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Indirect Effects of Lightning Discharges

Gururaj S. Punekar[1], Chandrasekaran Kandasamy[2]

Abstract: The occurrence of lightning strokes due to indirect effect of lightning discharges, has assumed a lot of importance in the recent times. This is due to the sensitive, vital electronic equipment which are highly vulnerable to such indirect effects. In this article, attempts are made to bring out the salient features and related parameters of lightning discharges (with specific reference to indirect effects). Glimpses of the experimental research efforts to understand the phenomenon are described based on the published scientific work, along with some of the typical simulation results of the authors. These simulation results (computed electromagnetic fields) are validated by some of the important results described in the literature. This being a review article, the vital electrical and electronic systems/components which have been researched with reference to indirect effects have been enumerated, and the present understandings have been discussed.

Keywords: Electric stress, Electromagnetic fields, Indirect effect, Lightning, Over voltages.

1 Introduction

Lightning is a natural electrical phenomena being the most spectacular to every common man. Of all lightning discharges only around 25% of the lightning bolt reaches the ground. Lightning being an intense power source (although of short duration), has the potential to cause significant damage to life and property. Attempts to understand the phenomena (being most spectacular in nature but destructive), has been a great challenge and forms one of the well researched area. In spite of enormous research efforts, when it comes to the question of "how likely is it that lightning will strike an object and cause damage?", deterministic answers are not possible yet. For such questions one needs to heavily depend upon the lightning statistics. One such geographic location based term is "keraunic levels". It is defined as the average number of thunderstorm days in a year for a given location. The frequency of Cloud to Ground (CG) lightning discharges, form yet another statistical data. The other

[1]Department of Electrical & Electronics Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore 575025, Karnataka State, India; E-mail: gsp652000@yahoo.com; gsp@nitk.ac.in
[2]Department of Electrical & Electronics Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore 575025, Karnataka State, India

variables on which the CG discharges depend are terrain, tall structures & trees, their relative spatial spread, shape and composition of the structures, and soil resistivity (which has bearing on dampness and its type), to name a few important ones [1].

Lightning CG discharges have many destructive effects, as is widely known. The more damaging effects have come to the fore due to its indirect effects on modern electronic gadgets, which are susceptible to surge voltages and currents. The effort here is to bring out the salient features of lightning with specific reference to indirect effects.

2 Effects of Lightning Discharges

The Physics of lightning is still a challenge to understand. CG discharges can be quite destructive, particularly when unprotected. The number of lightning related deaths in humans is small when compared to other causes of accidents. Livestock in the farms are more susceptible, particularly four legged animals with large spans between legs; e.g. cattle's. Lightning plays an important role in forest fires and associated damages. Interaction of CG discharges with power lines can cause a large number of power failures [2].

The effects of CG discharges can be broadly grouped into two categories, namely: (i) direct (direct strokes), and (ii) indirect (indirect strokes). Indirect effects can be further viewed as those due to: (a) conductive, inductive and capacitive coupling, and (b) radiative coupling.

2.1 Direct strokes

A lightning CG discharge, strikes an object directly, such as power-line or building, and it can result in significant damage. Direct effects generally result in physical damage and have associated fire hazards. In the case of buildings it can result in cracks in the masonry work. The injected voltages and currents associated with direct strokes being much higher compared to indirect strokes, will have ability even to damage power and distribution equipment. Most often the electrical motor insulations associated with the irrigation pump becomes the victim of direct stroke. Other common examples are welding of contactors of the motors starters and explosion of power distribution transformers.

The protections in the form of lightning rods and ground overhead wires can significantly reduce the chances of direct strokes. Having averted the direct strokes if one has to successfully reduce the probable secondary effects (resulting in Ground Potential Rise) an appropriate grounding and bonding system is a must [3].

2.2 Indirect effects due to Ground Potential Rise (GPR)

Even if the lightning rods and ground overhead wires effectively shield the buildings, power lines and other objects, the lightning hazard cannot be totally eliminated without reducing the ground potential rise (GPR). Once the lightning CG discharges are to the ground rod and wires, the charges tend to flow to the ground through the associated grounding system. For no GPR, the system needs grounding with zero ground impedance, ideally. In actuality the ground impedances are neither zero nor stable due to many of the soil properties and its associated parameters. There are guidelines related to the threshold permissible values of earth resistances depending on the criticality of the system being protected. GPR related issues are the next most severe causes of damages due to direct strokes of CG discharges. With GPR, like direct strokes, the lightning effects are situated very near to, in and around the CG-discharge location [4].

In the present modern world, with proliferation of electronics gadgets, the effects of CG lightning discharge can be far reaching due to electric and magnetic fields associated with the lightning. These indirect effects due to radiation have been gaining significance in recent times and are forming current topics of research.

2.3 Indirect effects due to Lightning Electromagnetic Pulse (LEMP)

Lightning stroke, particularly the return stroke part of the lightning, forms a high current electric discharge in air. The current peak magnitudes are of the orders of several tens of kilo amperes. This current is in the form of a pulse. Due to its rapidly time-varying characteristics (large time rate of change of current), it sets up time varying electromagnetic (EM) fields. These time varying EM fields induce voltage and current surges in electric circuits in the region illumined by Lightning Electromagnetic Pulse (LEMP). Solid-state electronic components and circuits are particularly vulnerable to these lightning induced voltages and current surges [5]. The first step towards protecting these devices would be to characterize the LEMP environment. This process of characterization involves the lightning currents and the associated electric and magnetic field pulses over the duration of the lightning flash.

3 Lightning Parameters, Measurements and Studies

The most important, fundamental parameters in lightning related damages are the lightning currents (in the case of direct strokes) and EM fields (produced due to lightning strokes; which can produce high induced voltages). Understanding related to the processes and parameters associated with atmospheric discharges have helped in coming to this conclusion. These are discussed briefly, along with the typical parameters of CG lightning associated with the EM pulse.

3.1 Lightning Parameters

Thunder cloud heights above the ground vary from 2-10 km. This wide range of distribution can be narrowed down based on the geographic location (tropic region or temperate region). Although the physics of charge separation at micro level is not well understood, at the macro level, in most cases the bottom of the cloud is negatively charged. Hence, 90% of the cloud-to-ground (CG) discharges are negative in nature. A small patch (10%) of lightning is positive due to positive charge pockets which are occasionally formed near the bottom of the cloud. Initiation of a discharge is always from the cloud, starting within the charged pockets present on the lower surface of the cloud. This process of initiation starting from the cloud is termed *pilot leader*. This pilot leader further advances through the air towards the earth in steps and is now termed a *stepped leader*. This step advancement will be in progressively decreasing steps in the range 50 to 10 m per step with step interval of 50 μs to 10 μs (as it progresses towards the ground). When such a discharge is at 100-200 m above the ground, a leader starting from the ground, called a *connecting leader* meets the stepped leader. Thus, a complete lightning channel is formed. This ionized channel contains surplus electrons and results in an upward traveling wave called *return stroke*. Measurements indicate that this return stroke radiation field is about 10 times that of the stepped leader. Hence, this fast moving (<100 μs) intense current (order 10-200 kA) return stroke can cause indirect effects due to field coupling and high induced voltages. Some other portion of the un-discharged cloud will use this channel and bring down negative charges to ground in the form of a *stepped-dart-leader*. This will be followed by a subsequent return stroke. Several return strokes constitute a lightning discharge; they will occur with a time interval of 50-100 ms between them. Thus a lightning event can extend up to one second. It is observed that subsequent return stroke carry less charge and hence they are relatively less intense [6].

The induced voltages (and indirect effects) causing EM disturbance (EMC issues) are mainly due to the *first return stroke*. The associated parameters of importance of the first return stroke are: (i) peak current of return stroke; (ii) current derivative of return stroke (iii) velocity of the return stroke wave; (iv) charge associated with the return stroke (integral of current); (v) energy associated with the return stroke (integral of square of current). Typical values of these parameters are listed in the **Table1**; Adopted from reference [7].

The other important factor in indirect effects is the distance of the exposed electronics/equipment from the striking point. Typical E and H fields at a distance of 2 km from the lightning are given in **Table 2**; as adopted from reference [8]. Their magnitude decreases with the increase in distance from the striking point.

These field magnitudes in turn depend on the parameters associated with the lightning return stroke. The parameters given in the **Table 1**, namely, the velocity of the return stroke also decides the induced EM fields. The induced transients in exposed equipment depend on the magnitude and direction of the EM fields. The soil conductivity (soil impedance) has its influence on the lightning effects and forms an important parameter. These soil parameters, (like conductivity, permittivity, type of soil and structure, moisture content etc) have a bearing on EM fields and also on the induced transient voltage [9].

The probability of lightning striking a point in a region depends on terrain, height of structure and density of structures, apart from the keraunic level of the place.

Table 1

Important parameters associated with lightning discharges [7].

Current Parameters	Unit	Typical value	
		First stroke	Subsequen t stroke
Peak value of the return strokes current (i_{max})	kA	30	12
Maximum time derivative of the return stroke current $(\mathrm{d}i/\mathrm{d}t)_{max}$	kA/µs	12	40
Charge of the return strokes current (Q)	C	5.2	1.4
Specific energy of the return strokes current	A^2s	5.5×10^4	6.0×10^3
Return stroke velocity	m/s	1.7×10^8	1.9×10^8

Table 2

Typical Electric and Magnetic field parameters associated with lightning discharge at a distance of 2 km *from striking point for subsequent return strokes* [8].

Electric field E [kV/m]	Maximum time derivative of Electric field $\mathrm{d}E/\mathrm{d}t$ [kV/m/µs]	Magnetic field H [A/m]	Maximum time derivative of Magnetic field $\mathrm{d}H/\mathrm{d}t$ [A/m/µs]	Time to peak [µs]
0.23	0.76	0.6	2	0.8

3.2 Measurements

The parameters discussed so far and many more have been part of the measurement activity for a very long time. The peak lightning currents data obtained are measured using instrumented towers with magnetic links. The magnetic links have their own limitations in measuring, as lightning is rarely a single stroke. Presently, the measuring systems are used not only to measure the parameters of this time dependent event, but also can record the same [10]. As capturing these data depends on the probability of lightning striking, instead, there are efforts to initiate the lightning by triggering a stroke using rockets. This is accomplished via an experimental setup in the field which initiates an artificial lightning discharge [11]. These interesting experiments are with artificial lightning discharges initiated from the charges that are residing on the charged clouds, prior to a thunderstorm. These *Triggered lightning* experiments have definitely yielded some more insight in understanding lightning discharges. They also show a certain degree of deviations from the parameters measured under natural lightning flashes [11].

Apart from understanding the process and the phenomena of lightning, of late there are *lightning location systems* (LLS), which are being employed to identify precisely the location of a lightning discharge [12]. LLS are becoming very important in establishing the damage to exposed equipment due to indirect lightning strokes due to induced effects. The field quantities like E&H due to lightning are measured by LLS to locate the striking point with geographically spread out measuring units. These results can be further used to correlate any damage reported (out of suspicion) to be due to lightning. This is useful particularly for the insurance companies in general [13].

3.3 Modeling and simulations

Having obtained a large amount of related field data, digital simulation efforts have advanced the understanding related to lightning discharge and its effects (EM irradiation).

In order to understand the behavior of these lightning induced voltages, which can causes damage to exposed equipment/electronics, it is imperative that the lightning EM fields at different distances from the strike point and different heights above the ground be computed. This modeling and simulation involves following steps:

- Modeling channel base current of the lightning stroke;
- Modeling of lightning return stroke current through return stroke channel;
- Computing the EM fields;

Such models yield results with perfect ground (infinite conductivity) and are further extended (with modifications) to account for the finite ground conductivity.

For determining the radiated electric and magnetic fields, it is necessary to know the current distribution along the lightning channel. Hence the lightning return stroke models form the important part of modeling. These models are classified as: (i) Gas dynamic or Physical models, (ii) Electromagnetic models, (iii) Distributed circuit models, and (iv) Engineering models [14].

Models in general are the templates held against ‘nature’. These models proposed by the researchers are to attempt prediction, matching with the facts observed in the ‘nature’. ‘Engineering’ models specify spatial and temporal distribution of the channel current and relate it to the channel base current in predicting electromagnetic fields [14-15]. The electromagnetic fields predicted by the models are compared with the observed data. ‘Engineering’ models deliberately lay less emphasis on the physics of the lightning stroke. The most commonly discussed ‘Engineering’ models in the literature are: (i) BG (Bruce-Golde) model, (ii) TL (Transmission Line) model, (iii) MULS (Master-Uman-Lin-Standler) model, (iv) TCS (Travelling Current Source) model, and (v) MTL (Modified Transmission Line) model. The variants of MTL models, based on the modeling of current decay process, have resulted into MTLL model (linear decay; as proposed by Rakov and Dulzon [16]) and MTLE model (exponential decay; as proposed by Nucci et al [17]). In order to compare the simulation model results with those of observed data Nucci et al [14, 15] have identified four characteristic features of the electromagnetic field parameters associated with the LEMP. Although great advancement is made in modeling, however no model is reported to be completely adequate in predicting all the features of the LEMP waveforms observed in the nature, completely [14]. Numerical solutions with Two Image Approximation (TIA) method is yet another possibility being discussed in the literature which is said to give good results both in case of near and far field regions field computations [18]. This is to assert that, there is enough scope still exists for research, in arriving at a holistic model.

This review not being intended to address the comparison of ‘Engineering’ models has adopted MTLE model, for the purpose of illustration (by implementing the same in MATLAB [19]). A few typical simulation results based on MTLE model, implemented by the authors in MATLAB and are given in this section. The simulation model implemented makes the following assumptions: (1) The lightning channel is perfectly vertical; and therefore can be considered as a straight vertical antenna along which the return stroke front propagates upward at the return stroke speed (2) The ground is assumed to be flat, homogeneous and characterized by its conductivity and its relative permittivity. These assumptions are similar to those described in the literature [16].

There are theoretical and experimental evidence that the ground conductivity affects the radiated EM fields. The discussion related to calculations of component of the electric field in case of finite ground conductivity can be found in reference [20]. Underground EM field due to lightning for finite ground conductivity at different depths below the ground level is calculated from the known field at the ground surface [21]. In recent years, the number of power installations lying underground have been rapidly increasing. Sensitive electronics components used in both power and communication systems may suffer logic upset or get damaged at significantly lower levels of induced lightning EM interferences. Hence, studies of lightning generated EM fields below the ground level have also become important. To facilitate such investigations, a detailed understanding of lightning EM fields is required at different depths, below the ground surface [22-23]. These EM irradiation fields due to lightning when coupled with overhead conductors or buried cables, would result in induced voltages and currents.

The typical electric fields computed (using the MATLAB implemented computer code) at a distance of 2 km from the lightning channel is as shown in the Fig. 1 and Fig. 2. As the *E* and *H* fields depend on the lightning parameters, these results have been generated for typical lightning parameters corresponding to the first return stroke (Fig. 1) and subsequent return stroke (Fig. 2) respectively, listed in **Table 1** [7]. These plots show three components of the total *E*-field due to lightning. Of these three, the radiation field component is of importance from the point-of-view of over-voltage inducement. The radiation fields generally die off within short time durations of few tens of microseconds from the instant of commencement of the lightning return stroke.

The channel base current corresponding to typical lightning first return stroke is generated using Heidler's function parameters I_{01}, τ_{11}, τ_{12} and n_1 as 28 kA, 1.8 μs, 95 μs and 2, respectively [8, 24]. In generating the typical subsequent return stroke, sum of two Heidler's function are used with parameters I_{01}, τ_{11}, τ_{12}, n_1, I_{02}, τ_{21}, τ_{22} and n_2 as 10.7 kA, 0.25 μs, 2.5 μs, 2, 6.5 kA, 2 μs, 230 μs, 2, respectively [8, 24].

The simulation results shown in Fig. 2 (for the subsequent return stroke) match with typical *E*-field results given in **Table 2** which are adopted from reference [8]. The effort here is to validate our implementation (MATLAB code developed) of the model with the help of published results. Having validated, further the code developed is used to observe the variation of the electric field at distances of 500 m, 50 km and 100 km, as given in Figs. 3, 4 and 5. The typical magnetic field variations at a distance of 500 m from the lightning channel obtained via simulation for first and subsequent return strokes are as given Figs. 6a and 6b. Based on the simulation results the radiation component (peak) of the electric field has been grouped in **Table 3**. From this table it is observed that, the LEMP generated electric field reduces drastically as one moves away from the lightning channel.

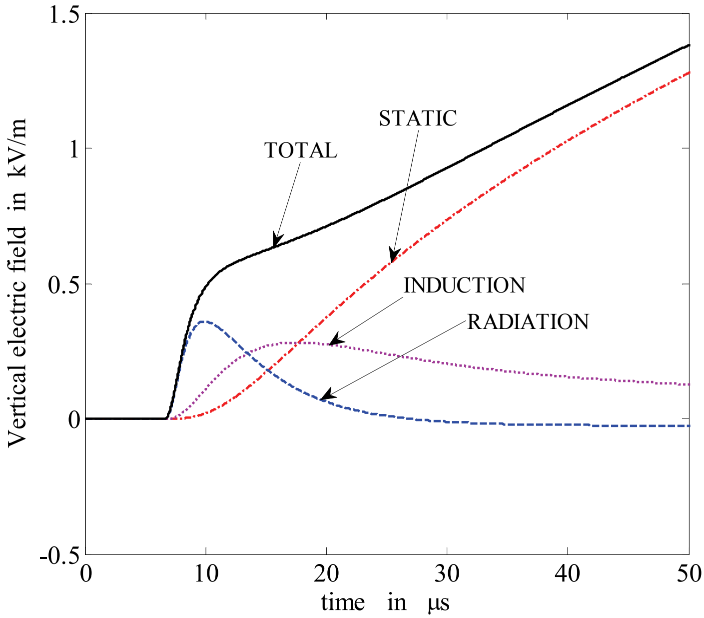


Fig. 1 – *Electric fields due to typical, first return stroke* (FS) *at a distance of* 2 km.

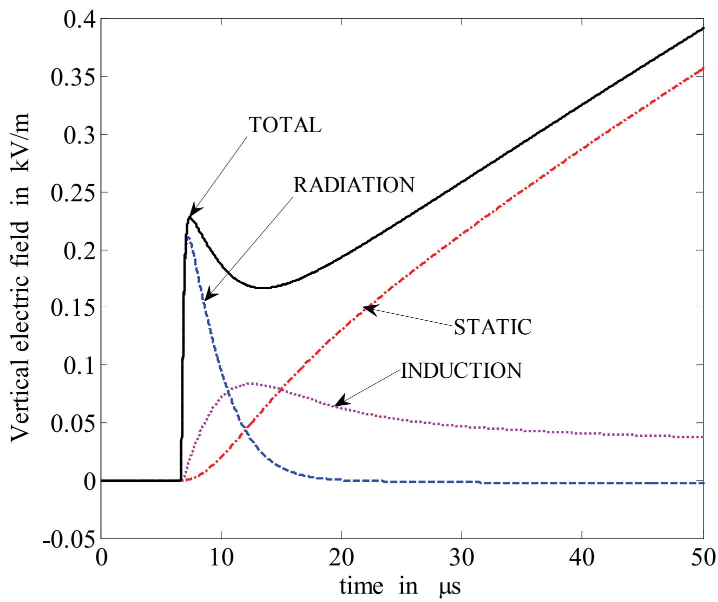
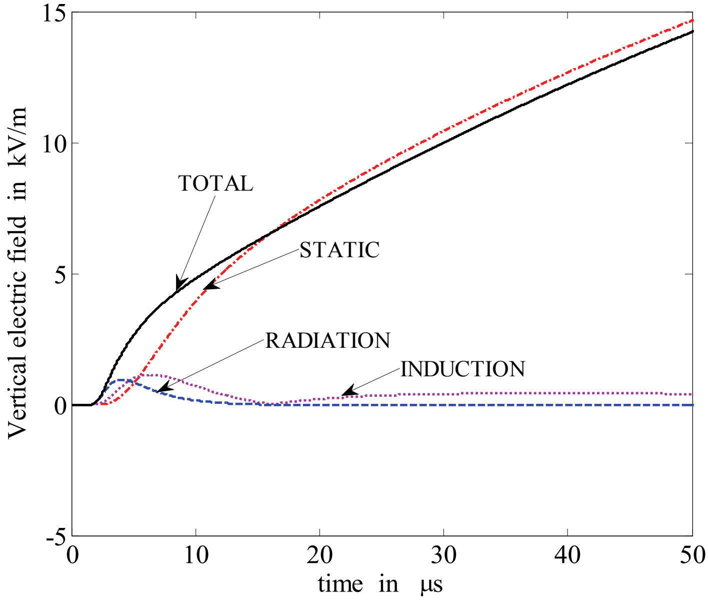
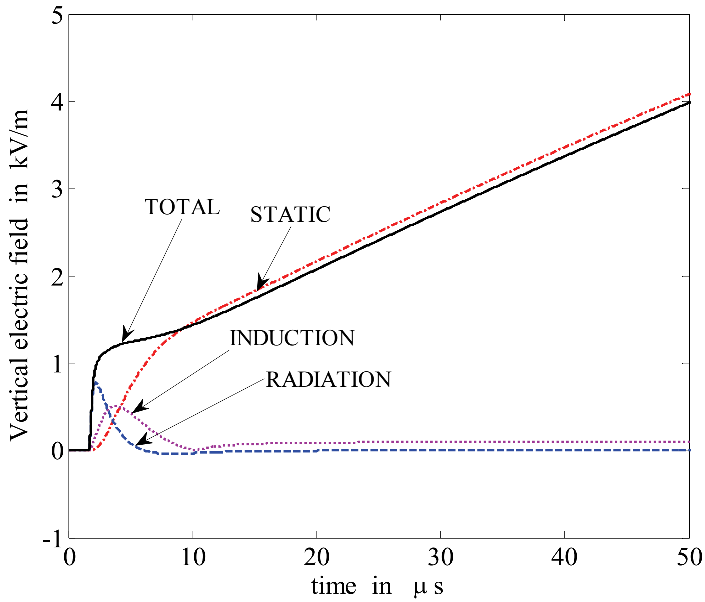


Fig. 2 – *Electric fields due to typical, subsequent return stroke* (SS) *at a distance of* 2 km.

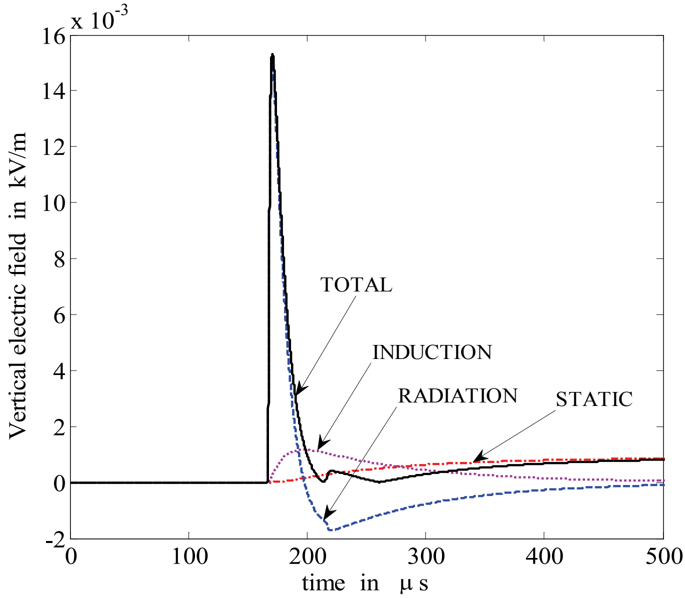


(a) *First stroke* (FS).

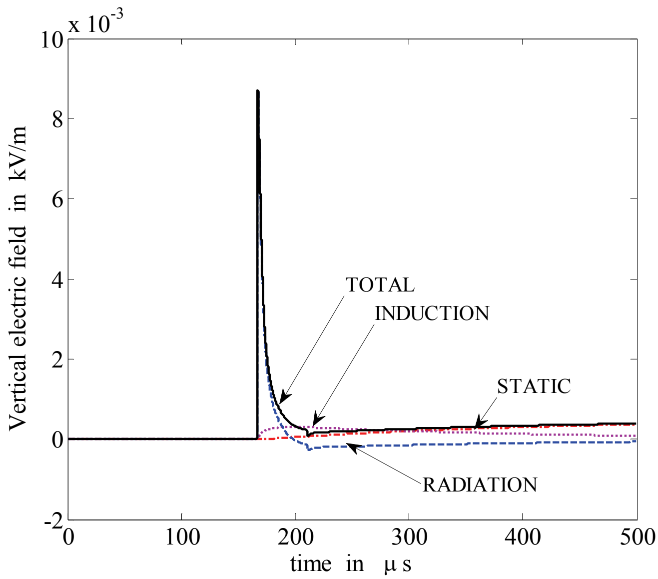


(b) *Subsequent stroke* (SS).

Fig. 3 – *Electric field variations due to typical, lightning first* (FS) and *subsequent* (SS) *return stroke at a distance of* 500 m *from the lightning channel.*

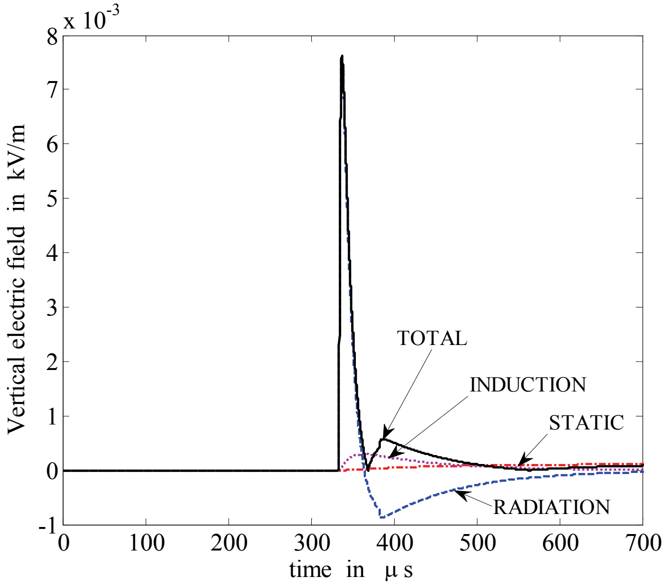


(a) *First stroke* (FS).

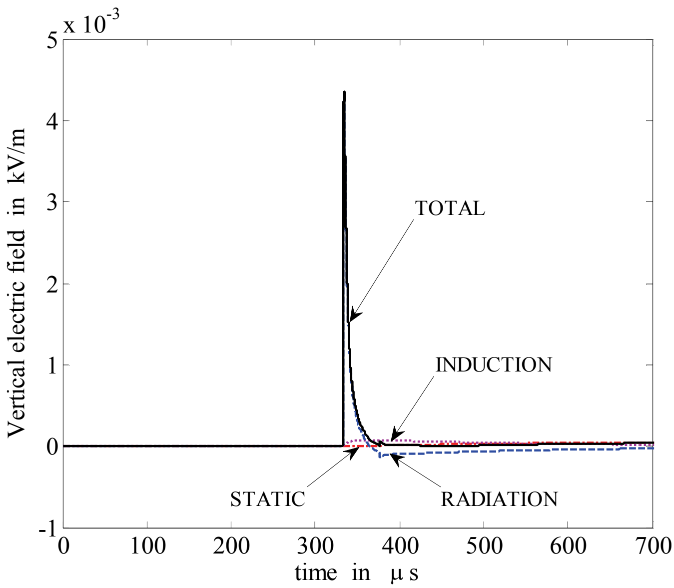


(b) *Subsequent stroke* (SS).

Fig. 4 – *Electric field variations due to typical*, *lightning first* (FS) and *subsequent* (SS*) return stroke at a distance of* 50,000 m *from the lightning channel*.

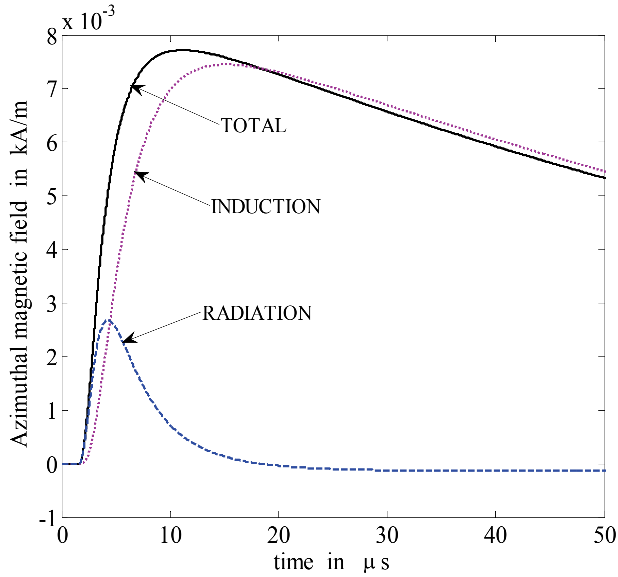


(a) *First stroke* (FS).

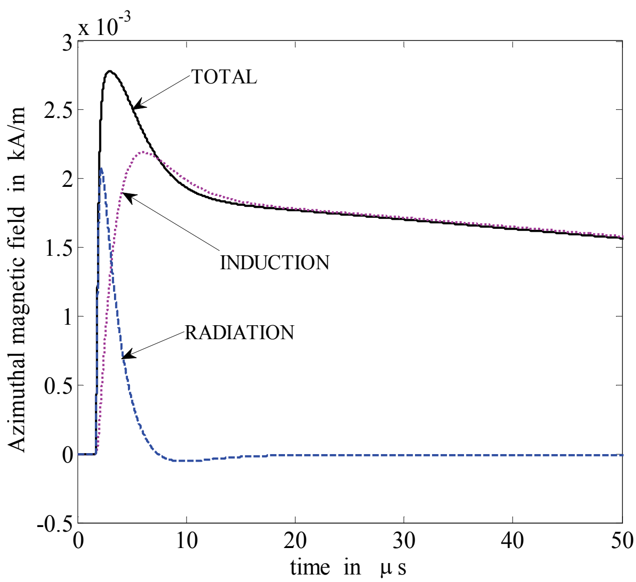


(b) *Subsequent stroke* (SS).

Fig. 5 – *Electric field variations due to typical, lightning first* (FS) and *subsequent* (SS*) return stroke at a distance of* 100,000 m *from the lightning channel.*



(a) *First stroke* (FS).



(b) *Subsequent stroke* (SS).

Fig. 6 – *Magnetic field variations due to typical, lightning first* (FS) *and subsequent* (SS) *return stroke at a distance of* 500 m.

Table 3
Radiation component of electric fields (peak) at different distances.

Return strokes	Distance from the lightning channel			
	500 m	2000 m	50000 m	100000 m
First return stroke Radiation Electric Field (V/m)	946.5	359.4	15.1	7.56
Subsequent return stroke Radiation Electric field (V/m)	776.4	211.2	8.68	4.34

4 Effects in the Region Irradiated by Lemp

Among the many objects which are influenced by the lightning irradiation, the most significant and well researched systems are power distribution and telecommunication lines. There are many other sensitive electronic equipment which either directly experience the lightning induced over voltages or experience indirect effect of induced voltages (induced elsewhere) as they are sourced (power & signal) through power lines or communication ports. Some of these issues of induced effects which have become highly relevant in the modern electronic world are discussed below.

4.1 Power lines

These networks are prone to lightning induced over voltages due to their vast exposed network area. With an increase in sensitive electronic devices connected to the system, customers demand high quality, stable and reliable power from electrical utilities. With lightning being a major source of disturbance on overhead line many studies have been carried out on medium voltage (MV) line to improve the quality and reliability of the power, through system study and analysis [25].

The indirect strokes due to LEMPs have a relation with critical flash over voltage (CFO) of the line structure. For CFOs greater than 300 kV, the indirect strokes lose significance.

The experimentally recorded induced over voltage, on 2.7 km long line (MV) has shown a peak value of 25 kV [26]. The experimental results reported are for an un-energized situation with matching terminal impedances. These lightning induced over voltage (LIOV) amplitude and wave shape depend on lightning stroke parameters discussed in Section 3, apart from the distribution system dependent parameters like: (i) height of the conductors, (ii) line configuration, (iii) presence of shielding wire, (iv) surge arrester location, (v) surge arresters V/I characteristics, etc.

The induced LIOV and their impact on low voltage (LV) systems have been of research interest as well. The research findings have indicated that induced over voltages up to 5 kV have been recorded. Also, over-voltages have been induced by strokes which are as far away as 20 km [26].

Rocket triggered lightning experiment [27] in the vicinity of LV experimental line has shown a phase-to-earth and neutral-to-earth induced voltage of 2 kV-12 kV (in a series of experiments).

The influence of power system and telecommunication lines configuration/topology on induced LIOV has also been reported. It has been shown that the system connected load also affects the magnitude of induced over voltage. As expected the higher the load impedance, the higher is the induced lightning impulse over voltage [28].

4.2 Railway network

As in the case with the overhead distribution network, the railway network also has a spatial distribution and is hence prone to LEMPs. This has become more prevalent in recent time due to the introduction of modern sensitive electronic circuits for signaling, communications and control. Such a specific, detailed study is seen in the literature [29] for the Swedish railway network. The report concludes that the over voltage diversion alone will not be a viable solution and the EMC-EMI issues need due consideration.

4.3 Aircrafts

Lightning can have direct and indirect effects on aircraft. Direct stroke can lead to physical damage due to the high concentration of energy. A structural design incorporating ‘Faraday-cage’ characteristics has shown remarkably high performance against direct stroke. The indirect effects mainly leads to EMI problems, although due stringent shielding, bonding measures apart from segregating the critical circuits have almost eliminated the associated problems [30].

4.4 Electronic measuring devices and computers

Although GPR is the major indirect cause of lightning related damages, the LEMP related coupling through cables etc is yet another source of induced over voltages. Industrial equipment, electronic measuring and control devices can be damaged from LEMP induced transients entering through the power source. The other possible entry points are the communication line, phase modems, analog and digital i/o port and antenna connectors. A LEMP induced over voltage, tolerated by LV power distribution systems or a telephone line may lead it to the sensitive equipment as a traveling wave. The induced over voltage traveling wave may result in sufficient over voltage to damage computers and electronic devices [31].

5 Conclusion

Although a very well researched area (as seen from the literature/references), with more and more sensitive electronic systems being used (which are vulnerable to induced effects), the lightning phenomenon still calls for much better understanding. Research activities, both from physics and engineering (electrical/electronic system design including protection and mitigation) point-of-view in understanding this natural phenomenon, are needed.

Although mitigation is not discussed in this paper, protection against lightning is case-specific and involves shielding, bonding, grounding and suppression. This is particularly true when it comes to lightning protection against indirect effects. Thus, in general lightning protection plans are case specific.

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