Studies for the more effective protection of MV/LV substations against lightning overvoltages

CHRISTOS A. CHRISTODOULOU VASILIKI VITA LAMBROS EKONOMOU
Department of Electrical and Electronic Engineering Educators
A.S.PE.T.E. - School of Pedagogical and Technological Education
N. Heraklion, 141 21 Athens
Greece
emails: christ_fth@yahoo.gr, vasvita@aspete.gr, leekonomou@aspete.gr

Abstract: - The installation of surge arresters is the common practice for the protection of the distribution substations against lightning overvoltages that may cause serious damages to the equipment. However, the protection level that surge arresters offer depends on various factors, i.e., the installation position, the length of the connecting conductors and the grounding resistance. In the current work, the developed overvoltages at the entrance of a distribution substation, due to lightning stroke to the connected line are computed, considering different configurations. The obtained results can be useful for engineers and power utilities for the improvement of the lightning performance of already existed substations or for the more effective design of new ones.

Key-Words: - Lightning; Substations; Surge arresters; Transformers.

1. Introduction

The uninterrupted and effective operation of the distribution substations is of great importance for the reliability of the electrical networks, considering the vital role of the distribution transformers that step down the voltage level and provide the demanded electrical power to the consumers. However, the distribution substations, due to their installation in wide-open areas and their connection with overhead lines, are susceptible to atmospheric discharges that may cause serious damages to the equipment and result in interruptions and malfunctions of the system. The installation of surge arresters at the entrance of the power transformer is the main protective measure to mitigate the deleterious repercussions of an arising lightning surge, taking into consideration that the installation of overhead ground wires is not appropriate due to the low insulation level, the difficulty to improve the grounding resistance and the insulation withstand capability [1, 2]. Nevertheless, the installation position of the arresters, the length of the connection conductors and the grounding resistance are factors that influence the effectiveness of the protection that surge arresters provide [3, 4].

In the current work, the developed overvoltages at the medium voltage (MV) side of a distribution transformer (20/0.4 kV) are computed, considering different connection configurations (cases). Furthermore the role of the grounding resistance for each case is also examined. The presented studies can be useful for engineers and power utilities for the improvement of the lightning performance of already existed substations or for the more effective design of new ones.

2. Protection of distribution substations against lightning surges

A distribution substation consists of several components (transformer, fuses, switches, conductors, measuring devices, etc.), intended to transform the voltage level and supply the low voltage (LV) consumers. Fig. 1 presents the configuration of a typical MV/LV substation of the

Hellenic distribution system. The primary winding of the transformer is usually in delta (Δ) connection and the secondary winding is in star (Y) connection.

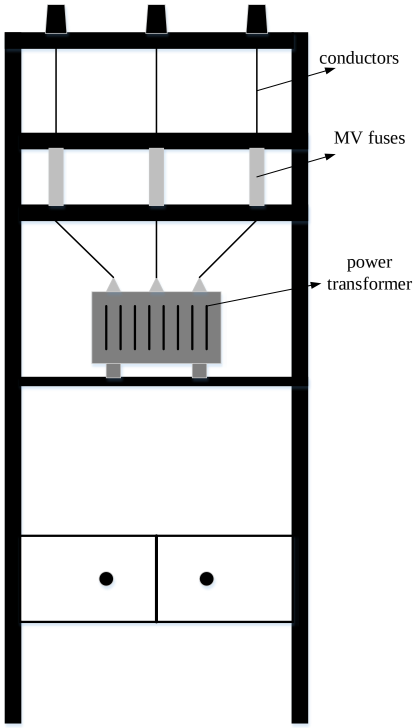

Fig. 1 Configuration of a distribution substation

Electrical distribution substations are endangered by overvoltages either due to lightning strikes or switching operations that stress and downgrade their insulation, increasing the probability of serious damages of the equipment resulting interruptions in the power supply. Hence, the effective protection of the distribution lines and substations against external and internal overvoltages is necessary, considering the operational, the technical and financial consequences of a potential damage of the system's equipment. In contrast to the high voltage systems, the interception of the lightning flash by using shield wires or masts is not effective in the case of medium voltage installations, considering the geometry, the dimensions and the electrical characteristics of these systems. For this reason, the limitation of the developed overvoltages by using surge arresters is the common practice for distribution networks [5]. Modern surge arresters are gapless and consist of metal-oxide non-linear resistors connected in series, enclosed in a porcelain or polymeric housing. The non-linear resistor (varistor) behaves as an insulator in the case of the normal operation of the system and as a conductor in the case of an overvoltage event, diverting the surge current to earth and limiting the residual voltage across the arrester's terminals below the basic insulation level (BIL) of the system to be protected. The voltage-current characteristic of the varistor obeys to the equation [6, 7]:

$$I = k \cdot V^{a} \tag{1}$$

where:
I is the discharge current through the arrester,
V is the voltage across the arrester,
k is a constant depending on the type of the arrester type, and
a is a variable between 5 and 50, indicating the non-linearity of the varistor.

The main electrical characteristics of the metal-oxide gapless surge arresters, i.e., the continuous operating voltage, the rated voltage, the discharge current, the residual voltage, the nominal discharge current, the lightning impulse protective level and the energy absorption capability, are determined by the operational conditions and the type of the equipment to be protected. A critical parameter that influences the effectiveness of the lightning protection system is the energy absorption capability of the arresters, i.e., the maximum energy that can pass through the arrester without losing its thermal stability. If the energy absorbed by the arrester is greater that its energy absorption capability, arrester is damaged, since it cannot cool back-down to their normal operating temperature [6-8]; a failed arrester does not offer any protection to the equipment, so future arising surges can result in serious damages of the equipment.

The installation position of the arresters is an issue of great importance, since no surge protection is offered in the case that arresters are placed too far from the equipment [9]. Lightning surges behave as travelling waves, so they are positively reflected when arriving at the transformer, resulting in a doubling of the voltage magnitude (note that a transformer appears similar to an unterminated end [7]). The protective zone of an arrester is given by the equation:

$$PZ = \frac{\left(\frac{BIL}{K}\right) - U_p}{2 \cdot S} \cdot v \tag{2}$$

where:
BIL is the basic insulation level,
K is a coefficient equal to 1.15,
U_p is the protective level of the arrester,
S is the front steepness of the lightning overvoltage, and
v is the propagation speed of a traveling wave.

Except from the installation position of the arresters, the connection conductors' length has to be taken into consideration, in order to ensure the effective protection that these devices provide. Fig. 2 presents the current path of the lightning surge.

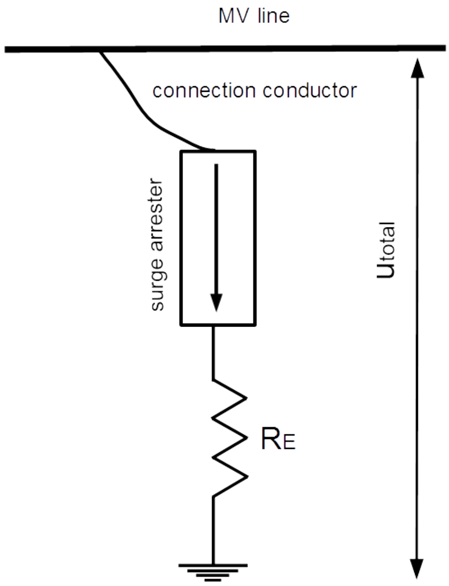

Fig. 2 Connection of surge arrester to a MV line

The developed voltage at the terminals of the equipment to be protected is not equal to the residual voltage of the arrester (for a specific impulse current, according to the voltage-current characteristics), but is also determined by the grounding resistance and the length of the connection conductors, according to the equation:

$$u_{total} = i_{dis} \cdot (R_{sa} + R_E) + l \cdot L \cdot \frac{di_{dis}}{dt} \qquad (3)$$

where:
u_{total} is the developed voltage at the terminals of the equipment to be protected,
i_{dis} is the discharge current,
R_{sa} is the resistance of the non-linear resistor of the arrester (depending on the voltage-current characteristic),
R_E is the grounding resistance,
l is the length of the connection conductors, and
L is the per-unit-length inductance of the connection conductors.

3. System configuration

The current work deals with the computation of the developed overvoltages due to lightning strikes at the MV side of a distribution transformer, examining various connection configurations for the surge arresters. Fig. 3 presents the three examined cases, taking into consideration different lengths for the connection conductors (Cases 1-3) [6].

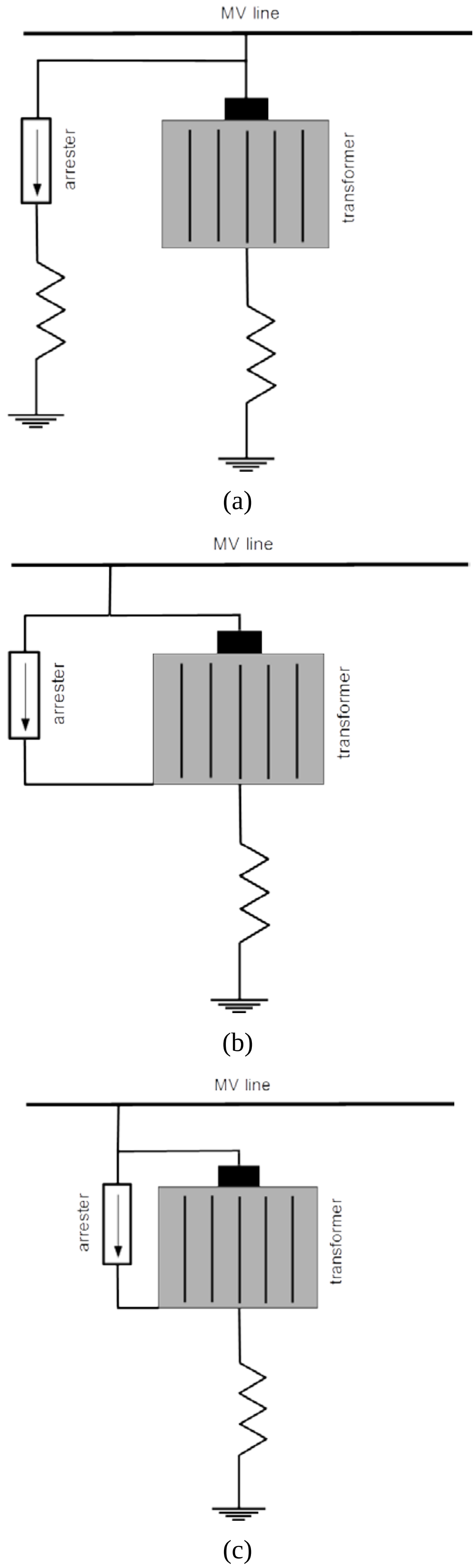

Fig. 3 System configuration (a) Case 1, (b) Case 2 and (c) Case 3

A lightning current 30 kA, 5.5/75 μs strikes the phase conductor of the connected MV line (20 kV, rms, phase-to-phase), 50 m away from the transformer (20/0.4 kV, 50 kVA, Dyn1). It must be mentioned that the lightning parameters have been selected according to [10], considering a probability of 50 %. The grounding resistance varies from 5 Ω to 50 Ω. The BIL is considered equal to 125 kV. The current impulse is represented according to [11]. Overhead lines were represented according to the Bergeron model, since the grounding resistance modeling takes into consideration the soil ionization [12, 13]. The connection conductors were represented as inductances or lossless distribution parameters line segments, depending on their length [14]. As far as the representation of the metal-oxide arresters is concerned, the IEEE model is applied [15]. Table 1 presents the electrical characteristics of the metal-oxide arresters.

Table 1 Electrical characteristics of the implemented arresters

Rated voltage		21 kV	
Residual voltage	8/20 μs	5 kA	56 kV
		10 kA	60 kV
		20 kA	69 kV
		40 kA	80 kV

4. Results

Fig. 4 presents the computed overvoltages at the entrance of the transformer, considering the three examined cases. The obtained results highlight the impact of the different connections of the arresters at the transformer and of the grounding resistance on the lightning performance of the substation. In Case 3, where the arresters are directly connected at the tank of the distribution transformer and the connection conductors' lengths are short, the developed overvoltages are lower compared with Cases 1 and 2. The Case 1, where the arresters and the power transformer are separately grounded, is not recommended, since it offers adequate protection only for low values of grounding resistance. Cases 2 and 3 seem to be effective even if the grounding resistance exceeds 20 Ω. Fig. 5 presents the percentage reduction of the developed overvoltages for Cases 2 and 3 compared with Case 1, highlighting the improvement of the lightning performance of the substation if the length of the connecting conductors is reduced.

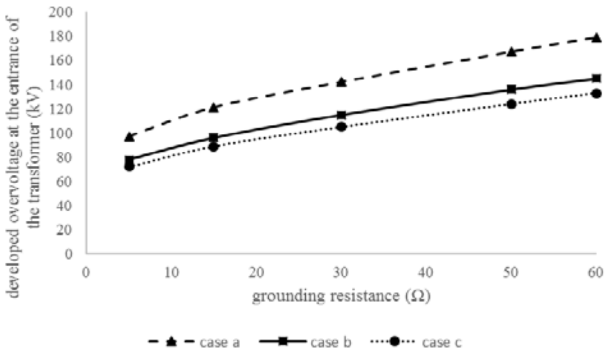

Fig. 4 The developed overvoltages at the entrance of the transformer in comparison to the grounding resistance for the examined cases

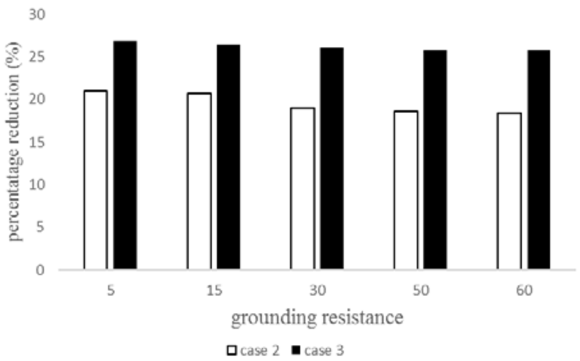

Fig. 5 The percentage reduction of the developed overvoltages for Cases 2 and 3 compared to Case 1

5. Conclusion

The current work computes the developed overvoltages at the entrance of MV/LV distribution substations. The substation's transformer is protected against lightning surges by metal-oxide gapless surge arresters, considering three different configurations for the connection of the arresters at the tank of the transformer. The conducted studies examine also the effect of the grounding resistance. The obtained results indicate that surge arresters connected directly to the tank of the transformer with short length connecting conductors provide a more effective protection against the incoming lightning surges, compared to the case where the surge arresters and the transformer are separately grounded and long length connection conductors are used. The finding of this paper can be useful for electrical engineers and electric power utilities in order to improve the lightning performance of already existed substations or for the more effective design of new ones.

References:

[1] IEC 71-2, *Insulation co-ordination, Part 2: Application guide*, 1996

[2] J. Pansini, *Guide to Electrical power distribution systems*, 6th Edition, CRC Press, 2005

[3] M. Trainba, L. Ekonomou, Lightning performance of a HV/MV substation, *10th WSEAS Int. Conf. on Energy & Environment (EE '15)*, Budapest, Hungary, 2015, pp. 28-32

[4] C.A. Christodoulou, V. Vita, A. Mitropoulou, D.S. Oikonomou, L. Ekonomou, Interface construction for the computation of the optimum installation position of metal oxide surge arresters in medium voltage substations, *5th IASME/WSEAS Int. Conf. on Energy & Environment (EE '10)*, University of Cambridge, United Kingdom, 2010, pp. 334-338

[5] A.J. Eriksson, D.V. Meal, Lightning performance and overvoltage surge studies on a rural distribution line, *IEE Proceedings C - Generation, Transmission and Distribution*, Vol. 129, No. 2, 1982, pp. 59-69

[6] ABB Application Guide, *Overvoltage protection: Metal oxide surge arresters in medium voltage systems*, 2011

[7] V. Hinrichsen, *Metal-oxide surge arresters, Fundamentals*, 1st Edition, Siemens, 2001

[8] C.A. Christodoulou, L. Ekonomou, G.P. Fotis, V. Vita, P.M. Kyrtsopoulos, Computation of the injected energy to medium voltage surge arresters for the Hellenic distribution network, *9th WSEAS Int. Conf. on Power Systems (PS '09)*, Budapest, Hungary, 2009, pp. 142-145

[9] C.A. Christodoulou, L. Ekonomou, G.P. Fotis, I.F. Gonos, I.A. Stathopulos, Assessment of surge arrester failure rate and application studies in Hellenic high voltage transmission lines, *Electric Power Systems Research*, Vol. 80, No. 2, 2010, pp. 176-183

[10] Cigré TB 287, *Protection of MV and LV systems against lightning Part 1: Common Topics*, 2006

[11] CIGRE Working Group 33.01, *Guide to procedures for estimating the lightning performance of transmission lines*, Technical Bulletin 63, 1991

[12] H. Dommel, *Electromagnetic transient program reference manual (EMTP theory book)*, BPA, 1986

[13] W.A. Chisholm, W. Janischewskyj, Lightning surge response of ground electrodes, *IEEE Transactions on Power Delivery*, Vol. 4, No. 2, 1989, pp 1329-1337

[14] IEEE Task Force, Modeling guidelines for fast front transients, *IEEE Transactions on Power Delivery*, Vol. 11, No. 1, 1996, pp. 493-506

[15] IEEE WG 3.4.11, Modeling of metal-oxide surge arresters, *IEEE Transactions on Power Delivery*, Vol. 7, No. 1, 1992, pp. 302-309