Lightning monitoring system for sustainable energy supply: A review

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Abstract

A lightning monitoring system is used to observe, collect and analyse lightning activities so that a preventive measure to protect power equipment from severe damage can be planned. An effective lightning monitoring system is crucial to ensure the reliability and sustainability of the electrical energy supply. Despite numerous published papers on this topic, there seem to be an absence of comprehensive review papers that evaluate monitoring technologies and their performances. Owing to the literature gap, this paper is written to summarise the working principles of the relevant sensors and the various methods of data transmission, storage and analysis, as well as the various ways of predicting the occurrence of lightning strikes. This knowledge will contribute to the development of a new online lightning detection system that will be more efficient, without reducing the effectiveness and sensitivity of the system, by utilizing the available technology for data transmission and analysis.

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1. Introduction

Reliability is a crucial aspect of modern electrical power supply—regardless whether the system is conventional or distributed generation. A sustainable supply of energy requires that the transmission and distribution of electrical power are guaranteed. Particularly for a distributed generation system, it is inevitable that the available energy from renewable sources (e.g., wind turbines and photovoltaic arrays) will be maximized in order to recover the high capital cost. In addition, with the expected proliferation of smart grid systems, the protection of sensitive equipment, such as telecommunication and control facilities (in smart distributed generation), must be given the priority.

Ideally, it is desirable that these power supplies be as robust as possible; however, a zero level of vulnerability is practically unattainable [1,2]. In many cases, system failures or disruptions due to natural disasters, such as severe lightning and thunderstorm events, can interrupt the energy supply to 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 exaggerate the problem.

For a lightning discharge, the resulting large current and/or voltage fluctuations can temporarily disrupt or permanently damage parts or components of the power supply chain [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, for example, can cause damage to the components of a distribution system (transformers, relays and switches)—resulting in a long recovery time. In a renewable energy system, the most vulnerable part is the power electronics equipment (dc-ac, dc–dc). A lightning strike (direct or indirect) can result in a total collapse of generation capability. Very likely, the electronics equipment will have to be replaced. As far as a smart grid is concerned, there is a need to adequately protect the telecommunication and control facilities. 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 characterised by an extremely high current, high voltage and short-lived electrical discharge. To reduce the risk of being damaged or affected by lightning, various types of monitoring systems have been developed to detect and alert individuals of its eminent occurrence. It is important to note that lightning phenomena cannot be prevented, but they can be intercepted or diverted 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: (1) to summarise the functions and working principles of the various sensors used in the system, (2) to elaborate on the methods of predicting the occurrence of lightning strikes and their locations and (3) to describe the periphery instrumentation required for data transmission, storage and analysis. At the end of the paper, a brief comparison of the commercially available lightning monitoring systems is also provided. To complement the analysis, an exhaustive list of references is provided for those interested in further probing the issues raised in this paper.
2. 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 sensor 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 analysed using certain mathematical prediction tools, and the results will be used for further actions. Fig. 1 shows the general block diagram of a typical lightning monitoring system.

3. Atmospheric electric field (AEF) and lightning sensor

An 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 stage characteristics; (3) estimating the values of the lightning parameters, such as transferred charge characteristics; and (4) predicting the location of lightning occurrences [14]. 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 [15].

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 [15–26]. 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.

3.1. Electric field mill (EFM)

One of the most widely-used AEF sensors is the electric field mill (EFM). It functions by detecting the charge induced on the sensor electrode. In principle, the EFM measures the electric field by alternately exposing and shielding the conductor in the atmosphere, as shown in Fig. 2. The fixed induction conductor is known as a stator, while the rotated conductor that alternately shields the stator is known as the rotor. Therefore, the periodic changes in the electric field signals can be acquired accordingly. When the sensor plate is shielded by the rotor, the sensor plate is charged with an electric field [15,16,18,19]. The number of vanes in the stator and rotor can be varied, depending on the design of the EFM.

The charges induced from the electrostatic field can be expressed as follows: [27]

\[ q = \int D \, dA = \varepsilon_0 E A |C| \]  

(1)

The output voltage of EFM, \( V_o \), is given by

\[ V_o = \frac{\varepsilon_0 E A}{2C} [V] \]  

(2)

where \( D \) is electric flux density, \( \varepsilon_0 \) is the permittivity of the medium of the measuring field, \( E \) is the electric field, \( A \) is the area and \( C \) is the sensor variable capacitance. The electrostatic electric field can be calculated as shown in Eq. (3) [17].

\[ E = \sum_{i=1}^{n} \frac{Q_i H_i}{2\pi\varepsilon_0 (H_i^2 + L_i^2)^{3/2}} [V/m] \]  

(3)

where \( Q_i \) is the volume of the charge region, \( L_i \) is the horizontal distance between the observation point and each charge region.
and $H$ is the total distance to each charge region. The measured electric field will become larger and larger as the charges of the cloud increase and approach the electric field mill.

The atmospheric electric field is approximately perpendicular to plane surface [20,28]. Even though the electric field mill is far from perfect, the technology has improved over time. Table 1 shows the summary of the types of EFMs and their features.

### 3.2. Integrated electro-optic sensor

AEF measurement using an integrated electro-optic sensor can reach close to 1000 kV/m [29]. This sensor exhibits several advantages: (1) It has a non-lensing system, which is necessary in a high-voltage environment; (2) it is easy to assemble and (3) it does not require earthquake-proofing, because the system is fully integrated before being placed in the high-voltage environment.

The structure of an integrated electro-optic sensor head utilises a Mach–Zehnder interferometer, as shown in Fig. 3. The input light is divided into two equal parts by a left Y-coupling and is then transmitted through two horizontal waveguides, namely Waveguides 1 and 2. The light that travels through Waveguide 1 is modulated by an electric field. Then, the waveguides interfere with each other at the right Y-coupling. The output power of the sensor is an optical signal that is proportional to the applied signal. There is a path difference of one quarter of the wavelength between these two waveguides, which forms an optical bias of $\pi/2$. This is desirable because it allows the sensor to be driven without a DC bias voltage and allows the output to vary linearly with the input voltage.

The popularity of integrated optical electrical field sensor continued to grow until 2011; three variations have been developed [30–32]. These sensors have been designed and fabricated with various features, as shown in Fig. 4: (a) with a vertical dipole with two electrodes, (b) with a horizontal dipole with two electrodes and (c) with a single-shield electrode. These sensors are fast and strong enough to measure AEFs up to 89.0 kV/m, 20 kV/m and 20 kV/m at a rate of 500 samples per seconds. In addition, they are fast and strong enough to measure AEFs up to 89.0 kV/m, 20 kV/m and 20 kV/m at a rate of 500 samples per seconds.

![Fig. 3. Structure of integrated electro-optic sensor head using a Mach–Zehnder interferometer.](Image 170x324 to 431x387)

### Table 1

|| Author | Type of EFM | Features |
|---|---|---|
| Hui [16] | Three-dimensional EFM | • A double electrode difference structure was applied in both the axial ($z$) stator and the radial ($x$, $y$) stators. • The axial stator has two interlaced induction electrodes, which have the same size and shape as a rotor, while the radial stator has two pairs of planar electrodes with the same shape and size that are perpendicular to one another. • Can reduce the measuring error effectively and improve the sensitivity, precision and reliability. • Is simplified in that the cost and energy consumption are reduced by excluding the earthing brush and photoelectricity synchrodetector. |
| Fort [15] | Optimized version of the field mill sensor | • The instrument body of the EFM is mostly made of aluminium, but some critical parts are made from stainless steel: the shutter, disk sensor and body cap. • Waterproof and easy to assemble. • Consists of a rotating shutter, sensors, shield, front end, motor control electronics and acquisition processing data storage. |
| Fort [21] | Boltek EFM-100 | • Data logging capabilities and GPS receiver. |
| Fort [21] | Vaisala EFM 550 | • Data logging capabilities and GPS receiver. |
| Zhu [17] | AMEO340 | • Detects lightning location in the range 0–20 km and has a measuring range from $–100$ kV/m to $+100$ kV/m. |
| Bennett [22–23] | JCI 131 | • No earthing of rotating chopper. • Has large gaps and long insulation tracking paths in the sensor unit to operate in a wet environment. |
| Piazzon [24] | Campbell scientific CS110 | • Uses a reciprocating shutter that is electrically connected to the ground potential. |
| Aranguren [25] | Field mill network of Bogota | • Can cover 196 km² area by using five electric field mills, with which it can measure the vertical electric field network. • Each mill can detect electric fields between $–20$ kV/m and $20$ kV/m at a rate of 500 samples per seconds. |
| Renno [26] | Miniature sensor of cylindrical field mill | • Developed an isolated electric field mill that can remove the error caused by wind-borne charge transfer. • The electric field ranges between 50 V/m and $1 \times 10^6$ V/m. |

### References

[A16–29] These references have been cited throughout the text.
The fundamental principle of electro-optic modulation is based on the phase shift of the light wave during propagation, i.e.,

\[ \varphi = \frac{n^2 \pi L \Gamma}{d} V \]

where \( n \) is the intrinsic refractive index of the crystal. The refractive index of some electro-optic crystals, such as lithium niobate (LiNbO\(_3\)), will vary when exposed to the electric field. The variable \( r \) is the electro-optic coefficient corresponding to the polarization of the electric field, \( L \) is the length of the electrode, \( \lambda \) is the wavelength, \( V \) is the voltage across the gap \( d \) and \( \Gamma \) (\(< 1\)) is the overlap factor of the electric field with the light wave in the crystal.

The modulator output of the optical power can be expressed as follows:

\[ P_o = \frac{P_i}{2} \left[ 1 + \cos(\Delta \varphi + \varphi) \right] \]

where \( P_o \) and \( P_i \) are the output and input laser power, respectively, and \( \Delta \varphi \) is the intrinsic phase difference between the two waveguides. The output of the optical power can be verified when the intrinsic phase difference between the two optical paths is \( \pi/2 \).

\[ P_o = \frac{P_i}{2} (1 - \sin \varphi) \]

If \( \varphi < 1 \), Eq. (4) can be expressed as

\[ P_o = \frac{P_i}{2} (1 - \varphi) \]

Finally, the half wave voltages, \( V_s \), can be identified as

\[ V_s = \frac{\lambda d \Gamma}{n^2 r L} \]

The design of the integrated electro-optic sensor has been improved further by Ben Niu [33]. The improvement focused on the phase difference between the two waveguides. The integrated electro-optic sensor with LiNbO\(_3\) crystal substrates is used to measure high-power impulse electric fields. It can measure an...
electric field of more than 1100 kV/m and is very effective for the measurement of lightning impulse electric fields. Fig. 5 shows the structure of the integrated electro-optic sensor proposed by Ben Niu.

The output power of the each arm can be expressed as follows:

$$P_o = \frac{P_i}{2} (1 \pm \phi)$$

### 3.3. Micromachined electrostatic field sensor

The micromachined electrostatic field sensor (EFS) can be used to measure AEF [34]. This sensor works at the resonant frequency for maximum sensitivity. The sensor architecture has three blocks, a comb-driven electrode, vibration shutter and sensing electrode, as shown in Fig. 6. The operating principle of the electrostatic field sensor is shown in Fig. 7. The shutter oscillates back and forth, thus covering the side walls of either the positive or negative sensing electrodes. This sensor is constructed via the silicon-on-insulator (SOI) process, in which the sensing electrode and grounded shutter are positioned in the same plane. The comb-driven electrodes in this sensor are designed to verify that the grounded shutter works at its resonant frequency automatically. The micromachined electrostatic field sensor features include low cost, small size and low power consumption. Furthermore, the advantages of this electric field sensor are high quality factor \(Q\), accuracy, sensitivity and reliability.

The differential output current of the electrodes of the electric field sensor can be expressed as follows:

$$I_{out} = \varepsilon_0 E dA$$

where \(\varepsilon_0\) is the permittivity of free space, \(A\) is the effective area of the sensing electrodes and \(E\) is the electric field.

### 3.4. Flat plate antenna

A flat plate antenna is used to detect the AEF and thus determine the lightning strike distance [35]. The flat plate antenna is capable of determining the location of a lightning strike within a short-range radius of 10 km by measuring electric field intensity. The plate is considered over ground level and the wavelength of the electric field is larger than the flat plate size [35,36]. Fig. 8 shows the flat plate antenna with the measuring circuit.

$$\int D ds = \int pdv$$

$$D = E_{\varepsilon_0\varepsilon_r}$$

$$D S = Q$$

By substituting Eq. (12) into Eq. (13), the normal electric field can be expressed as follows:

$$E_n = \frac{Q}{\varepsilon_0\varepsilon_r S}$$

Hence, the voltage between the flat plate antenna and the ground is shown below

$$V_g = - \int_0^d E_n dx = - \frac{Q}{\varepsilon_0\varepsilon_r S} \int_0^d (-1) dx = \frac{Q d}{\varepsilon_0\varepsilon_r S}$$

The equation can be simplified by substituting Eq. (13) into Eq. (14).

$$V_g = E_n d$$
where $D$ is the electric flux density, $S$ is the area of the plate, $E_0$ is the electric field normal, $Q$ is the induced charge, $\varepsilon_r$ is the free space permittivity, $\varepsilon_f$ is the relative permittivity and $d$ is the height with respect to the ground.

From Eq. (16), the voltage between the parallel flat plate antenna and the ground is directly proportional to the electric field normal to the plate and its height with respect to the ground. The height $d$ of the antenna is modified to obtain the effective height $d_{ef}$. The effective height is classified as the height between the measuring circuit and the antenna. The antenna has an effective height of approximately 0.25 m and a physical height of 1.5 m [36]. The measuring circuit is attached to the flat plate antenna, the RC circuit of which is shown in Fig. 8. Due to the effect of the RC circuit, $V_m$ becomes less than $V_g$. $R$ can be neglected because $R$ is assumed to be very large compared to $C$.

$$V_m = \frac{E_0 d_{ef} C_g}{C_g + C_c} + \frac{C_f}{C_g + C_c} V_g. \quad (17)$$

Eq. (17) shows that the measured voltage $V_m$ is the voltage $V_g$ times the capacitive divider, composed of the capacitance $C_g$ of the antenna capacitance with respect to the ground $C_g$ and the capacitance of the coaxial cable $C_c$. The standard value of $C_g$ is 59 pF, while $C_c$ is 100 pF for a 1 m coaxial cable [36]. The value of $C_c$ may change according to the length of the coaxial cable from the lower antenna to the input of the measuring circuit. Fig. 9 shows the structure of the parallel flat plate antenna; the diameter of the plate is 0.5 m, and the gap distance between the two plates is 0.03 m.

3.5. Passive optical lightning sensor

Rosolem [37] proposed using a passive optical lightning sensor to detect lightning’s electromagnetic pulses. This sensor was mainly designed to indirectly monitor lightning strikes on overhead power lines, substations or power generation plants. Dissimilar to others, this sensing technique does not require solar panels, batteries or electronic control circuits. It is a viable solution that can allow the power utility to provide fast power recovery and the precise preventive maintenance of transmission lines. This passive optical lightning sensor is fabricated using a dipole meander antenna [38], a low-cost Fabry–Perot semiconductor laser operating at 1310 nm and a single-mode optical fibre to carry the detected signal to a remote optical receiver, as shown in Fig. 10.

The process of lightning detection can be described as follows:

An electromagnetic field is created by the intense currents of lightning discharged over a wide frequency. Then, the electromagnetic fields propagate away from the lightning channel in the form of radio waves, and their attenuation depends on the frequency of the radiation. A transitory voltage will be induced in the antenna when the radio waves reach the sensor. This voltage generates an electrical current that instantly modulates a semiconductor laser attached directly to the antenna. The optical power emitted by the laser is proportional to the intensity of the lightning-induced electromagnetic field. Therefore, it can be transmitted to other locations by using optical fibre as the laser output.

3.6. Photon and infrasound detection

A combination of photon and infrasound detection is another approach to lightning detection. Photon detection has a high sensitivity and a fast response speed [39]. It involves photomultiplier tubes (PMT), a voltage biasing circuit, and a signal modulating circuit. The characteristics of the PMT allow it to be used with faint light signals, as well as fast-pulse light signal. Therefore, the PMT can be used to detect lightning.

Meanwhile, infrasound detection focuses on the audible sound and infrasound of thunder. Infrasound detection involves an infrasound sensor, a transformer circuit and a signal pretreatment circuit. In order to distinguish the thunder’s sound with other natural phenomena, such as wind, typhoons, earthquakes and volcanic eruptions, an infrasound acquisition and analysis system is required.

When the lightning signal occurs, PMT first attain it. Then, the infrasound sensor receives the signal. The channels in the PMT calculate the lightning flash azimuth and the time between the light and sound. The time between the light and infrasound arriving at the system, measured via the GPS-clock, is used to compute the lightning flash distance. Therefore, the exact longitude and latitude to the point of reference can be computed using this data.

4. Lightning location technique

The lightning location technique can be divided into two categories: single-station and multi-station lightning location techniques.

4.1. Single station lightning location technique

The single-station lightning location (SSLL) technique requires a single observation station to locate lightning. The implementation of this technique involves estimating the lightning distance that could be obtained by using several methods: (1) an amplitude-based lightning signal, (2) wave line theory, (3) electric field (EF) and magnetic field (MF) phase difference, (4) delay time difference, (5) group delay, (6) Schumann Resonance and (7) the wave impedance method. The wave impedance method is the latest SSLL method introduced by Mingli [40]. However, the single-station lightning technique is not so popular, as the accuracy of the SSLL still requires further improvement compared with a multi-station lightning location system.

4.2. Multi-station lightning location technique

In order to monitor the lightning, the most common electromagnetic radio-frequency-locating methods are magnetic field direction (MDF), time of arrival (TOA), IMPACT and interferometry.
These methods are reviewed in Sections 4.2.1, 4.2.2, 4.2.3 and 4.2.4, respectively. These methods provide the best real-time reallocation detection of individual lightning strikes.

4.2.1. 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 [41]. Fig. 11 shows the types of MDF antennas [35,42].

There are two types of cross loop MDF (CL-MDF) antennas utilised in lightning detection: narrow-band (tuned) CL-MDF and gated wideband CL-MDF [43]. Narrow-band CL-MDF operates in a narrow frequency band, with the centre frequency commonly in the range of 5–10 kHz. At this frequency, the lightning signal energy is quite high, and the attenuation in the earth ionosphere waveguide is quite low. However, there are several disadvantages of narrow-band CL-MDF when lightning distance is less than 200 km. The inherent azimuthal error (polarization error 10°) 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 section. Also, the fact that the magnetic fields are improperly oriented for the direction finding of the ground strike – which occurs due to ionospheric reflections and sky waves – causes error in narrow-band CL-MDF.

A gated wideband CL-MDF has been introduced to overcome 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.

Both narrow and gated wideband CL-MDF are susceptible to site error [44]. 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.

4.2.2. 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 [45]. 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 [46–48]. 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 [49].

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 kilometres) and (3) long baseline (hundreds to thousands of kilometres). 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 [50,51], while the VLF signal results from current flow in the lightning channels [52].

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 [43]. 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 [49].

Another method is a wideband sensor, which employs the TOA method. The Earth Networks Weather Bug Total Lightning Network (WTLN) is a lightning detection network that uses a wideband sensor to detect both cloud-to-ground (CG) and inter-cloud (IC) flash signals [53]. A real-time lightning cell tracking system and the subsequent dangerous alert system can be provided by using WTLN total lightning data.

4.2.3. Improved accuracy using combined technology (IMPACT)

Improved accuracy using combine technology (IMPACT) is a method that has been developed to combine the MDF and TOA methods’ techniques. In this approach, the direction finding and absolute arrival time provide azimuth information and range information, respectively [47,54]. Hence, IMPACT allows for an optimized estimate of location because it has redundant information regarding timing and angle. The combination of MDF and TOA provides some advantages compared to independent MDF or TOA. For example, a discharge that occurs along the baseline between two IMPACT sensors will be more accurately located by the intersection of two direction vectors.

The Global Lightning Detection network, GLD360, was implemented using the magnetic direction finder (MDF) and long baseline time-of-arrival (TOA) methods, combined with a proprietary lightning recognition algorithm in the VLF band. This GLD360 detects 80% of all large negative strokes (> 20 kA in magnitude) according to the National Lightning Detection Network (NLDN) [55]. The application of MDF and TOA methods are summarized in Table 2.

4.2.4. Interferometry technique

The interferometry technique is a technique used to locate the VHF pulses associated with lightning discharges. In the interferometry technique, no identification of individual pulses is needed, because the interferometer measures the phase difference between narrow-band signals corresponding to the noise-like bursts that occur during lightning. Then, these signals are received by two or more closely spaced sensors [43].

The principle of interferometry consists of determining the direction of the source of radiation using a combination of phase measurements in a relatively small bandwidth. The simplest interferometric system consists of two antennas located a few meters away from one another. Generally, the antenna is made up of an array composed of VHF dipoles that is connected with the interferometric receiver in order to determine the phase differences over a large dynamic range. The phase difference is commonly acquired by mixing the signals from several antennas, and the accuracy is achieved by integrating them over the desired time resolution. Finally, the phase differences are processed in order to obtain an azimuth from two-dimensional (2D) networks or azimuth and elevation from three-dimensional (3D) networks of the source. The information from several sensors is received by the central processor, which will determine the location of each individual event via triangulation [56–58].

The System de Surveillance et d’Alerte Foudre Par Interferometrie Radioelectrique (SAFIR) network is based on the VHF interferometry technique, which is able to observe lightning in 3D. In Table 3, a summary of research using the interferometry technique is presented.
Table 2
Summary of lightning location using the MDF and TOA methods.

<table>
<thead>
<tr>
<th>Author</th>
<th>Receiver</th>
<th>Method</th>
<th>Features</th>
</tr>
</thead>
</table>
| Ibrahim [41]| Orthogonal magnetic loop antenna and flat plate antenna | Magnetic direction finder (MDF) | ● Requires at least two stations  
● Stations are separated by distances of up to a few hundred km  
● The intersecting point provides the source location |
| Rakov [43]  | VHF (30–300 MHz) (Very short baseline and short baseline) | Time of arrival (TOA) | ● The time difference between the arrivals of an individual lightning VHF pulse at the receivers is short compared to the time between pulses, which is a microsecond to a hundred microseconds |
| Rakov [43]  | Electric field whip antenna     | Time of arrival (TOA) | ● Long baseline, also known as the Lightning Position and Tracking System (LPATS)  
● The stations are 200–400 km apart in order to determine the location by measuring the differences between the signal arrival times at the stations  
● A microprocessor-based system is used to store the location data, which is displayed on a video terminal  
● The output data of this sensor are serial number, polarity, latitude and longitude of striking points, error between actual time differences reported, the identity of the three receivers used in the solution and lightning current amplitude  
● The efficiency is in the range of 40–55% within 400 km of the detection station |
| Amir [56]   | Broadband circular flat antenna  | Time of arrival (TOA) | ● Three broadband circulating flat antennas having diameters of 30 cm each are used to locate the position |
| Chonglin [53,57] | Wideband sensor                      | Time of arrival (TOA) | ● The Earth Networks WeatherBug Total Lightning Network (WTLN) is a lightning detection network that uses a wideband sensor  
● Has a detection frequency in the range of 1 Hz to 12 MHz  
● The WTLN consists of an antenna, a global positioning system (GPS) receiver, a GPS-based timing circuit, a digital signal processor (DSP) and on-board storage and Internet communication equipment  
● The WTLN sensor works when the signal is detected and the waveform is recorded. It then sends the waveforms to the central lightning detection server via the Internet  
● The waveform of arrival time and signal amplitude can be used to determine the peak current of the strike and the exact location of the flash, including the latitude, longitude and altitude  
● The WTLN has good IC detection efficiency, which is up to 95% |
| Cummins [54,58] | IMPACT sensor                     | TOA and MDF                           | ● In the range of 0.4 Hz to 400 kHz, lightning can be detected by an IMPACT sensor  
● Provides azimuth and range information  
● Estimated parameters: longitude, latitude and discharge time |
| Ibrahim [59] | Small active antenna             | TOA and MDF                           | ● Known as the Pekan Lightning Detection System (PLDS)  
● Consists of two orthogonal magnetic loops  
● Does not contain polarization error  
● Simple, reliable and easy to use  
● Able to detect and analyse real-time lightning data, which can be displayed both textually and graphically |
| Lojou [55]   | Orthogonally oriented magnetic loop antenna | TOA and MDF, combined with a lightning waveform recognition algorithm | ● Known as the Global Lightning Detection network, or the GLD360  
● A worldwide detection of flashes with significant detection efficiency and location accuracy of the CG flashes, along with the polarity of the measured discharges and an estimate of peak current  
● Able to accurately locate most of the lightning discharged around the world  
● A long-range global network that uses multiple terrestrial sensors to calculate lightning discharge locations (latitude and longitude) and times  
● In a 24-h period, 598,200 events were detected  
● Provides accurate, early detection and tracking of severe weather  
● It has no data gaps, as satellite and radar systems do. Also, there is no need for maintenance or expenditures  
● The data received from the GLD360 can be derived in a week, which is quite quickly, thus providing better end-user service  
● In terms of accuracy, the GLD360 outperforms all other long-range lightning detection networks, including satellites  
● It correctly identified the polarity in 145,901 events, which represented 94% accuracy |

5. Methods of transmission and storage data

Data transmission is an important process in a lightning monitoring system. Several methods of data transmission collected from approximately 22 published works are reviewed in Section 5.1. Furthermore, because the received data must be stored securely, several methods of data storage are reviewed in Section 5.2.

5.1. Methods of data transmission

Data transmission is the physical transfer of data from one point to another point through a particular channel [59]. Some of the channels used to transmit data include coaxial cable [35,60–62], fibre-optic cable [63–66] and wireless communication [67–70]. Coaxial cable has a good bandwidth, low error rate and relatively low resistance. It can
support multiple channels and a wide range of services, i.e., voice, data, video and multimedia. The transmission speeds achievable via coaxial cable are as high as 10 Gbps. Coaxial cable is strong, but there are limits to its length; it will stop working if these limits are exceeded. Usually, coaxial cable is capable of reaching hundreds of meters in length. This type of cable is also suitable for transferring high-speed signals without high losses. However, coaxial cable has problems with deployment, such as bus topology [71]. The bus topology will be susceptible to congestion, noise and security risks. The coaxial cable may be a path via which the lightning current can infiltrate equipment or devices and cause damage if adequate maintenance is not performed on the lightning protection system. Fig. 12 shows the example of the coaxial cable connection in a single lightning detection station [41].

Fibre-optic cable uses thin strands of glass in its architecture. The pulse of light travelling along the core of the fibre allows it the highest available data transmission speed. Usually, the transmission speed of fibre-optic cable is between 100 and 2000 Mbps. Fibre-optic cable offers high bandwidth and long-distance terminals to transmit data, as well as resistance to lightning disturbances. However, the cable can only stretch over a certain number of kilometers before the signal becomes impossible to detect. Also, fibre-optic cable is expensive to install and fragile.

Wireless Local Area Networking (WLAN) technology is another option for data transmission. The coverage area of WLAN is close to 20 km² [62]. The advantages of using WLAN in data transmission are its flexibility (it can transmit data within the radio coverage area) and the fact that its nodes can communicate without further restriction. Ad hoc wireless networks allow for communication without planning, which makes them more convenient than wired networks [72]. WLAN technology is robust in that it is disaster-resilient [73]. In theory, the speed of standard WLAN is rated according to its maximum bandwidth, where 802.11b offers up to 11 Mbps, 802.11a and 802.11g offer up to 54 Mbps and 802.11n offers up to 300 Mbs. However, the performance of WLAN is not as good as these theoretical values. In reality, it is only capable of achieving 5.5 Mbps, 20 Mbps and 100 Mbps, respectively, according to the standard [74]. Nevertheless, WLAN also has disadvantages, such as lower quality of service (QoS), lower bandwidth due to limitations in transmission (1/10 Mbit/s) and high error rates due to interference from other sources [75]. Cordless phones, Bluetooth devices and motion detectors all employ radio frequencies that can interfere with WLAN [76]. This interference can

### Table 3
Summary of research using the interferometry technique.

<table>
<thead>
<tr>
<th>Author</th>
<th>Network</th>
<th>Features</th>
</tr>
</thead>
</table>
| Qing [63]| SAFIR 3000    | - Able to observe lightning in 3D  
- Located at over 1000 m in altitude  
- The interferometric array uses the differential phase measurement of lightning's electromagnetic waves for the long-range detection of lightning activity  
- The SAFIR LF discrimination sensor is a wideband antenna that is capable of identifying the cloud-ground characteristics of lightning  
- Has the capability to provide lightning warnings via a moving trace of thunderstorm cells and also to detect the three-dimensional distribution of lightning discharges  
- CG and IC lightning can be located, and this information is then displayed in three dimensions at a high temporal and spatial resolution  
- Provides lightning warnings based on a moving trace of thunderstorm cells almost 30 min in advance |
| Baran [64]| SAFIR         | - Has the highest location accuracy and detection efficiency and also provides the maximum warning time  
- The detection efficiency is 95%, and the location accuracy is in the range of 1.0 to 2.0 km  
- The typical range of interferometry is about 50–150 km, and an interferometer is composed at least three sensors |
| Ahmad [49]| SAFIR         | - Uses five dipole arrays to determine the direction of the lightning sources based on phase differences of the signal at each dipole  
- Can be used for accurate 2D mapping of cloud flashes, as well as efficient CG flash location  
- Provides an increase in the detection range of the VHF total lightning sensors of more than 30%, as well as more stable operations |
| Lojou [55]| Total lightning sensor TLS200 | - Provides an increase in the detection range of the VHF total lightning sensors of more than 30%, as well as more stable operations |

Fig. 12. Coaxial cable connections in a single lightning detection station.
reduce the quality of WLAN service, and it also can weaken WLAN security.

Data can also be transmitted by using a remote file transfer protocol (FTP) server via a Global System for Mobile–General Packet Radio Service (GSM–GPRS) modems [77,78]. A GSM–GPRS modem can exist in the form of an external unit or a PC card. The external unit could be connected through a serial cable, a USB cable, Bluetooth or infrared. The GPRS has much higher data transmission speed in that large amounts of data can be transferred to and from the mobile device over the Internet. One advantage of GPRS is that it has a great backup option. The portability factor has diminished with the emergence of much faster data cards. GPRS can also be used to transmit SMS. The data can also be transmitted via modular phone SMS [79,80].

Hussein Ahmad presented an SMS system as a method of data transmission [81]. The time, date and the number of lightning strikes are required so that a lightning counter can send this information to a specified mobile phone via SMS. The AT command plays an important role in sending out SMS signals in that it is important to focus on the auto SMS function. There are a few procedures that must be followed before writing the AT command. The mobile phone must perform a test in order to determine the types of SMS modes that the mobile phone can support before it can perform the task. There are two types of SMS modes, which are PDU mode and text mode. The message contents in PDU mode must be converted to Hex code before being sent. Meanwhile, for text mode, an SMS can be written normally in alphabetical format. Fig. 13 shows a lightning flash counter with an SMS data sender.

### Table 4

<table>
<thead>
<tr>
<th>Transmission type</th>
<th>Quality and significant difference</th>
<th>Cost benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coaxial cable</td>
<td>• Good bandwidth, low error rate and relatively low resistance</td>
<td>Moderate installation cost</td>
</tr>
<tr>
<td></td>
<td>• EMC/EMI susceptible without proper protection system</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Suitable for transferring high-speed signals without high losses</td>
<td></td>
</tr>
<tr>
<td>Fibre optic</td>
<td>• High bandwidth and long-distance terminals to transmit data</td>
<td>High installation cost</td>
</tr>
<tr>
<td></td>
<td>• EMC/EMI resistance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Moderate speed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Frigile</td>
<td></td>
</tr>
<tr>
<td>WLAN</td>
<td>• Flexible—it can transmit data within the radio coverage area</td>
<td>Low installation cost</td>
</tr>
<tr>
<td></td>
<td>• Disaster-resilient</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• EMC/EMI susceptible</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Moderate speed</td>
<td></td>
</tr>
<tr>
<td>GSM–GPRS</td>
<td>• EMC/EMI susceptible yes</td>
<td>Zero installation cost</td>
</tr>
<tr>
<td></td>
<td>• Low speed</td>
<td>• Monthly subscription payment</td>
</tr>
</tbody>
</table>

The AES measurement information can also be transmitted using wireless data transmission by using the Global System Mobile Communication (GSM) network [77]. The coverage of GSM, which can reach across distances of hundreds or thousands of kilometres, is able to transmit the data through an Internet provider to a PC. This method offers low cost and the ability to transmit data using worldwide coverage. In addition, it will reduce the manpower needed by eliminating the routine inspections that were previously necessary to collect the data manually, and the computing system does not need to be installed on-site. In Table 4, types of transmission related to the quality and cost benefit is presented.

### 5.2. Methods of data storage

It is important to safely store the data collected before analysis is carried out. The acquired data can be stored in a secure digital card, also known as an SD card. This can protect important data from being accidentally overwritten. These SDs card are provided with a mechanical switch that acts as a write protector. One advantage of using an SD card in data storage is its non-volatile memory, meaning that it keeps data stable on the card. The data on this card are not threatened by the loss of power and do not
need to be periodically refreshed. Furthermore, such cards are free from mechanical difficulties and damages. An SD card does not produce any noise while at work, allows immediate access and is also easy to keep track of. Moreover, it has a relatively large amount of storage space compared to old backup devices. Unfortunately, the SD card also has the disadvantages of being easy to break, lose, misplace or smash. In addition, SD cards may be affected by various forms of electronic corruption, such as viruses, making the entire card unreadable or broken.

In addition, the digital signal oscilloscope (DSO) is used to capture and store the electric field signal [35]. The DSO provides advanced trigger, storage, display and measurement features. The data also can be stored by using a MySQL database, which is a database management system. The data sent from the GSM module will be sent to the MySQL database and displayed as a Hypertext preprocessor (PHP) page [77,82]. Using this method results in better data storage because the data are saved in an HTML page, which is viewable via a web browser. Thus, it is easier for users to read the data collected.

6. Methods of observation and analysis data

The data obtained from lightning monitoring systems can be analysed further. The data are not only used for detecting lightning but can also be used for observing and analysing climate changes in the atmosphere. Discovering useful information within the observational data allows us to suggest conclusions and supports decision making. Several methods of lightning data analysis and observation have been compiled in Sections 6.1 and 6.2. The informative data from the sensors can be used in various ways via these methods.

6.1. Methods of data observation

Several types of methods are used to observe the data. An isokeraunic-level (IKL) map is used to estimate the values from the mapped thunderstorm data yearly because it is difficult to measure the ground flash density directly [83]. The IKL map is related to the number of flashes per unit area per year. Thus, it is possible to determine the frequency of lightning in an observed region quite easily. Even so, the accuracy of this approach is low. Because the data collection depends only on the sound of thunder being heard by observers in weather observation stations, only thunderstorms occurring near the stations are registered. When the lightning location is far enough from the station, the sound of thunder is very quiet. Consequently, some data may be lost for that location. In addition, the IKL map shows the average figures for thunderstorm days gathered over many years. The IKL map only shows the variation in lightning activities in a given area per year.

In order to present developing storms, a dynamic cloud model is introduced [84]. In this model, the colours blue and red are defined as the positive charge and negative charge, respectively. The arrow pointers represent their random positions, and their magnitudes correspond to the sizes of the circles. Some important parameters are required to obtain the dynamic cloud model, i.e., (1) the positive and negative charges (+Q), (2) the distance between the positive and negative charges and (3) the cloud height. These are used to calculate the electric field for a particular time interval. Fig. 14 shows the dynamic cloud model, in which the positions and magnitudes of the positive and negative charges change with time as the thundercloud propagates.

In the Beijing and Hebei areas, the meteorological data, as well as the locations of lightning discharges and the number of flashes, were collected by using the SAFIR 3000 network [85]. The recorded lightning discharge locations were related to the storm distribution along a southwest-northeast frontal disturbance at which the two independent thunderstorm cells moved separately to the north and south.

Furthermore, a prototype of a single-station lightning locating system (S-LLS) has been developed that consists of three configurations. There are lightning signal sensing (LSS), lightning data acquisition (LDA) and lightning data display (LDD) modules [86]. The LSS module is responsible for electromagnetic signal capture. This module consists of a flat-plate antenna, two crossed-loop antennas, a cloud-to-ground/cloud-to-cloud (CG/CC) logic circuit and a lightning simulator for testing. Then, the results from three analog signals and CG/CC logic are transmitted to the LDA module for processing. The LDA module is a micro-computer-based data processor with embedded A/D converters. This module processes the signals from the LLS based on a proposed lightning-locating theory. The CG/CC logic circuit in the LLS module provides information regarding the lightning impulses. Meanwhile, the LDA provides the time, location, strength and flash type for the lightning events to an on-board memory and then transmits these data to the LDD module via the Internet. The LDD module is a software pack installed on a PC. The LDD module provides real-time lightning monitoring and off-line data playback functions, as well as the visualization, statistical analysis and permanent storage of lightning events.

High-speed video cameras are used to record the lightning flash propagation. The temporal upward and downward leaders’ progress can be captured by using a high-speed video camera. One kind of high-speed video camera can capture 5000 f/s at the highest resolution of 1024 × 800 [79,87].

Instead of using a high-speed video camera, a high-speed charge-coupled device (CCD) video camera could be deployed to capture the development process and physical form of lightning discharges [88]. Given the high frame rate and large resolution, the lightning can be observed clearly. The recording of a high-speed CCD video camera system was used to synchronize the picture output with electromagnetic field waveform data. The synchronization accuracy between the picture output from the high-speed CCD video camera and the electromagnetic field waveform data can be nearly 100 ns.

A low-speed video camera, such as one that captures 50 f/s, could be also utilised in observing lightning, but its function may be limited to detecting significant upward lightning strikes on the
tall telecommunication antenna and locating low-current lightning strikes [79].

A recent research was carried out by Yang et al. [89] worked on to integrate Geographic Information System (GIS), databases, Remote Sensing (RS), visual reality, 3D visualisation, spatial information grid and computer networking to develop a Digital Lightning Prototype System (DLPS) from the perspective of the digital earth.

6.2. Methods of data analysis

Data analysis is important in obtaining conclusions from research. Therefore, several methods have been used to analyse data regarding lightning events. LabVIEW 8.5 software was used to collect, calculate and analyse lightning data by developing a virtual instrument. Using a statistic function provided in LabVIEW, the time maximum for each signal from the receiver – a VHF antenna (2 MHz cut-off frequency) and a microphone – was determined. The arrival time difference (time delay) between the electric field and acoustic signals was calculated. Meanwhile, the noise in the captured signals was eliminated digitally by using a high pass filter (HPF) in LabVIEW [60,90].

Another virtual instrument developed using LabVIEW was used to monitor lightning activity within a 25 km radius from Pekan [35,91]. The incoming lightning strikes’ signals were analysed by using various statistical functions and techniques. Afterwards, the lightning strike locations were estimated by calculating the ratio of EMF to EF. The Pekan Lightning Detection System (PLDS) system analyses the raw lightning data and transforms it into real-time lightning data [92]. The change of colour to either yellow or red in the border of the window is used to provide an alert. A yellow alert will be triggered when the strike is within a 50 km radius, while a red alert will be triggered when the strike is within a 10 km radius of the sensor location. A special ‘storm’ is depicted to indicate the detected flashes. When one of these storms is shown, there is a good chance that lightning will occur in that area. The threat assessment window is a description of storm activity over the previous 5–20 min. This window shows information about the average position of all lightning flashes detected in the previous 5–20 min. To calculate the placement of the coloured area in the threat assessment window, the average range of all strikes in a similar direction is used. Moreover, the strike rate graph shows the rate of change in lightning activity at a glance. The window rate is also analysed, and this analysis is shown in the form of six counter displays. The six counters are the total rate counter, the strong strike rate counter, the noise rate counter, the strike rate percentage change counter and the strike rate counter.

In addition to LabVIEW, Microsoft Visual Basic 6.0 was used to develop a graphical user interface (GUI) that was intended to record and count every time lightning struck a specific structure. The GUI was connected with a database that was created using Microsoft Access. The database consisted of two columns. The first column is used to store the frequency of lightning current discharge through a conductor, while the second column is used to record the date and time of each discharge [81].

Another method of analysing the data used a numerical simulation. The numerical simulation was developed to investigate the relationship between AEF and cloud height. The partial differential equation (PDE) toolbox in Matlab was applied during this analysis to simulate the static electric field distribution in a courtyard [20].

Furthermore, the data collected from lightning events can be analysed using artificial intelligence techniques (AI), which consist of fuzzy logic analysis, neural network analysis and neuro-fuzzy analysis [93]. The fuzzy logic method can be used to analyse the data with a multiple-input multiple-output (MIMO) system. Because the neural network develops learning, the input-output relationship can be used to determine the threat level in real time. By using a neural network, the exact location of positive and negative charges based on the AEF can be predicted. The neural network consists of an input layer, a hidden layer and an output layer [39,94].

Neuro-fuzzy analysis is derived from two reliable techniques: fuzzy logic and neural networks. The output is usually presented in polynomial form with input variables x and y. There are two types of neuro-fuzzy modes: Sugeno and Mamdani. Neuro-fuzzy analysis can be performed using several methods, such as mean percentage error, root mean square error and mean squared error [95].

The area of a lightning strike can be found based on latitude and longitude. Analysis using the fuzzy logic method created a graph of lightning level and also a graph of the number of lightning incidences corresponding to the type of lightning. From the results obtained, the lightning was mapped onto the Malaysian map using Google Earth. The characteristics of the lightning were represented by blue, purple and red icons to indicate low, medium and high levels of current, respectively. Nevertheless, there are some limitations when mapping lightning characteristics by using Google Earth; the map merely displays the lightning current value, the level of current and the region represented.

7. Discussions

It is difficult to determine the best sensors/methods for several reasons, such as the following: (1) in the literature, system sizes, working principles and sensor structures vary; (2) the efficiency of sensors/methods vary; (3) their limitations vary; (4) there are differences in location installation and (5) the hardware used in the sensors/methods vary. Based on these difficulties, a summary of the working principle of every sensor/method is provided. The electric field mill (EFM) is based on the electromagnetic induction principle, which uses a rotor and stator to expose and shield the sensor plate. The working principle of this sensor is approximately the same as that of a micromachined electrostatic field sensor, which oscillates the shutter back and forth to measure the electric field. The integrated electro-optic sensor uses light to drive the sensor, while photon detection also uses a fast-pulse light signal to obtain the lightning signal. The passive optical lightning sensor’s working principle is based on detecting the radio frequency emitted by lightning.

In lightning location networks, the magnetic direction finder (MDF) measures the voltage signal on the loop; two antennas are used in this method. The direction of the flash can be determined by comparing the voltage signals from both antennas. The time-of-arrival (TOA) method also uses a minimum of two antennas; the intersecting hyperbolas at the two stations are used to locate the lightning flash. The TOA method uses the time difference between sensings of the arrivals of the electric pulse emitted by lightning. Ideally, the TOA method is more sensitive than MDF. On the other hand, the interferometry method also can be performed using a minimum of two antennas. It can locate the VHF pulse in order to determine the direction of the source using a combination of phase measurements.

In order to transmit the data, an effective method of transmission is crucial. The connection between the sensor/antenna and the data acquisition system requires a cable, WLAN technology or GSM–GPRS. In terms of length and coverage area, fibre-optic cable is capable of operating over longer distances than coaxial cable. Given the short distance between the sensor/antenna and the data acquisition system used to monitor the signal onsite, the researchers preferred to use coaxial cable. The coverage area for WLAN can
reach 20 km², while GPRS-GSM can transmit information for hundreds or thousands of kilometres via an Internet provider. Fibre-optic cable has the highest transmission speed, around 100 to 2000 Mbps. Coaxial cable is only capable of reaching transmission speeds of 10 Gbps. WLAN can reach a high transmission speed, but it is not as good as fibre-optic cable or coaxial cable, because many factors limit WLAN speed, such as radio interference, physical obstructions of the line-of-sight between devices, the distance between devices and multiple devices communicating over the network simultaneously. GPRS has a slower speed than the other methods, having an average rate of 40 to 50 kps. In terms of the installation process and cost, fibre-optic cable is expensive and fragile. Coaxial cable is affordable, and its installation is easier than that of fibre-optic cable. The wireless method is preferable because of the ease of connection. GSM–GPRS usually has associated charges based on the volume of data sent.

Generally, data storage can be performed on a device or online. The SD card and digital signal oscilloscope (DSO) are devices used to store data. MySQL is the online form of storage in which data are stored in a database. The SD card offers many types of memory capacity, i.e., 4 GB, 32 GB, etc. Unfortunately, it can be exposed to viruses and can be easily lost or broken because it is small in size. The DSO cannot store data permanently, because the device has storage limitations. If the memory limit is exceeded, the oldest data will be deleted. MySQL is a safer way to store the data. It is typically easier to obtain the data online than to find the device on which the data are stored. Currently, the development of worldwide multimedia has made it easier to acquire information online.

Observational data are important in monitoring behaviour, events or physical characteristics. The iso-keruanic-level (IKL) dynamic cloud model, SAFIR 300, and single-station lightning-locating system (S-LLS) are methods of collecting thunderstorm data in order to estimate the location of strikes, lightning impulse information and meteorological data. High-speed video cameras, low-speed video cameras and high-speed charge-coupled device video cameras are able to record the physical characteristics of lightning.

Generally, the data analysis is used in discovering useful information in order to support decision making. Some of the methods are simple, while others are complex. For LabVIEW, the analysis is related to graphical programming because it uses a visual programming language. The program contains a block diagram, a front panel and a connector panel, which contain the graphical source code. It is very interactive compared to writing in a traditional language. On the other hand, Microsoft Visual Basic and Matlab have been used to develop a graphical user interface (GUI). A GUI can be created interactively or programmatically [96]. Nevertheless, C/C++ is the most common programming language used to develop software applications. The artificial intelligence method of neural networks is complicated because it includes a multi-layer network that must be trained in order to obtain the prediction results. On the other hand, fuzzy logic is much simpler than neural networks, but its performance is lower. In order to improve the performance of fuzzy logic, it can be combined with neural networks. The combination of both methods increases the complexities involved.

8. Conclusion

This paper reviews and summarizes lightning monitoring systems according to their technologies and data acquisition systems based on various academic journals. This paper provides the working principal and structure of each sensor/method 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, as well as the advantages and disadvantages of the methods of transmitting and storing data, observational methods and algorithms of the analysis methods. It is hoped that the information in this paper can be a source of information for future research.

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