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New Monitoring Methods in Modern Lightning Location Systems and Their Applications

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***Abstract* -** A lightning monitoring system is used to observe, collect and analyze lightning activities so that a preventive measure to protect power equipment from severe damage can be planned. A proper system increases sustainability of the electrical energy supply. Regarding to this topic, no comprehensive review papers for evaluation of utilized technologies and their performances, are prepared. Owing to the literature gap, this paper is written to summarize the working principles of the relevant sensors and the various methods of data transmission, storage and analysis the acquisitioned data for localization of strike occurrence. Furthermore, new developed systems and compare of the detection techniques are also presented in this essay. The methods to transmit the required data of lightning signals are also discussed in details.

***Keywords* -** Sustainable energy, High Voltage, Lightning monitoring.

I. INTRODUCTION

Reliability is one of the most important factors in modern power system networks. A sustainable supply of electrical energy requires no collapse in power system and its apparatus. Furthermore, for distributed generation systems, it is important that the delivered energy from renewable sources (like wind turbines and photovoltaic arrays) will be maximized in order to recover the cost. Also concerning smart grid systems, the protection of sensitive equipment, such as control facilities and telecommunication must be given the priority.

It is ideal that power supplies be as robust as possible; however, a zero level of vulnerability is practically unattainable [1, 2]. In most cases, system disruptions and failures due to natural disasters, such as thunderstorm and severe lightning events, can interrupt the power supply to the consumers. More recently, the more frequent occurrence of extreme weather conditions due to global warming and the El Niño effect [3, 4] have also been identified as factors that reduces the reliability.

Concerning lightning phenomena, the resulting large voltage or current fluctuations can disrupt permanently or temporarily damage parts or components of the power system [5-7]. The most common scenario is a direct or indirect strike on exposed transmission cables, with the consequence of switchgears and relays tripping. In a more severe situation, a direct strike on a substation, can cause severe damage to the components of the power system for example voltage or current transformer explosion that result to a long recovery time. In a renewable energy system, the most vulnerable part is the power electronics parts. A direct or indirect lightning strike can result in a total collapse of generation capability. Very likely, the electronics equipment will have to be replaced. When we concern smart grid, there is a need to adequately protect the control facilities and telecommunication. They are the backbone of the distributed generation, and the loss of communication significantly reduces the effectiveness of the system. From the above discussions, it is clear that lightning discharge must be considered one of the main variables in estimating risk factors [8-10]. It has to be evaluated meticulously in order to adjust the cash flows of power supply plants [11].

Lightning is a transient discharge of static electricity that serves to re-establish electrostatic equilibrium within a stormy environment [12]. It is commonly characterized by an extremely high current, high voltage and short-lived electrical discharge. To reduce the risk of affect and damage by lightning event, various types of monitoring systems have been designed to detect and alert individuals of its eminent occurrence. It is important to note that lightning and other natural damaging factors cannot be prevented, but can be diverted or intercepted to a path that results in less damage [13].

Besides being used as an early warning system, monitored data can be used for the long-term meteorological evaluation, which in turn, can improve the understanding of worldwide climate change. As the interest in this issue has grown, substantial effort has been devoted to designing a reliable and cost-effective lightning monitoring system. With the proliferation of various commercial products using different concepts, the need to understand the principles behind their operations becomes more crucial. This is particularly vital when selecting the appropriate product for a particular meteorological condition or geographical location. Unfortunately, its importance has always been overlooked, even though the cost of a monitoring system is only a small fraction of the total investment of a power plant.

Despite the numerous published research studies carried out in this area, there appears to be an absence of a single, comprehensive review paper that evaluates the relevant lightning monitoring technologies and their performances. Owing to the literature gap, this review paper is written with the following goals in mind: to summarize the functions and working principles of the various sensors used in the system, to elaborate on the methods of predicting the occurrence of lightning strikes and their locations.

II. LIGHTNING LOCATION TECHNIQUE

A. *Lightning Locating System – LINET*

European lightning locating system (LINET) was designed in Germany, regarding to this system 30 electromagnetic sensors are installed around the country. Also, 65 sensors are installed in other different European countries. The established sensor network covers the most of European territory (Fig. 1). The LINET lightning locating system started to operate in the year 2006 [14].

- Ability to detect and locate the total atmospheric discharge with same locating error for inter-cloud (IC) and cloud-ground (CG) discharges;
- Good accuracy in localization of both IC and CG discharges of low current amplitude.
- Novel 3D technique for a reliable discrimination of CG and IC discharges.
- Altitude reports for IC discharges;
- Locating accuracy up to 100 m.

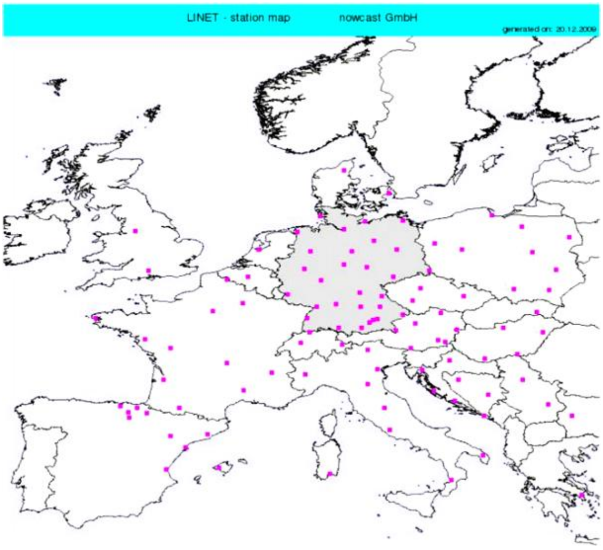

Fig. 1. Location of LINET sensors in Europe [14]

The LINET sensors measure the density of magnetic flux directly into the dependence of time. This feature is useful for the treatment of small signals. Magnetic flux component of detected signals are measured using orthogonal loop (antenna) in real time. Amplified value is induced current, not voltage, and as a result, the time dependence of the magnetic induction in the range 0.1 to 130 nT is obtained [15].

The system LINET uses TOA (Time–Of–Arrival) method for determining the location of lightning impact assisted with method for determining the direction (DF, eng. Direction Finding). Primarily TOA method is used for determining the location, where minimum four detection sensors are required. By combining TOA and DF methods the discharge can be detected by two or three sensors, but in this case, the location determine error is increased [14]. In the LINET important components are optimized to determinate all lightning discharge, including the amplitude factor which is less than 5 kA, resulting that sensors should not be too far away [16].

LINET utilizes the same VLF and LF method for detection of IC and CG lightning strikes[4]. Special consideration should be noted into account to distinct two types of lightning [17].

For this reason, a new three-dimensional (3D) geometric algorithm for VLF - LF networks was developed [5]. The procedure relies on the well-known fact that CG strikes broadcast VLF- LF discharge dominant in ionized channel near the ground level, while IC discharge occurS in the ionized channel between clouds, high above the ground [18].

The corresponding differences in time spreading of electromagnetic waves (Fig. 2) caused by high and low centers of stationary discharge were used to locate the discharge position. This method is satisfactory, as long as the distance between the lightning stroke and the nearest sensor does not exceed 100 km (corresponding to distance between sensors of 200 km), or differences in results of this method become too small to be noticeable [4]. All the signals are processed regardless of their waveform; this is possible because the ICCG resolution is carried out using specially developed 3D algorithms in the central processing unit, not with measurement of waveform in sensors. This 3D technology is very reliable, especially if it is possible that the minimum distance between the sensors does not exceed 200 to 250 km.

Particular efforts were made to achieve high location accuracy in monitored area. Today, it is achieved that the mean location accuracy is approximately 100 m [6].

Output data is discharge time, location, current amplitude (including sign), the division between IC and CG discharge, discharge height for IC and 2D locating error.

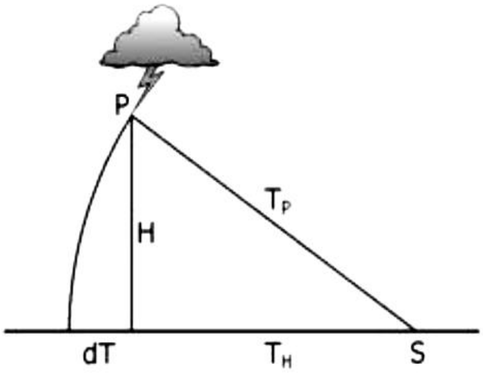

Fig. 2. The principle of detection of IC discharge - IC and CG signals from the same 2D location come from the time difference dT = TP-TH (P = VLF emission center, S = sensor location; H = height of emission source) [13].

LINET is capable of detecting multiple-stroke flashes where every stroke is represented by individual set of data. A LINET sensor consists of two passive parts: the GPS antenna and the antenna for measuring magnetic flux (two orthogonal cooper rings); and one active unit – the sensor PC. Such sensor design enables the sensor to be very cost effective with a straightforward installation (Fig. 3).

Fig. 3. LINET sensor antennas (orthogonal rings) and GPS antenna [14]

B. FORTE Photodiode Detector

We use optical lightning data from the photodiode detector (PDD) on the Fast On-Orbit Recording of Transient Events (FORTE) satellite [19].

The PDD is a no imaging silicon photodiode which gets light from a circular field of view of diameter 1200 km at ground level. Because the PDD is non imaging, any event it detects can be located only at 1200 km distance. The PDD is so designed to be triggered by a rising optical signal. When the signal level exceeds the threshold and a trigger occurs, a 128-sample register is stored in memory, including 32 samples preceding and 96 samples following the trigger.

The sample step is 15 ms, so the record duration is about 1.9 ms. The FORTE satellite is in a circular orbit at 800 km altitude. Thus the PDD ‘‘spotlight’’ sweeps out the entire region where lightning is found on Earth [20] .

As noted before PDD instrument is satellite based, it observes lightning from above, meaning that it can only detect light that crosses from the cloud tops. Previous researches have shown that the majority of

PDD detected events are related to in cloud (IC) lightning , although the PDD is also able to detect scattered light a cloud to ground (CG) lightning stroke [21].

It has been shown that PDD has an efficiency of detection lower than, but constant relative to, LIS detection efficiency over all areas of the world. Thus we are confident that PDD data serve as an adequate proxy for OTD or LIS data, with the proviso that the PDD locates lightning only to within the 1200 km diameter circle, as opposed to an individualized pixel of an image device. An advantage of PDD for this study is that we can examine optical waveforms relative to the VLF lightning trigger. For this study we assume equal PDD detection efficiencies for ocean and land.

C. *World Wide Lightning Location Network*

The WWLLN provides real-time lightning locations globally by detecting, from 28 stations worldwide, the VLF radiation emanating from lightning discharges. For a lightning stroke to be accurately detected with error analysis, the VLF radiation from the stroke is required to be detected at a minimum of 5 of these 28 receivers. Each receiver locally processes a stroke's waveform and sends the time of group arrival to the central processing station for location [22].

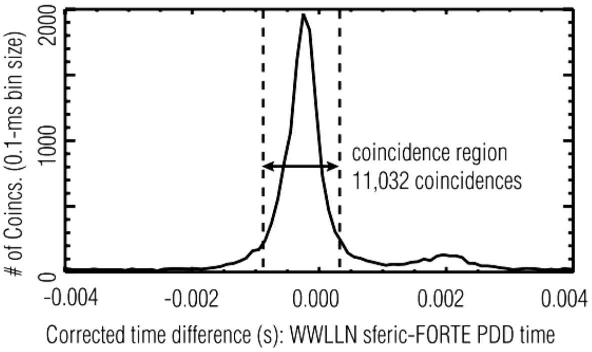

Fig. 4. Histogram of time difference of WWLLN time minus FORTE PDD trigger time, corrected for optical signal delay to satellite. The peak occurs at approximately 250 ms, indicating that the PDD is triggered 250 ms after WWLLN detects [14].

In this manner, the WWLLN provides continuous lightning detection coverage of the entire globe [23]. The location accuracy and efficiency of the WWLLN have been estimated for certain regions by comparison to regional, ground-based lightning detection systems. Rodger et al. completed a comparison of WWLLN data in Australia to the local Australian lightning location network and found a detection efficiency of 26% of CG strokes in Australia and 10% of IC strokes, with a location error of 4.2 ± 2.7 km. By comparison to the Los Alamos Sferic Array (LASA) in the southeastern U.S., Jacobson et al. found that WWLLN detects 4% of all strokes, CG and IC, with peak current greater than 30 kA, and detects with a spatial accuracy of 15 km. Of the coincident events between WWLLN and LASA, 26% were IC lightning. Rodger et al. found a similar result by comparison to the New Zealand Lightning Detection Network (NZLDN) of flat detection efficiency for strokes with peak currents larger than 40 kA.(Fig.4)

These previous comparisons to ground-based networks have provided essential information regarding location and timing accuracy of the WWLLN. However, we cannot study the efficiency of WWLLN on a global scale using ground-based networks as a reference. Thus the comparison of WWLLN-located lightning strokes to optically detected waveforms measured by the FORTE-PDD instrument is the first global comparison using the WWLLN data set and is intended to verify the relative detection efficiency of WWLLN, in all regions, and over land versus over ocean. After the verification of the relative detection efficiency, we can expand our analysis to the entire WWLLN data set, as opposed to being limited by WWLLN events coincident with PDD-measured optical events [24].

D. *Magnetic direction finder (MDF) method*

Magnetic direction finder (MDF) is a method used to determine the location, movement and intensity of lightning. The observational data can be displayed textually or/and graphically. The MDF method can be implemented by using a vertical and orthogonal magnetic loop/cross loop antenna and a flat plate antenna [25]. Fig. 5 shows the types of MDF antennas [26, 27].

Two types of cross loop MDF (CL/MDF) antennas are introduced which utilize in lightning detection : 1-narrow band (tuned) CL/MDF and 2-gated wideband CL/MDF [28]. Narrow band CL/MDF operates in a very narrow frequency band, with the center frequency in the range of 5–10 kHz. At this frequency, the lightning signal energy is quite high comparing to total energy, and the attenuation in the earth ionosphere waveguide is quite low. It is important to note that there are several disadvantages of narrow band CL/MDF for lightning distance less than 200 km. The inherent azimuthally error (polarization error) will occur. This error results from the detection of magnetic field components from the non-vertical (horizontal) channel. The magnetic field lines of circles in a plane are perpendicular to the non-vertical channel.

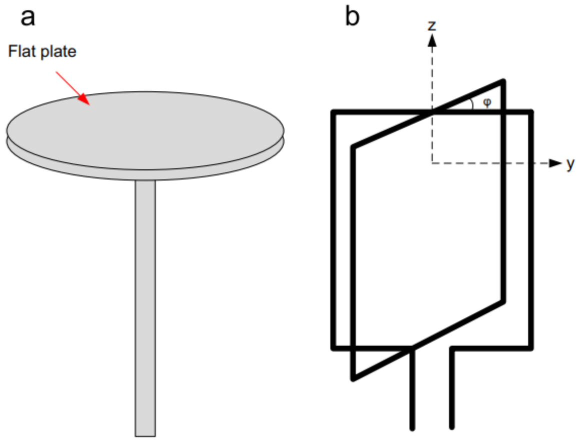

Fig. 5. (a) Flat plate antenna, (b) cross loop antenna [15].

A wideband CL/MDF is introduced to solve the problem of large polarization errors in narrow band CL/MDF. The north–south and east–west components of the initial peak of the return strike magnetic field were sampled to achieve gated wideband CL-MDF. Gated wideband CL/MDF has an operating bandwidth from a few kilohertz to 500 kHz [8].

Both narrow and gated wideband CL-MDF are susceptible to site error [29]. Site error can be defined as a systematic function of direction, but generally, it is time-invariant. The presence of unwanted magnetic fields– non-flat terrain and nearby conducting objects, such as underground and overhead power lines and structures – is the source of the errors. To avoid this problem, the area surrounding the CL-MDF must be flat, and no conducting objects can be close to the area.

E. *Time of arrival (TOA) method*

The time-of-arrival (TOA) method is able to determine the location of lightning accurately by using at least two stations [30]. The distance is obtained by calculating the arrival time of the lightning's electromagnetic signal at the stations because the velocity of signals in space is a constant [31-32]. The time-of arrival differences among remote stations will be calculated, and this will result in several time-difference hyperbolas. The intersection of the hyperbolas will be assumed to be the location of the lightning strike [33].

The TOA method uses three types of lightning location, which are as follows: (1) very short baseline (ten to hundreds of meters), (2) short baseline (tens of kilometers) and (3) long baseline (hundreds to thousands of kilometers). Very short baseline and short baseline commonly operate at VHF 30–300 MHz, whereas long baseline usually operates at VLF 3–300 kHz. Generally, the VHF is related to the air breakdown process [34, 35], while the VLF signal results from current flow in the lightning channels [36].

For the very short baseline, the time difference between the arrivals of an individual lightning strike's VHF pulse at the receivers is shorter than the time between the pulses; it is in the microsecond to hundred microsecond range. Short baseline generally purports to offer electromagnetic images of lightning channels and to study the spatial and temporal development of the discharge. Long baseline is commonly used to classify the ground strike point and the location of the flash. The long baseline system is known as the Lightning Position and Tracking System (LPATS). LPATS has been established since the 1980s, and it can operate at VLF/LF. The LPATS sensor has a higher sensitivity in terms of detecting lightning strikes as compared to IMPACT. This sensor is expensive due to the high operating cost [33].

Another important method is a wideband sensor, which utilizes the TOA method. The Earth Networks Weather Bug Total Lightning Network (WTLN) is a lightning detection network that employs a wideband sensor to detect both cloud to ground (CG) and inter cloud (IC) flash signals [37]. The real time lightning cell tracking system and the subsequent dangerous alert system can be provided by using WTLN total lightning data.

F. *Video Camera and acquisition software*

The system used in this work in order to capture short length videos of lightning events over an area is composed mainly by: a video camera, a GPS device and software that processes and store the information on a PC.

In order to obtain a time stamp along with the video image, the GPS time signal was mixed with the video signal [38] and then processed through commercial software [39] that monitors a fixed image:

in the event of a change on it, it was programmed to record 2s of video before and after the event. For all the videos obtained, the depuration of the information in order to discard videos not corresponding to lightning events was done manually. An example of a photograph obtained from this system is shown in Fig. 6.

Fig. 6. Lightning event captured by the video camera system [16].

The camera location allowed having a view of an important percentage of the region occupied by the city of Medellin. Based on geographical references as buildings and mountains, the coverage area of the camera was obtained using Google Earth [40] and resulted in about 30% of the total area occupied by this city. From this analysis, the camera was able to capture videos of events occurring at distances up to 20 km approximately from its location as shown in Fig.7. Note that events not causing significant changes on the video image, given the low resolution of the camera, were not recorded.

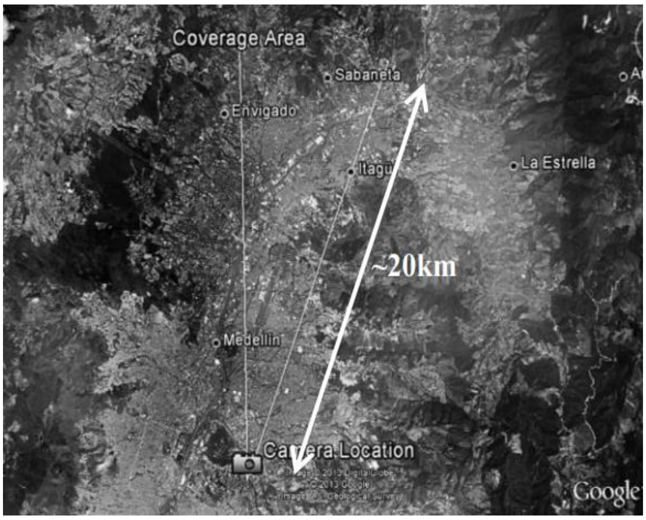

Fig. 7. Video Camera - Covering area [16].

III. OVERVIEW OF LIGHTNING MONITORING SYSTEM

There are two categories of lightning monitoring, namely earth- and space-based systems. In this review, only the former is considered. Generally, lightning monitoring and detection systems have the same objective, that is, to predict the location and intensity of lightning occurrences. The main components are the sensors. In a typical system, the sensors configuration varies. It may consist of (1) several atmospheric electric field (AEF) sensors along with lightning sensors or (2) lightning sensors alone. The advantage of the former configuration is that it can track thundercloud development processes and movements. Therefore, it provides an opportunity to predict the thunderstorm's location before it appears. Using the latter, such predictions cannot be achieved.

Other components of a sensing system include a signal conditioning unit to process the output signal from the sensor. Generally, it consists of a signal amplifier and filter components. It may also involve a microcontroller to manage the input and output signals from the signal conditioning unit. Then, the conditioned signal will be transmitted in the form of an analogue or digital signal, depending on the data transmission protocol adopted. Finally, the data are collected and stored in a computer system. They will be analyzed using certain mathematical prediction tools, and the results will be used for further actions. Fig. 7 shows the general block diagram of a typical lightning monitoring system.

IV. ATMOSPHERIC ELECTRIC FIELD (AEF) AND LIGHTNING SENSOR

AEF sensor is a device that is used to sense the presence of an electric field in the atmosphere. It monitors the magnitude of the atmospheric electric field between the clouds and the ground. The characteristics of lightning can be discovered by measuring the atmospheric electric field (AEF), which is produced by the motion of an electric charge within the clouds. The changes in the magnitude and polarity of the AEF can be observed during thundercloud formation and lightning discharge. The ability to measure the AEF enables the following: (1) identifying the thunderstorm's duration; (2) differentiating between the various storm stages characteristics; (3) estimating the values of the lightning parameters, such as transferred charge characteristics; and (4) predicting the location of lightning occurrences [41].

Furthermore, by knowing the trends in AEF variation, one can predict the future weather conditions. For example, in normal fair weather, the AEF (close to the ground) is 100–200 V/m, while during a storm; this value can increase by as much as four orders of magnitude. Furthermore, lightning occurrence can be detected by measuring fast variations characterized by short AEF pulses [42].

The electric field mill is the most popular device, but other types, such as electro-optic integrated sensors, flat plate antennas, micro-machined electrostatic sensors, passive optical lightning sensors and photon and infrasound detection systems, are also used [42-43]. For an accurate measurement, the sensor must be installed far from buildings, trees and other tall objects. The lightning sensor has a similar general objective to the AEF sensor, that is, to monitor lightning occurrences. The difference, however, is that the lightning sensors detect this by means of an electromagnetic field, which is the combination of the electric and magnetic fields. The AEF sensor provides critical lightning information, which provides an advanced warning before lightning actually strikes.

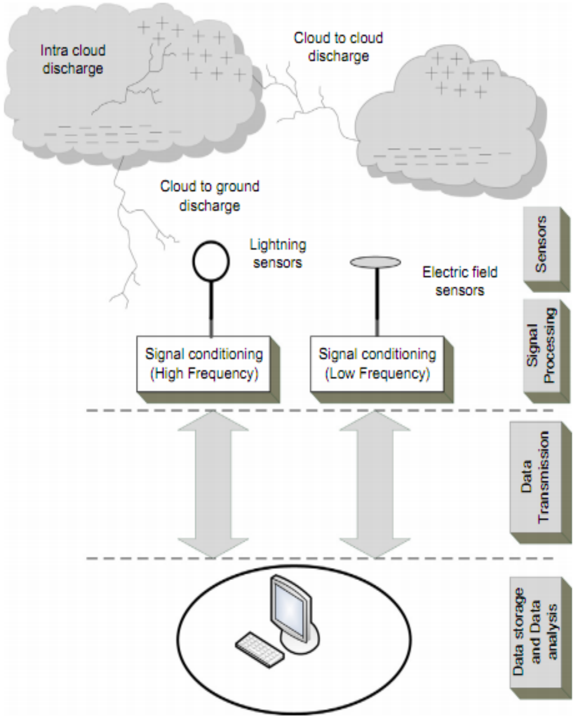

Fig. 8. General block diagram of lightning monitoring system.

V. CONCLUSION

This essay reviews and summarizes lightning monitoring systems according to their data acquisition systems and technologies based on various academic journals. This paper provides the working principal and structure of each method/sensor in every lightning monitoring system that has been constructed. Furthermore, it reviews the methods of data transmission, data storage, data observation and data analysis. It is difficult to discuss the details of every sensor/method because every sensor/method has its own benchmarking. Therefore, this paper includes only a general discussion of the structure and working principle of each method/sensor. It is hoped that the information in this paper can be a source of information for future research.

VI. REFERENCES

[1] Verbruggen A, Laes E, Lemmens S., *Assessment of the actual sustainability of nuclear fission power*, Renewable Sustainable Energy Rev 2014;32:16–28

[2] Kandilli C, Ulgen K., *Review and modelling the systems of transmission concentrated solar energy via optical fibres*, Renewable Sustainable Energy Rev 2009;13(1):67–84.

[3] Bo Z, et al., *An analysis of previous blackouts in the world: lessons for China' s power industry*, Renewable Sustainable Energy Rev 2015;42:1151–1163.

[4] Mabel MC, Raj RE, Fernandez E., *Analysis on reliability aspects of wind power*, Renewable Sustainable Energy Rev 2011;15(2):1210–1216.

[5] Saidur R, et al., *Environmental impact of wind energy*, Renewable Sustainable Energy Rev 2011;15(5):2423–2430.

[6] Eltawil MA, Zhao Z., *Grid-connected photovoltaic power systems: technical and potential problems—a review*, Renewable Sustainable Energy Rev 2010;14 (1):112–29.

[7] Cooperman A, Martinez M., *Load monitoring for active control of wind turbines*, Renewable Sustainable Energy Rev 2015:189–20141 2015:189–201.

[8] Joselin Herbert G, Iniyan S, Amutha D., *A review of technical issues on the development of wind farms*, Renewable Sustainable Energy Rev 2014:619- 641.

[9] Hameed Z, et al., *Condition monitoring and fault detection of wind turbines and related algorithms: a review*, Renewable Sustainable Energy Rev 2009;13 (1):1–39.

[10] Kaundinya DP, Balachandra P, Ravindranath N., *Grid-connected versus standalone energy systems for decentralized power—a review of literature*, Renewable Sustainable Energy Rev 2009;13(8):2041–2050.

[11] Wu C, et al., *Multistage stochastic inexact chance-constraint programming for an integrated biomass-municipal solid waste power supply management under uncertainty*, Renewable Sustainable Energy, 2015, 1244–5441.

[12] Sidik MAB, et al., *Study on the effectiveness of lightning rod tips in capturing lightning leaders,* Electr Engin 2013;95(4): 367–81.

[13] Betz H. D., Kulzer R., Gerl A., Eisert B., Oettinger W.P., Jakubassa D., *On the Correlation between VLF-Atmospherics and Meteorological data,* ICLP Firence, 1996.

[14] Betz H. D., Schmidt K., Fuchs B., Oettinger W.P., Hoeller H., *Cloud Lightning: Detection and Utilization for Total Lightning Measured in the VLF/LF Regime*, Journal of Lightning Research, August 2007.

[15] Betz H. D., Oettinger W.P., Schmidt P., Wirz M., *Modern Lightning Detection and Implementation of a New Network in Germany, Europe,* European Geosciences Union 2005, Geophysical Research Abstracts, Vol. 7, 00685,2005.

[16] Betz H. D., Schmidt K., Laroche P., Blanchet P., Oettinger W.P., Defer E., *LINET – A new lightning detection network in Europe*, 13th International Conference on Atmospheric Electricity, August 13-18, 2007., Beijing, China.

[17] Fishman, G. J., et al. (1994), Discovery of intense gamma-ray flashes of atmospheric origin, Science, 264, 1313 – 1316.

[18] Fukunishi, H., Y. Takahashi, M. Kubota, K. Sakanoi, U. S. Inan, and W. A. Lyons (1996), *Elves: Lightning-induced transient luminous events in the lower ionosphere*, Geophys. Res. Lett., 23, 2157 – 2160.

[19] Goldberg, R. A., J. R. Barcus, L. Hale, and S. A. Curtis (1986), *Direct observation of magnetospheric electron-precipitation stimulated by lightning*, J. Atmos. Terr. Phys., 48, 293 – 299.

[20] Hays, P. B., and R. G. Roble (1979), *A quasi-static model of global atmospheric electricity: 1. The lower atmosphere*, J. Geophys. Res., 84, 3291 –3305.

[21] Holden, D. N., C. P. Munson, and J. C. Devenport (1995), *Satellite observations of transionospheric pulse pairs*, Geophys. Res. Lett., 22, 889 – 892.

[22] Holzworth, R. H., R. M. Winglee, B. H. Barnum, Y. Q. Li, and M. C. Kelley (1999), *Lightning whistler waves in the high-latitude magnetosphere*, J. Geophys. Res., 104, 17,369 – 17,378.

[23]] Ibrahim, W, M Ghazali, *Measurements of electric and magnetic fields due to lightning strokes based on single-station detection*, In: IEEE Asia Pacific conference on applied electromagnetics (APACE2012), Avillion Legacy Melaka; 2012 .

[24] Ibrahim, WI, et al., *Measurement of vertical Electric fields from lightning flashes using parallel plate antenna*, In: International conference on electrical, control and computer engineering (INECCE); 2011.

[25] Sharshar, AA, SH Zainud-Deen, SM El-Halafawy, *Crossed square loop antenna. In: IEEE antennas and propagation society*, international symposium Digest, 1997; 1997.

[26] Rakov V., *Electromagnetic methods of lightning detection*, Surv Geophys 2013:1–23.

[27] Tao, L, C Mingli, D Yaping, *Site errors estimation and correction for MDF/TOA combined lightning location network*, In: International conference on lightning protection (ICLP); 2012.

[28] Nastos P, Matsangouras I, Chronis T., *Spatio-temporal analysis of lightning activity over Greece—preliminary results derived from the recent state precision lightning network,* Atmos Res 2014:207–17144 2014:207–17.

[29] Fagan, D, R Meier, *Intelligent time of arrival estimation*, In: IEEE forum on integrated and sustainable transportation system (FISTS); 2011.

[30] Yoshida S, et al., *Initial results of LF sensor network for lightning observation and characteristics of lightning emission in LF band*, J Geophys Res Atmos 2014;119(21) 12,034-12,051.

[31] Ahmad, H, M Alam, *Review of lightning warning system: technical and economic aspect*; 2008.

[32] Takai H, et al., *Lightning detection at the telescope array cosmic ray observatory,* Bull Am Phys Soc 2014:59.

[33] Behnke S, McNutt S., *Using lightning observations as a volcanic eruption monitoring tool*, Bull Volcanol 2014;76(8):1–12.

[34] Dentel LM, da Rocha BRP, de Souza JRS, *Evaluation of STARNET lightning detection performance in the Amazon region*, Int J Remote Sens 2013;35 (1):115–26.

[35] Chonglin, L, S Heckman, *Using total lightning data in severe storm prediction: global case study analysis from North America, Brazil and Australia*, In: International symposium on lightning protection (XI SIPDA); 2011.

[36] Betz H. D., Schmidt K., Laroche P., Blanchet P., Oettinger W. P., Defer E., Dziewit Z., Konarski J.: “LINET – An international lightning detection network in Europe“, 2007.

[37] Ibrahim, WI, et al., *Measurement of vertical Electric fields from lightning flashes using parallel plate antenna*, In: International conference on electrical, control and computer engineering (INECCE); 2011.

[38] Tao, L, C Mingli, D Yaping. *Site errors estimation and correction for MDF/TOA combined lightning location network*, In: International conference on lightning protection (ICLP); 2012.

[39] Motion Capture Software – UFOCapture, available in: http://sonotaco.com/e_index.html.

[40] Satellite Images of Colombia in Google Earth®, available in: http://earth.google.com.

[41] Aranguren, D, et al., *Estimation of lightning electrostatic parameters based on atmospheric electric field measurements and genetic algorithms,* In: Proceedings 2006 ILDC/ILMC conference, Tucson, AZ, USA; 2006.

[42] Fort, A, et al., *Design and modeling of an optimized sensor for atmospheric electric field measurement*, In: IEEE sensors applications symposium (SAS), 2010; 2010.

[43] Renno NO, et al., *A miniature sensor for electrical field measurements in dusty planetary atmospheres*, J Phys Conf Ser 2008;142(1):012075.