Lightning

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This is a summary of main details about lightning, written in simple form as notes on *Blixt och Åska* [1], then extended with more detail from *The Lightning Flash* [2] and notes from the two relevant Ludvika-HVV courses on Gas Discharges [3] and EMC [4], and finally with a few further points from the older [5], [6] and [7].

Weather for thunderclouds

The altitude at which clouds begin to form, from vapour turning into droplets, is the lifted condensation level (LCL), often within 1 km of the ground. The 0 °C isotherm is typically at 4 – 5 km; clouds that form in this situation consist therefore of purely liquid droplets, and these *single phase* clouds have not been found to have significant separation of electric charges.

There are three necessary conditions for the development of a thundercloud: water vapour in the air; an *unstable* atmosphere, in which the warmed, damp, air can rise high beyond the 0 °C isotherm; and a source of rapidly rising air, such as strong heating by the ground, winds pushed up by mountains, or strong horizontal pressure gradients. Quite a lot of weather conditions can lead to thunder cloud formation; on the other hand, there are cases where high clouds form without lightning, when the updraught or the vigour of mixed-phase processes is insufficient for strong charge-separation.

Around ground level, up-moving dry air typically cools by 10 °C per 1 km, due to expansion, and damp air by 6 °C per 1 km. If the usual temperature gradient of the lower atmosphere — temperature decreasing with height — is not as much as the pressure-induced change of rising hot air, then this is an *unstable* atmosphere in which the air will rise high until the atmosphere's temperature gradient reduces and starts getting warmer, at the *tropopause*, which is at about 15 km in the tropics and 10 – 12 km in temperate zones.

By the point at which the rising air is at 0 °C, some of the contained water starts to become small ice crystals, and some gets supercooled. Collision of crystals and supercooled droplets forms larger crystals, *graupel*, and as these get larger they reach the point of sinking even within the continued updraught: the cloud is *mature*.

Falling graupel cools the updraught, and the process slows, slowing even more when melting graupel and condensing water vapour fall as rain and cool the hot air below; a strong downdraught ensues.

A whole thundercloud may have many *cells* with largely independent generation of updraught and charges. *Mesoscale convective systems* (MSCs) are huge collections of thunderclouds, capable of very large charge-transfers.

The vigour with which a thundercloud can form, generally an indicator of high electrical activity, can be estimated from the *convective available potential energy*, CAPE, a measure of the amount of lift available for the updraught as a consequence of warmth at the ground level and cold air higher up.

Charge separation

Collision with updraughted smaller particles causes charge-transfer, electrons being more on the larger particles (why?). Charge centres build up, positive on the top of the cloud, negative on the bottom. The centre of the lower, negative charge is generally around the point where the air is at $-10\,°$C; this is at about $7-10$ km in the tropics or $2-3$ km in temperate zones. The vertical distribution of the negative charge can be quite compact, often less than 1 km; the higher positive charge is usually much more diffuse, extending even to near the top of the cloud.

A lightning discharge usually takes negative charge to the ground. The main exception is when strong winds move the top and bottom parts of the cloud to expose the ground to some of the top, positive charge.

Measurements of charge induced by thunderclouds shows a part of the bottom to have some positive charge — the positive charge pocket, PCP. This is thought most likely to be due to temperature dependence of graupel collisions[3], where at temperatures above about $-20--10\,°$C the falling graupel can receive a positive charge. Another source of the PCP may be ionisation of air around objects on the ground, due to the field from the thundercloud; the ionised air drifting up from the ground and attaching to some parts of the bottom of the cloud. [1].

Note that lightning (atmospheric discharges) can also occur around sandstorms, volcanic eruptions and nuclear explosions, but the mechanisms of charge separation are different.

The microphysical mechanisms of charge separation are not well understood. Some of the electrical characteristics of a thunderstorm, that must be consequences of any proposed model, are: cloud depth more than 3 km or so is needed, with strong electrification only for clouds extending above the freezing level; high electrification is strongly associated with the existence of an ice-water mixture; charge-centre location is determined by temperature rather than by altitude; charge separation is associated with precipitation; the first radar-detectable precipitation is around 10 minutes before the first flash, and all flash activity takes about 30 minutes; the charge-moment destroyed by a 20 C lightning flash is about 100 C km, and may even lie so far from the simple case as to be horizontal.

Development of a lightning flash

One whole lightning event, as perceived by the eye, is called a *flash*; this consists usually of several rapid discharge events, *strokes*, through the same ionised channel.

The most common type of lightning is within the thundercloud, called *intra-cloud* discharge (sheet-lightning). This generally is initiated from the negative charge near the bottom, travelling upwards at about $1.5{\times}10^5$ m/s then having multiple discharge pulses over about a 200 ms flash duration.

Discharges between a cloud and the ground are the most important for practical purposes of protection, and the most accessible for measurement. They are sometimes divided into four categories, on the two parameters of: negative or positive charge injection to the ground, and downward or upward initiation.

Upward initiation is uncommon, and is mostly relevant to very tall structures; for example, buildings of 500 m height have a good chance of initiating a leader to a close-by thundercloud. The mechanism is a stepped upward leader, followed by a downward dart-leader and upward return stroke; upward-initiated strikes thus have the same later development as downward-initiated ones.

Most ground-flashes are negative: they transport negative charge to the ground. This type of flash is much the most studied, in terms of photographs and of current and field measurement. Much less is known about positive ground flashes: these are thought to have generally just one return stroke, and to have a more continuously travelling leader; they have a more extreme range of charges.

Negative ground-flash

A thundercloud is overall approximately neutral, and the field from the lower part of the cloud to the ground is not sufficient to initiate a streamer. Somehow, not well understood, a negative downwards lightning ground-strike process is thought to start with a *pilot leader* discharge between some part of the negative centre and this low positive part. In [1] the low positive part is shown as covering the central part of the bottom of the cloud, though some other books have shown as being only a trailing part. Then, with the small positive charge neutralised in about a 1 ms event, there is lots of negative charge sitting right at the bottom of the cloud, and the discharge progresses into the air as a *stepped leader*.

The *stepped leader* is a series of quick discharges that spread negative charge into the leader's channel. It advances in steps of 10 – 100 m with average 50 m near the cloud and 10 m near the ground, with inter-step intervals of about 50 µs, near the cloud and 10 µs near the ground, at a mean speed of $10^5 - 10^6$ m/s, with the speed of each step as high as 10^8 m/s. The steps appear bright while forming, but the channel is dark. There is some increase in step length with a greater interval since the last step. From field measurements, the stepped leader channel contains from about 3 – 20 C; it is thought to have a hot core of 0.1 – 0.5 m radius. This is surrounded by a *corona sheath* of charge from the streamers of the leader's formation and charge from corona around the hot core; for a 1 mC/m leader (that would give a 30 kA return stroke) the corona sheath is estimated to have about a 3 m radius. Some researchers consider, from field-measurement, that the charge distribution along the leader channel is quite uniform; others, from analysis of capacitance, propose an exponential decline in charge density going up from the ground. The stepped leader's radiation field is about a tenth of that of the return stroke, suggesting its step-current to be about a tenth of the return stroke value, or more if the steps are slower than the return stroke.

When the stepped leader is within 100 – 200 m of the ground, the positive ions already present around the ground can spread, by increasing ionisation of the surrounding neutral gas and towards the negative charge of the stepped leader, forming another leader starting from the ground, the *connecting leader*. There can be several connecting leaders, but generally only one connecting leader makes contact with the stepped leader to complete the lightning channel. The current at the base of a connecting leader is around 100 – 200 A, regardless of whether it will be the successful one. Before a connecting leader, there may be a visible glow around the earthed objects, due to recombination in the ionised air; this is *St. Elmo*s fire'.

Once the channel is completed, the path of the stepped leader contains a surplus of electrons, and the bottom end of the connecting leader is a connection to the earth. The resulting *return stroke* is an upwards travelling wave of downward discharge of the electrons in the channel, at about 10^8 m/s, and therefore taking generally less than 100 µs to discharge the channel. The charge that flows at the ground is the excess charge in the channel and the charge induced by the background field. The return stroke speed varies moderately between ground and cloud ends, negative first and subsequent return strokes or positive strokes: near the ground, the first negative return stroke is at about 1.7×10^8 m/s, subsequent strokes are some 10% faster, values near the cloud are some 30% slower, and positive return strokes are only about half the speed of negative ones, some 10% greater at the cloud than at the ground. The return stroke may carry typically 5 C of charge, with common values of current being 30 kA, although as much as 200 kA has been recorded in some cases of positive flashes. The temperature in the channel can reach about 30 000 K, and stays high for a while after the stroke itself, about 3 000 K even after some 10 ms. The pressure reaches about 800 kPa within a few microseconds, then declines within 20 µs.

After supplying the stepped leader, the part of the cloud where the channel originated is much less negative than before, and after the return stroke the channel too is relieved of much negative charge: a further discharge may then occur in the cloud, sending electrons down the still somewhat hot and ionised channel, as a *dart leader* that can travel at about 10^7 m/s without the hesitancy of the original stepped leader. In the thick air near the bottom of the channel, the dart leader may become stepped, a *dart-stepped leader*, due to the channel having become less conductive there, so the lower part of the channel may attach to a different point. Some 20% of flashes (observed in Florida) have multiple termination, i.e. different ground connection points of strokes.

When a dart leader or dart-stepped leader completes the gap, a *subsequent return stroke* results. There are typically several return strokes in a lightning flash; the greatest number recorded is 26, and the mean is 4. Subsequent return strokes tend to carry less charge than the first, typically about 1 C. The time between return strokes is about $50-100$ ms, so the events of a lightning flash can last for a time in the order of a second.

There are some extra current pulses that can be seen from measurement of electromagnetic field in the surroundings. *K-changes* are currents from *partial* discharges that occur between the newly neutralised top of the return-stroke channel and the negative charge in the cloud. *M-components* are currents from when discharges of the same sort as for K-changes *do* manage to connect significant negative charge with the top of the return-stroke channel, and the channel is sufficiently conducting to produce a dart-leader.

It is emphasised in [5], using data about flashovers of rod-plane and rod-rod gaps under switching-impulses, and images of shapes of lightning channels, that the stepped leader's passage is unaffected by objects on the ground (other than enormously high objects, as discussed in relation to upward-initiated strikes) until it comes close to the striking distance of them where their connecting leaders start to approach the stepped leader. Further, it is noted (quoting Berger of the Mount San Salvatore lightning observatory in Switzerland) that it would take all summer for the point-discharge current leaking from a tall tower to discharge a thundercloud as much as a single lightning strike. Thus, certain objects within some small area may have higher probability than others of being struck by lightning, on account of how high they are and how easily able they are to sink a connecting leader current to earth, but the matter of 'will there *be* a strike to some part of this area' is not affected by anything that can be done; only in the last short part of its travel is a stepped leader from the cloud affected by the finer details of what is on the ground. Radioactive rods, sharp points, and the like, are of no real use, but a good solid conductor that can sink lightning current to earth *is* of use.

Currents and charges in a flash

For a downwards negative flash, the typical parameters are[4]: a first return stroke with peak current $\widehat{I}$ of 30 kA, peak current-derivative $\mathrm{d}I/\mathrm{d}t$ of 110 kA/µs, transferred charge $\int i\,\mathrm{d}t$ of 4.5 C, prospective energy $\int i^2\mathrm{d}t$ of 55 kJ/Ω; subsequent return strokes with half this peak current, unchanged derivative, a fifth of the charge and a tenth of the prospective energy; the extreme (high) values are quite similar for first and subsequent return strokes, related to a typical first return stroke by about twenty times the prospective energy and three times the value of the other parameters; the interval between strokes is typically 50 ms but possibly as low as 3 ms, and a continuing current with respectively typical and extreme values of 100 A and 200 A may persist for 100 ms to 500 ms.

For a positive downwards flash, $\mathrm{d}I/\mathrm{d}t$ is about a twentieth as much as for negative, from $2.4-20$ µs; typical $\widehat{I}$ is similar, around 35 kA, and typical charge and prospective energy are higher by respectively about four and ten times; extreme values of current, charge and energy are much more greater than for negative flashes, at about 250 kA, 150 C and $2{\times}10^7$ J/Ω; positive flashes generally consist of just one stroke.

There is an important distinction between those strokes where the current decays to zero in about 100 µs, and those where a following current of about 100 A continues even for some 100 ms afterwards. These are called, respectively, *cold* and *hot* lightning, since although the channel is similarly hot during the main discharge in either case, the *hot* discharge's much longer time during which the channel stays hot makes it far more likely to start fires.

Lightning around the world

The *keraunic level* is the number of thunderstorm days per year, heavily dependent upon the part of the world. About 2/3 of all lightning flashes are in the tropics. From [2], southern Europe has a keraunic level around 20–30, northern Europe 5–10, USA 20–60 (and getting much less on the west coast), and sub-saharan Africa having the highest levels, peaking at 100 near Zaire and Uganda; lightning activity over oceans is about a third of the level over land in the same climate area. From a 1956 keraunic map in [5], the USA spread is a larger 5–80, and the central-African peak is about 180, but Europe is roughly the same as shown in [2].

A more interesting measure is strikes per square kilometre per year, called *lightning density*, N; this is mentioned in [8], wherein a typical value within France is given as $2-6$ $\mathrm{km}^{-1}\cdot\mathrm{yr}^{-1}$.

A single lightning cloud can produce several flashes per minute, or in severe cases some tens of flashes per minute. About 100 lightning strokes happen per second, as an average across the whole world, with a mean power dissipation of about 20 GW. Satellites for monitoring nuclear explosions are useful in picking up the whole lightning picture.

The overall supply of negative charge to the earth, and positive charge to the ionosphere[1], causes the $\sim 300-400\,\mathrm{kV}$ voltage between the ionosphere and the ground, whose field around ground level is about 100 V/m. This drives a continuous current through the air, discharging the ionosphere. *Schumann resonances* from lightning's perturbations of this spherical capacitor can be detected all around the earth, at frequencies of about 8 Hz and its harmonics. During the presence of a thundercloud, this fair-weather field of about 100 V/m is changed to around $-20\,\mathrm{kV/m}$.

The ratio between cloud and ground flashes is approximately described by the empirical formulae (Prentice and Mackeras) $N_c/N_g = 1 + T/16 = 4.1 + 2.1\cos 3\lambda$, where T is the keraunic level, and λ is the latitude. The total flash density is about $N = \exp(3.7 - \lambda/15)$ per square kilometre per year, with N ranging from about 1 to 10. The most influential single factor in the variation of lightning with season and latitude is the Clausius-Clapeyron relation of saturation concentration to temperature, an exponential relation giving roughly a doubling of water concentration for a 10 °C rise in temperature.

[1] The *ionosphere* is the layer of ionised gas extending from about 60 km above the earth; it is not clearly defined or homogeneous in ion density, and its properties vary during the day; it is not one of the group of separate *spheres* (tropo, strato, meso, thermo, exo) but is a region mainly within the thermosphere.

Effects on objects of attachment

The lightning channel, measured by holes burned in glass-fibre plates on exposed buildings, has a width of about $2-20\,\mathrm{cm}$, giving the whole channel's volume as about $2-200\,\mathrm{m}^3$ if it is of this diameter all the way up.

When lightning reaches the ground, its considerable charge has to be dissipated very quickly; a build-up of charge would lead to fields large enough to cause long horizontal discharges until the charge could get to earth. Particularly in dry ground, lightning has been seen to make craters or to make long trenches of dried earth and grass, of the order of 100 m.

Lightning can kill trees, sometimes many at a time. Lightning current passes usually just under dry bark, where the most sap is, else sometimes on the surface of wet bark, which is much less damaging. Even the 100 A or so of an unsuccessful connecting leader may be enough to damage a tree. Roots of trees around a struck tree may be damaged by ground currents, particularly if the ground has low conductivity. Side-flashes may cause a strike to affect several trees. Subsequent return strokes may be to different trees if a dart-stepped leader gets met by a connecting leader from a tree other than the recipient of the first return stroke. The likelihood of a tree being struck depends on its roots as well as on the height, conductivity and sharpness of its top part.

Buildings of steel-reinforced concrete construction are pretty good, with the building structure generally able to conduct all the lightning current. Using a continuous network of steel reinforcement as a down-conductor is advantageous in that it has many parallel paths, thus low inductance, and is unlikely to become mechanically damaged by wear and vandalism. It is important that the steel parts *are* continuous; laboratory experiments with lightning-like currents between steel reinforcements inside concrete have found that there is no trouble with conduction of the current when the steel parts are simply tied together with wire where they meet, but if there is a short gap between the reinforcements then the current between them causes explosion of the concrete[5]. At the top of the building, a well-connected air-termination system is needed, to avoid lightning puncuring the concrete and possibly sending concrete parts into the air. At the bottom there usually should be an external ground termination well connected to the reinforcements.

At the other extreme of buildings, a dry wooden house is a difficult path for lightning, and discharges to large metallic objects in the house are likely. Large systems such as wires and metal pipes are particularly likely to be caught. Discharges into electrical wiring can cause fire due to follow-through currents from the power supply as well as the lightning's heating. Other metallic objects may become steps in the passage of the lightning. An approximate probability of a house being struck ([1], considering Sweden) is given as one time in three-hundred years.

People die quite often[2] from lightning: e.g. $\sim 150-200$ per year just in the USA, and on average 10^{-8} deaths per person per thunder day (a day when thunder is heard at a particular place). Those who do not die usually recover very well. The way in which the lightning current travels to ground is very important in determining the injuries. Direct passage of 30 kA lightning currents through the body would cause great damage to internal organs; if skin is dry rather than wet and salty, there is a chance that within the 0.3 µs or so in which the current has reached about 1 kA, the voltage across the $\sim 1\,\mathrm{k\Omega}$ body will be enough to cause flashover on the surface, vastly reducing the current through the body, although still exposing the body to burns. Current in the body due to shunting of lightning currents flowing in the ground may be reduced by thick rubber boots and standing with feet close together. Such leg to leg currents don't in any case go to such important parts of the body as head to foot ones would. Some possible effects of lightning strikes are the cessation of heartbeat and breathing, loss of sight or hearing, memory loss, and poor concentration.

[2] '... quite often': that is, I would surely have guessed a lower number, having never actually seen a mention of such a death except in lightning books, although I'd have guessed that this subject would excite the popular press.

Return stroke models

For calculation of the effects of lightning on apparatus, the return stroke is the most important of the lightning phenomena, with its high values and time-derivatives of currents. Modelling of the return stroke is of interest to those who perform such calculations, to give results of the currents at the point of attachment and the fields around a return stroke; in this case the physics of the lightning channel itself is not directly important, but only the *output* properties of the system. More detailed channel models are proposed mainly by lightning researchers, with an interest in what is actually happening in the flash.

Electromagnetic fields from lightning

The leader introduces space-charge to the channel, causing a rising field; the return stroke rapidly neutralises this charge, with a current that generates a strong magnetic field. Some values, from [4], of the electric and magnetic fields around a *typical* lightning stroke at a distance of 10 m, are: $E = 300\,\mathrm{kV/m}$, $\mathrm{d}E/\mathrm{d}t = 600\,\mathrm{kV/m/\mu s}$, $H = 500\,\mathrm{A/m}$, $\mathrm{d}H/\mathrm{d}t = 1800\,\mathrm{A/m/\mu s}$; for large strokes the fields and their time-derivatives are respectively given as a little over twice and thrice as much, these values falling linearly with distance up to 500 m. These values are of interest for calculation of induced transients in exposed equipment.

Coupling of lightning EM fields

From an EMC perspective, lightning couples to structures by several paths: conduction of HF&LF currents, capacitive and inductive coupling of LF fields, and radiative coupling of HF fields.

A ground-strike may couple conductively to a buried metallic pipe or cable that enters a building; the catchment area is sometimes greater than for an overhead line.

EM field interaction for components within a building may be by direct strikes on the building sending their current through reinforcement in the concrete, or by strikes nearby the building; the latter presumably includes external lightning conductors. The magnetic field is the significant coupling mechasism.

An overhead line may sustain a direct lightning strike; the probability can be estimated, in strikes per hundred kilometres of line per year, as $N_{\mathrm{s}} = 2.8 \times H^{0.6} \times N_{\mathrm{k}}/7$, where H the height above ground, N_{k} is the keraunic level (thunder days per year), and the factor of 7 (apparently) relates ground flashes to total flashes. Lines in transmission systems, over about 100 kV, are usually provided with earth conductors to shield the phases. A back-flashover from a struck tower to a phase conductor presents some risk of disturbance even if the shielding works. The voltage around the attachment point can be estimated as the product of half the lightning current and the line's surge impedance, i.e. the assumption is that the lightning is a current source splitting both ways on the line. Voltages in the order of megavolts are then to be expected.

The EM field from lightning interacts with overhead power lines, potentially inducing excessive currents and voltages in them. This *indirect lightning* is a more common cause of short interruptions and voltage sags than is direct lightning strike. Nearby (50 m) lightning strokes can induce tens of kilovolts in a line, even with common, modest discharge currents of 12 kA. This indirect coupling is not likely to affect lines of several hundred kilovolts, but can clearly result in insulation breakdown for distribution lines and connected equipment.

The analysis of indirect lightning often starts with assumptions of a vertical lightning channel, perfectly conducting ground plane, and a single horizontal conductor at some distance from the ground. The long length of power lines, and the high frequencies of lightning fields, in the order of some megahertz, make a quasi-static analysis invalid; the length of the line is *not* electrically small. On the other hand, the height of the line from the ground can generally be treated as being electrically small, leading to a reasonable use of quasi-TEM (transverse electromagnetic) transmission-line theory. Antenna effects, violating the zero-sum current assumptions, are less significant at the ends than in the middle, and mainly the ends are of interest in analysis of disturbance to system components; a low-resistance ground-plane reduces antenna effects anyway.

Consider [2] a simple single-conductor line in the x direction, at height h in the z direction above a perfectly conducting ground-plane, and exposed to arbitrarily directed electric and magnetic exciting fields E^{e} and B^{e}, which are calculated as the values in the absence of the conductor (incident field plus ground reflection). The *Agrawal, Price and Gurbaxani* model, widely used in power and lightning work, uses the x and z components of the electric field, E_x^{e} and E_z^{e}, within an LC transmission line. The *Taylor, Satterwhite and Harrison* model, widely used in EMC, uses E_z^{e} and B_y^{e}, to give the forcing parallel current source and series voltage source. The *Rachidi* model uses B_z^{e} and B_y^{e}. All of these formulations are equivalent, for the case where the fields are part of a travelling wave rather than quasi-static fields; the components of the two fields are thus linked by the relation $j\omega \int_0^h B_y^{\mathrm{e}}(x,z)\mathrm{d}z = E_z^{\mathrm{e}}(h,z) - \frac{\partial}{\partial z}\int_0^h E_x^{\mathrm{e}}(x,z)\mathrm{d}z$ [9]. Other models are used as simplifications for specific cases, e.g. the Rusck model for a vertical lightning channel and horizontal line.

With perfectly conducting ground, the induced voltage along the line is proportional to height. For resistive ground, the relation is generally sub-linear. Beyond distances of 2 km or so from the lightning, there is little coupling to distribution lines. The point of maximum overvoltage may, however, be far from the point nearest to the stroke. Strokes as close as a few hundred metres induce voltages largely independent of stroke speed; beyond several kilometres, the induced voltage is almost proportional to stroke speed.

A resistive ground leads to electric and magnetic fields permeating the ground, capable of inducing voltages even in fully buried conductors; this may be significant for sensitive modern electronics, though generally not for HV power cables.

Substations give some special problems, where lightning currents on incoming lines will be diverted by surge arrestors into the earthed mesh of conductors around the substation, and equipment joined to various parts of this mesh has signal cables connecting to a control room. There arise differences in potential across the earth mesh during the passage of lightning current, which give rise either to dangerous (to people) voltages between shields of incoming signal cables, or dangerous (to equipment) voltages between shields and signal conductors if the shields are bonded together.

Telephone networks are more sensitive, even if the lines are generally lower and more often (?) underground. A French study that is poorly described in [2] showed tens of cases of voltages over 2 kV over two years and several sites. Current values from another investigation (theoretical?) on a 1 km overhead telephone line are, for direct and indirect strikes respectively, about 3 kA and 0.5 kA for about 350 µs and 20 µs.

Low-voltage distribution networks are often the bearers of mild transients, though the localised result is seldom considered by network operators. The results from several types of network in Switzerland and combined results from the US are shown in figure 9.13 of [2], with about a 1/(100 year) frequency (how is that measured?) given for about 2 – 7 kV transients in most environments, up to 1 – 200 per year at 0.5 kV, a rural farm being a clear exception with 10 kV once per year and quite similar lower-voltage values to the other cases.

Lightning protection of networks

Protection against lightning has some similarity to protection against fast transients, the lightning being the more demanding case except in $\mathrm{d}i/\mathrm{d}t$. Some important quantities are [2]: *peak current*, relevant to resistive voltage drops, which are usually dominated by inductive drops, making the peak current relevant mainly to cases such as earth electrodes where there is not a good metallic path; *peak current derivative*, $\mathrm{d}i/\mathrm{d}t$, which may be around 150 kA/µs and sometimes even rather higher for fast transients; *peak rate of change of voltage*, $\mathrm{d}v/\mathrm{d}t$, around 0.1 – 1 MV/µs for lightning when peak voltage is 100 kV – 1 MV, or 1 – 10 MV/µs for fast transients; *total charge*, $\int i\,\mathrm{d}t$, as low as 50 µC for fast transients or 70 C for lightning, gives a measure of energy dissipation in typical *clamping* voltage limiters; *action integral*, $\int i^2\mathrm{d}t$, for thermal dissipation in resistances and magnetic forces in loops, typically thousands of times more in lightning than in fast transients.

For protection against conducted lightning currents[4], overvoltage suppressors are the usual family of protection components, comprising gas tubes, varistors and zener diodes; some series impedance, such as an inductor, may be added between such components in order to give earlier, slower, higher-capacity devices time to operate before the energy reaches smaller devices. Gas tubes are often used to reduce the high-energy transients at the point of entry to a building: these are crowbar devices that can reduce voltage to less than the normal value after a discharge; they have very low capacitance, high permissible current e.g. up to 20 kA for 10 µs even for a miniature ceramic-tubed gap as used in telephone circuits, but they have a time-derivative dependent turn-on and require several hundred volts. Metal oxide varistors are clamping devices, limiting the voltage: they respond in about 0.5 ns, can conduct several kiloamps for some microseconds, but have high parasitic capacitance; at rated operating voltage they pass only small currents, less than 0.1 mA, but they have a power-law I/V relation with an exponent between 25 and 60; parasitic inductance in the leads must be kept low in order to use their potential quick response. Avalanche diodes or zener diodes are clamping devices, clamping sharply above a point chosen in the range 6.8 V to 200 V: they have response times of about 0.1 ns, large parasitic capacitance of some nanofarads, and small maximum current of < 100 A; silicon diodes can be used for electronics voltages from 0.7 – 2 V, with the advantage of low parasitic capacitance. Typically, a gas discharge tube or varistor would be the first shunt element, with other varistors or diodes closer to specific protected apparatus.

Protection against fields from lightning channels is generally only acheived by shielding, since the position of a channel is not known in advance to allow increased distance. Field sources of known position, such as down-conductors of a building's lightning protection system, may be weakened by moving equipment further from them or by reducing their current by sharing currents in parallel down-conductors.

An EMC system designed well for lightning can easily be extended to cope with fast transients; the converse is not true.

Lightning protection of buildings

The *Franklin* system in its classic form is a rod or group of rods, above the protected structure, connected well to the ground by down-conductors and electrodes. An alternative type of collector is a mesh of wires. The four main parts are the *air termination* (collector), the *down-conductor*, the *earth electrode*, and any *supplementary bonding* to other metal parts to which flashovers may otherwise occur.

The distance at which a earthed conductor can *capture* lightning, sometimes known as the *striking distance*, is dependent on the charge of the lightning leader, which in turn is a factor determining the lightning current; higher prospective currents mean higher charges in the channel, which mean greater distances of possible attachment. In calculating the adequacy of an air termination for intercepting strikes to a structure, one has to put a lower bound on the prospective lightning current; below this, the design may allow strikes to get past the air termination system. Using the familiar *rolling sphere* method, checking that a sphere rolled on the structure would not touch the structure rather than the air termination, a radius of 15 m is used for a 2 kA current, and 90 m for a 30 kA current. The maximum permissible current for the structure is therefore important.

In spite of many beliefs about the usefulness of sharp points, either in an attempt to *discharge* or *neutralise* the cloud or because of ideas that they encourage successful connecting leaders, there is not currently known to be any advantage of sharp points on an air termination; the sole purpose is to be a safe sink of the current after having preferentially acquired a lightning strike that would otherwise have been on the protected structure.

The presence of St. Elmo's fire around lightning air terminations can make them less effective at producing a successful connecting leader, so reducing the protection to the structure; the reason is not understood.

The down-conductors should be several (preferably many) parallel paths taking the shortest route to continue the air termination system down to the ground. Bonding must be made to conductive parts of the building, at least at ground level and every 10 – 20 m. It is good to use structural metal as a supplement, and in some cases such structural metal may be a sufficient down-conductor system by itself. Some conductive parts, notably live conductors entering the building or within the building close to down-conductors, cannot be bonded directly to the lightning system's conductors, but have to be connected to through a surge protection device, to operate only on overvoltage, or in some cases may simply be well insulated so as to be able to tolerate any such overvoltages as may occur.

Accessible down-conductors are acceptable from the perspective of human electric shock if: there is insulation of at least 100 kV 1.2/50 µs, e.g. 3 mm XLPE; or, the ground's surface for 3 m around the down-conductor has $\rho \geq 5000\,\Omega$m, e.g. 5 cm of asphalt or 10 cm of gravel; or, there are good, multiple, deep conductors or equipotential mesh conductors in the ground to reduce touch potential.

The earth termination may be a single horizontal conductor, a mesh, or driven (vertical) rods. The ground resistivity must be low enough to sink the lightning current without excessive voltage gradients around the earth termination. The inductance of all connections is often the dominant cause of voltages, so adding further electrodes tagged beyond the end of the down-conductor might not help much to reduce the voltage at the first electrode.

A ring conductor in the ground around a building can be useful in keeping currents through the ground, due to strikes to the ground or adjacent objects, out of the building. Objects, such as trees, that could cause cause side-flashes to a house, should be at least 5 m away, and the use of a ring conductor is particularly important for collecting lightning currents from nearby tree roots.

Protection against lightning currents coming in through other sources is important. Metal objects in the ground, such as pipes, can pick up ground currents. Metal objects in the air, such as electric power and telephone wires, can pick up direct strikes or induced pulses. Bonding of such conductors to lightning protection systems, through surge-divertors in the case of electrical services, is needed in order to prevent ingress of lightning currents through them or breakdown from the lightning protection system into these normally earthed services while the protection system is carrying a large strike current. Lightning strikes to unprotected TV aerials can cause explosion of the whole aerial cable; even with bonding of the aerial to a lightning protection system, damage to the set is likely to occur.

Less conventional protection systems may be completely detached from the protected structure, for example a tall mast, or a group of masts with wires between, protecting a building below.

Safety in thunderstorms

The electrical dangers of lightning are from connecting leaders forming from part of the body, particularly dangerous if the connecting leader is successful, or by sharing a lightning current with another object due to contact or side-flash, or to *stride potential* caused by lightning currents in the ground. For the bipedal human, stride potential is not as dangerous as the other mechanisms or as it is to four-legged creatures.

The passage of current through the body is not well understood. Work with wood has suggested that a discharge does not have strong effects both internally and externally; an external discharge tends to divert almost all current away from the internal paths. Models of the body have much higher resistance at the surface than internally. Skin is modelled as a parallel capacitance and resistance, 0.25 µF and 10 kΩ, at each hand, foot and head contact point, but just some 300 Ω resistances inside the limbs and trunk. It is currently thought that the orifices of the head may be important attachment points into the low-resistance insides. The skin components are considered to break down with about 5 kV across them, and surface flashover is considered to occur at about 500 kV across the whole body. The internal passage of current is thought to split mainly in the ionic fluids such as blood and cerebrospinal fluid, then muscle tissue, with nerves probably not being specially conductive overall due to the fatty layers. IEC479 is often cited about harmful combinations of currents and their durations, in the human body.

If unable to avoid being outside, without some high structure that offers a wide zone of protection even beyond the region of its ground currents not being worrying, then crouch down, feet well together, preferably in a depression in the ground, to reduce probability of a strike. Keep away from metal objects that might be attached to by flashes across the ground; this is particularly important in mountainous areas where the ground is not well conducting.

Avoid conductive objects that could conduct direct strikes or ground currents and thereby cause side-flashes to oneself. This includes for example fences and trees. Around any object that conducts lightning into the ground, there will be a strong potential gradient in the ground; stay away from them and keep feet close together.

Being dry-skinned may be helpful[1], in encouraging discharges around rather than through the body. Note the contradiction of section 11.3 of [2], which suggests (only based on work with wood) that surface flashover even of the body may be enhanced by wetness.

Cars, when providing a metal cage all around, are not a bad place to be! (But, note that some modern cars may even have large sections made of composite non-metals.) Shelter may also be found in the space under power lines, especially those with earthed lightning wires on top, but well away from the towers or poles.

Don't be in water; currents from strikes to the water may cause drowning by making a swimmer unconscious, or may cause more direct damage.

In a house, unless it is of a very well protected construction, avoid: telephones with direct connection to external lines; proximity to the outside walls; proximity to apparatus connected to pipes or wires whose networks may pick up lightning that passes through the house, e.g. electrical appliances, showers, taps, etc.; proximity to more localised metallic objects, for the same reason.

Effects and observation of lightning

Observations of lightning electric and magnetic fields are done by various means depending on the desired sensitivity and frequency response. The *field-mill* periodically exposes an electrode to the measured field then shields the electrode with an earthed screen, and the strength of the field is then related to the current needed to keep the electrode at earth potential; the response is thus limited by the maximum speed of covering and uncovering the electrode, nowadays some $1-10$ kHz, but the measurement can be performed even on static fields. An antenna for electric fields is a plate or rod whose capacitive coupling to the field is taken to an amplifier. An antenna for magnetic fields is a loop with both ends connected by coaxial cable to a differential mode amplifier.

As an example of radiated field values, the 50 km values are shown[3] in log-log against frequency ranging from 1 kHz to 10 MHz, with two approximately straight lines (power-law): under about 1 MHz the spectral amplitude falls off at $1/f$, above this it is more as $1/f^2$; over the whole frequency range the change in amplitude is about 80 dB.

Each metre of lightning channel has about 40 kJ of energy dissipation in a typical single return stroke.

The chemical reactions in lightning strikes lead to changes of the gases of the air: in particular, there is nitrogen fixing, providing about 10% of the fixed nitrogen that the earth's plant life needs (some bacteria can fix nitrogen too).

Lightning's very rapid heating of a channel of air causes shock waves, experienced as loud sounds with a wide spectrum.

The sound is seldom heard beyond 20 km or so, due to upwards refraction of sound waves in the air-temperature gradient of warm surrounding air but cold air under the thundercloud.

Sound, at $\sim$340 m/s, takes a considerable time to travel the length of a single groundflash; the return stroke (or even the stepped leader at 10^5 m/s) can be considered as instantaneous by comparison, as of course may light from the flash. There is the well-known method of measuring distance to a flash by the time taken for the noise to arrive (after the light), but the duration of the noise is also of interest: a cloud flash may sound like a single, short noise; a ground flash, particularly if near, can provide noises over all the time of transit of sound from the length of the lightning channel, $7\,\mathrm{km}/340\,\mathrm{m/s} \approx 20\,\mathrm{s}$.

The electric discharge leads to radio waves that can be detected on normal AM receivers from up to 100 km away.

The present opinion of the thunderstrom sequence is that the first rain is usually generated after the first lightning, due to more eager combination of water after a pocket is discharged and stops repelling the surrounding negative charged water so much; people have considered this 'problem' for millenia, bearing in mind that lightning travels much faster than rain, so the winner at the cloud needn't be indicated by the winner at the ground.

Triggered lightning, usually by rockets with trailing earthed metal wire, is popular for measurement of lightning parameters; the similarity to naturally triggered lightning is somewhat unclear as the metal vapours [may]affect the channel. *Ball* lightning has never been witnessed other than by 'laypeople'. It is described as slow moving, various-coloured, giving out heat, leaving an acrid or ozone smell, etc. It seems pretty likely to be any or all of impaired vision due to a nearby strike, epilepsy, imagination, etc. etc. rather than some as yet unobserved and not convincingly explained physical phenomenon, but ....

Lightning in the upper atmosphere

Different sorts of discharges occur above thunderclouds, in the very different atmospheric conditions there, taking positive charge further up into the atmosphere. In spite of occasional reports since more than a century ago, and some pilots' reports in the mid twentieth century, it was only in 1989 that a sensitive video camera's evidence of a discharge from a cloud to high in the atmosphere convinced the mainstream of lightning researchers about ionospheric lightning; since then, space stations too have provided data. The observed phenomena can be classified into three groups: sprites are discharges over a volume of some 30 – 60 km height and 5 – 30 km diameter, positioned somewhere between 40 and 100 km from the earth, lasting 10 – 100 ms, and arising from quick return of displaced charges when a large (>40 kA) positive ground strike removes positive charge from the top of a thundercloud; blue jets are lightning travelling upwards at about 10^5 m/s from a thundercloud, spreading out to as much as 5 km in the upper atmosphere of 40 km or so height, and lasting some 250 ms; elves are the result of currents induced by lightning near the ground, causing a short-lived (1 ms) expanding ring of light high in the ionosphere.

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