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Lightning-Induced Overvoltages

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1. Introduction

The problem of disturbances produced by lightning-induced overvoltages on distribution lines has been carefully reconsidered in the last years by power utilities. This is motivated by the widespread use of sensitive electronic devices in the power system equipment (circuit breakers, disconnectors, control and protection circuits) and, in parallel, by the increasing demand by customers for good quality in the power supply. Indeed, lightning-induced voltages are responsible of the majority of faults on distribution overhead lines, causing microinterruptions and, more in general, disturbances to sensitive electronic devices.

2. What causes induced voltages and how to evaluate them ?

A cloud-to-ground lightning flash generates a transient electromagnetic field which can induce overvoltages of significant magnitudes on overhead power lines situated in the vicinity. The *return stroke* phase of the lightning discharge is considered to be the major responsible for the induced voltages, because the most intense electromagnetic radiation occurs during this phase [1][1]. The calculation of lightning-induced voltages requires the following stages.

– first, a *return-stroke model* which specifies the spatial and temporal distribution of the lightning current along the channel during the return-stroke phase is adopted;
– then, the electromagnetic field change produced by such a current distribution, ideally including propagation effects on the field, is calculated along the line, and
– finally, voltages resulting from the electromagnetic interaction between the field and the line conductors are obtained by using a *coupling model*.

Return Stroke Current Models

A return-stroke model to be employed in the calculation of lightning-induced voltages is a specification of the distribution of the return stroke current as a function of height and time along the lightning channel. This distribution is generally specified in terms of the current at the channel-base, which is a directly-measurable quantity and for which collected statistics are available. A certain number of return stroke models have been proposed in the literature (e.g. [2-4]) among which it has been shown that the TL and its more physically plausible modifications [5,6] are a good compromise between simplicity and accuracy in terms of predicted electric and magnetic fields.

[1] For close distances (of the order of a few tens of meters) separating the lightning discharge and the overhead lines, however, important overvoltages can be induced due to the preceding *downward leader* phase [46].

Lightning electromagnetic field calculation

For distances not exceeding a few kilometers, the perfect ground conductivity assumption is shown to be a reasonable approximation for the vertical component of the electric field and for the horizontal component of the magnetic field [7,8]. The horizontal component of the electric field, on the other hand, is appreciably affected by the finite ground conductivity. Simplified expressions have been proposed [8-10] which are able to predict with a reasonable approximation electric field at various distance [8,9,11].

Coupling Models

Three coupling models are commonly adopted in the power literature to describe the coupling between lightning return-stroke fields and overhead lines: the model by *Rusck* [12], the model by *Chowdhuri and Gross* [13], and the model by *Agrawal et al.* [14]. Only the *Agrawal* model and its equivalent formulations [15] can be considered as rigorous within the limits of the adopted hypothesis (transmission line approximations) [16,17].

Experimental validation of Coupling Models

The coupling models have been tested by means of natural lightning [18-20] and triggered lightning [21-22]. The use of lightning is complicated by the intrinsic difficulty in performing a controlled experimenting, although triggered lightning is clearly more promising in this respect. The agreement regarding the wave shape can be considered satisfactory, but regarding the intensity, there are still unexplained discrepancies. Possible causes for the disagreement can be: calibration errors, an incorrect determination of the angle of incidence of the electromagnetic wave, uncertainties about the ground conductivity, the presence of trees and other objects in the vicinity of the line, etc..

More controlled conditions can be obtained using NEMP simulators [23,24] or reduced-scale models [25,26]. Indeed, the comparison between theory and experimental results for this case is satisfactory (see Figs. 1 and 2).

3. What magnitudes and shape are typical overvoltages ?

Fig. 3a shows the induced voltage by a typical subsequent return stroke characterized by a channel-base current presented in Fig. 3b. The line is a lossless, 1-km long, 10-m high overhead wire, matched at its two terminals. The lightning strike is located at 50 m from the line center and equidistant to the line terminations. As it can be seen by this figure, lightning-induced voltages are characterized, in general, by faster risetimes and shorter duration with respect to the originating return stroke current.

Lightning-induced overvoltages can reach magnitudes up to few hundreds of kV and, therefore, can occasionally cause line flashover. If the line terminal is not protected by a surge arrester, but rather by a spark gap, microinterruptions could occur due to the spark gap operation. The induced voltage magnitude and shape significantly depend upon lightning return stroke parameters (channel-base current parameters, return stroke velocity), distance and relative position with respect to the transmission line, ground electrical parameters, and, line configuration and terminations [11,27].

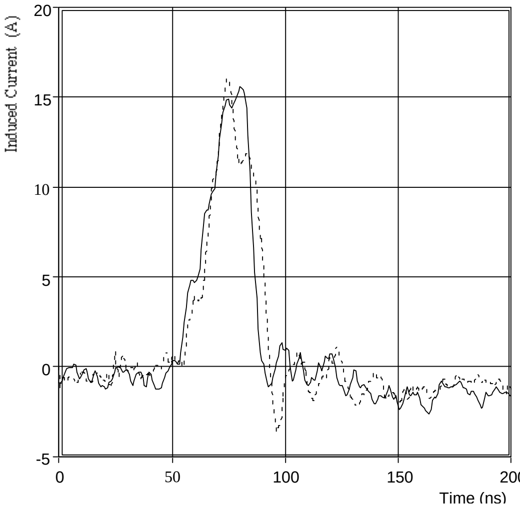

Fig. 1 – Induced current on an experimental line model illuminated by an EMP simulator. Solid line: measured current, dashed line: computed current. (For details on the experiment, see [24])

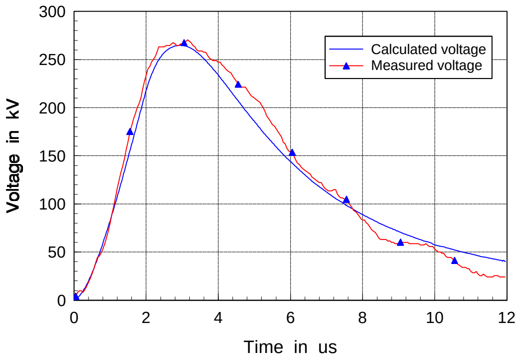

Fig. 2 - Comparison between measurements on a reduced-scale model and simulation results. (Experimental data courtesy of A. Piantini. For details on the experiment, see [26])

4. How far away can lightning strokes be that cause an induced voltage flashover ?

The distance within which a cloud-to-ground lightning discharge can cause an induced voltage flashover is generally within 200 m. This distance depends on the severity of the stroke (current peak and maximum time derivative, return stroke speed), line configuration (length, height), stroke location, ground electrical conductivity, and the BIL. Lightning strokes occurring beyond a few hundred meters from the line can cause a line flashover for poor conducting soils [20].

5. How does the induced voltage drop as a function of distance from the line ?

For the same return stroke parameters and assuming a perfectly conducting ground, the induced voltage at a given point along the line can be approximately assumed to decrease inversely proportional to the distance. Fig. 4 presents the induced voltage as a function of distance for the same parameters as in Fig. 3.

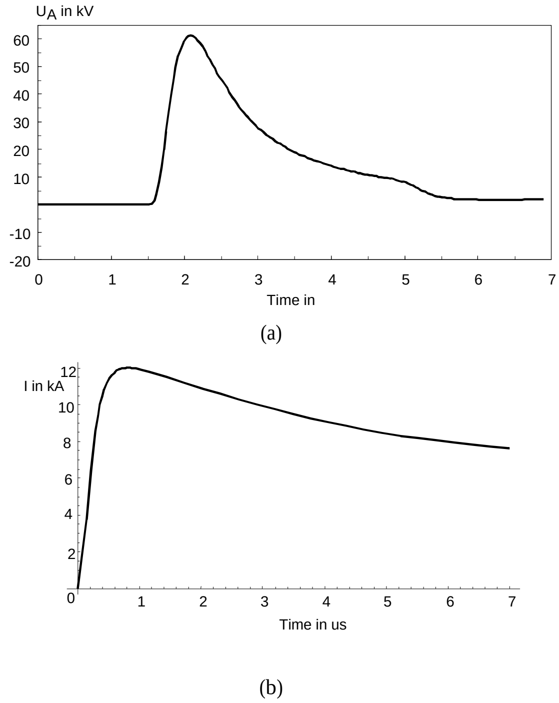

Fig. 3 – Induced voltage on a 1-km long, 10-m high, lossless, matched line over a perfectly conducting ground. Stroke location: 50 m from the line center and equidistant to the line ends. Return stroke parameters correspond to typical subsequent strokes. (a) Induced voltage. (b) Lightning channel-base current.

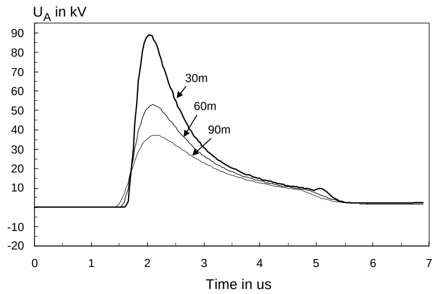

Fig. 4 – Dependence of the induced voltage as a function of the distance. Same configuration as in Fig. 3.

6. What BIL is needed to prevent induced flashovers ?

In contrast with direct strokes for which, regardless of the BIL, generally flashover occurs, the number of induced flashovers decreases as a function of BIL. That is the reason for which lightning-induced overvoltages are of concern essentially for distribution lines [28-30]. The line height and the ground conductivity affect considerably the number of induced voltages greater than a given BIL [31]. In Fig. 5, taken from [31], we show the dependence of the number of events as a function of the BIL for a 2-km long line and considering different values for the ground conductivity. As it can be seen from this figure, Lines with a BIL less than about 300 kV are prone to induced flashovers.

7. What arrester spacing is needed to prevent induced flashovers ?

In order to prevent direct-stroke flashover, arrester spacings of 300-400 m is generally recommended. For the case of induced flashovers, a given configuration of line arresters can result in different performances depending on the location of lightning strike [32]. Further studies are needed in this respect.

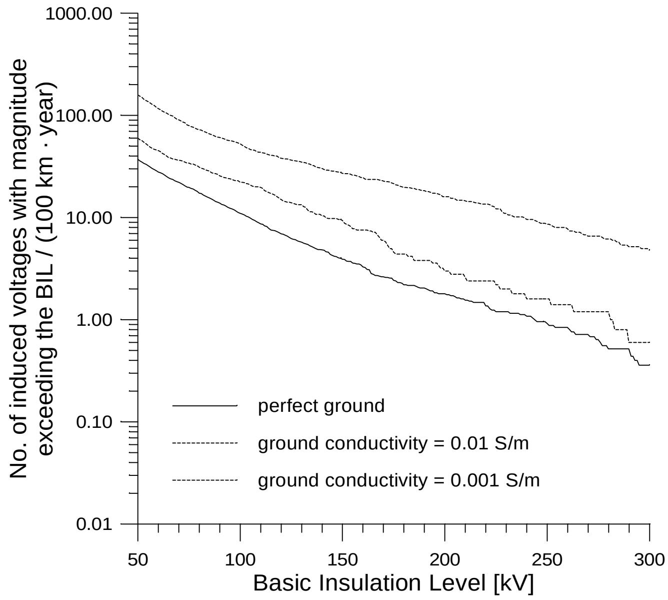

Fig. 5 – Number of events vs BIL for a MV line. (Adapted from [31])

8. Will a shield wire help ?

Shield wires help in reducing the magnitude of induced voltages by a factor of about 20 to 40 % [12,33,34]. This implies about the same reduction of the fault frequency.

9. Is horizontal or vertical construction best ?

The induced voltage magnitude for typical distribution lines is virtually proportional to the line height. As a consequence, an important factor determining the magnitude of lightning-induced voltage is the line height above ground, rather than the type of construction. In general, a construction allowing a shorter height for the conductors is expected to experience lower induced overvoltages. Examples of induced voltages on typical horizontal and vertical configurations can be found in [34].

10. What effect does pole grounding and ground resistivity have ?

Pole grounding affects the performance of the ground wire in reducing the induced overvoltages. In general, lower the pole ground impedance, better the performance of the ground wire.

The ground resistivity has a major effect on the waveshape and magnitudes of the induced voltages. It affects both the lightning electromagnetic fields and surge propagation along the line. However, its effect depend strongly on the line configuration and the stroke location. It can produce an increase, a decrease, and/or an inversion of polarity of the lightning-induced voltages [11,35].

11. Some of the current researches which are being done on induced voltages

- Lightning electromagnetic field characterization using natural and artificially-initiated lightning [36-39]
- Experimental validation of field-to-transmission line coupling models [22,25,40]
- Development of engineering tools for the protection of power networks against lightning-induced overvoltages [41-45]
- Leader-induction effect [46]
- Effect of ground conductivity on lightning-induced overvoltages [9,11,25,35,47,48]
- Return stroke modeling and influence of elevated strike objects on lightning current and radiated fields [2,4,49-53]
- Adequacy of the available lightning return stroke current statistical data [50,54,55]
- Effect of corona on lightning-induced voltages [56,57]
- Lightning detection and location systems [58-59]
- Lightning channel tortuosity and inclination [60]

12. What is the CIGRE working group doing on induced voltages ?

Within the framework of the CIGRE working group WG 33.01 "Lightning", Task Force 33.01.01 "Lightning induced voltages" established some years ago has already produced two papers published in Electra [3,27] dealing respectively with lightning return stroke models and lightning electromagnetic field-to-transmission line coupling models. A third paper, dealing with a sensitivity analysis and aimed at providing ranges of overvoltage values to be expected in the different typical line configurations, is in preparation.

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