Atmospheric Electric Field Measurement Advances in Southern Peninsular Malaysia

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***Abstract*—Lightning, which is also known as electrical charge separation in atmosphere, performs energetic discharge. By monitoring the atmospheric electric field (AEF), it helps to give precaution against the risk of lightning. The rotating electric field mill (REFM) is a sensor used in measuring AEF. REFM comprises of signal processing circuit (consists of amplification unit, filtering, conversion, and signal conditioning unit) for connection to data acquisition equipment in order to display, collect, and analyse the data. An investigation of different materials on REFM rotor and stator was performed to reveal their sensitivity and stability towards the high voltage atmosphere. The calibration results showed that aluminium sensor had been more suitable for AEF measurement compared to stainless steel sensor. The research purpose was to track the thundercloud development processes and movement. In addition, in order to investigate the characteristics of the signal from a thunderstorm cloud prior to cloud ground lightning discharges, the REFM was installed in UTM area. The data collected on-site revealed the characteristic signals of AEF in the atmosphere and the characteristics of the signal from a thunderstorm cloud prior to CG lightning discharges.**

Keywords—REFM, atmospheric electric field (AEF), lightning

I. Introduction

The atmospheric electric field (AEF) are generally monitored using an AEF sensor or lightning sensor. The purpose of this sensor is to monitor the magnitude of the atmospheric electric field between the clouds and the ground. The magnitude of the AEF is used as a benchmark of lightning occurrence. The warning for the hazard is issued when the atmospheric electric field exceeds a given limit. The continuous measuring AEF can offer effective information of weather changes as well as lightning forecast. AEF that is close to the ground is susceptible to the surface features, lightning incident, humidity, precipitation, aerosol presence in the atmosphere and air pollution [1-2].

One of the most widely-used AEF sensors is the rotating electric field mill (REFM). It functions by detecting the charge induced on the sensor electrode. In principle, the REFM measures the electric field by continuously exposing and shielding the conductor in the atmosphere. The fixed induction conductor is known as a stator, while the rotated conductor that alternately shields the stator is known as the rotor. Therefore, the periodic changes in the electric field signals can be acquired accordingly. When the stator is shielded by the rotor, the stator is charged with an electric field [3-8]. Then, this continuing process is generating the AC signal on the sensor plate.

In this paper, the investigation of the different material of REFM sensor between stainless steel and aluminium and the characteristics of the signal from a thunderstorm cloud prior to CG lightning discharges are presented. The development of REFM consisted of a rotating vane (rotor), a sensor plate (stator), a 12 V DC motor inside the chamber, motor controller, signal processing unit, and 12 V power supply. The REFM is shown in Fig. 1. The detail information about the design electronic circuit that used to convert AC to DC signal could be found in the previously published paper with the same authors. The material of REFM body usually made from the strongest and corrosion free material which is suitable for the outdoor environment.

Fig. 1 Rotating electric field mill

II. Effects of Sensor Material

The REFM vanes, which consisted of rotor and stator (sensor plate), were tested with two different materials. The materials used for this testing were aluminium and stainless steel. Both materials have the ability to resist corrosion due to passivation phenomenon. The different sensor material could affect the effectiveness of the REFM to measure electric field. The sensitivity and stability of sensor may change due to the different type of materials. The tested materials used in this testing are shown in Fig. 2.

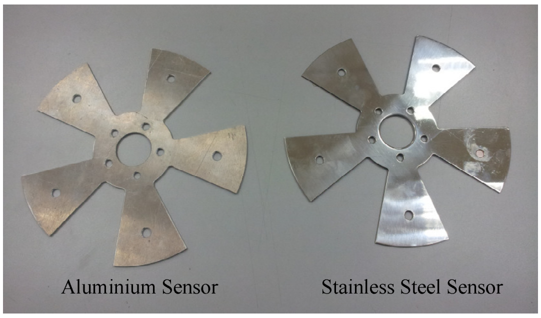

Fig. 2 The tested materials: Aluminium (left) and Stainless Steel (right)

The calibration of REFM had been necessary before it was used in the actual situation. The calibration process must be implemented in order to identify the correlation factor between the actual electric field strength and the output voltage (V_{out}).

The calibration process was performed in IVAT Laboratory with the experimental setup shown in Fig. 3. The REFM was placed beneath the cloud simulator, which was connected to HVDC supply. The cloud simulator was constructed from an aluminium flat rectangular plate (dimension of 3.25 m x 1.5 m), which was supported by a PVC pipe. The height between the cloud simulator and the ground was 3.2 m.

The input voltage of HVDC was controlled by HAEFELY High Voltage test unit consisted of Digital Measuring Instrument DMI 551 and Operating Terminal OT 276. The REFM was calibrated by varying the gap distance between the cloud simulator and the REFM, *d*. The gap distance settings were 0.3 m, 0.5 m, and 0.8 m.

In addition, the output voltage (V_{out}) was captured by using an analogue to digital converter device (PicoScope 5203) as an interface to a notebook PC. Then, the results of electric field strength and the output voltage were plotted to construct a curve fitting in order to obtain the correlation factor.

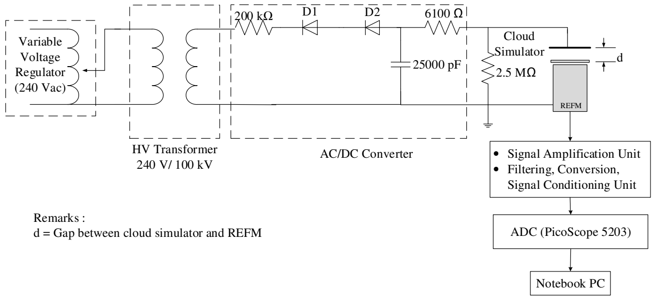

Fig. 3 The experimental setup of REFM calibration [9-10]

III. Calibration Results and Discussion

The acquired data were analysed using regression analysis in order to obtain a linear equation and also to present the relationship between electric field (E) and V_{rms}. The α and β were constants where α indicated the slope of the regression line, whereas β indicated the measured value when the regression line crossed the y-axis. The linear equation of this mathematical model is shown in (1).

$$Vrms = \alpha E + \beta \tag{1}$$

The correlation coefficient (r) and multiple correlation coefficients (R^2) were determined to measure the strength and the direction of a linear relationship between E and V_{rms}. Meanwhile, the standard error regression analysis (S) denoted the average distance of the data that fell from the regression line.

Table 1 provides the calculation and the correlation coefficients of linear regression analysis of the stainless steel sensor. From this table, the correlation coefficient, r, was only strong when d=0.8 m, but most of the gap distance for the relationship between V_{rms} and E for the stainless steel sensor had been weak since the r value was lower than 0.5. Moreover, it had been the same for R^2 as it was the square of the correlation coefficient. Furthermore, the standard error of the regression analysis was better when d=0.8 m since the value was smaller, as it indicated that the observation was closer to the regression line, but the other gap distance provided higher results compared to d=0.8 m.

TABLE I. The Calculation and The Correlation Coefficients of Linear Regression Method for REFM (Stainless Steel Sensor)

d	α	β	r (correlation coefficient)	R^2 (multiple correlation coefficient)	S (Standard Error)
0.8 m	0.0005	3.7944	0.8692	0.7555	0.0031
0.5 m	-0.0003	3.8068	0.0193	0.0374	0.0205
0.3 m	-0.0001	3.7817	0.2095	0.0439	0.0174
Overall	-0.0003	3.8011	0.3018	0.0911	0.0155

In addition, Table 2 shows the calculation and the correlation coefficient of the linear regression method for aluminium sensor. The obtained data in each table present a strong linear relationship between V_{rms} and electric field as the correlation coefficient, *r*, was greater than 0.8. The aluminium sensor gave a very small standard error of regression analysis, which expressed that the observation data had been closer to the regression line.

TABLE II. THE CALCULATION AND THE CORRELATION COEFFICIENTS OF LINEAR REGRESSION METHOD FOR REFM (ALUMINIUM SENSOR)

d	α	β	r (correlation coefficient)	R^2 (multiple correlation coefficient)	S (Standard Error)
0.8 m	0.0014	3.6920	0.9554	0.9128	0.0043
0.5 m	0.0008	3.7110	0.9425	0.8882	0.0047
0.3 m	0.0002	3.7375	0.9774	0.9553	0.0010
Overall	0.0008	3.7052	0.8797	0.7739	0.0089

The stainless steel sensor showed contradictory results with the aluminium sensor. Furthermore, there was strong possibility that the different results between both the sensors had been due to the resistivity of the materials. The resistance of metallic material generally followed the ohm's law, by which the current flow had been directly proportional to the voltage applied. A low resistivity material has strong ability to transfer energy. The aluminium material has been categorized as an excellent conductor (conductivity, $\sigma=3.500\text{x}10^7$ S/m and resistivity, $\rho=2.820\text{x}10^{-8}$ Ω.m [11]) compared to the Stainless Steel 304 which has a poor conductor (conductivity, $\sigma=1.450\text{x}10^6$ S/m and resistivity, $\rho=6.897\text{x}10^{-7}$Ω.m [12]).

The calibration of REFM also could determine the sensitivity of the REFM. The sensitivity of the measurement was defined as the relationship between the measures of the change in the output reading for a given change of the input. This relationship can be either linear or non-linear. Thus, sensitivity is a ratio, as shown in (2) [13].

$$\text{Sensitivity} = \frac{\text{change of the output}}{\text{change of the input}} \qquad (2)$$

Therefore, the sensitivity of the measurement was the slope of the straight line. Based on the results presented in Table 1, the stainless steel sensor gave the slope a value of -0.0003 V/kV/m for the overall data, while Table 2 shows the slope of 0.0008 V/kV/m for the overall data of aluminium sensor. Besides, the findings showed that the sensors had a linear relationship between output and input. The aluminium sensor had been the most sensitive because it could indicate a large movement of output for a small input change compared to the stainless steel sensor. Moreover, the stability and the linearity of the sensor were varied due to the different materials. It can be assumed that the good conductivity of the material had excellent specification in regard to stability and linearity. From these results, the aluminium sensor was more effective in measuring electric field and had high efficiency compared to the stainless steel sensor. Therefore, the aluminium sensor was chosen for further investigation.

IV. FIELD TEST RESULTS AND DISCUSSION

The experimental setup for the installation of REFM and humidity sensor is shown in Fig. 4. The height of the REFM was adjusted to 2.64 m above the roof surface. The power supply and the earthing cable were laid to the nearest power source and earthing point for the building respectively. The coaxial cable RG58 (50Ω) was used as a medium to transmit the data to PicoScope 3206B as an interface to the notebook PC. The setting of PicoScope 3206B was adjusted to enable the captured data that was saved automatically to the notebook PC. Furthermore, the Labquest®2 was used to measure the humidity around the installation locations.

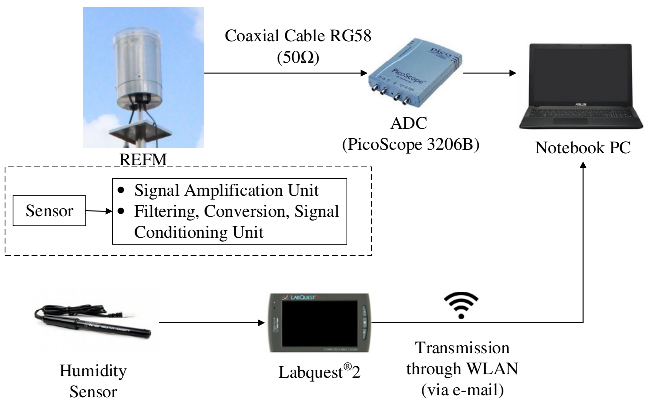

Fig. 4 The experimental setup for installation of REFM and humidity sensor

Two locations were chosen to install the REFM in order to investigate the characteristics of the signal from thunderstorm clouds prior to CG lightning discharges. The locations were in the UTM area, which were Balai Cerapan (the highest spot in UTM) with latitude and longitude of 1.570043 and 103.644628 respectively; and on the rooftop of the IVAT Laboratory with latitude 1.560587 and longitude 103.643343. The altitude from the sea level of Balai Cerapan and IVAT Laboratory were 133.0 m and 42.0 m respectively. Fig. 5 presents the electric field and the relative humidity monitored at Balai Cerapan measured from 10:45:29 AM until 4:01:18 PM on 18th November 2014. As shown in Fig. 5, there were relatively slow changes in the electric field before the shower of rains occurred. The relative humidity was also in high range because the value for this period was greater than 90%.

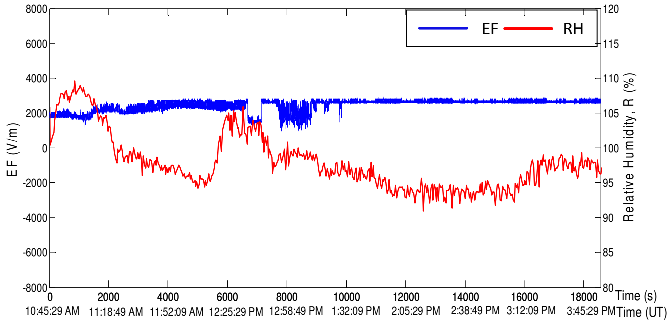

Fig. 5 Electric field and relative humidity monitored at Balai Cerapan measured on 18th November 2014

In addition, the AEF changes can monitor the whole process of thundercloud development before the CG lightning discharge occurs. In order to investigate this process, a continuous electric field measurement was conducted at the IVAT Laboratory from 24th November 2014 until 26th November 2014. Fig. 6 shows the electric field and the relative humidity monitored for 24 hours, which started from 9:43:59 AM on 24th November 2014. This observation was continued, as shown in Fig. 7, which presents the results for 24 hours, beginning from 9:42:45 AM on 25th November 2014 and was continued until 4:36:47 PM on 26th November 2014.

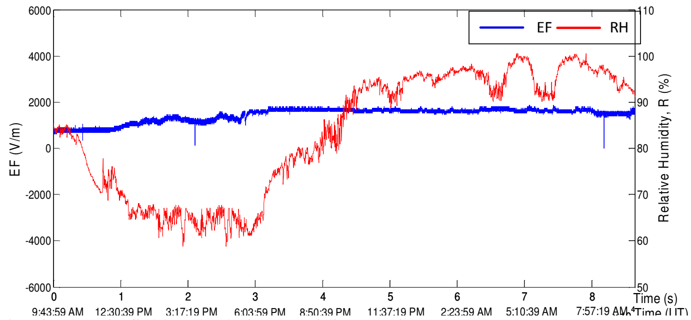

Fig. 6 Electric field and relative humidity monitored at IVAT Laboratory measured from 24th November 2014 until 25th November 2014

The findings that appear from the data collected shows the variation of electric field strength before the CG lightning discharge occurred. In fact, there was a significant trend that showed the deviation of electric field strength and the relatively slow changes of the field. This slow change had been due to the cloud electrification and the rearrangement of space charge in the atmosphere [14]. Besides, the presence of fluctuation in the data clarified the formation activity of the vertical development of cloud.

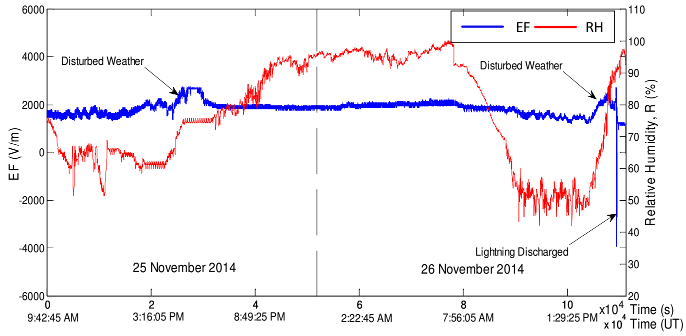

Fig. 7 Electric field and relative humidity monitored at IVAT Laboratory measured from 25th November 2014 until 26th November 2014

In addition, there had been a possibility that the results of electric field were connected to the relative humidity changes. From the results shown in Fig. 6 and Fig. 7, the relative humidity had a high percentage, and at the same time, it showed high electric field value from night until dawn. The most significant reason that led to the high value of relative humidity was the existence of dew and fog that usually occurred during that period. Besides, the rain showers and the disturbed weather were also associated with the changes of the electric field and the relative humidity. The presence of fog and low cloud also caused the atmosphere to be strongly electrified, which contribute to the greatest separation of electrical charge [15]. These findings are consistent with the claims that stated that the electric field strength is positively correlated with the relative humidity in the atmosphere, aerosol content, temperature, and other weather factors, but negatively correlated with atmospheric conductivity [16].

Furthermore, the relative humidity has been commonly measured in percentage, whereby 100% relative humidity indicates that the air is saturated. However, in real condition in the atmosphere, the relative humidity may exceed 100% [17]. From Fig. 5, the results showed that the relative humidity was greater than 100% in several periods. These results seemed to indicate that the atmosphere encountered the supersaturated environment [18].

On top of that, the REFM had a possibility to detect the changes in the electric field under the cloud, as well as the electric charge that appears in the cloud. For this reason, the status of electric charge accumulation in the thundercloud could be observed to give a probability of the existence of a thunderstorm nearby. Besides, Fig. 7 presents that the fluctuation of the electric field started around 10:00:00 AM on 25th November 2014 and the electric field kept increasing to exhibit the thunderstorm weather in the evening. The condition became stable after the thundercloud passed to an "End of Storm Oscillation", which indicated that there was no lightning and the fine weather condition recovered [5]. Fig. 7 also reveals the lightning discharge occurrence on 26th November 2014. The result is magnified in Fig. **8**, which showed the exact time of lightning discharge occurrence.

Besides, there were similarities in the characteristics of the disturbed weather on 25th November 2014 and 26th November 2014. However, on 26th November 2014, the CG lightning discharge occurred at 4:07:09 PM nearby the REFM sensor. The lightning discharge occurred after electrification in atmosphere was developed for around 10 minutes. At this moment, the active stage stayed for a few minutes, depending on the characteristics of the lightning [5]. Then, the lightning suddenly reversed the polarity of the electric field when it was discharges, and finally, arrived at “End of Storm Oscillation”.

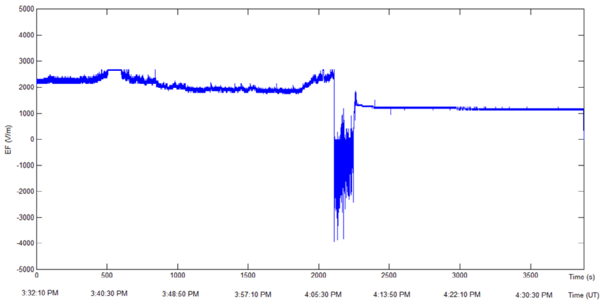

Fig. 8 Lightning discharge at IVAT Laboratory on 26 November 2014 at 4:07:09 PM

From the discussion above, it can be concluded that the continuously charged and discharged REFM sensors were able to measure the changes in of the electric field constantly. In fact, the AEF monitoring had been very helpful in investigating the characteristics of the signal from the thundercloud by observing the trends of the electric field variations.

V. Power Consumption

The power consumption of REFM included motor, motor controller, and a signal processing circuit, as presented in Table 3. Moreover, Table 3 shows that the power consumption of REFMs was around 6 W and 7 W, and the flow of current to the REFM was above 0.4 A during motor operation. The commercial instruments, which proposed the continuous motor operation, presented high power consumption. For example, Electric Field Mill II by Global Atmospheric Inc [19], Electric field meter sensor by Mission Instruments [20], Vaisala EFM II [21], and Boltek EFM-100 [22] offered 16 W, 8 W, 16 W, and 6 W respectively.

TABLE III. Power Consumption of REFM

REFM	AC Voltage (V)	Current (A)	Frequency (Hz)	Power (W)
1	241.7810	0.4526	49.9087	7.5547
2	242.6623	0.4414	49.9563	6.2439
3	241.3788	0.4709	50.0918	7.0619

However, there are field mills with very low power consumption compared to the results obtained. The Ada Fort [23] and CS110 EFM by Campbell Scientific [24] used reciprocating approach, where the stepper motor powered off frequently when it was operated. This approach reduced power consumption that offered <1 W for 1 measurement/second.

VI. Conclusion

REFM is a technology to measure AEF continuously. The information from the REFM had been very effective to validate the accuracy of weather forecast, as well as prediction of lightning occurrence. Therefore, by monitoring the AEF, it helps to give a precaution against the risk of lightning. The purpose of this research is to improve and to develop REFM as an AEF sensor. This development was done by improving the design of REFM from previous research. Furthermore, the investigation of the different sensor materials was aimed to improve the effectiveness of the REFM. From the results, it had been revealed that the aluminium sensor was better in terms of sensitivity and stability compared to stainless steel sensor. In addition, the installation of REFM in Johor Bahru Campus was proposed to observe the AEF changes in its vicinity. From the investigation of the AEF changes, it can be concluded that the REFM had been able to demonstrate the characteristics of the signal from a thunderstorm cloud prior to lightning discharges through continuous measurement.

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