International Journal of Power and Energy Research, Vol. 1, No. 1, April 2017
https://dx.doi.org/10.22606/ijper.2017.11001

Lightning Protection of Distribution Substations by Using Metal Oxide Gapless Surge Arresters Connected in Parallel

Christos A. Christodoulou[1], Vasiliki Vita[2*], Theodoros I. Maris[3]

[1]Department of Electrical and Computer Engineering, University of Thessaly, Volos, Greece

[2] Department of Electrical and Electronic Engineering Educators, ASPETE - School of Pedagogical and Technological Education, N. Heraklion, Athens, Greece

[3] Department of Electrical Engineering, Technological Educational Institution of Central Greece, Psachna Evias, Greece

*Email: vasvita@aspete.gr

Abstract. The adequate protection of the distribution transformers is a critical issue, in an effort to avoid interruption of the power supply and damages of the equipment. The installation of metal oxide gapless surge arresters at the entrance of the transformers improves their lightning performance and reduces the expected annual failure rate. However, arresters can be damaged, if the discharge current that passes through them is high enough, resulting in thermal stress of the device and possible failure. The parallel connection of arresters contributes to equal current sharing, reducing their failure probability. In the current work, the parallel combination of two metal-oxide gapless surge arresters installed at the MV side of a distribution transformer is examined, considering how the voltage – current characteristic of each arrester influences the expected voltage surges at the entrance of the transformer, the current sharing between the non-linear resistors and the arresters failure probability.

Keywords: Substations, lightning, transformer, surge arresters, parallel connection

1 Introduction

The reliable and uninterrupted operation of the medium voltage/low voltage (MV/LV) substations of the distribution electrical networks is necessary, in order to ensure the continuity and the quality of the power supply. The MV/LV transformer is the most important component of the distribution system that has to be adequately protected against several factors, considering various technoeconomical and safety parameters. Lightning overvoltages are the main cause of damages and outages in the distribution substations [1]. The implementation of overhead ground wires is not recommended in the case of MV installations, considering the low insulation level and the difficulty in improving the grounding resistance and the insulation withstand capability, in an effort to prevent backflashover phenomena [2-4]. The installation of metal oxide gapless surge arresters is the common practice to improve the lightning performance of the network and restrain the arising overvoltages that could stress the insulation of the equipment [5-8]. However, in the case that the energy that passes through the arresters exceeds their withstand capability a failure is occurred. The failed arresters do not protect anymore the substation and have to be replaced, something that is not always immediately attainable, since the operation of the arresters is rarely monitored. So, the transformers remain unprotected, and severe damages can be occurred. The parallel combination of arresters definitely reduces the absorbed energy of the arresters, since the lightning current is shared; furthermore, the residual voltage is also altered, according to the voltage – current characteristic of the non-linear resistor of the arresters [9, 10].

In the current work, the impact of the parallel combination of two metal-oxide gapless surge arresters installed at the MV side of a distribution transformer is examined, revealing the influence of the voltage – current characteristic of each arrester on the expected voltage surges at the entrance of the transformer, the current sharing between the non-linear resistors and, consequently, the arresters failure probability.

2 Lightning Protection of Distribution Substations

A distribution substation includes all the necessary devices for control and protection, terminations of the distribution lines and switchgears. The MV/LV transformer is the basic part of the distribution network, which steps down the voltage level and ensures the distribution of the electrical energy over long distances. Distribution transformers are usually located outdoors, hung from crossarms, mounted on poles directly or placed on platforms, so they are vulnerable to lightning surges, mainly incoming from the connected overhead medium voltage line, resulting in insulation stresses and consequent potential damages [4]. The repercussions of a transformer fault include interruption of the power supply to the consumers and need for replacement or repair of the equipment, leading to poor reliability of the system and important economic losses. To mitigate the deleterious effects of lightning strikes and reduce the annual outage rate of the MV/LV substations, appropriate protections schemes have to be adopted, in order to protect the several components of the system against the developed overvoltages. In general, distribution transformers are equipped with arresters between phase and earth, installed at the entrance of the medium voltage side, in order to limit the incoming voltage surges below the Basic Insulation Level (BIL) of the system. Surge arresters are semiconductor devices that act as conductor for high-energy surges and as insulators during the normal operation of the network. Nowadays, modern surge arresters are gapless, consisting of a metal-oxide (ZnO) non-linear resistor (varistor), enclosed in a polymeric or porcelain cylinder [5-10]. Fig.1 depicts a typical configuration of an outdoor distribution substation of the Hellenic distribution network.

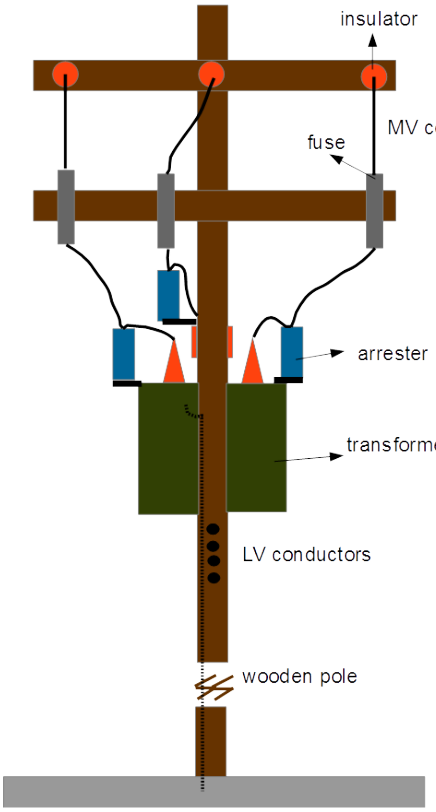

Figure 1. Typical configuration of an outdoor distribution substation of the Hellenic distribution network

The installation position of the arresters has a great impact on the lightning performance of the substation, considering that lightning surges behave as travelling waves that refract or reflect at any position where the surge impedance changes [11]. In the case of a distribution substation, the transformer behaves as an un-terminated end, resulting in reflections and doubling of the voltage magnitude. For this reason, the arresters have to be installed near to the equipment to be protected, to avoid the above reflection phenomena. Moreover, the length of the connection wires should be also short, to restrain the voltage drop along them, considering also their per-uni-length inductance. In addition, the achievement of low grounding resistance values is a requirement for the proper operation of the arresters [12]. Fig. 2 presents a simple configuration of a line protected by a gapless surge arrester, where the developed travelling waves are shown. The voltage transmitted voltage wave is given by the equation [5]:

$$u_t = i_3 \cdot \left(R_{var} + R_g\right) + l \cdot L \cdot \frac{di_3}{dt} \tag{1}$$

where

u_t is the transmitted current wave,

i_3 is the current through the arrester,

R_{var} is the resistance of the varistor,

R_g is the grounding resistance,

l is the length of the connection conductors, and

L is the per-uni-length inductance of the connection conductors

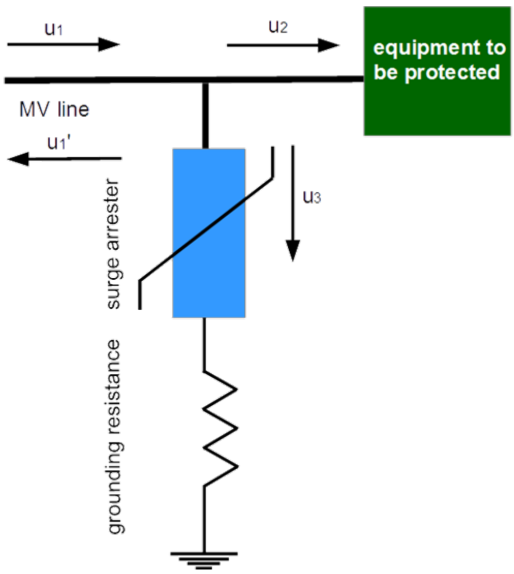

Figure 2. Line protected against lightning overvoltages by surge arresters

The metal oxide surge arresters constitute the basic protective measure against external and internal transient phenomena, installed at the entrance of the substations, ensuring that the incoming voltage surges will not exceed the insulation withstand capability of the system. However, surge arresters are stressed by the discharge currents flowing through them and their effectiveness and normal operation may be degraded. In the case that the absorbed energy exceeds their energy absorption capability, arresters cannot cool back-down to their normal operating temperature and, consequently, they fail [13, 14]. A damaged arrester cannot protect anymore the installation against lightning and switching overvoltages and has to be repaired or replaced. If not, subsequent lightning hits can cause serious damages to the substation. Metal oxide surge arresters can be combined in parallel connection, in order to improve their energy absorption capability. Necessary requirement for the equal sharing of the impulse current and the energy that passes through the arresters is the good matching of their voltage – current characteristics. It is worth mentioning that even slight differences in the residual voltage of the arresters can result in differences in uneven current sharing and consequently to an overstress of one of the arresters [9]. Moreover, the parallel connection of the arresters contributes to the limitation of the arising residual voltages, offering a lower protection level [9].

The installation of parallel surge arresters contributes to the reduction of the absorbed energy by them, since the lightning current is shared, diverted to earth by two paths. In this way, the energy rating of the arresters is doubled and the arresters failure probability due to lightning overvoltages is reduced. Indeed, manufacturers of surge arresters recommend their parallel installation, taking into consideration their voltage – current characteristics. In case that voltage – current characteristics are not carefully matched, the sharing of the discharge currents will be not adequate to reduce the failure probability of the arresters [9].

When the absorbed energy by the arresters exceeds their maximum acceptable level of energy, then they will fail (damage). The arresters' failure probability $ArrFP$ is given as [15-17]:

$$ArrFP = \int_{T_r}^{\infty} \left\{ \int_{I_L(T_t)}^{\infty} f(I_p) \cdot dI_p \right\} g(T_t) dT_t \quad (2)$$

where:

$I_L(T_t)$ is the minimum stroke peak current in kA required to damage the arrester, when lightning hits on a phase conductor, depending on each time-to-half value,

$f(I_P)$ is the probability density function of the lightning current peak value, and

$g(T_t)$ is the probability density function of the time-to-half value of the lightning current.

3 System Configuration

Fig. 3 presents the configuration of the system under study. A MV overhead line (20kV, rms, phase-to-phase) feeds a distribution transformer (20/0.4kV, 50kVA, Dyn1). The secondary winding of the transformer is grounded, considering a grounding resistance equal to 1Ω. The transformer is protected against the incoming surges by two surge arresters, combined in parallel. Fig. 4 presents the voltage – current characteristics of three different arresters (A, B, C), connected in six different ways, i.e., A-A, B-B, C-C, A-B, A-C and C-D. A 10kA, 5.5/75μs lightning current hits the phase a of the unshielded MV line, 70m away from the transformer, which corresponds to the average span length between the wooden poles. The current impulse is represented according to [18]. Overhead lines were represented according to the Bergeron model, since the grounding resistance modelling takes into consideration the soil ionization [19, 20]. The connection wires were represented as inductances or lossless distribution parameters line segments, depending on their length [21].

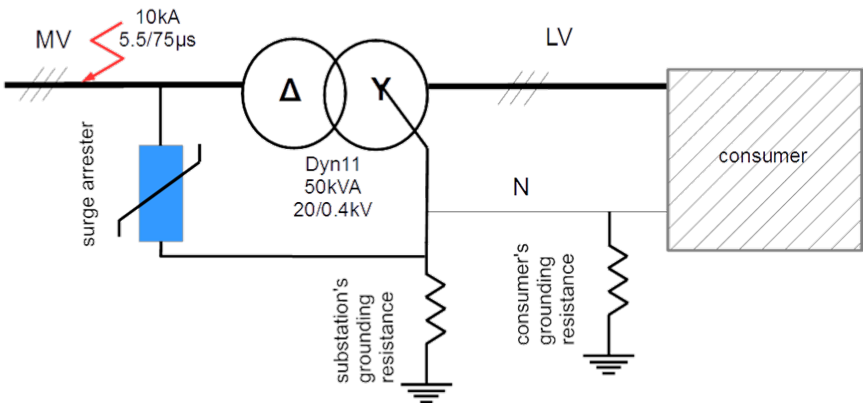

Figure 3. System configuration

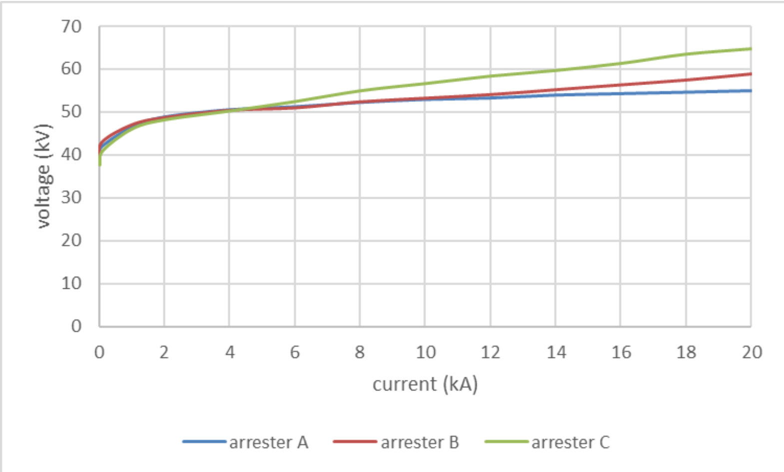

Figure 4. Voltage – current characteristics of the examined arresters

4 Results and Discussion

Figures 5-7 present the results of the performed analysis. The current sharing is strongly depended on the differences between the voltage – current characteristics of the combined arresters. Even slight differences between the characteristics result in uneven sharing of the lightning discharge current. The arresters which present more intense non-linearity of its characteristic are stressed more and present greater probability to fail. So, the appropriate selection of the electrical characteristics of the arresters to be connected is critical, in order to achieve an adequate sharing of the lightning current and reduce the annual failure rate of the arresters.

Fig. 5 and 6 depict the current sharing between the two installed arresters and the failure probability of each arrester, respectively.

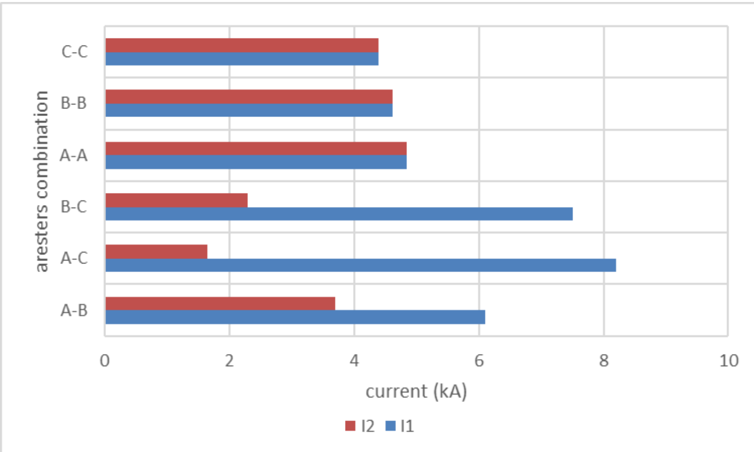

Figure 5. Current sharing

In the case of installation of same arresters (A-A, B-B, C-C) the injected impulse current is equally shared, resulting in equal energy stress of the devices. Considering the other three cases (A-B, A-C, B-C) the arresters that present the lower impedance (see declination of the voltage – current characteristic), absorb higher part of the injected current and consequently they are stressed more intensively. Indeed, the arresters that absorb higher part of the discharged lightning current have higher probability to fail.

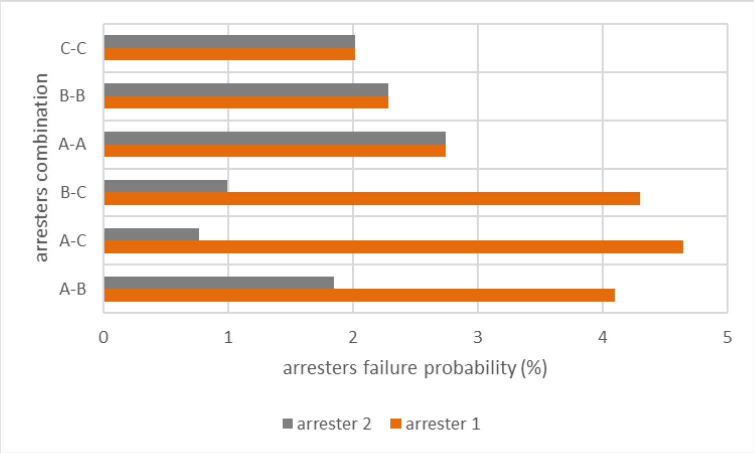

Figure 6. Arresters failure probability

Fig. 7 presents the arising overvoltage at the entrance of the transformer for the six examined cases. The parallel combination of the arresters results in the reduction protection level, since the current sharing leads to lower residual voltage values, according to the voltage – current characteristic of each device; for example, in the case of the parallel connection of two same arresters (A-A) the injected current (10kA) is equally shared, so the residual voltage corresponds to the half current (5kA) for each arrester.

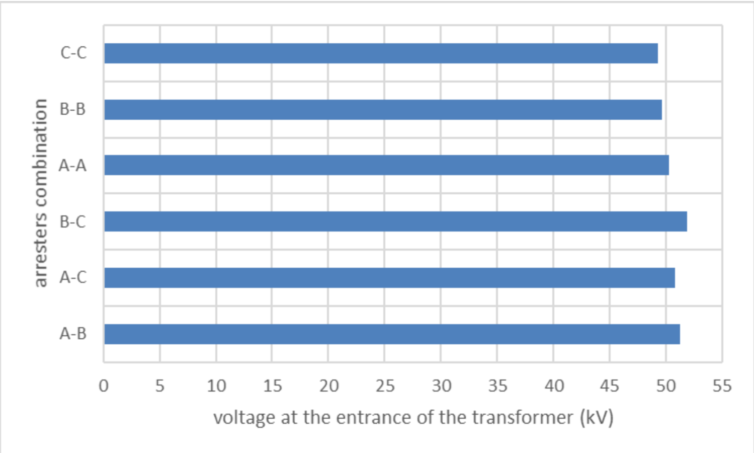

Figure 7. The developed voltage at the entrance of the transformer

5 Conclusions

The parallel installation of metal oxide gapless surge arresters intends to reduce the lightning current that passes through them and consequently to restrain the absorbed energy, that can cause irreparable damages. Moreover, parallel arresters have a positive impact on the magnitude of the developed overvoltages across the terminals of the equipment to be protected, since the current sharing results in lower residual voltages according to the voltage-current characteristic of each varistor. The current work examines how the voltage – current characteristics influence the current sharing and the residual voltages, in an effort to improve the lightning performance of a distribution substation, considering various cases. The obtained results indicated the important role of the good matching of the characteristics, since even slight differences can result in significant unequal sharing of the lightning current. The arresters which present more intense non-linearity of their characteristic are stressed more and present greater probability to fail. So, the careful selection of the electrical characteristics of the arresters to be connected is of great importance to achieve an adequate sharing of the lightning current and reduce the failure probability of the arresters.

References

1. M. Trainba, and L. Ekonomou, “Lightning performance of a HV/MV substation”, *10th WSEAS Int. Conf. on Energy & Environment (EE '15)*, Budapest, Hungary, pp. 28–32, 2015.
2. A.J. Eriksson, and 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, pp. 59-69, 1982.
3. IEC 71-2, " Insulation co-ordination, Part 2: Application guide", 1996.
4. A. J. Pansini, “Guide to electrical power distribution systems”, 6th Edition, CRC Press, 2005.
5. IEC 60099-4, Edition 1.1, 1998-08 Surge arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems.
6. IEC 60071-1, Seventh edition, 1993-12 Insulation co-ordination – Part 1: Definitions, principles and rules.
7. IEC 60071-2, Third edition, 1996-12 Insulation co-ordination – Part 2: Application guide.
8. IEC 60099-5, First edition, 1996-02 Surge arresters – Part 5: Selection and application recommendations.
9. ABB Application Guide, “Overvoltage protection: Metal oxide surge arresters in medium voltage systems”, May 2011.
10. V. Hinrichsen, “Metal-oxide surge arresters, fundamentals”, 1st Edition, Siemens, 2001.
11. C.A. Christodoulou, V. Vita, A. Mitropoulou, D.S. Oikonomou, and 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,pp. 334–338, 2010.
12. C.A. Christodoulou, L. Ekonomou, G.P. Fotis, V. Vita, and 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, pp. 142–145, 2009.
13. IEEE Std C62.22-1991, IEEE guide for the application of metal-oxide surge arresters for alternating-current systems.
14. IEEE Std 1410™-2004 (Revision of IEEE Std 1410-1997) 1410TM IEEE guide for improving the lightning performance of electric power overhead distribution lines.
15. L.C. Zanetta, “Evaluation of line surge arrester failure rate for multipulse lightning stresses”, *IEEE Transactions on Power Delivery*, vol. 18, no. 3, pp. 796–801, 2003.
16. C.A. Christodoulou, L. Ekonomou, G.P. Fotis, I.F. Gonos, and 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, pp. 176-183, 2010.
17. K. Nakada, S. Yokoyama, T. Yokota, A. Asakawa, and T. Kawabata, “Analytical study on prevention for distribution arrester outages caused by winter lightning”, *IEEE Transaction on Power Delivery*, vol.13, no.4, pp.1399-1404, 1998.
18. CIGRE Working Group 33.01, “Guide to procedures for estimating the lightning performance of transmission lines” (Technical Bulletin 63, 1991).
19. H. Dommel, “Electromagnetic transient program reference manual (EMTP Theory Book)”, BPA, 1986.
20. W.A. Chisholm, and W. Janischewskyj, “Lightning surge response of ground electrodes”, *IEEE Transactions on Power Delivery*, vol. 4, no. 2, pp 1329–1337, 1989.
21. IEEE Task Force: “Modeling guidelines for fast front transients”, *IEEE Transactions on Power Delivery*, vol. 11, no. 1, pp. 493-506, 1996.

