Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania



# The Effects of Lightning Induced Overvoltages on Low Voltage Power Networks

M. Costea, *Member, IEEE*, and B. Nicoară

***Abstract*** **– The issue of lightning induced overvoltages in distribution networks has been treated in numerous works. Approaching of various models and accepting simplified assumptions allowed the calculation of their parameters and comparison with experimental data. Thus, about the amplitude and shape of induced overvoltages a relative consensus exists although research is still far to be completed.**

**The paper discusses only how the overvoltages induced by lightning in distribution networks can affect the end user, connected to a low voltage network, after having traveled along an overhead line and passed through step-down transformers. It studies a real network configuration case and analyses the opportunity of arresters disposal both on the low voltage transformer terminals and to the end user connection point and also the necessity of own user ground. The conclusion is that these combined measures ensure the protection of the user, regardless of the distance at which it is situated relating to the point where induced overvoltages were injected.**

*Index Terms*- **lightning-induced overvoltage; conducted disturbances; low voltage surge arrester.**

## I. Introduction

The lightning induced overvoltages, by their relatively reduced amplitudes (the probability to surpass 300 kV is negligible for distribution lines), can lead to insulation breakdown only for medium and low voltage overhead lines. They are considered responsible for large majority of insulation breakdown of distribution powerlines, because of high frequency lightning stroke near the line, compared with the localization directly on its elements. The shape of these overvoltages differs substantially from the lightning current generating them. The majority of the studies lead to the conclusion that the appropriate shape is an impulse having usually a front up to about 1 μs and duration to half amplitude of few μs [1]-[3]. Other lightning-induced overvoltage parameters, the behavior of the line insulation, the importance of adequate modeling of various elements of the network were also presented in numerous papers, using simulations [4]-[8], or scale model [9].

Even in the case that no breakdown is produced, because of a low amplitude, smaller than the insulation level withstand (should be noted that the 50% breakdown voltage of MV external insulation is higher for short tail lightning impulses than the standard lightning impulse, [10]), these overvoltage can seriously affect the end low voltage user because of their propagation on the line and the transmission through step-down power transformer.

The paper studies only the problem of lightning induced overvoltage transmission from the medium voltage network to the point of connection of low voltage consumer. In the low voltage networks, the overvoltages having lightning as origin create very often significant damages if no adequate protection is taken. The aim was to identify the influence factors (and theirs weight) on the amplitude and temporal parameters of the overvoltage arriving at the point of connection of low voltage consumer, in order to adopt adequate measures to reduce the dielectric stress of their insulations at the accepted standardized level [11]. Such a study is required in order to ensure, through appropriate means and methods, an acceptable power quality level to the low voltage consumers, because of the diversification of the equipment used and with increasing of their susceptibility to conducted disturbances. As a result, it was analyzed the influence of the propagation distance of lightning induced overvoltage through medium voltage overhead lines, the values of common ground – for both medium and low voltage equipment – in the transformer sub-station (usual practice in Romania), the length of the low voltage line, the effect of low voltage consumer load, the existence (and, in this case, the value) of a local ground to the consumer. It should be noted that the vast majority of low voltage networks in Romania are TN-S type, and the existence of a local ground to end user in order to ensure the electric safety is not imposed. Another practice commonly met in Romania is that the terminals of low voltage step-down transformers are not protected with arresters, the protection against overvoltages being adopted only at the medium voltage terminals of transformers.

## II. The Network and Its Model Description

Simulations were carried out using the software package ATP-EMTP with data entry parameters of the real lines and transformers considered, the scenarios being considered also realistic and taking into account the possible configurations of the network in operation. The network topology is also a real one for which there was reported numerous incidents associated with lightning storms.

M. Costea is with Politehnica University of Bucharest, Power Engineering Faculty, Bucharest, 060042, Romania (e-mail: costea@el.poweng.pub.ro).

B. Nicoară is with Politehnica University of Bucharest, Power Engineering Faculty, Bucharest, 060042, Romania (e-mail: bnicoara@yahoo.fr).

978-1-4244-2235-7/09/$25.00 ©2009 IEEE

The analyzed network is made up of overhead and cable power line with the rated voltage of 20 kV (figure 1). The studied medium voltage line supply two identical transformer substations (having a single transformer of 250 kVA, 20/0.4 kV, Dyn winding connections) located at different distances (one of them at 70 m and powered by a cable line and the other at 31 km, connected via an overhead line) from the 20 kV busbar. The 20 kV network is powered by an overhead line of 110 kV rated voltage from the national power grid. Each transformer substations supply a local low voltage network.

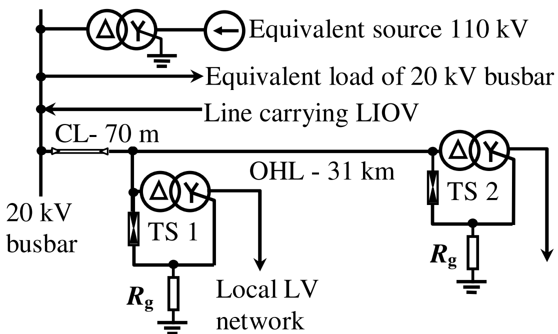


Fig. 1. Equivalent diagram of the studied network (used acronyms: CL –cable line; OHL – overhead line; LIOV- lightning induced overvoltage; TS – transformer substation).

All power lines, except those of low voltage were considered by their distributed parameters, the data being rigorously known. For transformers a three leg core saturable power transformer model was adopted in addition with a capacitor network (as shown in figure 2) known by low frequency measurements.

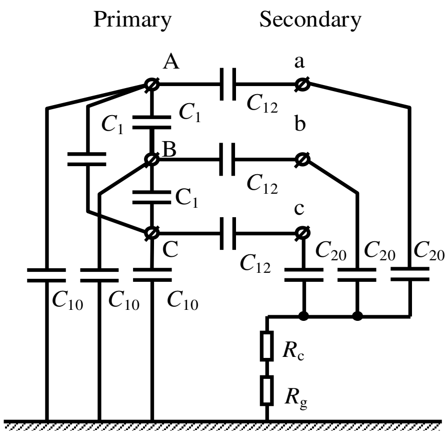


Fig. 2. The capacitances added to complete the saturable power transformer (250 kVA, 20/0,4 kV) model in ATP-EMTP ($C_1$ = 5 nF; $C_{10}$ = 0.5 nF; $C_{12}$ = 5 nF; $C_{20}$ = 10 nF; $R_c$ – the resistance of neutral conection to ground; $R_g$ – the resistance of ground, 4 Ω).

The model for arresters was a metal oxide type without spark gaps (type 92). The connections to ground and the ground were considered to be invariable resistors, an optimistic hypothesis regarding their behavior in transient regimes. The LV consumer is supplied by mean of a overhead line (typical for the rural distribution) having 100 m.

The paper did not approach the issue of the coupling between the lightning channel and the medium voltage line. The induced overvoltage is considered having an impulse shape with short tail (1/5 µs) and the amplitude equal to the withstand voltage of the line insulation (125 kV), al three phases being equally stressed. The point of overvoltage injection was considered the 20 kV busbar of the 110/20 kV substation, one of the overhead line being the source of overvoltage. It was also performed, based on manufacturer data, an analysis of arrester behavior, taking into account multiple possible values of current impulses, less, equal or greater than its rated current. The main parameters of the transients (amplitude of voltages and currents) are noted as shown in figure 3.

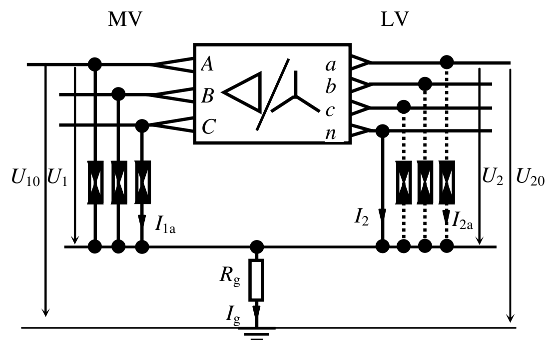


Fig. 3. The notations of main studied parameters at each transformer substations (MV- medium voltage terminals; LV-low voltage terminals; Rg- resistance of ground).

## III. The simulation results

### A. Transient voltage amplitude analysis

The main results of the simulation are presented in two tables: in the Table I, the amplitude of the voltages between the medium voltage terminals and ground ($U_1$) and, respectively, reference ground ($U_{10}$) and also between the low voltage terminals and ground ($U_2$) and, respectively, reference ground ($U_{20}$) for the case without low voltage arresters connected at secondary. The surge arresters connected at the medium voltage terminals of the transformers have 10 kA rated current and residual voltage 81.6 kV.

The actual current through MV arresters is $I_{1a}$ , through neutral connection to ground is $I_2$ , and through LV arresters (if they exist), $I_{2a}$ . The Table II shows the voltage amplitudes in the case with low voltage arresters (having clamping voltage $U_p$=1.8 kV and rated current 10 kA, 8/20 µs) connected at the secondary terminals of the step-down transformer. The transformer substation located in the vicinity of the 20 kV busbar is noted TS1, and that located at 31 km and supplied by an overhead line is noted TS2.

One can observe that without arresters, for TS1, the peak differential voltage between a phase conductor and the neutral (connected to the common ground of the substation) can reach about 14 kV, the oscillations being damped after a time duration which did not exceed approx. 7 µs (figure 4).

TABLE I
THE AMPLITUDES OF TRANSIENTS VOLTAGES IN THE CASE WHEN NO ARRESTERS ARE CONNECTED AT LOW VOLTAGE TERMINALS OF TRANSFORMER SUBSTATIONS

| Transformer substation | $U_1$ | $U_{10}$ | $U_2$ | $U_{20}$ |
|---|---|---|---|---|
| | kV | | | |
| TS1 | 72.0 | 111.0 | 14.1 | 34.9 |
| TS2 | 51.0 | 52.8 | 4.1 | 5.6 |

A dangerous transient ground potential rise (above 30 kV) is transmitted to the neutral conductor. The amplitudes of the overvoltage at the secondary terminals of the transformer are considerably reduced for the TS2, located far away from the MV busbar. The duration of the transient process has the same order of magnitude as for TS1 (figure 5), but the amplitude of the phase to ground voltage is limited at 4 kV.

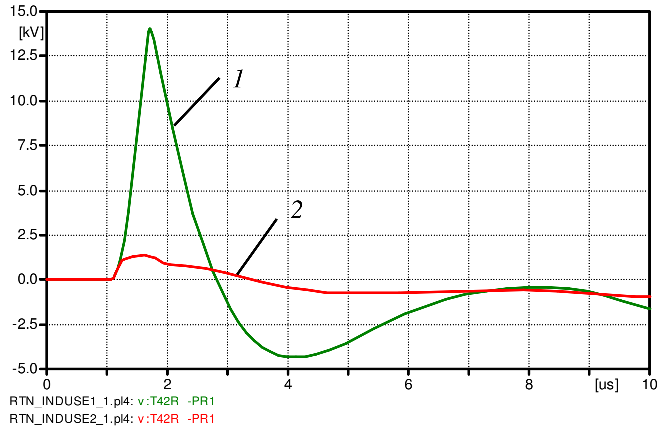


Fig. 4. Potential difference between low voltage terminal and neutral (connected to ground) at TS1: *1* - without low voltage surge arresters; *2* - with low voltage surge arresters.

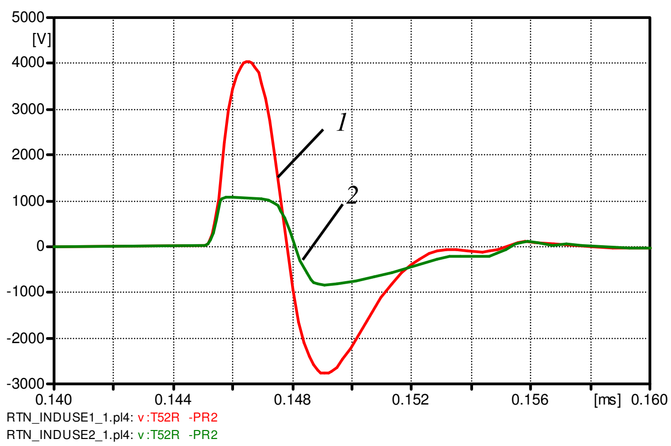


Fig. 5. Potential difference between low voltage terminal and ground at TS2: *1* - without low voltage surge arresters; *2* - with low voltage surge arresters.

After propagation over 31 km along the overhead medium voltage line, the amplitude of the overvoltage at primary terminals of TS2 transformer is reduced about 2.1 times.

If, for the TS1 the ratio between the primary and the secondary amplitude of the overvoltages reach as about 5.1, for TS2 this ratio increases up to 12.4. (Greater ratio means a diminished coupling between the primary and the secondary windings of the transformer.)

TABLE II
THE AMPLITUDES OF VOLTAGES IN THE CASE WHIT ARRESTERS CONNECTED AT LOW VOLTAGE TERMINALS OF TRANSFORMER SUBSTATIONS

| Transformer substation | $U_1$ | $U_{10}$ | $U_2$ | $U_{20}$ |
|---|---|---|---|---|
| | kV | | | |
| TS1 | 72.1 | 111.0 | 1.3 | 38.6 |
| TS2 | 51.1 | 52.9 | 1.1 | 2.7 |

Then, for the closer transformer to the initiation point of the overvoltage, the lowest ratio of the voltage amplitudes was recorded and no association with the transformer ratio (at power frequency voltage) can be made in the case of fast transient voltage applied to the primary windings. A sensitive factor in the overvoltage transmission between the transformer windings is the value of the coupling capacitance $C_{12}$ (fig. 2). Some simulations have shown that a larger capacitance increase the value of the transmitted voltage to the secondary winding, then an accurate value is very important to be introduced in the transformer model. Regarding the average steepness of the overvoltage it decreases by propagation along overhead line from 95 kV/µs at TS1 MV terminals to about 17 kV/µs at TS2 MV terminals, and consequently the overvoltage transmission ratio diminishes.

Connecting LV arresters at the secondary terminals of the transformer considerable reduces the differential voltage between phase and neutral (see Table II) for both transformers, but the transient ground potential rise for TS1 remains dangerous. In this case, the ratio between the primary and the secondary overvoltage amplitudes reaches about 55.5 for TS1, and about 46.5 for TS2, and then the effectiveness of LV arresters, for phase-neutral insulation, was demonstrated, the peak voltage at their terminals being less than 1.3 kV, even for the closest transformer to the overvoltage source. But the potential difference between each secondary terminals and reference ground are still very high for the TS1. Then, at the terminals of the low voltage consumer the common mode voltage could be converted in a dangerous differential voltage. As a result, an own ground to the consumer may be an efficient solution to reduce the transient voltage at which it can be subjected.

### B. Transient currents amplitude analysis

Using the notations presented in figure 3, the Table III shows the distribution of the transient currents for the case without LV arresters and the Table IV, shows the situation with arresters connected at LV terminal of the transformers.

In the case without arresters at the LV terminals, while the magnitude of current through the medium voltage arresters reaches about 3.3 kA, the amplitude of current through the neutral connection is about 1.8 kA for the transformer in TS1.

Other simulations performed with the lightning induced overvoltage source closer to the transformer demonstrate that the maximum peak current through the medium voltage arresters remains under 5 kA. For TS2, the ratio between the two currents is reversed: through the medium voltage arresters flows only 0.15 kA, while through the neutral connection about 0.38 kA. The explanation is given by the voltage-current characteristic of the MV arresters.

TABLE III
THE AMPLITUDES OF CURRENTS IN THE CASE WHITOUT ARRESTERS AT LOW VOLTAGE TERMINALS OF TRANSFORMER SUBSTATIONS

| Transformer substation | $I_{1a}$ | $I_2$ | $I_g$ |
|---|---|---|---|
| | kA | | |
| TS1 | 3.26 | 1.82 | 9.78 |
| TS2 | 0.15 | 0.38 | 0.46 |

TABLE IV
THE AMPLITUDES OF CURRENTS IN THE CASE WHIT LV ARRESTERS CONNECTED AT TERMINALS OF TRANSFORMER SUBSTATIONS

| Transformer substation | $I_{1a}$ | $I_2$ | $I_{2a}$ | $I_g$ |
|---|---|---|---|---|
| | kA | | | |
| TS1 | 3.30 | 0.35 | 0.72 | 9.82 |
| TS2 | 0.15 | 0.16 | 0.09 | 0.46 |

A delay of 2 μs is recorded between the peak values of these currents, the current through the neutral connection being the first, practically the same for both transformers (figure 6 shows the case of TS2). Because the capacitive coupling between the primary and the secondary windings is mainly responsible for the fast transients transmission, the current through the neutral connection will be proportional to the derivative of the voltage applied to the medium voltage terminals, which explains the difference between the moments of the maximum values for the currents flowing through the two connections to ground. The duration of the transient current are greater for those through the arrester connections, compared to neutral connection one. The explanation could be the same as above: the decrease of the voltage slope leads to faster decreasing of the current through the low voltage winding.

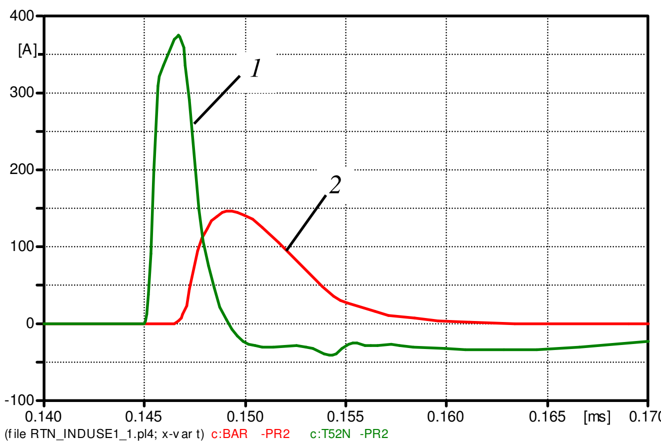


Fig. 6. The transient currents at TS2 through: *1* – medium voltage surge arrester; *2* - connection to ground of low voltage network neutral.

In the case when the surge arresters were connected to the low voltage terminals of the transformer, these will take over a part of the current flowing to the ground, the maximum reached values through them being in advance compared with the maximum currents through the medium voltage arresters connection to ground. Figure 7 shows the currents flowing through the connections to ground at the TS2 transformer.

The presence of arresters at the low voltage terminals of the transformer do not modify the value of the maximum current through the ground, then this can remain unchanged using such a solution and no supplementary costs to reduce the value of ground resistance of transformer substation will be involved. Of course, in order to reduce the insulation stress both for the medium and the low voltage equipment of the substation, a lower value of the ground must be had in mind.

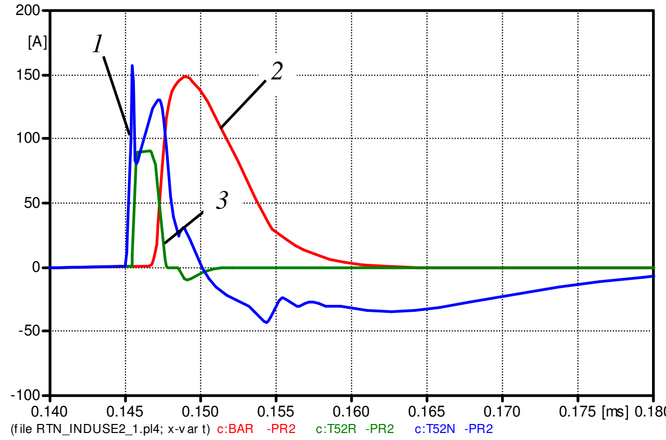


Fig. 7. The transient currents through TS2: *1* – connection to ground of low voltage network neutral; *2* – medium voltage surge arresters; *3* - low voltage surge arresters.

In the second part of the paper were analyzed the consequences of a local earthing at the low voltage consumer. From the step-down transformer, with low voltage surge arresters at the secondary terminals, to the end user it was considered a low voltage overhead line with a length of 100 m (cross section of conductors 35 mm$^2$).

The consumer is no protected with surge protection devices, in the first hypothesis, but a local ground exist. In this case at the connection point of the consumer supplied by the transformer located close to the MV busbar (TS1), it was found that the potential difference between phase and neutral riches about 34 kV if no load was connected. This value could be very similar with the voltage measured between neutral and reference ground in the transformer substation because of the resistive coupling between the ground of the substation and the consumer ground. A usual load (of 40 Ω) reduces substantially the overvoltage amplitude between the phase conductor and the neutral (figure 8). Then, the worst case regarding the amplitude of the transmitted overvoltage is if few consumers are at the same time connected to the low voltage distribution line or their overall load is reduced.

In the case of a transformer located away from the lightning strike point (TS2), the voltage between a phase and the neutral is reduced to no more than approx. 3 kV.

In order to ensure an adequate protection of the low voltage consumer installation, simulations were carried out including low voltage arresters at the connection point, combined with the consumer ground. Thus, even if the consumer is connected to the transformer nearby to the overvoltage initiation point, the voltage between a phase and the neutral is lowered substantially (reaching approx. 1.5 kV) and the potential difference between conductors and reference ground is not exceeding 11 kV (figure 9).

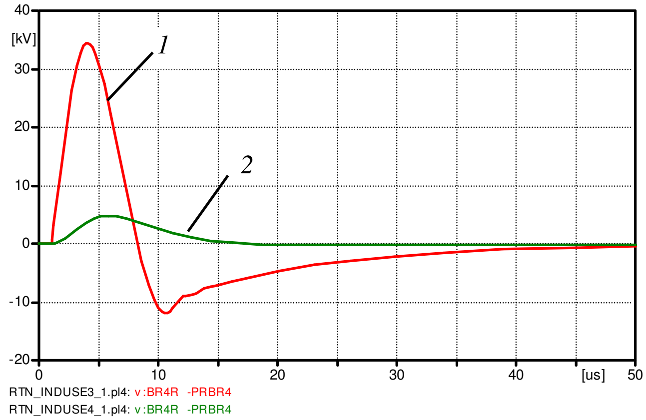


Fig. 8. The phase-neutral voltage at point of connection of low voltage consumer supplied by TS1: *1* – with no load connected; *2* – with a usual load of 40 Ω.

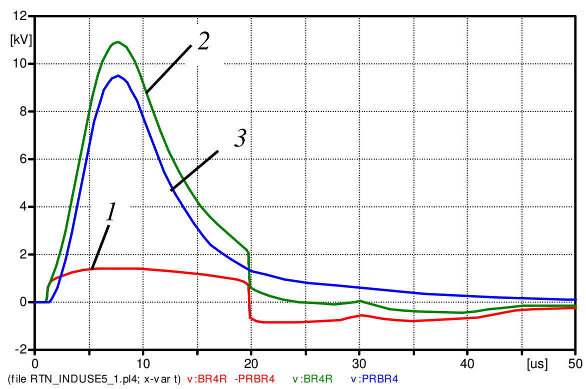


Fig. 9. The transient voltages at connection point of low voltage consumer supplied from TS1 between: *1* –phase-neutral; *2* – phase-reference earth; *3* - neutral-reference earth.

For the consumer supplied from the transformer located far from the overvoltage initiation point, the voltage between a phase and the neutral do not exceeding 1 kV. The benefits of the surge protective device and consumer ground, in order to limit the conducted overvoltages, were emphasized. In the figure 10 are shown the transient voltages at the connection point of the low voltage consumer supplied from TS2.

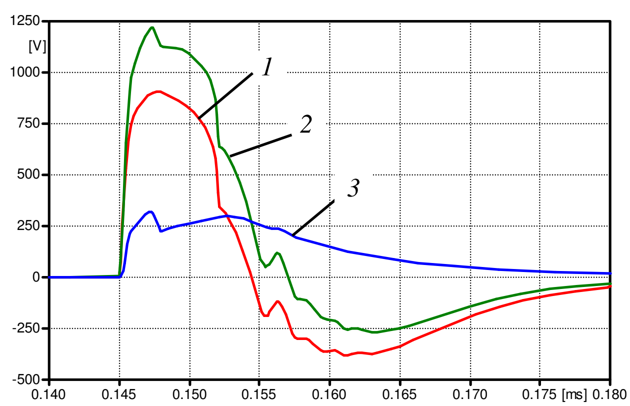


Fig. 10. The transient voltages at connection point of low voltage consumer supplied from TS2 between: *1* –phase-neutral; *2* – phase-reference earth; *3* - neutral-reference earth.

## IV. Conclusions

Even if a particular MV/LV network case was studied, can be drawn some general conclusions. The maximum stress for the low voltage insulation of the step-down transformer occurs if the lightning strike is located nearby and the amplitude values reache some tens of kV (about 20 % of the incident overvoltage). The diminution of this dielectric stress can be obtained by connecting low voltage arresters at the secondary terminals of the transformer. This solution could be applied without modifying the value of the ground because the same global current flows through it, only its distribution through the different connections is modified. The steepness of the overvoltage decreases by propagation along the MV distribution line and the ratio between the primary and the secondary amplitudes of the overvoltages transmitted through the transformer increases with the distance from the lightning strike. The parameters of the step-down transformer present an important influence on the overvoltage level transmitted to the low voltage network, particularly the coupling capacitances between windings. The most stressed low voltage network is that supplied by the nearest transformer to the striking point, particularly in the case when a reduced load is connected. The existance of a ground at the low voltage consumer do not solve the problem of overvoltage transmitted to him even in the case of low voltage arresters presence in the transformer substation, because of the transient ground potential rise and the resistive coupling between the ground of the substation and the consumer ground. Then, regarding the low voltage consumer, a combined set of measures (own ground and surge protection device at the connection point) lead to a reduced insulation stress.

## V. References


[1] C.A. Nucci and F. Rachidi, "Lightning-Induced Overvoltages," presented at the IEEE Transmission and Distribution Conference, Panel Session "Distribution Lightning Protection", New Orleans, USA, April 14, 1999.

[2] V. Cooray and V. Scouka, "Lightning-Induced Overvoltages in Power Lines: Validity of Various Approximations", *IEEE Trans. on Electromagnetic Compatibility*, vol. 40, no. 4, pp. 355-363, Nov.1998.

[3] M.T. Correia de Barros, J. Festas, M.E. Almeida, "Lightning induced overvoltages on multiconductor overhead lines", *Proc. of. Int. Conf. on Power System Transients*, Budapes-Hungary, June 1999, pp. 365-369.

[4] C.A. Nucci, F. Rachidi, M.V. Ianoz, C. Mazzetti, "Lightning-induced voltages on overhead lines" *IEEE Trans. on Electromagnetic Compatibility*, vol. 35, no. 4, pp. 75-86, Feb.1993.

[5] A. Borghetti, C.A. Nucci, M. Paolone, "Lightning performances of distribution lines: sensitivity to computational methods and to data", *Proc.. IEEE. Power Engineering Society Winter Meeting, 2001,* vol. 2, pp 796-798.

[6] M. Bemardi, A. Borghetti, C.A. Nucci, F. Napolitano, M. Paolone, F. Rachidi, R. Vitale, K. Yamabuki, "Lightning-Correlated Faults in Power Distribution Networks", *Proc. PowerTech 2007* Lausanne, Switzerland, 27-30 July 2007, pp.585-591.

[7] A. Borghetti, F. Napolitano, C.A. Nucci, M. Paolone, M., A.S. Morched, "Lightning-induced overvoltages transferred from medium-voltage to low-voltage networks", *Proc. PowerTech 2005* St. Petersburg, Russia, 27-30 June 2005, pp.1-7.

[8] M. Saran, M. Martinez, H. De Oliveira, C. Nucci, M. Paolone, "Performance analysis of medium voltage overhead distribution line against lightning", *19th Int. Conf. on Electricity Distribution*, Vienna, May 2007, Paper 0860, pp.1-4.

[9] A. Piantini, J.M. Janiszewski, A. Borghetti, C.A. Nucci, M. Paolone, “A scale model for the study of the LEMP response of complex power distribution networks”, *IEEE Trans. on Power Delivery*, vol. 22, no. 1, pp. 710-720, Jan.2007.

[10] A. Ancajima, I. Baran, M. Costea, A. Carrus, E. Cinieri, G. Dragan, C. Mazzetti, “Breakdown characteristics of MV distribution and electric traction lines insulators stressed by standard and short tail lightning impulses”, *Proc. PowerTech 2005* St. Petersburg, Russia, 27-30 June 2005, Rep.108, pp.1-7.

[11] *Insulation coordination for equipment within low voltage systems. Part 1: Principles, Requirement and Tests,* IEC 60664-1/2000.