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State of Research on Effects of Cloud to Ground Lightning Transients on High Voltage Polymeric Insulated Power Cables

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ABSTRACT

Lightning continues to possess threats to the reliable supply of electrical energy by causing damages to electrical equipment. Lightning transient causes outages either by directly hitting electrical equipment or by the electromagnetic interference induced by it upon hitting the ground near to the equipment. An electrical equipment which is witnessing a rise in application over the years are the insulated power cables. Use of these cables are not only confined to transferring electrical energy over distances but they are also used as transformer winding in a type of transformer pioneered by ABB called powerformers. Using XLPE insulated power cables as a case in point, the present study seeks to unravel the trajectory of research undertaken so far in this area of transient behaviour of insulated power cables against lightning transients. In particular, attention has been focused on the response of insulated power cables against non-standard lightning transient voltage waveforms. This review brings to the light that while transients response against standard 1.2/50 µs lightning waveform is relatively well studied but more work needs to be further undertaken to fully appreciate the behaviour of insulted power cables against the non-standard lightning transient waveforms which are more prevalent in actual field.
Keywords: High voltage transient analysis, non-standard lightning transient voltage waveform, power cables

Introduction

Lightning is electric discharge in air and consists of inter-cloud, intra-cloud, cloud-to-air and cloud-to-ground transfer of energy through the flow of current accompanied by thundering and other phenomena. The first three types constitute about 75% of all lightning flashes and do not involve ground [1]. The last category involving ground represent about one-fourth of all lightning flashes and is of interest to us as it results in the deleterious effects on electrical equipment and also has been studied much [2]. Though there are various schemes of lightning protection but none of them provides a foolproof protection mechanism against lightning related outages [1, 3]. Additionally, lightning study is challenging due to its random nature and its complex discharge mechanism. The process of lightning has not yet been understood completely. Lightning induced overvoltages are not only detrimental to over ground electrical equipment but also to underground cables [4]. As such, it is imperative that the protection schemes against lightning are made more robust which, in turn, warrant better understanding of the effects of lightning transients on insulation characteristics of various electrical equipment.

Modern civilization stands on the foundation of uninterrupted and reliable supply of electrical power. This necessitates that the overall system and the motley of individual equipment employed for achieving resilient supply of electric power function reliably. Power cables are one such component of electrical system employed for transporting electrical energy over short, medium, or long distances and their application has ballooned over the years. With an ever expanding use of power cables and predominantly cross-linked polyethylene (XLPE) insulated cables [5, 6] for not only transferring power but for linking various electrical components, it is imperative that they serve their design life with fidelity. Using transient characterization of XLPE insulated power cables as a case in point, this study seeks to review the trajectory of

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research undertaken so far in the response of insulated power cables against lightning transients.

Insulation integrity of an electrical system against lightning overvoltages is characterized by subjecting the same with the standard lightning voltage waveform having a front time of 1.2µs ±30%, tail time of 50µs ±20% and a tolerance on the peak voltage of ±3% [7]. However, in practice there exists, in addition to the standard lightning voltage waveform, various types of complex waveforms having varied front and tail time and even oscillatory in nature which affect the electrical system in actual field [8-10]. These so-called non-standard lightning voltage waveforms are more prevalent and occurs naturally during lightning or are generated due to interaction of traveling transients with various components of an electrical system by reflection, refraction, attenuation, and superimposing of the impulse. Therefore, to achieve better insulation rationalization without compromising the reliability and safety, there is a need to review the standard test voltage waveform for a more holistic understanding and characterization of power equipment in actual field. In this work we have attempted to present a comprehensive review of the research on these more prevalent non-standard lightning waveforms and their effects on insulated power cables.

A glance at the available literature in this field reveals that lightning transient studies on electrical equipment have mostly focused on overhead lines and transformers [11-18]. As the application and usage of insulated power cables is increasing and for higher voltages, correlation between power cables and lightning transients have to be studied. But very few have studied its behavior against the more prevalent non-standard lightning transient wave shapes. This paper first trace the path of research on lightning transients in general followed by that for insulated power cables. Thereafter, we have attempted to look at the characterization of XLPE cables against lightning transients with an emphasis on the various non-standard lightning waveforms that are more prevalent in actual field.

Cloud-to-Ground Lightning Transients

Lightning has been observed and revered by mankind since the dawn of history but its effects on major electrical utility equipment was first experienced in 1926. A transformer of the Walenpaupack-Siegfried 220 kV line in Pennsylvania broke down due to lightning in that year and heralded the beginning of lightning transient analysis of high voltage power equipment [14]. The front and tail time of the measured lightning impulse current waveform at that time was 1 *µ*s and 40 *µ*s [15] respectively and historically [8] it varied from region to region as they, respectively, were 0.5/50 µs for VDE Standard, 1/50 µs for IEC Standard, and 1.5/40 µs for AIEE standard before the presently agreed standard test lightning voltage waveform of 1.2/50µs proposed by IEC in 1962 [9,13]. That lightning induced overvoltages in electrical systems have detrimental consequences on the reliability and safety of the system to serve its purpose properly is uncontested. So the reliability of insulation system requires that overvoltages due to lightning are predicted accurately.

Fast transient phenomenon such as lightning results in complex behavior of grounding topology and has the potential of degrading or destroying the protection given for the system and [19] notes that this aspect is usually not considered and caution against either assumming constant values of grounding resistance or ignoring it altogether. Studies on grounding systems are usually undertaken employing quasi-dc analysis wherein modeling are based on classical circuit theory and performances under such low frequency systems are well documented [20, 21]. But grounding systems under high frequency regime such as during lightning transients are different and introduces nonlinear ionization of the earth and consequently quasi-static theory is not effective nor fully appropriate for high frequency analysis. Grcev and Heimbach in their magestrial paper [21] reports that parameters such as frequency, soil resistivity, shape of current impulse, location of feed point, effective area of ground grid, and depth of ground grid all have varying degree of influence on the characteritics of grounding systems under high frequency lighnting transients.

Lightning radiated electromagnetic fields depends on many factors which includes soil properties [22] upon which it strikes causing indirect disturbances on systems and moderate or high soil resisitivity regions experience outages on transmission lines primarily due to backflashover [23]. Actually soils are nonhomogeneous and during transient studies this fact is accounted for by employing multi-layer or two-layer soil model and using the later [24] observed that upper layer depth and reflection coefficient parametrs of soil have significant influence on the performance of ground rod both at low and high frequencies. Changing seasons alter soil properties by changing the resisitivity of surface layer thereby influencing the grounding systems [25] and raining season results in higher touch voltage but the step voltage remain within the safe limit. Additionally, during extreme cold conditions the touch voltage increases sharply because the thickness of the freezing layer exceeds the burial depth of the grounding system which increases soil resistivity.

To test electrical equipment against lightning transient overvoltages, its withstand capacity is measured by subjecting them with the standard lightning voltage waveform as shown in Figure 1. However, as can be seen from Figure 2 and as reported in various works [8-10], actual lightning transients have varied waveforms and the standard lightning wave shape seldom occurs in nature or on the utility system. It has been argued [8-10, 12, 13, 16-18] that the presently agreed standard 1.2/50 *µ*s lightning waveform need to be revised to take into consideration the advancement achieved in the field of lightning transient studies and the actual measured lightning waveforms in nature as well as on power equipment.

Given the prevalence of the so-called non-standard lightning transient voltage waveforms in actual field than the traditional

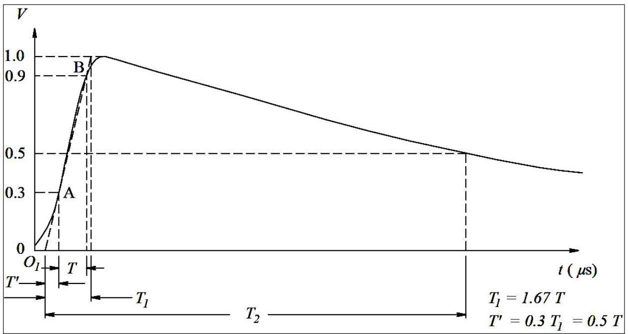

Figure 1. Standard lightning impulse voltage waveform [7]

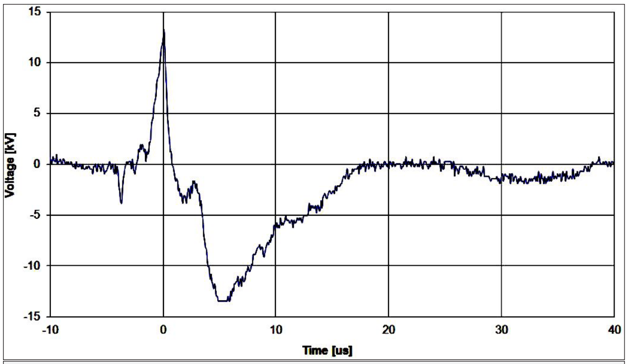

Figure 2. Typical lightning surge waveform observed at actual substations [26]

1.2/50 μs standard waveform, Lightning and Insulator Subcommittee of the T&D Committee of IEEE formed a Task Force 15.09 on Non-standard Lightning Voltage Waves to compile the works that has been undertaken in this area till the year 1994 [8]. This Task Force carried out an exhaustive and extensive review on relevant works from the repository of research that have been undertaken in the studies of lightning effects on electrical systems and equipment. The Task Force observes that further work needs to be undertaken for a better understanding of the behavior of electrical apparatus under non-standard lightning voltages, particularly those with front times in the nanosecond regime. Shigemitsu Okabe [17] himself and researchers [13, 16, 17] under his direction and in collaboration with him undertook studies on the interaction of non-standard lightning voltage waveforms on gas insulated substation (GIS) and its paraphernalia and observes that insulation rationalization could be organized in better ways to achieving economy of cost without compromising reliability of insulation system by using non-standard lightning voltage waveforms as test voltage instead of the standard waveform of 1.2/50 μs. Thus, a revision of the standard lightning waveform is advisable for a more realistic correlation between lightning transients and various power equipment.

Since the actual lightning voltage transient is a combination of many complex waveforms, it is not feasible in practice to generate and test power equipment with all these waveforms. To account for this an analytical method known as disruptive effect (DE) model is used for analyzing the effects of non-standard waveforms on an insulation system [18] and is defined as:

$$DE = \int_{t_0}^{t} [V(t) - V_0]^K dt$$

where $V(t)$ is the applied voltage and t_0 is the first instant at which $V(t) > V_0$; V_0 and K are constants fixed by the standard test voltages. The DE method based on equal area criterion provides useful results only in cases of unidirectional voltage waveforms and is not reliable for non-standard waveforms having bidirectional nature. This issue was addressed by [27] and the authors therein proposed and validated their unconditionally sequential approach using a power transformer to characterize insulation strength of power equipment against bidirectional oscillating voltage waveforms. Studies undertaken using these theoretical tools have also yielded the fact that the non-standard lightning impulse waveforms have more impact on power equipment and employing them in insulation rationalization merits more studies.

Polymeric Insulated Power Cables

A power cable connects two or more electrical apparatus and fundamentally consists of a conductor surrounded by an insulator. With advancement in technology, the core conductor of a power cable is surrounded not only by a single insulator but also by various other layers of materials each serving a different purpose and function. Use of wire with insulation started in 1812 in Russia for exploding mineral ore [28]. Thereafter, application of cables for distribution of electricity first started in 1870-80 in Paris and London [28]. Since then, much progress has been made in cable technology in terms of manufacturing them economically and their application for higher voltages. Initially the majority of underground power cables were of fluid-impregnated-paper-insulated type and after the development of polyethylene in 1930s, polymer based insulation cables came into use. However, it was only after Al Gilbert and Frank Precopio of the General Electric Company developed the cross-linked polyethylene (XLPE) insulation in 1963, proportion of insulation used for power cables titled toward solid polymers.

Various derivatives of synthetic polymers such as PVC, XLPE, EPR, etc. are widely used for power cable insulation. Choice of a particular insulation material depends on the purpose for which the cable would be used and also on the environment it would be subjected to. Table 1 highlights few of the properties of some insulation material candidates revealing that XLPE has overall functional features as compared to other materials.

Although there are various insulating material candidates for power cables each with certain advantages as well as disadvantages over the others, crossed-linked polythene (XLPE) is one such insulating material, which has found wide acceptance use across a broad spectrum of electrical apparatus due to its overall attractive features as compared to others [5, 6]. XLPE is also

Table 1. Properties of various polymeric insulation material [5]

Properties	PVC	PE	XLPE	EPR
Density (g/cm^3)	1.2-1.5	0.9	0.92	1.2-1.4
Tensile strength (MPa)	10-25	12-15	12-19	9-12
Elongation, %	150-350	500-700	500-600	250-350
Dielectric Constant	5-9	2.3	2.3	2.5-3.0
Dissipation factor at 20ºC, %	4-12	0.03	0.03	0.16-0.3
Maximum Operating temperature, ºC	60-75	75	90	90

Table 2. Electrical aging mechanism of cable insulation [33]

Aging Factor	Aging Mechanism	Effects
AC Voltage DC Voltage Impulse Voltage	Partial Discharge	Erosion of insulation
	Electrical Treeing	Partial Discharges
	Water Treeing	Increased losses
	Dielectric losses and capacitance	Immediate failure
	Charge injection	Increased temperature and thermal aging
	Intrinsic breakdown	
Current	Overheating	Increased temperature, thermal aging and thermal runaway

being used as a base material for future novel insulation material by adding in it various additives like nano particles and the likes [29, 30]. It is, therefore, unlikely that the use of XLPE and for that matter other polymer based insulation materials will completely dwindle in the future.

Transfer of electrical energy employing insulated cable are increasing and many projects involving power cables and at higher voltages are coming up at different regions of the world particularly across Europe. Cables are also finding wide application in high voltage direct current(HVDC) technology and as links between off shore and mainland utilities and their use will only increase with each passing year [31, 32]. With these increase in application there is an increase in the probability of their failure and as such, factors causing premature aging of power cables needs thorough study to mitigate their effects. Table 2 reveals that a factor which causes or accelerate aging of polymeric insulated cables is overvoltage induced by lightning transients. Therefore, it is imperative that characterization of polymeric insulated power cables along with its accessories against lightning transients is studied and understood to achieve optimum protection.

Transients Analysis of Power Cables

Polymeric insulated power cables and insulation system in general deteriorates due to many reasons. Electrical, thermal, mechanical as well as environmental factors individually or in combination contribute to the weakening or complete damage of insulation system [33, 34]. This paper is concerned with the electrical factor focusing on lightning induced transient overvoltages which even if do not immediately result in the breakdown of insulation, can always accelerate the aging thereby adding to the deterioration of insulation. The use of power cable for ever increasing voltage and longer distances is increasing with each passing year and this makes it susceptible to various factors that may hinder its reliable performance. Both lightning as well as swtiching transients have effects on power cables and this section review the interaction of cables against lightning transients.

Compared to overhead lines that consist only of the conductors, cables have much more complex structures owing to various layers it has over the core conductor and consequently require much more rigorous analysis. Lord Kelvin in 1854 was the first to initiate a transient voltage analysis by deriving the Kelvin Arrival Curve to express distortion of a signal along a cable while investigating wave propagation characteristics on the then planned Trans-Atlantic telecommunication cable [16]. Behavior of transients due to energization of cables is determined by many factors [35] including the the energizing agent (type of waveform) and the response of the cable (structure and material component of cable). Knowledge of the attenution behavior of power cables is required for overvoltage protection of the same. Over the years power cables are being subjected to various voltage shapes other than the usual sinusoidal votage [36] and insulation behavior of eletcrical system depends not only on the amplitude but also on the waveshape of the voltage [18] thus warranting that behavior of cable against these voltage waveforms is studied.

Power cables have undergone tremendous transformation over the years and various layers are added to the main central conductor serving different purposes. Semiconducting screens are one such layer used in cables to reduce electric field stress and [37] analyzed its effects on transient characteristics and wave propagation of cables observing that cables with semiconducting screens attenuates the transient voltage more and also its oscillation becomes greater than those without the semiconducting screens. Gustavsen and Sletbak in [38] observes that by applying sheath-armor bonding at regular intervals or using semiconducting layer between the two, transient voltages between the sheath and the armor in cables can be restricted to a reasonable level. Since power cables are concentric and also accompanied by other cables in practice or by design (three core cables), skin as well as proximity effects have consequence on their behavior. Exploring proximity as well as skin effects in power cables, [39, 40] notes that in addition to having a considerable influence on sheath voltages, proximity effect augments the velocity, attenuation, and surge admittance of inter-sheath.

Insulation design of cables are depended on the voltage surge the cable is subjected to and during their operating lifetime, cable insulations are subjected to lightning impulses and using a lightning impulse of 1.2/40 μs, [14] observed that the breakdown strength of high density polyethylene is reduced due to repetitive application of lightning impulses. Also high temperature superconductors (HTS) or superconducting cables are not immune to lightning transients and [41] unveiled its performance against lightning current injected into the outermost conductor when lightning strikes the ground near the cable. Tower footing impedance plays an important part in the response against lightning surges but measurement of its value possess challenges particularly due to lack of dedicated instrument. As a result tower footing grounding resistance remains the most commonly used parameters though the same may provide conservative results under high frequency studies [23].

Hybrid OHL-cable system develops higher overvoltages and differences in characteristics impedance of OHL and cables result in reflections and refractions of traveling surges at the transition points of the two and consequently the transient behavior is different from that of the individual circuits [47, 48]. Cable overvoltage is influenced by both the sheath grounding impedance and the length of cable segments and [48] notes that sheath to ground overvoltage due to lightning strike on overhead ground wire or tower top is more severe at the cable entrance but the same undergoes significant attenuation inside the cable or at the farther end. Induced overvoltage in hybrid systems depends on the surge impedances of the cable and the OHL, length of the cable and OHL sections, characteristics of lightning impulse, and equipment connected at the end of the line etc [49].

Severity of lightning effect depends on both the characteristics of the lightning itself and on the response of the electrical system being subjected to the lightning stress [2]. Performance of power cable does not depend only on the cable parameters but also on the properties of the ground in case of undergrounded cables [45], adjacent cables because of proximity effects and other electrical systems [46, 47, 50] and these should be incorporated in the transient analysis of cables for a holistic understanding of their behavior. Moreover, insulated power cables are exposed with AC and DC voltages for studying electrical tree [42] and other phenomena related to its insulation but these phenomena against transients and particularly lightning transient has not been taken up seriously. Additionally, cable joints and terminations are one of the least reliable components of cable system [43] and as such their performance under transient conditions needs rigorous analysis. In terms of the response of cables against non-standard lightning transient waveforms which are more prevalent in actual field, only few literatures are available such as [44]. As discussed above, most of the works on the effects of non-standard lightning waveforms have been done on overhead lines or on transformers and as such, the field of interaction of power cables with non-standard waveforms is a fertile ground and merits much works.

Conclusion

This review paper highlights the facts that considerable progress has been achieved in our understanding of the lightning phenomena and particularly on the determintal effects of it on the motley of electrical equipment in operation. Still more clarification and refinement is required on the background of the formation of thunderclouds which results in lightning and the consequent discharge mechanism. In power cable technology, the primary challenge lay in assuring their reliable performance at higher voltages. To meet this challenge the insulation requirements for the same needs to be robust and which in turn warrant that the insulation withstand the onslaughts of various electrical, mechanical, and thermal stresses throughout its design life. Having undertaken a review on lightning transients in general and non-standard impulses in particular and their influence on the insulation performance of insulated power cables, the following perspectives and inputs have been afforded by this review paper:

1. Non-standard lightning waveforms being more prevalent in actual field, it is advisable that the presently agreed 1.2/50 μs standard lightning waveform is revisited for a more practical understanding of its effects on various electrical apparatus.
2. As far as possible simulation studies on lightning transients should be compared and validated with field experiments and in this regard results from artificially triggered lightning experiments could be of much help and merit further exploration.
3. Cables are seldom used standalone but invariably in combination with other electrical systems. Consequently, performance analysis of cable should be done taking into account the environment and the system that the cable is going to be used with. Additionally, the points of transition between cable and other equipment/systems deserve special attention as the differences in parameters particularly impedances changes its behavior.
4. This review paper shed lights on the fact that most of the works concerning the effects of non-standard lightning voltage waveforms were limited to its study on either power transformers or GIS with corresponding auxiliary. As such, there is need to undertake research in the study of effects of nonstandard voltage waveforms on power cables and corresponding accessories.

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