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Energy incident from lightning induced voltages on low voltage power installation due to cloud to cloud flashes in Sri Lanka

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Abstract— **In modern world electronic and electrical appliances are used in abundance and such devices are constantly plugged onto the low voltage power installations (LVPI). Thus, savvy on amount of energies incident by induced voltages on overhead utility lines is important in protecting such equipment. In this paper, preliminary observation of incident energy by induced overvoltage signals on the interface between overhead utility lines and LVPI by cloud flashes is presented. Recorded waveforms were first segregated into cloud to ground (CG) and cloud to cloud (CC), then all recorded CC discharges categorized under three distinct wave shapes unipolar, bipolar and pulse-burst as described previously by [3] and [4]. Observed highest energy corresponding to the unipolar, bipolar and pulse-burst pulses were 0.56 J, 1.51 J and 7.30 J against the peak to peak voltages of 405 V, 662 V and 1056 V with pulse durations of 33.64 µs, 95.00 µs and 222.69 µs respectively. It was further observed that overall mean values of incident energies for unipolar and bipolar were 0.25 J and 0.69 J respectively, compared to 1.46 J observed for pulse-burst pulses. Analysis revealed that profile of the induced voltages and the pulse duration play a major role in deciding the magnitude of the incident energy. It was observed that common mode (CM) induced voltages with pulse-bursts type signatures inherently having longer pulse durations and hence contains comparatively higher energy than lenient pulses. Further, it was observed that in many occasions, there were multiple induced voltages appeared in the 200 ms window. Therefore, the outcome of the study lead to valid conclusions that CC discharges could incident sufficiently high energies to harm sensitive electronics and great attention should be made to confront with CC discharges with special attention to pulse burst type induced voltages.**

Keywords- CC, flashes, CM induced voltage, LVPI

I. Introduction

During past few decades lightening related equipment damages have been gone up unprecedentedly [8]. This particular study intended to surface severity levels of CC discharges in terms of energy incident by the CM induced voltage on LVPI. Since CC discharges are much higher in number comparatively to CG discharges, if CC threat levels are found significant, then CC would be the most significant contributor towards damages. Thus to adhere towards much precious and sustainable mitigation options, one need to understand the threat levels and effects of CC lightning activities to a great depth.

A few studies have been done in understanding the energy of ground flash induced surges on utility lines [5], [6] and [7]. However, no study has been done on the same for cloud flashes as per our knowledge. Silfverskiöld *et al (1999)* [1] and Galvan et al [2] have revealed that not only the return stroke, but also the preliminary breakdown in ground flashes and cloud flashes could have potential for incident sufficient energy to drive sensitive electronic devices towards total or partial failures. Most of modern day sophisticated equipment contains several microprocessors for various purposes. Usually, they have very low immunity against surges due to their inherent compacted nature in construction. According to Keith Brashear (ILD Technologies, LLC San Antonio, TX) [7] microprocessors are subject to weakening damage from reverse electrical energy as little as one micro joules. Integrated circuits are subject to damage from with as little as 10 µJ. Inbuilt surge immunity ranges from no protection (zero) to up to about 12 J for commercially available electronic devices to electrical equipment such as switch mode power supplies, etc., Silfverskiöld *et al. (1999)* [1], have differentiated the degree of threat levels that could produce by a single pulse or pulse trains and managed to established that many energy absorbing devices were damaged by multiple overvoltage pulses, although they were not damaged by a single overvoltage pulse. They further elaborated that even though protective devices can withstand a single pulse by absorbing incident energy by the semiconductor devices (MOVs), they are more prone to degradation and thermal damage if they have to encounter with a sequence of over voltage pulses.

The wave shape of the CM induced voltage waveform at the interface of LVPI may have different shapes owing to various factors. Silfverskiöld *et al.*, [1] had explained that the wave shapes depend on the source of the fields, propagation paths, geometrical and electrical characteristics of the network and connected loads. Further, the induced voltage characteristics at widely separated outlets in the electric field network are expected to be different due to multiple reflections at branch points, loads, and other discontinuities.

Energy incident on the interface between the utility service wire and LVPI also could be varied subjecting to the characteristics of the internal network [10]. Thus energy could be discussed subjecting to some reference specific impedance. However, once calculated it could be adjusted to any given installation with known parameters.

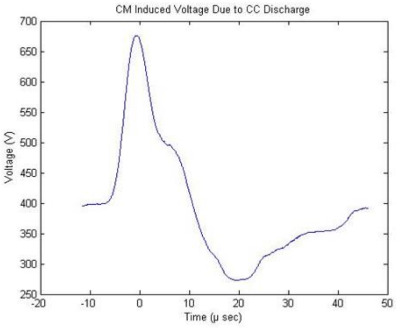


Figure 01: (a) Unipolar peak to peak Voltage 405 V CM Induced Voltage due to CC discharge. Incident energy of 0.59 J in 57.46 µs.

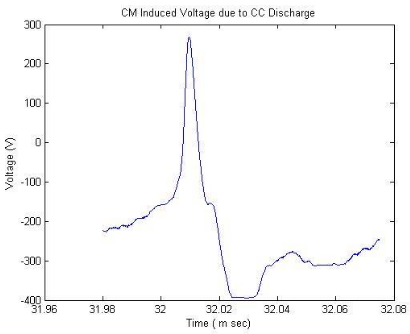


Figure 01: (b), Bipolar V peak-peak 662 V, CM induced voltage due to CC discharge. Incident energy of 0.15 J in 95.0 µs.

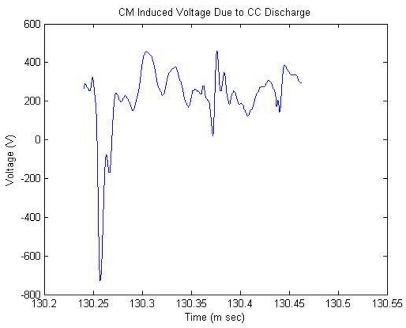


Fig. 01: (c), Pulse burst stoke V peak-peak 1056 V, CM induced voltage due to CC discharge. Incident energy of 7.30 J in 222.69 µs.

The specific energy W/R of an impulse current, I is the energy deposited by the impulse current in a resistance of 1 Ohm. This energy deposition is the integral of the square of the impulse current over the time, t for the duration of the impulse current.

$$\mathrm{W/R} = \int i^2 \mathrm{dt} \quad (1)$$

Thus for the energy W deposited in a conductor with resistance R we have

$$\mathrm{W} = \mathrm{R}.\int i^2 \mathrm{dt} = \mathrm{R.W/R} \quad (2)$$

R (Temperature dependent) DC resistance of the conductor

II. DATA

The isolated dwelling unit was selected in the Western province of Sri Lanka (6.7167° N, 80.0500° E) to collect CM induced voltages. Measurements were conducted at first inter-monsoon period (April-May) of the year 2014. Data mining process accomplished by tapping the live and the neutral bar conductors at the interface between LVPI and the utility service wire via high voltage probes. The dwelling unit internal wiring configured to the terra-terra (TT) topology and energized by a 230 VAC, 50 Hz single phase utility supply. High voltage probe was connected parallel to the live (L) wire at the interface to measure the (CM) induced voltages.

Throughout the entire period of data acquisition all electrically driven accessories and appliances were isolated from the LVPI. Surge protection devices (SPD) are not connected to the LVPI and the internal wiring of the dwelling unit was fed through an overhead bare utility service wires. The utility own step down transformer (33 kV: 400 V) was located approximately 800 m away from the selected LVPI.

Figure 02: Thunder cloud formation map at the time of measurement, 17 April 2014, (www.weatherunderground.com/17-04-0214/12:00-20:00 SLST)

Electric fields were measured by a flat plate antenna system having a 30 MHz bandwidth and 20 ms a decay time. A Tektronix P6015 high voltage probe with 1000:1 attenuation ratio with 70 MHz bandwidth was used to measure the induced voltages. Signals from the high voltage probe and the flat plate antenna system were fed into a digitizer having a 12-bit resolution. Data were recorded at the 6.4 ns sample interval on a 200 ms sample window and recorded from a single trigger mode with the pre-trigger delay time of 60 ms. Low voltage TT grounding of the LVPI was used as the ground reference.

III. RESULTS AND DISCUSSION

CM induced open circuit voltages having more than 150 V (peak to peak) were considered for this analysis. All recorded waveforms were divided into the above mentioned three broader categories considering the time domain voltage profiles.

Subjecting to above said criteria induced voltage profiles further analyzed to recognize their total pulse duration and subsequent (minor) pulses. Accordingly, 20 unipolar, 11 bipolar and 159 pulse-burst, were identified.

UNIPOLAR PULSES

Recorded 20 unipolar pulses were extracted onto Microsoft Excel platform and numerically calculate the incident energy.

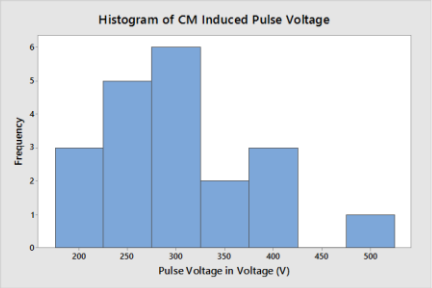


Figure 03: (a) Histogram of the CM induced peak to peak voltage on LVPI due to unipolar type pulses. Maximum, minimum and mean values of peak to peak voltages are 405 V, 181 V and 302.8 V respectively.

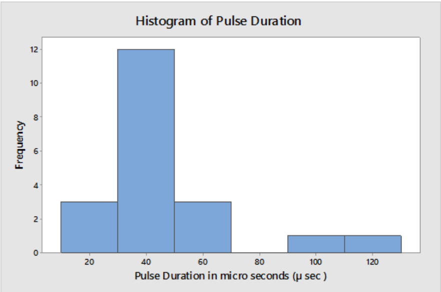


Figure 03 (b) Histogram of the total pulse duration of unipolar type induced voltages. Maximum, minimum and mean values of pulse durations are 123 μs, 11.4 μs, and 44.7 μs respectively.

It can be observed that peak to peak voltages and pulse duration of CM induced unipolar pulses approximately follow lognormal distribution.

Energy Incident:

According to the outcome of the goodness of fit test analysis, it was found that data set closely follow a lognormal distribution than other available distributions.

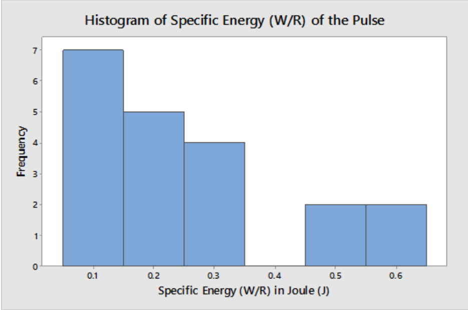


Figure 04: Histogram of the energy incident at LVPI by unipolar type CM induced voltages. Maximum, minimum and mean values of incident energies are 0.59 J, 0.06 J and 0.25 J respectively.

To calculate vulnerabilities associated with commonly available electronics and electrical equipment in terms of probabilistic viewpoint following statistical analysis was employed.

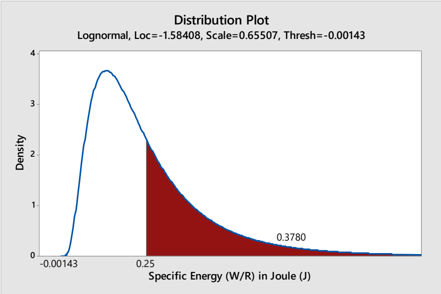


Figure 05: Probability of exceeding mean value of the distribution

Fig.05 suggests that such recorded CM induced unipolar type pulses have 0.378 probabilities to damaged devices having 0.25 J or less surge immunity. Figure 06 represents percentages that can exceed certain incident energy levels.

According to the Figure 06 it can be seen that 50% of the energies are below the mean value 0.25 J. Further only 5% surges have energies beyond 0.74 J.

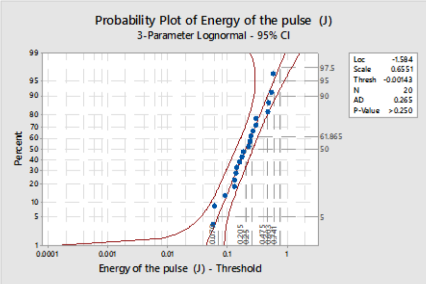


Figure 06: Probabilities that exceeding certain values of incident energy levels

Thus microprocessor based devices and other integrated electronics can be impaired by unipolar type CM induced voltage. However, above statistical interpretation excluded the chances of damaging equipment like switch mode power supplies, uninterruptible power supplies (UPS) etc., by unipolar type induced voltages.

Further, statistical indices surfaced that CM induced unipolar signatures have been concentrated around peak to peak voltage of 300 V and majority of the pulses are having pulse duration close to 45 µs.

BIPOLAR PULSES

Eleven CM induced bipolar pulses due to CC discharges were selected for the analysis.

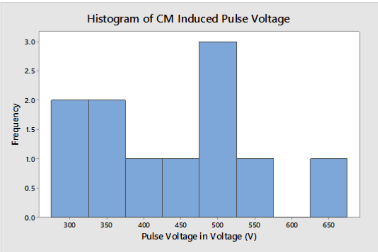


Figure 07: (a) Histogram of the CM induced peak to peak voltage on LVPI due to unipolar type pulses. Maximum, minimum and mean values of peak to peak voltages 662 V, 29 V and 449.6 V respectively.

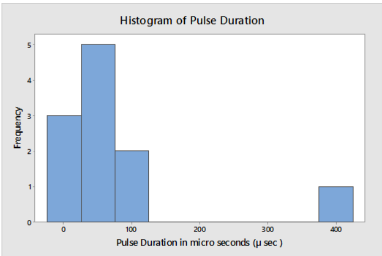


Figure 07: (b) Histogram of the total Pulse Duration of unipolar type induced voltages. Maximum, minimum and mean values of pulse durations are 401.2 µs ,10.7 µs and 77.5 µs respectively.

Energy Incident:

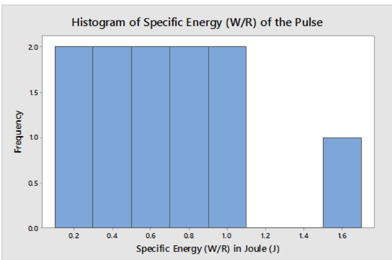


Figure 08: Histogram of the energy incident at LVPI by bipolar type CM induced voltages. Maximum, minimum and mean values of incident energies are 1.52 J, 0.22 J and 0.69 J respectively.

Fig.08 shows the distribution of pulse duration of bipolar type pulses. Figure 9 shows the energy incident on the power line by bipolar pulses. Available sample size is not rich enough to discuss the behavior of bipolar pulses in statistical point of view. Thus no further statistical analysis carried out.

PULSE-BURST PULSES

Hundred and fifty-nine pulse-bursts were identified in this study.

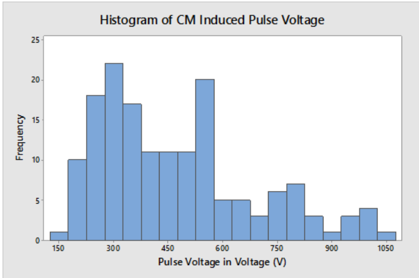


Figure 9: (a) Histogram of the CM induced peak to peak voltage on LVPI due to unipolar type pulses. Maximum, minimum and mean values of peak to peak voltages are 1056V, 171 V and 470.8 V respectively.

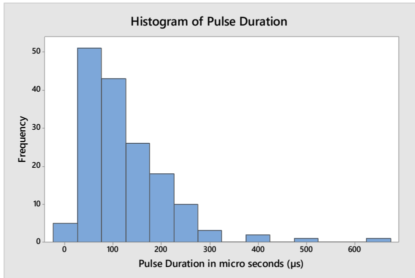
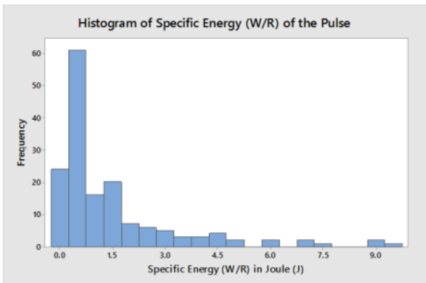


Figure 9: (b) Histogram of the total pulse duration of unipolar type induced voltages. Maximum, minimum and mean values of pulse durations are 626.3 µs, 10.69 µs and 121.8 µs respectively.

According to goodness of fit analysis, it can be concluded that peak to peak voltages of induced pulse-burst pulses closely follow Weibull and Gamma distributions and the total pulse duration of induced pulse burst pulses closely follows the Log Normal distribution.

Energy Incident:



Graph 10: Histogram of the energy incident at LVPI by pulse burst type CM induced voltages. Maximum, minimum and mean values of incident energies are 9.43 J, 0.04 J and 1.46 J respectively.

Incident energy on LVPI due to induced pulse-burst pulses were much concentrated on the left side of the probability distribution and their mean value is larger to the median.

According to the outcome of the analysis, data set closely follows a lognormal distribution than other available distributions. To further clarify Probability Plot (PP) test was employed

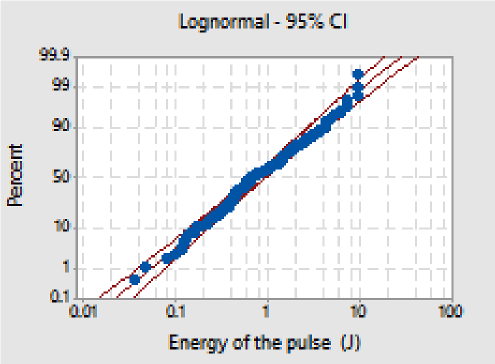


Figure 11: Probability Plot of data

According to the Fig.11 it can be reasonably concluded that energy incidences due to CM induced voltages due to pulse-burst type pulses follow lognormal distribution. Statistical analysis was employed to calculate the vulnerabilities associated with commonly available electronics and electrical equipment in terms of probabilistic viewpoint. For an example, suppose we wanted to find out the probability of damaging some equipment which is having inbuilt self-surge immunity of 1.46 J (here consider mean value) by a pulse-burst type CM induced voltage.

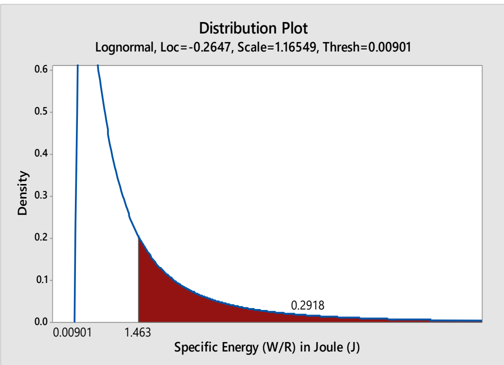


Figure 12: Probability of exceeding mean value of the distribution

As per Fig.12 there is a 0.29 probability to damage equipment which are having inbuilt surge protection level of 1.46 J by the pulse burst type induced voltages. Similarity probabilities of equipment damage can be calculated to any commercially available equipment.

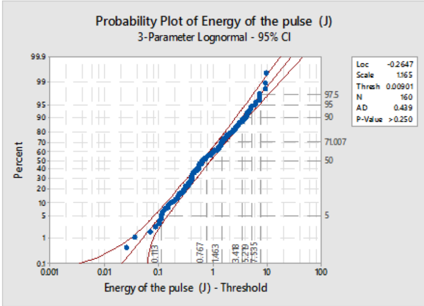


Figure 13: Probabilities that exceeding certain values of incident energy levels

According to the outcome of the Fig.13 it can be seen that 71% of the cases, energy of pulse-bursts are below the mean value 1.46 J. Thus, only 29% pulse-burst is having energies beyond the 1.46 J and only 5% surges have energies beyond 7.53 J. Commercially available microprocessor based electronic devices to various electrical equipment are having a range of surge protections from no protection up to about 12 J. Thus the outcome of the study can be used to estimate possible treat level if inbuilt surge protection level known.

IV. CONCLUSION AND DISCUSSION

This study disclosed that CM induced voltages due to CC discharges too have a considerable potential for incident sufficiently large energies on LVPI that can damage microprocessor based electronic systems and some electrical equipment which are having surge protection up to 8 to 9 joules. This study also concludes that the magnitude of the incident energy vastly depends on the time domain voltage profile and pulse duration.

The analyses also reveal that in many occasions, there are more than one induced voltage recorded within 200 ms measuring window and that number may be as high as five to six or even more.

Moreover, it was also revealed that the majority (more than 83%) of pulses comprise of pulse-bust type and balance belong to other pulse types. Pulse-burst type induced voltages are having much random fluctuations in time domain with elongated pulse durations. Thus inherently pulse-burst type pulses can have elevated amounts of incident energy compared to other pulse types. Therefore, vendors who undertake design and assembling of electronics shall be paid due attention to minimize vulnerabilities related to pulse burst type induced voltages.

According to the statistical outcome it was revealed that unipolar and bipolar type induced voltages can harm microprocessor based, highly compacted electronic devices [7] and pulse-burst type induced voltages have sufficient potential to damage electrical equipment such as television sets, fax machines, water motors etc., [1]. Following table summarized the statistical indices derived.

TABLE01. SUMMARY OF INCIDENT ENERGY CONSIDERING SINGLE PULSE

Specific Energy (W/R)	Unipolar	Bipolar	Pulse Burst
Maximum	0.59	1.52	9.44
Minimum	0.06	0.22	0.04
Mean	0.25	0.69	1.46
Median	0.21	0.65	0.66
Standard Deviation	0.16	0.39	1.86

Table 02 illustrates an energy incident on LVPI due to the contribution of all induced pulses within a single 200 ms window.

TABLE02. TOTAL INDUCED ENERGY WITHIN A SINGLE 200 ms WINDOW DUE TO PULSE TRAIN

Specific Energy (W/R) Incident due to Pulse Train in 200 ms	
Maximum	15.08
Minimum	0.84
Mean	5.64
Median	4.61
Standard Deviation	4.05

When comparing Table 01 and Table 02 it can be seen that energy incident by a train of pulses are much higher and since such energies incident on LVPI in much less time (less than 200 ms) the severity levels can be higher due to cumulative thermal effects and current hogging. Thus continuous deposition of excess energy on sensitive electronics can easily drive them to thermal runway and eventually push into a faulty condition.

Therefore, the outcome of the study lead to a valid conclusion that great attention shall have to be made to confront with CC discharges with special attention to pulse burst type induced voltages due to following basic reasons.

i. More than 83% CC induced voltages are pulse burst type.

ii. Pulse burst having high peak voltages naturally accompanied with subsequent pulses with comparable magnitudes.

iii. CC discharges can incident sufficiently high energies (mean 1.46 J and maximum 9.43 J) to kill microprocessor and electronic devices.

iv. Pulse burst is having comparatively large pulse time.

v. Incident energy due to compound pulses is even higher (mean 5.64 J and maximum 15.08 J incident less than 200 ms) and sufficient damage equipment with inbuilt surge protections.

Manufacture's and component assembler's attention should grab the fact that CC discharges could impart small but very steady and almost continues the train of surges on electronic equipment followed by each and every CC discharge. This high frequent and continuous energy deposit on electronics could be produced much adverse effects than larger but seldom CG events. Thus, small in magnitude, but frequent surges may accelerate the degradation process on sensitive electronics unless precautionary or mitigation attempt not made. Thus to protect valuable and critical electronics, one need to have dedicated equipment level protection to prevent the influx of minor surges which have been escaped through primary protection schemes due to their minute amplitudes.

Generally, an inherent surge immunity level depends on the design and the manufacture's policy. However, this study suggest to pay serious attention to have equipment level fine protection to shield from CC induced voltages since externally employed, dedicated protections may not sensitive enough to act on a continuous influx of CC surges as they have been designed to act on less frequent but comparatively very large CG induced surges.

IV. ACKNOWLEDGMENT

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