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# pH Based Smart Sensor for Condition Monitoring of Overhead Insulators

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## Abstract

In this paper a real time monitoring system is presented for predicting flashover voltage of overhead insulator, it uses pH level as the pollution severity indicator and a smart sensor is used for measurement of pH level. The performance of insulator is examined under artificially polluted conditions with different contaminants. The contaminants chosen for artificial pollution test is on the basis of the presence of different types of salts in natural polluted conditions. Flashover voltages (FOV) of the insulator for different pH value have been recorded to relate FOV with pH of the contaminants and designed a pH based condition monitoring system for predicting flashover voltage of the contaminated insulator.

**Keywords**: Flashover voltages (FOV), Pollution, Insulator, pH, Virtual Instrumentation, Labview

## Introduction

For economical and reliable use of power generated interconnection of multiple available power sources is required. Interconnecting the power system network improves overall reliability. However, this increase in reliability comes at a price of increased risk associated with the possibility of a minor disturbance propagating and resulting in complete shutdown of the whole system. In the last 10-15 years an increasing number of large-scale black-outs have been witnessed, throughout the world. The main reason for these blackouts is concurrent malfunctioning of a large number of transmission lines and power generators, often triggered by the initial failure of a single component of the grid e.g. the breakdown of a power line. Therefore efforts are going on to minimize the probability of such terrible blackouts by developing advanced techniques for monitoring of transmission lines [1]. The insulation used on the transmission line is one of the critical areas prone to failure, as this insulation is exposed to the effects of pollution which accumulate on its surface and an electrolyte layer forms on it under the influence of environment and weather conditions such as moisture and rainfall [2, 3]. This layer extends over time and in some cases, such as in the case of inappropriate insulation designing, leads to flashover and system outage. Thus, identification of the factors causing insulation surface contaminated, pollution severity measurement, and tackling its unfavourable effects has an important role in increasing the network reliability, about 70% of high voltage transmission lines errors result from the inappropriate performance of insulation. Thus, it is the need of hour to develop a reliable system for monitoring the performance of the insulator with the help of smart sensors [4, 5] by sensing some pollution severity parameter to minimize the possibility of the system outage.

With the ever increasing demand for power, there has been a steady growth in high voltage transmission line required for optimum and economic transfer of large blocks of power over long distances. As the level of transmission voltage is increased, switching and dynamic over voltage and withstand ability of the insulator under polluted conditions are important factors which determine the insulation level of the system. The reliability of the system mainly depends on the environmental and weather condition which causes flash over on polluted insulator leading to system outage.

It is generally recognised that the main events leading to flash over of polluted insulators under service voltage are:

a) The formation of a conductive layer on the insulator surface.

b) Leakage current surging with associated dry band formation and partial arc development along the insulator surface eventually spanning the whole insulator [14].

## Contaminated conditions in various areas

***Marine Contamination*:** Insulator in marine contamination is most heavily contaminated by strong winds from the sea, usually not accompanied

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by rainfall. Under these conditions, insulator is contaminated rapidly and this so called rapid contamination. Contamination flashover is apt to occur when rapidly fog, drizzle, dew & so on wet contaminated insulator.

The wind velocity bringing about rapid contamination is ordinarily 5-10 m/s, although influenced by topographical conditions like typhoon, hurricane, cyclone, contamination condition is severest & and ESDD is high as 1 mg/cm$^2$ has been observed. ESDD tends to decrease with the distance from seacoast, the influence of the marine salt, however can seen even at a place over 100km apart from sea coast [16].

Commonly occurring salts in marine pollution arc Sodium Chloride ($NaCl$), Calcium Chloride ($CaCl_2$), Sodium Nitrate ($NaNO_3$). Potassium Chloride ($KCl_2$), Magnesium Chloride ($MgCl_2$)[11].

***Industrial Contamination:*** Insulators used in the industrial districts are contaminated by smoke and soot. Chemical composition of contaminants varies depending upon the kind of industry. It is reported that particles of the contaminants have the diameter of about 0.5-2.0mm [11]. Once soot or an alike stick on the insulator surface, such material is hard to be washed down by rain and has a tendency to accumulate on the insulator surface. Therefore in the area where the insulator is contaminated by the large quantity of soot, periodically insulator cleaning is recommended. In case sticking material such as cement contaminates the insulator, it is recommended to be exchanged for a new one after the use for about 10-20 years [13].

***Dust Contamination Area:*** In the inland area the insulator is contaminated by sand or soil blown up by wind. In such area ESSD on an insulator generally show a low value[11].

It is considered that the soluble salt of the contaminants in dust contaminants area mainly consist of Calcium Sulphate ($CaSO_4$) and Sodium Chloride ($NaCl$) [16]. The composition of these materials varies depending upon the location and sometimes calcium sulphate occupies most part of the soluble salts of the contaminants. In the case of a typical serious area, Calcium Sulphate occupies 30-70% and the rest seemed sodium chloride [13].

***Desert Condition:*** in the desert contamination area in large quantity of contaminants is apt to accumulate on the insulator surface because rain cleaning effect cannot be accepted due to little precipitation. In a desert near the coast, insulator contamination show the characteristics of the inland desert, contaminants superimposed on the marine contaminants.

In Desert contaminants, the ESDD on the insulator roughly range from 0.1-0.25 mg/cm$^2$ in an inland region an amount of more than 0.4mg/cm$^2$ in a coastal region. These values vary depending upon locations[13].

Commonly occurring salts in desert pollution are Calcium Carbonate ($CaCO_3$), Ferric Oxide ($Fe_2O_3$). Sodium Sulphate ($Na_2SO_4$,), Potassium Nitrate ($KNO_3$), Magnesium Carbonate ($MgCO_3$), Calcium Sulphate ($CaSO_4$), Potassium Chloride (KCI) & Sodium Chloride ($NaCl$)[11].

In this work pH level of the contaminant is used as a pollution severity indicator and a system is designed using pH sensor and Labview to monitor the pH value of the contaminated surface and predict the respective flashover voltage. Hence, the system will act as a forewarning system and be helpful in devising preventive maintenance schedule.

## Smart sensor

The term “Smart Sensor” was first raise in mid-1980’s and is used as expression of special features for progressive sensors that has improved properties compared to that of an ordinary sensor. It we consider the meaning of this term from when it is first introduced we observe that is was used by many different definitions which changed with time. Bringnell and Atkinson [6] defined as sensors having data conversion, information processing, and communication and excitation control. Only here the use of excitation control is mentioned as aspect of intelligence. Ko [7] defines two categories of smart sensors. One is representative for sensors with processing circuits and active devices to improve signal-to-noise ratio. Another one is sensors with electronic circuits for signal processing and decision making to convert signals to various forms ready for further manipulation.

However, Institute of Electrical and Electronics Engineers (IEEE) committee has been actively consolidating terminology that applies to microelectronic sensors. The recently approved IEEE 1451.2 specification defines a Smart Sensor as “A sensor that provides functions beyond those necessary for generating a correct representation of a sensed or controlled quantity. This function typically simplifies the integration of the transducer into applications in a networked environment” [8].

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If we consider all definitions of smart sensors, we find out that smart sensors are those sensors which can perform one or more of the following functions:

a) Logic functions
b) Two-way communication
c) Make decisions

## $P^H$ based condition monitoring

Contamination is of little significance under dry conditions. However in the presence of light rain, freezing rain, fog or dew the contaminants dissolve to form a conductive layer on the insulator surface initiating leakage current and partial arcs (dry band arcing) which can ultimately lead to flashover. There are known pollution severity indicators such as conductivity, ESDD, leakage current for assessment of degree of pollution [9,10]. The use of leakage current as a parameter for determining the level of contamination is limited. It works well if the relative humidity is less than 90% and it does not facilitate a reliable forewarning system [11]. In addition to the above indicators pH of pollutants have also been used for analysis of insulator performance [11-13]. Studies have dealt with cases where the contaminant pH of an area has altered due to environmental improvement resulting in pH of rain water changing from 5.6 towards 7. pH of contaminants has been identified as an effective pollution severity indicator[14-16]. In this paper a real time monitoring system is presented for predicting the flashover voltage of the overhead insulator, it uses pH level as the pollution severity indicator and smart sensor is used for measurement.

## Experimental setup

Tests were carried out using disc insulator having a diameter of 254 mm, spacing 146 mm and leakage distance 280mm. The surface of the specimen insulator were cleaned and dried (in sunlight). Each unit then dipped in a salt solution of different salinity so that we have four readings for each contaminant salt. The pre-treated insulators were thoroughly contaminated with contaminants listed below:-

1. Calcium Chloride ($CaCl_2$)
2. Sodium Chloride (NaCI)
3. Magnesium Sulphate ($MgSO_4$)
4. Sodium Nitrate ($NaNO_3$)
5. Calcium Carbonate ($CaCO_3$)
6. Calcium Sulphate ($CaSO_4$)
7. Mixture of $CaSO_4$+CaO
8. Mixture of NaCl+CaO

Experimental setup for flashover test

***Supply and measurement of high voltage:*** During an artificial contamination test, large leakage current flow frequently. If drop in the test voltage due to the leakage current is high it is anticipated that the resultant apparent withstand voltage becomes high, thus the testing equipment should be as stiff as possible.

Voltage regulator and high voltage transformer

The high voltages were obtained from a testing transformer of 150 KV, 50Hz single phase, 30 KVA rating of British Power Transformer Co. Ltd. The short circuit current of the testing transformer is 15 Amp. The voltages were measured using a voltmeter (accuracy ±1%) connected to the primary side of the transformer, that reads the low side voltage. The corresponding high voltages are obtained from a

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calibration curve drawn by using the sphere electrode system having diameter of 25 cm (IS: 1876-1963).

***Controlling Unit-*** The controlling unit consists of the different knobs and buttons to increase or the decrease the voltage supply to the low voltage side of the transformer through voltage regulator and also a voltmeter is provided on it to observe the voltage. Below is the figure showing controlling unit.

Controlling Unit

## Result and discussion

**(i) $CaCO_3$ as Contaminant**

| S.No. | *Contaminant (g/l)* | *Temp. (˚C)* | *Humidity (g/m³)* | *Wet FOV (kv)* | *pH level* |
|---|---|---|---|---|---|
| 1 | 10 | 27 | 10 | 69 | 8.52 |
| 2 | 30 | 27 | 10 | 67 | 9.03 |
| 3 | 50 | 27 | 10 | 64 | 9.07 |
| 4 | 70 | 27 | 10 | 60 | 9.1 |

**(ii) $NaNO_3$ as Contaminant**

| S.No. | *Contaminant (g/l)* | *Temp. (˚C)* | *Humidity (g/m³)* | *Wet FOV (kv)* | *pH level* |
|---|---|---|---|---|---|
| 1 | 10 | 20 | 10 | 72 | 8.03 |
| 2 | 30 | 20 | 10 | 62 | 8.31 |
| 3 | 50 | 20 | 10 | 55 | 8.46 |
| 4 | 70 | 20 | 10 | 50 | 8.67 |

**(iii) $MgSO_4$ as contaminant**

| S.No. | *Contaminant (g/l)* | *Temp. (˚C)* | *Humidity (g/m³)* | *Wet FOV (kv)* | *pH level* |
|---|---|---|---|---|---|
| 1 | 10 | 25 | 12 | 54 | 8.71 |
| 2 | 30 | 25 | 12 | 51 | 8.74 |
| 3 | 50 | 25 | 12 | 50 | 8.46 |
| 4 | 70 | 25 | 12 | 48 | 8.38 |

**(iv) $CaCl_2$ as contaminant**

| S.No. | *Contaminant (g/l)* | *Temp. (˚C)* | *Humidity (g/m³)* | *Wet FOV (kv)* | *pH level* |
|---|---|---|---|---|---|
| 1 | 10 | 25 | 12 | 54 | 7.78 |
| 2 | 30 | 25 | 12 | 50 | 7.6 |
| 3 | 50 | 25 | 12 | 48 | 7.56 |
| 4 | 70 | 25 | 12 | 43 | 6.73 |

**(v) NaCl as contaminant**

| S.No | *Contaminant (g/l)* | *Temp. (˚C)* | *Humidity (g/m³)* | *Wet FOV (kv)* | *pH level* |
|---|---|---|---|---|---|
| 1 | 10 | 27 | 10 | 55 | 8.24 |
| 2 | 30 | 27 | 10 | 50 | 8.07 |
| 3 | 50 | 27 | 10 | 46 | 7.39 |
| 4 | 70 | 10 | 10 | 42 | 6.91 |

**(vi) $CaSO_4$ as contaminant**

| S.No. | *Contaminant (g/l)* | *Temp. (˚C)* | *Humidity (g/m³)* | *Wet FOV (kv)* | *pH level* |
|---|---|---|---|---|---|
| 1 | 10 | 26 | 8 | 69 | 7.51 |
| 2 | 30 | 26 | 8 | 64 | 7.56 |
| 3 | 50 | 26 | 8 | 55 | 7.61 |
| 4 | 70 | 26 | 8 | 50 | 7.65 |

**(vii) $CaSO_4$+CaO as contaminant**

| S.No. | *Contaminant (g/l)* | *Temp. (˚C)* | *Humidity (g/m³)* | *Wet FOV (kv)* | *pH level* |
|---|---|---|---|---|---|
| 1 | 10+10 | 22 | 12 | 75 | 8.18 |
| 2 | 30+10 | 22 | 12 | 71 | 7.81 |
| 3 | 50+10 | 22 | 12 | 67 | 7.34 |
| 4 | 70+10 | 22 | 12 | 60 | 7.04 |

**(viii) NaCl + CaO as contaminant**

| S.No. | *Contaminant (g/l)* | *Temp. (˚C)* | *Humidity (g/m³)* | *Wet FOV (kv)* | *pH level* |
|---|---|---|---|---|---|
| 1 | 10+10 | 25 | 12 | 67 | 8.52 |
| 2 | 30+10 | 25 | 12 | 64 | 8.21 |
| 3 | 50+10 | 25 | 12 | 60 | 7.59 |
| 4 | 70+10 | 25 | 12 | 54 | 7.29 |

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**pH level vs FOV graphs for various salts**

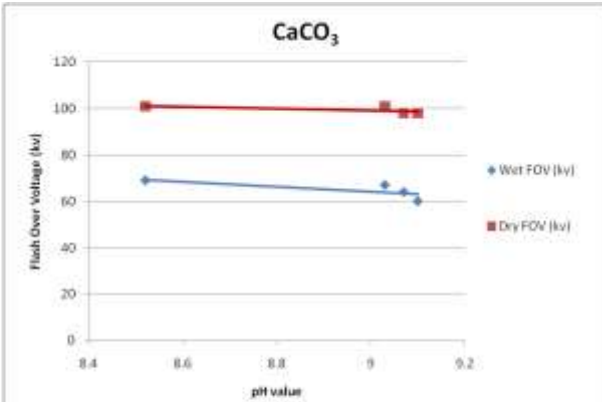


**Fig 1** *pH vs FOV graph of insulator contaminated with $CaCO_3$*

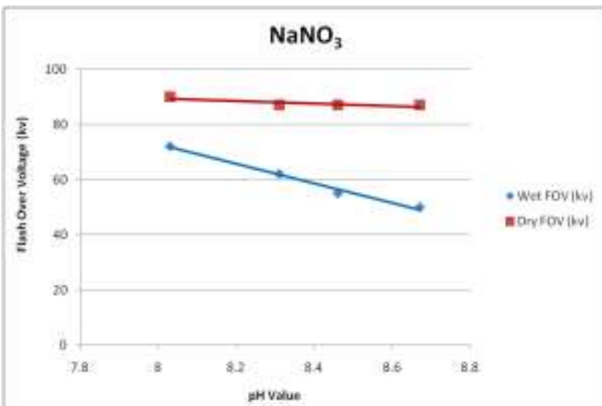


**Fig 2** *pH vs FOV graph of insulator contaminated with $NaNO_3$*

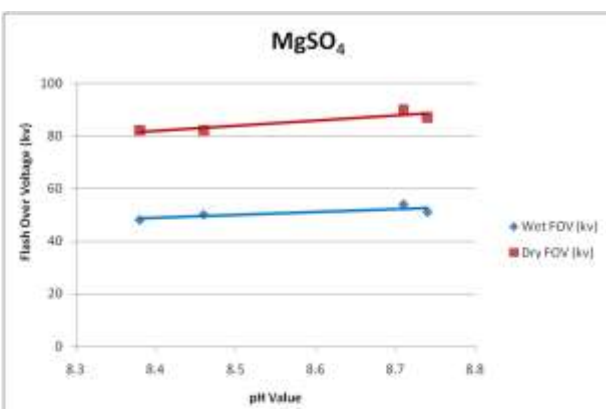


**Fig 3** *pH vs FOV graph of insulator contaminated with $MgSO_4$*

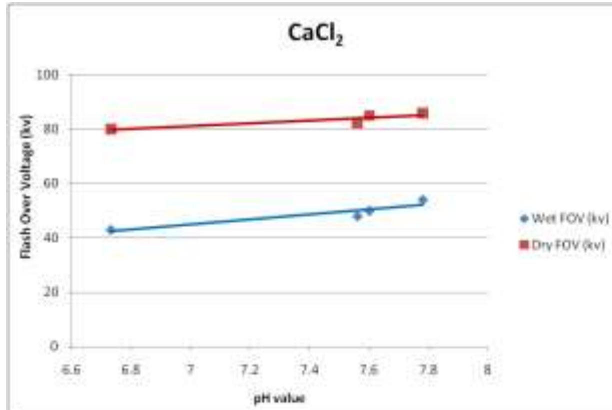


**Fig 4** *pH vs FOV characteristic of insulator contaminated with $CaCl_2$*

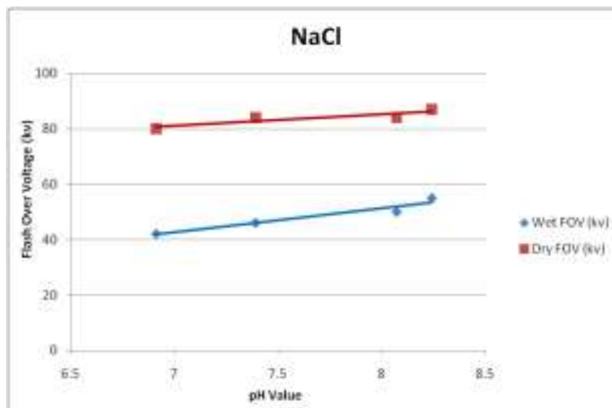


**Fig 5** *pH vs FOV characteristic of insulator contaminated with NaCl*

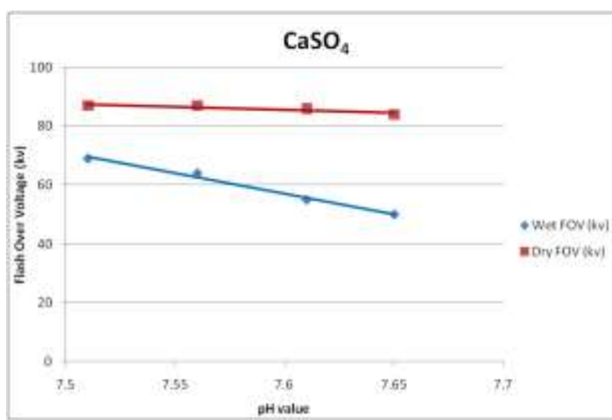


**Fig 6** *pH vs FOV characteristic of insulator contaminated with $CaSO_4$*

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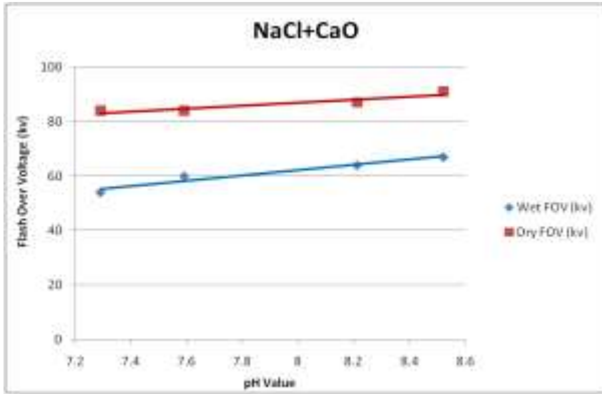



**Fig 7** ***pH vs FOV characteristic of insulator contaminated with NaCl+CaO***

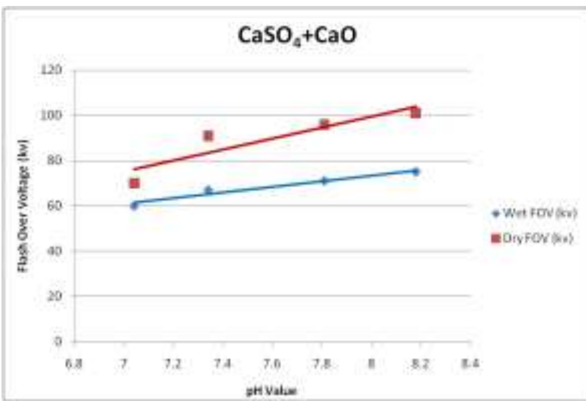



**Fig 8** ***pH vs FOV characteristic of insulator contaminated with $CaSO_4$+CaO***

## $P^H$ based Monitoring System

**Hardware Description**

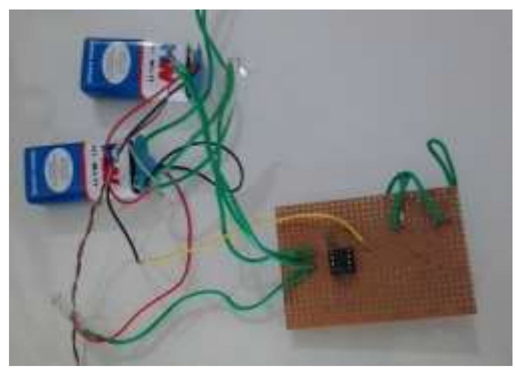
***Sensor-*** The sensor used to measure the pH level is LI 120 pH electrode, it is a combined electrode, it uses a differential electrode technique which employs two pH glass measuring electrodes. One electrode is used as the active or measuring electrode, and the other is used as part of a reference assembly. It generates 59.16mV/pH of voltage.

***TL082 Op-amplifier-*** The TL082 is low cost, high speed, dual JFET input operational amplifiers with an internally trimmed input offset voltage. They require low supply current yet maintain a large gain bandwidth product and fast slew rate. In addition, well matched high voltage JFET input devices provide very low input bias and offset currents. These amplifiers may be used in applications such as high speed integrators, fast D/A converters, sample and hold circuits and many other circuits requiring low input offset voltage, low input bias current, high input impedance, high slew rate and wide bandwidth. The devices also exhibit low noise and offset voltage drift.

***Impedance matching circuit*** To acquire the generated voltage to Labview 7.0 from a pH sensor we need an impedance matching circuit because the input impedance of a pH sensor is in the range of 10-100MΩ and the input resistance of the Labview DAQ card (9205) is around 147kΩ which is very low hence we have to use some impedance matching circuit of impedance at least 100 times to the input impedance of the sensor to interface the pH sensor to Labview DAQ card.

However, with electronic elements available today it is not very difficult to create an amplifier of very high input impedance, we can easily built a simple high impedance matching circuit using an inexpensive operational amplifier IC (a TL082 Dual JFET- input IC), 2 batteries of 9V each. The circuit works as unity gain buffer between the high impedance of the pH sensor and the DAQ card.

Here's the view of the impedance matching circuit used for interfacing the pH sensor and the Labview setup. The IC is soldered on a PCB and to the pin 6 & pin 7 are shorted to get almost unity gain, the input is given to pin 5 and the output can be taken from 7.



View of the Impedance Matching Circuit

***System program-*** pH and respective flashover voltage monitoring is done by Graphical programming language written in LabVIEW. This type of programming give rise to virtual instruments which mimics the real hardware without actually using it. Below figure shows the pH sensor connected to the LabVIEW through the impedance matching circuit with DAQ card and monitoring the pH value and predicting the respective Flashover voltage.

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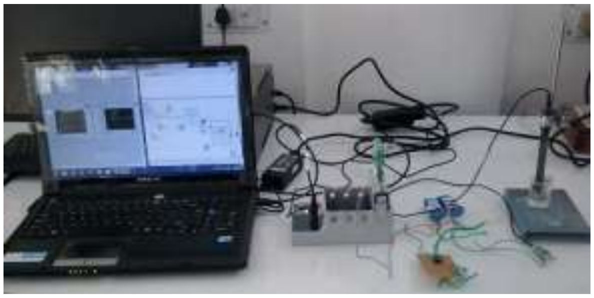

## Conclusion

In this work it is found that electrolytic behaviour of soluble salts as the contaminant is the main reason for the deteriorations of insulating capability of insulator. From the foregoing discussion and the study of polluted insulators, it may be concluded that the insulator flashover under contaminated conditions occurs when the contaminants on the insulator surface gets wet and the surface resistivity gets low. So the flashover voltage of polluted insulators depends on the kind and quantity of contaminants and its pH value. Accordingly, both chemical analysis of the contaminants and measurement of contaminant quantity are necessary from the point of design and maintenance of insulator under contaminated condition.

The main purpose of this work is develop a relation between pH level of the contaminant to the flash over voltage of the insulator under artificial polluted condition and to make a monitoring system which can monitor the pH value and predict the respective flash over voltage.

## Future work

In this work we have taken the effect of single salt and mixture of two salts as a contaminant at constant temperature and humidity. In future combination of more than two salts at different temperature and humidity near to the natural condition can be taken into account and the monitoring can be done using wireless sensor network.

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