Chapter 21
Lightning Effects on LED-Based Luminaires

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Abstract This chapter gives an extensive overview into the nature of the environment that luminaires and thus LEDs are subjected to during the event of a lightning stroke. Direct lightning stroke almost always results in instant damage for low-voltage connected devices, except in "extraordinary circumstances" where random components may survive. This is usually not a subject for debate and is not the subject of this monograph. Indirect consequences of lightning strokes, however, can be effectively mitigated as described. This chapter also delves into a realistic expected overvoltage levels for two typical systems, overhead lines and insulated cables, as obtained from lightning studies on a power network supplying power to LED devices and thus justifies the recommendations by several standards. In addition, it shows the importance of an often neglected device—MOV in mitigating attendant surges due to lightning to a level that can be withstood by LEDs and associated devices.

21.1 Introduction

Despite the advances and rapid improvements in the state-of-art of light-emitting diodes (LEDs), these devices are still sensitive and vulnerable to overvoltages; particularly the effect of overvoltages (otherwise termed surges) due to lightning—direct stroke and indirect strokes. It is known that low-voltage devices (in general)

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inclusive LEDs cannot survive a direct lightning stroke, except in *extraordinary circumstances*.

The magnitude of overvoltages due to such direct stroke is outrageously high that LEDs are damaged so fast beyond recognition, to a state where it becomes remotely difficult to ascertain the true sequence of event that lead to damage. A conservative lightning current magnitude of 10 kA within the vicinity of a luminaire housing LED devices with impedance of 50–100 W can produce an overvoltage as high as 1 MV!

As a result of this, protection against direct strokes for LED-based luminaires is not feasible technically and economically as this would defeat the benefits of an otherwise cheap device, and this is usually not a subject for debate.

A more common source of overvoltages that can be effectively mitigated with proper circuit layout, architecture, and extra measures is overvoltages due to indirect strokes, specifically those that are the consequences of lightning strokes. Main route of lightning-induced surges to LEDs is via the power network to which the LEDs are connected [1].

It should be noted early on that direct strokes in the context of this monograph are lightning strikes that hit a structure carrying a luminaire (luminaire in this text is assumed to be LED based) or stroke to the luminaire itself. On the other hand, strokes to ground in the vicinity of a luminaire cannot be termed a direct stroke in this context since the only means of propagation to the luminaire is via electromagnetic induction and/or via grounding lines which per se is indirect; albeit it is a direct stroke to ground [1]. Indirect lightning strikes are of course attendant of lightning strokes, but either some distance away from the position of luminaire or due to the apparent connection of luminaires and/or support structures. In fact, lightning stroke between two clouds tens of kilometres from ground could cause overvoltages in luminaires depending on the medium of power distribution overhead lines (OHL) or cables (overhead and underground) [2, 3]. This is usually referred to as the capacitive mode of propagation or more scientifically electrostatic mode of propagation as it deals with the movement of charges.

21.2 Mechanism of Lightning Propagation

The first step in identifying ways to mitigate surges due this natural and highly unpredictable phenomenon is to ascertain its mode of propagation. There are several known mechanism in which lightning surges could propagate through to the terminals of luminaires.

1. Induced overvoltages: This is the most common means of lightning propagation in power networks connecting luminaires to source of power. It is the main mechanism of indirect strokes. Electromagnetic fields attendant of a lightning current induce voltage in nearby structures, including houses, conductors, and underground cables. Magnitude of overvoltages is inversely proportional to the distance between points of stroke and location or structure housing LED

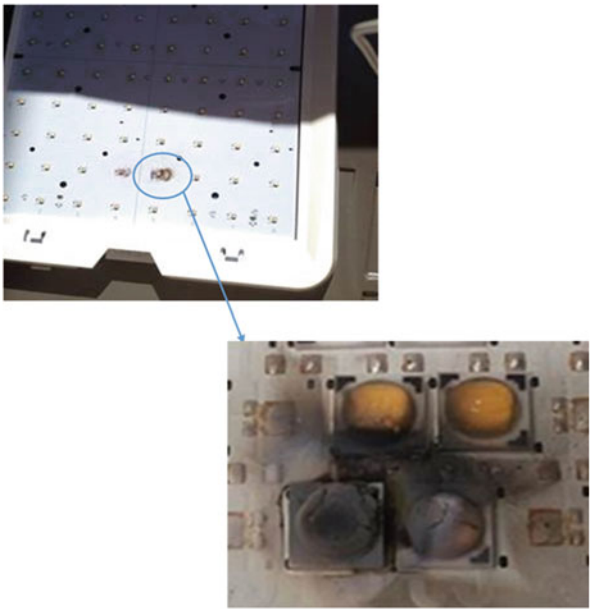

Fig. 21.1 Damaged LED device

devices [4]. At low system voltages (as is the case of luminaires and other LED-based devices), this may result in a few kilovolts (kV) with differential mode coupling (DM) and tens of kilovolts for common mode (CM) with consequent surge current in the region of tens of kilo amps for CM [2, 4, 5]. In the same vein, induced overvoltages can go from the medium-voltage (MV) system to low-voltage system (LV). Above 66 kV system-level voltages, this mechanism is not an issue as induced voltages may well be below the basic insulation level (BIL). But for LV systems, this is the main cause of damages and insulation breakdown. Figure 21.1 depicts the damages to the LEDs of a luminaire as observed in the field.

2. Ground overvoltages: This is due to strokes to ground within the vicinity of luminaires. Transfer to the power network thus depends on the mode of grounding. This mode of propagation is the source of the well-known ground potential rise (GPR) [4–6].
3. Line charging: This is more of a relatively understudied mode of propagation. This is mainly prevalent in OHL systems. Lightning studies on cable systems—overhead and underground cables—show that this method is not prevalent for cables. Generally speaking, it is widely agreed that clouds are mostly (but not always) negatively charged which induces opposite charges on ground and OHLs [7]. This is referred to as line charging. In the event that lightning discharge between two charged clouds occurs, these induced positive charges are no longer bounded as they initially were predischarge and will be forced to move. Hence, these charges move swiftly in lines resulting to overvoltages in devices connected to such lines. A good solution to this is the use of overhead insulated cables, but cost of installation may be a valid drawback.

21.3 Effects of Lightning on LEDs and Basic Mitigation Method

21.3.1 Effects of Lightning

In most cases, the ultimate effect of lightning on LEDs is instant damage. However, depending on the duration of the lightning stroke itself, partial damage may also be observed. In such a case, damages are usually to the devices closest to entrance point of a surge, while others at some distance remain healthy as the duration of stroke was too short to propagate. Nevertheless, the healthy devices may at some point in time malfunction due to the impact and stress induced by surge. Figure 21.1 depicts one of such possible damage observed in the field.

21.3.2 Basic Mitigation

Sources of surges in a practical systems include surges from supply sources, stroke within the vicinity of luminaires but not a direct hit, and lightning strokes between two clouds as already mentioned.

Metal-oxide varistor (MOV) is one of the most important and basic device for mitigation of surges. The importance of these devices is often neglected. To say the least, the life of a luminaire is a function of the life of the MOV connected to its terminals. Once an MOV has degraded to a point where it can no longer operate, it is just a matter of time before transient surges cause damage to luminaires. This is to underscore the significance of MOVs.

Another important design consideration for luminaires is the withstand strength. MOVs are not capable single-handedly to completely mitigate surges; luminaires (LEDs inclusive) must also take some responsibilities. MOVs are responsible for clamping down overvoltages to safe levels (but not in all cases). The voltage level that remains after an MOV clamps down on a surge depends on the magnitude of the overvoltage that arrives at the terminals of the MOV. Therefore, luminaires must be able to withstand whatever residual voltages remain after MOV clamps down on the surge. As an illustration, if an overvoltage of 30 kV impinges on the terminals of a luminaire where an MOV is situated, a properly installed MOV could clamp down this voltage to 1 kV or less. Thus, luminaire including all connected devices must be able to withstand 1 kV without damage. As a rule of thumb, luminaires should be designed to withstand a minimum voltage level which could be determined by lightning studies simulations or by resorting to recommended values in standards [8, 9].

21.4 Lightning Studies on Outdoor LED-Based Luminaires

21.4.1 Modelling in ATP-EMTP

The Alternative Transients Program (ATP) is a version of the famed Electromagnetic Transients Program for digital simulation of transient phenomena. ATP is widely regarded as the most widely used transient analysis program for simulation of electric power systems transients. ATP is a free of charge software program with extensive modelling capabilities and other computational capabilities. As described, it belongs to a family of EMTP-based programs. EMTP was initially developed in the public domain at the Bonneville Power Administration (BPA) of Portland, Oregon, before the commercialization of the program [11].

ATP program operates by predicting important parameters within an electric power network in time domain, prior to a application of a source of disturbance. ATP has an advantage of having many built-in models including transformers, electrical machines, surge arresters, transmission lines and cables, etc. Therefore, all that is required is data to make these models work. Frequency-domain computations and analysis can also be carried out using harmonic frequency scan technique.

Finally, algorithms are available for plotting of parameters and variables as a function of both time and also in the frequency domain1. Interested readers are referred to the reference manual of ATP, for more extensive information on the capabilities of ATP program [11].

21.4.2 Studies and Simulation

This section gives an overview of expected voltage levels that imping on luminaires when there are no MOVs to mitigate and why MOVs are indispensable devices. Result of simulation of lightning surge propagation in a low-voltage lighting power network for 15 poles in a series in an OHL configuration using an electromagnetic transients (EMT)-based program—Alternative Transients program (ATP)—in time domain is shown.

Typically, most systems to be simulated can be divided into subsystems for which models are already available for each subject to availability of other information required to make a model appropriate for simulation. Subsystem include, but not limited to, surge arrester, line, cable, and transformers, while support structures can be made up of components sufficient to model their behaviour under lightning surge. Internal model details and parameters are not the subject of this chapter and are not discussed further.

Figure 21.2 shows a typical low-voltage OHL system in ATP-EMTP program. Each line cable component (LCC) represents line segment between two support structures approximately 50 m distance apart. The distance is entered internally in

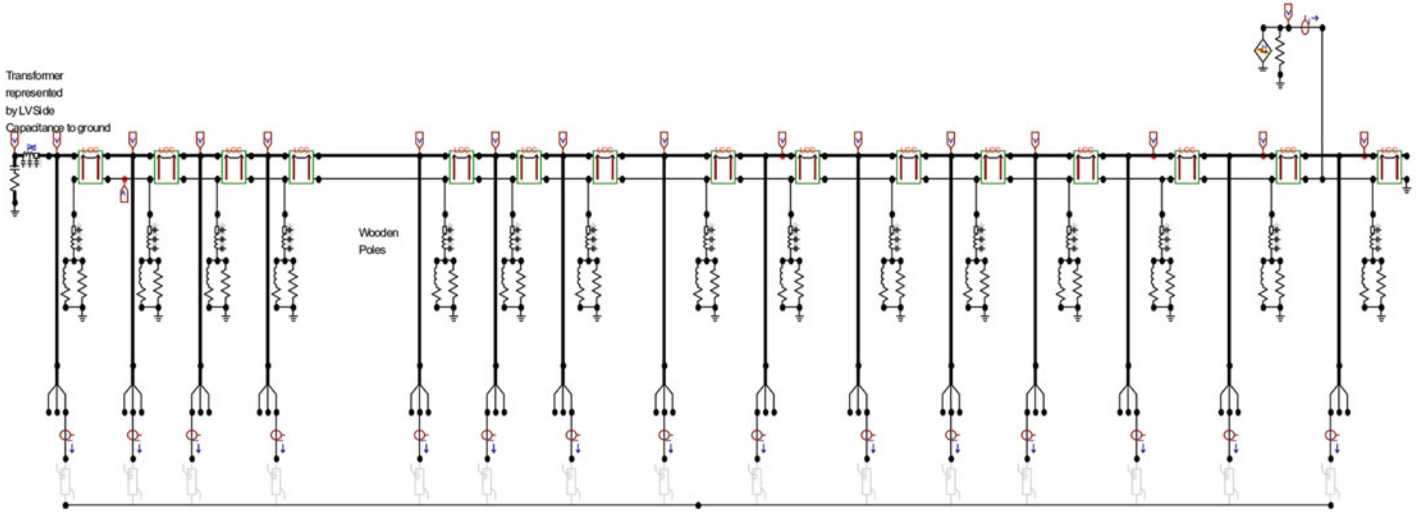

Fig. 21.2 Typical low-voltage OHL system in ATP-EMTP

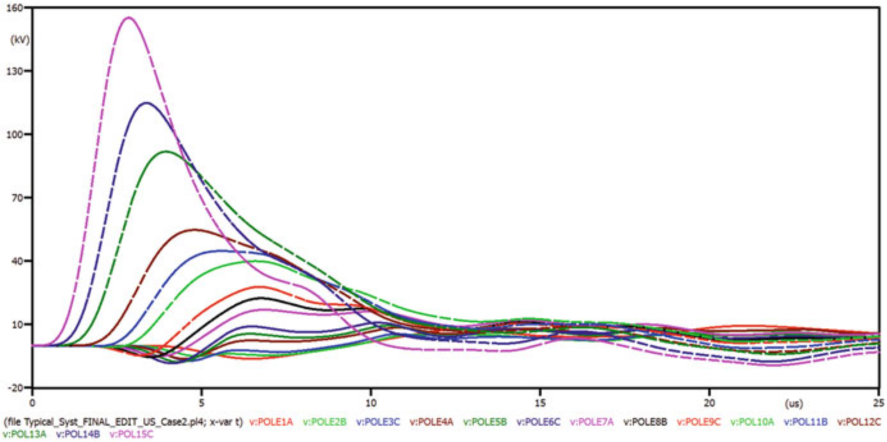

Fig. 21.3 Expected overvoltages for a typical OHL system

the LCC model. Below each LCC component is the MOV that provides a path dissipation of the energy contents of lightning. The high-voltage transformer is suitable represented by the low-voltage capacitance to ground, and this is sufficient for this scenario. Each parallel combination of inductor and resistor between each LCC component and MOV simulates the inductance and resistance of the supporting structure. All these, coupled with the lightning source, simulate the phenomena.

Location of lightning source in this scenario is at the end of a series of pole. It should be noted that the location of source affects how the waves travel. For simulation of a lightning stroke at midpoint of a series, the source should be located midpoint of the series.

Results give a generic overview of lightning-induced voltages carried out on a power network. These results are intended to show the influence, role of MOVs, and to show that increasing the rating of MOVs does not necessarily make a difference as is usually the first decision (except in regions prevalent with lightning strikes). Results provide an insight into the nature of the environment LEDs are exposed to during the event of lightning.

Figure 21.3 shows a graphical view of expected voltages based on a lightning current impulse of 10 kA 8/20s within the vicinity of an OHL system. This is a conservative lightning current stroke. In areas with prevalent strikes, lightning current of at 30 kA is possible, but currents above 30 kA are rare [7] and almost result in instant damage to luminaires as a whole. This highlights the importance of MOVs in reducing this overvoltages to levels that can be withstood by LEDs. As depicted in the plot (Fig. 21.3), overvoltages present an unfavourable environment during the event of lightning. This shows the need to pay attention to and improve the design of MOVs. As a matter of fact, MOVs will degrade overtime irrespective of how good it is, but improving designs to be able to operate for as long as necessary is imperative. As already pointed out, lifetime of LEDs under transient conditions is dependent on the lifetime of an MOV.

Figure 21.3 shows the results of a lightning studies simulated on an outdoor power network (OHL) supplying power to 15 luminaires attached to support structures. The above figure assumes there is no MOV to clamp down on overvoltages. A lightning stroke to ground within the vicinity of the 15th pole in the series was simulated. Highest voltage was observed at the terminals of the 15th pole at 150 kV which attenuated to approximately 5.5 kV at the far end. For such a system, luminaires attached to poles 1, 2, and 3 (being the farthest from point of stroke) have the best chance of survival without an MOV. Luminaires on poles 10–15 are likely to be completely damaged. This shows the kind of unfavourable environment LEDs are subjected to during a lightning strike.

21.5 Influence of System Type on Expected Overvoltage Levels

An important design consideration so often ignored is the choice of power distribution system type—OHL systems, insulated cable systems, and hybrid combination of OHL and cable systems (insulated cable systems may include underground and overhead cables). In certain areas of the world, there may not be a freedom of choice on what system to utilize for lighting applications. In other cases, the choice of what system to utilize borders around cost, technical factors, ease of construction, convenience, aesthetics, environmental impact, and so on.

A comparative modelling analysis carried out on an OHL system and an overhead insulated cable system showed the dramatic difference in overvoltages. Figure 21.3 shows the simulation for an OHL system as already analyzed. At the vicinity of strike, the peak voltage stood at approximately 150 kV and at the farthest point (from point of strike) in the series, peak voltage stood at approximately 10 kV. For such a case, any one pole without an MOV or improper operation of the MOV will incur some level of damage. The only components that can survive are those random components with high withstand strength.

As already described in Sect. 21.4, in most cases, the lowest peak voltage is not necessary at the farthest point, and for this case, the lowest voltage is actually at the third pole in the series at 5.5 kV; this has also being confirmed by reports from technicians in the field where a couple of poles between point of strike and farthest pole survived, but not the farthest pole or poles. Thus farthest point is only taken as a logical reference point. Reasons for this is beyond the scope of this monograph but is related to the wave reflection at exit points of the travelling wave [10].

Figure 21.4 shows the overvoltage profile of an insulated overhead cable system with the same number of poles, injected lightning current level, and similar conditions. At the point of strike, the peak overvoltage stood at approximately 17 kV, almost eight times less than that for a similar OHL system (non-insulated). In the same vein, the peak voltage at the farthest point (to point of strike) stood at a meagre 1.5 kV (negative) which the luminaire itself should withstand without an

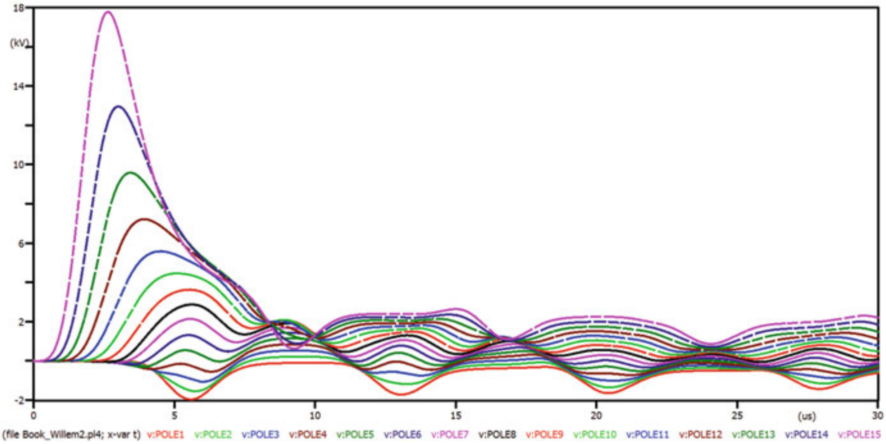

Fig. 21.4 Expected overvoltages for a typical insulated overhead cable system

MOV present. In such a case, with an MOV, overvoltages are effectively reduced to negligible levels. Even at 17 kV, there are several components of the luminaire that would survive the overvoltage without an MOV to reduce the burden.

Both cases compared above represent conditions whereby lightning strikes at one end of the series. In principle, there are infinitely possible points of strike along a series of support structures, and this is only a conservative choice. Strike could occur at midpoint of the series in which case simulation that shows voltages on both sides of this point will have more or less equal magnitude but different polarities depending on the actual conditions. The plots presented though represent models of actual configurations, but results are based on ideal models and only serve to give an insight into the whole problem and what to expect.

This is particularly important during the design stages of both LEDs and the luminaires itself to know what to expect when MOVs operate as expected, do not operate as expected, or do not operate at all. It could be observed that when MOVs operate as expected, the burden is dramatically reduced and represents a best case scenario. Withstand strength can be improved at the design stage given a minimum as obtained from simulation studies while assuming the MOVs do operate as expected. Little can be done at low-voltage levels if the MOVs do not operate. Therefore, the most imperative for such case is to minimize the damage.

Notwithstanding, there is an obvious dissimilarity between both systems. Observing the tail end of the graphical plots in Figs. 21.3 and 21.4, Fig. 21.4 shows tail-end oscillation compared to Fig. 21.3. This oscillation is peculiar to insulated cables due to the extra capacitance added to the system. A challenge that may be presented by such sustained oscillation is the energy content. Though both the voltages and currents are very low, the lengthy time duration of the oscillations may result to considerable high energy content that may or may not play a role. In such cases, standards may be referred to for more insight and considerations on mitigation [8, 9].

21.6 Conclusions

Lightning is a natural phenomenon that can neither be prevented nor avoided. Notwithstanding, its effect can be mitigated with the proper installation and coordination of protective devices in a way that ensures maximum protection. The effects of lightning cannot be completely mitigated, but can be reduced to a level that luminaires (and thus LEDs) can withstand for a short period of time (within the range of 50 ms a few milliseconds). For direct lightning strokes on luminaires and low-voltage devices, based on experimental data on current measured from direct strokes [1, 2], there is no cost-effective method to protect against such. Therefore, for luminaires, the goal is to protect against indirect effects of lightning.

In most cases, if standards are properly adhered to in the design and installation of both luminaire and the host power network, most of the damages incurred will be reduced. However, in less developed and developing regions in the world, standards and codes are seldom complied with, most especially with the installation and commissioning of power networks which would be eventual hosts to luminaires and LED devices. The most easily preventable source of surges is that which originates from the power supply, for example, surges that propagate from the supply transformer. If transformer were to be properly installed following recommendations from international standards and codes, this should never occur as relevant standards do specify that transformers should be protected on both sides with respective protective devices. If done accordingly, surges from the supply side will at best be clamped to such a low level that protective devices in luminaires need do nothing.

Finally, a few things are important to the long-term reliability of installed luminaires:

1. The minimum voltage level that luminaires should be able to withstand after MOVs must have clamped down on a propagating surge. Whatever the method to determine what such voltage level is, a statistical method is recommended. ANSI standard [8, 9] recommends a minimum of 6 kV for outdoor application. Simulation studies confirmed this as a great rule of thumb. It may be more or less depending on experiences obtained from the field.
2. There is a correlation between the life of an MOV and the life of a luminaire in the field. Point (1) assumes that is MOV is in fact healthy. If it is not, installed luminaire may not survive. The design of MOVs needs to be improved to ensure they can stay healthy for at least 10 years. Without MOVs, luminaires have very little chance of surviving a surge with amplitude greater than 10 kV which experience show is a conservative value for a surge. MOVs over the years have not changed much, and more attention should be given to their reliability over a minimum period. The moment an MOV can no longer operate, it’s just a matter of time before the luminaire it is protecting is damaged.

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