Transients that may affect low voltage electrical systems

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TRANSIENTS THAT MAY AFFECT LOW VOLTAGE ELECTRICAL SYSTEMS

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ABSTRACT

A comprehensive review has been done on the types of 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.

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 for "electrical transients", which is the scope of this paper.

A transient is a sharp increase in the voltage or current of 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 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). One of the purposes 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 six types of transient sources 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 (eg. 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 first return stroke current is totally different to that is expected in natural lightning due to the presence of the conducting wire through which the current flow.

In most of the recorded currents the initial pulse, which is in the microsecond scale is followed by a small current 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 ramp or plateau followed by exponential decay, which last for few tens to several hundreds of milliseconds [1-5]. It is often observed that humps are embedded on the continuing currents, termed M components. These almost symmetric swells have rise times of about few hundred microseconds and amplitude from few hundreds to about thousand Amperes [4, 6-8].

For the ease of analysis and testing purposes the two parts are separately referred; the initial impulse current is called 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 near by 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 has 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 [9]. 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 2b and Figure-3a 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, 9].

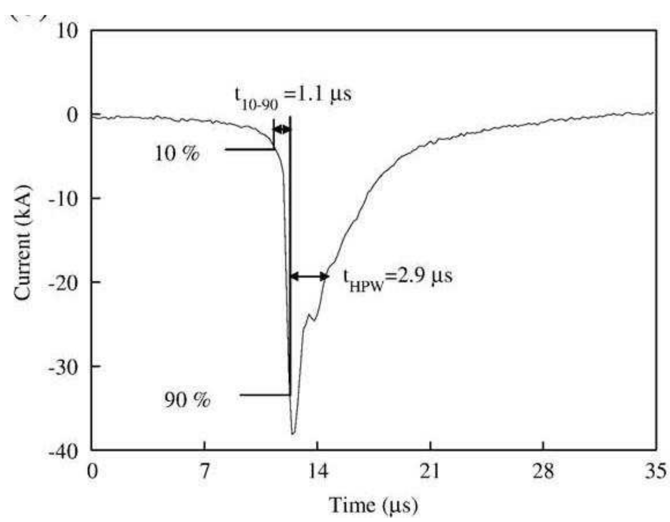


Figure-1: The channel base current waveform for a negative subsequent return stroke observed in a triggered lightning session in China [9]. The figure also shows the 10% - 90% rise time and half peak width.

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.

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
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

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					
[10]	11.9	21.0	6.6		0.8[a]	39		
[9]	17.6	41.6	6.6		2.6	30.7		
[1]	33	44	22	195[b]	0.25	1.35	2.3	4.5
[8]	12	29[c]	4.7[d]	28	0.37	18	2.5	3.5
[11]	9.9	49	4.5.9	37.1	1.14			4.7

Table-2: Parameters of current waveforms pertinent to negative and positive lightning according to the measurements of [12] and [13] 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

The IEC 62305-1 (2006) have made their recommendations for testing based on the current measurements done by [12] and [13]. 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 can not be directly compared).

Note that henceforth we stick 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".

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 and 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 line above the ground, branches of the line between the generation point and the victim etc. [14-22]

As it was reported by [17], 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 [23] 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 they have recorded that the peak induced voltage varies from 8 kV to 100 kV for peak lightning currents varying from 4 kA to 40 kA. Figure-2 shows the induced voltage and the corresponding channel base current for a negative subsequent stroke [23]. The studies on both natural and triggered lightning by [24] shows that the voltage induced in a 500 m long cable about few tens of meters (asymmetric locations) is in the range of few 10s 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 [25].

The theoretical work done by [26] and [27] reveals that the voltages induced at the mid point 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 can not 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 [28].

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 [29]. It may be of interest to investigate how such pulse trains interfere with very low voltage (VLV) data transmission systems. Several studies reported in [29] 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 several studies [16, 17] 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. However, one could expect the amplitudes of voltages induced by ground flashes will be much greater as the ground strike location becomes closer to the point of observation (as the cloud flashes can not be very close due to the height).

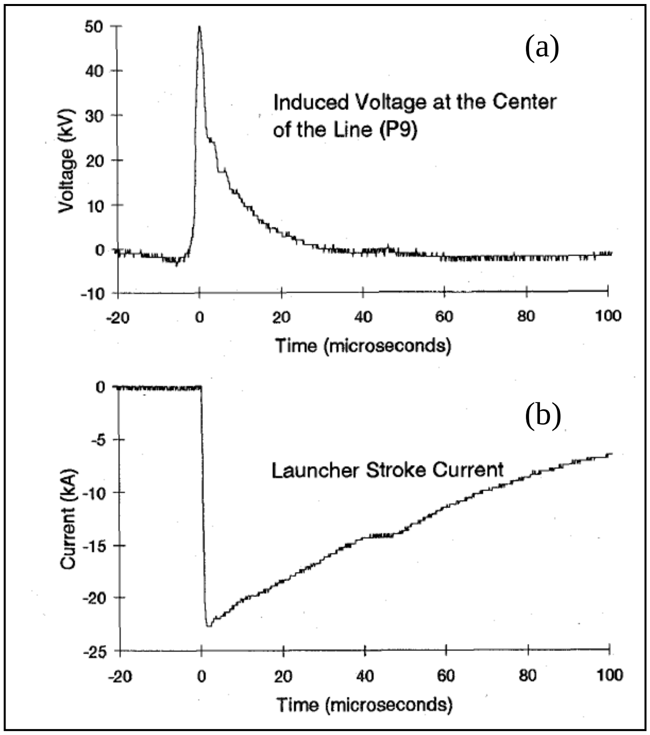


Figure-2: (a). The induced voltage at the centre of a 682 m long line for a triggered lightning subsequent stroke struck at 145 m away from the line, (b) The corresponding stroke current [23].

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 as 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 term as the Step potential Pulse (SPP).

The studies on triggered lightning by [30] 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 [30] observe 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 [30] 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 Ω m (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 part 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 system
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.

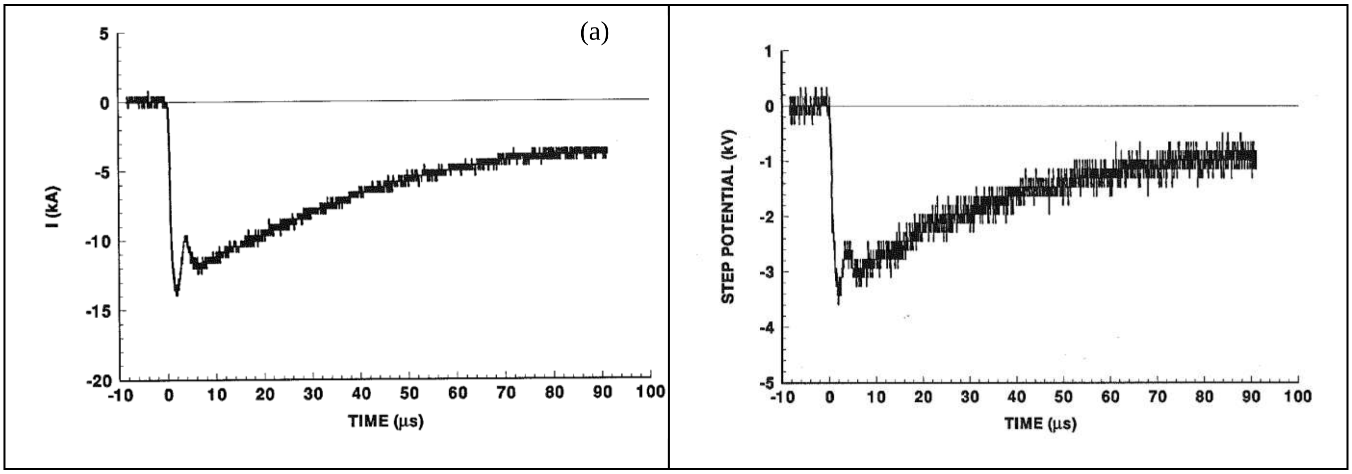


Figure-3: (a) The channel base current waveform for a negative subsequent return stroke observed in a triggered lightning session (b) the corresponding step potential pulse across two electrodes separated by 0.5 m at 20 m from the strike point. [30]

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

Most of the switching type PSGTs are oscillatory in nature. An oscillatory transient is a 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.

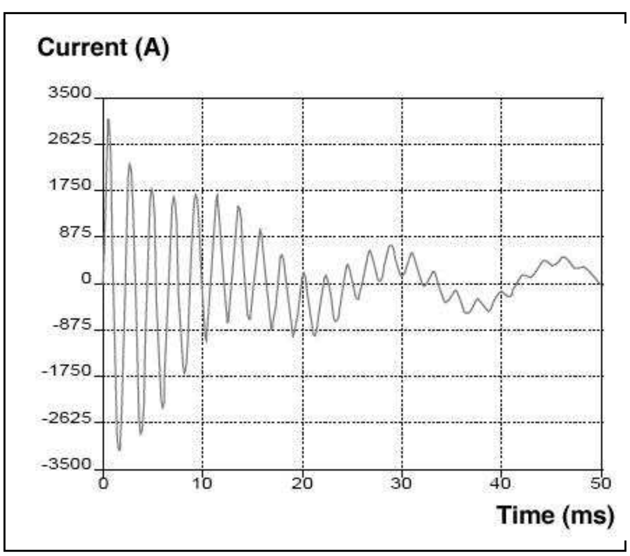


Figure-4: Oscillatory transient generated in a 34.5 kV system when a capacitor bank is energized [31]

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 kHz [31, 32, 33]. Figure-4 shows an oscillatory transient generated in a 34.5 kV system when a capacitor bank is energized [31]. The transient can be passed into LV system through magnetic coupling at the substations.

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 [34-36]. 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 that 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 [37-39].

NEMPs are much faster pulses than LEMPs therefore; special defenses are needed in shielding the systems from them. The study [40] 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 [41].

Over the years many theoretical studies have been done to investigate the similarities and differences of the interaction of LEMPs and NEMPs [39, 42-45]. 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 [44-46] argue that due to the much higher rate of rise and higher peak of the NEMPs the induced effects of NEMPs should always be always 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 [43] showed that at several frequency ranges the average lightning may cause more harmful induced voltages in small objects (such as air crafts) than that is done by NEMPs. They justified their argument with information given in [47].

The study [42] 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. Further more, 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, unlike in 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 [48]. 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 T/s and 20 A/m^2 for LEMPs and 40 000 T/s 90A/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 [49].

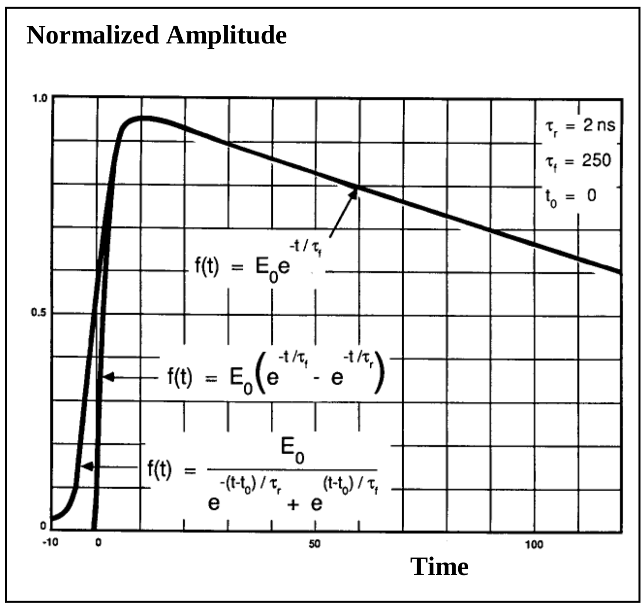


Figure-5: Waveform that is commonly used to represent NEMPs and the relevant parameters [49]

2.6 HPEM

Microwave sources may generate electromagnetic pulses in the GHz range that may induce voltages in electronics that may 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-90s due to the prediction of greater usage of EM warfare and a considerable amount of information has been available on the public domain for the last few years [50-58].

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 [59].

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 [60-64]

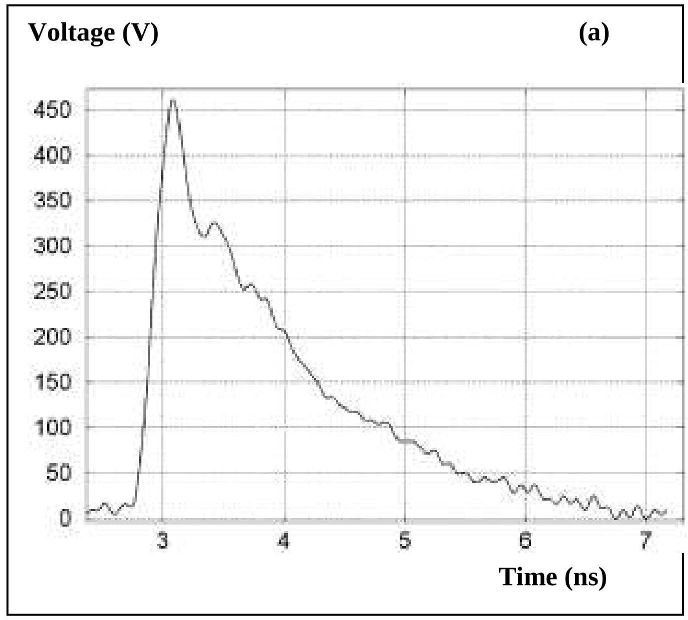
A voltage test waveform that represents a UWB pulse is given in Figure-6a (adopted from [61]). Due to the very high frequency content UWB pulses are attenuated significantly as they propagate along transmission lines. Figure-6b depicts the variation of the UWB pulse (shown in Figure-6a) at different 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 [65] discussed the urgent need of developing specific standards on HPEM. IEC Standard 61000-2-13 Ed. 1, 2005 provides some comprehensive information on radiated and conducted effects of HPEM.

3. 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. 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.



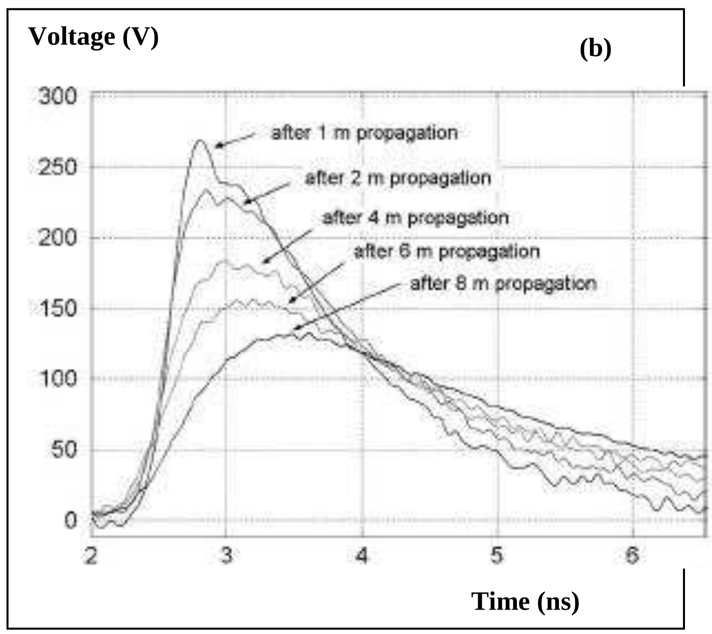


Figure-6: (a) A voltage test waveform that represents a UWB pulse (adopted from [58]). This pulse has a rise time in the order of 100 ps and a pulse width (FWHM) of about 1 ns. (b) The attenuation of the UWB pulse shown in igure-5 as the pulse propagates along the cable (adopted from [58]).

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, above 90% of these products are tested only for the current waveforms 8 / 20 µs and 10 / 350 µs and voltage waveform 1.2 / 50 µs. These waveforms are basically specified to test the protective devices that are designed to safeguard equipment against lightning transients.

4. 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.

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