ELECTROMAGNETIC TRANSIENTS IN RADIO/MICROWAVE BANDS AND SURGE PROTECTION DEVICES

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Abstract—A comprehensive review has been done on the types of electromagnetic transients that may affect low voltage electrical systems. The paper discusses various characteristics of lightning, switching, nuclear and intentional microwave impulses giving special attention to their impact on equipment and systems. The analysis shows that transients have a wide range of rise time, half peak width, action integral etc. with respect to both source and coupling mechanism. Hence, transient protection technology should be more specific with regard to the capabilities of the protection devices. Furthermore, we discuss the components and techniques available for the protection of low voltage systems from lightning generated electrical transients and the adequacy of International Standards in addressing the transient protection issues. The outcome of our analysis questions the suitability of $8/20\,\mu s$ test current impulse in representing characteristics such as the time derivative and the energy content of lightning impulses. The $10/350\,\mu s$ test current impulse better represents the integrated effects of the energy content of impulse component and long continuing current. A new waveform is required to be specified for testing the ability of protective devices to respond to the fast leading edges of subsequent strokes that may appear $100\,s$ of millisecond after the preceding stroke. The test voltage waveform

1.2/50 µs should also be modified to evaluate the response of protective devices for fast leading edges of induced voltage transients. A surge protective device that is tested for lightning transients may not be able to provide defense against other transients.

1. INTRODUCTION

The term surge is vaguely used with different meanings in the electrical engineering community thus, it is often misinterpreted by fellow researchers in the literature. The most common usage of the term surge is to identify "electrical transients", which is the scope of this paper.

An electromagnetic transient is a sharp increase in electromagnetic energy in space. Such electromagnetic transients in the kHz to MHz range may induce voltages and consequently currents in an electrical system of which the duration can vary from nanosecond scale to few milliseconds. Such transients may be generated in or injected into power supply, communication or any other system where electricity is involved in whatever the form and propagate along the same system to damage the system itself or any component connected to the system. The type and magnitude of the damage depends on the rate of rise, amplitude, duration, repetition etc. of the transient and the system response.

This paper presents the available information on the characteristics of electromagnetic transients that may affect systems that conduct electrical signals (power and communication). The main purpose of this study is to discuss the capabilities of devices meant for lightning protection, in providing defense for the equipment and systems against other transients.

2. TYPES OF TRANSIENTS

There are several sources of transients.

  a. Direct Lightning: Lightning Electro-Magnetic Pulses (LEMPs)

  b. Indirect Lightning: Lightning Induced Voltage Impulses (LIVI)

  c. Voltage pulses due to ground potential rise: Step Potential Pulses (SPP)

  d. Power system abnormally or Switching operations: Power System Generated Transients (PSGT)

  e. Nuclear explosions: Nuclear Electro-Magnetic Pulses (NEMPs)

  f. High power electromagnetic emitters: High-Power Electro-Magnetic pulses (HPEMs)

g. Static electricity generated discharges: Electro-Static Discharges (ESD)

Out of the above types of transients mentioned above, ESDs are not of concern to the investigators on surge protective devices as the source is most often very close to the victim (e.g., between IC chip and the pins). Hence we do not discuss regarding ESD in this paper.

2.1. LEMPs

Lightning is one of the main destroyers of electrical and electronic systems in many parts of the world. A significant amount of work has been done to investigate the properties of ground lightning which is of prime concern as far as system damage at ground level is concerned.

Lightning current at the channel base, in general, is double exponential in profile. Such currents are recorded either by tower-based measuring systems or in triggered lightning. Both methods have their own drawbacks; Currents in the tower base measurements are influenced by the presence of the tower and in triggered lightning, the current of the first return stroke is totally different to its expected counterpart in natural lightning, due to the presence of the conducting wire through which the initial current flow.

In most of the recorded currents the initial impulse, which is in the microsecond scale, is followed by another current component which is in the millisecond scale. This is popularly termed as continuing current which has amplitudes ranging from few tens to several hundreds of Amperes. They are either slow decaying ramps or plateaus followed by exponential decay, which last for few tens to several hundreds of milliseconds [1–4]. It is often observed that there are humps embedded in the continuing currents, termed M components. These almost symmetric swells have rise times of about few hundred microseconds and amplitude ranging from few hundreds to about thousand Amperes [3, 5–10].

For the ease of analysis and testing purposes the two parts are separately referred; the initial impulse current is called the short stroke and the slow continuing current is called the long stroke.

In the designing and testing of devices for protection against lightning transients the important parameters are

a. The peak impulse current: This determines the voltage that will be developed along the current path due to the resistive component of the impedance.

b. The rise time (usually given as the time between the 10% and 90% of the peak current): This is an important factor to determine the maximum response time of the SPD.

c. The time derivative of the rising part: The fastest part of the lightning current is in the rising edge, thus it has the highest current derivative. It determines the voltage that will be developed along the path due to the inductance component of the impedance. The current derivative also restrains the voltage induced in nearby conducting loops due to magnetic coupling.

d. Half peak width of the impulse current: This parameter represents the width of the pulse. A more appropriate representation is the zero-crossing time, however, due to the ambiguity in tracing the zero level this parameter may contain a large error.

e. Action integral ($\int i^2\, dt$): This is the energy dissipated per unit resistance through which the lightning current flows.

Most of the above parameters are inter-related and have a dependency on the charge brought down and channel conductivity during each phase.
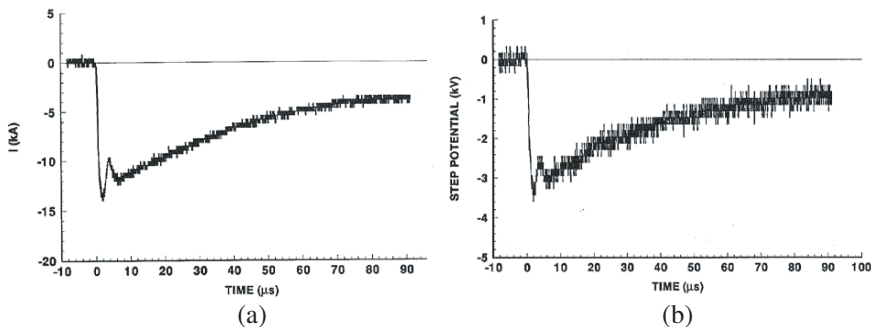
The Figure 1 depicts a typical channel base current waveform for a negative subsequent return stroke observed in a triggered lightning session in China [8]. The figure also shows the 10%–90% rise time and half peak width. Note that the typical half value width measured in other studies is one order greater than the same parameter in this stroke. Figure 2(b) and Figure 3(a) show typical subsequent stroke current waveforms measured in triggered lightning session in Florida, USA. It has been observed in several studies that the impulse duration of subsequent strokes tends to decrease with increase in amplitude [1, 8].
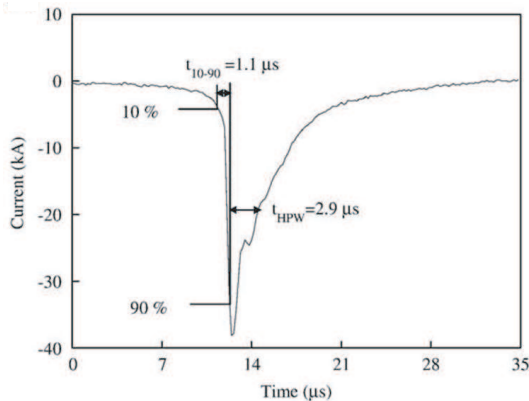
Figure 1. The channel base current waveform for a negative subsequent return stroke observed in a triggered lightning session in China [8]. The figure also shows the 10%– 90% rise time and half peak width.
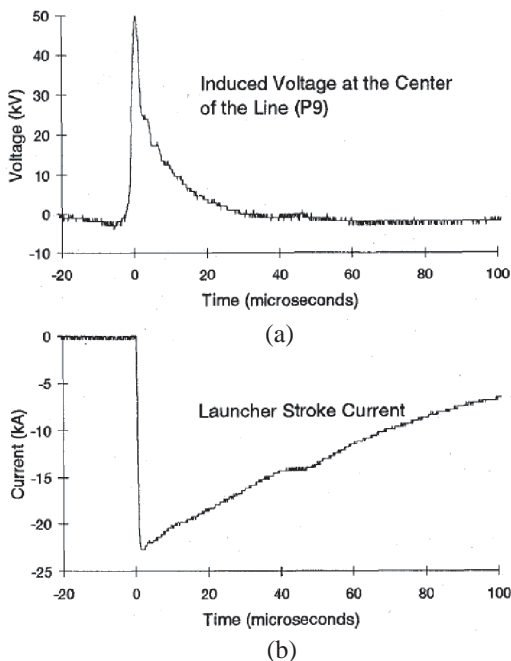
Figure 2. (a) The induced voltage at the centre of a 682 m long line for a triggered lightning subsequent stroke struck at 145 m away from the line, (b) the corresponding stroke current [16].

Figure 3. (a) The channel base current waveform for a negative subsequent return stroke observed in a triggered lightning session, (b) the corresponding step potential pulse across two electrodes separated by 0.5 m at 20 m from the strike point [23].

The Table 1 depicts the Impulse current parameters of triggered lightning carried out in several countries. Note that triggered lightning data is pertinent only to subsequent strokes.

Table 1. Parameters of current waveforms pertinent to negative subsequent strokes observed in triggered lightning experiments. Note that rise time given is 10%–90% of the peak value except for [a] 30%–90%. [b] maximum value [c] less than 5% of the sample exceeds the value (extreme value) [d] less than 95% of the sample exceeds the value.

Reference	Impulse current (Short stroke)							
	Amplitude (kA)			di/dt (kA/µs)	Rise time (µs)	Half peak width (µs)	Charge (C)	$\int i^2\, dt$ (kJ/Ω)
	Mean	Max	Min					
[9]	11.9	21.0	6.6		0.8[a]	39		
[8]	17.6	41.6	6.6		2.6	30.7		
[1]	33	44	22	195[b]	0.25	1.35	2.3	4.5
[7]	12	29[c]	4.7[d]	28	0.37	18	2.5	3.5
[10]	9.9	49	4.5.9	37.1	1.14			4.7

In general the impulse current of subsequent strokes show the following characteristics.

a. The peak value is few tens of kilo Amperes,
b. The derivative in the rising edge is few tens of kilo Amperes per micro second
c. The rise time is in the order of one micro second
d. The half peak width is few tens of microseconds
e. The action integral (energy per unit resistance) is few kilo Jules per Ohm

The IEC 62305-1 (2006) have made their recommendations for testing based on the current measurements done by [11] and [12]. The values given for each discharge event as per this tower based measurements is as given in Table 2 below.

Note that the values pertinent to the negative subsequent strokes of tower based measurements, in general, are in agreement with those pertinent to the negative subsequent strokes of triggered lightning measurements (although some parameters cannot be directly compared).

Henceforth, we adhere to the following reference, unless otherwise stated.

If less than 5% of the sample exceeds a certain value we call it the "extreme value"; and if less than 50% of the sample exceeds a certain value we call it the "representative value".

Table 2. Parameters of current waveforms pertinent to negative and positive lightning according to the measurements of [11] and [12] based on tower measurements. The information was consequently adapted by IEC Standards. Note that rise time given is 10%–90% of the peak value. The values of parameters other than those of the current amplitude are the representative values (50%). [a] less than 80% [b] less than 98%. Note that there is no information on positive subsequent strokes. This is due to the rarity of multiple stroked positive lightning (less than 1% of the positive lightning is multiple stroked).

Discharge Event	Impulse current (Short stroke)							
	Amplitude (kA)			Max di/dt (kA/µs)	Rise time (µs)	Total stroke duration (µs)	Charge ($\int i\,dt$) (C)	Specific Energy $\int i^2\,dt$ (kJ/Ω)
	50%	5%	95%					
Negative first stroke	20^a	90	4^b	24,3	5,5	75	4,5	55
Negative subsequent stroke	11,8	28,6	4,9	39,9	1,1	32	0,95	6
Positive stroke	35	4,6	250	2,4	22	230	16	650

2.2. LIVI

A lightning may induce voltage impulses in the conductors in the vicinity due to electromagnetic coupling. The amplitude and the profile of such voltage impulses depends on the peak value and peak time derivative of the lightning impulse current, proximity to the lightning, ground conductivity (propagation effects), length of the conducting line exposed, its orientation and termination, height of the line above the ground, branches of the line between the generation point and the victim etc. [13–17].

As it was reported by [14], in an isolated small house, the induced voltages in a de-energized power line (which is decoupled from the external supply) exceeded 100 V for a ground flash that struck 24 km away. The rise time of the induced voltage was typically less than a microsecond and the individual pulse width was typically a few microseconds. Several triggered lightning studies reveal that even at

very close range the pulse profile is similar. As per [16] at 145 m from a 682 m line the 10%–90% rise time and half value width of induced voltages for negative subsequent strokes have representative values 1.6 μs and 4.1 μs respectively. In the same study the investigators have recorded that the peak induced voltage varies from 8 kV to 100 kV for peak lightning current that ranges from 4 kA to 40 kA. Figure 2 depicts the induced voltage and the corresponding channel base current for a negative subsequent stroke [16]. The studies on both natural and triggered lightning by [17] show that the voltage induced in a 500 m long cable about few tens of meters (asymmetric locations) is in the range of few 10 s to few hundreds of kV with rise time and pulse width of fraction of a microsecond and few microseconds respectively. Similar experimental results have also been given in [18].

The theoretical work done by [19] and [20] reveals that the voltages induced at the midpoint of an isolated transmission line of length about 680 m, is nearly double exponential for near lightning. For lightning strikes at 40 m symmetrically away from the line, the induced voltage has a peak value of about 120 kV and the 10%–90% rise time is in the order of 0.1 μs. As the point of strike moves to 400 m away from the line, the peak reduces to about 50 kA and the rise time increases to by 2 to 3 times the value at 50 m.

These voltage pulses give rise to current waveforms which depend on the characteristic impedance of the path along which they travel. The rise time of such current waveforms cannot be much different from that of the induced voltage waveforms unless the current travels a long distance along the line so that the high frequency components will undergo selective attenuation [21].

The interaction of cloud lightning and discharge events of ground lightning that occur at cloud level has not been studied much in the literature. Bursts of electromagnetic pulses, pertinent to such cloud level events, have been observed at ground level [22]. It may be of interest to investigate how such pulse trains interfere with very low voltage (VLV) data transmission systems. Several studies reported in [22] show that in preliminary breakdown pulses (pulse trains that precede return strokes) recorded in Sweden and Denmark the maximum pulse amplitude is several times greater than that of the succeeding return stroke (such observation is not made in the PBPs measured in tropics). As it was observed in [14] the induced voltages due to such cloud flashes have amplitudes comparable with that of return stroke generated voltages pertinent to cloud to ground flashes (around 10–20 km away from the measuring site). However, one could expect the amplitudes of voltages induced by ground flashes to be much greater as the ground strike location reaches close range to the point

of observation (as the cloud flashes cannot be very close due to the height).

2.3. SPP

In the event of a ground lightning strike, the potential at the point of strike is raised to a very high value and decreases radially outwards. This is termed the Ground Potential Rise (GPR). The potential difference between two points in the proximity is called the step potential. In time domain the step potential at a given location (two close points) will be a transient for a lightning strike which we will refer as the Step potential Pulse (SPP).

The studies on triggered lightning by [23] reveal that SPP is almost identical in wave profile to the corresponding return stroke current at the channel base. Thus, the peak value of the SPP and the peak of the return stroke current shows a linear relationship. Figure 3 shows a return stroke current waveform of a triggered lightning (Figure 3(a)) and the corresponding step potential pulse (Figure 3(b)) across two electrodes separated by 0.5 m at 20 m from the strike point.

Theoretically, for a uniform hemispherical mass of earth around the point of strike the peak of the SPP should decrease following inverse square law (for a step distance much smaller than the radial distance to the point of concern). However, as per the limited data available (only at 10 m and 20 m), the study [23] observes that the relation is inverse distance, instead of inverse square distance. Understandably, they explained the discrepancy as due to the limited skin depth at lightning frequency spectrum.

The data given in [23] shows that for a current in the range of 20 kA the peak SSP is about 10 kV/m over soil of resistivity about 500 Ωm (the measurement has been done for two points separated by 0.5 m). With the correlations that they have observed, there can be SPPs in the order of 5 kV/m at 100 m from the strike for return strokes of currents exceeding 100 kA.

2.4. PSGT

Power system generated transients (sometimes generally called switching impulses, although they are only a sub-set of PSGTs) are due to various operations and accidents. Following are some causes of generating SI.

 a. Switching on/off large inductive and capacitive loads or re-energizing of power systems.

b. Arcing in the power system due to over voltages, transformer failures, grid switching etc.

c. Short circuiting at various stages of power distribution

Unlike LEMPs which are always externally generated, PSGTs can be generated either inside or outside of a given installation.

The profile and magnitude of a PSGT depends on both the source of generation and the path propagation from the point of observation to the source. The waveforms can have the shapes of ringing, double exponential, bi-polar or even chaotic. The damage that a switching impulse may cause depends on the steepness of the rising and falling edges, amplitude and the duration (energy content).

Most of the switching type PSGTs are oscillatory in nature. An oscillatory transient is an abrupt, non-power frequency change in the steady state condition of voltage, current, or both, that includes both positive and negative polarity values. The instantaneous value of current and voltage of such transient changes polarity rapidly.

The characteristic of an oscillatory transient is described by its spectral content (predominant frequency), duration, and magnitude. The predominant frequency of an oscillatory transient may reach as high as $500\,\text{kHz}$ [24, 25]. Figure 4 shows an oscillatory transient generated in a $34.5\,\text{kV}$ system when a capacitor bank is energized [24]. The transient can be passed into LV system mainly through magnetic coupling at the substations; even capacitive coupling and resistive coupling (due to insulation failure) is possible.
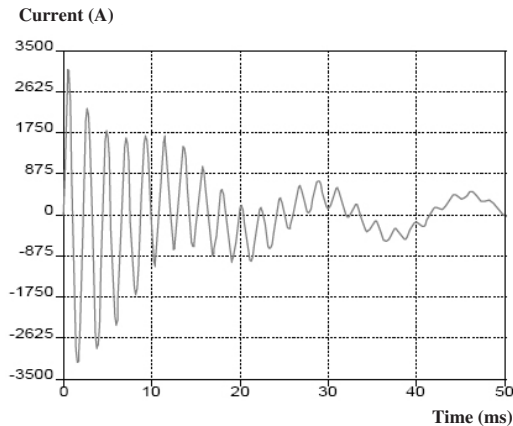
Figure 4. Oscillatory transient generated in a $34.5\,\text{kV}$ system when a capacitor bank is energized [24].

2.5. NEMP

The highly energetic Gamma rays (higher order MeV to GeV) released in a nuclear explosion will cause Compton scattering of the atmospheric molecules, thus a stream of law mass electrons will move away from the epicenter of explosion leaving behind the heavy positive irons. The moving charge will generate electromagnetic fields and also interact with ambient fields creating electromagnetic impulses [26–28]. The NEMPs generated by explosions occurring at high altitudes are also referred as High-altitude ElectroMagnetic Pulses (HEMPs). Henceforth, in most of the cases the transients that we refer as NEMPs are the HEMPs.

NEMPs that are generated by a nuclear explosion will have nanosecond scale pulse widths and rise times. The amplitude can exceed $60\,kV/m$, at locations directly under the explosion. Depending on the height and strength of the explosion, NEMPS may induce voltage pulses that are harmful to electronics within a radius of $500\,km$–$800\,km$ where the centre is taken as the point directly underneath the explosion [29, 30].

NEMPs are much faster pulses than LEMPs therefore; special defenses are needed in shielding the systems from them. The study [31] discussed in detail the behavior of different media for the penetration and transmission of NEMPs. The low frequency components of NEMPs will also be able to induce large currents and voltages in the long-distance communication and data lines. Unfortunately, many available scientific work on NEMPs do not reveal the actual characteristics of electromagnetic pulses, instead the studies at present are more inclined towards the aspects of defense and political risk assessment [32].

Over the years many theoretical studies have been done to investigate the similarities and differences of the interaction of LEMPs and NEMPs [30, 33, 34]. In many of these studies the comparison is done between NEMPs at long distance which are essentially plane waves (for small systems) and LEMPs at very short range (few meters to several tens meters away) of which the amplitude is inversely proportional to the distance. Studies done in [35] argue that due to the much higher rate of rise and higher peak of the NEMPs the induced effects of NEMPs should always be greater than that due to very near lightning; unless the lightning current is exceptionally high (such as in super bolts). By analyzing the Fourier spectra of LEMPs and NEMPs, the investigation described in [34] showed that at several frequency ranges the average lightning may cause more harmful induced voltages in small objects (such as aircrafts) than that is done by NEMPs. They justified their argument with information given in [36].

The study [33] showed that the comparison of the induced effects of LEMPs and NEMPs is much more complicated than that has been done in previous studies. Although the rate of change of electric field pertinent to subsequent strokes of triggered lightning is somewhat similar to that of NEMPs, the nonlinear response to NEMPs may not be the same as the nonlinear response to LEMPs. Furthermore, due to the large areas exposed to a NEMP (systems such as power grids and communication networks), the entire network may be stressed almost simultaneously. Also, in contrast to the event of a lightning, in the event of a nuclear explosion, an entire fleet of military aircrafts, ships, and missiles can be simultaneously exposed to NEMPs.

The most convincing information on the differences between LEMPs and NEMPs is given in [37]. This information is pertinent to experimental data on lightning to (or near) aircrafts and simulated experiments on the interaction of same aircrafts with NEMPs. It has been revealed that the rate of change of magnetic flux density on the surface of the aircraft and the total normal current density are $3750\,\mathrm{T/s}$ and $20\,\mathrm{A/m^2}$ for LEMPs and $40\,000\,\mathrm{T/s}$ $90\,\mathrm{A/m^2}$ for the NEMPs. The data clearly indicates that there is a marked difference between NEMPs and LEMPs.

NEMPs are most often simulated as double exponential waveforms. Figure 5 depicts a typical waveform that is commonly used to represent NEMPs [38].
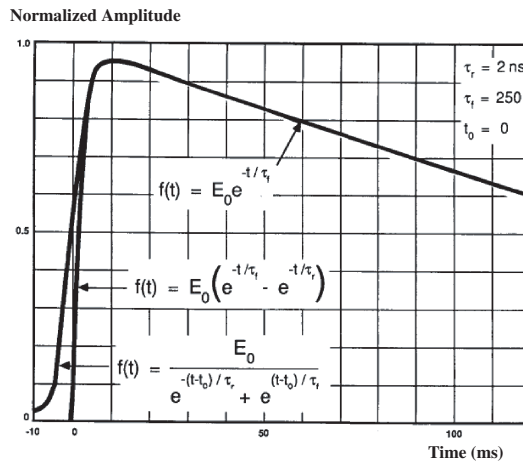
Figure 5. Waveform that is commonly used to represent NEMPs and the relevant parameters [38].

2.6. HPEM

Microwave sources may generate electromagnetic pulses in the GHz range that may induce voltages in electronics that can severely affect their performance. Such microwave emission may most often be intentional (for warfare, sabotage etc.) or sometimes be unintentional (due to unawareness, stubbornness or negligence). The investigations on HPEM were accelerated during the mid-90 s due to the prediction of greater usage of EM warfare. Although, not as comprehensive as one would expect, a considerable amount of information is available now on the public domain, in this regard, based on the work done for the last few years [39–43].

Basically the intentional microwave emission is classified into two categories. They are high-power microwaves (HPM) which are continuous high-energy signals of narrow bandwidth and variable center frequency, and Ultra-Wide Band (UWB) pulses which cover a broad frequency spectrum due to their fast rise times in the pico-second range and short pulse durations of a few nanoseconds. However, HPEM can be generated in several other forms as well [44].

Due to the large bandwidth UWB pulses have a higher chance of interacting with electronics, hence under studies on Intentional ElectroMagnetic Interference (IEMI), UWB pulses are investigated with greater interest [45–48].

A voltage test waveform that represents a UWB pulse is given in Figure 6(a) (adopted from [46]). Due to the very high frequency content UWB pulses are attenuated significantly as they propagate along transmission lines. Figure 6(b) depicts the variation of the UWB pulse (shown in Figure 6(a)) at different lengths of the cable along which it propagates. Note that with the distance of propagation the pulse amplitude is significantly reduced while the rise time and pulse width increases.

The study [49] discussed the urgent need of developing specific standards on HPEM. IEC Standard 61000-2-13 Ed. 1, 2005 [50] provides some comprehensive information on radiated and conducted effects of HPEM.

3. PROTECTION SCENARIO AGAINST TRANSIENTS

In this section, we discuss in details the protection methodology of equipment against the electromagnetic transients using Surge Protective Devices (SPDs). The transient protection of LV systems is done basically with one-port SPDs which are connected in shunt (phases to neutral and neutral to ground or phases and neutral to ground). In a coordinated SPD system the wire length from one SPD to
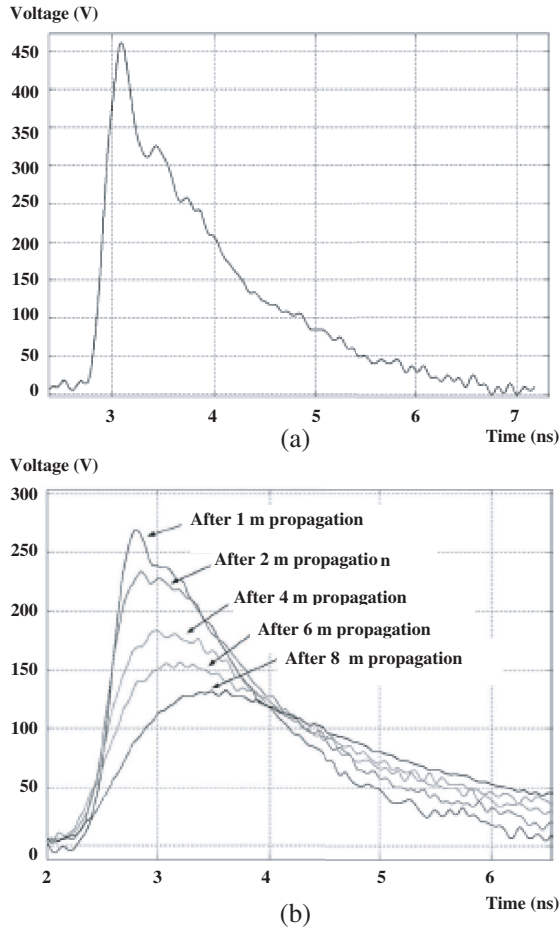
Figure 6. (a) A voltage test waveform that represents a UWB pulse. This pulse has a rise time in the order of 100 ps and a pulse width (FWHM) of about 1 ns. (b) The attenuation of the UWB pulse shown in igure-5 as the pulse propagates along the cable (adopted from [43]).

the other will provide the impedance (mostly in the form of inductance) to reduce steepness of the induced voltage waveform. In some devices, a coil has been inserted in between two parallel SPDs (en bloc) to simulate the inductance (together with parallel capacitors). These are sometimes called surge filters. It has been observed that in several products a non linear resistor (e.g., PTCR) has also been inserted in series with the power line (in between the two parallel SPDs) to absorb a part of the energy.

Basically, the main purpose of a SPD, irrespective of the wiring system (TNS, TNC, TNC-S and TT), is to divert both differential mode and common mode (not applicable to TNC) transients to ground. In TT system another important application is to equipotentialize (more accurately stating; to reduce the potential difference below hazardous level) the ground, neutral and phases in the event of a GPR.

In the event of current diversion, the downstream equipment will experience both common mode and differential mode transient potential differences due to the inherent impedance of the SPDs in the operational-mode and also due to the lengths of wire along which the transient travel wire lengths. In practice although the operation-mode impedance of a SPD is very small, due to the large amplitude and time derivative of transient currents, peak potential differences in the order of 1–2 kV is very common in most of the SPDs for transient currents of few tens of kilo Amperes. This is termed the "residual voltage" in the literature.

In a TT system, as the SPD between ground and neutral approaches low impedance mode, a current may flow from the ground of the utility to the transformer ground which is at a different potential (through the SPD). This will induce a voltage across the equipment ground and the neutral which will not be that high due to the long length of neutral wire from the utility to the transformer.

The following factors of SPDs are of prime importance in the protection of equipment

  a. The peak transient current that the SPD can handle
  b. The energy per resistance (action integral) and the charge that the SPD can withstand
  c. The number of sequential transients that will be withstood by the SPD
  d. How fast the SPD can respond to a transient
  e. The magnitude of the residual voltage that will be encountered by the downstream equipment
  f. The magnitude of the leakage current through the shut SPD, when the SPD is in non-operational mode
  g. In a low power quality situation; the maximum sustained over voltage (at operational frequency) under which the SPD will remain non-operational (high impedance mode).

To address these requirements the standards introduce several protection zones to the protection strategy. They are termed,

  a. Zone-1: The SPDs that will encounter direct lightning currents, induced voltage transients and SPPs.

b. Zone-2: The SPDs that will encounter induced voltages and let-through voltages of protectors in the Zone-1

c. Zone-3: the SPDs that will encounter induced voltages and let-through voltages of protectors in the Zone-2

It should be noted that SPDs which are meant to be at Zone-2 or 3 may subject to direct lightning currents and SPPs due to incorrect engineering practices (examples: Taking an outdoor power feeder line from an undesired point or haphazardly grounding more than one point of a given power network).

In the commercial literature, one may find the term "Current arrester" used for Zone-1 protectors and the term "Surge arrester" used for Zone-2 & 3 arresters.

In the manufacture's brochures, one can find a large number of classifications of surge protective devices based on various factors. (e.g., zone of application, impulse current rating, technology, mounting method etc.). In the scientific literature, SPDs are basically, divided into two categories, depending on their temporal response to a transient,

a. Voltage Switching Type or Crowbar type: The device undergoes an abrupt change from high impedance to low impedance at a certain value of the transient (e.g., Spark gaps, gas discharge tubes, thyristors, triacs etc.)

b. Voltage limiting type or Clamping Type: the device undergoes somewhat continuous change from high impedance to low impedance with the increment of the transient (Metal Oxide Varistors, zener diodes etc.)

Each of the above categories has its own advantages and drawbacks with respect to the response time, current handling capacity, let through voltage, leakage current and follow current etc. While attempts are made to improve each type of component individually, in the last few decades, SPDs are also made by cascading different types of components s, in order to compensate for the drawback of one type. Such devices are termed hybrid systems. Several such hybrid SPDs are available commercially. However, in the case of combining several components it will be very significant to have a proper coordination to avoid one component being overstressed.

4. TEST WAVEFORMS

As per the Section 2, apart from some switching impulses, most of the transients can be represented by a double exponential waveform with various decay constants. The Figure 7 depicts the basic waveform
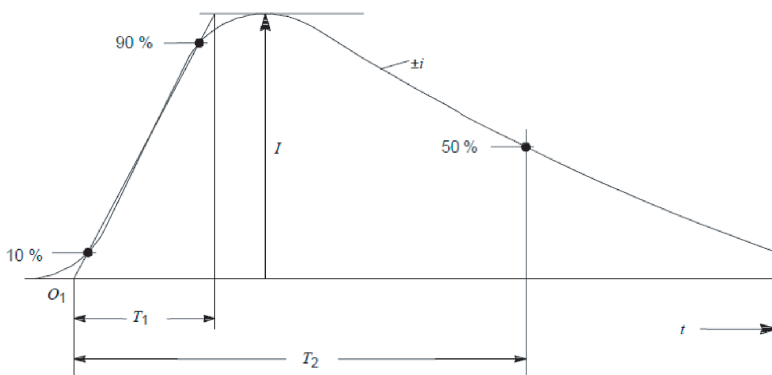
Figure 7. The basic waveform given in [1] to represent the lightning current.

given in [51] to represent the lightning current. The time T_1 is a representative value for the rise time of the waveform. The time T_2 represents the half peak width of the waveform. The values of T_1 and T_2 distinguish one test waveform from the other.

4.1. 10/350 μs Current Waveform

The current of first return stroke in a cloud-to-ground lightning will be represented by a waveform where T_1 and T_2 are 10 μs and 350 μs respectively (Figure 7). This is termed the 10/350 μs waveform.

A qualitative investigation on the available scientific data shows that the representative value of rise time of the negative first stroke and the positive stoke are approximately 50% and 200% respectively of T_1. Taking the large variation of lightning current waveforms into account, one may conclude that 10/350 μs test waveform is not a bad representation for both types of ground flashes.

Assuming that the half peak width of lightning current is approximately 50% of the total flash duration, one can see that the time T_2 is one order larger than the average half peak width of negative first strokes and 3 times higher than that of positive strokes. As per the data of [11] and [12], less than 5% of the negative flashes have total duration exceeding 200 μs. The same figure for the positive flashes is 2000 μs. According to these values, as far as only negative ground flashes are considered, apparently the 10/350 μs waveform seems to be unnecessarily long in duration. However, considered (a) the energy of long stroke is also included in the waveform and (b) the waveform covers a majority of the positive ground lightning, the parameter T_2 is

reasonable to represent the first stroke current. The waveform has high
significance for the testing of SPDs meant for the regions where positive
lightning density is high. For the information of the reader, in some
thunderstorms in Europe and winter storms in Japan the percentage
of positive lightning (out of all ground lightning) is as high as 35%–
40% [21, 52]. The long term data from lightning detection in Sweden
shows that about 12% of the ground flashes are positive [53]. On the
other hand, in tropics the same percentage is less than about 3% [22].
Note that IEEE/ANSI Standards do not recommend the testing of
SPDs for 10/350 μs waveform [54].

The amplitude of the current test waveform is to be determined
by the manufacturer as per the withstanding capability of the product.
As per the data of [11] and [12] less than 5% of the negative flashes
have peak current exceeding 90 kA. The same figure for the positive
flashes is 250 kA.

When lightning strikes a power line, the current will travel
in opposite directions in the line, with each component having
approximately half the original peak. Consider an overhead system
that has no branches of an overhead wiring system between the strike
point and the power entrance to the utility of concern. Thus, a 100 kA
strike to the phase wire will deliver 50 kA to the utility power entrance
in a case that there are no arcing between the lines.

For the 10/350 μs impulse with 50 kA peak value, we get the
approximate values of the charge and the specific energy (action
integral) as 25 C and 1.3 MJ Ω^{-1} respectively.

The charge of the above waveform covers 50% (as only half the
current flows towards the utility) of the extreme value of charge in the
first negative ground strokes (excluding the long continuing part) and
representative values of charge in positive ground strokes but 3 times
less than the 50% of extreme value [11, 12].

The action integral of the above 10/350 μs waveform is more than
4 times of the 50% of both the extreme values of action integral in the
negative first stroke and the representative value of that of positive
strokes [11, 12]. The 50% of the extreme values of the action integral of
positive strokes is about 5 times greater than the above value pertinent
to a 10/350 μs waveform with 50 kA peak value [11, 12].

The branching of current at the nodal points, the partial
discharges, the inter-line and side arcing and leakage through inductive
and capacitive coupling will even reduce the peak current that
approaches the entrance of a utility once a 100 kA strike hits a random
point of a LV power line.

4.2. 8/20 µs Current Waveform

As per the IEC standards SPDs at both Zone-1 & Zone-2 should be tested for the 8/20 µs waveform [54, 55]. In this wave form the profile is similar to that is given in Figure 1 with T_1 having a value of 8 µs and T_2 a value of 20 µs. As per the IEC standards the waveform simulates the current that will be resulted by induced voltages due to nearby lightning. As per [54] the same waveform represents the directly injected lightning current.

The information presented in Section 2 reveals that as per the voltages induced in cables at lightning at close range, recorded with high resolution measuring devices in the recent years, the rise time is a fraction of a microsecond and the width is few microseconds. If we assume that the current due to induced voltage also have the same wave profile, the 8/20 µs current impulse hardly represents the rise time of the actual negative subsequent strokes, unless a suitable decoupling inductance is introduced between the source and the SPD. The pulse width is reasonable as it covers a large range of lightning induced voltage waveforms.

For the Zone-1 protectors it is meaningless to conduct the testing for both 10/350 µs and 8/20 µs as once the device passes the test with the first waveform it will be totally immune to the second waveform.

As a waveform representing the injected lightning current, 8/20 µs waveform only represent negative subsequent strokes and totally beyond the characteristics of positive strokes.

4.3. 1.2/50 µs Voltage Waveform

The 1.2/50 µs voltage waveform has a profile similar to that is given in Figure 7 with T_1 and T_2 are 1.2 µs and 50 µs respectively. This waveform has been recommended in IEC standards to test the spark-over voltage of arresters that include crowbar type SPDs (at Zone-1 and 2). The spark-over voltage indicates the voltage at which the device impedance changes from a very high value to a very low value in the presence of a fast increasing wave front.

The spark over voltage of a SPD strongly depends on the rate of rise or the rise time. Therefore, in order to ensure that the protected downstream equipment is not subjected to a large voltage, the test waveform should have a rise time that resembles the rise time of induced voltages due to lightning. As per the information presented in the study, the rise time of the induced voltages due to subsequent strokes of close lightning, is about one order less. The rise time of NEMPs and HEMPs is about two orders less than that of the test waveform. Hence, the suitability of this waveform to assess the spark

over voltage of SPDs is somewhat questionable.

Zone-3 protectors supposed to be tested for a waveform which shows $1.2/50\,\mu s$ profile for open circuit voltage and $8/20\,\mu s$ profile for short circuit current. This is termed the combinational waveform which serves the assessing of both spark-over voltage and let-through voltage at the same time. The argument against the applications discussed above applies for this case as well.

4.4. Other Waveforms

The IEC Standards [51] describes a double exponential current waveform specified as $0.25/100\,\mu s$ to represent subsequent return strokes (of which T_1 is $0.25\,\mu s$ and T_2 is $100\,\mu s$). However, the waveform is not exclusively recommended to test the SPDs, citing "If SPDs are specified for the first short stroke threat, the subsequent short strokes cause no additional problems. If inductances are used as decoupling elements, the higher current steepness facilitates coordination between SPDs".

We would like to pay the attention to the following two observations on multi-stroked lightning.

  a. More than 50% of the multi-stroked lightning have multiple strike points at ground (strokes of the same flash hit more than one ground point) [56, 57];

  b. The inter-stroke interval can exceed even $500\,ms$ in some flashes [58, 59],

The first observation shows that a Zone-1 SPD can be subjected to a subsequent stroke without being exposed to the first stroke. The second observation reveals that there is a possibility of a Zone-1 SPD switching back to high impedance mode before the occurrence of the subsequent stroke. Thus, in both cases it is evident that the Zone-1 SPDs have a certain risk of exposing to subsequent strokes while they are in the high impedance mode. Therefore, the chances of the SPDs responding late to the impulse have a certain probability.

The IEC Standards [51] introduces a nearly rectangular waveform to represent the continuing current (long stroke) where the pulse width at 10% (T_{long}) is $500\,ms$. Note that the long stroke need not be considered for coordination purposes, thus it is insignificant for SPDs other than those at Zone-1. For Zone-1 SPDs, the additional stress factor, due to the charge and action integral, that is in cooperated with the long stroke is taken care of by the $10/350\,\mu s$ waveform. Therefore the long stroke waveform also is not recommended exclusively for the testing of SPDs.

5. DISCUSSION

A wide range of electromagnetic transients has been discussed in this paper. It is evident that depending on the source and coupling mechanism the total energy, average power and maximum transfer of power into a vulnerable system varies considerably. For the engineering convenience these effects are attributed to the rise time, maximum current derivative, peak of the impulse, half peak width, action integral, bandwidth etc.

As it was discussed the spectrums of these parameters have a wide range over different transients and even within the same type, especially in the cases of PSGTs and HPEMs. Hence it is evident that a surge protective device developed for the defense against one type of transient may not be effective against other types.

The analysis that we have conducted on marketing promotional brochures, shows that there are several surge protectors are introduced with the tag "all purpose transient protectors" or "wide spectrum transient protectors". These marketing promotional catalogues vaguely state that the product can protect equipment from all known transient ranging from NEMPs to sub cycle switching impulses. However such an all purpose protector should;

 a. have a response time of less than about one nanosecond
 b. be able to withstand impulse peak currents of over 100 kA
 c. be able to handle large energy components that spread over few nanoseconds to several milliseconds
 d. be able to handle charge in the order of several coulombs

It is highly unlikely that any of the products that we have come across possess or tested for all the above characteristics. Instead, more than 90% of these products are tested only for the current waveforms $8/20\,\mu s$ and $10/350\,\mu s$ and voltage waveform $1.2/50\,\mu s$. These waveforms are basically specified to test the protective devices that are designed to safeguard equipment against lightning transients.

The electrical system and related equipment of a LV system may be subjected to a number of transients from various sources. However, the general trend of the commercial and industrial sector is to concentrate on lightning related transients in the case of surge protection. The IEC Standard 62305 (2006) series and related testing standards are based on the protection against lightning transients. The information given in this paper clearly shows that SPDs tested for lightning transients may capable of handling the energy content and charge of other transients such as NEMPs and HPEMs however, the rise time of the standard test impulses is much longer than that of

these pulses. The lightning test impulses also do not represent the repeated stresses applied by mostly oscillatory switching transients.

Lightning transients that may affect electrical systems can be classified as follows based on the impulse characteristics.

  a. First negative stroke,
  b. Subsequent negative stroke
  c. Positive stroke
  d. Continuing current and M component

In a properly designed and installed surge protection system SPDs only in Zone-1 are exposed to direct lightning currents. Therefore, only Zone-1 SPDs are needed to be tested for direct current impulses. In a TT wiring system it should be noted that the SPDs at Zone-1 are not only subjected to the lightning currents that are injected into the lines. In the event of a lightning close to the utility ground, a sizable current may pass through the earth to neutral SPD and flow back to the ground at the substation (at a different potential).

The continuing current together with M component will stress the Zone-1 SPD due to its energy content (action integral) and the charge which are inter-dependent parameters. The effects of both of these parameters of continuing current are incorporated in the $10/350\,\mu s$ impulse. Thus, the $10/350\,\mu s$ waveform is a fairly reasonable simulation to represent the lightning effects at Zone-1. However, in some cases of intense lightning, especially those with positive polarity, it has been observed that currents of few tens of kilo amperes can flow for over 100 milliseconds draining hundreds of Coulombs to ground. In some cases the value may even exceed 850 C [60, 61]. Such cases are not represented by the $10/350\,\mu s$ impulse even at the maximum value $(200\,kA)$ available at present in laboratories.

The sub microsecond rise time of subsequent strokes is poorly represented by the $10/350\,\mu s$ impulse. The studies on the feeding of triggered lightning currents in to line networks through direct coupling show that the rise time of negative subsequent strokes remains sub microsecond region even after traveling over $100\,m$ [62, 63]. As there is a very high probability that Zone-1 SPDs are subjected to subsequent strokes while they are in high impedance mode, the impulses may pass into downstream equipment by the time the SPD switch into the low impedance mode. This drawback is highly significant in the case of crowbar devices.

This study also reveals that $8/20\,\mu s$ impulse recommended by IEC standards [51] for SPDs at Zone-1 (in addition to $10/350\,\mu s$ impulse) and other two Zones and by IEEE/ANSI Standards [52] for all Zones does not represent either the rise time or half peak width of any of the

recorded lightning current impulses mentioned above. The waveform also does not represent current waveforms due to induced voltages caused by nearby lightning or currents that may flow through the SPDs due to earth potential rise.

The 1.2/50 μs voltage impulse represents the pulse width of induced voltages due to lightning however; the rise time is nearly one order larger than that of the induced voltages due to subsequent strokes. This, in turn leads to a large voltage stress on the protected equipment before the SPD changes to low impedance mode. The waveform has no resemblance in the front edge with either NEMPs or HPEMs of which the rise time is two orders less. Even the propagation of these pulses through transmission lines for a considerably long distance will not increase the rise time to an extent closer to 1.2 μs. Further studies on LV system generated switching impulses should be done in order to assess the suitability of 1.2/50 μs impulse to represent damped oscillations generated by switching operations.

As per the above discussion we make the following recommendations for the improvement of Standards on surge protective devices that are meant for protecting equipment against lightning generated transients and also to develop ethics of surge protection industry.

1. The 8/20 μs current impulse should be discarded from the standards for the testing of SPDs at all zones.

2. The 10/350 μs impulse should be modified to have a rise time in the order of a fraction of a microsecond. For an example we propose 0.5/350 μs impulse.

3. The proposed 0.5/350 μs impulse should be recommended for the testing of SPDs at all Zones with reducing peak value from Zone-1 to Zone-3.

4. The rise time of the test voltage impulse should be reduced to sub-microsecond rage. For an example we propose 0.5/50 μs impulse in the place of 1.2/50 μs impulse

5. The standards should indicate the limitations of the recommended test impulses, especially in the application for the SPDs meant to be used in regions with high density of positive lightning

6. The manufacturers should not use the term "Transient Protectors" in general or give the impression to the customer that their SPDs provide protection from all types of transients, in their literature, when the SPDs are tested only for lightning test impulses.

7. Both scientific and industrial sectors should make greater effort to understand the nature of LV system generated transients (switching, fault, short circuit or breakdown generated impulses) and incorporate them into the lightning protection standards.

6. CONCLUSIONS

A comprehensive study has been done on the different types of electromagnetic transients with respect to their sources and coupling mechanisms. These transients may affect low voltage electrical systems due to their rapidness in rising to the peak value, the peak value energy content and the rate of dissipation of energy. These characteristics of the transients discussed; lightning, switching, nuclear and intentional microwave impulses; are substantially varies in a wide range. Hence the impacts of each transient on equipment and systems also differ from transient to transient. The analysis shows that transients have a wide range of rise time, half peak width, action integral etc. with respect to both source and coupling mechanism. Hence, transient protection technology should be more specific with regard to the capabilities of the protection devices.

We briefly discussed the types of SPDs that are commonly available, and how transients are simulated in the Standards for testing SPDs. It has been shown that the most refereed standards in this case are Lightning Protection Standards.

The test waveforms recommended by the IEC 62305 and other major Standards are only partially representing the possible lightning generated transients which have been understood through a large number of studies done in the last few decades. There are special concerns on the fast rise times of currents and induced voltages of negative subsequent strokes and the excessively high energy transferred during some positive lightning.

According to our observations and analysis we propose several major modifications to the test waveforms recommended by IEC 62305 (2006) series of standards. The other standard committees may follow the same recommendations on testing SPDs in their respective regions.

ACKNOWLEDGMENT

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