2018 25th International Lightning Detection Conference &
7th International Lightning Meteorology Conference
March 12 - 15 | Ft. Lauderdale, Florida, USA

Denoising CN Tower Lightning-Generated Magnetic Field Return-Stroke Signals Using the Empirical Mode Decomposition Method

Nedjah Ouarda and Ali M. Hussein
Electrical and Computer Engineering Department, Ryerson University, Toronto, Ontario, Canada
O2nedjah@ryerson.ca

Abstract— The Paper describes the process of denoising the lightning-generated magnetic field signals recorded in the vicinity of the CN Tower. The de-noising process adopts the Empirical Mode Decomposition (EMD) method. The analysis of different mode contents allows us to differentiate the modes, or parts of the modes, which are more likely associated with the noise, from those that belong to the signal. The noise only modes are either removed or reduced depending on the front steepness of the measured signal. The method achieved 3 dB improvement of the SNR for high amplitude signals and 5 dB improvement for the signals with amplitude in the same order of magnitude as the noise. The distortion associated to the denoise process was not of major effect on the signal front peak. But the major inconvenience of the method is that it is signal dependant.

Keywords—lightning; return stroke, radiated magnetic field; EMD Denoising;

I. INTRODUCTION

The Canadian National (CN) Tower is not only a transmission hub and a jewel for tourists' attraction but it is also an effective equipped tall structure for the measurement of lightning strokes. The current, and the associated radiated magnetic and electric fields are measured at the tower and in its vicinity as described by [Hussein, 2008]. The current derivative of lightning return strokes were measured at the tower and simultaneously measured, 2 km north of the tower, the azimuthal and radial components of the magnetic field, as well as the vertical electric field. The measured data are used to calibrate and evaluate the Canadian Lightning Detection Network (CLDN) [Kazazi, 2015].

The recorded current and the radiated electromagnetic field data has also helped to design models for estimating the lightning current based on the measured data. To establish the models or to calibrate a system it is desirable to have measured data free of noise. The tower being a transmission hub itself, it transmits communication signals from many transmission stations in Toronto.

The CN Tower being a 553 m mass structure of concrete and steel planted in the ground acts as an efficient $\lambda/4$ monopole antenna, receiving perfectly waves around 140 kHz and their harmonics. Also, being made of pieces it transmits and receives higher frequencies. Due to this fact, the lightning currents measured at the tower and the electromagnetic waves emanating from it and measured in its vicinity are affected by the signals both received and transmitted by the tower. This is why 27 years of recorded data at those measuring systems such as the lightning current derivative measuring system situated at the tower. The measured radiated fields in the vicinity of the tower are noise-laden. The noise spectrum extends from DC to the limit range of the recording system that depends on its sampling frequency which is 100 MHz.

Denoising the magnetic field waveforms recorded 2 km from the tower is the object of this paper. The method used is the Empirical Mode Decomposition technique. In this technique, the measured magnetic field is decomposed by the EMD method into its intrinsic modes. The contents of the different modes are analyzed and the modes are either rejected or thresholded, based on their content depending if it is linked to the noise or to the signal. A description of the magnetic field recording system and the recorded magnetic signal waveform, is presented the used denoising technique, followed by the obtained results. We finally end by a discussion of the results and a conclusion.

II. THE LIGHTNING MAGNETIC FIELD MEASUREMENT SYSTEM AND THE MAGNETIC FIELD CURRENT WAVEFORM

The magnetic field waveforms are captured by broadband field sensors located on the top of a 20 m-high building situated 2 km north of the tower. The sensors for both the azimuthal (H_{φ}) and radial (H_r) magnetic field components are made as small-loop antennas type having a sensitivity of 0.166 V/(A/m) and bandwidths spanning from 635 Hz to 134 MHz for the first field sensor and 697 Hz to 150 MHz for the second one. The dynamic range of each sensor is 60 dB and their maximum linear output voltage is 0.88 V that corresponds to a maximum magnetic field of 2.1 A/m incident field. The two sensors are orthogonal to each other and vertically oriented towards the CN Tower to capture a maximum emanating magnetic field from strikes to the tower. The sensors were connected through 50-Ω coaxial cables to a digitizer (Tektronix 710A, 10-bits, 10ns) linked to a computer recording system.

A typical recorded radial magnetic field component occupies 17k memory (8k samples of 10 bits that occupies 2 bytes each) is shown on Fig.1 and its frequency spectrum is shown on Fig. 2 and 3 respectively. The measuring system records data constantly and saves the data only when the recorded field is above a pre-established threshold. When the data is saved, 2kb of the data before the threshold is saved as well, and is considered as part of the analysed data; this portion of data allows us to record the full waveform front-end that helps in the determination of the waveform risetime. Since the starting of the waveform is mostly immersed in the noise, denoising the signal will help in the accurate determination of the starting time, hence improves the accuracy of the risetime.

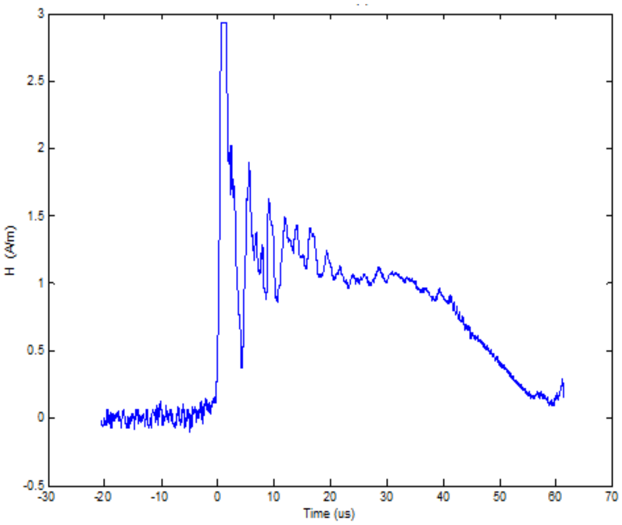

Figure 1. A typical recorded magnetic waveform

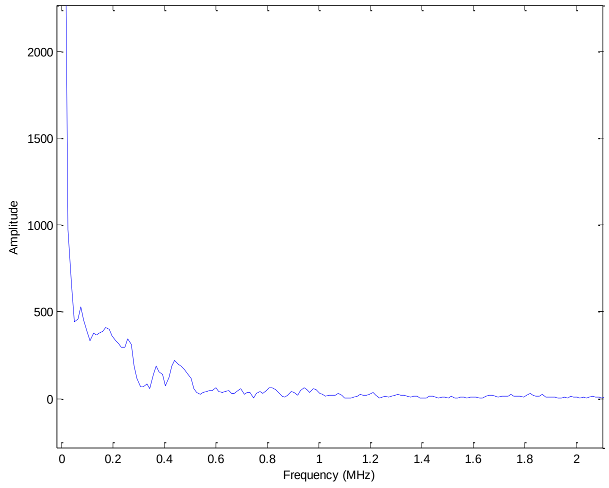

Figure 2. Amplitude spectral representation of the magnetic waveform

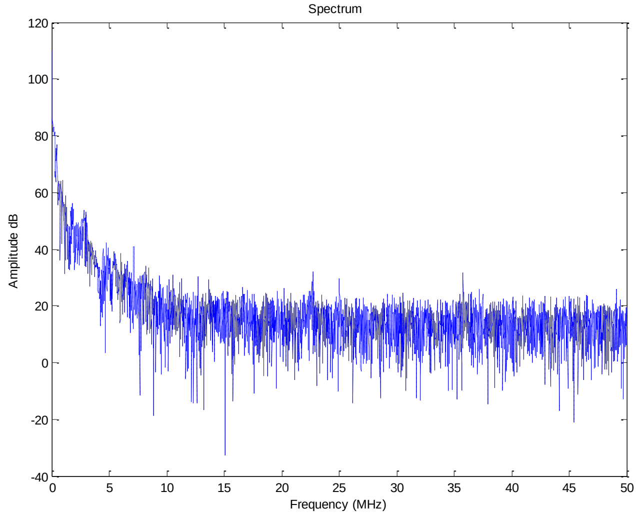

Figure 3. Power spectral representation of the magnetic waveform

As we can notice, the recorded field signal has frequency components extending from DC to 50 MHz. We notice from Fig. 2 that most of the energy is concentrated in the lower frequency range.

III. DENOISING THE MAGNETIC FIELD

A. *EMD Denoising Technique*

Any intricate signal could be brought down to a summation of its multiple components most of the time by a linear decomposition process such as the Fourier, the Wavelet, and many other processes Nedjah O. [2010]. The Empirical Mode Decomposition (EMD) technique is one method that separates the signal into its Intrinsic Mode Functions (IMF) without using any external dictionary, the process is empirical and follows the intrinsic content of the signal. Supposing that the signal is accompanied by noise that most of the time, is supposed to be independent and not correlated with the signal as described by the equation (1) , it is thought to be easy to separate from the EMD signal decomposition.

$$Y = s + \sigma z, \qquad (1)$$

where z is supposedly a Gaussian $N(0,1)$ additive noise and σ *is* the noise level.

To remove the noise from the signal in the EMD method of denoising, the noised signal is decomposed into its IMFs by a recursive method which searches the signal for its extremums at many levels. Those extremums will build the different modes or frequencies in time. The first mode is found by looking for the minimums and the maximums in the signal, then joining the maximums points together through interpolation and hence building a maximum curve $e_{max}(t)$. By the same process is built a minimum curve $e_{min}(t)$. A median curve m (t), is then, generated by calculating the mean values between the maximums curve and the minimums one eq. (2). This curve is then subtracted from the initial signal eq. (3) and the result is tested for if it represents an intrinsic component of the signal; if it responds to the criteria that its number of maximum peaks and minimum peaks are similar or they differ only by one peak. If so, it represents a one-tone wave which is called an IMF of the signal, if not the process is recursively repeated on the difference until the condition applies. Once the condition is met, the IMF is removed from the initial signal and the process is repeated on the difference until there are no more extremum in the data which will represent the residue or the DC part of the signal. This process is called sifting as we sift the signal to separate its intrinsic components Victor [2012]. The signal can be reconstructed by summing the different IMFs eq. (4).

To denoise a signal, the different IMFs, also called modes are analyzed and the parts of them that are likely appertaining to the noise are either removed or shrinked, then, the signal is reconstructed by summing the modes of interest. Hence the noise can be reduced by selecting only the modes that have no noise and the ones that have the noise part in them reduced.

$$m(t) = \frac{e_{\max}(t) + e_{\min}(t)}{2} \qquad (2)$$

$$r(t) = s(t) - m(t) \qquad (3)$$

$$s(t) = \sum_{i=1}^{N} C_i(t) + r_N(t) , \qquad (4)$$

where $C_i(t)$ is the ith IMF and $r_N(t)$ is the final residue.

B. *Magnetic Field Waveforms Denoising by the EMD*

As stated before in the magnetic waveform description, the first 20μs of the signal is supposed to be zero voltage as it corresponds to the time before the return stroke takes place that means; before the recording threshold is reached. Since there is a signal as we notice on Figure.1, this signal is due to the noise. The noise is present at all time during the recording and usually increases with the presence of a magnetic field surrounding the recording system. For some magnetic field signals as the one shown in Figure.4, the signal is in some order of magnitude as the noise, in this case it becomes difficult or sometimes impossible to determine the starting time of the recorded signal, which is important in the determination of the signal rise time. This is why it is important to get rid of the noise. To do so, the magnetic waveform is decomposed into its intrinsic modes as shown in Figure. 5, for the signal of Figure 1, and then the modes are analysed in the purpose of finding a strategy to remove the noise without affecting the useful signal. We note that the signals with less noise decomposed into 11 to 12 modes, while the signals with more variations decomposed into 13 or 14 modes. The High frequency modes such as the mode 1 and sometimes also the mode 2 that are supposed to appertain only to the noise, are removed as they don't present any variation linked to the signal. The higher frequency modes beyond the second one are shrinked by values proportional to the absolute value present in the noise only area of the signal. The modes that are more linked to the signal as the lower frequency ones, are kept in their integrity as their removal distorts enormously the signal.

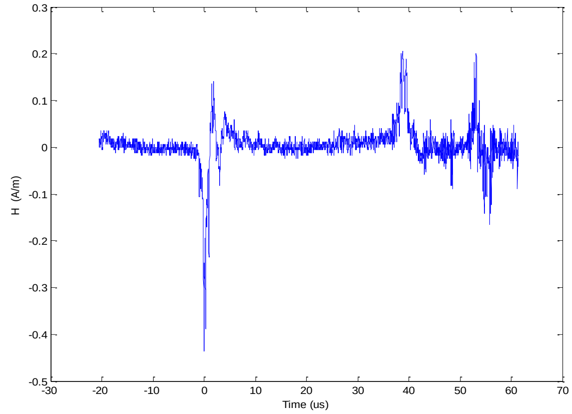

Figure 4 A low amplitude magnetic waveform

IV. RESULTS AND DISCUSSION

The achieved results consisted of SNR values improvement varying between 3 dB for the signals with high level signal amplitude compared to the noise level (a value of 57.5 dB for the denoised signal compared to a 54.75 for noised ones, such as the signal of Figure.6), and 5 dB for the more noisy ones (a value of 38.08 dB for the noisy signal versus 33.35 dB for the denoised one such as for the signal of Figure. 7). From the analysis of the different modes we also observed that many modulated signals were present in some modes as shown in Table.1 and Figure.8, from these modes contents we can note that the EMD technique cannot separate the non-linear components in a signal such the modulated ones.

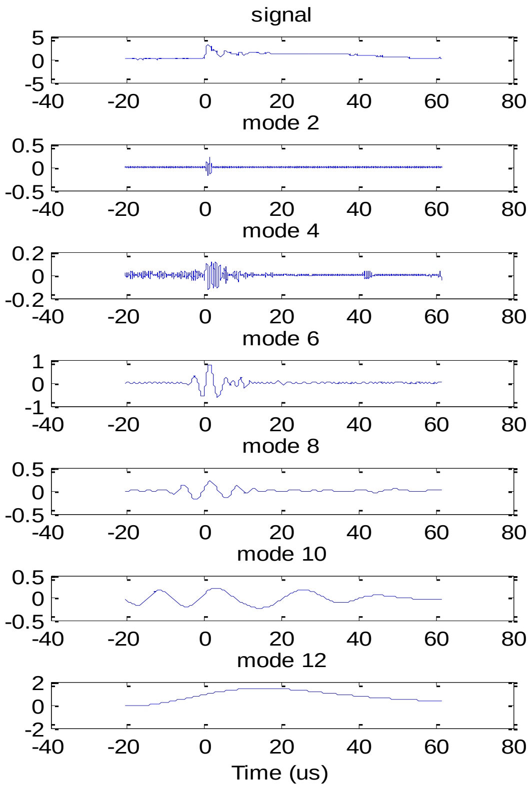

Figure 5. IMF's distribution of the Analysed magnetic waveform

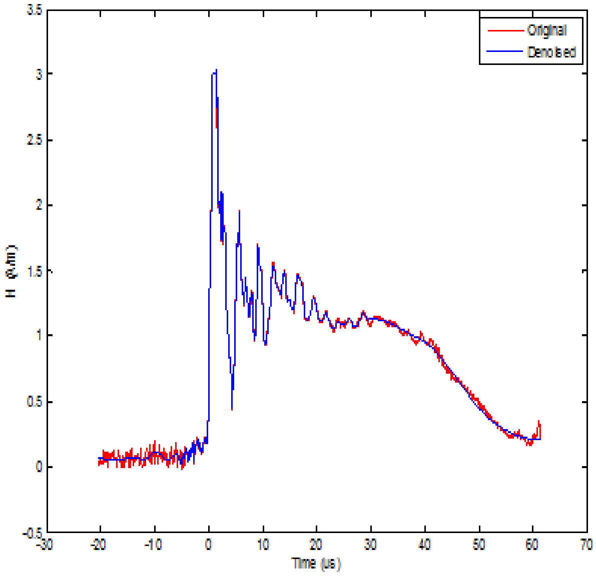

Figure 6. High amplitude denoised signal

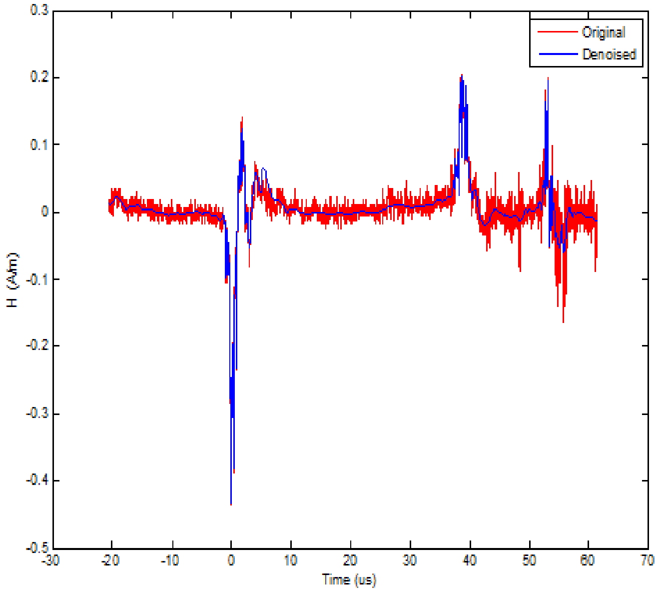

Figure 7. Low amplitude denoised signal

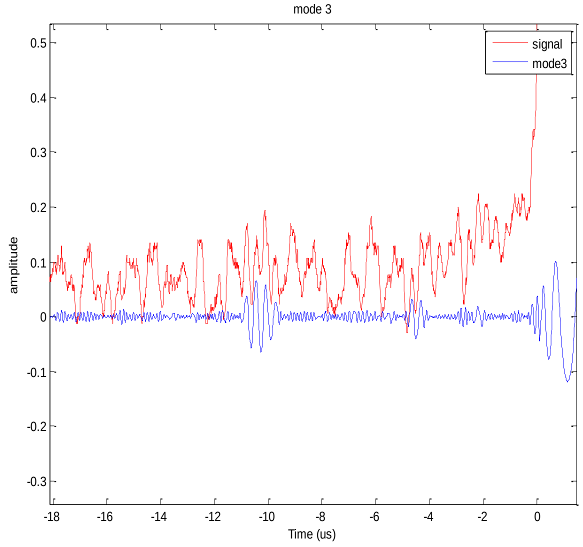

Figure 8. Modulated signals present in mode 3

Table 1. Frequency content of the different modes.

Mode	Area distribution	Modulating frequency	signal
mode1	All signal		33.33MHz 25MHz
Mode 2	All signal		11.11MHz
mode 3	All signal		5MHz
mode 4	All signal	230KHz	1.61MHz 4.55MHz
Mode 5	All signal		83kHz 1.54kHz
Mode 6	noise area Signal area		1.11MHz 400kHz
Mode 7	Signal area Noise area	454kHz	714kHz 217kHz
Mode 8	All signal		151kHz
Mode 9	All signal		111kHz
Mode 10	All signal	44kHz	76kHz
mode 11	All signal	28kHz	52kHz
Mode 12	All signal		33kHz

V. CONCLUSION

The EMD technique was used to denoise the lightning magnetic field recorded in the vicinity of the CN Tower. We noticed that this technique separates only the independent components of the signals while it fails in separating the correlated signals such as the modulated ones. We were able to notice that the signals transmitted and/or received from the CN Tower affects the lightning magnetic waveforms measured in the vicinity of the tower. With the adopted denoising technique, we were able to achieve up to 5 dB improvement of the SNR of the denoised signal compared to the noised one without major distortion of the waveform front-end.

REFERENCES

S. Kazazi, A.M, Hussein and P.Liatos, “Evaluation of the Performance Characteristics of the North American Lightning Detection Network Based on Recent CN Tower Lightning Data.” International Symposium on Lightning Protection (XIII SIPDA), Balneario Camboriu, Brazil, 2015.

A.M. Hussein, W. Janischewskyj, M. Milewski, V. Shostak, J.S. Chang and W. Chisholm, “Current waveform parameters of CN Tower lightning return strokes,” Journal of Electrostatics, Vol. 60, Nos. 2-4, pp. 149-162, March 2004.

W. Janischewskyj, AM Hussein, S. Kazazi, Hostack, I Rusan, J.X, Li and J.S. Chang, “ Statistics of Lightning Strikes to the Toronto CN Tower, (1978-1995), “IEEE Trans. Power Delivry, Vol. 12, No. 3, pp. 1210-1221, July 1997.

P. Liatos and A.M. Hussein, “Characterization of Noise in the Lightning Current Derivative Signals Measured at the CN Tower,” IEEE Transaction on Electromagnetic Compatibility, vol. 47, No. 4, pp. 986-997, November, 2005.

Norden E. Huang, “An Adaptive Data Analysis Method for Nonlinear and nonstationary Time series; The Empirical Mode decomposition and Hilbert Spectral Analysis”, Wavelet Analysis and Applications, Tao Qian, Mang I, Xu Yesheng, Eds. Applied and Numerical harmonic Analysis, 363-376@2006 Birkhauser Verlag Basel/Switzerland.

Nedjah O., Hussein A. “Denoising CN Tower Lightning Current Derivative Signals Using Empirical Modes Decomposition Method”, APL 2017, 10th Asia-Pacific International Conference on lightning, Krabi Resort, Krabi, Thailand, 17-19 May 2017.

O. Nedjah, A.M. Hussein, S. Krishnan, R. Sotudeh, “Comparative study of adaptive Techniques for denoising CN Tower lightning current derivative signals,” European Association for Signal Processing (EURASIP) Journal, Volume 20, Issue 2, pp. 607-618, March 2010.

Voctor, “Introduction to Empirical Mode Decomposition Method,” https//www.mql5.com/en/articles/439?print=

Ali M. Hussein,Mariusz Milewski, and Waasyl Janischewskyj, “Correlating the Characteristics of the CN Tower Lightning Reurn-Stroke Current with Those of Its Geneated Electromagnetic Pulse,”IEEE Transactions on Electromagnetic Compatibility, Vl.50, No 3, August 2008.