STUDIES ON LIGHTNING DETECTION AND PREDICTION SYSTEMS

A Thesis Submitted in Partial Fulfilment of the Requirements for the

Degree of Master of Electrical Engineering

By

BANIBRATA GHOSH

Examination Roll No.: **M4ELE19022**

Registration No. : **140669 of 2017-18**

Under the guidance of

Dr. DEBANGSHU DEY

Assistant Professor

&

Dr. SOVAN DALAI

Associate Professor

Department of Electrical Engineering

Faculty of Engineering and Technology

Jadavpur University

Kolkata-700032, India

JADAVPUR UNIVERSITY

KOLKATA- 700032, INDIA

FACULTY OF ENGINEERING AND TECHNOLOGY

CERTIFICATE OF RECOMMENDATION

I hereby recommend that the thesis titled "**STUDIES ON LIGHTNING DETECTION AND PREDICTION SYSTEMS**", submitted by **BANIBRATA GHOSH** (Registration No. 140669 of 2017-18), be accepted in partial fulfilment of the requirement for the degree of "Master of Electrical Engineering" of Jadavpur University which has been carried out by him under our guidance and supervision. The project, in our opinion, is worthy of its acceptance.

Dr. Debangshu Dey

Assistant Professor,

Dept. of Electrical Engineering,

Faculty of Engineering and Technology,

Jadavpur University

Dr. Sovan Dalai

Associate Professor,

Dept. of Electrical Engineering,

Faculty of Engineering and Technology,

Jadavpur University

Prof. Kesab Bhattacharyya

Head, Dept. of Electrical Engineering,

Faculty of Engineering and Technology,

Jadavpur University

Prof. Chiranjib Bhattacharjee

Dean,

Faculty of Engineering and Technology,

Jadavpur University

JADAVPUR UNIVERSITY

KOLKATA- 700032, INDIA

FACULTY OF ENGINEERING AND TECHNOLOGY

ELECTRICAL ENGINEERING DEPARTMENT

CERTIFICATE OF APPROVAL*

The foregoing thesis is hereby approved as a credible study of Master of Electrical Engineering and presented in a manner satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinion expressed or conclusion therein but approve this thesis only for the purpose for which it is submitted..

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DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS

I hereby declare that the thesis entitled "**Studies on Lightning Detection and Prediction Systems**" contains literature survey and original research work as part of the course of Master of Engineering studies. All the information in this document have been obtained and presented in accordance with academic rules and ethical conduct.

I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name (Block Letters)	:	BANIBRATA GHOSH
Exam Roll no.	:	M4ELE19022
Registration no.	:	140669 of 2017-18
Thesis Name	:	STUDIES ON LIGHTNING DETECTION AND PREDICTION SYSTEMS
Signature with date	:	

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Thank you,

Banibrata Ghosh

DEDICATED TO MY PARENTS

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CHAPTER-1

INTRODUCTION

- Importance of Lightning Warning & detection System
- Objective of the present work
- Prior art
- Thesis overview

1.1 ***Importance of Lightning Warning & detection System:***

With the rapid development of social economy and improvement of the level of modernization, the economic loss and social impact caused by lightning disasters are more and more serious problems almost all industries involved. Such as power, building aerospace, defence, satellite communications, navigation, electronic industry, petroleum chemical industry, financial securities and so on. Therefore, it is more and more important for the early warning of lightning prediction.

Lightning is a discharge of electrical charges through a dielectric medium in the form of current which results in enormous temperature and acoustic shock wave. That high current and hot temperature is highly dangerous for electrical apparatus and living beings. Every year lightning strikes claim many lives, according to the National Crime Records Bureau at least 2,000 people have died in lightning strikes in India every year since 2005 [19] and that count keeps on increasing. An early warning system can reduce these kind of threats and casualties with the help of proper lightning protection system.

1.2 ***Objective of the present work:***

This research work is aimed at the development of an expert system for local lightning prediction and alert signal generation (e.g. at airports, playgrounds, buildings etc.). An integrated system is to be developed consisting of a measurement & data acquisition system and an analysis software to process the data to predict the probability of lightning strike and to generate an alert signal thereby [4]. The system will be able to give a prediction based on now-casting whether lightning will strike or not within some specific area. Initially data will be collected using a prototype from both laboratory and outdoor conditions and an expert system will be developed which can predict the probability of lightning strike for generation of alert signal to minimize casualties.

1.3 ***Prior art:***

Lightning strikes can be detected in many different ways. Most notably the discharge of thousands of amperes of current in a fraction of a second generates temperatures estimated to be as hot as 30,000 °C, hotter than the surface of the sun, with a brilliant flash of light and an acoustic shock wave, called thunder [20]. At the same time, the surging electrical currents release a wide spectrum of electromagnetic radiation and modify the strength of the local atmospheric electrical field [4].

The flash and bang of nearby lightning strikes are hard to ignore, even without special instrumentation. Distant lightning flashes can often be seen by an alert observer, particularly at night. For applications involving safety, however, these techniques are not reliable and are only appropriate in the absence of more quantitative technologies. Some of the existing methodologies involve [4]:

1. Acoustic detectors.
2. Optical detectors (e.g. Vaisala TSS-928).
3. Atmospheric Electric Field Measurements. One of the most common instrument for measuring the atmospheric-electric field is the Field Mill.
4. Electromagnetic-Emissions from Lightning Strokes.
5. Lightning Detection by Networks of Electromagnetic Sensors.
6. Lightning Detection from Space

1.4 ***Thesis overview:***

The work in this thesis describes the progress towards the development of a lightning detection and warning system. Section 1.2 introduced the importance of the work undertaken and summarized the approach in this thesis to develop such classification tools. Section 1.3 discussed several significant previous attempts regarding this topic. The rest of the thesis is organized as follows:

Chapter 2 describes a detailed overview about lightning phenomenon. It is seen that lightning strike depends upon several factors like electric field, cloud density, atmospheric pressure, wind velocity etc. And different kind of lightning protection system and lightning prediction methodologies are also discussed in this chapter.

Chapter 3 presents a detailed study of software and hardware tools used in this thesis. In software section Fuzzy Logic Tool is used for decision making and for hardware interface C code has been used. And for hardware design AS3935 Lightning sensor has been used.

Chapter 4 presents AS3935 hardware and software setup and shows experimental results by using C coding and Fuzzy Logic decision making.

Chapter 5 consists of conclusions and future aspect of that thesis works.

CHAPTER-2

LIGHTNING PHENOMENON, DETECTION & PREDICTION TECHNIQUES

- Mechanism of lightning:
- Lightning Detection Technologies
- Lightning prediction technology

2.1 ***Mechanism of lightning:***

Lightning strike is quite a dramatic process which produces fear and awe. It is faster than a speeding bullet, it is six times hotter than the surface of the Sun, it seems to defy the laws of gravity and it can strike us dead. Lightning is one of the weirdest, most destructive and important phenomena on earth. When lightning strikes, giant sparks of static electricity tear through the atmosphere at a hundred million kilometers an hour up to a billion volts rip the air apart, in that instant the current creates light waves and a brilliant bolt light race across the sky can be seen. The air heats up to almost 28,000-degree Celsius and it expands so rapidly that it explodes and we hear a deafening clap of thunder. It all happens in less than a blink of an eye up to eight million times every day. This is nature's one of the most frequent and best observed phenomena but also it is one of the least understood.

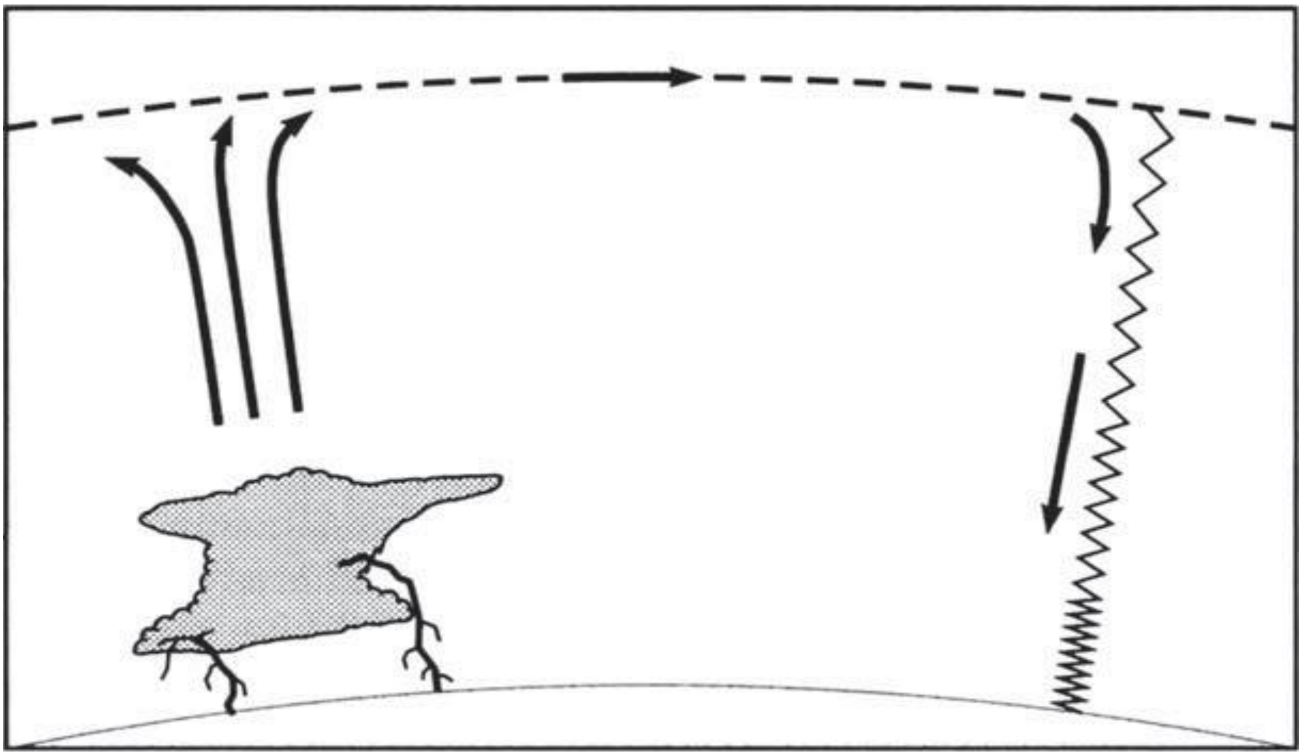


Fig 2.1: A model of global circuit [4]

Atmosphere of Earth is an integrated part of natural electrical system where earth and its atmosphere work as a spherical capacitor, and the earth as lower conducting surface and atmosphere as higher conductive medium [5].

2.1.1 Formation of thundercloud:

Due to solar heating there is vertical air movement that meets the cooler upper air and deposits water vapor. Since mountaintops are higher than the valleys, they become warmed first which often results in the unstable air condition. Earth's rotation gives birth of new storms which move west as the day progress. This rising air streams carries water vapor which helps to the formation of the thundercloud late in the afternoon.

Small and midsized clouds very often produce natural lightning. Initiation of lightning discharge demands huge amount of charge separation which is found in the large convective storms. The size of storms is varying from 3 km to more than 50 km [1] and to generate lightning the cloud needs to be 3 or 4 km deep. The deep the cloud, the more frequent the lightning. There are many other factors which influence thunderstorms, such as water vapor, location, temperature etc. Though are many factors still unknown to us. Generally, before lightning upper portion of clouds have to cool to at -20 °C, and during charge separation happens when cloud temperature is around -5 °C and -20 °C (24 °F to -5 °F) [4].

Fig. 2.2: Cloud dipole [4]

Charge separation process happens due to particle collision, strong updrafts and downdraft and size sorting. Smaller sized particles prone to collect negative charges while ascending particles are positively charged. This charge separation results in cloud-diploe, positive charges gather in the top section and negative charges grouped in the middle and lower section of the cloud [4] can be noticed in Fig. 2.2.

2.1.2 Point Discharge:

Earth's surface is negatively charged which is – 15* 10^5 C, that produces an electric field intensity of nearly 0.13 kV.m^{-1}. On the other hand, opposite positive distributed space charge stays in the lower atmosphere [1]. When charges are carried by the rain drop towards the earth the cloud turns into a dipole having positive charge in the upper side and negative charge in the down side. If the value of field strength is greater than 1.5-2 kV. m^{-1}, objects having small radii become point discharge of ions. Point discharge process happens naturally on trees, within water droplet, or on any sharp pointed metal. In the form of corona discharge electrons produced in an electron avalanche. This process starts if there is an initial electron which is delivered by cosmic ray activity or radio activity. This radioactive decay causes ionization of air. An electric current that weakens the electric field, flows due to this ionized air. It is observed if electric field strength is $10^4 V.m^{-1}$ the current density is 10 nA.m^{-2} [2]. Point discharge current is the foundation for the multipoint discharge system.

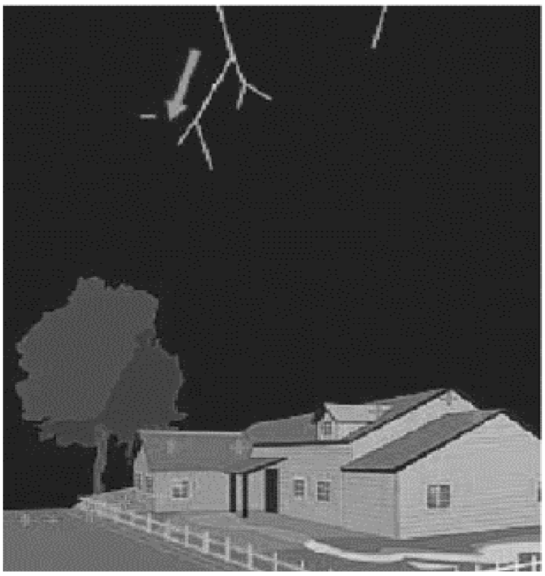


Fig. 2.3.1

The initial " steep leader" propagates down, towards the ground in a series of

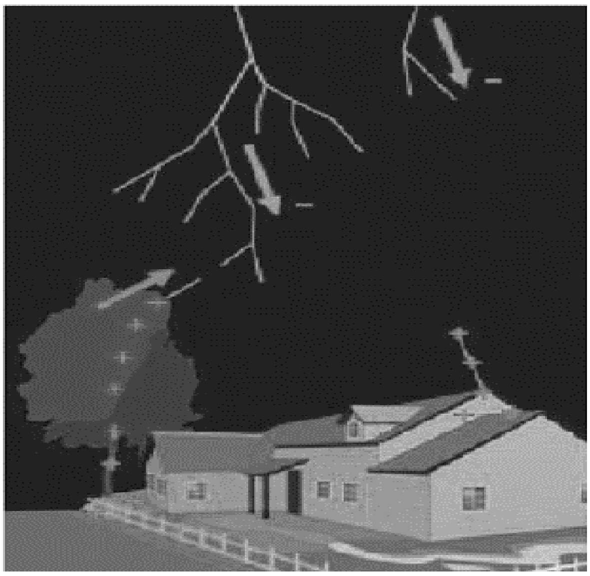


Fig. 2.3.2

As the stepped leader nears the ground it strongly attracts positive charges, including positive channels from the surface, called ' *short steps, branching out , looking for the easiest path to reach the ground*

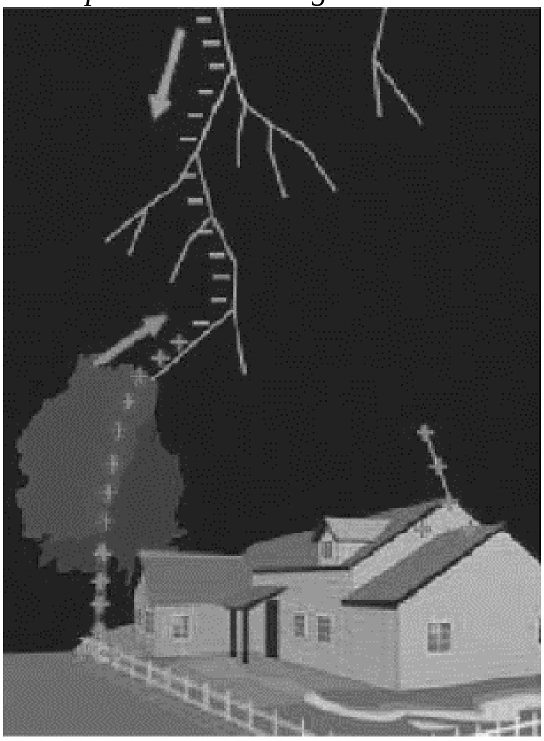


Fig.2.3.3

When these two currents connect they provide a highly conductive channel for charge transfer between the cloud and the ground. Negative charge starts flowing down the channel from the cloud to the ground

streamers' to reach up towards the descending current

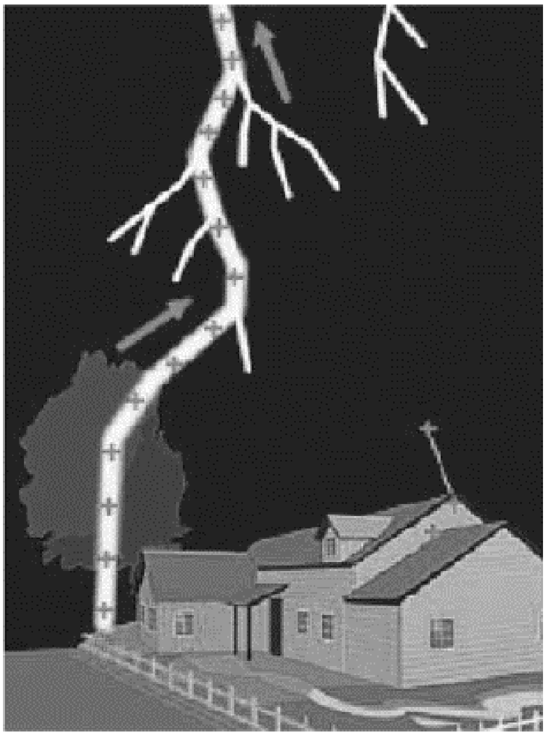


Fig. 2.3.4

The initial surge current is followed by an even stronger 'return stroke' that shoots up the channel as a brilliant pulse from the ground to the cloud, another leader, termed a 'dart leader' as it uses the existing channel and has a continuous path, this new stroke can be followed by additional return strokes. In a series of discharges between the cloud and the ground.

Fig. 2.3, Point discharge is happened through tree [4]

2.1.3 Different kind of lightning Discharge:

Four kind of lightning discharge can be found naturally [1].

a) Intra-cloud discharge(IC)

b) Cloud to cloud

c) Cloud to air, and

d) Cloud to ground(CG)

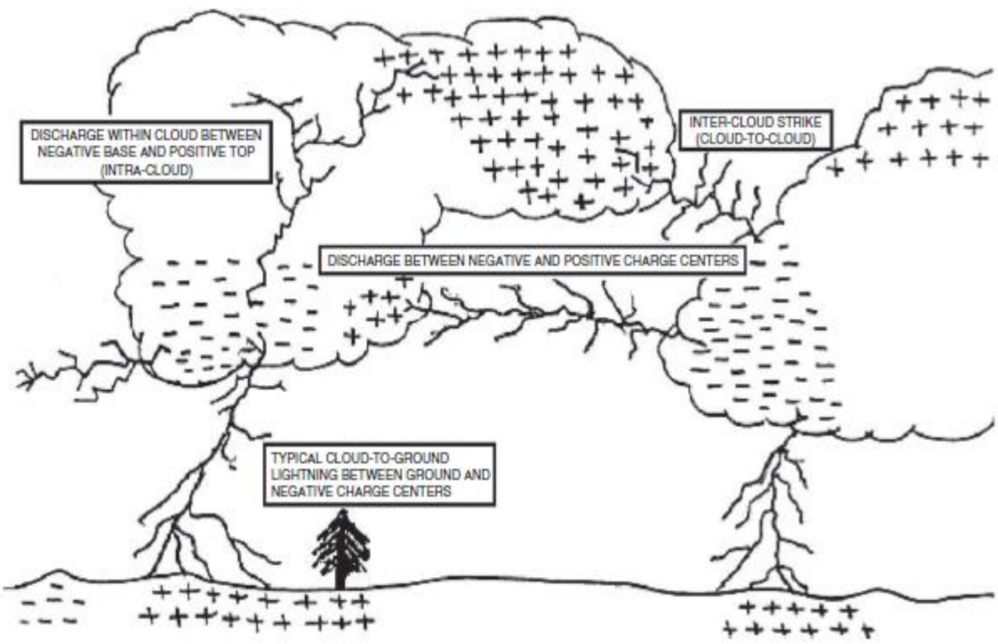


Fig.2. 4 All different kinds of lightning strikes happen naturally [4]

Fig. 2.4 shows all four kinds of lightning strikes mentioned above. Nearly 70% -80% lightning happens within the clouds [4]. Some lightning flashes happen within the cloud or in the air are sometimes called as atmospheric strikes which is less concern than the cloud to ground strike. Electronic equipment can be protected from this kind of discharges [5-6].

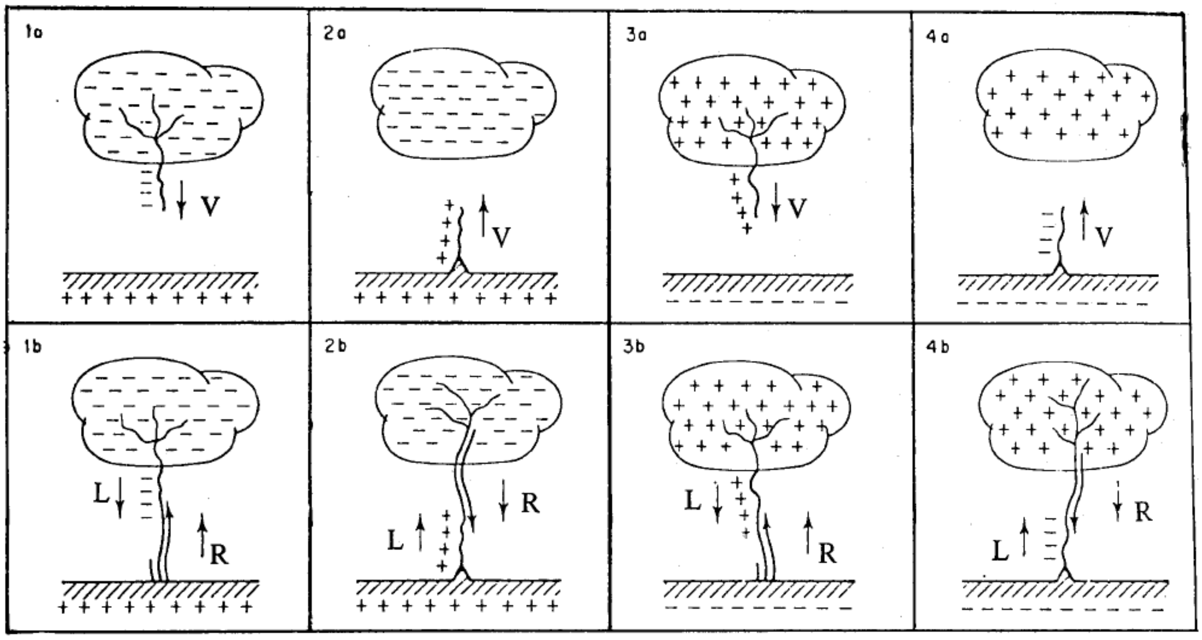


Fig 2.5: 8 different types of lightning strikes, typically based on L (leader), R (Return stroke), V (direction of propagation), and polarity types [1]

Cloud-to-Ground strike has different types of category. Uman [7] has classified it into four types, while Golde [2] has eight types. The return strikes are taken into account by Golde. See Fig. 2.5.
90 percent of CG flashes belong to category 1 of Table 2.1 [1], here discharge initiates as a negative leader from the cloud which has positive charge at the top side. Whereas 10 percent cases it can be found that discharge starts as a positive leader from the top of the cloud and moves down toward the earth, these kind of discharges belong to Category 3, Table 2.1 [1].
The upward moving ground-to-cloud leaders are extremely rare and they belong to Categories 2 & 4 from Table I. This kind of flash occurs from high mountain-tops and tall manmade structures. Uman reported that an individual storm at Kennedy Space Center breeds 1 to 4000 lightning strokes, where 30% to 40% of these flashes were CG and roughly half of them were IC [1].

Table 2.1: Different types of Lightning between Cloud and Ground [7]

Category	Originate from	Leader Polarity
1	Cloud	Negative
2	Earth	Positive
3	Cloud	Negative
4	Earth	Positive

Table 2.2: Types of Lightning Classifications [2]

Type	Originate From	Leader Charge	Return Stroke
1a	Cloud	Negative	None, Air discharge, open country, no buildings.
1b	Cloud	Negative	Yes, Ground Strike.
2a	Earth	Positive	Charge flow to Earth, Tower is Negative.
2b	Earth	Positive	Multiple flash, example Empire State Building.
3a	Cloud	Positive	Intra-cloud displacement current.
3b	Cloud	Positive	Positive up return stroke, rare.
4a	Earth	Negative	Tip cathode, positive cloud and positive continuous current. rare
4b	Earth	Negative	Imitated as 4a, after 4-25 ms Sever positive down discharge, mountain areas

2.1.4 *The mechanism of lightning strike:*

Several types of lightning strikes can be found where negative leaders from cloud to the ground strikes are common. On the other hand, ground to cloud strikes are not common in nature. Polarity of leader depends upon the location of the facility. Lightning strokes result in electromagnetic coupling with electrical system which can be harmed for huge induced voltage [5-6].

For the lightning mechanism, let us consider negative leader CG strikes. At first, negative leader moves downward by creating a series of distinct steps. At the bottom of the cloud, ionization happens as described above for the point discharge. When wind blows the ionized clouds, charge accumulates and produce the ionization break down of the air, and lightning happens.

Some typical parameter values for the leased as follows [20]:

a) Leader length is in the range of tens of meters.
b) Time gap between two steps is 20-50 µs.
c) A potential leader can effectively lower 10 C or more of negative charge.
d) Propagation speed is about 2 $\times 10^5$ ms^{-1}.
e) The average leader current is 100 to 1000 A.
f) Down branches are produced during starting and stopping of the leader.
g) In generally potential difference between the leader and earth is about 10^7 V.

With the increasing value of the electric field, point discharges happen on the ground. Due to proper potential difference between leader and the earth, breakdown happens and ground discharging process starts with moving up toward the downward moving leader. When these two leaders meet lightning happens, in generally this meeting point is of meters of above the ground.

Uman [6] describes the transfer of charge. “The leader is effectively connected to ground potential. The leader channel is then discharged by an ionizing wave of ground potential that propagates up the previously ionized leader channel. This process is the first return stroke. The electric field across the potential discontinuity between the return stroke, which is at ground potential, and the channel above, which is near cloud potential, is what produces the additional ionization.”

There are some typical values of return stroke are given below [6]:

a) Speed of the return stroke near the ground is one sixth of the speed of the light speed and gradually decreases as it approaches the cloud.
b) Time taken by the return stroke to reach to the cloud from the ground is about 100 µs.
c) First return stroke has peak current of 30kA.
d) Taken time to reach zero to peak is few microseconds.
e) At ground currents decrease to one-half within 50µs.
f) Hundreds of ampere may flow within few hundred milliseconds.
g) During this process channel is heated to 30000 K.
h) Range of the current is from 20 – 400kA.
i) Time interval between return strokes 3 – 100 ms.
j) Total charge transferred during return stroke is from 2 – 200 C.
k) The number of return strokes varies from 1 -30.

After completion of that process remaining charges can be used by another leader and additional return stroke can develop.

From the upper part of the cloud positive leader CG stroke occurs as upper portion of cloud contains positive charges. The main difference between the positive and negative stroke is the leader polarity and is continuous without steps. The highest amount of current due to the positive stroke is from 200 – 300 kA. Although they are rare during the summer storms, only 1% to 15% of total flashes [6], the final stroke may be a positive stroke. In the higher altitudes or in mountainous regions, positive strokes happen during winter season. Initiation of large current occurs due to the return stroke and a continuous current continues to flows.

Information provided by WSI Real-Time Lightning Information shows that the number of positive strokes may be larger than indicated above. In northeast Texas, in every 6-hour time period, the graphical display showed that nearly 35% of the lightning strikes were positive. During another 21 min period of the 78 strokes recorded on March 11, 1993 at *5:00* PM, 32% were positive strokes. It is evident that additional studies are needed [1].

Leader having any polarity either positive or negative can be generated by the tall man-made structures and mountain peaks, Categories 2 and 4, Table I. The positive leaders, either from cloud-to-ground or from earth-to-ground, are continuous whereas the negative leaders are stepped. The positive leaders from ground-to-cloud discharge between 100 and 1000 A of current.

Not only must the engineer, in selecting lightning protection, be concerned with the Isokeraunic Map, with the expected number of thunderstorms per day, but the latitude and height of the structure must be considered also.

2.2 Lightning Detection Technologies:

There are many different methods to detect Lightning flashes and strokes. Most notably, within a fraction of a second the discharge of thousands of amperes current produces temperatures estimated to be as hot as 30,000 °C which is hotter than the surface of the sun, with a bright flash of light and an acoustic shock wave which is called thunder. During that time, the surging electrical currents release a wide spectrum of electromagnetic radiation and modify the strength of the local atmospheric electrical field [4].

2.2.1 Flash and Bang:

Without any specific technologies, flash and bang of nearby lightning strikes can easily be detected. Particularly at night, an alert observer can notice any distance lighting flashes. However, this kind of technology is not reliable for application involving safety.

These "technology free" can only estimate the distance of the lightning flash in a conventional way, the difference in time between the arrival of the sound of thunder and the observation of a flash to measure the distance of lightning, though direction cannot be measured by using that method. The lightning flash can be seen instantaneously, but sound travels 1 mile in every 5 sec, due to speed difference, time interval (in seconds) happens. The time interval created by the flash and the bang multiplied by 5 that gives the distance in miles. Unfortunately, many small airports do not equip with lightning detection technologies, they can estimate lightning distance only [4].
Acoustic detector is used to detect sound of thunder which is easily recognized, but it is quite difficult to use in quantitative way. It was tested, a networks of acoustic detectors to locate lightning strikes, and that experiment did not get any significant success, and thus this acoustic detection system does not for any safety purpose operating system [4].

Optical detector technology can be used to detect flash that is produced by lightning strike, but during the day time sensor does not work properly which creates error in measurement system and that is the reason it does not often use for quantitative applications. To develop this optical detector, sensitive detectors and narrow bandwidth filters are used. By using these developments optical lightning detection system can be used in day time also. Furthermore, to reduce the false alarm, magnetic and electro-static pulse analysis are connected with this detector. For example, the Vaisala TSS-928 local-area lightning-detection sensor [4].

2.2.2 Atmospheric Electric Flied Measurement:

Now-a-days, the atmospheric electric field measurement instruments are used for lightning warning and lightning detection technologies. Electric field intensity changes in every half an hour before thunder storm. To measure the electric field filed mill is used (see Fig. 2.6), there is a sudden change in the local electric filed strength due to nearby lightning, and this sudden change can be detected for lightning detection without knowing the direction of lightning. Overhead cloud becomes nearby charge center that dominates electric field of that locality and results in limitation in detection of distance lightning strikes. Electric field mill can detect the build-up surroundings electric field, which generally happens before lightning strikes. Most recently lightning detection system employs field mills to inform one about the building up of electric filed. Basically this concept used for predicting lightning strike rather than lightning detection within a certain area. However, there are some limitations like uncertainty in range and detection efficiency. The main technical parameters are given below in Table 2.3 [8].

T*able 2.3: Electric Field Mill parameters [8]*

Parameters	***Performance Index***
Range of electric field value	0~±100kV/m
Radius of detection area	I5km-30km
Measuring error	<±5%
Communication Specification	GPRS/3G/4G
Baud rate	7200bps
Required average power	3W
Environment temperature	-40'C-+8S'C
Installation distance from target	<15km
Spacing between instruments	>30km

Fig. 2 6. Electric Filed Mill (from Boltek) [8]

From historical meteorological data, main lightning discharge happens 15-30 minutes later than the weaker one [9]. Electric field is also commercially used for lightning detection and lightning prediction technologies.

2.2.3 Electromagnetic Emission:

Most recently lightning detection technologies available in the market detect lightning by using the Electromagnetic Emission, mainly radio frequency (RF) which is associated with lightning discharge (Fig. 2.7). RF static is produced by lightning strikes and AM radio signals use this frequency range for broadcasting purpose. A strong signal of low frequency (LF) band, generated by CG strikes, can be detected from several hundreds of kilometers, whereas, IC strokes produces predominately VHF which is a line-of-sight emission [4].

RF electro-magnetic emission based lightning detector system is generally simple and low cost and hand-held devices. A detection network is a collection of a group of detection sensor to work properly and efficiently. Low ended detecting system results in uncertainty in sensitivity and false alarm. They are generally used for sports activity, public gathering and hikers. The main function of this system is that it does not give any information regarding direction of strike, although it tries to predict lightning strokes distance with the help of signal amplitude [4].

The response of this technology can be enhanced by using sensitive receivers which monitor the signals and examine the properties and time evolution of the signals to reduce false detection. CG flashes and discharges of IC strokes can be distinguished by the analysis of the incoming signals.

To determine the direction of the lightning signal from the detector, orthogonally crossed loop antennas are used, the SAFIR lightning detection technology (developed in France), VHF interferometric dipole antennas (for direction detection) or other direction finding technologies. With the help of signal amplitude algorithm these high ended receivers can determine direction as well as range of the nearby lightning strikes. It is mentionable that sometimes weather stations have such types of high ended sensors to achieve fully automatic METAR reports (aviation routine weather reports) which gives a brief of current weather report [4].

To get the current weather report at an airport these sensors are included to produce fully automatic METAR reports. In this application lightning detection system used to indicate the nearby thunderstorm for giving an approx. indication of the storm's location and distance from the airport.

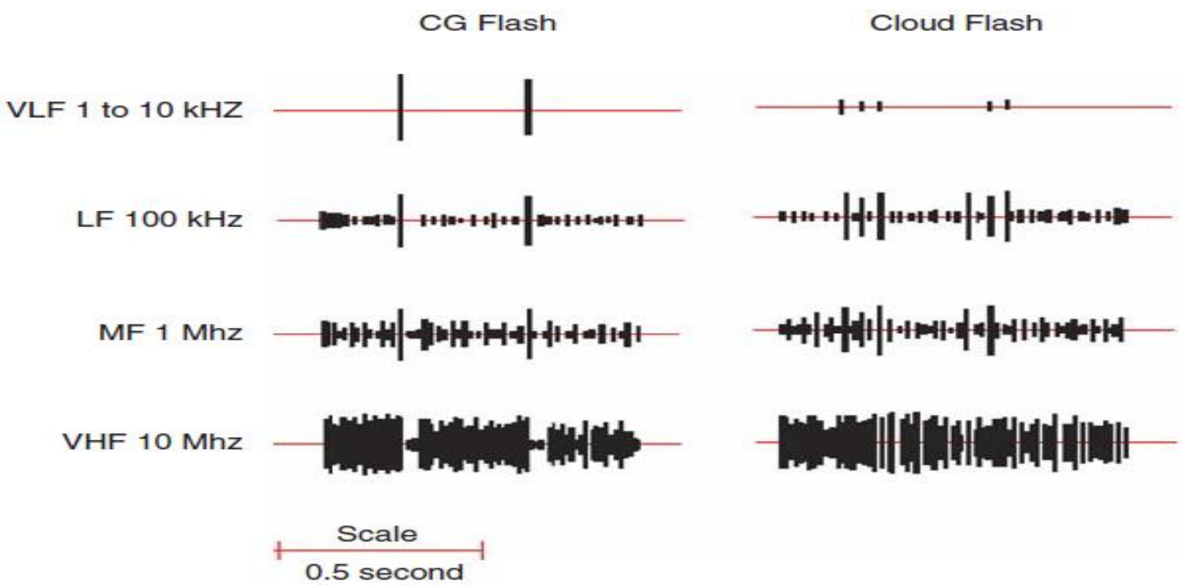


Fig. 2.7. Showing various frequencies of CG and IC flashes. VLF emission follows the curvature of the earth, so this frequency can be detected from as long as 300-600 km, whereas, VHF has line of sight propagation, so this can be detected from 200-300 km. Advantage of VLF emission is that it reflects from ionosphere, results in increment of detection range. [4]

2.2.4 Lightning Detection by Networks of Electromagnetic Sensors:

Very precise location information for CG lightning can be obtained by networks containing sophisticated electromagnetic sensors. Two or more sensors are used to identify the direction of that strike through triangulation of the direction information. As ground lightning strokes generates very strong VLF and LF signals that propagate through the surface of the earth can be detected from many hundreds of kilometers away from the source. Thus to cover a very large area it is required to construct a network having adequate number of detectors, as an example: slightly over 100 sensors for CONUS [4].

With the help of global positioning system (GPS) this sensor networks are able to detect the position of lighting strike, as GPS provides high accuracy time-references [4]. Position can be achieved by finding the time difference between two or more detectors' observations of the same lightning stoke. The "time of arrival" is different for every separately located sensors and by using suitable algorithm, the time and location of the lightning strike can be determined. Depending on the spacing and position of the detectors and the position of the lightning strike, time of arrival solutions can require as many as three or more detectors to record the signal from the same lightning stroke.

CG lightning strikes are generally detected by ground based lightning detection networks which provides information regarding every strikes within the range. Recently, development has been done so that this network system can detect nearby IC lightning strokes, though efficiency varies as properties of strokes changes. As IC lightning strokes are generally horizontal in nature and stretched over a long distance, it is quite hard to assign a single position to each strike, on the other hand, if CG strikes stretch over long distance inside the cloud, ground strike position can be defined with efficiently. Factually, IC strikes happen more frequently that CG strike, and since within-cloud lightning is normally observed preceding the first ground strokes, cloud lightning detection systems that are optimized for VHF emissions have a great potential for enhancing our current detection capabilities [4].

2.2.5 Lightning Detection from Space:

Sensors attached to satellite can also detect electrical emission from lightning, these sensors are based on optical detection technologies. Optical detectors, generally look at a strong oxygen emission band in the near infrared (IR) and examine to discover short bursts generated by lightning strikes and that can be detected during night as well as day time [4]. The Geostationary Lightning Mapper (GLM) being developed for GOES-R is expected to provide full coverage over the United States, South America, and adjacent oceanic areas. From geostationary orbit, the GLM lightning sensor will not be able to match the accurate positioning of the current ground-based networks, but will provide uniform, high efficiency detection of total lightning, including both cloud and ground flashes over virtually all of the visible earth disk as seen from space [4]. This new data set will not replace the current ground-based lightning networks, but will provide extremely valuable "total lighting" information to augment the high-resolution CG flash information currently available.

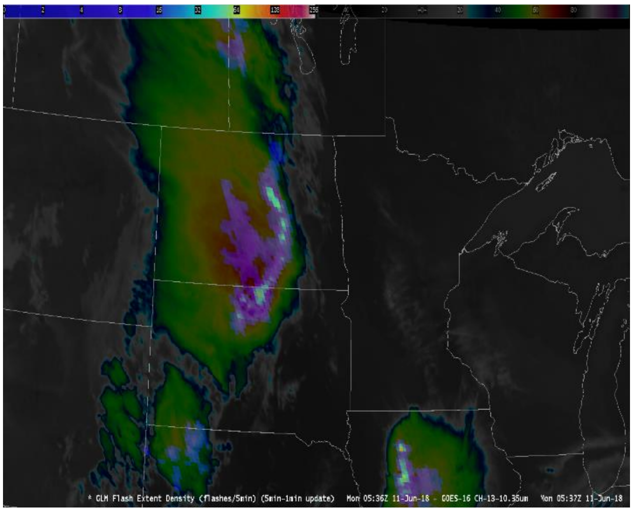


Fig. 2.8, This GOES East GLM imagery shows a high concentration of lightning flashes over the Northern Plains on June 11, 2018. (Image Credit: NOAA Virtual Lab)[10]

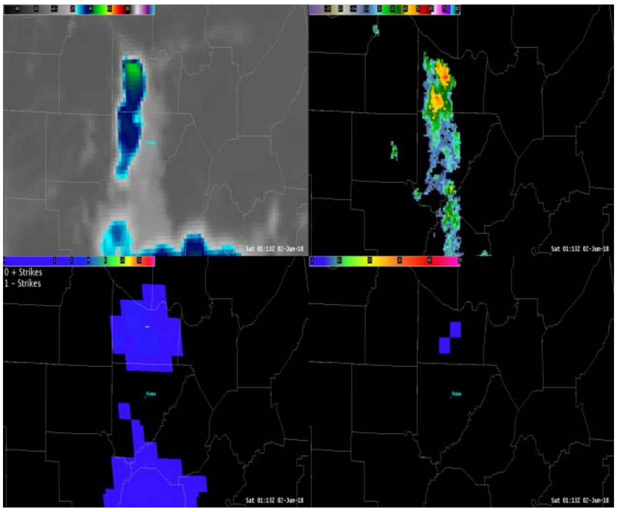


Fig. 2.9, bottom left panel of this image maps the location of lightning from the GLM Flash Extent Density product. The concert location is marked "Home" in light blue. (Credit: NOAA GLM Virtual Lab) [10]

The groundbreaking instrument on-board the NOAA GOES East (GOES-16) satellite has allowed us to see lightning from space like never before, mapping cloud-to-ground [10], cloud-to-cloud, and intra-cloud lightning from more than 22,000 miles above Earth. The GLM is the first optical lightning detector on-board a satellite in geostationary orbit [10].

2.3 <u>Lightning prediction technology:</u>

Happening of lightning is highly connected to electric field of atmosphere. Thunder storms happen in three steps which are preliminary produce, development and starting and that takes approximately half an hour. So, 4 threshold levels are set for lightning warning. Level 1, electric field value 30 minutes before the thunderstorm. Level 2 is 15 minutes before, level 3 is 5 minutes before and level 4 is the occurrence moment. Details of these level givens below [8].

- Level 1: 1.5 kV/m is the threshold value of electric field. Electric filed jitter starts appearing due to cloud charge and that time electric field mill should pay close attention to the change of electric field.
- Level 2: At this level filed threshold value is 3.0 kV/m, which indicates that the thunder storm is in close proximity to the measuring instruments.
- Level 3: Threshold value is 5.0 kV/m, thunder storm is approaching, and lightning has occurred near the instrument.
- Level 4: The threshold of electric field is 8.0 kV/m. That indicates that monitoring area is in high alert.

Above mentioned threshold values work in most environments. As electric filed value does depend on altitude, environment, location of instruments, the threshold values need to be modified according to the operating conditions, thus the accuracy of the system can be improved. The thunderstorm changes filed of environment very rapidly and slope of electric field changes is relatively steep. This situation on the ground is performed as a pulsed type changes, and atmospheric electric field increases exponentially as charged cloud electrify whole nearby environment. Determination of Cloud to ground lightning cannot be done only by electric field intensity, the change of field value should be considered to avoid false alarm. Slope of electric field can be found out by using time differential of electric field. The intensity of atmospheric electric field frequency (of once per second) can be measured by the atmospheric electric field.

Instruments, this instrument gives output in discrete form. The formula of 1st order differential equation of atmospheric electric field and time is given below [8],

$$E(t)' = \frac{E(t_1) - E(t_0)}{t_1 - t_0} \qquad (2.1)$$

E(t)´ = the time-differential value, any two adjacent times t_1 and t_0, for electric field instrument sampling interval time is 1s, and $E(t_1)$ *and* $E(t_0)$ are corresponding electric field values.

To obtain lightning warning ahead of occurrence set the electric charge rate before the thunderstorm 5 min, 15 min, 30 min and the happening time to analysis, and respective electric filed time differential values are 0.5 kV/(m*s), 1.5 kV/(m*s), 2.0 kV/(m*s) and 3.0 kV/(m*s) respectively. These above discussed threshold values are to be set to the warning levels [8].

Before the happening of lightning, the rapid change of atmospheric electric field is monitored, the rate of change of electric field intensity over time and lightning contact activity is more closely connected than the contact of lightning activity and electric field value. To, reduce the false alarm, atmospheric electric field time-differential calculation should be modified rather than only electric field [8].

To predict lightning phenomena, the whole process is divided into four steps, are given below:

2.3.1 Lightning Location System(LLS)

2.3.2 Thunderstorm Clustering Algorithm

2.3.3 Thunderstorm Linear Prediction

2.3.4 Distance Warning of Thunderstorm

2.3.5 Two area method

2.3.1 Lightning Location System(LLS):

Lightning Location System (LLS) is one of the most reliable technologies for the detection of lightning in lightning engineering field technology. This is a real time fully automatic lighting detecting set having high precision and it covers large area. It is cable of displaying of place and the time of any CG lightning stroke with lightning current, magnitude, polarity, number of strokes, and other parameters of strokes [8]. This technology uses the combine location method for finding the direction and arrival time, which reached the technical index that lightning flashover checking rate is greater than 90%, location error is less than 800m, peak amplitude value error is less than 15% [11].

Lightning is integral part of a strong convective weather which is random in nature, so high density lightning area indicates thunderstorm. Depending on the LLS data, it can easily examine thunderstorm by using clustering method of targeted area data of lightning and excluding sparse points in thunderstorm cloud distribution. After that it calculates the speed and the direction of movement of clustered thunderstorm, thus it provides small scale and short time lightning warning and false alarm can be reduced effectively [12-13].

2.3.2 Thunderstorm Clustering Algorithm:

Clustering algorithm based on density, so it is most suitable to analyze the information of high density lightning location by this clustering algorithm, and there is a classic algorithm is DBSCAN [14-15].

Basic working principle of BDSCAN is to check total data set and arbitrarily find a core point, and search all density connected data points to expand this core point and gather into clusters.

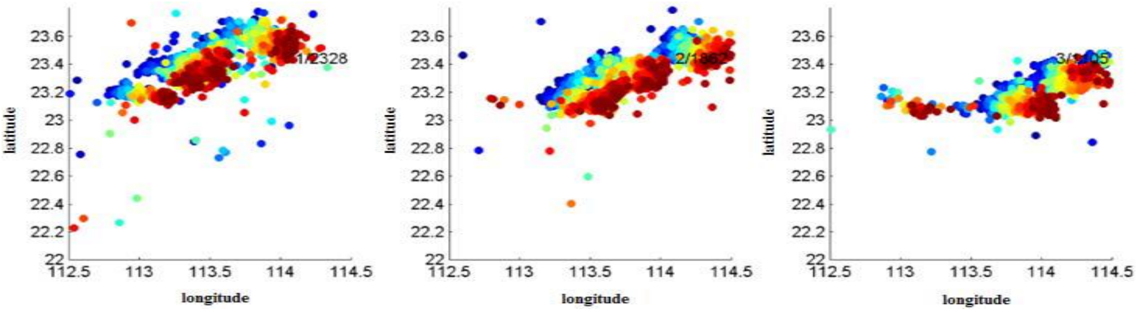


Fig 2.10, Continuous time CG flash coordinates [8]

DBSCAN algorithm given below:

- Input: During lightning coordinate collected as A, nearby radius α, $P_{min}$is minimum cluster number.
- Step1: Need to randomly select a core point from A.
- Step2: That selected core is to be traversed within the selected radius α, search all density connected pints until no extension can be done.
- Step3: The core and the expanded points are gathered inside the cluster, after that all points are marked as has been processed.
- Step4: Above mentioned steps 2 to 4 are repeated until all the points are processed.
- Output: All lightning clusters that meet the requirements of the density.

2.3.3 Thunderstorm Linear Prediction:

The output of clustering is in continuous time, with the help of below given equation, the center point of clustered thunderstorm can be obtained for each time [8].

$$G_x = \frac{1}{n} \sum_{i=1}^{n} x_i \qquad (2.2)$$

$$G_y = \frac{1}{n} \sum_{i=1}^{n} y_i \qquad (2.3)$$

From the above written equations (2) & (3), G_x and G_y can be found, those values provide longitude and latitude of the center of the clustered thunderstorm cloud, and x_i and $y_i$are respectively longitude and latitude of the lightning location inside the range of the clustered cloud.
By linear fitting of the obtained points, one can predict future position of the cloud for continuous time interval, linear curve fitting uses least square method of clustered thundercloud, thus the movement of thundercloud can be described. The finding of a separate line for each thundercloud center to fit, it is easy to obtain an appropriate set of a and b for all the given data points (x_i, y_i), i = 1…n, which make the linear fitting as close as possible to the every center point of clustered thundercloud [8].

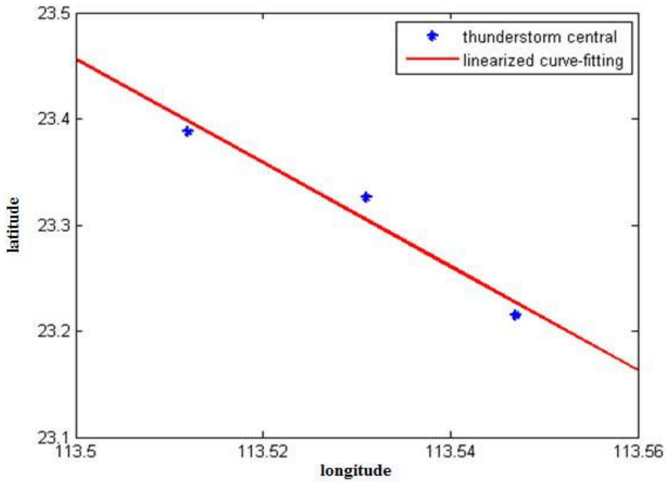


Fig 2.11, Thundercloud curve central point by linear fitting [8]

In reality, lightning location monitoring system continuously works for thirty minute, where this time span is sub divided into three equal part having time span of 10 minutes each, with the help of clustering method DBSCAN algorithm is applied for each division, after that the center of these three periods will be obtained, then linear fitting has been done to develop the trajectory, thus direction and velocity of the thunderstorm can be evaluated very easily and efficiently by this method.

2.3.4 Distance warning of Thunderstorm:

According to the above calculation of distance between the positions lightning will happen and protected objects. When it within 10 ~ 15 km, as warning of level 1, as level 2 when it within 5~ 10 km, and as level 3 when it within 0~5 km [8].

2.3.5 Two area method:

The Two area method was introduced by Muypy et al [17-18]. This method defines two concentric areas at a geographical point called Point of Interest - PI. The first area that surrounds the PI is called Area of Concern - AOC. This region includes zones highly vulnerable by any stroke without notice. The second area or Warning Area - WA surrounds the AOC. When the atmospheric activity is reported over the second region, the thunderstorm warning should be triggered, and the preventive actions must be started. Fig. 2.12 shows the two areas method analysed in this work [16].

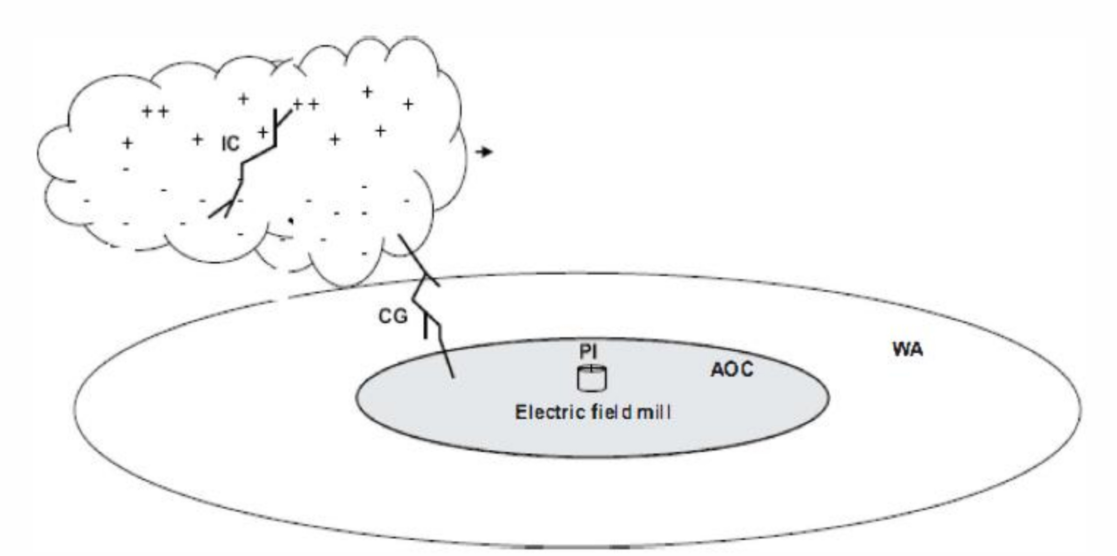


Fig. 2.12: The two are method [16]

The size and shape of the regions should be adjusted according to the detection efficiency and localization accuracy of the detection system and the target shape. This work employed Electric Field Mill - EFM records and data from the Lightning Location Network - SID, allowing designing multiple criteria for triggering warning alarms [16].

Disadvantage of electric field instrument is that it is non directional and cannot predict the movement of lightning. Though LLS can locate lightning in real time and thus it reduces of false alarm tendency. Lightning warning level is calculated on the base of two aspect shown in the Table 2.4

Table 2.4: Different lighting warning according to probabilities [16]

Lightning warning level	**1**	**2**	**3**	**4**
Warning signal	Blue	Yellow	Orange	red
Probability of lightning	0%- 25%	25%-50%	50%-75%	75%-100%
Pulse of two type of warning	1	2 or 3	4 or 5	6 or 7

According to the existing research literature and metrological department lightning warning divided into 4 grades. If the probability is less means 0% - 25%, warning color is blue (no lightning), for 25%-50% it is yellow, as moderate probability 50%-75% it is orange and if high chances of lightning, means above 75%, it is red [16].

CHAPTER-3

DETAILED DESCRIPTION OF THE DEVELOPED SCHEME

- Fuzzy Logic
- AS3935 Lightning sensor

In this research work, detection of real time lightning strike and calculation of lightning strike probability due to incoming or existing thunderstorm can be done. That prediction model has been defined with the help of Fuzzy rule base inference system which is typically based on Mamdani Fuzzy logic. In fuzzy logic, parameters are represented as membership functions which are taken as the input of fuzzy inference system to produce fuzzy output which is the probability of the lightning strikes.
On the other hand, AS3935 IC is used to detect lightning strikes. With the help of an interfacing board that IC communicates with computer where it can be noticed the detection of lightning and its approximate distance from measuring device. That measuring distance is one of the most important parameters for the prediction of lightning strike. The overview of the software and the hardware tools used in this thesis are described below.

3.1 Fuzzy Logic:

Fuzzy logic is advancement of the classical (Boolean) logic which can handle numerically the vagueness of human linguistics and thinking (Tanaka, 1996). It can be said that formalize approximate reasoning can be obtained by that system (Zedeh, 1994; 1996). However, currently there is a growing tendency to use fuzzy logic term as almost synonymous with fuzzy set theory (Zedeh, 1994).

3.1.1 Advantages of Fuzzy Logic:

- The theory of fuzzy logic is based on intuition and judgement.
- Fuzzy set provides smooth transition between members and non-members.
- It is relatively simple, fast, and adaptive.
- This system can implement those objectives which are difficult to be expressed mathematically and hence can be more conveniently expressed by linguistic or qualitative rules.

3.1.2 Classical set vs. Fuzzy sets:

- Classical set or crisp set:

A crisp set *C* is a set with crisp boundary. For example, a crisp set *C* can be expressed as:

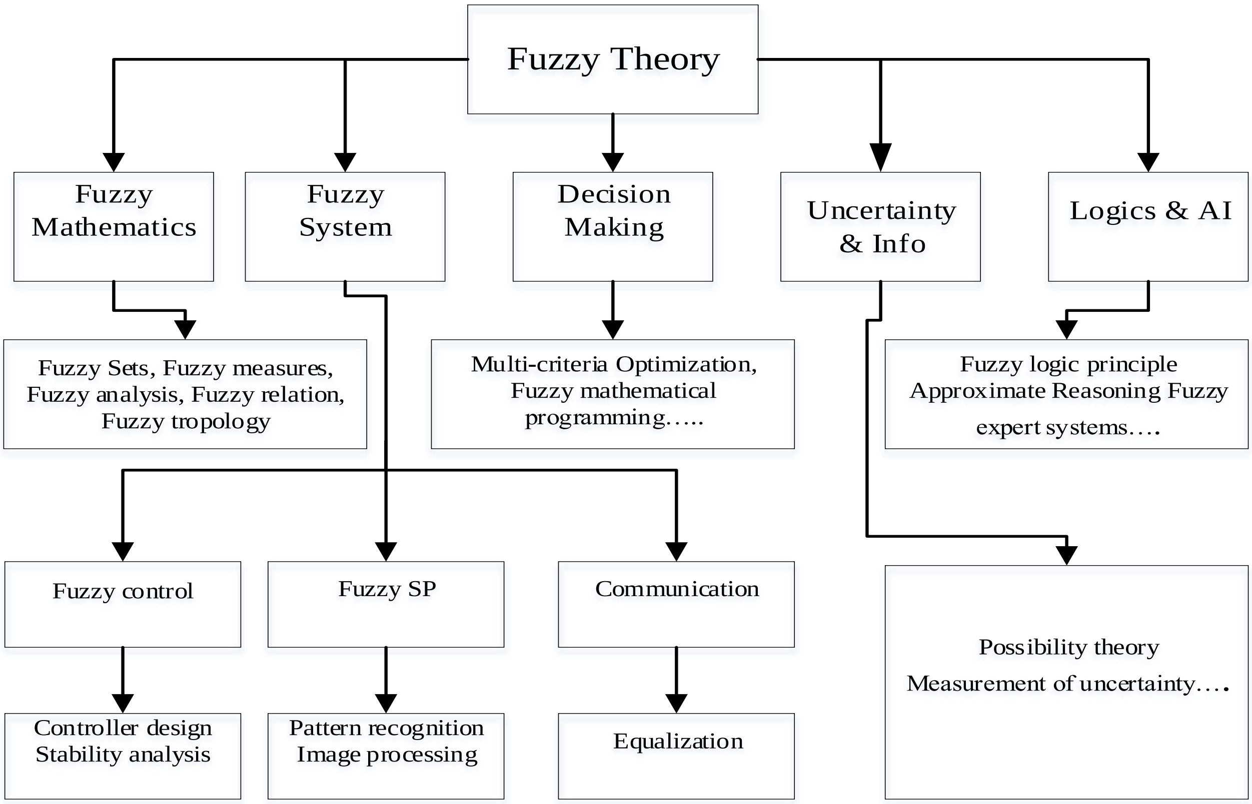
$$C = \{X \mid X > 6\}$$

In a crisp set *C* a member X either belongs to it or does not belong to it. Hence the membership value of a member X in *C* is either 0 or 1 [25].

- Fuzzy set:

A fuzzy set *A* is a set without any crisp boundary. The transition from belonging to a set to not belonging to a set is gradual. Hence fuzzy set *A* contains elements having varying degrees of membership in the set, ranging from 0 to 1 [25].

3.1.3. Classification of fuzzy theory:



3.1.4 Fuzzy sets and Linguistic Variables:

A fuzzy set is an extension of crisp set. Fuzzy set allows partial membership values. In fuzzy set concept partial membership, $\mu_A(x)$, is defined as [25]

$\mu_A(x) = 1$ if $x \in A$; $\mu_A(x) = 0$ if $x \notin A$ and $\mu_A(x) = p$ $(1 > p > 0)$

If x partially belongs to *A*. If a universe of discourse U, contains a fuzzy set *A* having membership function $\mu_A(x)$ which has values between 0 to 1, that can be expressed as [25]

$\mu_A: U \rightarrow [0, 1]$

Commonsense linguistic labels are used in the case of fuzzy representation, e.g. suitable, moderate, slow, fast, very fast etc. At a time a given element can be the member of more than one fuzzy set. *A* is a fuzzy set in U can be represented as a set of ordered pairs. Each pair of a generic element x and its membership function [25],

i.e. $A = \{(x, \mu_A(x) / x \in U)\}$

Where x is support value if $\mu_A(x) > 0$ [Zadeh, 1965]. The concept of linguistic variable has an important role in fuzzy logic, that variables are expressed in words or sentences in natural languages. For each input and output variables, fuzzy sets are created by dividing its universe of discourse into a number of sub-regions and are named as linguistic variable [Zimmermann, 1996], [25]

An alternative way to represent a fuzzy set given below [25],

$$A=\sum_{x_i \in X} \frac{\mu_A(x_i)}{x_i}, \text{ if X is discrete.}$$

$$A=\int \mu_A(x)/x, \text{ if X is continuous.}$$

3.1.5 Membership functions:

Fuzzy and classical can be defined by membership function (MF), the degree to which an element belongs to a classical subset is limited to 0 or 1. However, the membership function of fuzzy logic has curvature which defines how each point in input space is mapped into a membership value which is in between 0 to 1. Below given Fig. 3.1 & 3.2 are showing crisp and fuzzy set accordingly [25].

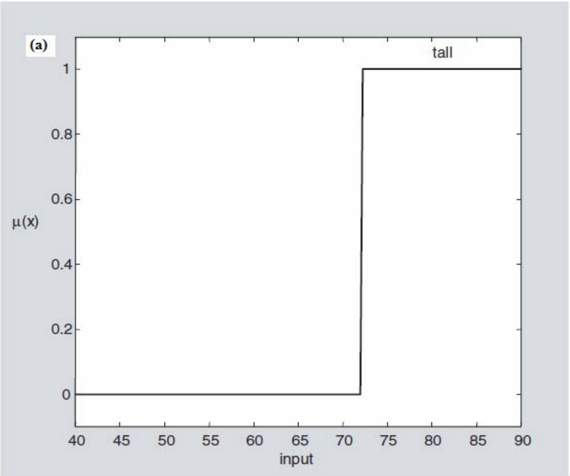


Fig.3.1: Crips MF[25]

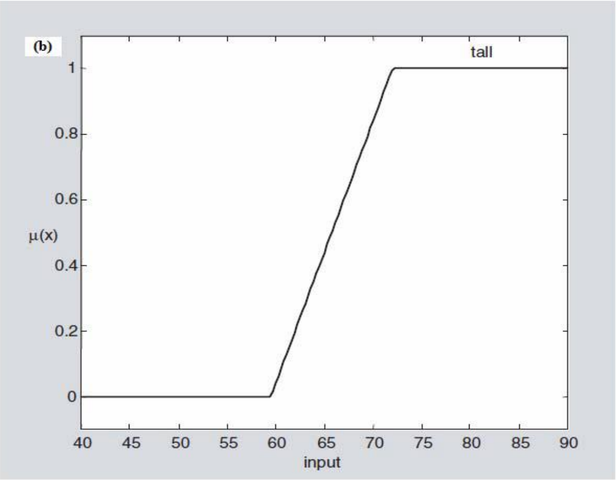


Fig.3.2: Fuzzy MF[25]

Many types of MFs are used in fuzzy logic depending upon the applications, e.g. trapezoidal, bell, triangular, Gaussian, sigmoid function. In the case of triangular MF, it depends on the values of three parameters a, b, and c, expressed as [Zimmermann, 1996], [25]

$$f(z; a; b; c) = \begin{cases} 0 & z \leq a \\ \frac{z-a}{b-a} & a \leq z \leq b \\ \frac{c-z}{c-b} & b \leq z \leq c \\ 0 & c \leq z \end{cases} \quad (3.1)$$

In the case of trapezoidal curve, parameters are a, b, c, and d, shown below [25].

$$f(z; a; b; c; d) = \begin{cases} 0 & z \leq a \\ \frac{z-a}{b-a} & a \leq z \leq b \\ 1 & b \leq z \leq d \\ \frac{c-z}{c-b} & c \leq z \leq d \\ 0 & d \leq z \end{cases} \quad (3.2)$$

Gaussian curves given below [25],

$$f(z; \sigma; m) = e^{-\frac{1}{2}(\frac{x-m}{\sigma})^2}$$

While designing a fuzzy inference system, MFs are associated with terms sets that in the consequent or antecedent of the rules. There are many different rules to determine membership functions. Some of them are like fuzzy clustering [Sugeno and Yasukawa, 1993; Yoshinari et al., 1996; Hwang and Woo, 1995], neural networking [Kosko, 1992] etc. In order to find optimal shape of membership function Genetic algorithm [Wiggins, 1992; Karr, 1991 a & b; Karr and Gentry, 1993; Park et al., 1994] is used. Sometimes, after gathering system information from the expert, MFs are constructed, that represent expert opinion [25].

3.1.6 Logical operation:

Union, intersection and complement are the most elementary operation of crisp set and also correspond to *OR*, *AND*, and *NOT* operators, respectively. Fuzzy set operation is analogous to crisp set operation. Let P and R are the two subsets of U. The union represent P ∪ R, contains all elements either P or R; i.e. $\mu_{P \cup R}(x) = 1$ if $x \in p$ or $x \in R$, containing all elements in either P or R. Intersection of P and R is detonated P ∩ R, which means . $\mu_{P \cap R}(x) = 1$ if $x \in P$ and $x \in R$. The complement of P is represented as P´ and this contains all elements which does not belong to P [25].

In fuzzy logic OR, AND, and NOT are represented as max, min and complement. They are defined below [25]:

$$\mu_{P \cup R}(x) = \max [\mu_P (x), \mu_R(x)]$$

$$\mu_{P \cap R}(x) = \min [\mu_P (x), \mu_R(x)]$$

$$\mu_{P'}(x) = 1 - \mu_P(x)$$

The union of two fuzzy set P and R is defined by a binary mapping S that aggregates two MFs as given below [25],

$\mu_{P \cup R}(x) = S [\mu_P (x), \mu_R(x)]$

Union operation in fuzzy logic is known as T- conorm or S-norm operators, and they have to satisfy given below conditions [25]:

Boundary: $S (1, 1) = 1, S (a, 0) = S (0, a) = a$

Monotonicity: $S (a, b) \leq S(c, d)$ if $a \leq c$ and $b \leq d$

Commutatively: S (a, b) = S (b. a)

Associatively: $S (a, S (b, c)) = S(S (a, b), c)$

And similarly fuzzy intersection operation is defined in binary mapping T (triangular norm) by [25]:

$\mu_{P \cap R}(x) = T [\mu_P (x), \mu_R(x)]$

It has to satisfy some conditions like [25]

Boundary: $T (0, 0) = 0, S (a, 1) = S (1, a) = a$

Monotonicity: $T (a, b) \leq T(c, d)$ if $a \leq c$ and $b \leq d$

Commutatively: T (a, b) = T (b. a)

Associatively: $T (a, T (b, c)) = T (T (a, b), c)$

3.1.7 If- Then rules:

Fuzzy system is a collection of if-then rules that is a staring input of linguistic variables to an output value [Kosko, 1992; Goktepe et al., 2008]. The number of rules depend on the number of input variable and linguistic variable. To construct a fuzzy system, required number of rules is given below [Kim et al., 2001; Xu et al., 2002] [25],

$$N=\prod_{j=1}^{m} n_j \ ; 1< j \leq m$$

Here m= the number of input variable, n_j= number of linguistic variables for each input variable.

Fuzzy rule assumes the form "IF x is P, THEN y is R," where x ∈*U* and x ∈*V*, here *U* and *V* are universe of discourse, and has a membership function, μ *A*→*B*(x, y), μ *A*→*B*(x, y) ∈[0,1]. In this, IF part of the rule, "x is *A*," is called the antecedent or premise, while the THEN part of the rule, "y is *B*," is called the consequent or conclusion [25].

3.1.8 Fuzzy inference system:

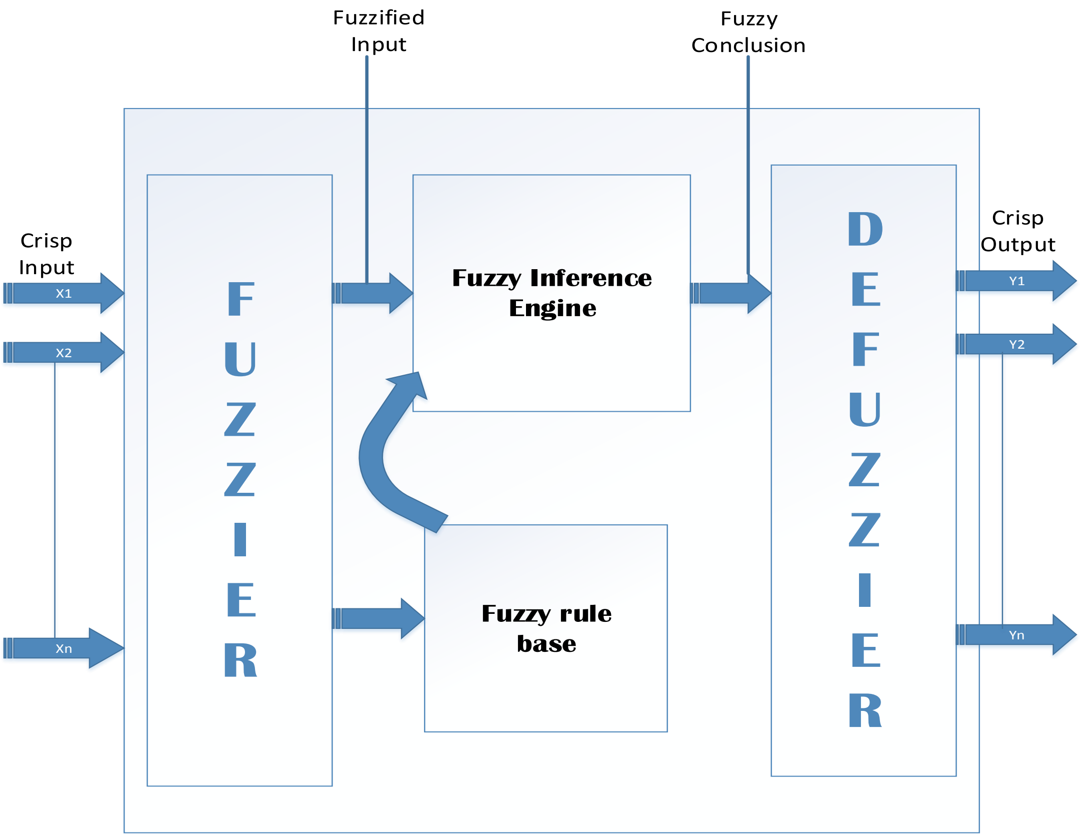


Fig. 3.3: Block diagram of Fuzzy I/O system

This figure shows how fuzzy inference system works and internal activities. Fuzzy inference system (FIS) transfers an expert's experience into system design which contains four blocks shown in Fig. 3.3. The FIS transforms the crisp input into fuzzy input by using membership functions which is the fuzzy sets of input vector, the concept base that contains the information given by an expert in the form of linguistic fuzzy rule, the inference engine uses them with the knowledge base for inference by a method of implication and aggregation, then defuzzifer transforms the fuzzy results of the inference into a crisp output by using defuzzification method [Herrera and Lozano, 2003; Roychowdhury and Pedrycz, 2001] [25].

The first fuzzy inference system was given by Mamdani, in this system fuzzy set has the following structure [Mamdani and Assilian, 1975]，[25]

IF x is *A* and y is *B* THEN *z is C*

Second fuzzy system was proposed by Takagi, Sugeno and Kang (TSK) having an interface engine where the conclusion of a fuzzy rule comprises a weighted linear combination of the crisp input rather than a fuzzy set. The zero order Sugeno method is given below [25]

IF x is *A* and y is *B* THEN z = *C*

A and *B* are fuzzy set and *C* is a constant. And the first order Sugeno model is

IF x is *A* and y is *B* THEN *z* = px+qy+r

Where *A* and *B* are fuzzy sets in the antecedent and *p, q*, and *r* are constants

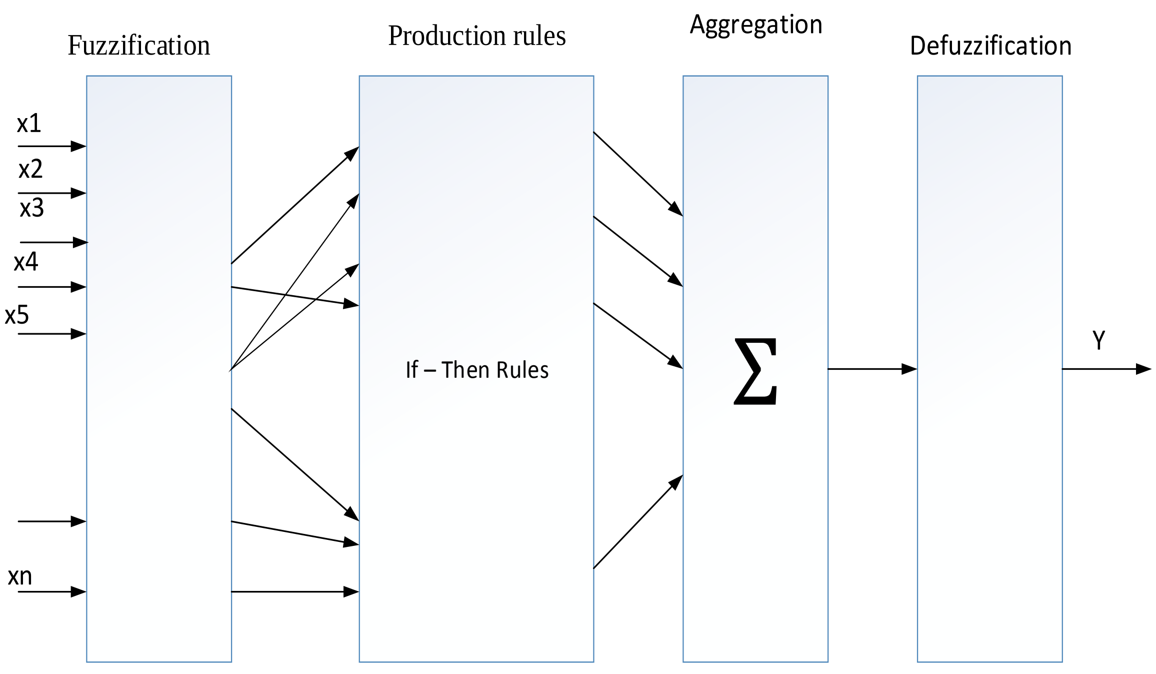
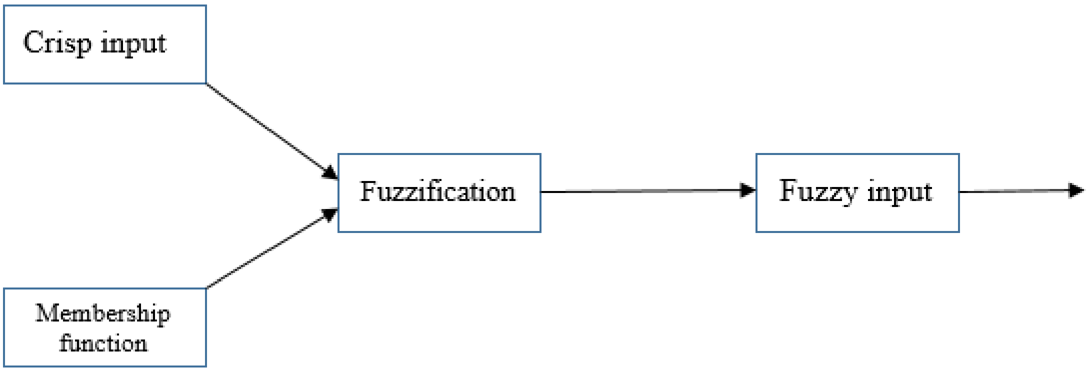


Fig. 3.4: General schematic diagram of fuzzy inference system [25]

3.1.9 Fuzzy inference process:

3.1.9.1 Fuzzification:

The very first step of FIS system is to convert crisp input into fuzzy input, by MFs find out the degree to which they belong to each of the fuzzy set. When membership functions are defined, fuzzification takes real time input and compares it with the stored MS to produce fuzzy input [25].



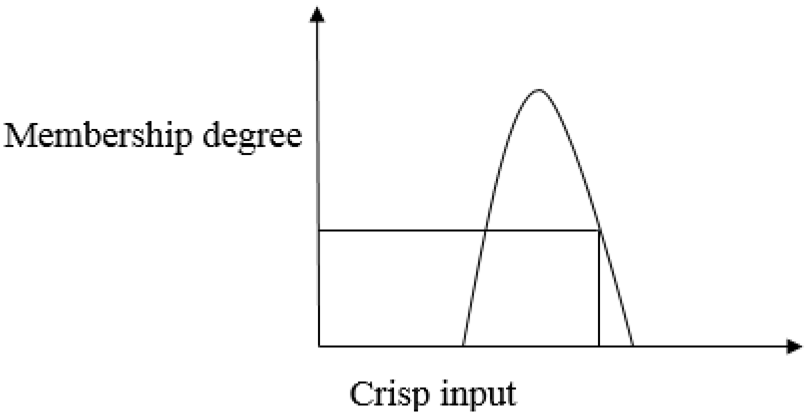


Fig. 3.5: Fuzzification [25]

3.1.9.2 Applying fuzzy operator:

A fuzzy rule base contains a set of fuzzy rule R. For multi-input, single-output system is represented by [25]

R= $(R_1, R_2, R_3, \ldots\ldots\ldots\ldots, R_n)$

Here R_i is represented as

R_i= if (x_1 *is* T_{x_1} , and ………, x_m *is* T_{x_m}) then ($y_1$is T_{y_1})

Here m is precondition of R_i from a fuzzy set ($T_{x_1} \times T_{x_2} \times \ldots\ldots \times T_{x_m}$), if-then rule works by using given below three rules [25]:

i) Resolve all fuzzy statements in the antecedent to a degree of MF between 0 and 1.

ii) If there are several antecedent of the rule, the fuzzy operator is applied to obtain one number that represents the result of applying that rule. It is called as weight factor or firing straight rule.

Weight factor is represented by either product or intersection operator [25].

$$\alpha_i = \min(\mu^i_{x_1}(x_1), \mu^i_{x_2}(x_2))$$

$$\alpha_i = \mu^i_{x_1}(x_1) \times \mu^i_{x_2}(x_2)$$

iii) The weight factor is used to shape the output of fuzzy set that represents consequent part of the rule.

3.1.9.3 Applying implication method:

It is represented as the shaping of the consequent that is the output of fuzzy set based on antecedent. A single produced by the antecedent is the input of implication process and the output is a fuzzy set. Two commonly methods are minimum or product [Kim et al., 2001; Xu et al., 2002; Mazloumzadeh et al., 2010] is given below [25]

$$\alpha_i(o) = \min(\alpha_i, \mu^i_y(o))$$

$$\mu^i_y(o) = \alpha_i\ \mu^i_y(o)$$

Here o is a variable which represents support value of membership function.

3.1.9.4 Aggregation method:

The truncated or modified output of the implication process is the input of this stage and combines these output into a single fuzzy set. This output is the input of defuzzification process. This process happens only once for each output variable, this method is a commutative process. The aggregation method uses max method generally, that can be defined as [25]

$$\mu_y(\text{o}) = \max(\mu^i_y(o), \mu^i_y(o))$$

In Mamdani system, let two input variables are x_1 *and* x_2 in the premise part and variable (y) In the consequence part [25]:

Rule 1: if ($X_1 is\ T^1_{x_1} and\ X_2 is\ T^1_{x_2}$) then (y is$T^1_y$)

Rule 2: if ($X_1 is\ T^2_{x_1} and\ X_2 is\ T^2_{x_2}$) then (y is$T^2_y$)

Considering, input $x_1 and\ x_2$are for correspond to X_1andX_2. The calculation of weight factor, aggregation and implication use two rules given below [25]

I. The weight factor α_i is calculated by using min (AND) operator given below

Weight factor of Rule 1: $\alpha_1 = \min(\mu^1_{x_1}(x_1), \mu^1_{x_2}(x_2))$

II. Weight factor of Rule 2: $\alpha_2 = \min(\mu^2_{x_1}(x_1), \mu^2_{x_2}(x_2))$

III. The output fuzzy set of each rule are obtained by applying weight factor given below

Implication of Rule 1: $\mu^1_y(o) = \min(\alpha_i, \mu^1_y(o))$

Implication of Rule 2: $\mu^2_y(o) = \min(\alpha_2, \mu^2_y(o))$

An overall fuzzy set is obtained by aggregating the individual output fuzzy sets of each rule using max (OR) operation is given below [25],

Aggregation of Rule 1 and Rule 2: $\mu_y(o) = \max(\mu^1_y(o), \mu^2_y(o))$

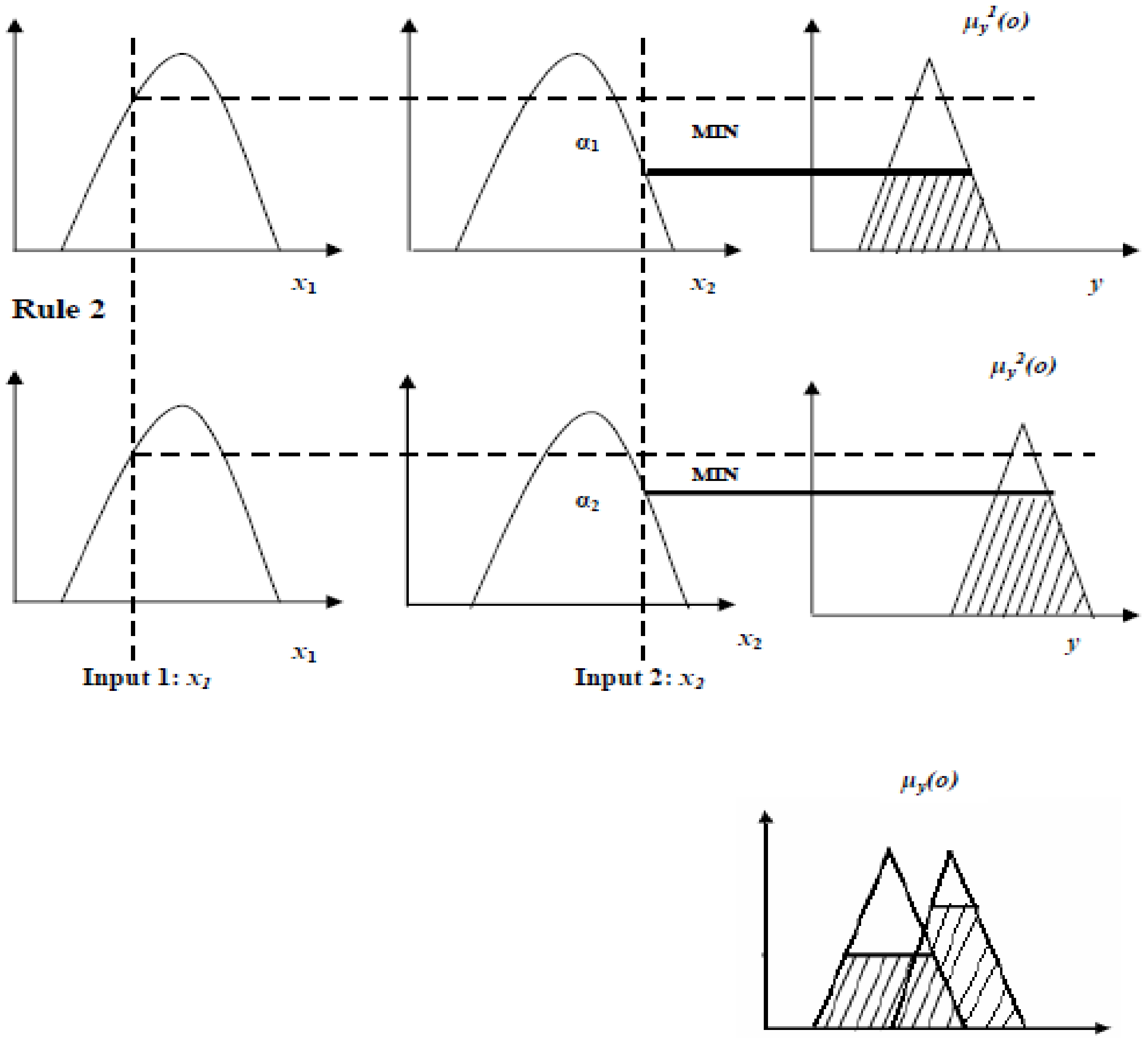


Fig. 3.6 showing weight factor, implication and aggregation methods in Mamdani system [25].

3.1.9.5 Defuzzification:

The defuzzifier maps output fuzzy sets into a crisp number. Defuzzification can be performed by several methods such as: center of gravity, center of sums, center of the largest area, first of the maxima, middle of the maxima, maximum criterion and height defuzzification. Of these, center of gravity (centroid method) and height defuzzification are the methods commonly used (Mazloumzadeh et al., 2010). The centroid defuzzification method finds the center point of the solution fuzzy region by calculating the weighted mean of the output fuzzy region. It is the most widely used technique because the defuzzified values tend to move smoothly around the output fuzzy region [25].

Thus it can be noticed mamdani fuzzy system can give prediction about any crisp system input by fuzzy logic. Fuzzy cluster and rule base system can consider weather and lightning parameters as input and through several intermediate steps it can forecast of weather and lightning phenomenon.

3.2 ***AS3935 Lightning sensor:***

AS3935 is known as Franklin Lightning Sensor Integrated Circuit which is world's first lightning sensing IC. This programmable IC is totally integrated Lightning sensor, and it can detect existing and approaching lightning activity by sensing the electrical emission from the lightning strokes, within its range, and it is also capable of proving estimated distance of thunderstorm. In-build lightning algorithm checks signals to recognize pattern and understands signal's nature, whether signal is threat or man-made disturbances.

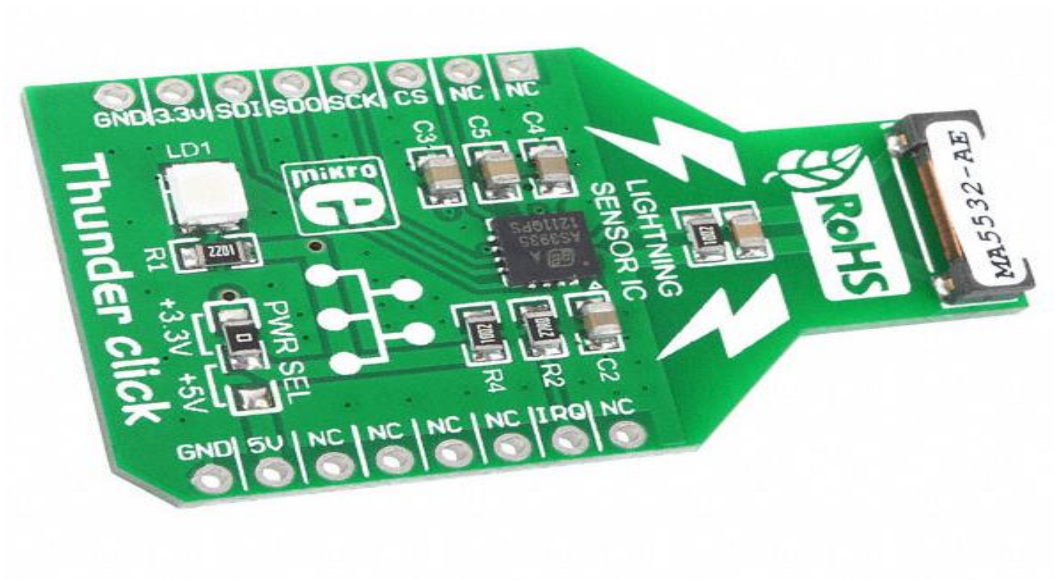


Fig. 3.7: Shows AS3935 basic picture

With the help of the noise floor generator and evaluation block, it can detect noise and provides that information to the microcontroller. A 4 wire standard serial peripheral interface (SPI) or inter-IC (I2C) connection helps to program AS3935, and also three different addresses can be chosen here. Internal clocks are controlled by TRCO and SRCO (RC- oscillators). Power source of this IC can be either VDD or internal voltage regulator [21].

3.2.1. Benefits of using AS3935:

- Gives an advance warning before humane can sense.
- Able to detect CG and IC lightning phenomenon.
- Decently efficient.
- Flexibility to different kind of applications.
- Reduces false detections.
- Supply rang is flexible and alternative options are available.

- Power mode is also configurable.
- Compact in size.

3.2.2. Some key features of AS3935:

- It can detects thunderstorm activity within 40 km of radius.
- Capable of detecting both lightning flashes.
- For optimal controls threshold values can be adjusted.
- I2C and SPI, both interface can be used here, depending upon the applications.
- Fully programmable IC, thus can be modified on the basis of other situations.
- Tuning of antenna is also available here, if required.
- Supply voltage range from 2.4 V to 5.5 V.
- Three modes are available (power-down, active, listening mode)

3.2.3. Some area of applications:

- Weather Stations.
- Equipment of sports.
- Pool safety
- GPS
- Watches
- Golf field
- Uninterruptible power supply

3.2.4. AS3935 Pin details:

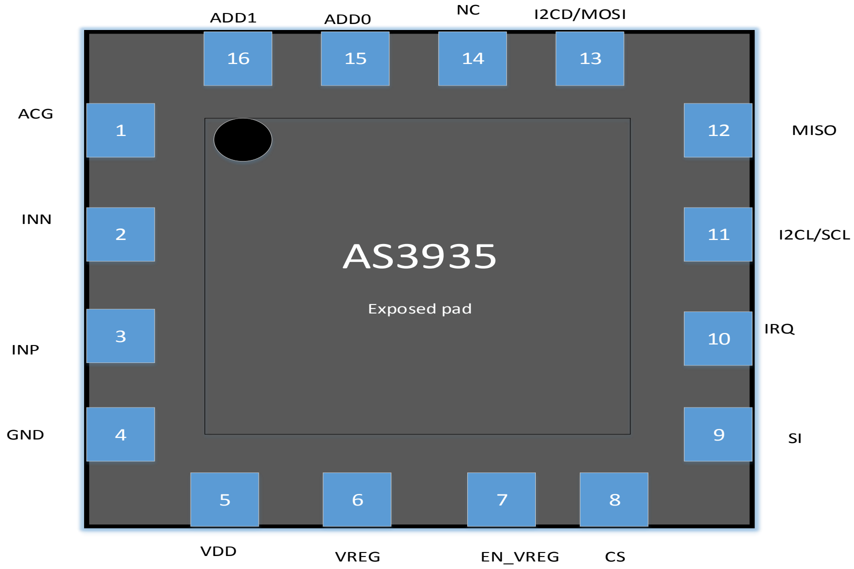


Fig. 3.8, pin diagram of AS3935 [22]

Table 3.1: AS3935 Pin details [22]

Pin Number	Pin Name	Type	Details
1	ACG	Analog I/O	AC-Ground
2	INN		Antenna ground
3	INP		Antenna positive input
4	GND	Supply pad	Ground
5	VDD		Positive supply voltage
6	VREG		Positive supply voltage / Regulated voltage
7	EN_VREG	Digital input	Voltage Regulator Enable
8	CS		Chip Select (active low)
9	SI		Select Interface (GND → SPI or VDD → I2C)
10	IRQ	Digital output	Interrupt
11	I2CL/SCL	Digital input	I2C clock bus or SPI clock bus (according to SI setting)
12	MISO	Digital output	SPI data output bus
13	I2CD/MOSI	Digital I/O with pull-up / Digital input	I2C data bus or SPI data input bus (according to SI setting)
14	NC		Not connected
15	ADD0	Digital input	I2C address selection LSB
16	ADD1A		I2C address selection MSB
Exposed pad		Supply pad	Connect to Ground via the GND plan and pin 4

3.2.5. Block diagram of AS3935:

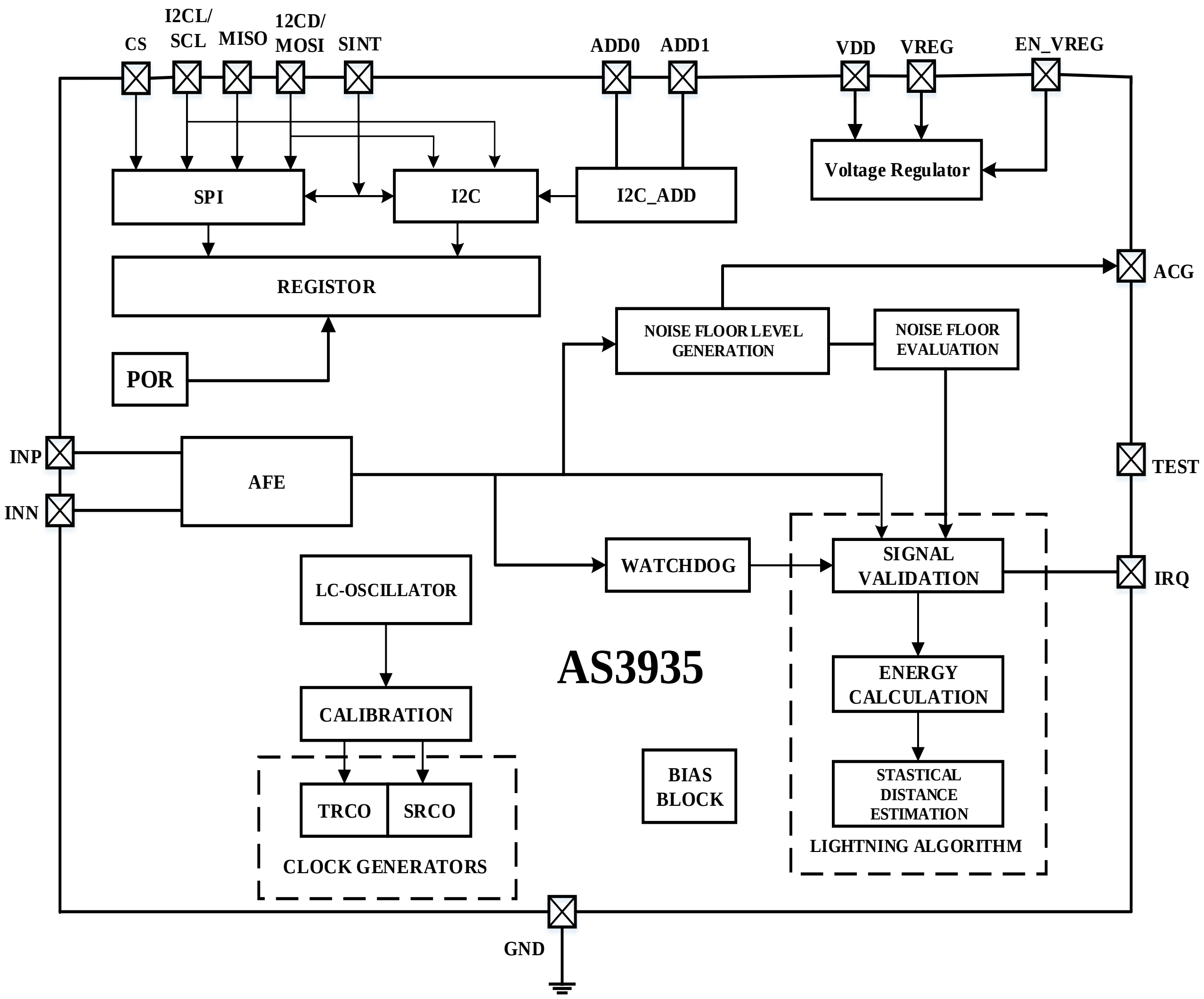


Fig. 3.9 shows the internal structure with all components of AS3935 [22]

AS3935's internal block diagram can be shown in Fig. 3.9. External antenna has to be attached to AFE (Analog Front – end) which helps to demodulates and amplifies the received signal. The output of AFE is continuously monitored by in-built watchdog which also alerts the lightning algorithm block if any signals comes. The lightning algorithm block validates the signal by checking the pattern of the signals. After checking the pattern, it can inform whether this signal is created by lightning or caused by some other means. If the incoming signal is recognized as manmade disturbances, that event is rejected and sensor goes back into listening mode and if incoming signal considered as lightning strikes, distance estimation block activated and calculates the distance of the storm [22].

TRCO and SRCO are the LC oscillators, generate clock to compensate process variations.

3.2.6. Description of internal blocks of AS3935:

a. Voltage Regulator:

AS3935 can be operated by either direct power supply or internal voltage regulator. Internal voltage regulator increases consumption of current around 5µA. In order to activate the internal voltage regulator, EN_VREG and VDD pins are required to be connected to the supply voltage. It is required to achieve the stability of the voltage regulator, thus a capacitor having value greater than 1µF is needed to be connected at VREG to ground it [22].

If it is required to supply this IC by a battery, EN_VREG needs to be connected to the ground and VREG and VDD must be connected to the supply voltage [22].

b. Watchdog and AFE:

Whenever the antenna picks up any signal, the AFE amplifies and demodulates that AC signal. That IC is based on narrowband receiving technology having a mid-frequency of 500 kHz and 33 kHz is its bandwidth, within that bandwidth range the gain of AFE is considered as constant by making antenna bandwidth less than the AFE bandwidth [22].

AFE has two operating mode depending on its gain value, the default mode is indoor. Mode can be selected by changing the value of zero no register (REG0x00). Depending on the environmental condition that mode has to be selected [22].

Table 3.2: AFE setting for register values [22]

AFE setting	**REG0x00[5:1]**
Indoor	10010
Outdoor	01110

Output of AFE is monitored by watchdog block. If the signal crosses the threshold WDTH of the watchdog, chip forwards the signal into Verification mode. Threshold level can be set in REG0x01 [3:0]. As threshold increases AS3935 becomes more robust against disturbances, but this increment results in less sensitive to weaker signal, thus far away lighting detection becomes less efficient. Fig. 3.10 shows efficiency vs. distance graph as watchdog threshold changes [22].

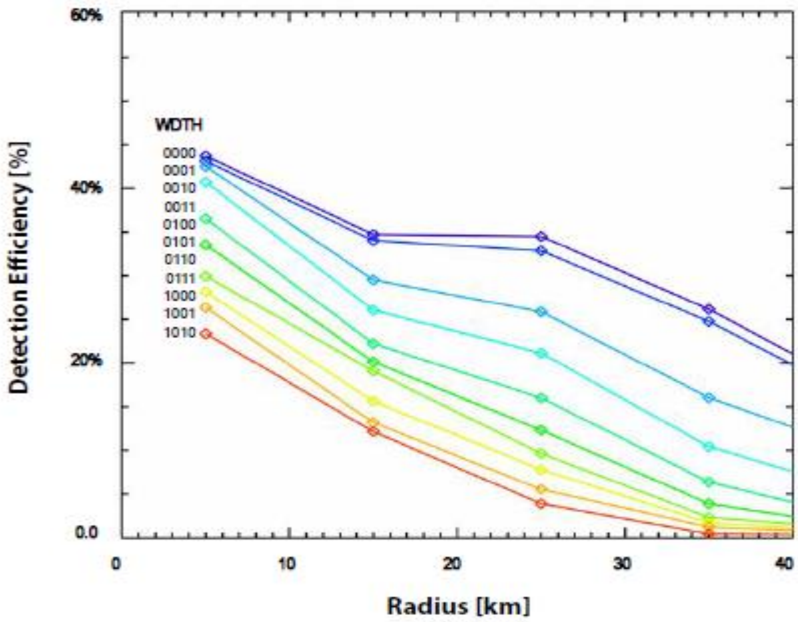


Fig. 3.10: Efficiency changes as watchdog value changes [22]

c. Signal Verification:

The signal verification mode depends on Lightning Algorithm block. Whenever, signal value crosses the WDTH value AS3935 goes into signal verification mode. During verification if signal is assigned as disturbance, the chip stops processing and goes back into listening mode. Otherwise, distance estimation and energy calculation happens [22].

d. Noise floor generator:

Output of AFE generates the noise floor level that continuously compared with noise threshold (i.e. reference voltage). If noise floor level crossed the reference voltage, AS3935 introduces an interruption i.e. INT_NH to inform the external unit that due to high noise collected by antenna the AS3935 cannot operate properly. Threshold of noise floor limit can be modified by bits value of REG0x01 [6:4]. Default value of REG0x01 [6:4] is 010.

Table 3.1: Noise threshold values and register bits [22]

Input Noise Level for outdoor [µVrms]	Input Noise Level for indoor [µVrms]	REG0x01[6]	REG0x01[5]	REG0x01[4]
390	28	0	0	0
630	45	0	0	1
860	62	0	1	0
1100	78	0	1	1
1140	95	1	0	0
1570	112	1	0	1
1800	130	1	1	0
2000	146	1	1	1

e. Lightning Algorithm:

Detection of lighting triggers AS3935 to initiate calculation of distance estimation and energy of lightning, whereas, for the case of disturbances AS3935 rejects those process immediately. Lightning has three inter-mediate blocks [22]:

1. Signal validation:

   Verification, whether incoming signal is for lightning or not. Manmade generally has properties of random spikes and lightning signals shows the pattern characteristics. The spike rejection settings SREJ of watchdog can be adjusted in REG0x02 [3:0] that enhances robustness against false alarm [22].

2. Energy calculation:

   Energy calculation happens only if signal considered as lightning strike. Calculated energy stored in the registers REG0x06 [4:0], REG0x05 [7:0] and REG0x04 [7:0]. This values are just pure number and has no physical meaning [22].

3. Statistical distance estimation:

   In this block, distance of lightning is to be measured. Calculation is done using statistical calculation. The output of the energy calculation block is stored along with timing information in AS3935 internal memory.

   Estimated distance output is stored in REG0x07 [5:0]. The stored values are in the form of binary, to get distance in kilometer it is needed to convert those into binary form. Below given table shows estimated binary form into kilometer. The stored value in REG0x07 [5:0] will change only if the new value comes out from calculation, which means storm coming closer or going away farther [22].

Table 3.2: Some experimental distance values of AS3935 for lightning detection [22]

REG0x07 Received Data in Hexadecimal Form	REG0x07 [5:0].	Distance in Kilometer
3F	011111	Out of range
28	101000	40
25	100101	37
22	100010	34
1F	011111	31
1B	011011	27
18	011000	24
14	010100	20
0E	001110	14
0A	001010	10
05	000101	5
01	000001	Storm is Overhead

If incoming signal does not have the shape characteristic of lightning, validation fails and the signal considered as disturbance, then chip goes back to listening mode without performing other activities. Shortest time length between two consecutive lightning strikes that the chip can consider is approximately one second. AS3935 gets deactivated for 1.5 seconds after encountering a disturbance.

f. Interrupt Management:

When any event happens, AS3935 makes IRQ high and display the interrupt in REG0x03 [3:0], shown in Table 5. If IRQ goes high, external unit has to wait for 2 ms before fetching the interrupt register [22].

Table 3.3: Three different kind of interrupts [22]

Name of Interrupt	REG0x03 [3:0]	Description
INT_L	1000	Lightning interrupt
INT_D	0100	Disturber detected
INT_NH	0001	Noise level too high

Interrupt INT_NH is assigned only when noise level exceeds the noise floor value in REG0x01 [6:4]. INT_NH persists as long as the noise level is higher than the threshold value. The interrupt INT_D is shown when the signal validation assigns the signals as disturber event. AS3935 issues INT_L (Lightning interrupt) if any new event is detected. All the events are stored in the internal memory and make a lightning statistic used by the distance estimation algorithm. When the chip assigns an interrupt and REG0x03 [3:0] =000 the distance estimation changes due to purging of old events in the statistics, based on the distance estimation algorithm. Minimum number of lightning events is set in register REG0x02 [5:4].

Table 3.4: Minimum number of lighting and register bits [22]

Minimum number of lightning	REG0x02 [5]	REG0x02 [4]
1	0	0
5	0	1
9	1	0
16	1	1

When this feature is utilized a minimum number of lightning events must occur before the sensor triggers the lightning interrupt. Once the threshold is passed, the sensor will resume its normal interrupt handling. This eliminates false triggers by man-made disturbers that may pass the validation algorithm. It is possible to clear the statistics built up by the lightning distance estimation algorithm block by just toggling the bit REG0x02 [6] (high-low-high).

g. Antenna Tuning:

Using parallel LC resonator a loop antenna is made for AS3935. The resonance frequency of antenna is 500 kHz and quality factor has to be around 15. If register REG0x08 [7] =1, the antenna's resonance frequency will be displayed on the IRQ pin as a digital signal. It is important to tune the antenna with its accuracy of ± 3.5%, thus it can be optimized the performance of the IC [22].

h. Clock generator:

It has two different kind of RC oscillators: one is system RCO (SRCO) and second one is TRCO (a timer RCO). SRCO works with 1.1 MHz and provides main clock to whole digital part. On the other hand, TRCO runs at 32.768 kHz, it is a low power and low frequency oscillator. Due to temperature change, frequency changes of these oscillator are automatically compensated [22].

3.2.7 Register Details of AS3935:

Table 3.7: Register details of AS3935 [22]

Address	Register Name	Bit	Type	Default values	Description
REG0x00	Reserved	[7:6]	R/W	0	Reserved
	FE_GB	[5:1]		10010	AFE Gain Boost
	PWD	[0]		0	Power-down
REG0x01	NF_LEV	[6:4]	R/W	010	Noise Floor Level
	WDTH	[3:0]		0010	Watchdog threshold
REG0x02	Reserved	[7]	R/W	1	Reserved
	CL_STAT	[6]		1	Clear statistics
	MIN_NUM_LIGH	[5:4]		00	Minimum number of lightning
	SREJ	[3:0]		0010	Spike rejection
REG0x03	LCO_FDIV	[7:6]	R/W	00	Frequency division ration for antenna tuning
	MASK_DIST	[5]		0	Mask Disturber
	Reserved	[4]		0	Reserved
	INT	[3:0]	R	0000	Interrupt
REG0x04	S_LIG_L	[7:0]	R	00000000	Energy of the Single Lightning LSB
REG0x05	S_LIG_M	[7:0]	R	00000000	Energy of the Single Lightning MSBYTE
REG0x06	Reserved				Reserved
	S_LIG_MM	[4:0]	R	00000	Energy of the Single Lightning MMSBYTE
REG0x07	Reserved	[7:6]			Reserved
	DISTANCE	[5:0]	R	000000	Distance estimation
REG0x08	DISP_LCO	[7]	R/W	0	Display LCO on IRQ pin
	DISP_SRCO	[6]		0	Display SRCO on IRQ pin
	DISP_TRCO	[5]		0	Display TRCO on IRQ pin
	TUN_CAP	[3:0]		0000	Internal Tuning Capacitors (from 0 to 120pF in steps of 8pF)
REG0x3A	TRCO_CALIB_DONE	[7]	R	0	Calibration of TRCO done(1=successful)
	TRCO_CALIB_NOK	[6]	R	0	Calibration of TRCO unsuccessful(1=not successful)
	Reserved	[5:0]	R	000000	Reserved
REG0x3B	SRCO_CALIB_DONE	[7]	R	0	Calibration of SRCO done(1=successful)
	SRCO_CALIB_NOK	[6]	R	0	Calibration of SRCO unsuccessful(1=not successful)
	Reserved	[5:0]	R	000000	Reserved

3.2.8 Some basic characteristics of AS3935:

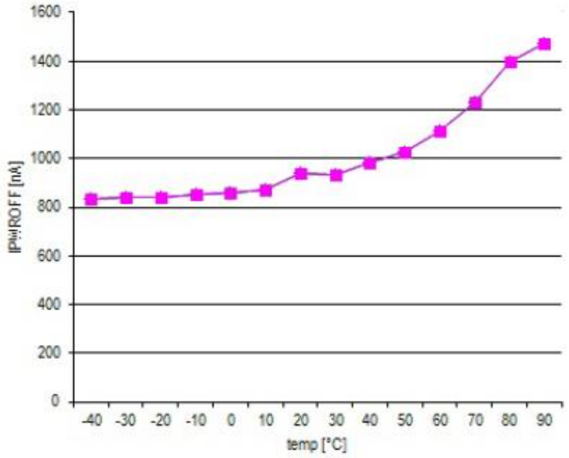


Fig. 3.11
Power-down Current if Voltage Regulator is OFF @3V over Temperature [22]

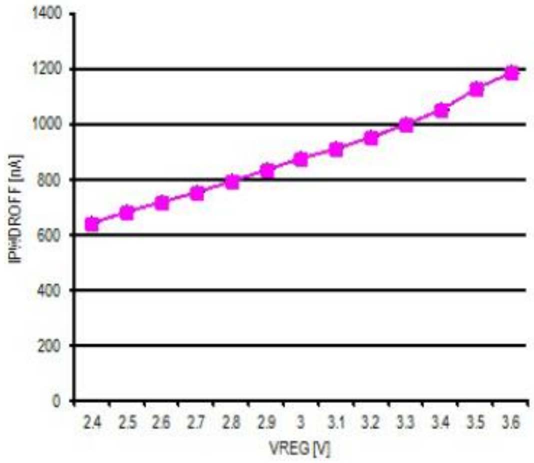


Fig. 3.11
Power-down current if Voltage Regulator is OFF over Supply Voltage (VREG) [22]

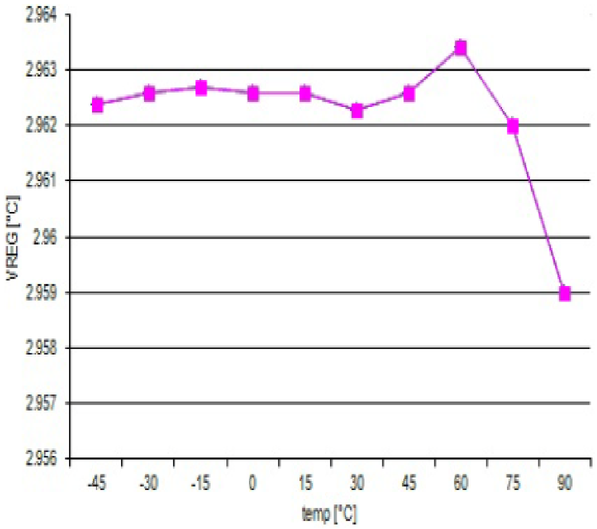


Fig. 3.12
Output Regulated Voltage (VREG) @VDD=5V over Temperature [22]

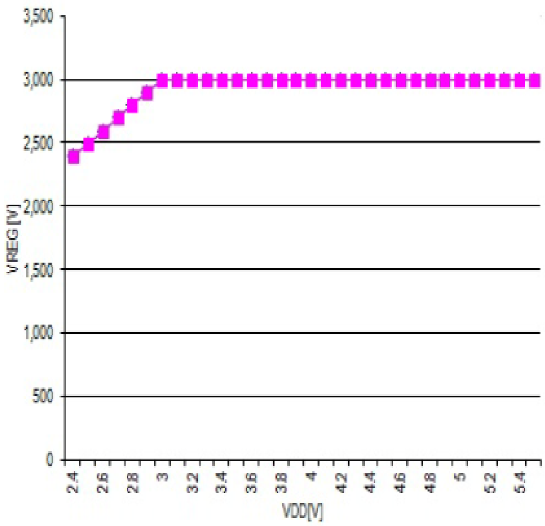


Fig. 3.13
Output Regulated Voltage (VREG) @ Room Temperature over Supply Voltage [22]

3.2.9 Thunder storm detection by AS3935:

The AS3935 can detect the presence of an approaching storm with lightning activities and provide an estimation of the distance to the leading edge of the storm, where the leading edge of the storm is defined as the minimum distance from the sensor to the closest edge of the storm. The embedded hardwired distance estimation algorithm of the AS3935 issues an interrupt on the IRQ pin. The estimated distance which is displayed in the distance estimation register does not represent the distance to the single lightning but the estimated distance to the leading edge of the storm [22].

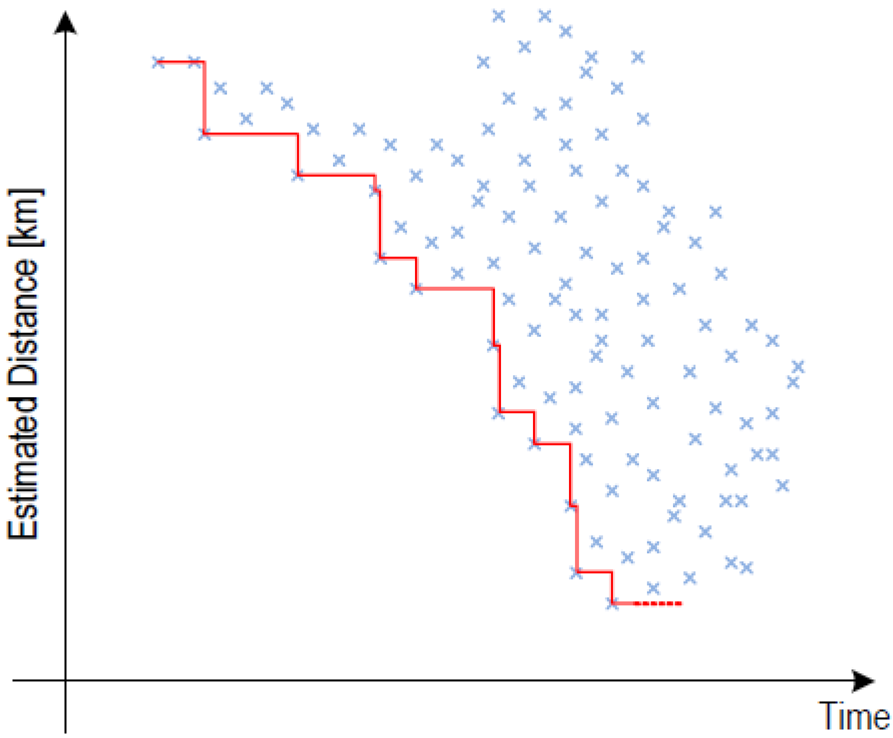


Fig. 3.13: Detected lightning strokes estimated distances [22]

Here, red line is the distance estimation by AS3935 and blue crosses are single lightning strikes.

From the above discussion some brief knowledge about Fuzzy Logic mamdani system and lightning sensor AS3935 have been gathered. In the next chapter, experimental result and analysis, those concepts are going to be used to conduct an experiment regarding lightning detection and apparent lightning prediction calculations.

CHAPTER-4

EXPERIMENTAL RESULTS AND DISCUSSIONS

- Introduction
- Specification of used instruments
- Methodology
- Interfacing of AS3935 with computer
- Hardware setup & Working principle
- Command structure form MSB to LSB
- Parameter tuning and results
- Fuzzy rule base prediction design
- Logic of rule base design
- Matlab based model of Fuzzy Rule base
- Summary

4.1 ***Introduction:***

The purpose of this thesis is to develop a lighting detection setup which can detect lightning within a specific range of area. After developing this kind of device, next step is to detect lighting, later prediction process initiation will be done by using fuzzy logic. Different lightning parameters has been collected from many research papers, by using those parameters a model has been designed for prediction purpose.

4.2 ***Specification of used instruments:***

Table 4.1 lists the specification of the required equipment during the entire project work. All the items are readily available at the Electrical Measurement and Instrumentation Laboratory and High Voltage laboratory of Electrical Engineering department in Jadavpur University, Kolkata.

Table 4. 1: Instrument Specifications:

Sl. No.	Device Name	Maker's Name	Specifications
1	Impulse generator	Philip's , Holland	1400 kV/ 16 Kilojoule, No of stage conductor = 8
2	Sphere Gap	N/A	Diameter = 25 cm At S.T.P. peak voltage= 42.9kV
4	Piezo ignition device	N/A	800 V- 5 kV voltage
3	AS3935	ams AG	Spc. Details given in chapter 3 in Table 3.1

4.3 ***Methodology:***

In the proposed lightning detecting system AS3935 is the heart of the hardware setup. At the very first AS3935 IC is connected to the Lightning Activity Interfacing Board which was provided by the manufacturing company. After this stage a code in C language is written to access that above mentioned chip so that tunable parameters can be modified to detect lighting activity efficiently. With the help of a micro-USB to USB cable that chip has been connected with a computer where the code was developed. AS3935 activates when that code runs.

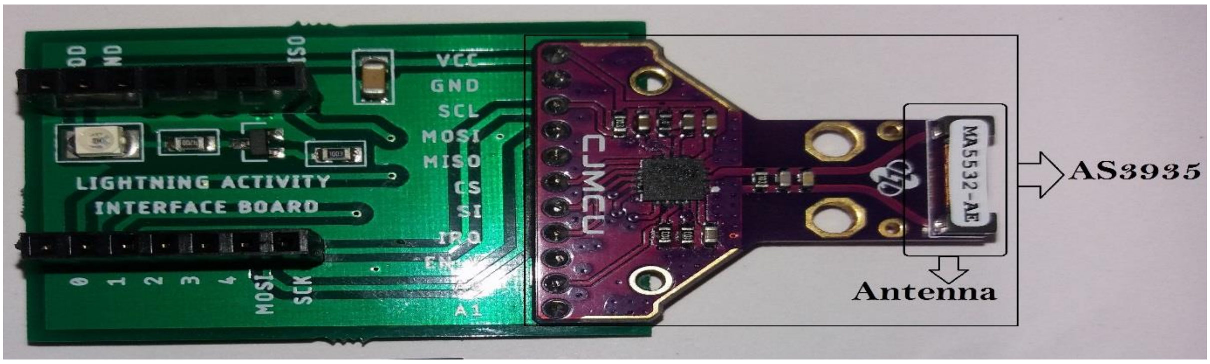


Figure 4.1AS3935 IC without interface circuit

In High Voltage Laboratory, using Impulse Generator and Sphere Gap which generated electric spark, but most of the time for the easy availability of spark piezo ignition is used that easily found in gas lighter. This spark was detected by the instrument as lightning stoke or noise or disturber depending on Noise Floor Level threshold values. That detecting data and other lightning parameters collected from different authentic sources by which fuzzy logic rule is developed primarily and that will help in lightning prediction system.

4.4 ***Interfacing of AS3935 with computer:***

The interfacing board is based on ADM00421: USB-A to SPI evaluation kit. This board converts USB protocol (from computer) to SPI protocol (for AS3935). AS3935 communicates using SPI protocol in mode-1 which is set in the ADM00421 board during the beginning of the communication between AS3935 and computer. In that computer a DLL file is provided, that DLL file is accessed through C programming for this communication purpose between computer and the IC.

Basic communication codes are provided for ADM00421 board as a standard header file so that user need not to be involved in complicated programming. Below given Fig. 4.2 showing interfacing circuit which is connected to AS3935 as shown in Fig. 4.3.

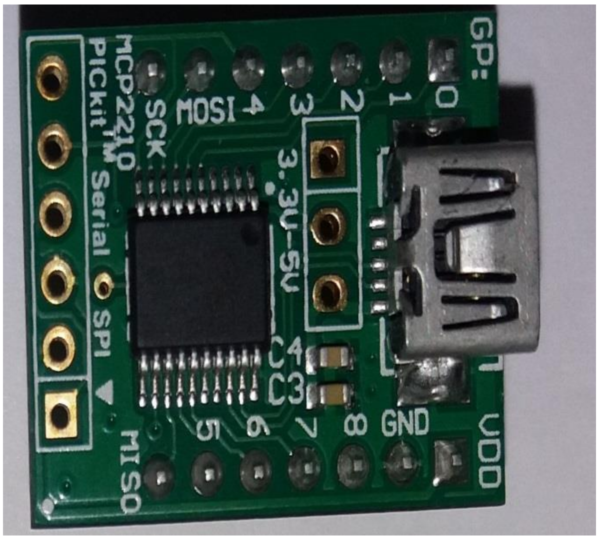


Fig. 4.2: Interfacing Circuit

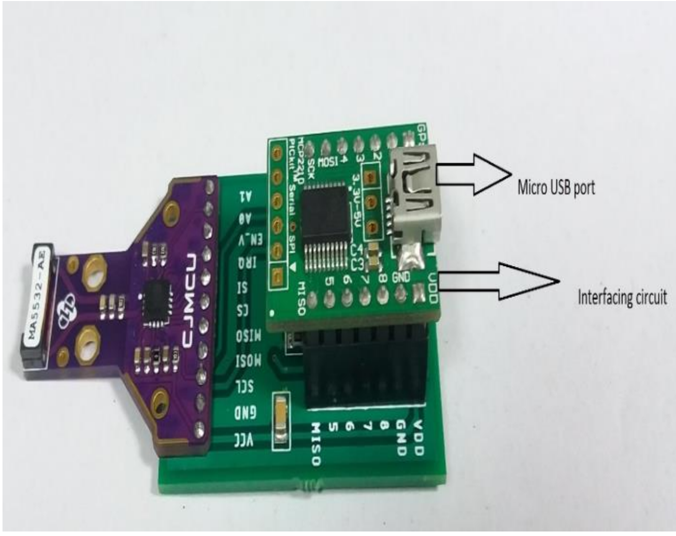


Fig. 4.3:AS3935 IC with interface circuit

4.5 <u>***Hardware setup & Working principle:***</u>

AS3935 can work in two different protocols, one is SPI mode and another is I2C mode. Here SPI connection mode has been introduced. In SPI mode, every read is also a write which doubles the speed of bus, however, while implementing the SPI protocol it is noticed that most of the time we didn't have data to send one direction. When motivation is to read from the device, a "dummy bytes" is sent to the device to trigger the clock signal that allows the slave to send data. Below given figure shows block diagram of AS3935 having SPI protocol connection.

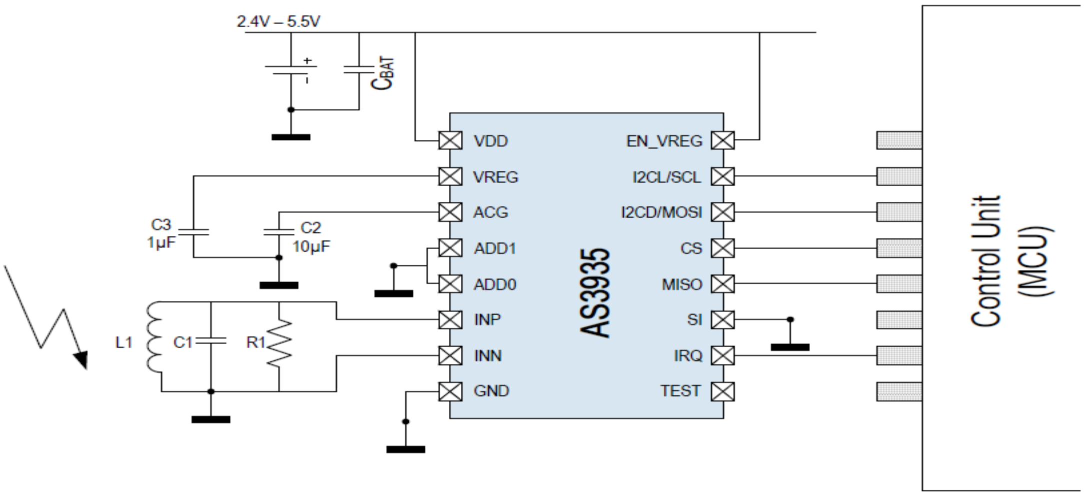


Fig. 4.4: SPI protocol with voltage regulator ON [22]

To active SPI protocol SI (select interface) pin need to be grounded and here maximum operating frequency is 2MHz.

When any signal captured by the antenna, that signal is amplified and demodulated. On the other hand watchdog alerts algorithm block about that incoming signal. AFE generates a noise floor level for that incoming signal and this generated noise floor level compared with previously set noise threshold. If generated noise is above the threshold value, chip triggers interrupt depending on the value of noise whether that noise is manmade or any random electrical noise. If the nature of the signal pattern matches with lightning signal pattern, algorithm block starts to analyze the signal.

That algorithm block consists of signal validation, energy calculation and distance estimation. In that block first signal verification is done after watchdog crosses its threshold value. If the signal is detected as a noise or disturber, chip aborts signal processing and goes back to listening mode. On the other hand, after recognizing the signal as a lighting impulse signal processing starts where energy calculation and distance estimation is done. Given below diagram shows steps of lightning detection.

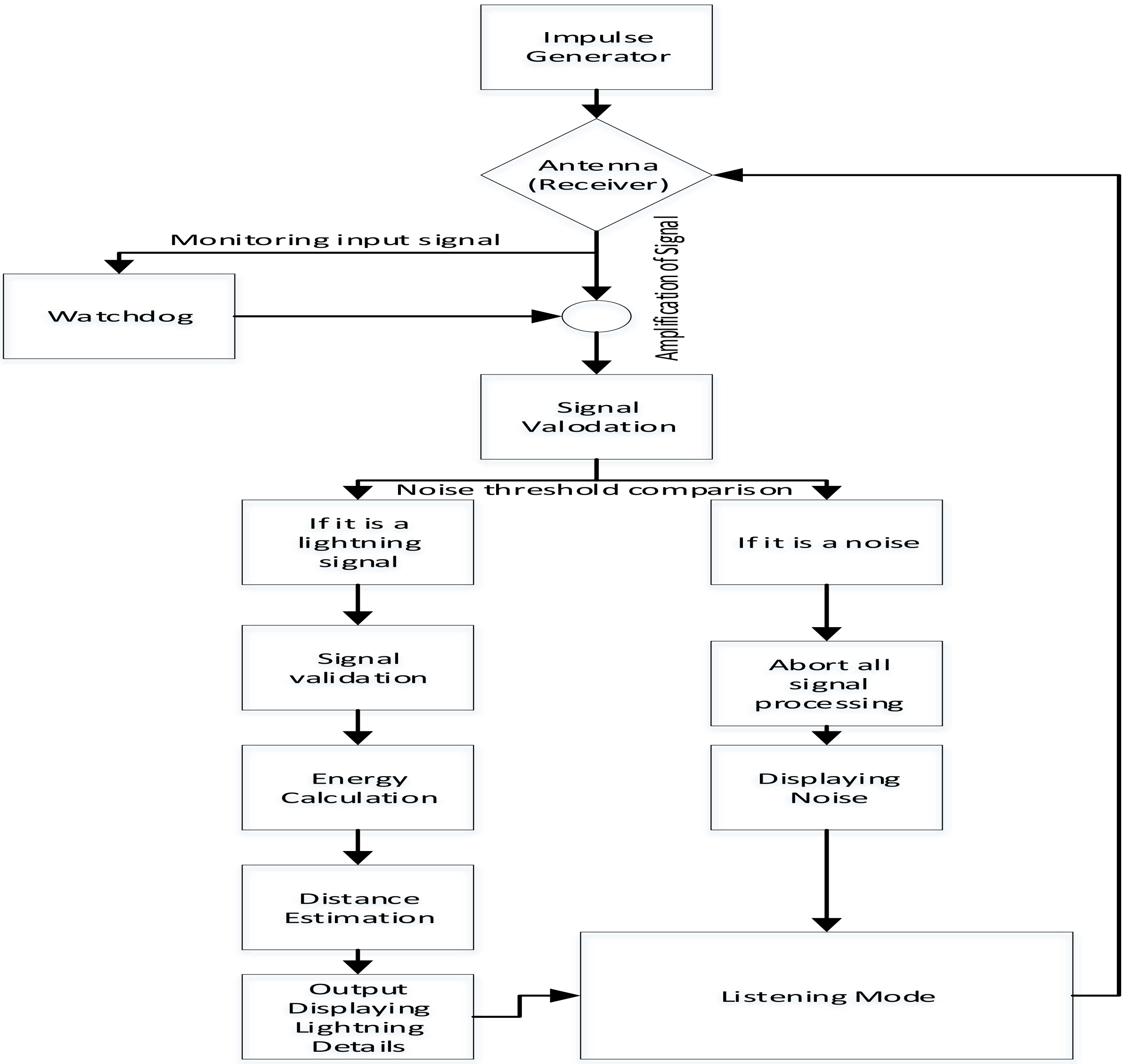


Fig. 4.5: Flowchart of AS3935 working steps

That signal detection and processing is highly depending on some tunable parameters, e.g. Noise floor, AFE setting, Disturber detector, Watchdog threshold and Tuning capacitor.

4.6 ***Command structure form MSB to LSB:***

In this thesis work SPI protocol has been used. In SPI protocol, reading and writing method is bit different from I2C method. Here any data can be written directly to an 8 bit register by a single step but to read a data from a register first, need to send a command to chip that we are interested to read a data, then the register comes to reading mode after these steps a data can be read from that same register. AS3935 uses 11 number of 8-bit registers.

Table 4.2: Bit grouping of AS3935 [22]

Mode		**Register address / Direct command**						**Register data**							
B15	B14	B13	B12	B11	B10	B9	B8	B7	B6	B5	B4	B3	B2	B1	B0

Above given table shows bit groups and their functions. B14-B15 are used for mode selection of register whether write mode or read mode. B8-B13 store register address and B0-B7 hold register data.

Table 4.3: W/R command mode [22]

B15	**B14**	**Mode**
0	0	Write / direct command
0	1	Read

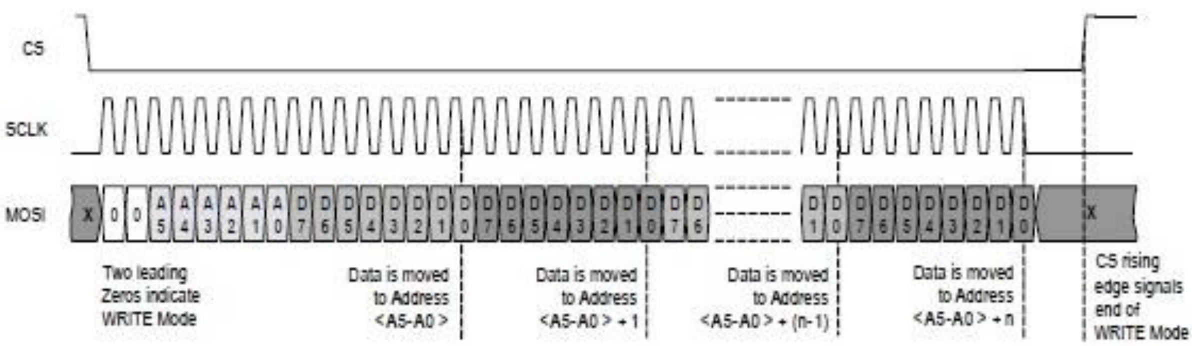


Fig. 4.6: Timing diagram of write data to register [22]

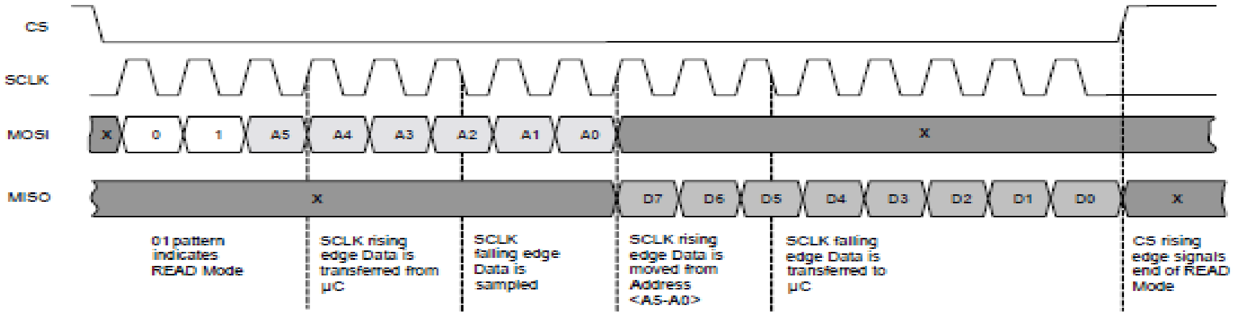


Fig. 4.7: Timing diagram of reading data from register [22]

4.7 <u>*Parameter tuning and results:*</u>

AS3935 chip has some tunable parameters e.g. Noise floor, AFE setting, Disturber detector, Watchdog threshold and tuning capacitor. Among those parameters AFE setting and noise floor are most important.

Analog Front-end setting helps to select indoor or outdoor mode in AS3935 chip. REG0x00 register is assigned for that activity. B5 to B1 bits are to be modified to set the mode. In the case of out-door 01110 and for the indoor 10010 values are used given by the manufacture company. To obtain robustness and less noise affected, it is required to set that value at outdoor setting. Using this setting unwanted indoor noises like mobile phone, computer, electrical machine etc. can be avoided. Watchdog setting is sometimes useful for fine tuning [22].

Table 4.4: Tunable parameters register details [22]

Parameters' name	Register with R/W bits
AFE	REG0x00[5:1]
Noise floor level	REG0x01[6:4]
Watchdog	REG0x01[3:0]
Spike Rejection	REG0x02[3:0]

During the experimental process, some different values have been applied into those register. Details given in Table 4.5.

Table 4.5: Different setting and corresponding output [22]

Sl. No.	**AFE setting REG0x00 [5:1]**	**Noise floor REG0x01 [6:4]**	**Watchdog REG0x01 [3:0]**	**Spike rejection REG0x02 [3:0]**	**Result of AS3935**
1	10010 (indoor)	010	0010	0010	Detecting very small value of noise present inside the room and on-board LED is ON all the time.
2		011	0010	0010	No improvement in the output,
3		110	0010	0011	same
4		111	0110	0011	Performance improved, a switching spark is detected as disturber from 15cm away.
5		111	1110	0011	System becomes robust and noise threshold is increased to a significant level. Lighter spark is not detected within 6 m distance
6	01110 (outdoor)	010	0010	0010	Very nearby spark is detected as disturber and close proximity to laptop as "too high noise"
7		011	0010	0010	Spark detection within 15 m as disturber.
8		110	0011	0011	Becomes less sensitive to noise and
9		111	0110	0011	No noise or disturber detection within 30m range, only very close proximity high spark is detected
10		111	0111	0111	No noise or disturber is indicated by device.

Above table shows different point of operation of AS3935. For the switching spark, a lighter is used. Lighter spark is done by piezo ignition methodology. As the threshold value of noise is increased, the device becomes robust to noise and disturber. This is the reason small valued spark was not detected over 30 m radius. Tough this robustness decreases sensitivity of that device and sometime it may not detect actual lightning.

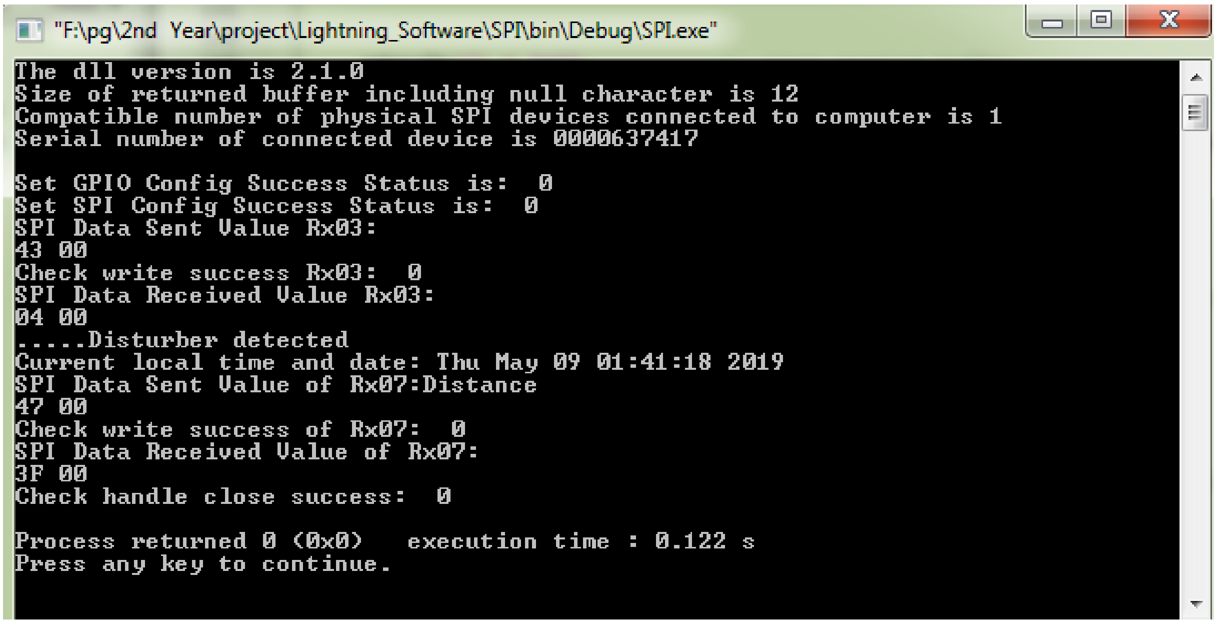


Fig. 4.8: Disturber detected by AS3935 in SPI mode

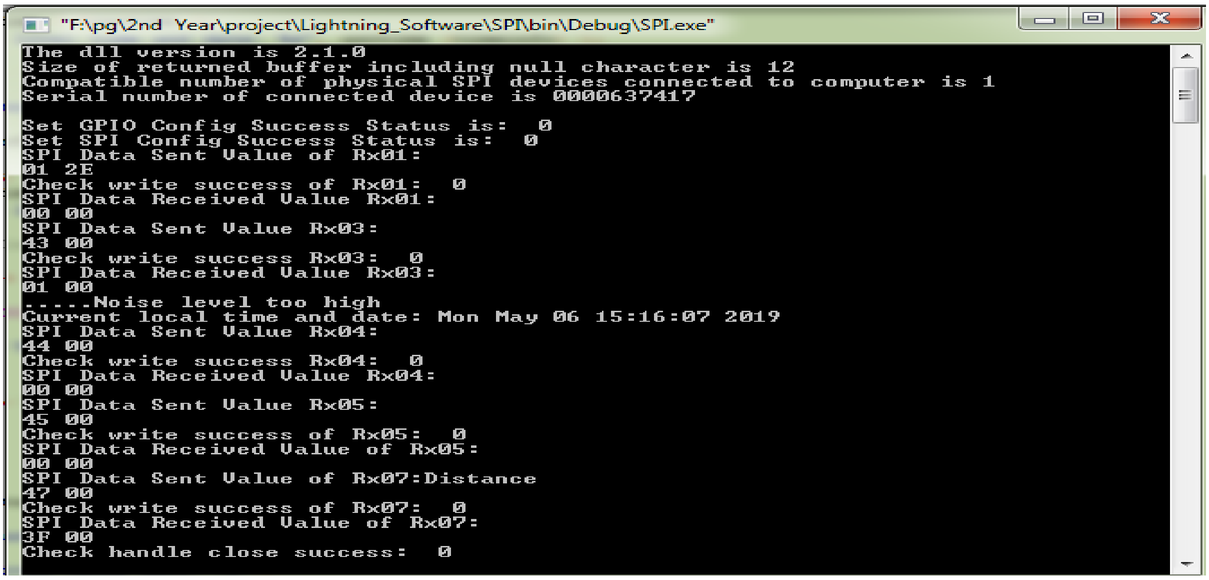


Fig. 4.9: Noise detected by AS3935 in SPI mode

It can be seen in Fig. 4.8 and Fig. 4.9 disturber and noise have been detected respectively. As those incoming signals are not lighting signal in nature, thus interrupt went high and no signal processing happened. The distance measurement was not done, so output of Rx07 is 3F which means B5 – B0 = 111111, this indicates lightning did not happen from Chapter-3, Table no.4.

Among all the data set, the most suitable setting was Sl. No. 8, where tunable parameter values are given as below,

AFE = outdoor, Noise floor level = 110, Watchdog = 0011, and Spike rejection = 0011.

This setting was able to capture real lightning and thunder storm distance from the device. Below given figure shows natural lightning detection which was happened 19th may 2019 at 4:16 pm near Rajarhat area, Kolkata, West Bengal. That location is proximately 15km away from Jadavpur, location of the measure device.

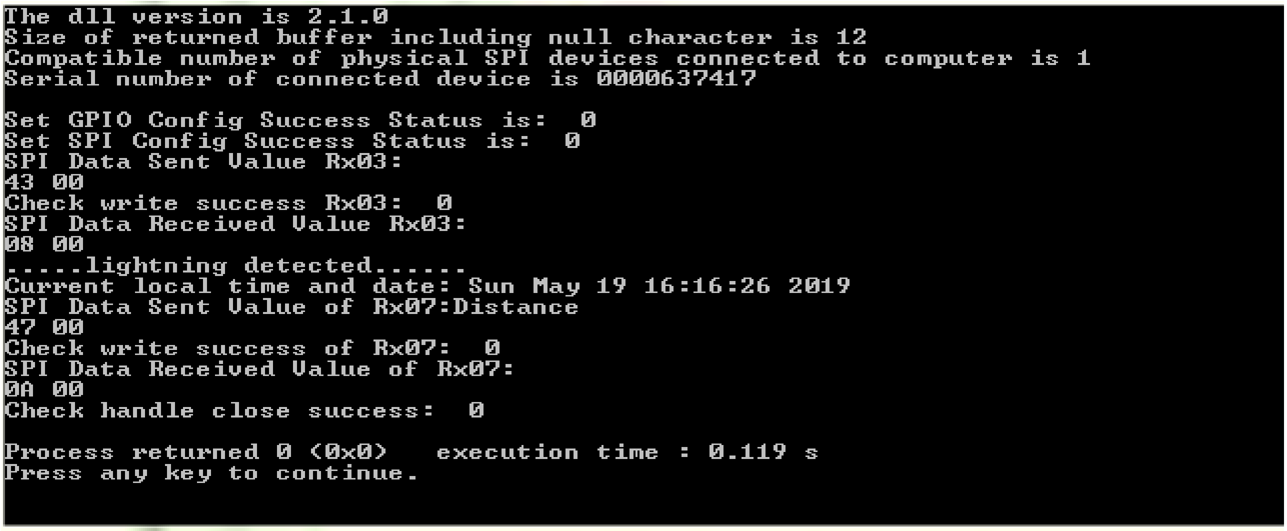


Fig. 4.10: Lightning detected by AS3935 in SPI mode

In the above figure showing lightning detection and indicating its distance which is stored in REG0x07 [5:0].

It can be seen the Received value of Rx07 = 0A which is in hexa.

0A = 00001010 in binary.

So, B5-B0 =001010

By comparing this value with Chapter-3, Table no.4, it is found estimated lightning distance is about 10 Kilometer.

This is how the measurement of lightning distance with the help of AS3935 is done. This lightning distance will be introduced in fuzzy logic rule base system, and rule base will be used to predict the lightning probability within PI (Point of interest).

4.8 ***Fuzzy rule base prediction design:***

Fuzzy rule base system is being used to design a prediction rules for lightning phenomenon within a particular region. Here, Mamdani Fuzzy Inference system is going to be used to predict lightning phenomenon. So it is required to study some specific parameters which deeply encourage lightning strike, especially CG strike. With the help of the result of the previously done research work, it is evident that electric field and electric field gradient are the most important parameters to understand lightning strikes. Along with those two parameters atmospheric pressure, wind direction and latest lightning distance from PI are also required for this prediction model.

4.9 ***Logic of rule base design:***

Atmospheric pressure is highly influencing parameter for the formation of thunder-cloud which initiates lightning phenomenon. Low pressure indicates incoming thunderstorm and high pressure indicate storm going away from that region. Wind direction also helps to understand thunderstorm characteristics. If PI is present in between any high and low pressure zone, wind direct helps us to determine moving direction of thunderstorm.

Already, it has been discussed regarding Electric field strength and filed gradient in the topic **2.3**, and fixed some threshold values for field strength and field gradient for the prediction purpose of lightning strikes. Electric filed strength and field gradient have 4 and 3 threshold regions respectively, shown in the given below table,

Table 4.6: Electric Field Strength ranges

Electric Field Strength	**Rng1**	**Rng2**	**Rng3**	**Rng4**
	Less than 1.5kV/m	1.5<,>3 kV/m	3<,>5kV/m	5<,>8kV/m

Table 4.7: Electric Field gradient ranges

Field gradient	**Low**	**Medium**	**High**
	0.5<,>1.5 kV/(m*s)	1.5<,>2.0 kV/(m*s)	2.0<,>3.0 kV/(m*s)

And Local lightning distance from PI is also defined in three ranges,

Table 4.8: Local lightning distance ranges

Local lightning distance	**Rng1**	**Rng2**	**Rng3**
	15-10 km	10-5 km	5-0 km

Output Warning is categorized into four different intensity level, given below

L1= very high chance of lightning strike, L2 = High chance, L3 = Moderate chance, L4 = Low chance, L5 = No warning.

By using above threshold values, a Logic Table has been introduced for Fuzzy implementation, given below,

Table 4.9: Prediction rule base

Sl. No.	**Pressure**	**Wind direction w.r.t. PI**	**Electric field strength near PI**				**Field Gradient @ PI**	**Local lightning distances**			**Warning level**
			Rng 1	Rng 2	Rng 3	Rng 4		Rng 1	Rng 2	Rng3	
1	Low	Toward				Y	High			Y	L1
2	Low	Toward				Y	High		Y		L1
3	Low	Toward				Y	High	Y			L2

4	Low	Toward			Y		High			Y	L2
5	Low	Toward			Y		High		Y		L2
6	Low	Toward			Y		High	Y			L3
7	Low	Toward		Y			High			Y	L2
8	Low	Toward		Y			High		Y		L3
9	Low	Toward		Y			High	Y			L3
10	Low	Toward	Y				High			N	L4
11	Low	Toward	Y				High		Y		L3
12	Low	Toward	Y				High	Y			L3
13	Low	Toward				Y	Moderate			Y	L1
14	Low	Toward				Y	Moderate		Y		L2
15	Low	Toward				Y	Moderate	Y			L2
16	Low	Toward			Y		Moderate			Y	L2
17	Low	Toward			Y		Moderate		Y		L3
18	Low	Toward			Y		Moderate	Y			L4
19	Low	Toward		Y			Moderate			N	L4
20	Low	Toward		Y			Moderate		Y		L3
21	Low	Toward		Y			Moderate	Y			L4
22	Low	Toward	Y				Moderate			N	L5
23	Low	Toward	Y				Moderate		N		L5
24	Low	Toward	Y				Moderate	N			L5
25	Low	Toward				Y	Low			Y	L1
26	Low	Toward				Y	Low		Y		L2
27	Low	Toward				Y	Low	Y			L3
28	Low	Toward			Y		Low			Y	L3
29	Low	Toward			Y		Low		Y		L4
30	Low	Toward			Y		Low	N			L4
31	Low	Toward		Y			Low		N		L5
32	Low	Toward	Y				Low		N		L5
33	High	Away				Y	High			Y	L1
34	High	Away				Y	High		Y		L2
35	High	Away				Y	High	Y			L3
36	High	Away			Y		High			Y	L2
37	High	Away			Y		High		Y		L3
38	High	Away			Y		High	Y			L3
39	High	Away		Y			High			N	L4
40	High	Away		Y			High		Y		L3
41	High	Away		Y			High	Y			L3
42	High	Away	Y				High			N	L5
43	High	Away	Y				High		Y		L4
44	High	Away	Y				High	Y			L4
45	High	Away				Y	Moderate			Y	L3
46	High	Away				Y	Moderate		Y		L3
47	High	Away				Y	Moderate	Y			L4
48	High	Away			Y		Moderate			N	L4
49	High	Away			Y		Moderate		Y		L3
50	High	Away			Y		Moderate	Y			L4
51	High	Away		Y			Moderate			N	L5

52	High	Away		Y			Moderate		Y		L4
53	High	Away		Y			Moderate	Y			L5
54	High	Away	Y				Moderate		N		L5
55	High	Away				Y	Low			Y	L2
56	High	Away				Y	Low		Y		L3
57	High	Away				Y	Low	Y			L4
58	High	Away			Y		Low			N	L4
59	High	Away			Y		Low		Y		L3
60	High	Away			Y		Low	Y			L4
61	High	Away		Y			Low		N		L5
62	High	Away	Y				Low			N	L5
63	High	Away	Y				Low		N		L5
64	High	Away	Y				Low	N			L5

This table will be used to obtain the predictive warning system in probabilistic manner.

4.10 ***Matlab based model of Fuzzy Rule base:***

To implement the whole logic through Fuzzy Logic inference system, each parameters are represented in the form of membership function. During establishment of membership function, their values are normalized with the respect to their highest limiting value, so that overall range of each membership function belongs to 0 – 1 range. And MF curve is taken Gaussian type, as this curve increases and decreases gradually and highest point is not steep which is desirable for this kind of system representation.

$$\text{Normalization Peak Value} = \frac{\text{Highest value of individual range}}{\text{Highets value of a that parameter}}$$

Let’s design the MFs of above discussed parameters:

4.10.1 MF of Electric filed strength and Field gradient :

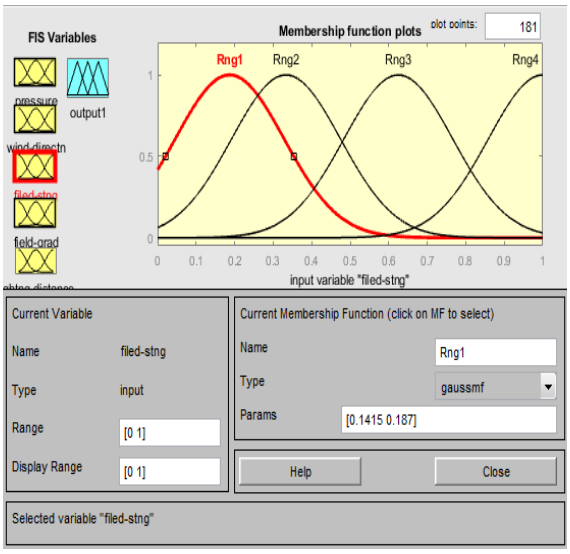


Fig. 4.11
MF of Electric Field Strength

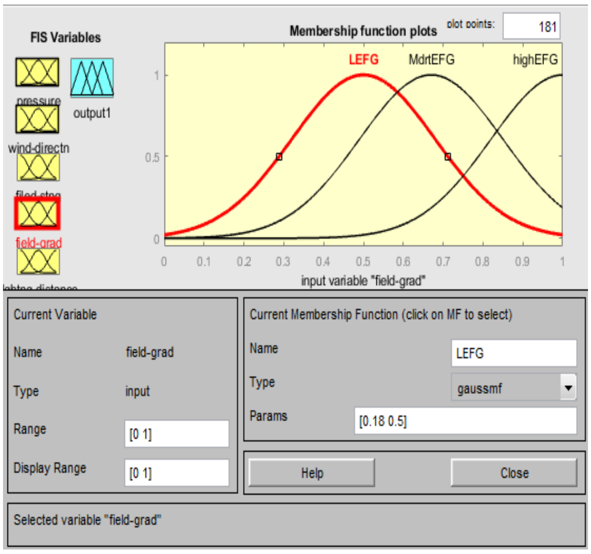


Fig. 4.12
MF of Electric Field Gradient

Above given figure (Fig. 4.11) shows field strength MF. They have same standard deviation (SD) = 0.1415.

Rng1 normalized peak value = $\frac{1.5}{8}$ = 0.187, for Rng2 peak= $\frac{3}{8}$ =0.275, Rng3 peak= 0.625 Rng3 peak= 1.

Fig. 4.12 shows field gradient MF. Here also Gaussian type MF whose SD is 0.18

Low EFG peak = 0.5, Moderate EFG peak = 0.67, High EFG = 1.

4.10.2 MF of Pressure and Wind Direction:

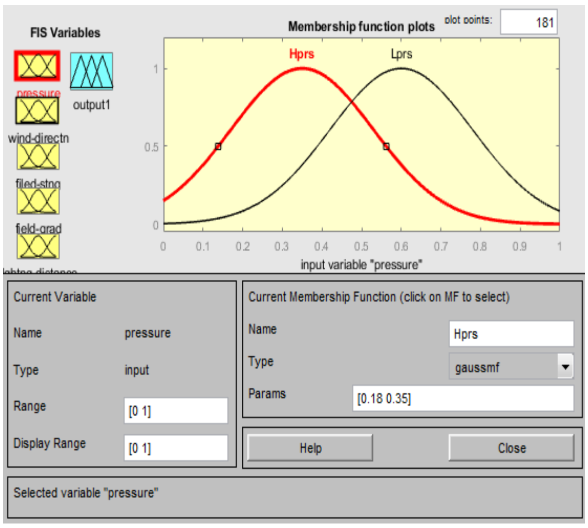


Fig. 4.13
MF of Pressure

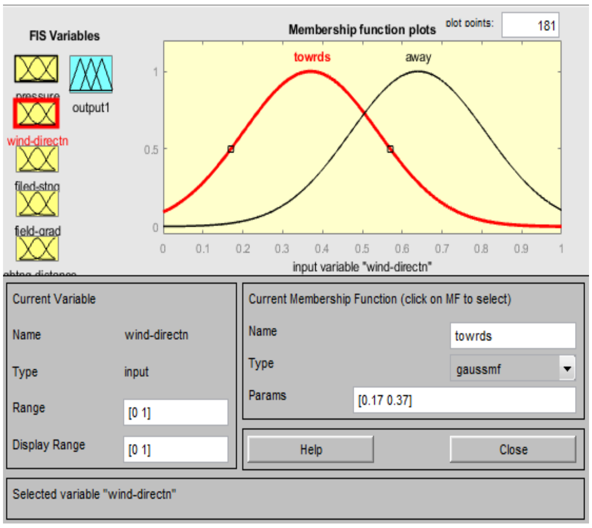


Fig. 4.14
MF of Wind Direction

Fig. 4.13 shows the MF of atmospheric pressure near PI, MF is Gaussian in nature and SD = 0.18, High pressure normalized peak = 0.350 and Low pressure normalized peak = 0.6

Fig. 4.14 shows MF of Wind Direction, SD = 0.17, Towards Normalized peak = 0.37, Away Normalized peak = 0.64

4.10.3 MF of Local Lightning Distance and Warning Levels as Output:

Fig. 4.15
Lightning Distance MF

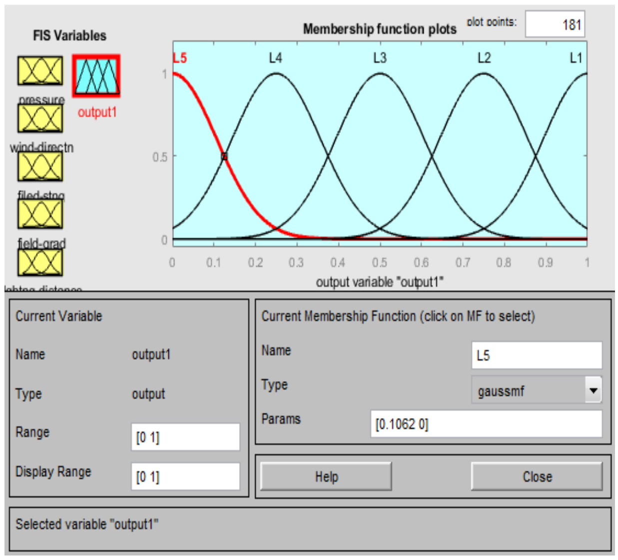


Fig. 4.16
Warning Level MF

Fig. 4.15 shows MF of Lightning Distance. Chosen MF is Gaussian type, SD= 0.17, Rng3 Normalized peak = 0.33, Rng2 = 0.6, Rng1 = 1.

As there are 5 warning levels so five numbers of MFs having SD of 0.1062 as it can be noticed in the Fig. 4.16.

Now, in the fuzzy toolbox, it can be applied all the rules which are defined in the above Table 4.9.

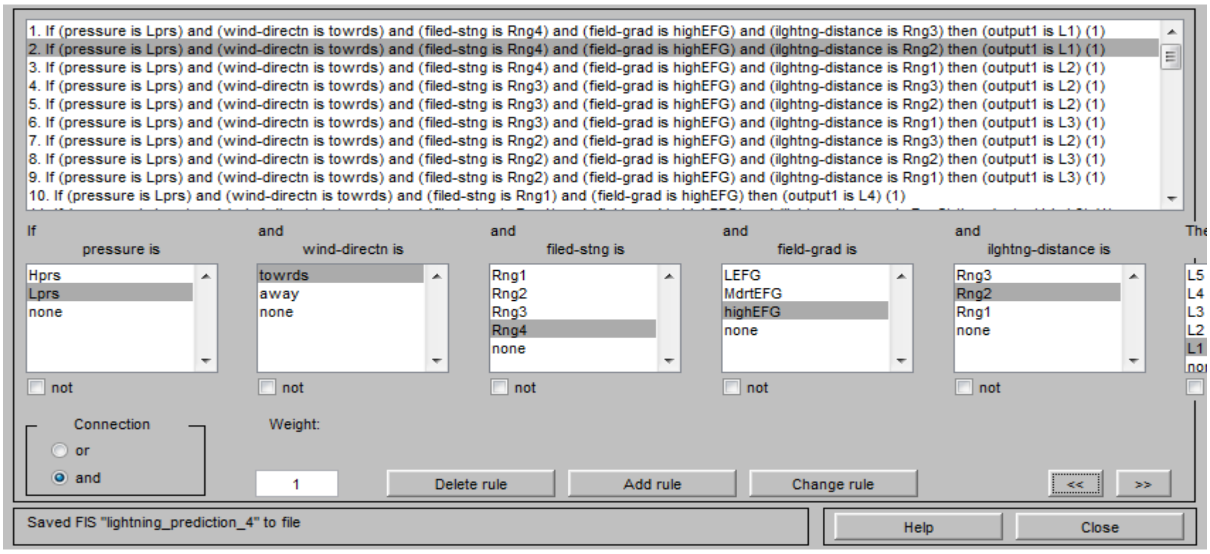


Fig. 4.17: Fuzzy rule editor where rules are added

In the Fig. 4.17 it can be noticed how the rules are implemented by the fuzzy toolbox. These rules will simulate output using all given input, and will predict lightning strike probability depending upon the condition of input parameter.

Example 1: let us consider the rule no. 1 given below, from the Table 4.9.

Sl. No.	**Pressure**	**Wind direction w.r.t. PI**	**Electric field strength near PI**				**Field Gradient @ PI**	**Local lightning distances**			**Warning level**
			Rng 1	Rng 2	Rng 3	Rng 4		Rng 1	Rng 2	Rng 3	
1	Low	Toward				Y	High			Y	L1

By applying this condition the lightning strike probability will be calculated. This probability is the output of fuzzy rule system.

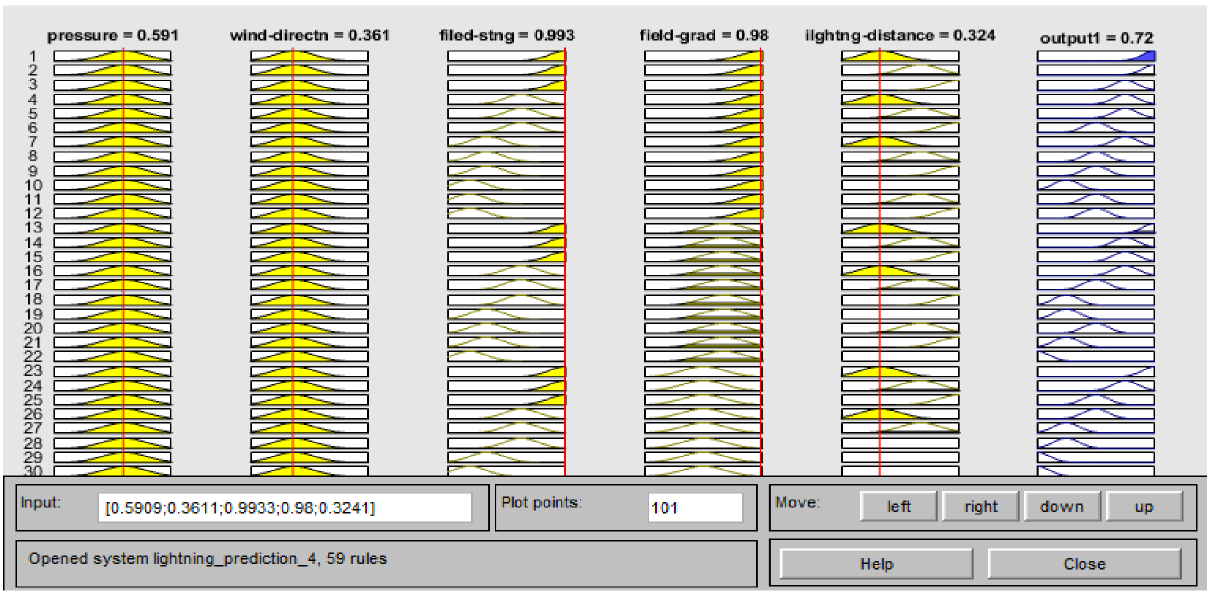


Fig. 4.18: Fuzzy rule base output Sl. No.1 is implemented

Here, in the Fig. 4.18 it can be noticed all the input parameters values are kept near to its normalized peak value of specified range as mentioned in the rule table. The output value is 0.72 (comes under L2 warning of the output) which means lightning probability is 72% under this circumstances.

Example 2: Considering the rule no. 28 given below, from the Table 4.9

Sl. No.	**Pressure**	**Wind direction w.r.t. PI**	**Electric field strength near PI**				**Field Gradient @ PI**	**Local lightning distances**			**Warning level**
			Rng 1	Rng 2	Rng 3	Rng 4		Rng 1	Rng 2	Rng3	
28	Low	Toward			Y		Low			Y	L3

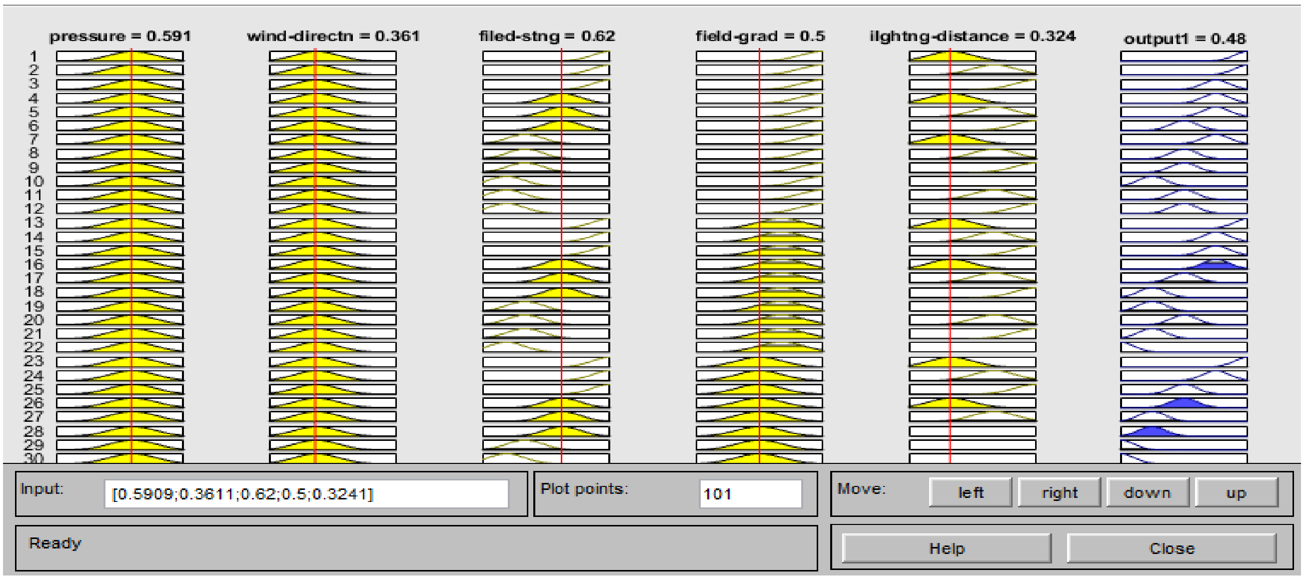


Fig. 4.19: Fuzzy rule base output Sl. No.28 is implemented

In the Fig. 4.19 it is evident that all the input parameters values are kept near to its normalized peak value of their specified range as mentioned in the rule Table 4.9. The output value is 0.48 (comes under L3 warning of the output) which means lightning probability is 72% under this circumstances. Hence Table 4.9 rule no. 28 is matching with probability calculation by fuzzy inference system. This is rule base type numerical output.

There is another type of output that can be found by which it can be understood how input parameters varies with respect to each other. Below given Fig. 4.19 and Fig. 4.20 are showing surface plotting between field strength, field gradient and lightning distance.

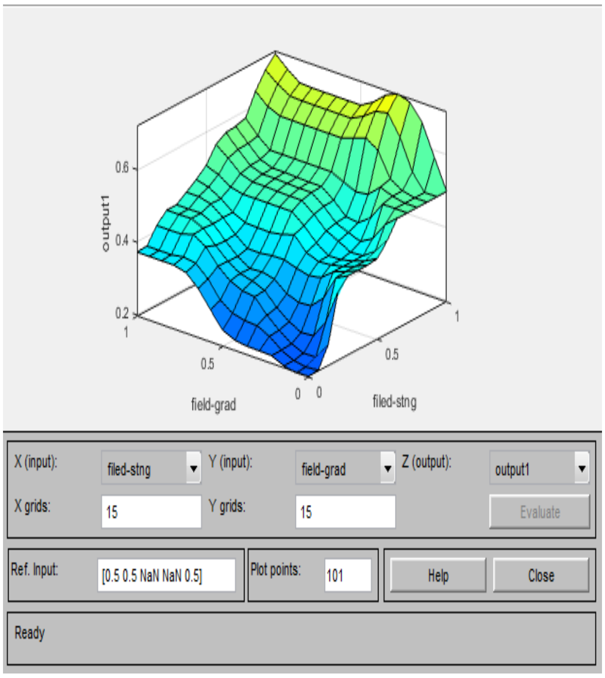


Fig. 4.20
Field strength vs. Field grad.

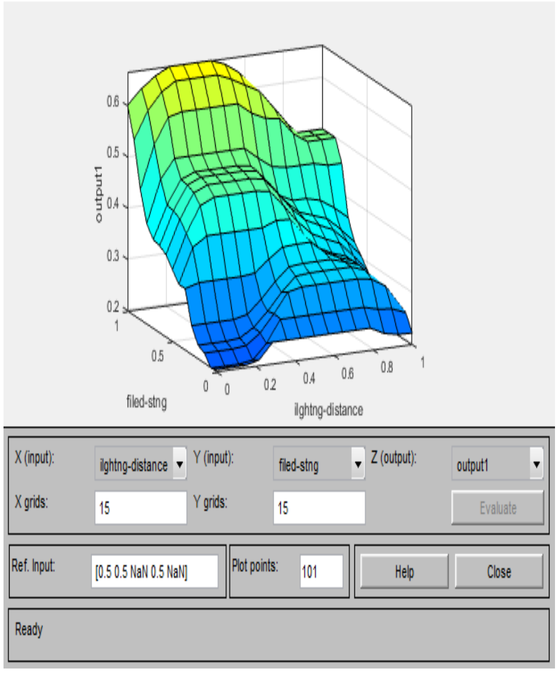


Fig. 4.21
Lightning distance vs. Field strength

From the above figures, it is evident that surfaces are gentle, there is no abrupt change on that surface, hence this control system will be stable and easier to design, and parameter variation may help to improve system efficiency and accuracy.

4.10 <u>Summary:</u>

From the above experimental result it can be concluded that Fuzzy Logic rule base prediction system is working apparently. All the rules in Table 4.9 are defined according to different literature and general concept. To make that system more robust, productive and less error free, filed work is highly required and used data must be collected from local authentic weather station. All the parameters used here are very volatile and typically dependent on the longitude, latitude, sea level height etc. Here, those parameters values are generalized and it has been tried to show the prediction system that can be designed with help of Fuzzy Logic system which is easier and less complicated than ANN based system. Also, AS3935 chip accuracy varies from one place to another, so, tunable parameters have to be modified accordingly.

CHAPTER-5

CONCLUSIONS

- Conclusions
- Future Scope

5.1 ***Conclusions:***

This present scheme has been developed with two objectives, one of them is to detect electromagnetic wave produced from lightning discharge for detection of lightning strokes with AS3935 lightning sensor and another one is to design a fuzzy rule base inference system for lightning prediction model with matlab fuzzy logic toolbox. As elaborated earlier, thousands of people are killed and many instruments are damaged due to lightning stroke which is nature's one of the most unpredictable and devastated phenomenon till now. So research work in this field is highly required to attain some level of efficiency for safety purpose.

Contribution of the work:

- To design and develop a hardware module with the lightning sensor AS3935 and interfacing board connection.
- Develop an algorithm and to implement it to send and receive data to AS3935 registers, thus output is obtained from AS3935.
- Identify the tunable parameters and to tune them to suitable values so that the module works properly ignoring surrounding noise.
- To Develop and implement a Fuzzy rule base using Matlab so that lightning occurrence probability can be calculated.

5.2 ***Future scope:***

Lightning discharge is a very complex process which includes many more volatile parameters which were not introduced in this thesis due to some unavoidable circumstances. For the future development purpose, all those parameters may be considered to design a complete instrument with all of the sensors which can work more efficiently for lightning prediction system. In case of hardware, more number of sensors can be integrated for lightning detection. Incorporation of above mentioned modification may improve the accuracy and sensitivity of the whole system.

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