# Factors influencing the probability of an apparatus damage in an extended earthing arrangement

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*Abstract*—In the present paper lightning overvoltages on apparatus bonded to an extended earth arrangement are investigated. A case study of a large earthing grid (200m x 200m) covering an industrial plant is considered where a stand-alone power supply system (no connection to external lines) is supplying apparatus powered by a secondary board, earthed to a different point from the main distribution board. The values of the stressing voltage on the apparatus due to resistive coupling, the protection measures to be adopted according to the different characteristics of the lines connecting the distribution boards, and the probability of apparatus failure are evaluated. The analysis, performed by several simulations by means of the transient software EMTP-RV, show that protection against lightning of structures and of industrial plant may require the adoption of technical solutions that, even if in accordance with standards [1-4], need a particular study.

*Keywords—Overvoltage protection; Surge Protective Device; Apparatus safety;*

## I.    INTRODUCTION

Protection against lightning of structures and of industrial plant may result in the adoption of technical solutions that, in accordance with standards [1-4], require a particular study.

In the dispersion of the lightning current to ground through an earthing arrangement, in addition to its resistance and its conductance to ground, also the inductance and the capacitance to ground play an essential role. The influence of grounding conditions on apparatus to be protected and subjected to surges due to resistive coupling for an extended earth arrangement shall to be investigated.

Apparatus to be protected is earthed at an equipotential bonding bar (*EBB*) different from the main bonding bar at which the SPD1, installed at the line entry point into the structure (main switch board) for the protection of distant apparatus, is connected.

In previous contribution [5] meshed earth-termination in different soil resistivity (type B of standard IEC/EN 62305-3) has been investigated. The values of the conventional earth impedance Z as function of soil resistivity $\rho$ for a meshed earth-termination complying with IEC 62305-3 have been calculated.

Aim of the present contribution is to provide information on proper selection of measures in order to achieve protection, with a given probability, for apparatus subjected to surges due to resistive coupling in an extended earth-termination. A meshed earth-termination in a soil of resistivity $\rho = 100$ $\Omega$m (type B of standard IEC/EN 62305-3) and lines of different characteristics connecting the *MB* to *SB* have been investigated.

The analyses have been performed by several simulations obtained by means of the transient software EMTP-RV. Results are presented and discussed and some practical conclusion are drawn.

## II.    CASE STUDY UNDER CONSIDERATION

The case under consideration consists of a large industrial plant where apparatus are supplied by a Secondary Distribution Board (*SB*) earthed to meshed earth-termination system in points different from the Main Distribution Board (*MB*) (see Fig. 1). In these cases a direct stroke to the *MB* causes a warpage of the equipotentiality of the earth-termination and then a voltage stress on the apparatus connected to *SB*. This phenomenon is usually disregarded where the secondary distribution boards are earthed at the same point of the *MB*.
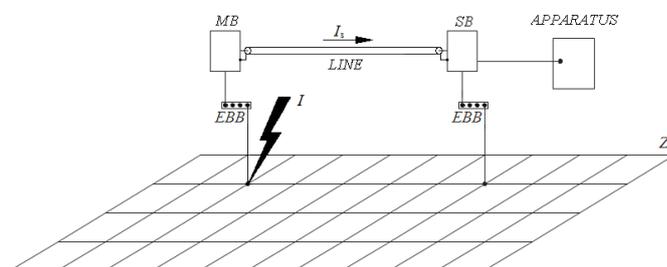


Figure 1.   Example of circuit diagram where a stand-alone power supply system (no connection to external lines) is supplying apparatus powered by a *SB*, earthed to a different point from the *MB*.

Lightning current I flowing on the earth-termination of a structure protected by an LPS where the Main Distribution Board (*MB*) is installed, gives rise to an earth-termination voltage $U_{TOT} = Z\,I$, being Z the conventional impedance of the

earthing arrangement. The conventional impedance $Z$ depends on the point where the lightning current is injected in the earth-termination and on the number and characteristics of circuits bonding different points of earth-termination, which can bridge parts of earth-termination itself ; moreover due to warpage of the equipotentiality of the earth-termination, the earth-termination voltage assumes different values from point to point of the meshed grid. The voltage drop on the earth-termination represents a strong stress for the apparatus to be protected because easily reaches the value of some tents kV even in earth-termination with low value of $Z$, taking into account that the lightning current amplitude is higher than 3 kA with a probability of 99% [5].

The value of the stressing voltage on the apparatus depends on the soil resistivity, on the characteristics of the earth-termination and of the number of lines connected to the MB and the probability of apparatus failure depends also on protection measures provided.

For the case under consideration, the values of the voltage on the apparatus to be protected and the probability of damage are evaluated in two conditions, namely:

*A. Lines connecting the MB to the SB are not shielded*

In this case the value of the voltage $U$ stressing the apparatus is equal to the voltage drop ($U=U_Z$) between the two points of the earth-termination where the two boards are connected; the voltage is so high that often suitable surge protective devices (SPD) should be installed on the *SBs* for the protection of the apparatus.

If the SPD are properly installed according to the standards [1, 4], namely:
- connecting leads of SPD no longer than 0,5 m,
- circuit between SPD and apparatus to be protected as short as possible with live and PE conductors routed in the same cable or in the same conduit,

then the voltage drop $\Delta U$ on connecting leads of SPD, the induced voltage $U_i$ and the propagation phenomena on the circuit between SPD and apparatus can be disregarded and an SPD with protection level $U_P$ slightly lower than the impulse withstand voltage $U_W$ of apparatus can be selected. According to [6-8], $U_P \leq 0,8\ U_W$ is an adequate safety margin.

Then, the probability $P$ of apparatus failure coincides with the probability $P_{SPDQ}$ that the SPD will not withstand the charge stress that occurs in the place of installation [6].

In this case, the problem is to select the characteristics of the SPD in order not to exceed the required probability $P$ of apparatus failure.

*B. Lines connecting the MB to the SB are shielded*

In this case the voltage $U$ stressing the apparatus is equal to the voltage drop on the resistance $R_S$ of the screen of the cable due to the part of current $I_S$ flowing along the screen ($U = R_S \cdot I_S$) and this value is therefore the smaller, the larger is the cross section of the screen and lower is the length $L$ of the cable and the value of the current $I_S$.

Then, the probability $P$ of apparatus failure coincides with the probability $P_U$ that the voltage drop on the resistance $R_S$ of the screen of the cable will overcome the impulse withstand voltage $U_W$ of apparatus.

In this case the problem is to select the characteristics of the cables screens in order to exceed the rated impulse withstand voltage $U_W$ of the apparatus with the required probability $P$ of apparatus failure. As a consequence the installation of SPD system could be avoided.

III.    TRANSIENT BEHAVIOUR OF EARTH-TERMINATION

The transient behaviour of earth termination systems has been extensively investigated in previous papers [9-22] through experimental tests as well as analytical investigations by means of computer simulations.

In previous contribution [5] meshed arrangements earthed in different soil resistivity (type B of standard IEC/EN 62305-3) has been simulated by means of a network of π elements consisting of a capacitance $C$, an inductance $L$ and a resistance $R$. It was recognized that for values of soil resistivity $\rho$ non greater than 3000 Ω m and for typical dimension of earth conductors of the earth-termination, the transient behaviour of the earth-termination becomes predominantly inductive, the more so the lower is the resistivity of the soil and the shorter the rise time of the lightning current. The model validity has been confirmed on the base of experimental results presented in [9-10] up to ten of MHz relative to lightning currents as proposed in [1].

Waveshapes of lightning current, namely representative of first stroke of positive flashes (10/350 μs), first stroke of negative flashes (1/200 μs) and subsequent stroke of negative flashes (0,25/100 μs) have been considered and simulated by the so-called Heidler function [1].

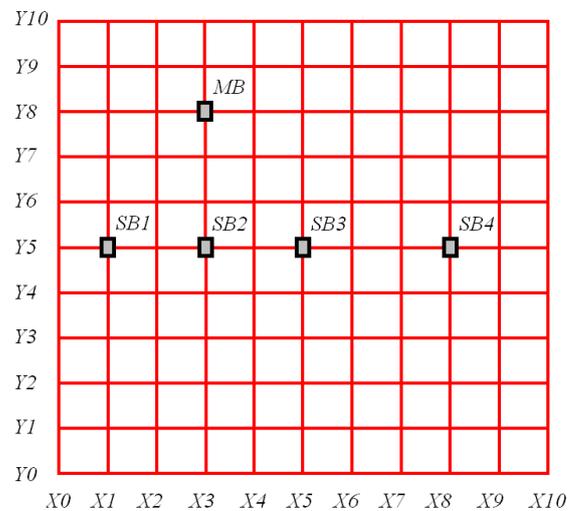Several simulations obtained by means of the transient software EMTP-RV, were performed.



Figure 2.   Ground grid used for the simulation.

The same simulation methodology has been applied to the case under study where a meshed network 20m x 20m of total dimensions 200m x 200m in order to cover the whole area of the industrial plant under consideration, is earthed in a soil of resistivity $\rho = 100$ $\Omega$ m. In the Fig. 2 the position of the *MB* is identified by the coordinates $x = 3$ m and $y = 8$ m; the four *SBs* are placed at coordinates *SB1* $x = 1$ m and $y = 5$ m; *SB2* $x = 3$ m and $y = 5$ m; *SB3* $x = 5$ m and y = 5 m; *SB4* $x = 8$ m and $y = 5$ m.

The conventional impedance of the earth-termination depends on the point where the lightning current is injected; in the case under consideration, it is assumed that the current is injected where the *MB* is positioned.

Results of simulation show that in the case of direct strike to the *MB*, placed at point $x = 3$ m and $y = 8$ m of the earth-termination, the values of the conventional impedance are:
- $Z = 1,2$ $\Omega$    for positive flash
- $Z = 2,5$ $\Omega$    for first stroke of negative flashes
- $Z = 4,05$ $\Omega$ for subsequent stroke of negative flashes

If the values of current amplitude associated to the lightning protection level I (LPL I), according to the standard IEC/EN 62305 are assumed, namely :
- 200 kA for positive flash;
- 100 kA for first stroke of negative flashes;
- 50 kA for subsequent stroke of negative flashes,
the earth-termination voltage $U_{TOT} = Z\,I$ is :
- $U_{TOT} = 240$ kV for positive flash;
- $U_{TOT} = 250$ kV for first stroke of negative flashes;
- $U_{TOT} = 202$ kV for subsequent stroke of negative flashes.

Note that the positive flashes and the first stroke of negative flashes represent the most severe cases for the apparatus to be protected connected to an *SB*.

In Fig. 3 and in Fig. 4 the maximum values are shown (respectively in 2D and 3D graphics) of the voltage $U_{TOT}$ which can be measured for direct strike to the *MB* by a positive flash of 200 kA.
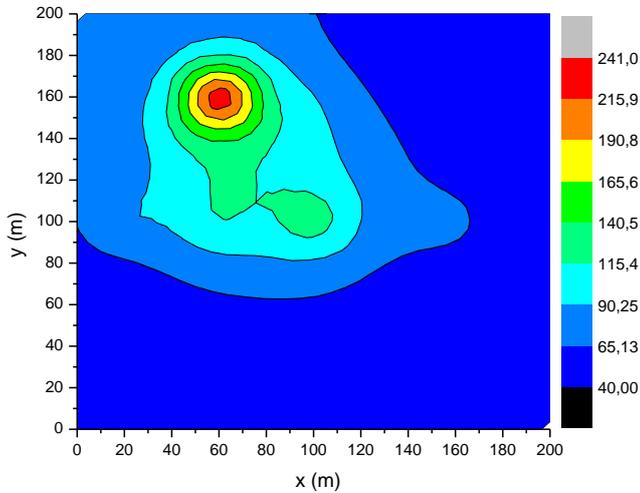


Figure 3.   Trend of the voltage $U_{TOT}$ due to the current of 200 kA (positive flash) on the *MB*; soil resistivity $\rho = 100$  $\Omega$ m.
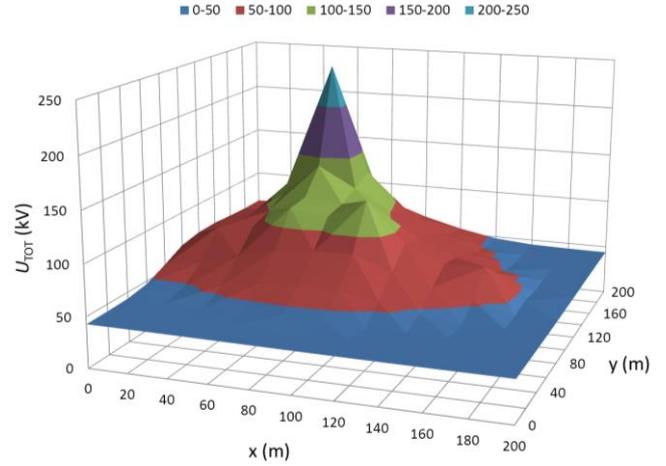


Figure 4.   Trend of the voltage $U_{TOT}$ due to the current of 200 kA (positive flash) on the *MB*; soil resistivity $\rho = 100$  $\Omega$ m.

## IV.   CURRENT AND VOLTAGE VALUES ON THE CONNECTING CABLES

For a current of 200 kA of a positive flash and of 100 kA of first stroke of negative flash, both referred to LPL I according to the International standard [1], in Table 1 are reported:
- the voltage value $U_{TOT}$ at the equipotential bonding bar where the *MB* or the *SBs* are connected;
- the values of the current $I_S$ flowing on the screen of the cables connecting the *SBs* to the *MB*;
- the values of charge $Q_S$ associated to the current $I_S$, needed for the SPD dimensioning, if needed.

TABLE I.       DIRECT FLASH TO THE *MB*. VALUES OF VOLTAGE $U_{TOT}$, CURRENT $I_S$ FLOWING ON THE CABLE SCREEN AND CHARGES $Q_S$ ASSOCIATED TO CURRENTS $I_S$. VALUES RELEVANT TO PROTECTION LEVEL I (LPL I).

| Parameter | MB | SB 1 | SB 2 | SB 3 | SB 4 |
|---|---|---|---|---|---|
| $U^+_{TOT}$ (kV) | 240 | 88 | 115 | 130 | 75 |
| $U^-_{TOT}$ (kV) | 250 | 69 | 105 | 120 | 68 |
| $I_S^+$ (kA) | -- | 9,7 | 8,2 | 17,3 | 11,4 |
| $I_S^-$ (kA) | -- | 4,7 | 3,9 | 8,2 | 5,3 |
| $Q_S^+$ (C) | -- | 5,4 | 4,6 | 9,8 | 7,6 |
| $Q_S^-$ (C) | -- | 1,4 | 1,2 | 2,6 | 1,9 |

## V.   PROBABILITY OF DAMAGE OF APPARATUS CONNECTED AT SECONDARY DISTRIBUTION BOARD

As mentioned in Section 2, two practical cases have to be considered:
- lines connecting the *MB* to the *SB* are not shielded or, if shielded, the shield is not connected to the bonding bars of both boards;
- lines connecting the *MB* to the *SB* are shielded and the shield is connected to the bonding bars of both boards.

At the assumption that the rated impulse voltage is $U_W = 2500$ V for power apparatus, plots are reported in Fig. 5 relevant to the probability of apparatus damage $P$ as a function of $I_{imp}$ of the selected SPD class I test, where the cable between the apparatus and the $MB$ is not shielded.
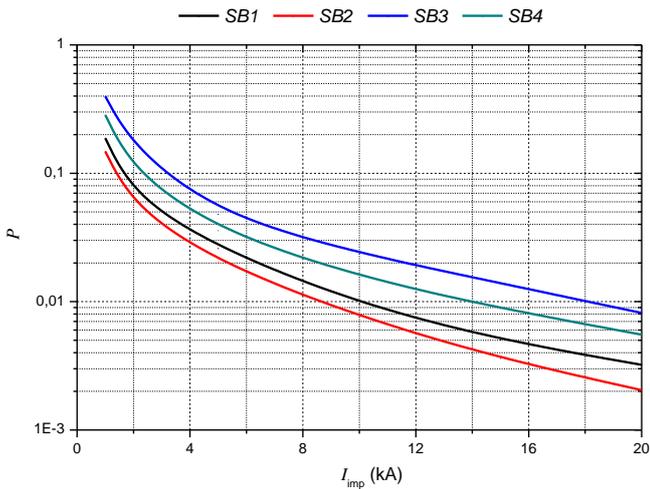


Figure 5. Probability of apparatus damage $P$ as function of $I_{imp}$ of the SPD class I test where the cable between the apparatus and the $MB$ is not shielded.

In Fig. 6 plots are shown of the probability of apparatus damage $P$ as function of screen resistance $R_S$ of the cable connecting the apparatus to the $MB$, where bonded to the earth-termination in two different $EBB$.
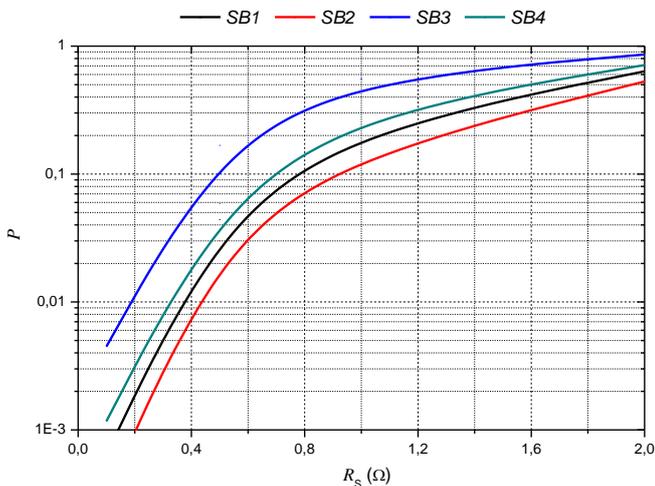


Figure 6. Probability $P$ of apparatus damage as function of screen resistance $R_S$ of the cable connecting the apparatus to the $MB$, where bonded to the earth-termination in two different $EBB$.

## VI. CONCLUSIONS

The obtained results allow to draw the following conclusions:

- in electrical systems with extensive earth-termination systems, very high overvoltages may stress apparatus powered by $SB$ connected to the earth-termination points other than the one which is connected to the $MB$, even with highly meshed earth-termination with low conventional impedance;

- the highest values of voltage on the apparatus are obtained when the lines connecting the $MB$ to the $SB$ are unshielded or, if shielded, the shield is not connected to the bonding bars of both boards; in that case an SPD system must be installed for apparatus protection. In stand-alone electrical system or in system connected to mains via isolating interface, the values of current and charge reported in Tab. 1, as well as the plot of Fig. 5, may be useful to dimension this SPD system; in the other cases, such current and charge should be combined with the one belonging to electrical system where the $EBB$ of $MB$ and of $SB$ are bonded to the earth-termination at the same point [6,7];

- in stand-alone electrical system or in system connected to mains via isolating interface, lower values of the overvoltage can be obtained if the lines connecting the $MB$ to the $SB$ are shielded and the shield is connected to the bonding bars of both boards; as shown in Tab. 1 and Fig. 6, with a suitable sizing of cable screens the probability of failure of the apparatus can be reduced to acceptably low values without necessarily resorting to the installation of the SPD.

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