Impacts of poor *Earthing* in electricity transmission and distribution systems, in lightning protection systems (LPS), and in the protection of electronic equipment

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Jigme Tobgyel, www.drukcare.bt, drukcare@gmail.com, 17607226 / 77453939

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1 Background & Rationale

The role of *Earthing* installations have a major impact at all levels of electricity utility including generation, transmission, distribution, lightning protection of structures, surge and transient protection of electrical and electronic devices, ICT (digital communications), etc. It plays a vital role in: determining the electrical network efficiency and reliability; maintaining power supply quality; protection of lives and property; and in reduction of the overall electricity safety hazards. *Earthing* has generally been undermined or misunderstood. For example, there are many builders and home owners that install an *Earthing* only for the sake of getting electricity service connection (it is forgotten thereafter). There is also confusion in the implementation of *Earthing* methods such as TT, TN-C, and TN-S. Further, standards and specifications adopted by concerned authorities should first identify the functional requirements and then choose the means (technology) in order to fulfill the functional requirements. For instance, the salt and charcoal based pipe and plate *Earthing* are still prescribed in the tenders and contract documents in spite of the ample evidence of poor performance (i.e. not reliable nor durable). Such obsolete *Earthing* technology will not meet the functional requirements of most *Earthing* applications. The intent of this paper is explain the why and how aspects of *Earthing* so as to show the importance of its role in the overall electrical system.

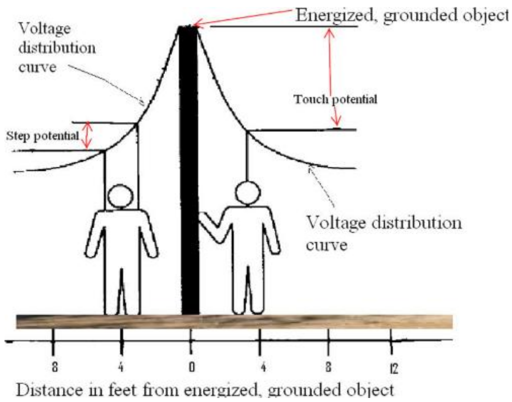
This paper is also intended to raise awareness on the need for proper lightning protection of structures especially in the lightning prone regions of Bhutan. Lightning related disasters are one of the worst natural disasters in the neighbouring countries such as Nepal in recent times. The lightning hazard risks are increasing with many taller structures being built and with electrical and telecom grid infrastructure expanding to every corner of Bhutan. Presently, most houses in the lightning prone regions of Bhutan do not have any lightning protection systems. Without proper lightning protection guidelines and standards thus far, most builders and house owners are not sure on how to protect houses from lightning hazards. The lightning protection installed by some of the few houses that have some form of lightning protection, could actually be counterproductive (i.e. more harm than good). This paper attempts to explain the principles and concepts of the most prescribed international standard for lightning protection (BS EN/IEC 62305). Also, our socio-economic lives in Bhutan (as in all progressive countries) are inevitably becoming increasingly dependent on electronics that enable voice and data communication, security systems, medical diagnosis equipment, computers, printers, faxes, photocopiers, TVs, etc. Such electronic equipment and appliances can easily malfunction or be destroyed by power surges and transients. A power surge or transient can destroy components of a large public institution’s computer network system and cause much inconveniences besides huge monetary losses. Similarly, an expensive medical diagnosis equipment could be damaged which could mean life or death for some patients. Presently in Bhutan, apart from the conventional AC protection devices such as fuses, MCCBs, MCBs, ELCBs, etc being used in houses, the use of protective devices against power and lightning transients is practically non-existent. This paper therefore also attempts explain Surge Protection Devices (SPD) and how it can be used to protect sensitive electronic equipment and systems.

2 What is *Earthing* (or grounding) and why is it essential?

Earthing *(or Grounding)* is an electrical installation designed to safely divert any unintentional hazardous currents/voltages into the *Earth*/ground. It also provides a common reference voltage point in an electrical circuit/system. Because it plays a vital role, it is a mandatory installation by regulation for all houses, power, telecom, IT systems, other facilities, etc. An *Earthing* installation has the following three main functions*:*

2.1 Safety of lives

Electrical faults occur occasionally and even small fault/leakage currents can be hazardous (and even fatal). *Earthing* installations must maintain the Step and Touch voltages within safe limits. Power utility O&M personnel that handle electrical infrastructure regularly and the general public (especially those that are not electricity literate) are more vulnerable to electrical hazards.



The illustration on the left explains what step and touch potentials mean. A good *Earthing* installation should have minimal step and touch potential. This means that the voltage distribution curve should have a minimal peak and thus a flatter profile (lesser voltage gradient).

It only takes a very small current (if allowed to flow through human body long enough) to electrocute a person. According to Statistical investigations, deaths are most likely according to the following current magnitude:

$$\mathbf{I = 116/\sqrt{t}}$$

Where, I = current (mA)

t = time of current flow (s)

116 = empirical constant, expressing the probability of a fatal outcome

2.2 Protection of facilities, houses, machines and equipment

A good *Earthing* installation is essential for fixing the reference voltage at 0V (or very close to 0V at all times). Electrical/electronic protection devices will not function properly without proper *Earthing* and hazards (including fire) may occur. For example, without low resistance *Earthing* installations, an MCB may not open (i.e. to isolate a fault) in the event of accidental

Live-*Earth* short circuits. Lightning Arrestors and Surge Arrestors will not function properly without a good and reliable *Earthing*. Consequently, expensive electrical equipment (e.g. transformers) and communication equipment can be damaged due to lightning and switching power surges. Electronic products (computers, modems, routers, etc) are also occasionally damaged due to power surges (that are not shorted to the *Earth* via surge protection devices).

2.3 Proper operation of electrical, telecommunication, and IT equipment

(a) Electricity – All electrical equipment need to be properly *Earthed* for proper operations. E.g. With poor *Earthing*, distribution transformer (Delta-Star) Neutral voltage will not be near 0V (but will shift/fluctuate with unbalanced loads and also due to triplen harmonics) and will subject consumer loads to large voltage variations (especially during faults). Consequently, consumer electronics can malfunction or can be damaged or degraded (life shortened). A reliable transformer *Earthing* is therefore imperative in order to improve the quality of electricity supply.

(b) Telecom and IT – A very good *Earthing* is necessary to establish a common reference voltage for all the interconnected electronic devices (computers, printers, telefaxes, photocopiers, modems, routers, remote terminals (E.g. ATMs) etc). Mismatches in reference voltages existing between interconnected devices will result in ground loops that can result in ICT hardware malfunction and corruption of data (E.g. computer crashes and network malfunctions). Much time, money and productivity can be lost in troubleshooting and fixing computer system crashes and malfunctions. Banks and other similar institutions that are heavily dependent on ICT are especially vulnerable without a reliable *Earthing* system.

Important notes:

(a) An *Earthing* installation must not only be seen as an individual installation but must also be seen from the perspective of the overall system that it is a part of. For instance, a house *Earthing* installation is not a standalone installation but it is a part of a TT or TN-C or TN-S *Earthing* system prevailing in the locality serviced by a distribution transformer. Similarly, the distribution transformer neutral *Earthing* not only concerns the transformer station but is also an integral part of the prevailing *Earthing* system in the locality.

(b) It is essential to understand the functional requirements of an *Earthing* installation for a given application and to understand what the implications would be if it does not perform as desired (i.e. prior to selection of *Earthing* technology). Presently there are thousands of conventional salt-charcoal based pipe and plate *Earthing* installations in the country that are either defunct or deteriorating rapidly. There are too many of them for concerned authorities to monitor and these will definitely have undesirable impacts in the form of safety hazards, power quality issues, malfunctioning of protective devices, harm to electrical and electronic equipment, etc.

3 What are the basic functional requirements of an *Earthing* installation (i.e. desired properties of an *Earthing* installation), the choices in *Earthing* technologies and basis of standards and specifications?

The importance of *Earthing* is often undermined or misunderstood. It plays a far bigger role than what it is normally credited with and it is very unfortunate that such an important role is often entrusted to conventional *Earthing* technologies that do not perform reliably or durably. It is therefore essential to identify objectively the desired functional requirements (or characteristics) of an *Earthing* installation prior to selection of an *Earthing* technology. The functional requirements will generally depend on the *Earthing* application (such as those for: transformer stations, generators, electrical switchgear, power switch yards, power lines and towers, electronic equipment, servers, digital communication infrastructure, house *Earthing*, etc). However, some of the common functional requirements (or characteristics) desired of an *Earthing* installation are the following:

(a) Low resistance and low impedance throughout the year (with the few exception where high *Earth* resistance is intentionally built in to limit fault currents)
(b) Consistent and reliable performance (irrespective of wet or dry seasons)
(c) Durable installation (at least 25 years or more)
(d) Maintenance free (or very minimal maintenance requirement)
(e) Safe touch and step potential (i.e. no hazardous voltage gradients)

In Bhutan, the predominantly employed *Earthing* technologies are those pertaining to: (i) Salt-Charcoal pipe *Earthing*, (ii) Salt-Charcoal plate *Earthing*, (iii) *Earthing* rods/spikes, (iv) Strip *Earthing*. However, these conventional *Earthing* technologies (especially the pipe and plate based salt-charcoal *Earthing*) are neither reliable nor durable (the reasons and justifications are provided in Section 3.1 below). Such *Earthing* installations invariably do not meet even the basic functional requirements identified above. Because of the deficiencies of conventional *Earthing* technologies, a conductive cement based *Earthing* technology known as Ground & Electrode Enhancement (GEE) *Earthing* slabs have been developed, field tested and proven over the last ten years (details are provided in Section 3.2 below). Similarly there are also other *Earthing* technology options that offer far better performance than the salt-charcoal based *Earthing* installations. Therefore, it would be beneficial if *Earthing* standards and specifications issued by concerned authorities promote better/superior *Earthing* technologies rather than the conventional salt-charcoal based plate and pipe *Earthing* (in the interest of the general public as well as for the betterment of the overall electrical system).

3.1 Salt-charcoal based pipe or plate *Earthing* installations do not provide a reliable nor durable *Earthing* installation

In Bhutan (and the neighbouring Himalayan regions), it is usually difficult to achieve low resistance *Earthing* installation in a reliable manner due to the unfavourable soil conditions (i.e. high soil resistivity). Driving one or two *Earthing* rods (E.g. 1.8 m long x 16 mm dia) into the ground in the Himalayan region will seldom provide adequately low *Earth* resistance unlike many other regions around the world. Similarly, the installation of a salt-charcoal based pipe or plate *Earthing* does not provide reliable and durable *Earthing* installation. Irrespectively, the salt-charcoal based pipe and plate *Earthing* continues to be the most widely used *Earthing* technology in Bhutan despite ample empirical evidences showing that such installations only provide temporary utility at best. This is mainly due to the fact that the salt-charcoal based pipe and plate *Earthing* installations were initially prescribed in the Indian Electricity Rules of 1956 and has since been adopted as a standard over subsequent decades. However, because of the deficiencies of such conventional *Earthing* systems, many better alternatives have now been developed. Other main reasons for the continuing use of such conventional *Earthing* systems include: the lack of awareness of the importance of *Earthing*; the poor visibility of *Earthing* installations (i.e. since they are buried underground); and the difficulty for electricity authorities to monitor thousands of such installations.

The above claim that salt-charcoal based *Earthing* installations do not provide a reliable and durable *Earthing* utility, is substantiated by the field data provided in **Table 1** below. This field data (as tabulated below) from the annual transformer *Earthing* inspection reports of erstwhile Central Maintenance & Training Division (CMTD), Beygana, BPC, corroborates this point beyond any doubt. The national averages shown below may actually be even higher if the more remote (i.e. less accessible to vehicles) transformer stations were included in the samples.

Table 1: ***The national average distribution transformer station Earthing resistances***

Year	No. of transformers sampled across Bhutan	National average transformer *Earthing* resistance measured (Ohms)	Type of *Earthing* installation for each transformer station (according to prevailing standards)
2007	165	53	3 sets of salt-charcoal based pipe *Earthing* connected in parallel
2010	165	165	
2011	220	455	

The prevailing standard for transformer station *Earthing* resistance was 5 Ohms or less which has been subsequently revised to 10 Ohms (or less) given the difficulties in achieving 5 Ohms. However, as can be seen in **Table 1** above, achieving 10 Ohms even with three interconnected salt-charcoal pipe *Earthing* installations in a reliable manner has not been possible (i.e. even if its achieved when newly installed, such *Earthing* installations deteriorates rapidly over a short period of time). The reasons for the poor performance of salt-charcoal based *Earthing* installations are as follows: Salt needs water to form an electrolyte and soil resistivity will be much higher without the help of salt solution. Therefore, salt based *Earthing* installations are not effective during dry seasons and the *Earthing* resistances fluctuate greatly between wet and dry seasons (therefore not reliable). In addition, during wet seasons, salt dissolves in water and in most case are completely depleted over time. This is further aggravated by the fact that salt accelerates corrosion of the metal electrode and the oxidation by-products increase the electrode-soil contact resistance. In many cases the pipe or plate electrodes are even totally electrically isolated from the surrounding soil after a few years (therefore not durable).

The adequacy or inadequacy of a salt-charcoal pipe or plate Earthing installation can also be gauged from *Earthing* resistance calculations using standard formulae as shown in the Table below.

Comparison of salt-charcoal based *Earthing* technologies (i.e. single pipe electrode and single plate electrode)

Electrode type	Formula to calculate earthing resistance (Ohm)	Calculated Earthing resistance (Ohm)									
soil-resistivity (Ohm-m) ---------------------->		50 Ohm-m	100 Ohm-m	150 Ohm-m	200 Ohm-m	250 Ohm-m	300 Ohm-m	400 Ohm-m	500 Ohm-m	750 Ohm-m	1000 Ohm-m
Single Pipe	$R = \frac{\rho}{2.73L} \, Log_{10} \frac{4L}{d}$	18	35	53	70	88	105	141	176	264	351
Single Plate	$R = \frac{\rho}{A}\sqrt{\frac{\pi}{A}}$ Ohms	145	290	435	580	726	871	1161	1451	2176	2902

Note:

(i) *The pipe electrode dimensions used in the calculation above are: Length=2.5m and Diameter=4cm*

(ii) *The plate electrode dimensions used in the calculation above are: Length=0.6m and Breadth=0.6m*

From the above Table and given that the soil resistivity at *Earthing* sites around the country is generally high (greater than 1000 ohm-m at many sites), the difficulty of obtaining lower *Earthing* resistance using a pipe or a plate electrode is evident. It is also clear from above that pipe electrodes will provide a more effective *Earthing* installation compared to plate electrode (i.e. for the standard sizes assumed above). It is important to note that such *Earthing* installations usually provide substantially lower *Earthing* resistance initially. This is only possible because of the initial abundance of electrolyte (i.e. dissolved salt in water) which permeates the immediate surrounding soil to drastically lower the soil resistivity. However, as the salt depletes and as the electrode corrodes, the *Earthing* resistance increases greatly.

The *Earthing* resistances obtained by installing multiple pipe *Earthing* connected in parallel (in a ring) in various soil resistivity can be estimated using the following formula.

$$R_R = \frac{\rho}{2\pi n \ell_r}\left(\ln\frac{294.3\,\ell_r}{d_r} + \frac{2\,\ell_r}{s} + \ln\frac{2n}{\pi}\right)$$

Source: US department of Agriculture, Rural Electrification Administration

Where: R_R = *Earthing* resistance (Ohms)
ρ = soil resistivity (Ohm-m)
n = number of electrodes
l_r = electrode length (m)
d_r = electrode diameter (m)
s = Spacing between electrodes (m)

Using the formula above for multiple pipe electrodes connected in a ring, the Table below provides a comparative estimate of *Earthing* resistances obtainable by a double, triple, and quadruple pipe electrodes in various soil resistivity. The main point being made here is that given the generally high soil resistivity of Bhutan, even installing four pipe electrodes in parallel (in a ring) with an inter spacing of 6 m each, it is very difficult to obtain adequately low *Earthing* resistances on a sustained basis. It must be kept in view that the *Earthing* resistances could be low initially (when new) while the salt lasts and while the electrode has not corroded significantly.

Salt-charcoal based pipe Earthing (by number of pipe electrodes in parallel)

Soil resistivity (Ohm-m)	Single pipe *earth* Resistance (ohms)	Double pipe *earth* Resistance (ohms)	Triple pipe *earth* Resistance (ohms)	Quadruple pipe *earth* Resistance (ohms)
50	18	10	7	6
100	35	20	14	11
150	53	30	21	17
200	70	40	28	22
250	88	50	36	28
300	105	60	43	33
400	141	80	57	45
500	176	100	71	56
750	264	150	107	83
1000	351	200	142	111

3.2 Ground & Electrode Enhancement (GEE) *Earthing* slabs

In order to overcome the problems (i.e. short life, poor reliability, need for regular monitoring and maintenance) associated with salt based *Earthing* installations, GEE *Earthing* slabs were developed over several years of research. Over 13000 GEE *Earthing* slabs have already been installed around the country and is now a proven and well established *Earthing* technology. These slabs are prefabricated electrically conductive concrete slabs that can be chain linked into various lengths according to the: site soil conditions; grounding application; and space availability. Unlike the conventional salt-charcoal pipe or plate *Earthing*, GEE slab *Earthing* provide a very durable, reliable, and maintenance-free *Earthing* utility. The following formula provides an estimate of the *Earthing* resistance obtainable for a given length (and installation depth) in a given soil resistivity:

$$R = K\frac{\rho}{2.73L}\ \mathrm{Log}_{10}\frac{2L^2}{WD}$$

Where,
K = 0.5 to 1 (Coefficient)
ρ = soil resistivity (ohm-m)
L = length of GEE slab *Earthing* (m)
W = width of GEE slab (m)

Using the above formula, *Earthing* resistance for various GEE *Earthing* lengths and soil resistivity tabulated in the Table below. Coefficient K=0.7 has been assumed in the calculations. K depends on the quality of installation (E.g. rock content in the trench, the quality of backfill soil used).

GEE slab Earthing resistance (by GEE *Earthing* trench length)

Soil resistivity (Ohm-m)	*Earthing* resistance (Ohm)			
GEE slab Earthing length (m) ----->	***5m***	***10m***	***15m***	***20m***
50 Ohm-m	6	4	3	2
100 Ohm-m	12	8	6	5
150 Ohm-m	19	12	9	7
200 Ohm-m	25	15	12	9
250 Ohm-m	31	19	14	12
300 Ohm-m	37	23	17	14
400 Ohm-m	49	31	23	19
500 Ohm-m	62	39	29	23
750 Ohm-m	93	58	43	35
1000 Ohm-m	124	77	58	46

The effectiveness of GEE *Earthing* technology can be gauged in Table above. A 10 meter long GEE *Earthing* installation will provide a lower *Earthing* resistance than a quadruple pipe/rod electrode *Earthing* installations for a given soil resistivity. In addition, if the reliability, durability, and maintenance aspects are considered, salt-charcoal pipe and plate *Earthing* is not even a feasible option.

Specifications (for 1 GEE slab)

a) Length x Breadth = 5 ft x 1 ft (i.e. including 6 inches GI flat protrusion from each end)
b) Thickness ~ 1.5 inches
c) Weight ~30 kgs +/- 1 kg
d) One 12 mm hole provided at each end of GI flat for bolting

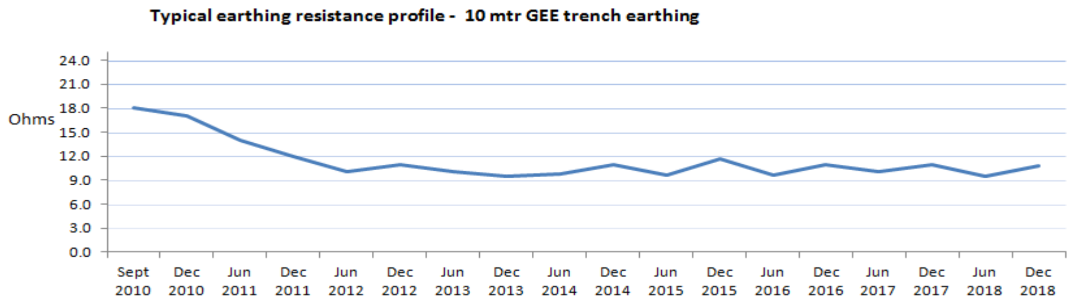
Note: The number of GEE slabs required per installation depends on the site soil conditions and the purpose (i.e. *Earthing* application). For residential house *Earthing*, a minimum of 6 GEE slabs (i.e. installed in accordance to manufacturer's recommendations) has generally been adequate for most sites that are **not** sandy or rocky. However, installing more GEE slabs per installation will provide better *Earthing* and will also provide the safety margin against variations in soil resistivity due to variations in soil moisture content, and soil temperature.

GEE slab *Earthing* is designed to facilitate convenient and rapid installation. The basic idea is to dig a trench and bury the interconnected GEE slabs in low resistivity backfill soil (Eg. loam). The installation procedure (in brief) is described below:

Installation procedure of GEE slabs

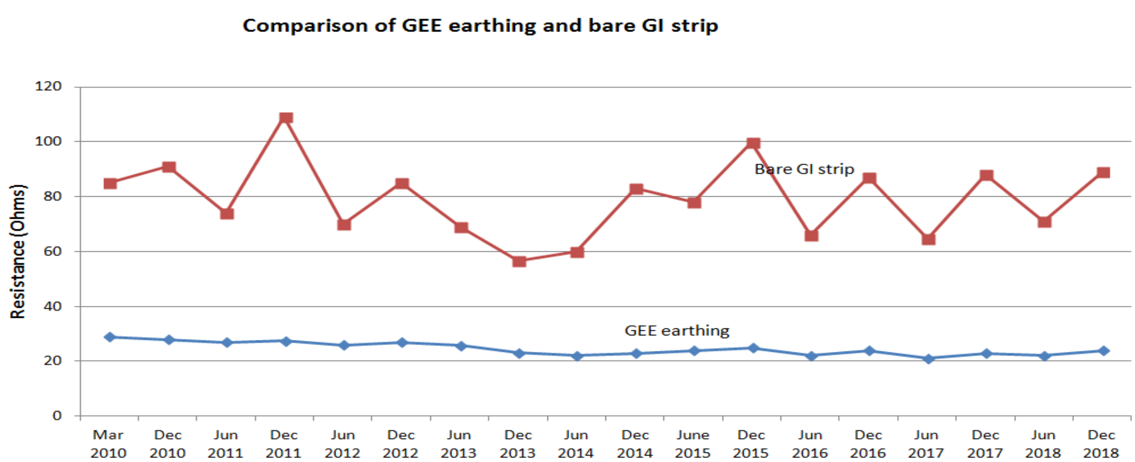
(1) Dig a trench (70-75 cm deep and 50 cm wide)
(2) Lay 7-8 inches (or more) of good soft soil (preferably sieved loam) before laying GEE slabs on top (do not use stony and sandy soil).
(3) Connect the GEE slabs end to end and bolt securely + all the *Earthing* conductors (in addition, welding the joints together is preferred)
(4) Encase all joints with cement mortar (after connecting the *Earthing* conductor(s) to the GEE slab joints)
(5) Now cover GEE slabs with 7-8 inches (or more) of good soft soil and tamp down gently with feet.
(6) Complete the installation by backfilling the rest of the trench with the excavated soil.
(7) Add water (the following day) to expedite soil compaction.

The GEE slabs can be used for all *Earthing* applications such as those in: building/house *Earthing*, power and telecom infrastructure, ICT infrastructure, lightning and surge protection, industrial machines/equipment, etc. In order to prove that GEE *Earthing* slabs provide: (i) a reliable, durable, and maintenance free *Earthing* installation, and (ii) a much better alternative than salt based pipe/plate/rod installations, the test results (over the last eight years) of an actual installation is presented in the graph below.



The graph above shows the performance of a GEE slab *Earthing* installation (i.e. 6 slabs) from September 2010 to Dec 2018. The soil resistivity at this site (during September 2010) was measured to be about 180 ohm.m. As can be seen from the graph, the *Earthing* resistance gradually decreases over time (i.e. in tandem with natural soil compaction) and has stabilized to around 10-12 Ohms. It may be noted that the number of GEE slabs necessary for an *Earthing* installation will depend primarily on the soil resistivity and the *Earthing* resistance value demanded by the *Earthing* application.

Further, in order to prove the effectiveness of encasing *Earthing* conductors in conductive concrete, a study was conducted (over last eight years) comparing the performance of: (i) 4.7 mtr GI flat directly buried in the ground, and (ii) 4.7 mtr GI flat encased in conductive concrete and buried in the ground adjacent to the first. The results are self explanatory as seen in the graphs below.



As can be seen from the above graph, the *Earthing* resistance provided by directly buried GI flats in the soil fluctuated greatly between wet and dry seasons. Since most transmission footing *Earthing* and switchyard *Earthing* is presently done by directly burying GI flats in the soil, significant variations in the *Earthing* resistance between wet and dry seasons can be expected. However, if the GI flats are encased in conductive cement (as in GEE slabs), only small variations in *Earthing* resistance can be expected.

Another test to confirm durability of GI *Earthing* conductors when buried in conductive cement (as in GEE slabs) is shown in the pictures below. The picture (left) shows the end of the GI flat (with soil around it removed) and protruding out of the conductive cement. The picture (right) shows the same GI flat and also the portion exposed when the conductive cement cover was broken. As evident from the exposed GI flat portion (which was found to be in original new condition) when the conductive cement cover was broken, the conductive cement does inhibit corrosion and extend the life of GI flat encased.

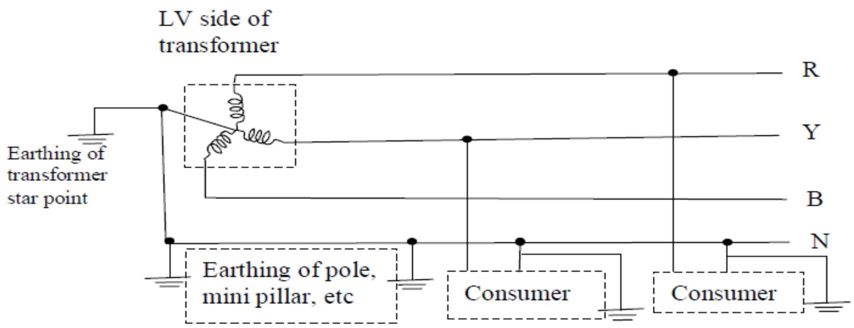
4 What *Earthing* method are we supposed to use in Bhutan for LV distribution system (i.e. TN-C, TN-S, TT, etc), what are they and their implications, and which is the best?

Bhutan Electricity Authority's (BEA) Distribution Code - Regulations, 2006, Section 3.9.4 specifies the *Earthing* system for distribution system as "***Multiple Earth Neutral (MEN) method shall be adopted for Earthing of distribution system***." Since the existing standard distribution transformer is of Delta-Star type, the above regulation on *Earthing* essentially requires the use of TN-C and TN-S *Earthing* systems with multiple *Earthing* along the supply Neutral (for TN-C) or along a dedicated Protective Earth (for TN-S) as illustrated in **Figure 1** and **Figure 3** respectively.

4.1 TN-C MEN *Earthing* system for LV electricity distribution

This *Earthing* system is illustrated in **Figure 1** below. For the TN-C MEN system to work effectively, sufficient number of reliable *Earthing* installations must exist along the supply Neutral and the *Earth* installations must function effectively and reliably. This will require capital investments in adding several new *Earthing* installations along each LV service line.

Figure 1 : *TN-C Multiple Earth Neutral (MEN) system for power distribution*



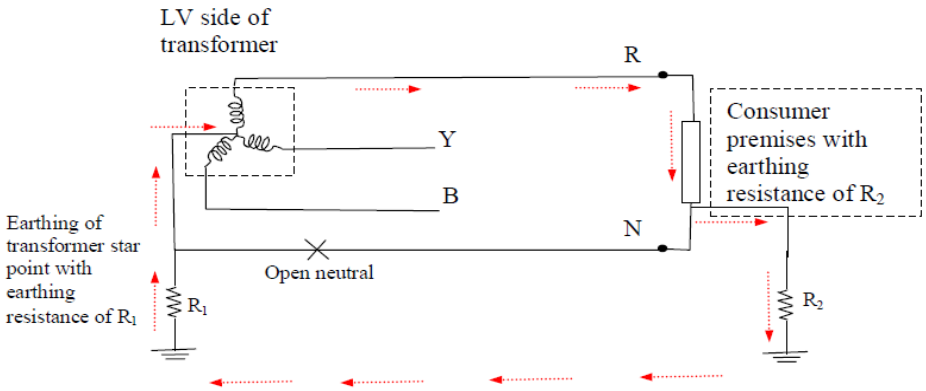
T is “Terre” which means earth in French
N means Neutral
C implies that the Supply Neutral also functions as Earth conductor (i.e. Combined)

This *Earthing* method will entails greater risk of fire hazards due to higher fault currents. Also with increasingly many non-linear loads (i.e. induction motors, converters, reactors, fluorescent lamps, high efficiency bulbs, car battery chargers, multitude of SMPSs of computers and other ICT electronics, etc) coming on line, the TN-C *Earthing* system is generally not preferred for operating sensitive electronics (E.g. computers and other communications electronics) due to the higher levels of electrical noise, electromagnetic interferences, disturbances, and harmonics. Moreover, since the Neutral carries the live line currents, there will be voltage drop along the Neutral which could pose problems for operating digital communication electronics due to the resultant ground loops (E.g. different reference voltages occurring at different parts of a Local Area Network).

Caution! If this TN-C *Earthing* system is used, it is imperative for the concerned local electricity authorities (i.e. ESDs) to at least ensure that there are sufficient reliable *Earthing* installations along the supply Neutral prior to connecting the consumer’s house *Earthing* to supply Neutral. Please note that many service connections have been given to consumers with the consumer house *Earthing* connected to the supply Neutral with only one other *Earthing* installation (i.e. the transformer Neutral *Earthing*). Such a situation could be disastrous in the event of a bad Neutral (i.e. loose, damaged, or broken) and especially if both the *Earthing* resistances at the transformer and consumer ends are high (which is very likely). This situation is illustrated in **Figure 2** below.

As can be seen in **Figure 2**, in the event of an open Neutral condition, the fault current will flow through the *Earthing* to complete the return path. If the two *Earthing* resistances (i.e. transformer *Earthing* and the consumer house *Earthing*) are not adequately low (i.e. <10 Ohm each), the fault current may not be large enough to trip a pertinent MCB and prevent hazards. This also means that connected appliances with exposed metal bodies and the *Earth* conductors (often bare and exposed) will bear dangerous voltages. It will only be a matter of time for hazards to happen if not corrected urgently.

Figure 2 : ***Earth fault in a T-N Earthing system (with broken Neutral)***

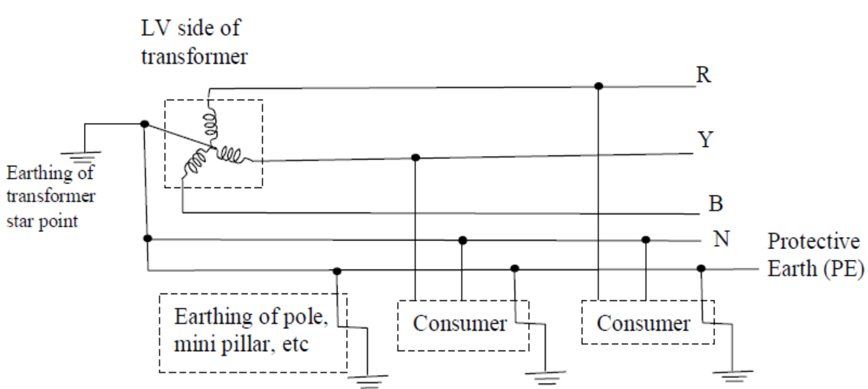


Please note that the fault current may not be large enough to trip the pertinent MCB if *Earthing* resistances R_1 and R_2 are large (i.e. bad *Earthing*)

4.2 TN-S MEN *Earthing* system for LV electricity distribution

The next option available for compliance with BEA regulation is the TN-S *Earthing* system as illustrated in **Figure 3** below. In the TN-S *Earthing* system, a separate and dedicated protective *Earth* (PE) conductor connected to the distribution transformer LV star point is installed. The "MEN" method entails connecting all the *Earthing* installations to the PE conductor at several points (E.g. at poles, at mini-pillar, at consumer premises, etc). Like a TN-C MEN system shown in **Figure 1** above, this method in principle helps ensure a low impedance path for *Earth*-fault current in order to blow a fuse or trip a circuit breaker. Like the TN-C MEN system, the higher fault levels entail higher risks of fire hazards. Similarly, the TN-S MEN system will also require the *Earthing* installations to be reliable and durable.

Figure 3 : ***TN-S Multiple Earth Neutral (MEN) system for power distribution***



T is "Terre" which means earth in French
N means Neutral
S means Separate protective earth (PE) conductor

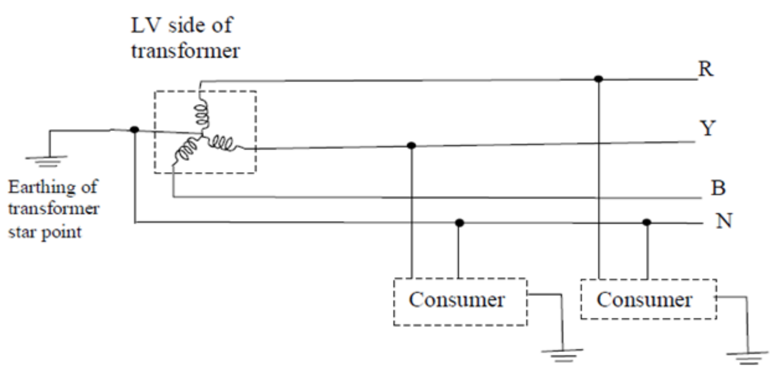
However, unlike the TN-C MEN system, the risks associated with a broken Neutral are avoided. A broken PE conductor with multiple *Earth* points will also **not** result in all connected metal items bearing dangerous touch potentials (unless an *Earth*-fault also occurs simultaneously).

Further, the supply Neutral here would not be polluted by the ground disturbances since the linkage of PE and supply Neutral is only at the transformer LV star point and at the consumer distribution board. It is therefore clear that the TN-S *Earthing* system is technically the safer and also the superior option of the two. But it is also the more expensive option since it involves installing separate PE conductor in addition to the additional necessary new *Earthing* installations along the PE conductor.

4.3 T-T *Earthing* system for LV electricity distribution

This *Earthing* system is illustrated in **Figure 4** below. As can be seen from the illustration, the consumer *Earthing* installations are not connected to the supply Neutral nor is there a dedicated protective *Earth* (PE) conductor. It is simpler and cheaper for the electricity service provider since it does not have to invest in installing additional intermediate *Earthing* and also in installing dedicated PE conductor (as in TN-S MEN *Earthing* system).

Figure 4 : *T-T Earthing system for power distribution*

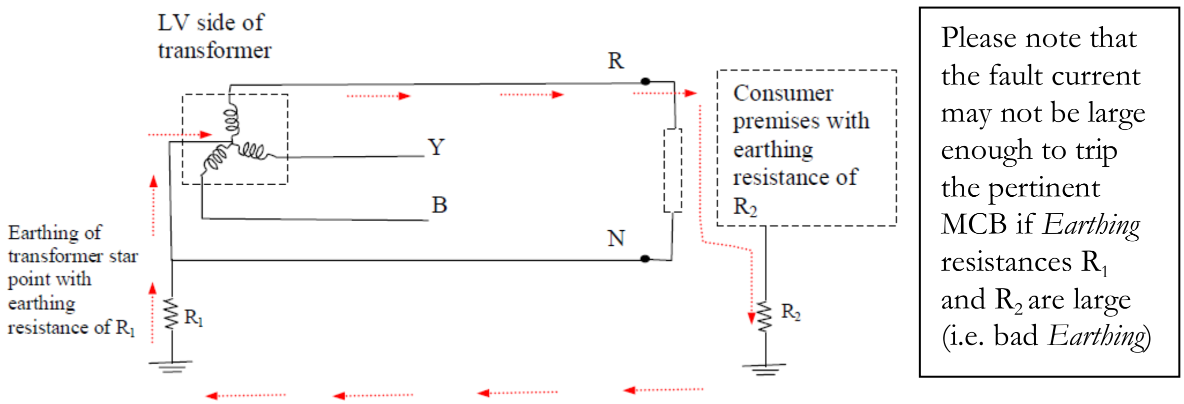


T is "Terre" which means earth in French

The second T implies that the consumer house *Earthing* is isolated (not connected to the supply Neutral).

Here the electricity service provider only has to ensure that its transformer *Earthing* is good while the consumers are responsible for their own *Earthing* installations at their premises (which **must** be good and reliable for this *Earthing* system to function safely). However, this type of LV power distribution *Earthing* system is not in conformance to the prescribed BEA regulation but continues as a legacy *Earthing* system across the country. This *Earthing* system could be hazardous if the two *Earthing* installations (one at the transformer and the other at the consumer premises) do not give adequately low *Earthing* resistances in a reliable manner. The risks are illustrated in **Figure 5** below.

Figure 5 : *Earth fault in a T-T Earthing system*



Caution! Since most houses do not employ suitable *Earth* Leakage Circuit Breakers (ELCBs) presently, in order to mitigate electrical hazard risks during an *Earth* fault, it imperative to have low transformer *Earthing* resistance (R_1 < 10 Ohms) as well as a low consumer house *Earthing* resistance (R_2 < 10 Ohms). From **Figure 5** below, it is evident that in order to clear an *Earth* fault (i.e. to open a pertinent MCB), R_1+R_2 should be adequately low in order to avert any associated electrical dangers. If such *Earth* faults are not isolated by pertinent MCBs, connected appliances with exposed metal bodies and the *Earth* conductors (often bare and exposed) will bear dangerous voltages. However unlike the TN-C *Earthing* system, the T-T *Earthing* method does not pose any risks of hazards if the supply Neutral is broken or damaged. The *Earth*/ground would also be cleaner (i.e. lesser harmonics, electrical noise, etc) and therefore more suiTable for powering sensitive electronics. Since the fault levels are also smaller with such systems, the risk of fire hazards is also reduced. But the installation of suitable *Earth* Leakage Circuit Breakers would be imperative in T-T *Earthing* system.

Summary (of the three *Earthing* methods discussed above)

(i) TN-S MEN *Earthing* system is the best of the three described above. Although this system would be more expensive for the electricity service provider to implement, it does not poses the associated dangers arising from a broken Neutral (as in the case of TN-C system) and it also does not require the use of ELCBs to avert the associated dangers arising from *Earth* fault (as in the case of TT systems). The implementation of the TN-S MEN *Earthing* system would also comply with BEA's Distribution Code (Regulations, 2006, Section 3.9.4).

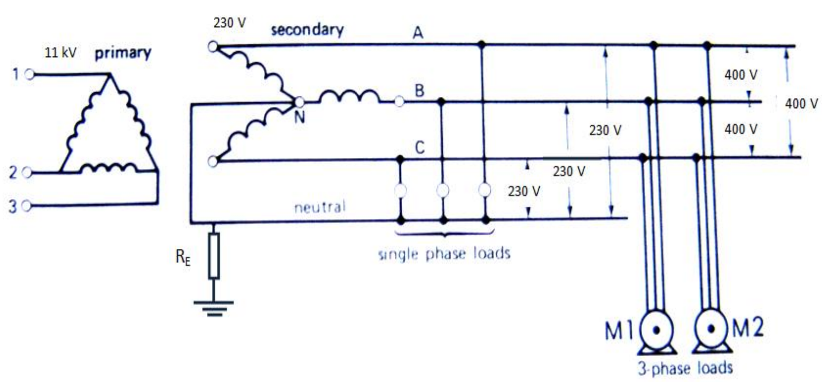
(ii) It is also clear that while implementing LV distribution *Earthing*, it is not only important to install proper individual *Earthing* but must also recognize the overall LV power distribution *Earthing* system that an individual *Earthing* installation is a part of.

(iii) It is also clear that the need to have reliable *Earthing* installations is crucial in all three systems. In the present situation, the need to have low resistance *Earthing* installations (<10 ohms each) at the transformer station and at the consumer end is urgent since there are very few (if any) reliable *Earthing* installations in between. This is to maximize the chance of tripping pertinent MCB so as to safely isolate a fault (i.e. open neutral in TN-C and *Earth* fault in TT system).

(iv) From the above discussions, it is evident that there is much to do even at a fundamental level of *Earthing* aspects pertaining to the mitigation of potential safety hazards risks. The subsequent stages will then need to address *Earthing* applications and implications relating to electricity supply quality (sags, swells, surges, harmonics, electromagnetic interferences, etc), protection of electrical and electronics devices, applications for analog/digital communications, etc.

5 What are the impacts of inadequate *Earthing* at the distribution transformer stations and are there other methods for *Earthing* transformer neutral?

There are several methods of neutral *Earthing* such as: *UnEarthed* neutral system, Solid neutral *Earthed* system, Resistance neutral *Earthing* system (Low resistance *Earthing*, High resistance *Earthing*), Resonant neutral *Earthing* system, Transformer *Earthing* system). Each of these has their respective applications. However, for distribution transformers of Delta-Star 33/0.4 kV and 11/0.4kV Neutral *Earthing*, a solid neutral *Earthing* (i.e. low *Earthing* resistance) is normally used which is also the norm in Bhutan.



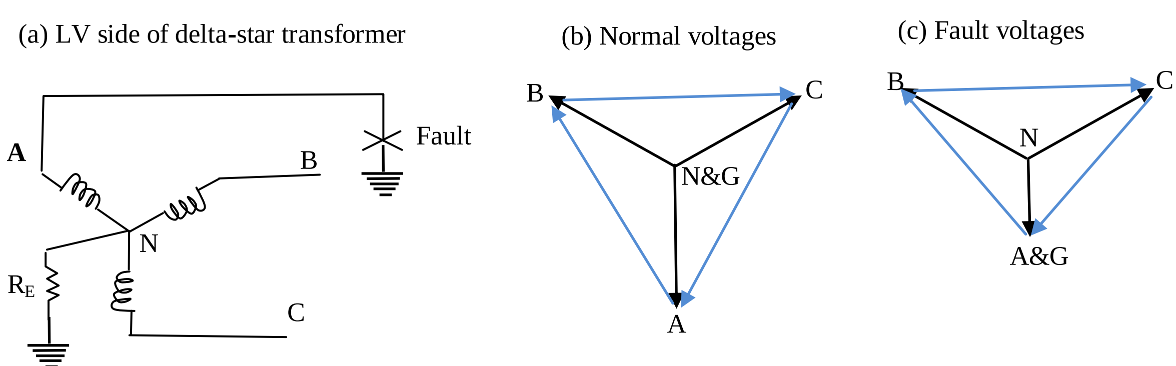
In the picture (left), for our distribution transformers we need the neutral *earthing* resistance (R_E) to be minimal (as small as possible). The reasons are provided below.

(i) As explained in section 4 above, although the BEA regulation prescribes the MEN method of *Earthing* for LV power distribution, it is apparent that there are practical complexities and difficulties in complying with the regulation. Under the present LV electricity distribution circumstances, generally there are only two *Earthing* installations relevant to a single service connection (i.e. consumer *Earthing* and the transformer *Earthing*). Both these installations must have low *Earthing* resistance in order to trip a MCB and safely isolate a fault. (Refer to sections 4.1 and 4.3 above for explanations). From this point of view, it becomes essential (i.e. not optional) to have low *Earthing* resistance at the transformer neutral (i.e. preferably less than 10 Ohms) in a consistent and reliable manner.

(ii) The Lightning Arrestor (LA) *Earthing* at the distribution transformer station is part of the common *Earthing* (to which the transformer neutral *Earthing* is also bonded). If the LA *Earthing* (i.e. common transformer station *Earthing*) is inadequate (i.e. high *Earthing* impedance), the LA will not be able to discharge effectively. This will subject the transformer to damaging over voltages (due to lightning strikes i.e. direct and indirect) resulting in expensive power supply outages and rectifications. This will also result in the injection of damaging power surges along the supply Neutral that will have a detrimental impact at consumer end (where the use of sensitive electronics has grown rapidly over the years). **Note**: When dealing with lightning discharges, it is far more important for the *Earthing* system to have low *Earthing* impedance rather than low *Earthing* resistance. This is explained in section 6.1 below.

(iii) If transformer Neutral *Earthing* resistance is high, the Neutral conductor (connected to the star point) will develop a potential (i.e. Neutral shifting) especially when the Neutral carries significant current (i.e. under unbalanced load conditions and also due to triplen harmonics generated from single phase non-linear loads). Neutral shifts will result in low voltage on one phase and high on other two.

(iv) A fault on a phase will deliver high voltages on the other two phases endangering consumer appliances, surge arrestors, and other connected devices. This is illustrated using phasor diagrams below.



From the illustration above, an *Earth* fault of phase A (i.e. phase A is shorted to ground via *Earthing* resistance R_E), the Neutral rises above ground voltage in proportion to the *Earthing* resistance R_E. Accordingly, the phase B and phase C voltages increase in proportion to *Earthing* resistance R_E. The point being made here is that the risk of damaging consumer electronics and appliances is reduced during line faults if the *Earthing* resistance R_E is small.

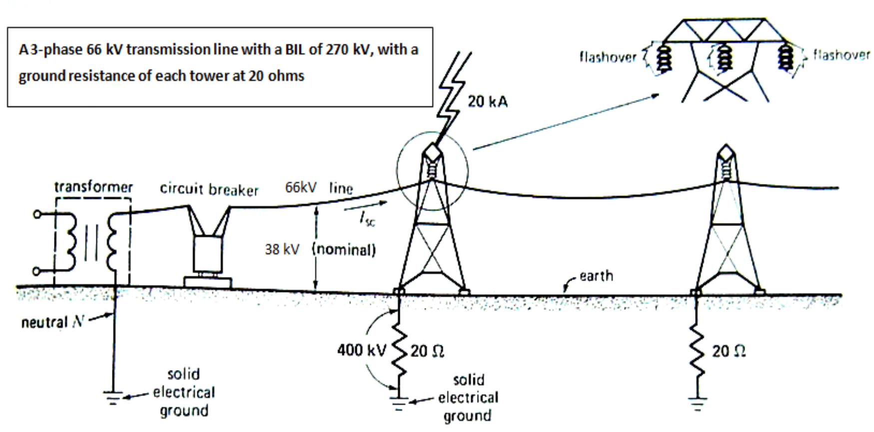
(v) When the neutral develops a potential (due to high *Earthing* resistance R_E), eddy currents won’t discharge effectively resulting in transformer heating, higher energy losses, loss of capacity, and increased risks of winding faults not getting cleared.

(vi) Inadequate transformer *Earthing* also entails increased risk of electrical protection not working during faults, and also higher risk of dangerous touch and step potential.

6 How important is *Earthing* in electricity transmission and distribution systems?

Proper *Earthing* is arguably even more important in power transmission systems than in distribution systems. A single transmission line outage can cause a “black out” of an entire region and also entail huge economic losses. It is common knowledge that hydropower generation and sales is Bhutan’s economic “backbone” and is needless to point out that transmission infrastructure is a critical component. Of paramount concern are the impact of lightning and the role of *Earthing* in the dissipation of lightning surges. Transmission lines traversing the rugged and mountainous Himalayan terrain are very vulnerable to lightning strikes and the line towers are deliberately installed on sTable rocky foundations. Such sites may provide a strong foundation but are certainly not favourable for achieving good reliable *Earthing* (due to very high soil resistivity). The importance of transmission tower *Earthing* is illustrated in **Figure 6** below.

Figure 6 *: Impact of high tower footing resistance*

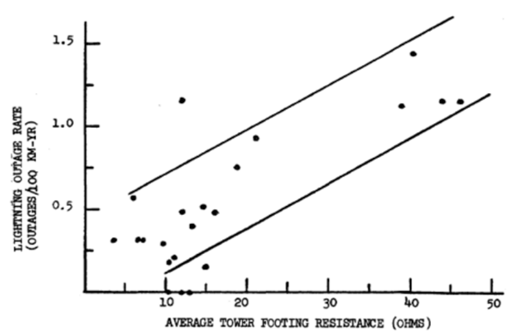


Tower footing earthing electrodes that provide larger area of contact with soil will provide higher capacitance necessary to lower *surge impedance* during lightning discharges.

Figure 6 above illustrates a key *Earthing* application and shows a 66 kV line with a BIL of 270kV and tower footing resistance of 20 Ohms that is struck by a lightning of 20 kA. As can be seen in the illustration, 400 kV will appear across the insulators and will flash over (i.e. will transfer the excess surge voltage to the transmission line conductors) since the Basic Insulation Level (BIL) of 270 kV is exceeded. However, if the tower footing resistance is 10 ohms, the lightning would be safely discharged with be no flashover across the insulators since the momentary 200kV surge that would be generated is lesser than the insulator BIL. Actually the tower footing impedance (rather than resistance) would be more relevant here but resistance is assumed for simplicity to explain the concept. This example uses a case where lightning strikes the tower (or shield wire), but lightning flashovers also can happen when it strikes the phase conductors (happens even when shield wires are installed). It is also possible to have flashovers when lightning strikes the ground near a transmission line (by electromagnetic induction). In all these cases, *Earthing* plays a vital role in the protection and returning transmissions systems to normalcy.

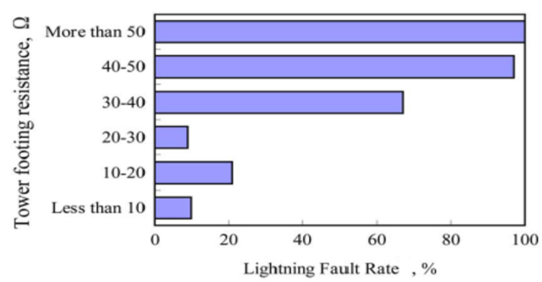
Field studies conducted abroad have shown that the transmission line outage due to lightning strikes is directly proportional to the tower footing resistance. The results of two such studies are reproduced below.

Lightning outage rate vs tower footing resistance for a 500 kV line



Source: James T. Whitehead, Lightning performance of TV's 500-kV and 161-kV transmission lines, IEEE Transaction on Power Apparatus and Systems, vol. PAS-102, No. 3, pp. 752-768, 1983.

Tower footing resistance vs. lightning fault rate

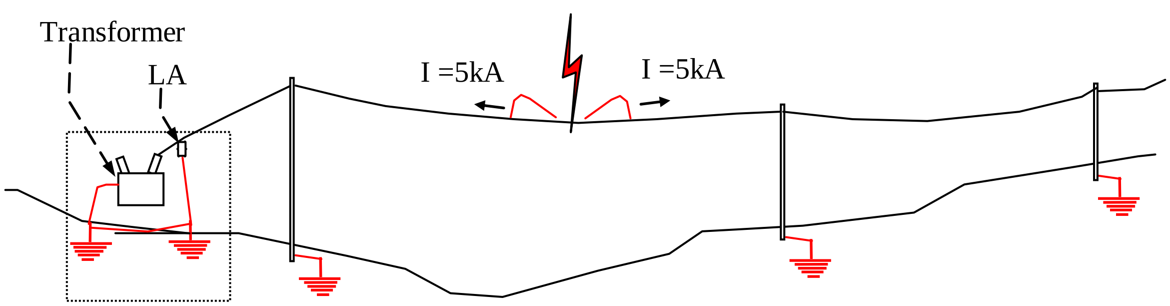


Source: Tomohiro Hayashi, Yukio Mizuno and Katsuhiko Naito, Study on transmission- line arresters for tower with high footing resistance, IEEE Transaction on Power Delivery, vol. 23, No. 4, pp. 2456-2460, 2008.

Another study even concluded that higher transmission footing resistance, E.g. 50Ω, may cause outage rate of the shielded transmission line higher than that of the unshielded one! [**Source**: P. Chowdhuri, S. Li and P. Yan: Rigorous analysis of back-flashover outages caused by direct lightning strokes to overhead power lines, IEE Proceedings- Generation, Transmission and Distribution, vol. 149, No. 1, pp. 58-65, January 2002].

It is therefore not difficult to see the importance of ensuring proper transmission tower *Earthing* and it would certainly be worthwhile to regularly monitor our transmission tower footing resistances. This is the very reason why IEEE Std. 1313.2-1999 states that electrical resistance of the tower footing is a significant parameter affecting back flash over voltage across the insulator(s) in transmission systems and (BS EN 62305-3: 2011 Code of Practice for Protection of Structures against lightning recommends *Earthing* resistance < =10 ohms).

As in the case of power transmission systems, lightning strikes (i.e. direct and indirect) also subject MV electricity infrastructure (lines, switchgear, and transformer stations) to damaging surge voltages often in excess of the line insulation level. The over voltages therefore need to be sufficiently attenuated or shunted to *Earth* prior to reaching the connected line equipments (arrestors, transformers, switchgears, etc). While these voltage impulses are also attenuated as it travels along the line, the MV steel pole *Earthing* plays an importance role in reducing the voltage surges by conducting the flash over voltage to *Earth*. However, the MV pole *Earthing* should be reliable and of low surge impedance to minimize the step and touch potential (which could otherwise be hazardous to both humans and animals). This situation is illustrated below where a lightning impulse current of 10kA splits into 5kA each at the point of lightning strike which then travels (almost at the speed of light) in opposite directions along the MV line. Assuming a MV line surge impedance of 400 ohms (i.e. usually around 400 to 500 ohms), this translates to an impulse voltage of 2000kV travelling in the two opposite directions. Since 2000kV impulse is well over the insulation rating of MV insulators, it will flashover to the cross arms and the pole which must conduct the flashover safely to *Earth*.



From the illustration above, it is evident that huge lightning voltage impulses can overwhelm the LA (especially if the MV poles are not effectively *Earthed*). It is possible that the LA energy dissipation capacity is exceeded (MOV blocks typically have a specific heat capacity of about 3.3 J/cm^3/°C), leading to thermal runaway and failure of LA. The resulting thermo-mechanical shocks can also cause damage and failure of LA. With an ineffective LA, all connected equipment (transformers, switchgears) is vulnerable to damage and failure (it will only be matter of time).

Note: From above discussions, it is clear that the MV poles need to have reliable low impedance *Earthing* so that it diverts any large flashovers into *Earth* and reduces excessive voltage impulses reaching the arrestors. Also, it must be ensured that the MV pole *Earthing* do not create excessive voltage gradients (*MV poles with a single spike driven into the ground near the pole base will definitely not be adequate at least in Bhutan's rocky soil conditions*). Providing proper *Earthing* for MV poles need to be prioritized in the lightning prone regions of the country.

Equipment	33 kV	11 kV
Surge Arrestor maximum residual voltage - steep current impulse	100 kV (p)	30 kV (p)
Transformers/switchgear (BIL) Rated impulse withstand voltage (peak)	170 kV (p)	75 kV (p)

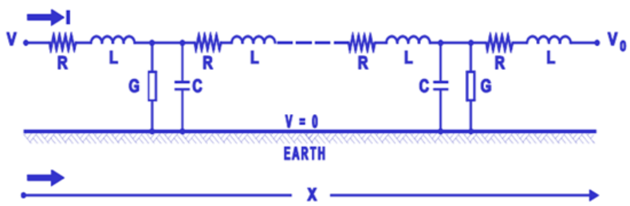
Equipment	33 kV	11 kV
Puncture voltage (pin insulator)	185 kV	145 kV
Puncture voltage (disc insulator)	330 kV	110 kV
Wet flashover voltage (power frequency, pin insulator)	95 kV	70 kV
Wet flashover voltage (power frequency, disc insulator)	135 kV	45 kV

Note: The basic rule is "The lower the surge impedance of the *Earthing*, the greater is the surge energy shunted to the *Earth*".

As can be seen from the typical BIL values for MV infrastructure tabulated above, it is evident that lightning over voltages (usually surges greater than 1000kV peak) due to lightning strikes (which commonly are in excess of 20kA) can easily cause MV line outages if Lightning Arrestors do not discharge effectively (which will not happen without proper LA *Earthing*).

6.1 What is the difference between low *Earthing* impedance and low *Earthing* resistance?

For protection and mitigation of lightning strikes, it is very important to distinguish impedance from resistance. As indicated above, low *Earthing* impedance is more important than low *Earthing* resistance when dealing with rapidly varying voltages and currents (i.e. transients) such as those of lightning surges (high frequency components are superimposed too). When dealing with surges/transients, the inductance and capacitance encountered by the transients/surges are very significant. Therefore to safely and efficiently discharge lightning surges, an *Earthing* system must have low surge impedance. The **surge impedance** (Z) of an *Earthing* system is estimated using the following model (i.e. same as "lossy" transmission line model).



$$Z = \frac{\sqrt{R + j\omega L}}{\sqrt{G + j\omega C}}$$

Z is Surge Impedance
R is resistance **(**is a function of material used for grounding)
G is *Earth* conductance (related to soil resistivity and contact resistance between *Earth* electrode and soil)
L is Inductance of the *Earthing* system
C is Capacitance between *Earth* and *Earthing* electrodes

From the Surge Impedance (Z) formula above, it can be seen that Z increases with the increase in R and L and that Z decreases with the increase in G and C. Since ω is 2πf (and f is frequency which is very large for a typical lightning surge), it obvious that L and C are the dominant parameters in determining the value of Z. Therefore in the installation of *Earthing* systems that must safely and efficiently dissipate lightning surges, we must minimize the inductance (L). This translates to minimizing the length of *Earthing* conductors and ensuring minimum bends. The other dominant factor is capacitance (C) which must be maximized. In order to maximize C, the surface area of an *Earthing* electrode in contact with the soil must be maximized.

Important notes:

As shown above in section 6.1, for protection against surges and transients (i.e. generated by lightning and network switching activities), low *Earthing* surge impedance is far more important than low *Earthing* resistance. It is well known that horizontally laid *Earthing* electrodes buried inside conductive concrete provides much larger soil contact area (i.e. higher capacitance and higher conductance) leading to lower surge impedance. Such conductive concrete *Earthing* installations are best suited for safe and efficient lightning surge dissipation. Conductive concrete based *Earthing* is also used because of the reliability and durability characteristics. [More details can be obtained from the websites of international companies such as Sankosha Corporation and Erico International Corporation].

It is also pertinent to point out that Ground & Electrode Enhancement (GEE) slab *Earthing* is a conductive concrete *Earthing* technology and is designed to lower surge impedance during lightning surge dissipation on account of its larger capacitance and higher conductance. GEE *Earthing* slabs have a large surface area. Each GEE slab has a surface area of around 2.7 times that of a standard GI pipe electrode (4 cm dia x 2.5 mtr long). Further, when many GEE *Earthing* slabs are chain linked, the surface area is increased greatly which presents a much higher capacitance and thus yielding substantially lower Surge Impedance (Z). In addition, GEE *Earthing* slabs are made of hygroscopic conductive concrete and also bonds well with surrounding soil in contact. This helps in lowering the contact resistance and thus ensures a higher conductance (G).

A low impedance *Earthing* is what is required for transmission tower footings, transformers and Lightning Arrester *Earthing*, MV poles, substation switchyards, etc. It would definitely be cheaper to improve the *Earthing* installations than upgrade the BIL of lines, switchgears and transformers.

7 Lightning protection of houses, lives, and sensitive electronics (and the role of *Earthing)*

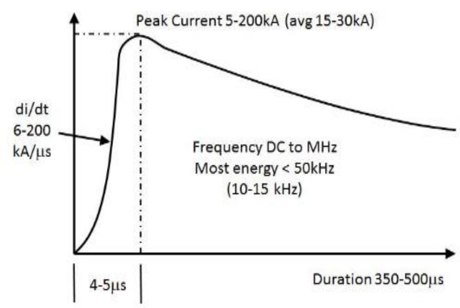
Section 5 and 6 above already reveals the importance of *Earthing* for protection and mitigation of lightning surge impacts in power infrastructure. While systems and standards have been put in place to mitigate the damaging effects of lightning strikes on HV and MV electricity infrastructure, there is only a bare minimum (if any) that pertains to LV electricity distribution and connected consumers in Bhutan. Also for protection of buildings and structures against lightning strikes, it is basically left to the public to find out what is best for their lives and their property. Presently in Bhutan, most of our taller structures that are more vulnerable to lightning strikes (and even fuel depots) do not have lightning protection systems. Lightning is one of the significant causes of natural disasters around the world. In Nepal, a five-year figure maintained by the National Emergency Operation Centre under the Ministry of Home Affairs shows that as many as 553 persons were killed and 1,132 others were injured by lightning strikes during the period of 2011-2015. Besides the April 2015 devastating *Earth*quake that took the lives of almost 9000 people, lightning damage tops the list as the worst natural disaster in Nepal in the recent times. [Himalayan News Service, Kathmandu, June 26, 2017].

In Bhutan, except for the occasional news reported by the media, we do not have a clear idea of the extent of damages and losses inflicted by lightning strikes. Kuensel (March 31, 2018), reported “People in Kanglung and Yongphula have lost electrical appliances worth thousands to lightning strikes”. Similarly, The Bhutanese March 17, 2018, reported of five casualties and some property damage in Dagana. Although the risks of lightning hazards are substantial, such risks are barely mentioned in our national disaster management plans nor do we keep a time series record of the lightning hazards that have occurred. However there is a genuine concern and a feeling of helplessness in the country (especially in the more lightning prone areas). There is an urgent need to inform and educate the Bhutanese populace on how to protect lives, houses, and particularly their sensitive electronics from lightning surges (and also from the power surges generated by switching activities in the electricity grid). Although people evidently worry most about direct strike of lightning on houses they live in, this is actually very rare in Bhutan (especially in the valleys where most settlements are). Most of the lightning damage inflicted in homes is from the strikes on nearby or distant objects which result in surges entering via power and telecommunication lines. The damage to property and especially the destruction of sensitive electronics is colossal in most lightning prone countries around the world.

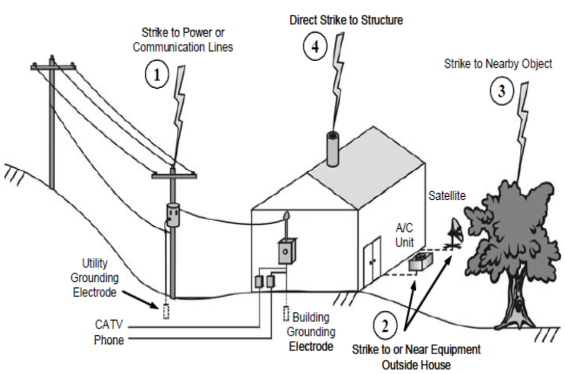
The lightning protection is a vast subject and it certainly cannot be explained adequately in a few pages. The most recognized standard for lightning protection is the BS EN/IEC 62305 which is over 470 pages and has the following four parts:
BS EN/IEC 62305-1 provides the general principles
BS EN/IEC 62305-2 is for risk management
BS EN/IEC 62305-3 is for protection of structures and life hazards
BS EN/IEC 62305-4 is for protection of electrical and electronics within structures

Explaining the details of these standards will be too lengthy and is beyond the scope of this paper too. None the less, it is felt that even understanding the basics will be very beneficial for the general public in minimizing the lightning hazards. So to begin, what is a l**ightning?** Lightning is a natural phenomenon caused by separation of electrical positive and negative charges by atmospheric processes. When the separated charge gets very large, the air between the positive and negative regions breaks down in a giant spark (an intra-cloud stroke), or a charged region breaks down to ground (a cloud-ground stroke). The resulting current flow ionizes and heats the air along the path to ~30,000 K (around 29,700° C). The ionized air glows brightly (the lightning), and the sudden increase in temperature expands the channel and nearby air, creating a pressure wave that makes the thunder. Most (~80%) lightning strokes are within a cloud; and most of the remainder are cloud-ground strokes. Strokes between clouds are relatively rare. Most cloud-ground strokes transfer negative charge from the cloud to ground. [*IEEE guide for Surge Protection of Equipment Connected to AC Power and Communication Circuits*]

For protection against lightning strokes, we are concerned with the strokes between the cloud and ground. Lightning strokes as we know, bear devastating power. The cloud-to-ground voltages leading to the discharge are tens of millions of volts or more. The peak discharge currents in each stroke vary from several thousand amperes to 200,000 A or more. The current rises to these values in only a few millionths of a second (microsecond), and the major part of each stroke usually lasts much less than a thousandth of a second. Each visible event, referred to as a flash, typically consists of 1–6 (or more) individual strokes, separated by <0.1 second.



It is also known that about 98% of the cloud-to-ground strokes deliver up to 200kA and the median is around 30kA. The frequency spectrum of a lightning strike contains frequencies ranging from DC (0 Hz) to 10 MHz. Graph at left describes the typical lightning impulse characteristics.



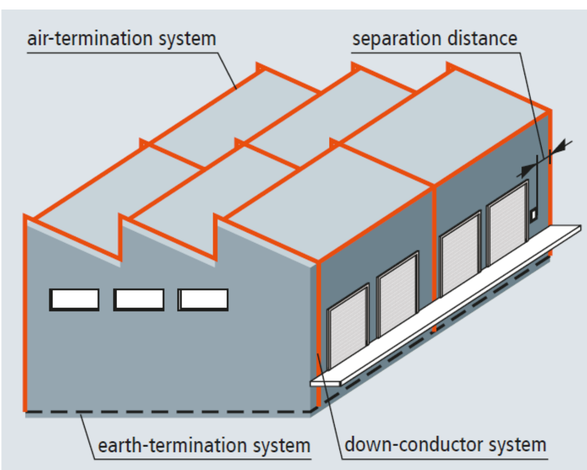
As illustrated in the picture (left), the IEEE guide identifies the following four most common modes of lightning damage listed in the order of precedence (from most to least likely). (1) lightning strikes on power and communication lines, (2) lightning strikes to, or near, the external installations such as air conditioners, satellite dishes, exterior lights, security systems, etc, (3) lightning strikes on nearby trees, flagpoles, signs, etc, and (4) direct lightning strike to the structure.

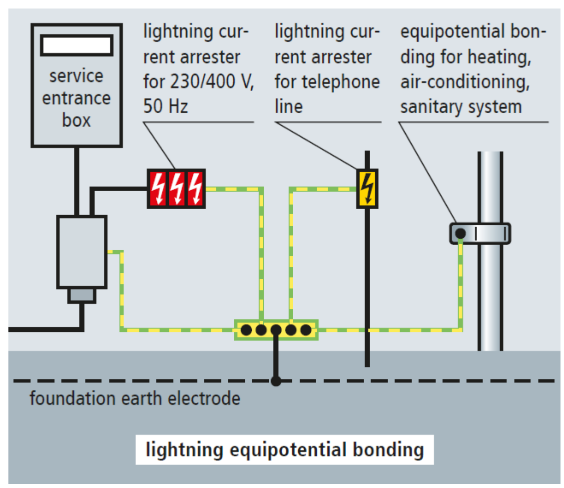
In addition, lightning can also enter houses via underground metallic pipes and cables.

Note: Each of these modes of lightning strike will send damaging voltages (directly or indirectly) through the cabling/wiring into the house that will damage electronics and appliances (if not adequately protected with Surge Protection Devices, EMI shielding, and reliable low impedance *Earthing*, etc)

7.1 Lightning protection system

The function of a lightning protection system is to protect structures from fire or mechanical destruction and persons in the buildings from injury or even death. According to BS EN/IEC 62305, a lightning protection system (LPS) consists of an external and an internal lightning protection system. The functions of the external LPS system are: (i) To intercept direct lightning strikes via an air-termination system, (ii) To safely conduct the lightning current to the ground via a down-conductor system, and (iii) to distribute the lightning current in the ground via an *Earth*-termination system. The functions of the internal LPS system is: To prevent dangerous sparking inside the structure. This is achieved by establishing equipotential bonding or maintaining a separation distance between the components of the lightning protection system and other electrically conductive elements inside the structure. These are illustrated in the two pictures below. In order to intercept direct lightning strikes via an air-termination system, the air-termination system can be of: (i) lightning rod, (ii) spanned wires and cables, or (iii) meshed conductors (as shown in the picture at left below).



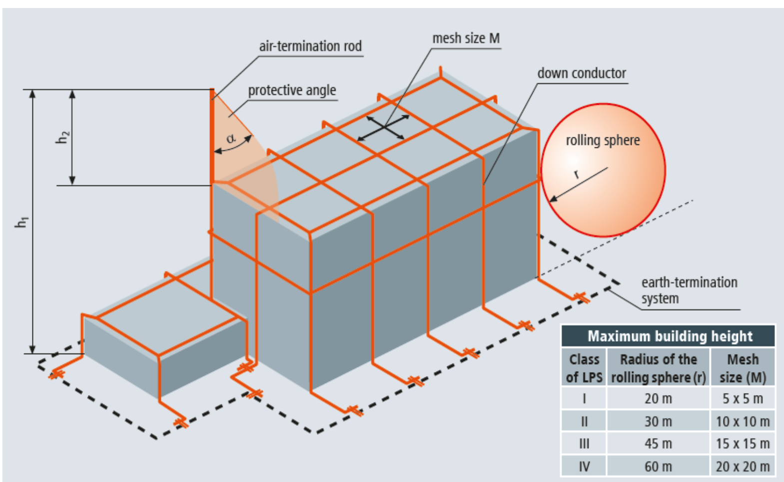


Source: *DEHN + SÖHNE – Lightning Protection Guide, 3rd Edition*

It may be worthwhile to note that the effectiveness of the air terminal systems such as Early Streamer Emission (ESE) air terminals and Charge Transfer Systems (CTS) air terminals as compared to the conventional lightning rod (Franklin rod) is not yet recognized by the IEC or the IEEE. Although such newer air termination systems are increasingly being used in many countries, scientific studies (even conducted at NASA, USA) have reportedly **not** found conclusive evidence that such air terminals are indeed more effective. [***Source:*** William Rison, IEEE Member, Professor, Department of Electrical Engineering, Institute of Mining and Technology, New Mexico].

Two conventional lightning rods (i.e. Franklin rod) are shown in the picture (left). Since these have been used for more than 250 years after its invention by Benjamin Franklin in 1749, we know for certain that the installation of such rods at proper locations will receive lightning strikes and divert them into the ground if bonded to proper down conductors and to a low impedance *earthing* (with equipotential bonding to mains *earthing* and other metallic structures such as those of water pipes)

BS EN/IEC 62305 recommends the three methods of: (i) rolling sphere, (ii) protective angle, and (iii) mesh, to determine the locations of the air terminals. These methods for designing air-termination systems for high buildings is shown in the picture below. The standard also specifies four classes of Lightning Protection System with Class I providing most protection and Class IV providing the least. The Rolling sphere method is usually used for more complex structure shapes.

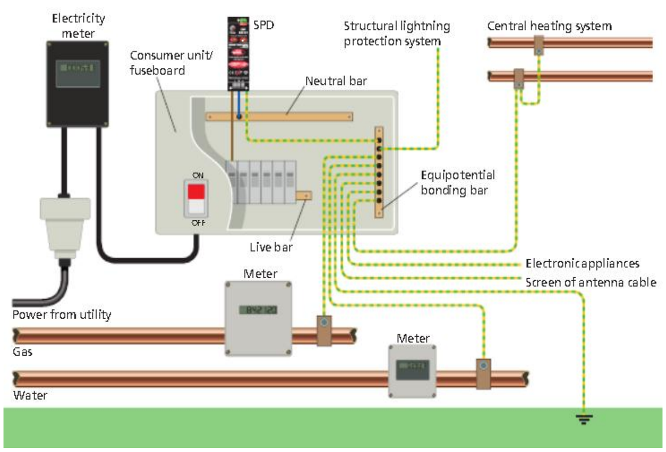


Source: *DEHN + SÖHNE – Lightning Protection Guide, 3rd Edition*

The Rolling sphere method is based on an electro-geometric model for cloud-ground lightning flashes. The rolling sphere radius is the typical striking distance. Although the IEC standard specifies the radius as 20m to 50m according to the class of LPS, a radius of 150 ft (about 45m) seems to be often assumed for approximate positioning of air terminals.

To safely conduct the lightning current to the ground via a down-conductor system, it is obvious that more down conductors would be more effective than a few. However these will need to be positioned carefully. Multi stranded conductors should be used instead of single solid core conductors. This is because high frequency or transients currents are only confined towards the surface rather than deeper inside the core (due to skin effect). In the event of having to choose between a flat and a round conductor, flat conductors are preferable to round conductors since flat conductors provide more surface area than round conductors for a given cross section area. Also, since bends and coils pose higher inductance to lightning surges, the down conductor installations should preferably minimize bends and coils. If lightning rods of copper are used, it would be better to use copper down conductors so that the joints do not corrode. Likewise, it would be better to use aluminium rods with aluminium down conductors. The minimum cross section area of down conductor (copper) recommended by IEC 62305 is 35sq.mm.

In order to safely and efficiently discharge the lightning current into the ground, a low impedance *Earthing* installation is essential. From the safety of lives point of view, the lightning protection system *Earthing* must be bonded to the mains *Earthing* (house *Earthing*) and to all metallic structures (water pipes, etc) in order to ensure equipotential (as illustrated in the picture below).



Source: *Guide to BS EN/IEC 62305 (By Furse)*

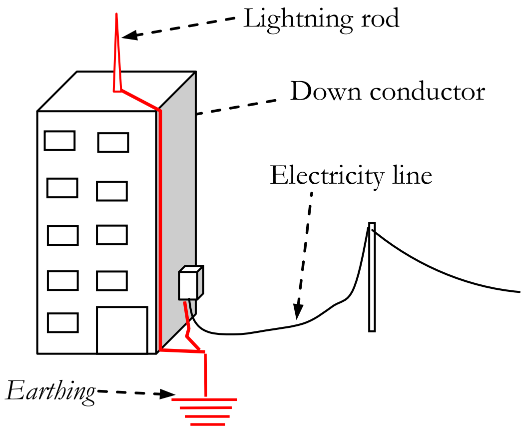
The lightning down conductors should preferably be placed as far away as possible from other utility (power, TV, telephone, etc) conductors entering the house. This is to minimize any electromagnetic coupling effects due to lightning strikes. Also, it would be prudent to put the down conductor in insulation plastic pipe at least in areas easily accessible to human. Irrespectively, the lightning protection system will only work effectively if bonded to a low impedance *earthing* system.

Regarding the *Earthing* resistance standards, BS EN/IEC 62305-3: 2011 Code of Practice for Protection of Structures against lightning recommends *Earthing* resistance <=10 ohms. Also, the Australian standard AS1768 (Clause 4.3.4) requires 10 Ω or less for an LPS *Earth* before bonding to other services (e.g. main electrical *Earth*). However, it is again emphasized that stating a maximum *Earth* resistance value (measured at D.C or low frequency) does not guarantee an acceptable LPS *Earth* – it is only indicative of performance under lightning conditions. The *Earthing* impedance posed during lightning surge dissipation is more important.

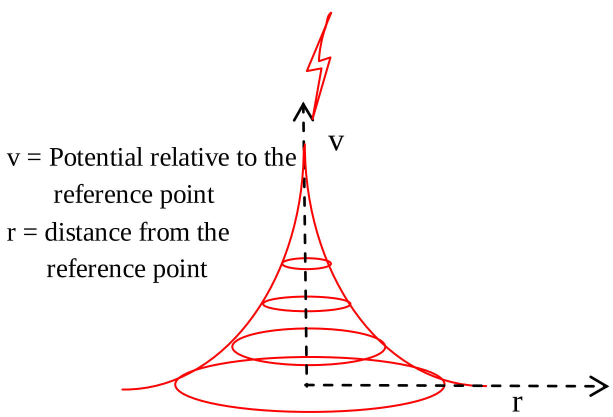
Caution!

At this point, it would be appropriate to point out the following dangers of improper installation of lightning protection system (LPS) for protection of houses in the Bhutanese context.

(a) Most of the houses in Bhutan have installed the conventional salt-charcoal based pipe or plate *Earthing*. All the old installations (more than 4-5 years) are most probably ineffective. As the field experienced electricians and engineers by now would know that such installations are neither reliable nor durable (refer to section 3.1 for explanations). In regions vulnerable to lightning hazards, connecting a Lightning Protection System to such a salt based *Earthing* installation used as the house *Earthing* would be counterproductive (i.e. more harm than good). It is likely to cause huge step and touch potential during lightning strikes. Lightning surges will be introduced into the house via the *Earthing* (especially if the *Earthing* is connected to the supply Neutral as in TN-C *Earthing* method). Moreover most (if not all) do not use Surge Protection Devices (SPD) to prevent such harmful surges from entering into the house wiring.

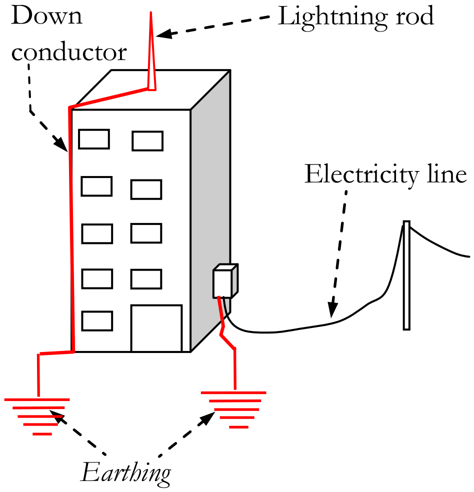


As shown in the illustration (left), the few houses that have installed an LPS in Bhutan usually have one lightning rod placed at the highest point) and one down conductor coming down to bond with *earth* (which is a conventional salt based installation). Applying the Rolling sphere method, such an LPS is not even likely to protect the house (lightning can hit the sides of the house instead of the rod). Even if it strikes the rod, lightning surges will enter the house via wiring and damage appliances. Dangerous step and touch potential will arise in the event of a lightning strike (see pictures below).



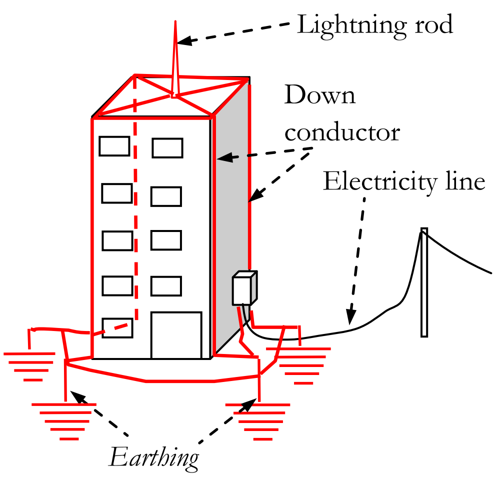
Conventional salt based *Earthing* when salt is depleted (or soil is dry) or electrodes have corroded will result in high voltage gradients (i.e. high step and touch potential) when discharging a lightning surge.

Animals killed by electric shock due to step voltage



As shown in the picture (left), some of the houses with lightning rod in Bhutan use separate *Earthing* installations for lighting protection system and for general house *Earthing* (contrary to all international standards which recommend equipotential bonding). However, while bonding will reduce the risks of step and touch potential in theory, bonding two non-functional (or ineffective) *Earthing* installations may even aggravate the hazard risks. In such cases (which are very likely with conventional salt based *Earthing*), bonding the lightning system *earth* with the general house *Earthing* will also inject huge lightning surges (in the event of a direct or indirect stroke) into the house (via the house *Earthing*) and most houses do not have SPDs. Keeping the two ineffective *Earthings* separate (far apart) may at least reduce the lightning surges going into the house.

But this is not to justify this option. The point here is that having reliable and low impedance *earthing* installations that are bonded together is imperative (and not an option).

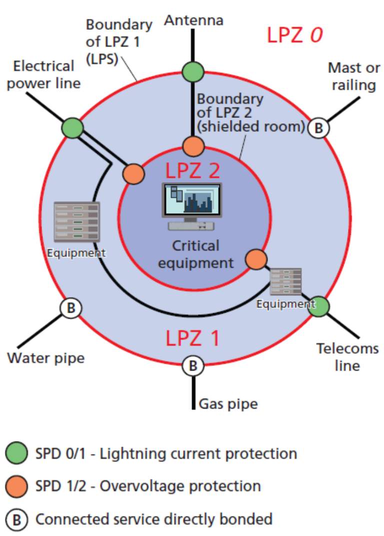


Using the same house from above examples, the illustration (left) provides a better Lightning Protection System and *Earthing* system (bonded to provide equipotential). In addition to the single lightning rod, conductors cover all the corners and edges, and down conductors run along the four edges of the house to bond with four earthing installations (all four are interlinked).
Note: Instead of four pit *Earthing* installations, several GEE slabs can be chain linked around the house and all the down conductors bonded to the chain. This will provide a cost effective, equipotential, reliable, and low impedance *Earthing*.

7.2 Protection of sensitive electronics from surges due to lightning and switching activities

When we talk about lightning damages, we are naturally drawn towards the safety aspects of lives and structures due to the awesome power that a lightning can discharge in microseconds. Direct strikes to houses are actually rare and the lightning protection system (LPS) to address such events is discussed in section 7.1 above. However, the most lightning caused damages and losses are due to lightning strikes on (or near) overhead power and communication lines. These overhead lines traverse a large area and are good collectors of lightning strikes (i.e. direct and indirect). Lightning surges then travels via these lines and come into houses which then destroys the connected sensitive electronics and electrical appliances (if there are no suitable surge protection devices to shunt these surges to *Earth*). Lightning is one of the leading causes of damage to electronics and disruptions of utility services around the world. Even when lightning strikes nearby objects (trees, poles, etc), it radiates a strong electromagnetic field, which can be picked up by wiring in the house, producing large voltages that can damage equipment. The LPS discussed in section 7.1 above is for mitigating the risk of shock or electrocution to a person in a house, and the risk of fires caused by lightning. However, such LPS are totally inadequate to prevent damage to electrical and electronic equipment. The intent of this section is therefore to provide some information on the application of service entrance Surge Protection Devices (SPD) specifically for residential and light commercial applications. It does not cover all the complexities of an industrial environment which is beyond the scope of this paper.

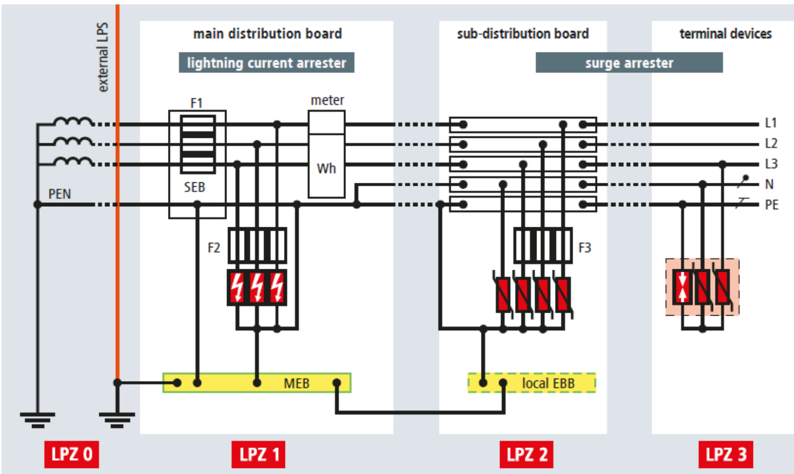
BS EN/IEC 62305-4 provides the state of the art specifications and standards for the protection of electrical and electronics within structures. It adopts a zonal approach (LPZ 0, LPZ 1, LPZ 2, LPZ 3, etc) where the areas at risk of direct lightning strike are designated under LPZ 0 (external zone), and the internal zones within a structure are designated under LPZ 1, LPZ 2, etc). In general, the higher the LPZ number, the lower the electromagnetic effects expected. Therefore any sensitive electronic equipment should be located in higher numbered LPZs and be protected against Lightning Electro-Magnetic Pulse (LEMP) by relevant Surge Protection Measures (as defined in BS EN 62305- 2011). This concept of LPZ (as prescribed by BS EN/IEC 62305-4) is illustrated in the figure below.



Source: *Guide to BS EN/IEC 62305 (By Furse)*

Surge Protection Measures (SPM) include proper design of lightning protection systems, equi-potential *earth* bonding, electromagnetic shielding, cabling techniques, etc. However, correct installation of coordinated Surge Protection Devices (SPD) is most essential for protecting electrical and electronic from damage. Appropriate SPDs must be installed where service cables cross from one LPZ to another. Poor coordination of SPDs would subject both itself and the equipments under protection to too much surge energy. SPDs must be coordinated with the insulation withstand voltage of the installation components and the immunity withstand voltage of the electronic equipment.

The zonal approach concept and surge protection coordination is illustrated in the figure below.



SEB = Service Entrance Box
MEB = Main Earth Busbar
EBB = Equi-potential Bonding Bar

Note: The Surge Protection Devices (SPDs) are those shown in red colour.

Source: *DEHN + SÖHNE – Lightning Protection Guide, 3rd Edition*

The classification of surge protective devices according to IEC and EN are shown in the Table below.

Standard / Type/designation	EN 61643-11:2012	IEC 61643-11:2011
Lightning current arrester/combined arrester	Type 1 SPD	Class I SPD
Surge arrester for distribution boards, sub-distribution boards, fixed installations	Type 2 SPD	Class II SPD
Surge arrester for socket outlets/terminal devices	Type 3 SPD	Class III SPD

From the above SPD coordination figure and the Table above, it is clear that Type 1 SPD or Class 1 SPD should be used in the Main Distribution Board (in zone LPZ 1) so that the bulk of the lightning surge is diverted to *Earth*. This means that smaller surges would be let through to enable the downstream SPDs to handle safely (i.e. divert to *Earth*).

Important note: In Bhutan, very few structures (if any) have SPDs installed. Given the society's rapidly growing and inevitable dependence on the use of electrical and electronic equipment, the use of SPDs has become crucial. For example, modern microprocessors employs millions of transistors packed onto a silicon wafer of about 1 sq.inch area and are becoming smaller and faster which means electronics are getting increasingly more sensitive and fragile. It may therefore be worthwhile to make the installation of appropriate SPDs at least in public and important buildings as a utility service entrance standard. Also, it must be noted that SPDs will not work properly without proper *Earthing*. Lastly, the *Earthing* for most of the houses in Bhutan do not employ equip-potential bonding which is another area that needs attention.

8 Conclusions

(a) *Earthing* is generally misunderstood and not given the due credit it deserves for its very important role in the electrical system.

(b) The basic functional requirements of a good *Earthing* system include the following:

- Low resistance and low impedance throughout the year (with the few exception where high *Earth* resistance is intentionally built in to limit fault currents)
- Consistent and reliable performance (irrespective of wet or dry seasons)
- Durable installation (at least 25 years or more)
- Maintenance free (or very minimal maintenance requirement)
- Safe touch and step potential (i.e. no hazardous voltage gradients)

(c) The conventional salt-charcoal based pipe and plate *Earthing* installations are neither reliable nor durable. The thousands of such *Earthing* installations presently existing around the country definitely have a huge negative impact the overall electricity distribution system and also on the individual house safety hazards risks (it may not be visible until a hazard occurs). *Earthing* standards and specifications promoting such salt-charcoal pipe and plate *Earthing* will not be beneficial to the generally public nor is it in the interest of improving the overall electricity system.

(d) Conductive cement based *Earthing* (such as GEE *Earthing* slabs) provides reliable, durable, and maintenance free *Earthing* installations. In addition, it provides lower surge impedance and therefore well suited for lightning and surge protection applications. Over 13000 GEE slabs have been installed around the country and is now a proven and well established *Earthing* technology.

(e) Using standard formulae for *Earthing* resistance calculations, it is seen that a 10 meter long GEE *Earthing* installation will provide a lower *Earthing* resistance than a quadruple (four) pipe/rod electrode *Earthing* installations for the same soil resistivity. In addition, if the reliability, durability, and maintenance aspects are considered, salt-charcoal pipe and plate *Earthing* is not even a feasible option.

(f) Bhutan Electricity Authority’s (BEA) Distribution Code - Regulations, 2006, Section 3.9.4 specifies the *Earthing* system for distribution system as “*Multiple Earth Neutral (MEN) method shall be adopted for Earthing of distribution system.*” Although this requires the use of TN-C and TN-S *Earthing* systems with multiple *Earthing* along the supply Neutral (for TN-C method) or along a dedicated PE conductor (for TN-S), practical complexities has not permitted compliance to this regulation. Consequently, a multitude (if not the majority) of house *Earthing* are still employing the T-T method. Although TN-S is the more expensive option, it is the superior *Earthing* method from the options available.

(g) *Earthing* also plays an important role in supply quality issues such as: sags, swells, surges, harmonics, electromagnetic interferences, etc, protection of electrical and electronics devices, and in analog/digital communications, etc.

(h) Under the present LV electricity distribution circumstances, generally there are only two *Earthing* installations relevant to a single service connection (i.e. consumer *Earthing* and the transformer *Earthing*). Both these installations must have low *Earthing* resistance in order to trip a MCB and safely isolate a fault.

(i) At the distribution transformer station, low impedance *Earthing* is imperative for Lightning Arrestors to work effectively. Otherwise, the transformer will be subjected to surges in excess of its Basic Insulation Level (BIL). A high impedance *Earthing* will also result in damaging surges being injected into the supply neutral that could damage consumer electrical and electronic appliances.

(j) Having high distribution transformer Neutral *Earthing* resistance can cause Neutral shifting which can result in low voltage on one phase and high on other two. A fault on a phase will deliver high voltages on the other two phases endangering consumer appliances, surge arrestors, and other connected devices. When the neutral develops a potential (due to high *Earthing* resistance), eddy currents won't discharge effectively resulting in: transformer heating, higher energy losses, loss of capacity, increased risks of winding faults not getting cleared, and increased risk of dangerous touch and step potential.

(k) Transmission lines are very vulnerable to lightning strikes (direct and indirect) and many studies have shown that transmission line outages due to lightning strikes are directly proportional to tower footing resistance. For efficient dissipation of lightning strikes, a low impedance *Earthing* would be more important than low resistance *Earthing*. *Earthing* conductors encased in conductive concrete provides lower surge impedance and thus more efficient dissipation of lightning surges. This is because it provides the necessary wide surface area (which provides larger capacitance) and lower soil contact resistance (which provides higher conductance).

(l) The MV distribution lines are also vulnerable to lightning strikes (direct and indirect). Since the MV pole *Earthing* plays an important role in dissipating the flashover voltages into the ground, a low impedance *Earthing* for MV poles (especially in the lightning prone regions) is crucial. Otherwise, the Lightning Arresters could be damaged which would in turn damage the transformer and connected switchgear. One *Earthing* spike inserted at the base of an MV pole will in most cases not provide the required low *Earthing* impedance.

(m) There is a growing need to have lightning protection systems for buildings and structures in Bhutan. Presently we do not have a comprehensive guideline or standards and specifications for lightning protection of structures (including houses). The internationally adopted standards and specifications pertaining to BS EN/IEC 62305 (Part 1 to 4) is introduced and the principles and concepts briefly discussed. *Earthing* is an integral part of a lightning protection system and low impedance *Earthing* that is reliable and durable is essential.

(n) BS EN/IEC 62305-3: 2011 Code of Practice for Protection of Structures against lightning recommends *Earthing* resistance <=10 ohms. Also, the Australian standard AS1768 (Clause 4.3.4) requires 10 Ω or less for an LPS *Earth* before bonding to other services (e.g. main electrical *Earth*).

(o) Although direct lightning strikes to a structure will do most damage, the vast majority of the lightning damages and losses are due to those surges that come into houses through the electricity and other service lines. Given the society's unavoidable dependence of sensitive electronic and electrical appliances, the need for surge protection is imperative. The principles and concepts for surge protection is discussed and explained in accordance with the provisions of the international standard BS EN/IEC 62305-4.

Disclaimer:
The views and opinions expressed in this paper are those of the author and do not necessarily reflect the views nor represent the official policy or position of any organization. This paper has been prepared voluntarily with the intent of helping in mitigating the risks of electrical hazards, mitigating lightning risks, and in protecting sensitive electronics from lightning and switching surges. While concerted efforts have been made to ensure accuracy of the information provided, the author accepts no responsibility or liability for any consequences arising out of any inferences, interpretations, and conclusions drawn by readers.