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ORIGINAL PAPER

The impact of distributed generation to the lightning protection of modern distribution lines

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Abstract The distributed generation (DG) has become very popular in recent years mainly due to their high efficiency, their benefits to distribution networks (e.g., improvement of voltage profiles and load factor, reduction of power losses, delivery of backup power, elimination of system upgrades, etc.) and their low emissions. On the other hand the continuous installation of DGs has raised several different issues that need to be considered. Lightning constitutes one of the main factors of failures in distribution lines and therefore the lightning performance of modern distribution lines with DGs is one of the issues that needs to be further studied. The lightning protection of the lines and the reduction or elimination of faults are mainly based on the protection measures undertaken by the electric utilities. In this work the impact of DG to the lightning protection of distribution lines is studied through extensive simulations that consider different factors that influence the efficiency of the protection systems and the developed overvoltages. The paper aims to contribute in the more effective lightning protection of modern distribution lines.

Keywords Distributed generation · Distribution lines · Surge arresters · Grounding resistance · Simulation

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1 Introduction

The configuration of the traditional electrical supply system has changed prominently over the last two decades when distributed generation (DG) power plants were reintroduced into the construction of the electricity network. The concept of DG, which can be traced back to the early 1900s, is based on small scale power plants that are connected to the electricity system close to consumers. DG has the potential to reduce emissions and increase the dependence on alternative energy sources, participating with this way in energy diversification. It also helps to deliver backup power during times of increased electricity demand, avoiding the investment in large power plants and transmission lines, having also as a result the reduction of the transmission and distribution power losses. Furthermore DG improves voltage profiles and the load factor, which minimizes the number of required voltage regulators, capacitors and their ratings and maintenance costs. These benefits however are counterbalanced by impacts on the distribution network since the integration of DG in it is not straightforward. The integration of DG into the distribution network and the larger penetration of renewable energy sources result in network connection issues as well as power system regulation and balancing issues. In addition DG increases the complexity of selective protection coordination resulting in conflicts in the normal operation of the existing networks. Major issues constitute also the distribution network stability with the DG to be able to remain synchronized after a major fault and the elimination of unintended islanding since this is of paramount importance for the general public, maintenance personnel and installed equipment. Finally the installation of DG influences significantly the lightning performance of distribution lines resulting in a higher lightning failure rate.

Lightning strokes and switching surges are the main factors of power supply interruptions and equipment damages and malfunctions. Shield wires, surge arresters and increased insulation levels are the most used protective means, in order to secure the reliability of the system and reduce the overvoltage faults [1]. Han, Seo and Kim analysed the lightning overvoltages according to the location of overhead ground wires [2], while Bhattarai et al investigated the protection of wood pole distribution lines using surge arresters [3]. In [4] the effect of grounding resistance and shield wire size in the lightning performance of distribution lines was studied. Similarly in [5] was studied the effect of grounding resistance and the pole topology. A statistical method that quantifies the effects of line parameters, soil resistivity, shielding of nearby objects and lightning crest current distribution on the lightning performance of distribution lines is presented in [6] having obtained results that are in close consistency with field data. Finally Araujo et al studied the performance of a distribution lines' protection system, against lightning overvoltages, in the presence of DG and of concepts of smart grids providing interesting results and conclusions [7].

In the current paper studies related to direct lightning strokes on distribution lines connected with DG are presented. The installation of surge arresters, their installation position and the distribution line's grounding resistance were considered in the conducted sensitivity analysis. The conclusions of this work aim to contribute in the more effective lightning protection and the reduction of the lightning failure rate of modern distribution lines connected with DG power plants.

2 System configuration

The distribution line is consisting of unshielded wooden poles of 9.2 m height with average span length of 70 m. The wooden poles and the conductors' geometries are shown in Fig. 1. Data from a real distribution line of nominal voltage of 20 kV (phase–phase, rms) has been used as a case study.

The distribution line uses porcelain insulators of basic insulation level of 125 kV. The characteristics of the three horizontally placed phase conductors are: Al, $3 \times 95\,\text{mm}^2$, $R_{line} = 0.215\,\Omega/\text{km}$ and $X_{line} = 0.334\,\Omega/\text{km}$. The distribution line that has a total length of 8 km is represented by distributed parameters based on the Bergeron's traveling wave method.

The lossless distribution line is characterized by two values: the surge impedance Z and the wave propagation speed v given by Eqs. (1) and (2).

$$Z = \sqrt{\frac{L}{C}} \tag{1}$$

$$v = \sqrt{\frac{1}{LC}} \tag{2}$$

where: L is the per-unit length inductance, and C is the per-unit length capacitance.

In order to improve the lightning performance of the line, surge arresters are installed in various positions of the system. In general, surge arresters are installed between phase and earth and lead the current of the overvoltage to the ground. In normal operation of the electric network they present high resistance (MΩ) and during overvoltages they behave like conductors. The main electric characteristics of a surge arrester are [8–10]:

(a) *Continuous operating voltage* the maximum permissible rms power frequency voltage that may be applied continuously between the arrester terminals.
(b) *Rated voltage* the maximum permissible rms value of power frequency voltage between arrester terminals at which is designed to operate correctly under temporary overvoltages.
(c) *Residual voltage* the peak value of the voltage that appears between the terminals of an arrester during the passage of the discharge current through it.
(d) *Energy withstand capability* the maximum level of energy injected into the arrester at which it can still cool back down to its normal operating temperature.

The IEEE Working Group 3.4.11 [11] proposed the model of Fig. 2 for a surge arrester. The model includes the non-linear resistances A_0 and A_1, separated by a $R - L$ filter. For slow front surges the filter impedance is low and the non-linear resistances are in parallel. For fast front surges filter impedance becomes high, and the current flows through the non-linear resistance A_o. L_0 is associated with magnetic fields in the vicinity of the arrester. R_0 stabilizes the numerical integration and C represents the terminal-to-terminal capacitance.

The equations for the above parameters are given as follows [11–13]:

$$L_1 = (15\,d)/n \quad \mu\text{H} \tag{3}$$

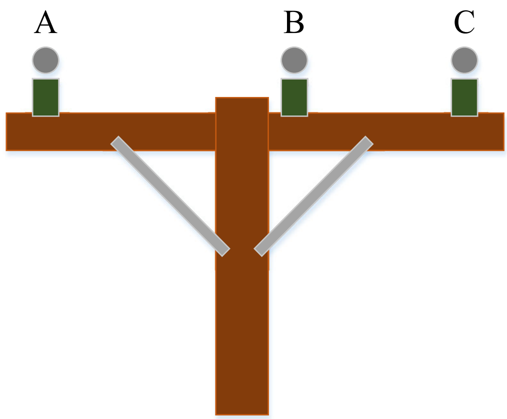

Fig. 1 Unshielded wooden pole of a typical 20 kV distribution line

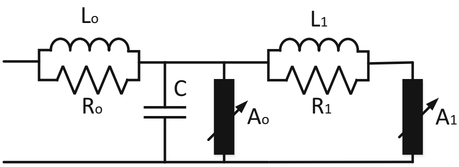

Fig. 2 The IEEE model [11]

Table 1 Surge arrester characteristics

Maximum continuous operating voltage	19.5 kV
Rated voltage	24 kV
Nominal discharge current	10 kA
Maximum residual voltage (8/20 μs, 10 kA)	67 kV
Energy capability	60 kJ

$$R_1 = (65\,d)/n \quad \Omega \tag{4}$$

$$L_0 = (0.2\,d)/n \quad \mu\text{H} \tag{5}$$

$$R_0 = (100\,d)/n \quad \Omega \tag{6}$$

$$C = (100\,n)/d \quad \text{pF} \tag{7}$$

where d is the length of arrester column in meters and n is the number of parallel columns of metal-oxide disks.

In Table 1 are shown the characteristics of the 20 kV surge arrester that is used in the examined distributed line.

The grounding resistance of the line is modeled as a lumped resistor, the wooden poles are modeled by a parallel combination of a resistor and a capacitor, while the insulators were modeled as voltage-dependent flashover switches [7,14]. The distributed generation power plants are considered as synchronous generators connected to the distribution network by transformers.

Finally the injected to the distribution line lightning current was modeled as a double exponential waveform, with peak magnitude of 15 kA, rise time 1.2 μs and time-to-half value of 50 μs.

3 Simulation results

The impact of DG to the lightning protection of modern distribution lines has studied through extensive simulations that have performed using MATLAB Simulink. The simulation model of the under study distribution line connected with three DG units is shown in Fig 3. The examined distribution line has been divided in four segments with length of 2 km each, in order to be defined different positions (A, B, C, D, E) along the line's length. At these positions surge arresters were installed and the developed overvoltages for each position were calculated. Simulated lightning discharges were applied at position A. Each one of the three DG units connected at points A, C and E were generated active power of 100 kW [15].

Simulations were conducted to the distribution line for each one of the six scenarios presenting in Table 2, in relation to the distribution line's grounding resistance that was varying from 1 to 60 Ohms. The obtained overvoltages at each one of the five different positions are shown in Figs. 4, 5, 6, 7, and 8.

Based on the obtained results it can be observed that in cases where no arresters were installed on the distribution line, the variation of the grounding resistance had no effect in the developed overvoltages. This was something that was expected since the poles

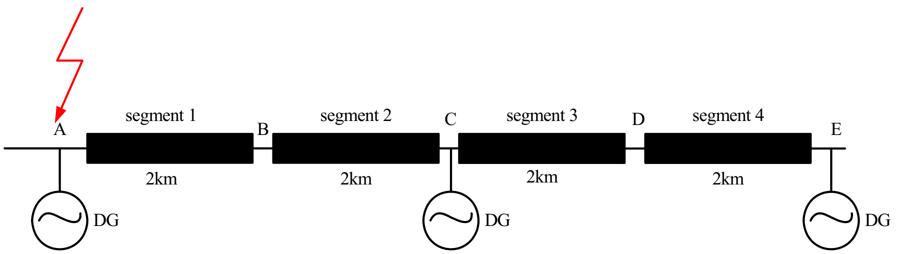

Fig. 3 Simulation model of distribution line with DG

Table 2 Simulation scenarios

No.	Surge arrester position					DG unit position		
	A	B	C	D	E	A	B	C
1	0	0	0	0	0	0	0	0
2	1	0	1	0	1	0	0	0
3	1	1	1	1	1	0	0	0
4	0	0	0	0	0	1	1	1
5	1	0	1	0	1	1	1	1
6	1	1	1	1	1	1	1	1

1 denotes the installation of equipment, *0* denotes the absence of equipment

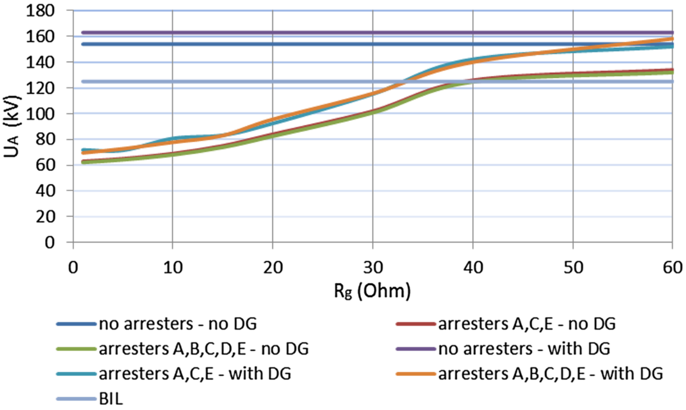

Fig. 4 Developed overvoltage at position A in relation to grounding resistance

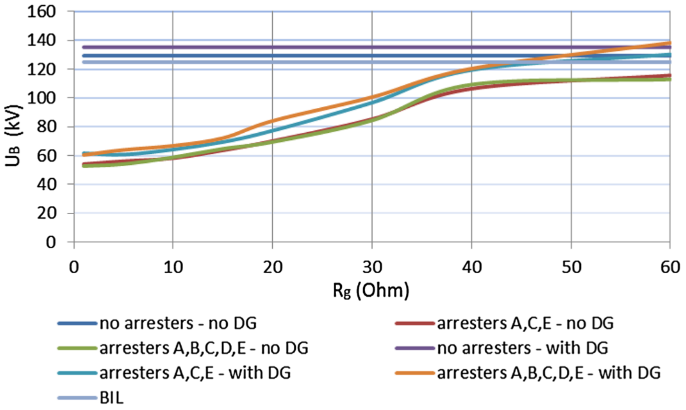

Fig. 5 Developed overvoltage at position B in relation to grounding resistance

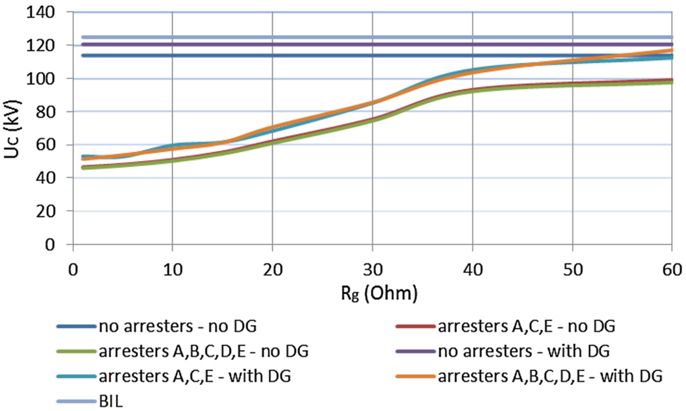

Fig. 6 Developed overvoltage at position C in relation to grounding resistance

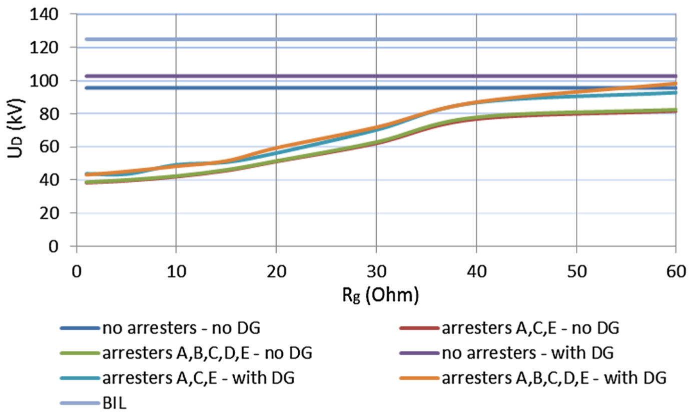

Fig. 7 Developed overvoltage at position D in relation to grounding resistance

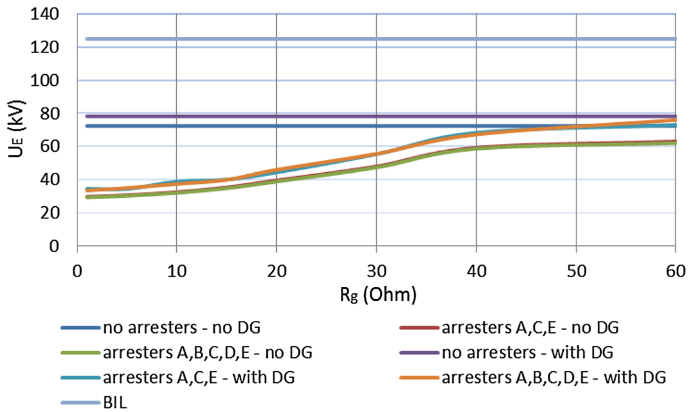

Fig. 8 Developed overvoltage at position E in relation to grounding resistance

were made of wood, there were no active (under voltage) parts of the line connected to earth and the line was unshielded. However the overvoltages were attenuated as the distance from the lightning hit point was increased.

The installation of surge arresters in all available positions (i.e., the closer installation) has shown that the developed overvoltages were reduced, although not significantly. Nevertheless the use of arresters in the examined distribution line is necessary since the overvoltages exceed the value of the basic insulation level of the line.

Finally based on the obtained results has been proven that the presence of DG power plants affects the magnitude of the developed overvoltages, something that must be taken into account in the lightning protection of the modern distribution lines.

4 Conclusions

The paper presents the simulations that have been conducted in a distribution line connected with DG power plants in order to study the impact of DG to the lightning protection of modern distribution lines. Real data from a typical distribution line has been used in this work. Factors that influence significantly the efficiency of the protection systems and the developed overvoltages such as: the installation of surge arresters, the surge arresters' installation position and the distribution line's grounding resistance were considered in the simulations. The obtained results can be very useful to electric utilities and researchers in an effort to upgrade/modify the existing lightning protection methods to include the presence of distributed generation.

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