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Wavelet analysis of lightning generated electric fields and induced voltages on overhead power lines due to cloud to cloud flashes in Sri Lanka

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***Abstract*—Investigations on the energy incident on low voltage power installation (LVPI) due to cloud to cloud (CC) discharges [3] revealed that incident energy can be driven microprocessor systems and electronic devices to malfunction, fault conditions or complete failure status. Therefore, it is worthwhile to investigate the energy concentration of the electric fields and common mode (CM) induced voltages on time-frequency common domain. The wavelet transformation technique is one of the proven tools that frequently use in many fields to investigate diverse natural phenomena [1], [2] and [4]. Accordingly wavelet technique was employed in this study to map the energy content of the selected signals onto time and frequency domains. This analysis revealed that energy content of the signal reach to its maximum just after the time domain voltage signal reach its local maximum or local minima. Also analysis indicates that equipment to be protected may become vulnerable to incoming surges if protection devices unable to clip the peak of the surge or delay to cut off the peak of the incoming signal.**

Keywords- Lightning, CC, Wavelet Analysis, CMinduced voltage.

I. Introduction

Investigation of incident energy on low voltage power installation (LVPI) by common mode (CM) induced voltages by cloud to cloud (CC) discharges has been discussed in [7]. They have only provided the information on the amount of incident energy on LVPI but does not address the questions such as energy intensity, what portion of the pulse contain more energy, at what instant energy intensity become maximum in time domain and what frequency corresponds etc. To extract such vital information embedded within the captured lighting induced CM voltages and Electric fields, it required a detailed study on energy distribution on time –frequency domains. Wavelet technique is one of the options that can be employed to accomplish said analysis. Wavelet has been heavily employed in analysis of real world signals generated by diverse natural phenomena such an earthquake, lightning, temperature variations, sounds etc., [5] and [6]. Therefore, in this study Wavelet is used as a tool for analysis and illustrates the energy intensity of the designated signal on the time and frequency common domain. To ease comparisons and enhance important differentiations Wavelet analysis done separately on three basic signature types described previously by [8] and [9], namely unipolar, bipolar and pulse burst.

II. Data

With the intention of capturing a set of rich lightning induced electric field and voltage data an isolated dwelling unit was selected in the Western province of Sri Lanka (6.7167° N, 80.0500° E). The data mining process accomplished by tapping the live and the neutral conductors at the interface between LVPI and the utility service wire via high voltage probes. The dwelling unit's 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 extraction 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 wires. The utility own step down transformer (33 kV: 400 V) was located approximately 800 m away from the selected LVPI.
Electric fields and CM induced voltages generated by the cloud to cloud flashes were measured by a flat plate antenna system having a 30 MHz bandwidth and 20 ms decay time. A Tektronix P6015 high voltage probe with 1000:1 attenuation ratio 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 captured from a single trigger. The pre-trigger delay time was set to 60 ms. Low voltage TT grounding of the LVPI was used as the ground reference. Total system was energized via uninterrupted power supply (UPS) by a local isolated petrol driven generator.

According to the Nanayakkara *et. al.*, [8] and [9] thunder clouds were formed directly above the measuring site during measurements as seen from fig. 01 below. The exact height of the charge center of the thunder cloud was not known, but the roughly cloud base was around 1-2 Km from ground level.

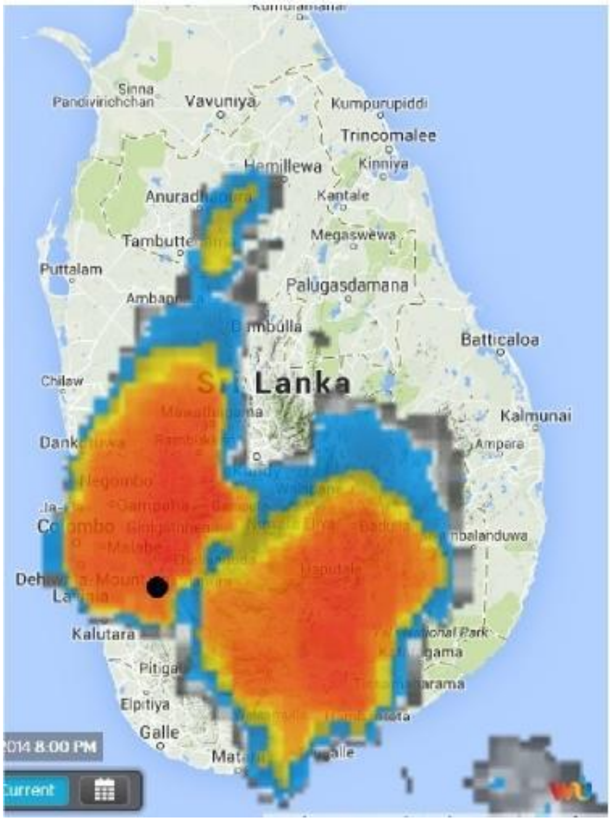

Figure 01. Thunder cloud formation map at the time of measurement, 17 April 2014, showing the active area of the thunder storm to be directly above the measuring site (black dot). (www.weatherunderground.com) (17-04-0214/12:00-20:00 SLST)

III. RESULTS AND DISCUSSION

For the intended analysis carefully selected three CM induced voltage pulses and their respective electric fields considering following two facts.

i. Covering all three basic pulse types unipolar, bipolar and pulse burst

ii. Signals associated comparatively high incident energy.

Accordingly, three voltage signals and respective electric fields were selected (see table 01) for the analysis.

Selected voltage signatures and electric field signatures extracted onto excel and then transferred to the Mat lab Figure02. software package respectively to carry out Wavelet analysis.

TABLE 01. SELECTED PULSES FOR WAVELET ANALYSIS

Pulse Type	Peak to Peak Voltage (V)	Specific Energy (W/R) (J)	Pulse Duration (μs)
Unipolar	405	0.595	57.45
Bipolar	662	1.516	95.01
Pulse Burst	1056	7.303	222.69

Wavelet analysis, demand extensive hardware capabilities and hence entire signal cannot be analyzed at once. Thus the iterative scheme used for analysis selected signals to identify an energy concentration in time and frequency domains. Time domain signals were sampled at 6.4 ns sample rate and hence the same sample rate was employed to wavelet analysis. Further starting scale, increment (step) and maximum scale selected as2.56×10^{-8}, 0.15 and 2048 respectively, for the first iteration. For the second iteration maximum scale of 4096 was used for more close investigation of areas where more energy concentration observed in the first iteration. Since time domain voltage waveform and electric field waveform have a strong correlation to each other in deciding time domain spans considered the length of the voltage waveform originating and diminishing points for both signals. (Note: general electric field waveform signal length is little larger than the voltage signal but cannot accommodate entire signal due to system hardware constraints).

The Morlet family of wavelet was selected for analysis the induced voltage pulse as Morlet wavelet is much suit to deal with signals having transient characteristics.

Fig. 02 illustrates the holistic view of the CM induced voltage and the corresponding electric field.

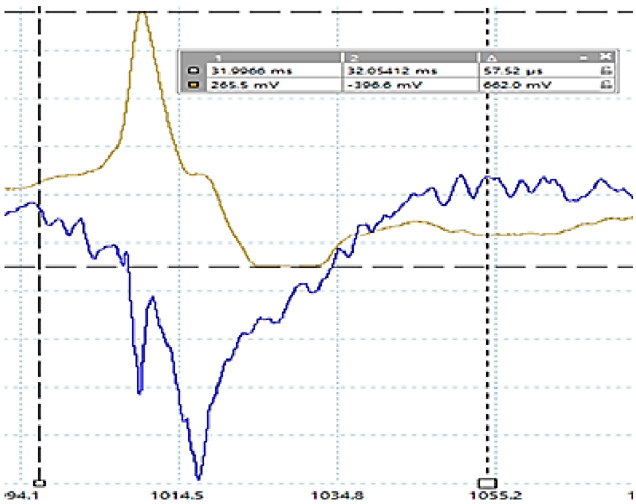

Figure 02. CM induced bipolar voltage peak to peak 6621 V (brown colour) and corresponding Electric field (blue colour)

Two vertical dotted lines on the fig. 02 illustrates the extracted portion of the original signal for Wavelet analysis. Fig. 02 evident that the entire voltage and significant ration of electric field signal have been reasonably captured and hence could be presumed that the selected portion could generally represent the entire scenario without distorting vital information embedded in respective signals.

UNIPOLAR PULSES

Wavelet Analysis of Induced voltage waveform:

An induced unipolar pulse identified with peak to peak voltage 405 V was selected for the analysis. The maximum scale factor 4096 (the optimum value suggested from the system) selected for analysis with other parameters constant. Fig. 03 (a) illustrates the selected portion of the time domain voltage signal and fig. 03 (b) describes the outcome of the Wavelet analysis.

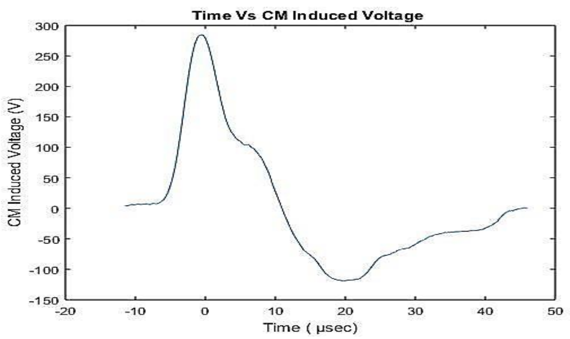

Figure 03(a) Time domain CM induced voltage.

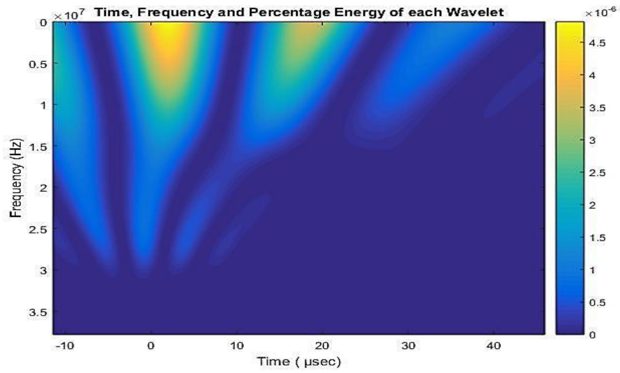

Figure 03(b) Time, Frequency and Percentage Energy of each Wavelet.

The colors of the spectrogram encode frequency power levels. Yellow colors indicate frequency content with higher power, whereas blue colors indicate frequency content with very low power. Fig. 03(b) revealed that two distinct energy distributions associated with CM induced voltage signal. Out of those, the energy associated with the upward peak much more prominent than downward peak. Further, these energies significantly concentrated in and around up to 2 MHz frequency range and spread across approximately from -2.5 µs to +5 µs at the rising portion of the signal.

Moreover, the highest energy concentration appears approximately around +2.5 µs just after the peak of the signal. Concentration of the minor energy distribution becomes to its maximum around 18 µsec and which is just before the time domain minimum. The maximum percentage energy of the wavelet found as $4.8X10^{-6}$ and the energy of the signal totally diminishing beyond 30 MHz. Furthermore, from the spectrogram it can be seen that significant portion of wavelet energy resides bellow 10 MHz.

Wavelet Analysis of Electric Field waveform:

Fig. 04 (a) illustrates time domain electric field waveform and figure 04 (b) depicts the energy concentration of the electric field in time– frequency plot.

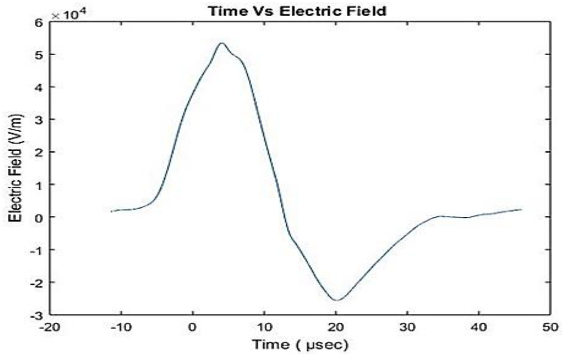

Figure 04(a) Time domain electric field.

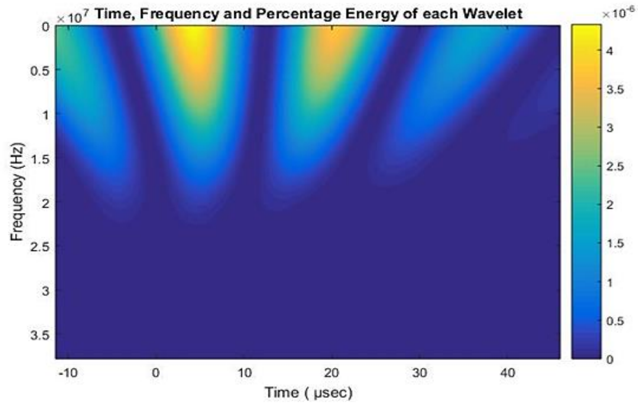

Figure 04(b) Time, Frequency and Percentage Energy of each Wavelet.

Fig. 04 (b) surfaced that two distinct energy distributions associated with an electric field. Much similar to the case discussed under induced voltage analysis, electric field too, having a prominent energy concentration aligned with electric field's upward peak and the minor band in line with downward peak. Moreover, these energies significantly concentrated up to 4 MHz and very prominent energy distribution visible from approximately 1 µs to + 7 µs and the peak reach approximately around +5 µs in time domain. According to the figure 04(a) time domain peak appears in and around 4 µs and energy of the signal become to maximum just after the upward peak. It is worthwhile to notice that wavelet energy become maximum for induced voltage too, just after its upward peak reached. Minor energy distribution, concentration becomes maximum around 20 µs and which almost overlap with the reach of minimum or downward peak. The Maximum percentage energy of the wavelet recorded as $4.8X10^{-6}$ and it keeps on diminishing when frequency increases and disappear beyond the 22.5 MHz. Moreover, from the spectrogram it can be seen that significant portion of wavelet energy resides bellow 10 MHz, which is similar to induced voltage scenario discussed above.

BIPOLAR PULSES

An induced bipolar pulse identified with peak to peak voltage 662 V selected for the analysis.

Wavelet Analysis of induced voltage waveform:

The maximum scale factor 4096 (optimum value suggested from the system) selected for analysis with other parameters constant. Fig. 05 (a) illustrates the selected portion of the CM induced voltage signal in time domain and figure 05 (b) describes the outcome of the spectrogram of the said induced voltage.

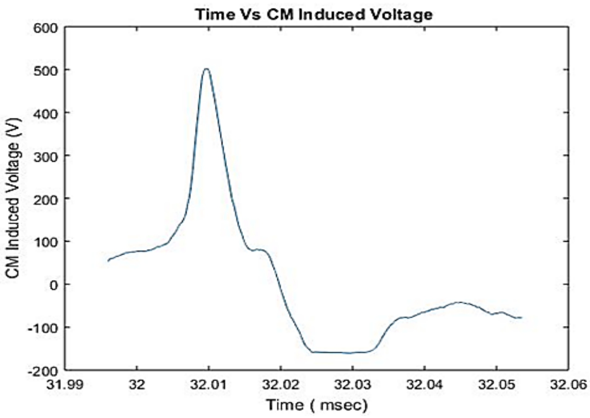

Figure 05(a) Time domain CM induced voltage.

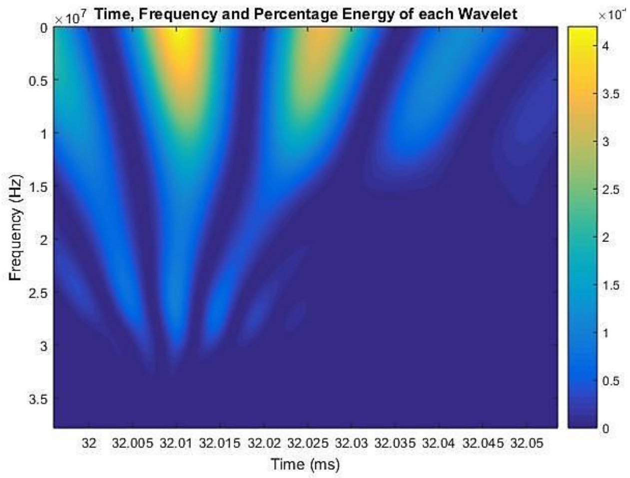

Figure 05(b) Time, Frequency and Percentage Energy of each Wavelet.

Similar to unipolar analysis fig. 05 (b) depicts the energy concentration of the voltage pulse in the time – frequency plot. This pictorial view reasonably evident that the energy concentration much higher, up to 2.5 MHz and which occupies in the signal at 32.01 ms in real time. Further, between 32.025 ms to 32.03 ms second energy band appears and energy concentration is high up to frequencies close to 0.5 MHz. According to the spectrogram energy content in the signal starts diminishing after about 3 MHz and significant portion of the energy of the signal vanishes after about 10 MHz.

Wavelet Analysis of induced Electric Field waveform:

Fig. 06 (a) illustrates time domain electric field waveform and fig. 06 (b) depicts the energy concentration of the electric field in the time – frequency plot.

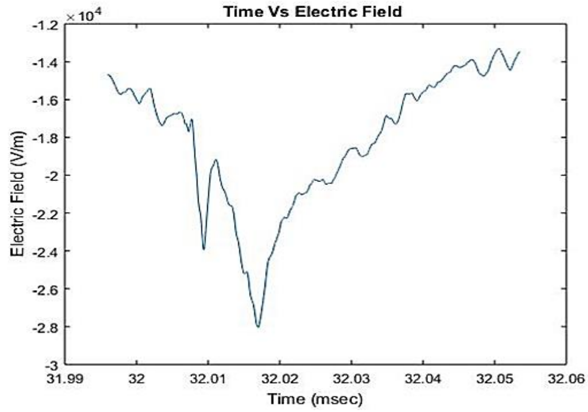

Figure 06(a) Time domain electric field.

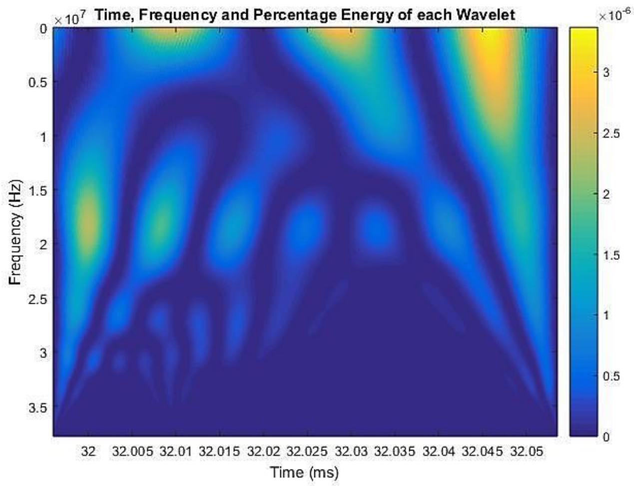

Figure 06(b) Time, Frequency and Percentage Energy of each Wavelet.

Fig. 06(b) gives spectrogram of the electric field which depicts that the electric field is having several isolated energy bands scattered over a vast spectrum of frequencies. Moreover, the latter part of the electric field signal contains more energy than other segments and significantly high energy concentration occupies up to 2 MHz and beyond 10 MHz energy content in the signal decayed and totally vanishes after 35 MHz. In addition to the said prominent band there are three other isolated energy concentrations can observe within the electric field and two such bands associated with low frequencies in comparison with a third one. Frequency shifted third energy band occupies frequencies from 15 MHz to 20 MHz and thereafter decaying and vanishes after 35 MHz as in the case of prominent band. The maximum percentage energy of the wavelet recorded around $3.6X10^{-4}$ subjecting to the selected scale of 4096.

PULSE BURST

Wavelet Analysis of induced voltage waveform:

CM induced voltage signal having pulse burst signature with peak to peak voltage 1056 V selected for the analysis.

The maximum scale factor 4096 (optimum value suggested from the system) selected for analysis with other parameters constant. Fig. 07 (a) illustrates the selected portion of the CM induced voltage signal in time domain and figure 07(b) illustrates the outcome of the spectrogram.

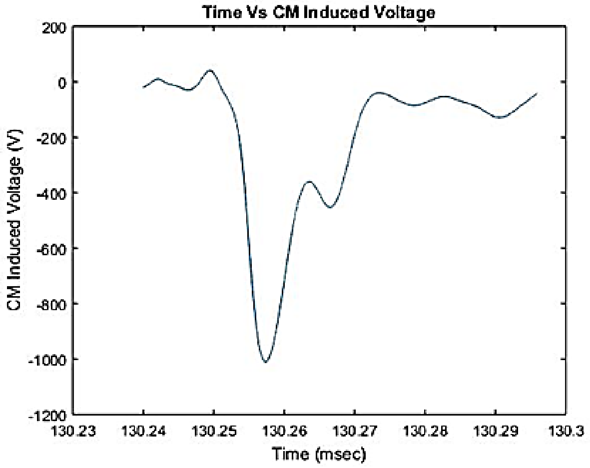

Figure 07(a) Time domain CM induced voltage.

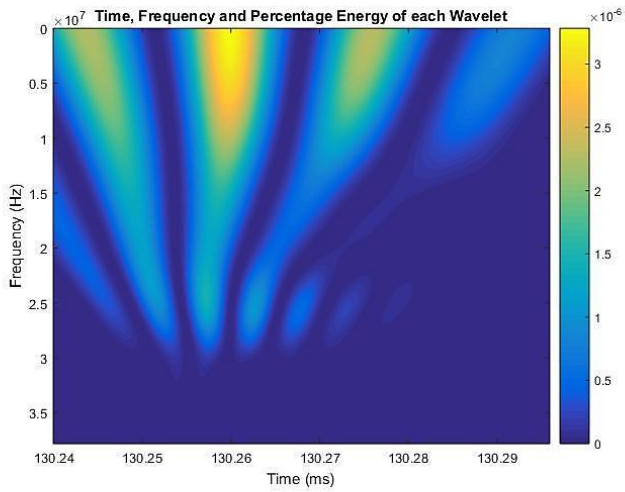

Figure 07(b) Time, Frequency and Percentage Energy of each Wavelet.

Fig. 07 (b) evident that the energy concentration much higher, up to 6.5 MHz and which occurs at 130.26 ms. Apart from that particular CM induced voltage signal has two other minor energy concentrations either side of the prominent band. Voltage signal energy content diminishes beyond 35 MHz. Percentage energy of the wavelet having maximum around $3.6X10^{-6}$.

Wavelet Analysis of Electric Field waveform:

Fig. 08(a) illustrates time domain electric field waveform and fig. 08 (b) depicts the spectrogram of the electric field.

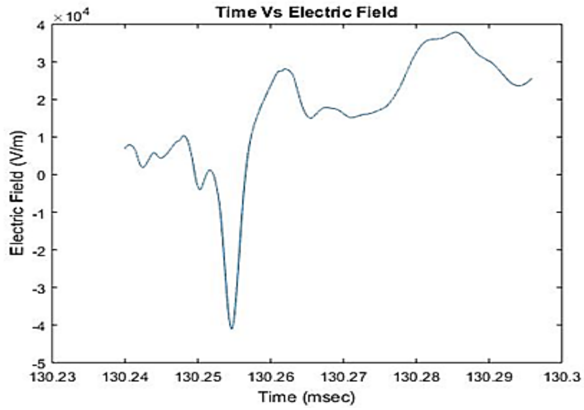

Figure 08(a) Time domain CM induced voltage Figure.

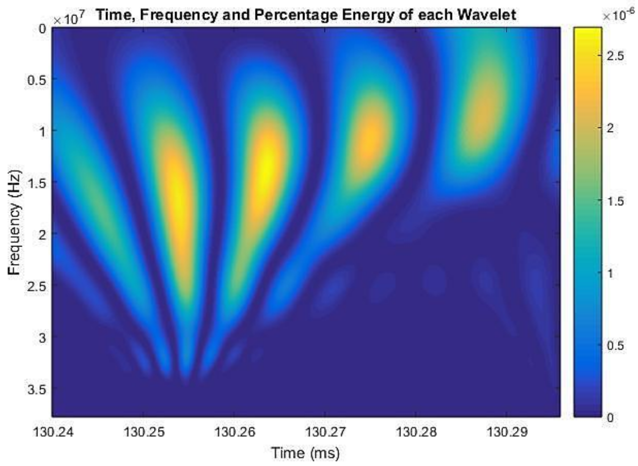

Figure 08(b) Time, Frequency and Percentage Energy of each Wavelet

Fig. 08(b) very precisely evident that electric field does not contain considerable energy in low frequencies and significantly high energies appears beyond 5 MHz. There are four isolated energy bands scattering over time domain and faded way along the signal. The first two energy bands are much more prominent and spread across 10 MHz to 25 MHZ over 15 µs and maximum energy concentration occurs in and around 15 MHz between 130.26 ms and 130.27 ms. Further, along the time axis energy content of the electric field gradually diminishes and energy bands transferring towards low frequencies. However, apart from, above selected cases, it was observed that the electric field signal contains small energy components up to high frequencies such as 35 MHz. Percentage energy of the wavelet having maximum around $2.7X10^{-6}$.

IV. CONCLUSION AND DISCUSSION

In this study CM induced voltage signals and relevant electric fields belongs to main three wave shapes were analyzed by wavelet transformation technique to obtain spectrogram of each signal to discuss energy embedded within the respective signals. The spectrogram is a visual illustration that can, maps energy content of the signal proportionate to the percentage energy terms of each wavelet on the time and frequency common template. This study employed Morlet wavelet family to owing to its capability to support transient nature. Analysis revealed that the energy content of the CM induced voltage signal reach to its maximum just after the time domain voltage signal reach its local maximum or local minima. This finding invites the attention of the designers and component assemblies to pay their due concerns on equipment to be protected as such equipment and devices may become vulnerable to incoming surges if protection devices unable to clip the peak of the surge or delay to cut off the peak of the incoming signal within the expected time band as energy reach to its maximum within few microseconds after the signal reach to its maximum. Further, the outcome of the study much effectively guide surge filter designers as spectrogram illustrates what frequencies contain high energy and up to what frequency, extent or span such energies embedded within the signal and finally at what threshold levels such energy diminishes.

V. ACKNOWLEDGMENT

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REFERENCES

[1] A. V. Gurevich, K. P. Zybin, "Runaway breakdown and mysteries of lightning, " Phys. Today, pp. 37–41, May 2005. [7] F. J. Miranda, "Wavelet analysis of lightning return stroke," Journal of Atmos. And Sol. Ter. Physics 70, 2008, pp. 1401-1407.

[2] S. R. Sharma, V. Cooray, M. Fernando, F. J. Miranda, "Temporal features of different lightning events revealed from wavelet transform, "Journal of Atmos. And Sol. Ter. Physics 73, 2011, pp. 507-515.

[3] Keith Brashear "Lightning and Surge Protection Of Modern Electronic Systems" *(ILD Technologies, LLC San Antonio, TX)*

[4] T. A. L. N. Gunasekara, U. Mendis, S. N. Jayalal, M. Fernando and V. Cooray "Wavelet Analysis of Narrow Bipolar Pulses observed in Sri Lanka" . ICLP, Nagoya japan 2015.

[5] M. Sifuzzaman1 , M.R. Islam1 and M.Z. Ali "Application of Wavelet Transform and its Advantages Compared to Fourier Transform ", Journal of Physical Sciences, Vol. 13, 2009, 121-134 ISSN: 0972-8791 : www.vidyasagar.ac.in/journal 121.

[6] Kurtis Gurley and Ahsan Kareem "Applications of Wavelet Transforms in Earthquake, Wind and Ocean Engineering "Department of Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame, IN, 46556.

[7] S. Silfverski¨old, R. Thottappillil, M. Ye, V. Cooray, and V. Scuka, "Induced Voltages in a Low-Voltage Power Installation Network Due to Lightning Electromagnetic Fields: An Experimental Study",*IEEE Trans. Electromagnetic compatibility* ,vol. 41, no. 3, Aug 1999.

[8] Sankha Nanayakkara, U Mendis, M Fernando , Sidath Abegunawardana, P Liyanage, V Cooray "Lightning Induced voltages in Over Head Power Lines due to Cloud to Cloud Flashes in Sri Lanka" *ICLP*, Nayoga, Japan, 2015.

[9] Sankha Nanayakkara, U Mendis, M Fernando , Sidath Abegunawardana, P Liyanage, V Cooray "Lightning Induced voltages in Over Head Power Lines due to Cloud to Ground Flashes in Sri Lanka" *ICLP*, Nayoga, Japan, 2015.