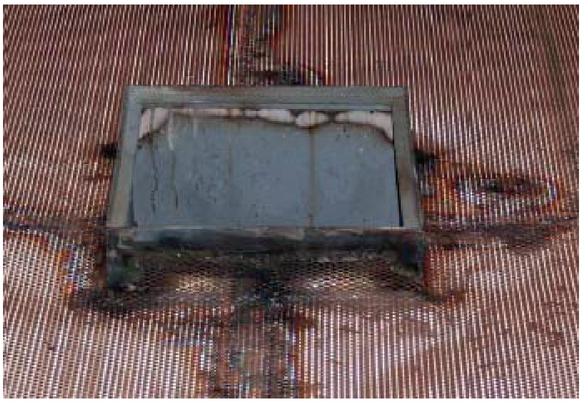

Figure 4. Cable connection box

electric component of the order of 1 MHz should be 40 ... 60 dB. For magnetic component lower values have to be accepted. Disturbance level inside the laboratory should be ≤ 10 pC, i.e. ≤ 2,5 μV.

4. TRANSIENTS ORIGINATING FROM CHOPPED LIGHTNING IMPULSE TEST

In this section computation of transients resulting from testing with the chopped lightning impulse is described. Such test can produce dangerous potential differences between different earth points, what can also happen when a lightning stroke hits a laboratory building.

The model of the impulse generator V2800/210 is developed for the computer simulation with the following data: C1 = 53.5 nF, R1 = 1560 Ω, R2 = 198 Ω. The inductance of the impulse generator is 49 μH (14 × 3.5 μH). The impulse wave with the voltage peak of 2.2 MV is simulated. The voltage divider is modeled with capacitances C2 = 626.25 pF and C3 = 973.8 nF. The transformer under test is modeled with inductance 100 mH and capacitance 5 nF in parallel. The connection line between the impulse generator and the chopping gap is modeled with the inductance of 12 μH on the HV side. On earth side, the chopping gap and the impulse generator are usually connected with a strip or braid of low inductivity. Additionally, there is also current return path through the Faraday cage. All together, current return path on the earth side is of low inductivity. The current return path conductors are defined with the inductance of 0.36 μH and the resistance of 0.12 mΩ.

The length of the connection line on the HV side, from the chopping gap to a transformer under test, is 10 m and it is modeled with the inductance of 10 μH. On the earth side, the current path is modeled with the inductance of 0.3 μH and the resistance of 0.1 mΩ. Chopping of lightning impulse occurs at 4 μs and the chopping gap is modeled with the switch and the arc resistance of 1 Ω. Parts of the fundamental earthing grid for the EMTP-ATP [7] simulation are modeled with concentrated parameters as depicted in Fig. 5. Each branch of earthing grid is replaced with its corresponding π-circuit. Values for G, L and R are dependant on a length of the branch. The ATP model of complete grounding system of the test laboratory is shown in fig. 8.

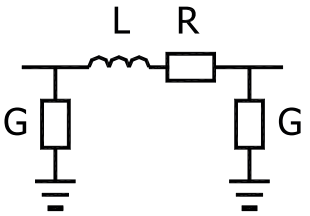

Fig. 5. Part of foundation earth grid electrode

A current which flows through the earth electrode from the transformer under the test to the impulse generator is shown in Fig. 6. Its first peak is the result of the impulse front and second one of the impulse chopping. This current produces transient potential differences between chopping gap and impulse generator earth points, as shown in Fig. 7.

Let us examine theoretically the worst case, when a conduit for secondary test cables, bonded with Faraday cage copper net at one end, is laid in parallel to the earth current path between impulse generator and chopping gap. All calculated voltages and currents are peak magnitudes.

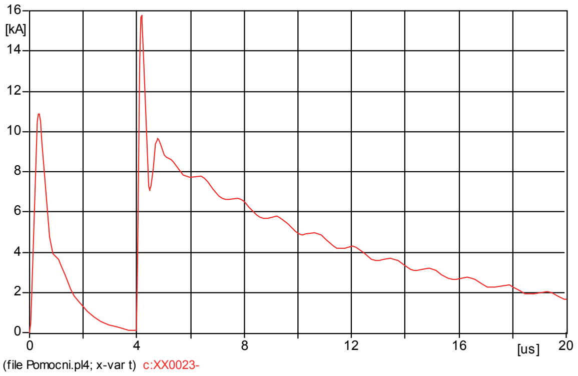

Figure 6. Return current flowing to the impulse generator through the floor copper grid

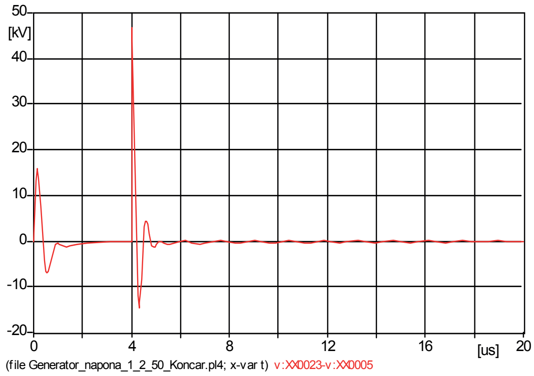

Figure 7. Transient potential difference between earth points of the sphere chopping gap and the generator, U_{max} = 46,8 kV

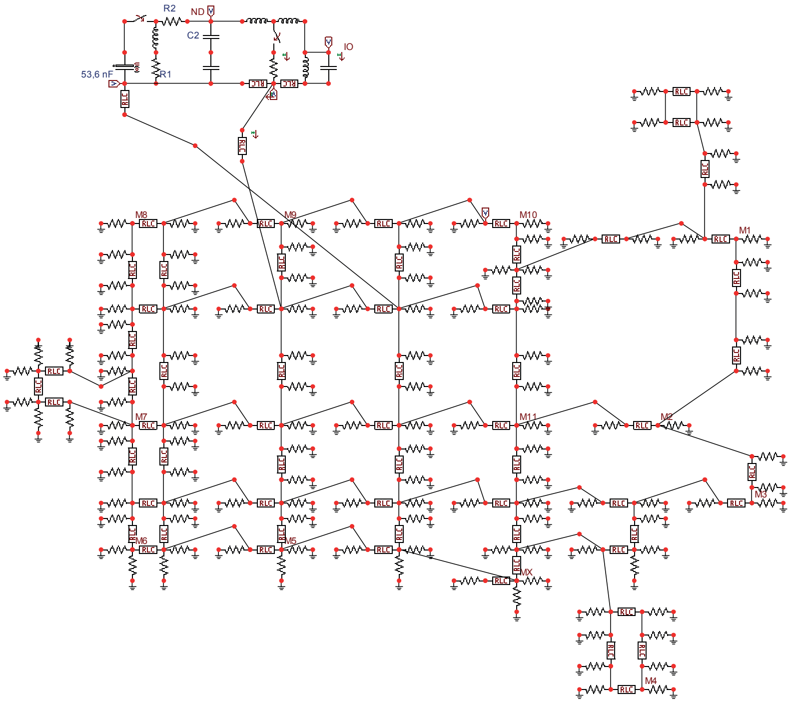

Figure 8. ATP model of impulse generator connected to foundation grid earth electrode

Induced voltage developed across such an open loop may be calculated, using the method described in [3], using the formula:

$$U_{cg} = (j\omega \cdot L_{\sigma} + j\omega \cdot M_{g}) \cdot \ell \cdot I_{g} = 2{,}63MV \tag{1}$$

where are: $j\omega \cdot L_{\sigma} \cdot \ell \cdot I_{g} \approx U_{maks} = j46{,}8kV$ (Fig. 8.)

$\omega = 2 \cdot \pi \cdot 1{,}845 = 11{,}6MHz$

$\ell = 12m$ - conduit length

$L_{\sigma} \approx 1{,}7 \cdot 10^{-7}\, H/m$ - external inductance of a conductor in the copper grid

$M_{g} \approx 94 \cdot 10^{-7}\, H/m$ – mutual inductance between the copper grid and the conduit

Mutual inductance between the copper net and the conduit depends, first of all, on geometric dimensions of the expanded net and its meshes and vertical clearance between the net and the conduit. When the conduit is earthed at both ends, current flowing through such a loop is defined by the expression:

$$I_{cg} = \frac{U_{cg}}{Z_{Th}} = 76kA \tag{2}$$

where is: Z_{Th} - Thevenin impedance of the circuit [3].

Voltage along a steel conduit at HF transient may be calculated by means of formula:

$$U_{r} = I_{s} \cdot R_{s} \tag{3}$$

where are: $I_s = I_{cp} = 76\ kA$ – the current flowing through the conduit;

R_s – transfer resistance of the conduit.

While for non-ferrous materials with high conductivity (Cu, Al) resistance R_s decisive for calculation of induced voltage peak magnitudes caused by HF transient currents with steep slopes is practically equal to ohm resistance, by ferrous materials this resistance has up to five times lower value (16% of resistance against direct current for the example presented in [8]). With regard to the calculation complexity and earth electrode configuration of test laboratory (copper net, foundation earthing grid, concrete armouring), it is performed with DS resistance value, i.e.:

$$R_i = \frac{\rho \cdot l}{\pi \cdot s \cdot (s + 2r)} = 0{,}71 m\Omega \qquad (4)$$

where are:

$\rho = 130\times10^{-9}\Omega$m specific steel resistance
$s = 4{,}5\ mm$ conduit wall thickness
$r = 75\ mm$ internal conduit radius

Finally, inserting $R_i = R_s$ in (3), voltage level at the conduit in case it was made of non-ferrous material is obtained:

$$U_r = 76 \cdot 10^3 \cdot 0{,}71 \cdot 10^{-3} = 54V \qquad (5)$$

In accordance with stated, peak voltage magnitude expected to be induced in the steel conduit will be up to five times less, i.e. of the order of 10 V. The resistance R_s of the armour material for transient HF impulse currents is decreasing with lower resistance ρ and higher relative permeability μ_r. As for ferromagnetic materials μ_r is significantly higher then 1 (for steel 200 ... 300), without considering relatively high specific resistance ρ, steel conduits are very efficient armouring against magnetic field penetration and present almost entire protection for signaling cables against electromagnetic interference, i.e. transfer inductive resistance conduit - conductor $Z_t \approx 0$ H/m.

The most effective armouring for the entire frequency range is achieved by double armouring – a metallic conduit earthed at both ends and a cable screen earthed at one end, where signaling circuit is earthed too, strictly considering user manuals for test and other equipment.

5. CONCLUSIONS

The design and construction of a new industrial high voltage test laboratory demanded solving of EMC problems.

The double wall with an air space is designed in order to provide required level of protection against external electromagnetic and noise interferences. Sheets of outside wall cladding are galvanically joined. The inner Faraday cage of copper and metal net is designed as an additional electromagnetic screen.

The analysis results of transient potential differences indicate that crucial role for their reduction has the inductance of the return current path. Prevention of dangerous high induced voltages in measuring circuits may be achieved by laying of cables through conduits made of ferrous materials bonded at both ends, with minimal distance between the conduit and the floor net. Accordingly, for transient potential differences reduction, mutual bonding of all metal parts using low inductance connections (strips, braids) is of utmost importance.

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