# USING LOW VOLTAGE SURGE PROTECTION DEVICES FOR LIGHTNING PROTECTION OF 15/0.4 kV POLE MOUNTED DISTRIBUTION TRANSFORMER

Fernanda O. RESENDE
INESC TEC – Portugal
fresende@inesctec.pt

João A. PEÇAS LOPES
INESC TEC and FEUP – Portugal
jpl@fe.up.pt

## *ABSTRACT*

*This paper evaluates the transient behaviour of the pole mounted distribution transformers following fast-front lightning strikes arising the Medium Voltage (MV) network and the Low Voltage (LV) network. The effects of installing Surge Protection Devices (SPD) in the LV terminals of the pole mounted distribution transformer is also evaluated. For these purposes, the transient studies were performed using the EMTP-RV software. The results obtained demonstrate the effectiveness of installing SPD in the LV terminals of the transformer for improving its safe operation following fast-front overvoltages.*

## INTRODUCTION

Distribution networks comprising overhead lines may experience faults due to overvoltages following lightning strikes and, therefore system outages. In rural distribution networks, the pole mounted Distribution Transformer (DT) plays a key role within this framework [1]. Therefore, according to the common practices in distribution networks, the pole mounted DT are protected against fast-front overvoltages originating for lightning strikes arising the Medium Voltage (MV) network by surge arresters installed close to its MV terminals. However, transformer failures may also result from fast-front overvoltages developed on their Low Voltage (LV) terminals [2]. These overvoltages may occur, due to the overvoltages transferred from the MV windings following lightning strikes arising the MV overhead lines and due to lightning strikes arising the LV distribution networks [3]. To assure the full protection of the pole mounted DT, the installation of Surge Protection Devices (SPD) close to their LV terminals has been recommended [4].

The DT are designed and manufactured with a specified Basic Insulation Level (BIL) rating. The BIL rating determines the level of lightning surge voltages that the transformer can withstand without damage **Erro! A origem da referência não foi encontrada.**. Thus, the overvoltages developed on the LV terminals of the pole mounted DT are evaluated to verify whenever the peak overvoltages exceed the BIL of the LV windings.

This paper analyses the fast-front overvoltages developed at the LV terminals of a 50 MVA, 15/0.4 kV, pole mounted DT following lightning strikes arising both the MV and the LV distribution networks. These overvoltages depend on the lightning strike parameters, such as the time of surge impulse and the lightning peak current, as well as on the grounding resistances of both the DT and the client loads. The effect of installing the SPD on the LV side of the MV/LV distribution transformer is also evaluated. The EMTP-RV software is used to perform the transient simulations. The results obtained are discussed with respect to the BIL of the pole mounted DT.

## DISTRIBUTION SYSTEM MODELLING

To evaluate the transient behaviour of the pole mounted DT following lightning strikes arising at both the MV and LV distribution networks, a suitable test system was used to perform the time domain simulations. This test system is presented through the single line diagram depicted in **Erro! A origem da referência não foi encontrada.**.

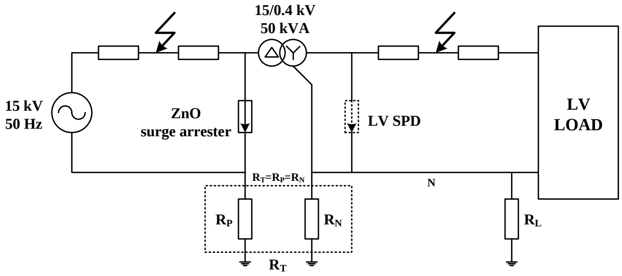


**Figure 1:** Single line diagram of the MV/LV distribution test system

As it can be observed from Figure 1, the implementation of the test system in the EMTP-RV software requires the implementation of suitable mathematical models of the main components. Also, the DT should be operated following the insulation coordination common practices.

### Mathematical models

Frequency dependent models were implemented in the EMTP-RV environment, exploiting the models available on the software library, aiming to represent the transient behaviour of the test system main components following fast-front lightning surges. These components include the pole mounted distribution transformer, the ZnO surge arresters installed at its MV terminals, the MV overhead lines, the twisted cable LV lines, the load representing typical costumers connected to the LV network and the SPD to be connected to the LV terminals of the pole mounted DT. The lightning surge model was also included in the simulation setup.

The DT is represented through the BCTRAN model combined with a $\pi$-equivalent capacitance model, as recommended in [3], [5] for purposes of addressing the overvoltages transferred through the DT. The BCTRAN model represents the DT behaviour at low frequencies and the π-capacitance represents the transfer of surges through the transformer at high frequencies. The π-capacitance model is based on the experimental measurements of the stray capacitances over a range of frequencies [3]**Erro! A origem da referência não foi encontrada.**. The values of the stray capacitances for the frequency of 100 kHz were chosen to represent the high frequency behaviour of the pole mounted DT as adopted in [1].

The surge arresters commonly used to protect the pole mounted DT are the Zinc Oxide (ZnO) surge arresters [7]. The model adopted to represent its transient behaviour follows the recommendations provided by the IEEE Working Group 3.4.11 [6]. It is composed by two sections of nonlinear resistances representing the nonlinearities of the ZnO varistors. The characteristics of the nonlinear elements are based on the nonlinear V-I characteristic presented in [7].

The MV overhead lines are represented through the frequency dependent line model available on the EMTP-RV software library. This model is based on modal decomposition techniques and represents the frequency dependence by approximating with rational functions the characteristic impedance of the lines and the propagation function for each mode following the J. Marti model [8]. The LV lines are also represented through a frequency dependent model to represent the LXS type conductors (twisted cables, multi-strand aluminium conductors with cross-linked polyethylene insulation). Their electrical characteristics can be found in [9].

The balanced three-phase LV load connected to the terminals of the LV distribution line is represented through a model based on the typical household load model proposed in [10]. This model was obtained based on measurements performed for frequency responses ranging from 5 kHz to 2 MHz of a typical household load and was also adopted in the transient studies performed in [1].

The lightning currents striking at both MV and LV lines are represented through the CIGRÉ current source available in the library of the EMTP-RV software connected in parallel with a resistance representing the resistance of the lightning current channel [11]. The analytical representation of the current shape is determined from the following parameters: The lightning peak current, the time of the surge impulse, the maximum steepness and the time to half value. The maximum steepness is determined as a function of the peak value of the lightning current, I (kA) as $Sm=3.9\times I^{0.55}$ [11]. A resistance of 400 Ω was considered to represent the lightning current channel.

The SPD to be installed at the LV side of the pole mounted DT is connected in parallel to its LV terminals [4]. The frequency dependent model (IEEE model) proposed in [6] was also adopted to represent the transient behaviour of the LV SPD. The LV SPD uses a compressed distribution grade ZnO varistors, so that the adopted mathematical model was based on the model available in the library of the EMTP-RV software, using data available in [4].

## Insulation coordination of pole mounted DT

The Figure 2 presents the typical configuration of a pole mounted DT following the Portuguese standards [7]. [7]

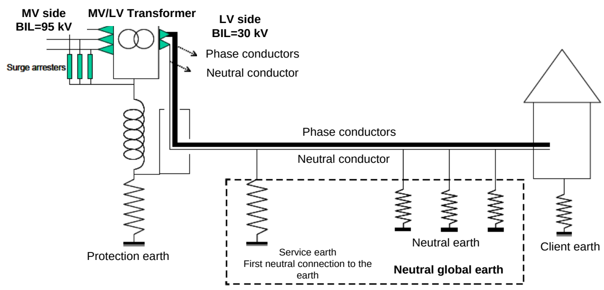


**Figure 2:** Typical configuration of a pole mounted DT with the protection and service earths separated [7]

The ZnO surge arresters are connected to the MV terminals of the pole mounted DT. No SPD are installed in the LV side of the DT. Also, the protection earth is separated from the neutral earth. The main requirements of this configuration are the following: The protection earth resistance should be lower than 20 Ω; The global resistance of the neutral earth should be lower than 10 Ω; The resistance of the first neutral to earth connection should be lower than 20 Ω; The distance between both the protection and the service earths is within the range of 20 to 50 meters. Therefore, it was assumed that these resistances ($R_T$) take the same value. The BIL of the MV windings of the DT is 95 kV and the BIL of the LV windings of the DT is 30 kV. No requirements are imposed to the client earth resistance ($R_L$).

However, in rural pole mounted DT, both the protection and service earth resistances usually are higher that the recommended practices. Sometimes, these resistances can exceed 100 Ω. Thus, it was considered that the grounding resistances of DT can vary in the range of 1 Ω to 100 Ω. Also, the grounding resistances are represented in time domain simulations through constant resistances [1]. The conductors used to connect the ZnO surge arrester to the MV side of the pole mounted DT are represented through concentrated inductances rated as 1µH/m [3], following the maximum distances defined in [7]. Also, the ground resistivity was 200 Ω-m.

# RESULTS AND DISCUSSION

## Lightning strikes arising the MV network

Lightning strikes arising the MV overhead lines may result in overvoltage surges developed at the MV terminals and transferred to the LV terminals of the DT. The effect of installing SPD was also evaluated. The above-mentioned overvoltages depend on the parameters of the lightning surges and on the resistances of both the protection and service earths. Therefore, these overvoltages were assessed considering increasing lightning peak currents and, for each lightning peak current, increasing grounding resistances of DT.

**Overvoltages arising at the MV side of the DT**

The waveforms describing the overvoltages observed on the MV windings of the DT are presented in Figure 3. These waveforms represent the effect of the lightning current following a 1/20μs, 5 kA lightning strike arising the MV network. The DT grounding resistance is equal to 20 Ω and no SPD are installed in the LV side of the DT.

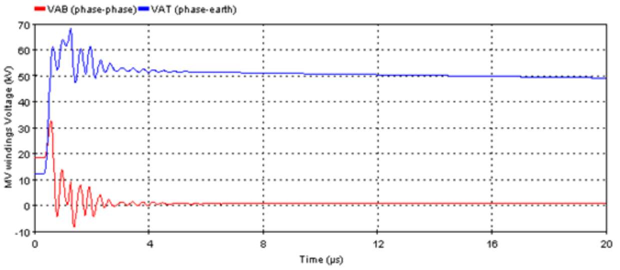


**Figure 3:** Waveforms of the overvoltages arising on the MV windings of the DT following a lightning strike arising the MV network

As it can be observed from Figure 3, a downward high frequency oscillations are superimposed to the peak of the impulse overvoltages due to the reflections of the travelling voltage waves [5]. Also, the phase-to-earth peak overvoltages is limited by the residual voltage of the ZnO surge arrester installed in the MV side of the DT. In turn, phase-to-phase overvoltages present a relatively small peak magnitude because it was assumed that, following direct strikes on the MV overhead lines, the lightning current waveforms present similar characteristics in the three phases of the lines. Therefore, the evaluation of the overvoltages arising at the MV side of the DT are based only on the phase-to-earth peak overvoltages.

The effect on the phase-to-earth peak overvoltages arising at the MV windings of the DT, considering the variations of the lightning current peak values and the transformer grounding resistance, are presented in Figure 4. Also, for comparison purposes, the BIL of the MV distribution network (95 kV) is presented through the dotted line. It can be observed that the phase-to-earth peak overvoltages arising at the MV windings of the DT increase with increasing lightning peak currents and trend to decrease with increasing transformer grounding resistances. Also, the BIL of the MV windings of the DT is exceed for lightning peak currents near to 17 kA when the transformer grounding resistance are lower than 20Ω.

**Overvoltages transferred to the LV side of the DT**

The evaluation of the overvoltages transferred to the LV windings of the DT are evaluated, considering that no SPD are installed in the LV side of the DT and with SPD installed in the LV side of the DT. Figure 5 presents the waveforms corresponding to the overvoltages transferred to the LV windings of the DT following a 1/20μs, 5 kA lightning strike arising the MV overhead lines, considering the transformer grounding resistance of 20 Ω, without SPD installed in the LV terminals of the DT.

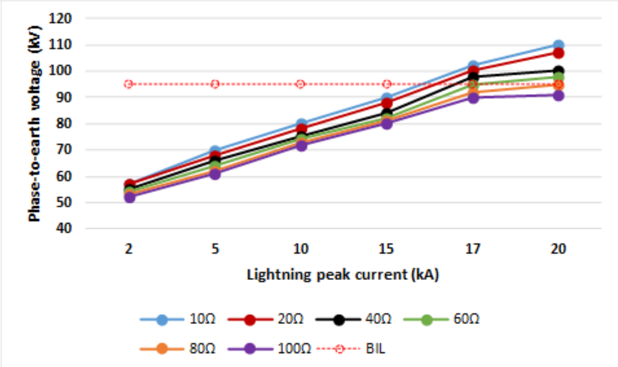


**Figure 4:** MV **p**hase-to-earth overvoltages arising as a function of the lightning peak currents for different DT grounding resistances

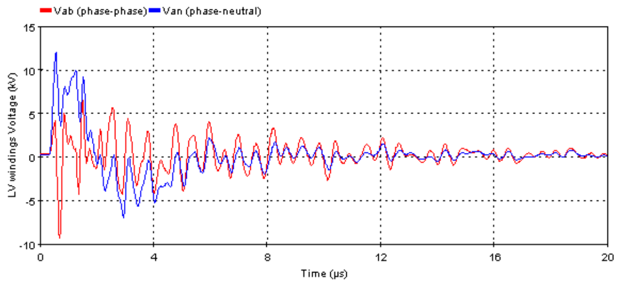


**Figure 5:** Waveforms of the overvoltages transferred to the LV windings of the DT following a lightning strike arsing the MV network

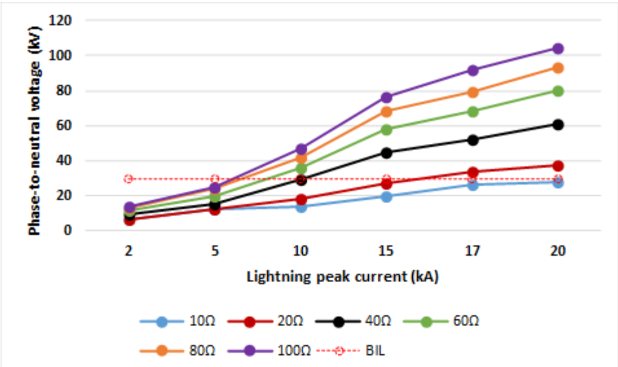


**Figure 6:** Phase-to-neutral overvoltages transferred to LV windings of the DT as a function of the lightning peak currents for different DT grounding resistances without LV SPD

As it can be observed from Figure 6, the phase-to-neutral peak overvoltages transferred to the LV windings of the DT increase significantly with increasing lightning peak currents and this effect is strengthened for higher DT grounding resistances. The overvoltages transferred to the LV windings of the DT exceed the BIL of the LV network for lightning peak currents nearly above 5 kA if the DT grounding resistance is above 60Ω.

The effect of installing SPD in the LV terminals of the DT, regarding the peak overvoltages transferred to the LV windings of the DT can be observed from Figure 7.

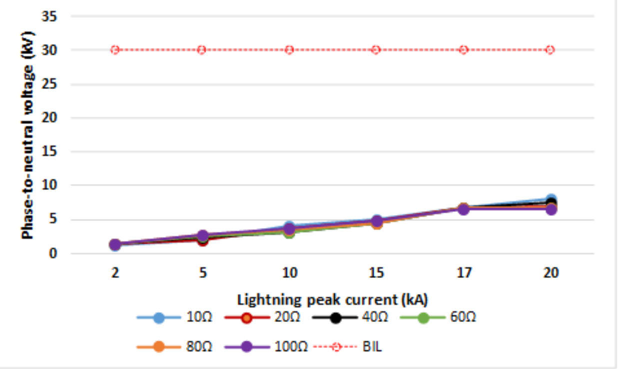


**Figure 7:** Phase-to-neutral overvoltages transferred to LV windings of the DT as a function of the lightning peak currents for different DT grounding resistance with LV SPD

The analysis of Figure 7 allows verifying that the phase-to-neutral overvoltages transferred to the LV windings of the DT trend to increase with increasing lightning peak currents, but are kept almost constant for each lightning peak current, independently of the DT grounding resistance. In fact, the peak overvoltages are determined by the V-I characteristic of the SPD installed at the LV side of the DT and limited by its residual voltage for the lightning current parameters. Also, the phase-to-neutral peak overvoltages transferred to the LV windings of the DT are significantly reduced. This effect is strengthened for higher lightning peak currents and higher DT grounding resistances.

## Lightning strikes arising the LV network

The overvoltages arising at the terminals of the DT following lightning strikes arising the LV networks were evaluated considering the variation of the lightning peak current, the transformer grounding resistance ($R_T$) and the load grounding resistance ($R_L$). The effect of installing SPD on the LV side of the DT is also evaluated. The ZnO surge arrester is permanently installed at the MV side of the DT. Also, it was assumed that lightning strikes arise the LV network at 20 m from the pole mounted DT.

### Overvoltages arising at the LV windings of the DT as a function of the DT grounding resistance

Figure 8 presents the waveforms of the overvoltages arising at the LV windings of the DT following 1/20 µs, 3 kA arising the LV distribution network, considering the DT grounding resistance and the load grounding of 20 Ω. The variation of the peak overvoltages arising at the LV windings of the DT with both the lightning peak current and the transformer grounding resistance are presented in Figure 9. The analysis of this figure allows verifying that the phase-to-neutral overvoltages increase significantly with increasing lightning peak currents, being this effect strengthened for lower transformer grounding resistances.

Also, the BIL of the LV windings of the DT is exceeded for lightning peak currents lower than 3 kA if the transformer grounding resistance is lower than 10 Ω. Therefore, it is expected that the pole mounted DT will fail with high probability. Also, it must be stressed that the ZnO surge arresters installed at the MV side of the DT do not offer protection against overvoltages arising at the LV windings of the pole mounted DT due to lightning strikes arising the LV distribution network.

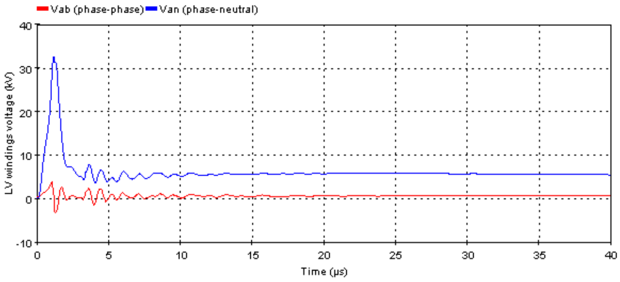


**Figure 8:** Waveforms of the overvoltages at the LV windings of the DT following a lightning strike arising the LV network without LV SPD

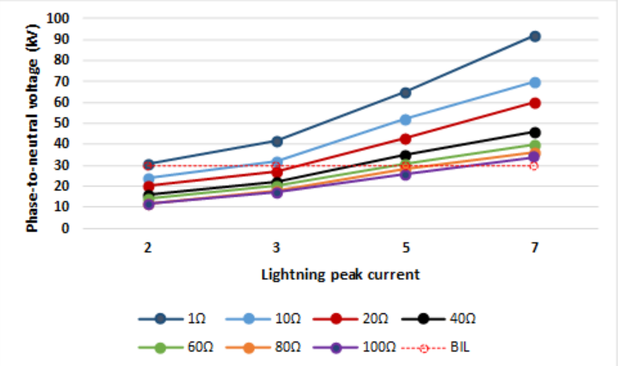


**Figure 9:** Phase-to-neutral overvoltages arising at the LV windings of the DT as a function of the lightning peak currents for different DT grounding resistance without LV SPD

The effect of installing SPD in the LV side of the DT was also evaluated considering the variations of the transformer grounding resistance for increasing lightning peak currents. The observed phase-to-neutral peak overvoltages arising at the LV windings of the DT are presented in Figure 10.

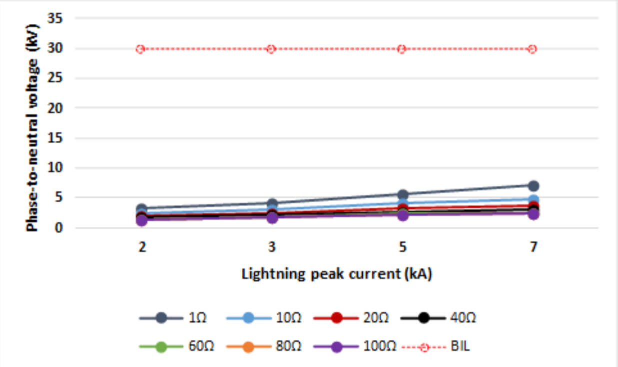


**Figure 10.** Phase-to-neutral overvoltages arising at the LV windings of the DT as a function of the lightning peak currents for different DT grounding resistances with LV SPD

The comparative analysis of Figure 10 and Figure 9 allows verifying that the phase-to-neutral peak overvoltages are significantly reduced when SPD are installed at the LV side of the DT. Also, this effect is stressed for increasing lightning peak currents and lower grounding resistances.

**Overvoltages arising at the LV windings of the DT as a function of the load grounding resistance**

The effect of the variations of the load grounding resistance on the overvoltages arising the LV windings of the DT following lightning strikes arising at the LV distribution network is presented in Figure 11. The analysis of this figure allows verifying that the phase-to-neutral overvoltages increase significantly with higher lightning peak currents and, for each lightning peak current, with increasing load grounding resistances.

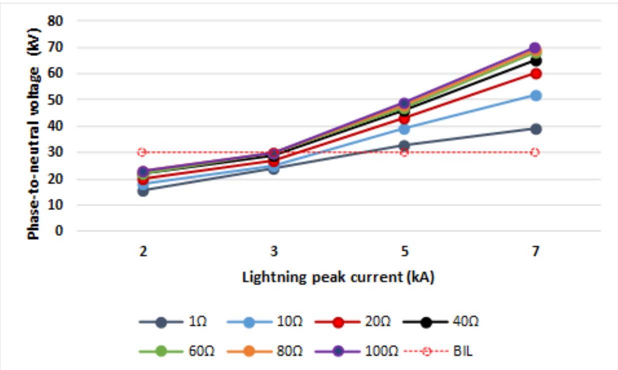


**Figure 11:** Phase-to-neutral overvoltages arising at the LV windings of DT as a function of the lightning peak currents for different load grounding resistance without LV SPD

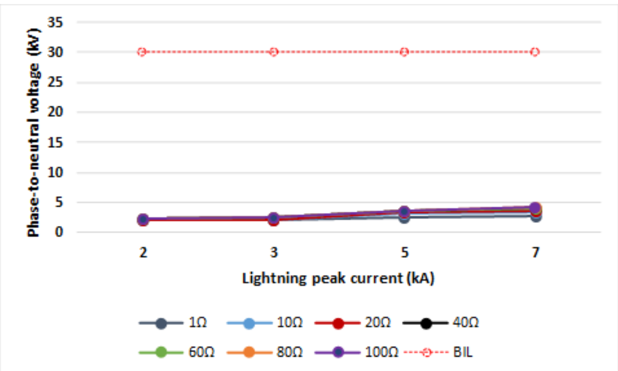


**Figure 12:** Phase-to-neutral overvoltages arising the LV windings of the DT as a function of the lightning peak currents for different load grounding resistances with LV SPD

The effect of installing SPD in the LV side of the DT was also evaluated. The observed phase-to-neutral peak overvoltages arising at the LV windings of the DT are presented in Figure 12. It can be observed that the phase-to-neutral peak overvoltages are significantly reduced when SPD are installed at the LV side of the DT. This effect is strengthened for higher lightning peak currents and higher load grounding resistances.

## CONCLUSIONS

This paper analyses the transient behaviour of the pole mounted DT following lightning strikes arising the MV and the LV distribution networks. The effect of installing SPD in the LV terminals of the pole mounted distribution transformer was also evaluated. For these purposes, transient studies were performed using the EMTP-RV software. The results obtained allow concluding that the ZnO arresters installed at the MV terminals of pole mounted DT are only effective in protecting their MV windings against overvoltages following lightning strikes arising the MV distribution networks. They are not effective to assure the full protection of pole mounted DT due to the overvoltages developed at their LV windings. Also, the pole mounted DT are not protected against overvoltages following lightning strikes arising the LV distribution network. Therefore, installing SPD in the LV side is required to assure the full protection the pole mounted DT.

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