Smart Sensor and Internet of Things Enabled Condition Monitoring for Electrical Substations

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Submitted by

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DECLARATION

I hereby declare that the work which has been presented in the dissertation entitled **"Smart Sensor and Internet of Things Enabled Condition Monitoring for Electrical Substations"** in partial fulfilment of requirements for the award of degree of Master of Engineering in Electronic Instrumentation and Control Engineering submitted in the Department of Electrical and Instrumentation Engineering at Thapar University, Patiala is an authentic record of my own work carried out under the supervision of **Dr. Gyan Ranjan Biswal** and **Dr. Ravinder Agarwal (Administrative Supervisor)** . It refers others research work which is appropriately recorded in reference section. The matter contained in this dissertation has not been submitted, neither partially nor in full to some other degree to whatever other college and organization aside from as detail in content and references.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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"Everything can be taken from a man but one thing: the last of the human freedoms—to choose one's attitude in any given set of circumstances, to choose one's own way."
— Viktor E. Frankl

Dedicated to

My mother, Dr. Kanta Sharma and

My sister, Prerna

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NOMENCLATURE

Main symbols and notations used in this study are listed below. Sometimes a symbol may have alternate meaning but in such a case; the context is sufficient to avoid confusion.

R=Radius of curvature of deflected micro-cantilever,

E=Young's Modulus of the beam,

δs = Differential surface stress on the micro-cantilever,

h= thickness of micro cantilever,

ν=Poisson's ratio of the micro-cantilever

$w(x,t)$ = the transversal deflection,

x =distance along the length,

t =time,

$\hat{E} = E/(1-\nu^2)$ =apparent Young's modulus of the cantilever beam,

ρ =volumetric mass density of the beam,

A=Area of cross section of the beam,

χ =added mass on the cantilever surface

$N = (S_1 + S_2)1$ =axial force generated by surface stress on microcantilever where S_1 and S_2 are the surface stress on the two sides of the microcantilever, and l is the microcantilever length.

f = resonant frequency of the cantilever beam,

k=effective spring constant for the cantilever beam

m_b =effective mass of the beam =n*m where n=0.24 for rectangular beam to account for the non-point mass distribution, m=actual mass of the beam

I =moment of inertia of the beam,

s_1, s_2 = surface stress on opposite sides of the cantilever.

s =surface stress,

ω =resonant frequency of the cantilever,

ω_0 = undamped resonant frequency of the cantilever

Q =Q factor of the cantilever.

Δm =additional mass on the cantilever

k = force constant= $\hat{E}(h/l)^3 b/4$ f_o =fundamental resonant frequency of the cantilever

f_m=resonant frequency of the cantilever due to added mass

$c(t)$ = the modulating signal

Vo= output voltage of the bridge circuit

Vex=Bridge Voltage=5V,

GF=Gauge Factor of Strain Gauge which is a constant,

ϵ=Strain on strain gauge

ABSTRACT

The objective of this thesis report is to present some of the possible uses of Sensors and Internet of Things in the Smart Grid environment while keeping a focus on Electrical Substations. A Micro-Electro-Mechanical Syatems (MEMS) sensor based moisture measurement system for SF_6 gas in Gas Insulated Switchgears has been designed along with COMSOL simulations. A possible scheme to connect the sensor to the internet has also been discussed. The MEMS sensor proposed is a rectangular microcantilever which can be used detect the added mass i.e. moisture deposited on it by measuring a change in its resonance frequency. A new scheme to detect the resonant frequency change by measuring a change in Q-factor has been proposed. Elementary experimental work has been performed using a polyimide strip cantilever to test the moisture detection principle.

Further, an Internet of Things (IoT) based system for sensing in Substation Automation has been proposed. The proposed system is a wirelessly connected system which will enable the sensors to send their data continuously to the internet, store it in a database as well as enable the users of the system to selectively receive data from the sensors they subscribe to. MQTT protocol has been proposed as the communication protocol for the system. It is an open source protocol that is lightweight and easy to implement. Open source hardware such as Arduino and Raspberry Pi have been proposed in the system for a cost effective solution. The possible alternatives for communication networking and security have been proposed.

Chapter 1

INTRODUCTION

1.1 A Brief Introduction to the Smart Grid

Electricity is one of the most important forms of energy in today's world that is slowly moving towards a future that might only consist of electricity consuming devices. It is becoming an issue of increasing concern how we manage the impending shortage of Electrical Power all over the world. Alternative sources of energy for electricity might not be sufficed to replace the conventional sources of energy. That is where minimizing of losses in the Electrical Grid Infrastructure comes into picture to balance the demand and supply equation of electrical power. The present Grid infrastructure already has devices working on the higher side of efficiency to minimize losses and make maximum energy available for utilization. So what must be done to further improve the system while not increasing the load on the existing ones is the question to be asked? The question already has an answer to it and it is "Smart Grid". A "Smart" entity has the ability to analyze, communicate and decide by using the resources made available to it and so will the Smart Grid.

The Smart Grid technology is expected to change the face of the Electrical grid by the integration of new solutions to manage the Power system infrastructure reliably and intelligently. It aims at improving the power reliability, quality and efficiency of the existing grid. It is achieved by automating the maintenance and operation and the deployment of Renewable and distributed energy sources. The overall objective of the smart grid is the smart and optimal utilization of all the available resources [1] – [3].

The smart grid can be defined as an electrical network which has the ability to intelligently integrate the actions of all its users to deliver sustainable, economic and secure supply of electrical energy. The users can either be the consumer of electricity, generator or both. The need of establishing a Smart Grid arises from various issue in the traditional grid infrastructure such as increasing blackouts, ageing infrastructure, the necessity of lower carbon emission and the need for efficient integration and deployment of increasing renewable energy sources and new loads such as electrical vehicles.

A smart grid enables a bidirectional flow of information as well as electricity unlike the traditional grid which facilitates only a unidirectional flow of electricity. Thus, the smart grid combines a Power infrastructure as well as a communication infrastructure. The Smart Grid essentially consists of the following major components:

- Distributed Generation
- Information Transfer
- Phasor Measurement
- Smart Metering Infrastructure

Each of these components help the grid to achieve the intended Smart capabilities as mentioned above. A Smart Grid must have some basic capabilities which include but are not limited to:

- It should have self-healing ability, that is, it should diagnose, analyse and recover from any unexpected Power disturbances occurring in the grid.
- It should be immune to both Physical and Cyber attacks and have a robust security feature.
- It is intended to have active participation by the consumers in the demand response side.
- It should be able to accommodate all generation and storage options. For instance, it should support renewable sources of energy along with distributed generation and storage of the energy generated from these resources.
- It should enable new electricity market and optimize the asset utilization to provide quality power and optimized operational efficiency

These are some major feature that a Smart Grid is expected to have; it should be able to accommodate any newer technologies that enhance its capabilities [2]. When it comes to Smart Grid Architecture, it can be divided into following parts:

- Conceptual Model
- Electrical Network
- Communication network

The Conceptual Model of the Smart Grid again composed of seven big domains as proposed by NIST (National Institute of Standards and Technology, USA):

- Bulk Generation
- Transmission

- Distribution
- Customers
- Operations Markets
- Service Providers

Thus, the Electrical Network essentially consist of all the physical elements of the grid which enable supply of power from generator to the end consumer. The Communication network is responsible for the transfer of information and data from one part of the grid to another. A variety of communication technologies are being used presently including wired, wireless and hybrid networks [3]. Broadly, four types of networks can be defined based on where they are used in the Smart grid environment as follows:

- Home Area Network (HAN)
- Neighbourhood Area Network (NAN)
- Field Area Network(FAN)
- Wide Area Network (WAN)

1.2 Role of IoT in Smart Grid

Internet of Things has emerged as a disrupting technology in the past few years and has been responsible for a major change in the way things interact, communicate and work. Internet of Things can take up a variety of roles in the present Smart grid scenario and help us to develop a comprehensive strategy to make the implementation of Smart grids easier and faster [37], [38]. Few of the scenarios where IoT can be implemented are as follows:

- Deploying multi-level implementation-The multi layered architecture of Smart grid requires an addressing mechanism that works at all layers such object layer, communication layer and application layer. IPv6 enables this deployment on multiple scales in homes, buildings, smart cities.
- Home Energy Management- IoT devices can be used to collect the energy requirements of the users through smart meters and also help a consumer save on electricity bills by managing their consumption by energy scheduling and management of renewable energy produced in homes. Smart storage devices can add power back to the grid allowing a two way flow of electricity and converting the consumer to prosumer. Producer + Consumer = Prosumer

- Integration of renewable energy sources - Real time prediction of weather data can help in understanding and estimating the energy production through renewable sources in near future.
- Electrical Vehicle Tracking – Electrical Vehicles can be sued as energy storage device when they are idle. IoT enabled devices can be used to collect information regarding the identity, battery state, location etc. of the electric vehicle to improve the efficiency of charging and discharging and scheduling.
- Improve the self-healing feature of the smart grid- Sensors and IoT can be used to detect unpredictable conditions and breakdowns and respond to them rapidly.
- Continuous Online Monitoring- IoT can provide the continuous monitoring of various parts of the smart grid such as powermplant, power lines, energy consumption and electrical equipments deployed at substations.

1.3 MEMS Microcantilevers

MEMS (Micro-Electro-Mechanical Systems) devices have gain popularity in the recent years due to their miniature size, greater accuracy and sensitivity. Microcantilver sensors are one of the MEMS sensors that are of particular interest due to their simplistic nature in addition to other advantages. The present work focusses on rectangular microcantilevers in particular. The basic working principle of microcantilevers is to transduce the mechanical deflection produced by an external force into detectable signals. Microcantilevers are preferred due to some distinctive advantages such as:

- They provide greater precision and reliability with the added advantage of decrease in overall dimensions.
- It can be produced easily in large scale and hence is commercially profitable.
- It can be interfaced with the auxiliary circuits easily along with suitable readouts which make it a more attractive option.
- The heating and cooling takes place rapidly for these sensors, usually in microseconds and hence it makes the reversal of molecular adsorption on the surface easier and faster resulting in rapid detection techniques.

The small size of the micocantilevers is largely responsible for the extreme sensitivity of the microcantilevers combined with the extensive research carried out in the recent years.

Usually microcantilevers have thickness of few micrometers, width in the range of tens of micrometers and length in hundreds of micrometers [32], [33]. Current, researches is focusing on even smaller cantilevers in the size of nanometers and are expected to have even higher accuracy. Hence micro-cantilever are an interesting option for sensors for making real time, in-situ measurements at considerably reduced costs.

1.4 Sensors and IoT in Substations

In our further discussion, two such possibilities of application of Sensors and IoT in Substations have been analyzed in detail and form the part of this Thesis work. While one of the application attempts at an overall design for monitoring in substation automation system, the other aims at more specific application relating to Gas Insulated Switchgear.

1.4.1 The Need to Redefine Substation Automation

Substation plays an integral role in the electrical generation, transmission and distribution system. Substation technology is continuously evolving to accommodate with the challenges presented by the more digitized and decentralized power distribution systems. The evolution of Distributed Energy Systems is also a reason why the substations need to adopt new technology. The deregulation of the power industry has led to an increased emphasis on Substation Automation for the emerging Smart Grid Environment [4], [5].

The use of intelligent devices, powerful substation computers, equipment knowledge modules and local storage could prove to be essential for the implementation of smart substations. The new assets must meet the technical requirements of the substation as well as be safe, secure, easy to use, configure and easily updatable for any future changes. The substation equipment should reduce the unscheduled downtime and increase the reliability of the system. For example, shifting from time based monitoring to condition based monitoring will allow optimizing the investment and maintenance costs. All the communication devices for substation automation should allow easy, sustainable and vendor agnostic exchange of the engineering data and built according to IEC61850 [6], [7].

Condition monitoring of the various equipment in a substation gives an overall picture of the state of the various components in the substation. The manual monitoring of the substation equipment is prone to human error and may reduce the system response speed which is critical in building an efficient monitoring system. These limitations can be overcome by condition based maintenance of the substation using online measuring instruments. The measured information can be transmitted and stored to a central location for easy remote monitoring and analysis [8], [9].

In the present Substations, Supervisory Control and Data Acquisition (SCADA) and Distributed Control Systems (DCS) are the most widely used standards for Substation Automation and control. With the recent advances in the Internet of Things (IoT), all the sectors have seen a big shift towards smart connected things. Connectivity and information exchange have become a common feature in the everyday objects. In this regard, the substation also needs to make a move to Internet of Things. IoT has proven to be complimentary with SCADA as the information gathered by SCADA systems can act as one of the data sources for the IoT. While SCADA focuses on monitoring and control, IoT focuses on monitoring, acquiring and analyzing the machine data to improve productivity.

The SCADA systems work perfectly for day to day monitoring of what is going on in the substation whereas the IoT solutions have the ability to address macro level questions such as the operational effectiveness across various sub systems, the process changes to improve performance, prediction of failures and planned and actual comparisons. These questions are of high relevance to the managers, planners and supervisors in the Substation environment. Hence, implementation of IoT alongside the present systems is expected to enhance the robustness, efficiency and convenience in the substation [10].

1.4.2 Moisture Measurement in Gas Insulated Switchgears

The recent and fast advances in the implementation of Smart grid technology necessitate the development of smarter components for efficient and continuous monitoring of parameters in the Smart grid environment. The monitoring system for moisture detection in SF_6 gas is a useful component for enhancing the system safety and reliability of Gas Insulated Switchgear (GIS).

Switchgear is an integral part of any Power System for optimum and faultless operation. Particularly, GIS are preferred since a long time due to their less ground to phase clearance and thus, lesser space requirements as compared to other switchgear assemblies. SF6 gas is the most widely used gas in the present GIS because of its high dielectric constant, higher arc quenching capability and better heat dissipation as compared to air. Despite its greater usefulness in enhancing the capabilities of a sub-station, the leakage of SF_6 in the atmosphere can prove detrimental to the environment by contributing to the Green House Effect. Thus, it necessitates continuous monitoring of SF_6- GIS to prevent its leakage and deterioration. To keep it in check, regulating standards have been implemented which make it mandatory that no more than 0.1% and 0.5% of SF_6 must leak per year for medium voltage (MV) and high voltage (HV) switchgear respectively.

However, the presence of trace level humidity in SF_6 in GIS also influences the equipment safety. An enormous amount of energy is released during each switching operation. It breaks the SF_6 into its constituents. S (Sulphur) and F (Fluoride) can [1] result in the formation of HF and SO_2 in presence of moisture and oxygen. Although S and F recombine after sometime to form SF_6 again, both of them are highly toxic and corrosive and prove to be detrimental for the safety of the equipment. They may also cause internal corrosion inside the GIS. As the time-in-service for the GIS increases, the resistance to humidity penetration of the GIS decreases. This makes it even more important to monitor the moisture content in SF_6 gas continuously [16] – [18]. Depending on the measurements the reusability and recyclability of the gas can be assessed properly.

An efficient moisture detection system for SF_6 with high sensitivity is therefore instrumental to enhance the robustness of the GIS. One of the major benefits of the SF_6 based GIS is its compactness as compared to other GIS. Thus, it is expected that the sensing systems employed with the GIS retain the compactness of the whole system. The traditional systems for resonant frequency detection use optical methods along with the Phase Locked Loop (PLL). These systems are large in size, high in costs and difficult to install despite being accurate [16]. Therefore, these methods are not preferred to measure the moisture concentration inside GIS environment. Micro-cantilevers are seen as a popular solution as they are simple to design, cost effective, high throughput, and very sensitive for detection of different species in the ambient environment. In the recent decades, micro-cantilever have been used to detect a number of signal types such as mass, temperature, stress by mechanical bending or by the change in resonant frequency[18] – [21], [26]. For different type of species different functionalized coatings are used to make the sensor more sensitive and selective [21] – [25]. There are many works reported on the use of micro-cantilever in the static mode which include capacitive method using a Polyimide substrate and an Al_2O_3 based thin film SAW sensor [23] – [25].

Thus, it can be safely concluded that Sensors and IoT have a major role to play in the Substation Automation domain in the Smart Grid environment. Also, it can be observed that embedding IoT in the present grid system will only make the grid more robust and efficient. Smart grid implementation is catching speed as we speak, opening up ample problems areas for research as well as application in the near future.

Chapter 2

MEMS SENSOR BASED SYSTEM FOR MOISTURE MEASUREMENT IN SF_6 GAS

2.1 Introduction

MEMS Microcantilevers have been used extensively since the past few years in applications such as chemical vapour detection, moisture detection, gas sensing, biological detection etc. Much credibility has been rightly attributed to these sensors majorly because of their simplicity, ease of use and accuracy. Here, in this work an attempt is made to take an advantage of the same fact to propose a design for the measurement of moisture in SF_6 gas in GIS. This chapter shall discuss the complete work done in this regard in detail including mathematical modelling, simulation of the sensor in COMSOL, MATLAB modelling, the elementary experimental work performed as well as the results obtained.

2.2 Theory of Operation and Mathematical Modelling of the MEMS Microcantilever

The sensing in Microcantilevers is done by using the deflection produced in them. Two modes of deflection of a microcantilever are static mode and dynamic. When we say that the microcantilevers is operating in static mode we imply that we are considering the displacement of the cantilever form its mean position and depending on that we calculate the output of the sensor and co-relate it to other physical and electrical parameters. The static mode deflection occurs when there is a differential stress present on the opposite sides of the cantilever, mostly due to the adsorption of species on one or both of the sides of the cantilever. In the case of dynamic mode, we consider the microcantilever to be a continuously vibrating structure and the r frequency of vibration is used for detection of the required quantity. The frequency of the beam is expected to change on the adsorption of any material on the surface of the microcantilevers. The frequency of vibration also changes with the change in viscosity of the medium in which it is vibrating.

In general, the static mode is the most widely used for sensing purposing as the measurement process and interfacing is easier unlike dynamic mode which generally requires an elaborate setup for the measurement of frequency of vibration alone. Although, the static mode is has the disadvantage of being slower and less accurate in measurements when compared to dynamic mode. This work attempts to propose a microcantilever design with a possible method to measure the resonant frequency of the microcantilevers in dynamic mode without the use of any large equipment, thus opening up the possibility for making in-situ dynamic mode measurements for a cantilever. It must also be noted that microcantilevers area available in various shapes such as triangular, V-shape etc. but the rectangular microcantilever continues to remain a preferred choice for many sensing applications due to it simple modelling and easy interfacing. We also use rectangular microcantilevers as the basis of design of the proposed sensor. As discussed earlier, the measurement of moisture in SF6 is critical to the GIS present in the substation to assess its quality for efficient operation of the switchgear as well to prevent environmental hazards due to mishandling of SF6. Thus, it would be much more efficient and convenient if a method can be devised for in-situ measurements of moisture as opposed to the current methods that involving pumping out and re-pumping of SF6 gas in the GIS posing a risk of leakage.

In the following part, the mathematical modelling of both the static and dynamic mode are discussed. The effect of surface stress on the microcantilevers is also discussed for both the modes. We also discuss how Q-factor and resonant frequency of the microcantilevers is related as well as the effects of temperature and pressure.

2.2.1 Modes of Operation of Cantilever

2.2.1.1 Static Mode

In general, when any material is adsorbed on to a microcantilever on its one surface, then a differential surface stress is induced on the side generating a bending moment along its length. The deflection of the free end depends on whether the beam is end-loaded or uniformly loaded. The radius of curvature R of the deflected micro-cantilever can be given by Stoney formula as follows [4]:

$$1/\mathrm{R} = 6(1-\nu)/\mathrm{Eh}^2 * \delta s \quad (1)$$

Where; R=Radius of curvature of deflected micro-cantilever, E=Young’s Modulus of the beam, δs = Differential surface stress on the micro-cantilever, h= thickness of micro cantilever, ν=Poisson’s ratio of the micro-cantilever.

2.2.1.2 Dynamic Mode

As mentioned above, dynamic mode offers the advantage of faster and accurate detection of parameters as compared to the static mode. It utilizes the change in vibration frequency to detect the change in mass adsorbed on the cantilever. In the dynamic mode, there are basically two models which are used for the modelling of the micro-cantilever beam viz. the Taut string model and the Euler-Bernoulli Beam model. The Taut string model is a 1-D approximation while the Euler Bernoulli Beam model assumes it as a 3-D object.

Taut string model of cantilever

This model assumes the beam to be a 1-D object i.e. the width and thickness of the beam is considered negligible and hence its approximation as a string. The governing differential equation for this model is [12], [13]:

$$N\frac{\partial^2 w(x,t)}{\partial x^2} + \rho A \frac{\partial^2 w(x,t)}{\partial t^2} = 0 \tag{2}$$

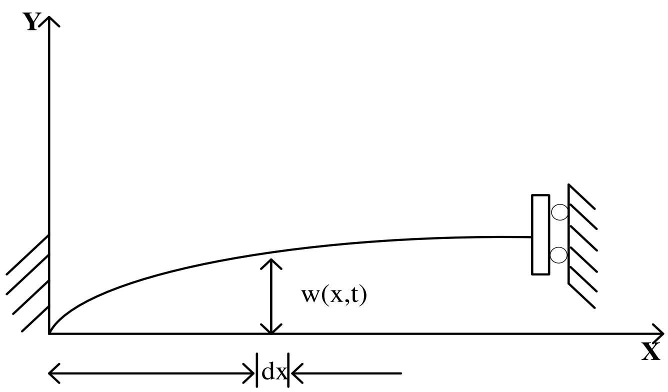


Fig. 1: Taut String Model of the microcantilever

Where; $w(x,t)$ is the transversal deflection, x =distance along the length, t =time, $\hat{E} = E/(1-\nu^2)$ =apparent Young's modulus of the cantilever beam, ρ =volumetric mass density of the beam, A=Area of cross section of the beam, χ =added mass on the cantilever surface and $N = (S_1 + S_2)1$ =axial force generated by surface stress on microcantilever where S_1 and S_2 are the surface stress on the two sides of the microcantilever, and l is the microcantilever length. It is modeled as a 1-D oscillator and its natural frequency is given by:

$$f = \frac{1}{2\pi}\sqrt{k/m_b} \tag{3}$$

Where; f = resonant frequency of the cantilever beam, k=effective spring constant for the cantilever beam and m_b =effective mass of the beam =n*m where n=0.24 for rectangular beam to account for the non-point mass distribution, m=actual mass of the beam.

Euler Bernoulli Beam Model

According to this model the microcantilever is considered to be a flat thin cantilever beam made of homogenous material. The differential equation governing the vibration of the beam (neglecting the effect of surface stress) is given by [12, 13]:

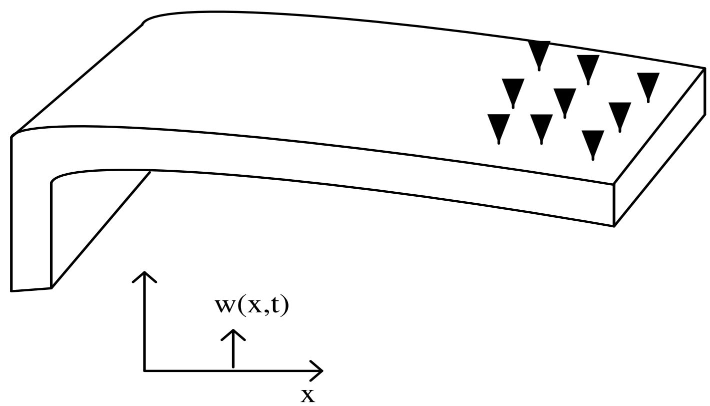


Fig.2: Microcantilever modeled as a prismatic beam

$$\hat{E}I\frac{\partial^4 w(x,t)}{\partial x^4}+(\rho A+\chi)\frac{\partial^2 w(x,t)}{\partial t^2}+C\frac{\partial w(x,t)}{\partial t}=q(x,t) \tag{4}$$

Where; $w(x,t)$ is the transversal deflection, x is the distance along the length, t =time, $\hat{E}$ = $E/(1-v^2)$ =apparent Young's modulus of the cantilever beam, ρ =volumetric mass density of the beam, A=Area of cross section of the beam and χ =added mass on the cantilever surface. The fundamental resonant frequency of the beam for added mass is given by [20]:

$$f=(\lambda_0/l)^2\sqrt{\hat{E}I/(\rho A+\chi)} \tag{5}$$

Where**;** f **=** resonant frequency of the cantilever beam, $\hat{E}=(S_1+S_2)L$ =apparent Young's modulus of the cantilever beam, I =moment of inertia of the beam, ρ =mass volume density of the beam, A=Area of cross section of the beam and χ =added mass on the cantilever surface.

- The amplitude of vibration is much smaller than the thickness of the cantilever. Hence, no non-linear term appears in the differential equation governing the motion of the microcantilevers.
- The length of microcantilevers is much greater than the width and thickness of the cantilever. This makes the equation for vibration of microcantilevers a one dimensional equation.

2.2.2 Surface Stress and Its Effects

When microcantilevers is considered as a platform for detection of chemical and biological species, surface stress is a microscale effect which affects the sensing ability of the sensor. Thus it becomes necessary to take it into consideration while calculating resonant frequency, amplitude, deflection and Q-factor. However, the effect on resonance frequency is given prime importance while optimizing and improving the cantilever structure. According to Thundat et.al. [32], the change in spring constant of the cantilever oscillator due to surface stress can be given by:

$$K_s = \frac{\pi^2 n}{4}(s_1 + s_2) \quad (6)$$

Where: K_s =spring constant attributed to surface stress ; n =factor to account for non-point distribution of mass on the cantilever ; s_1 , s_2 = surface stress on opposite sides of the cantilever.

In general, four cases can arise due to adsorption of molecules on the micro-cantilever according to [30]:

- There is negligible or no change in resonance frequency due to change in spring constant due to adsorption, that is, the change in resonant frequency is only due to the addition of added mass on the micro cantilever.
- A change in resonant frequency due to mass loading is negligible, but the differential surface stress can be high and an observable change is present in the static deflection of the cantilever.
- The contribution of mass loading in change in resonant frequency is negligible while the change due to surface stress has maximum contribution.
- Change in resonant frequency is a combined effect of both mass loading and surface stress.

For each of the models mentioned above in the dynamic mode, the resonant frequencies calculated can include the effect of added mass as well as the changes due to surface stress effects. It is necessary to analyze which of the above cased mentioned above apply to the micro-cantilever in question. The mathematical models mentioned above, while modelling the effects due to surface stress, assume that the axial force due to it is constant and acts at the end of the cantilever only. Furthermore, to model surface stress in the Taut string model, it is additionally assumed that the surface stress is sufficiently great and the bending rigidity is negligible. Using these both assumptions the, general surface stress on the microcantilevers cannot be accurately modelled. More importantly, if we only want to know the change in resonant frequency due to the added mass only then we must be able to decouple the effect on resonant frequency due to surface stress for more accurate calculations. This problem is solved by a third model proposed by [29] by the use of dimensional analysis. Since the effect of surface stress cannot be revealed directly by the existing models, by making the governing equations dimensionless, some dimensionless numbers are obtained. Evident Physical significance is attributed to these dimensionless numbers with regard to surface stress. These numbers are incorporated by modifying the above mentioned equations of the beam, and the effect of surface stress is analyzed. Two dimensionless numbers Π_1 and Π_2 are calculated, out of which Π_1 is of prime significance and is given by:

$$\Pi_1 = sl^3 / EI \tag{7}$$

Where; s =surface stress, l , E , I are length, Young's modulus and Moment of Inertia of the cantilever respectively. The value of Π_1 is used to assess the effect of surface stress on the resonant frequency. If Π_1 >> 1 then the effect of surface stress is significant while if Π_1 <<1 then surface stress effects on resonant is safely neglected. Accordingly, the equations for the beam model are modified and resonant frequency is calculated [29].

2.2.3 Resonant Frequency and Q-factor

Resonant frequency easily co relates with the added mass on the cantilever surface. However, it is a very cumbersome process to measure resonant frequency directly. Although, the Q factor of the resonating beam is correlated with the resonant frequency of the beam as follows [34]:

$$\omega = \omega_0 . [1 + 1/4Q^2]^{-1/2} \tag{8}$$

Where; ω =resonant frequency of the cantilever, ω_0 = undamped resonant frequency of the cantilever and Q =Q factor of the cantilever.

From (7), the shifted resonant frequency is calculated by measuring the Q factor of the beam. The Q factor is indirectly used to measure the added mass on the cantilever by using the following relation between surface mass distribution and resonant frequency of the cantilever [34]:

$$\Delta m = -k / 4\pi^2 n(1/ f_0^{\ 2} - 1/ f_m^{\ 2}) \tag{9}$$

Using equations (2) and (8), the added mass is directly co related with the Q-factor as follows:

$$\Delta m = -\frac{k}{4\pi^2 n f_0^2 Q^2} \tag{10}$$

Where; Δm =additional mass on the cantilever, k = force constant= $\hat{E}(h/l)^3 b/4$, n =0.24, is the geometrical parameter for rectangular beam to account for non-point like mass distribution, f_o =fundamental resonant frequency of the cantilever, and f_m =resonant frequency of the cantilever due to added mass. This eliminates the need of the large and costly setups for detection of resonant frequency and added mass.

2.2.4 Amplitude Locked Loop

The continuous measurement of Q factor is done by an Amplitude Locked Loop (ALL) system as proposed in [35]. Amplitude Locked Loop is a circuit an $x_I(t)$ to Phase Locked Loop (PLL). It is the mathematical dual of PLL. In ALL, there is a voltage controlled amplifier instead of a Voltage Controlled Oscillator (VCO); in place of phase detector there is an amplitude detector and the set point frequency is replaced by set point amplitude. It is a closed loop system with multipliers within the loop similar to PLL. Two types of outputs can be obtained from an ALL: an in-phase output proportional to the set point amplitude and another proportional to the inverse modulus of the input [35]. Moir [34] presented the analysis of the ALL. A short description of the ALL control circuit is presented here.

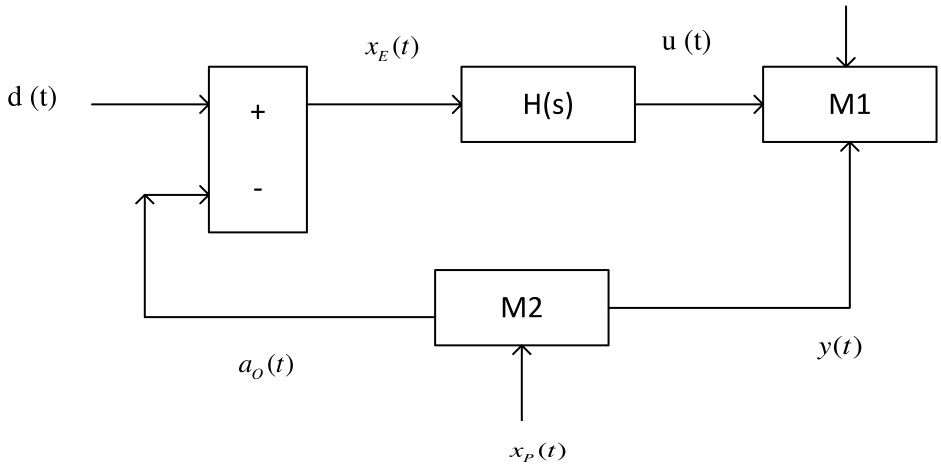


Fig.3: Control diagram of the Amplitude Locked Loop

In the Fig. 3 , the output of the multiplier M1 is, $y(t) = u(t)x_I(t)$. If we take an input, $x_I(t) = c(t)\cos(\omega_0 t + \phi_i)$.

Where; $c(t)$ is the modulating signal and $\cos(\omega_0 t + \phi_i)$ is the carrier. For now, $c(t)$ and ϕ_i are considered constants, but they can be time varying. It is assumed that $c(t)$ is non-zero. The signal $x_P(t)$ is given by:

$$x_P(t) = B_p \cos(\omega_0 t + \phi_P) \tag{11}$$

It is the output of a PLL tuned to frequency ω_0 . The output of multiplier M2 is:

$$a_O(t) = x_P(t)y(t) \tag{12}$$

When the ALL is in 'lock', the error signal can be given by:

$$X_E(s) = D(s) - A_O(s) = D(s) - X_P(s) * Y(s) \tag{13}$$

Where * denotes convolution. Neglecting the $2\omega_0$ terms and taking $H(s) = \frac{G}{s}$ and $B_p = 1$, it can be seen that: [format all math equations on bring it to same size]

$$U(s) = \frac{G}{s + c\frac{G}{2}\cos(\phi_n - \phi_i)} D(s) \tag{14}$$

With step input of magnitude D for $d(t)$ and with $x_E(t)$ tending to zero in steady state, the response is

$$u(t) = \frac{2D}{c\cos(\phi_n - \phi_i)} \tag{15}$$

If $\phi_n = \phi_i$, then

$$u(t) = \frac{2D}{c} \tag{16}$$

i.e. $u(t)$ becomes the scaled inverse of the amplitude c, of the input $x_I(t)$ and also:

$$y(t) = 2D\cos(\omega_0 t + \phi_i) \tag{17}$$

Which; is the scaled version of the carrier. Also, it does not involve the modulating signal, leaving only the carrier. $u(t)$ becomes the scaled inverse of the modulus of the input. This means that ALL can track the inverse of the modulus of the input. If we consider the microcantilever here then the Q-factor can be related to loss angle and resonant frequency as follows:

$$Q = \theta^{-1} = \frac{\omega_0 \tau}{2} \tag{18}$$

Where; τ is a constant and θ is the loss angle for the mechanical restoring force. Using the theory of ALL, it can be shown that the Q-factor is proportional to the inverse of the amplitude of the resonant frequency. Hence, it provides a way to relate the Q-factor and resonant frequency.

By using an Amplitude Locked Loop, it is possible to measure the Q-factor of the resonating beam. The Q-factor is related to the added mass and resonant frequency. The advantage of this method is that it does not require the SF_6 gas to be taken out of the GIS and recycled. It provides an in situ measurement technique as well as a continuous condition monitoring system.

2.2.5 Temperature and Pressure dependence of resonance frequency and Q-factor

Q-factor is independent of temperature [28]. However, the resonant frequency may vary with temperature. The shift in resonance frequency for a single material cantilever is directly proportional to the change in temperature. For a single material cantilever, the thermal sensitivity is calculated to be 1.23 Hz/K in Mertensa et. al. [27], which is a small value and can be easily accounted for and calibrated. The pressure of the SF_6 gas inside he GIS is maintained at a constant level, so no major shift in frequency or Q-factor is expected due to pressure variation inside the GIS. The sensor is proposed to be placed inside the SF_6 gas which is sealed inside the GIS and there is very little to no pressure variation. Simulations due to other polar molecules are not studied. In GIS, presence of other polar molecules is negligible so the study can be deliberately avoided.

2.3 Simulation of the Proposed Microcantilever Sensor

The modelling of the MEMS sensor is done in COMSOL Multiphysics platform and verification of mathematical model is done using MATLAB. The above models are implemented in MATLAB for different values of added mass on the microcantilevers. The resonant frequency is calculated in each case. Also, the dimensionless numbers for surface stress are calculated and analyzed. Micro-cantilever of length, l=200**μ**m, width, w=2**μ**m, and thickness, t=3**μ**m is modeled.

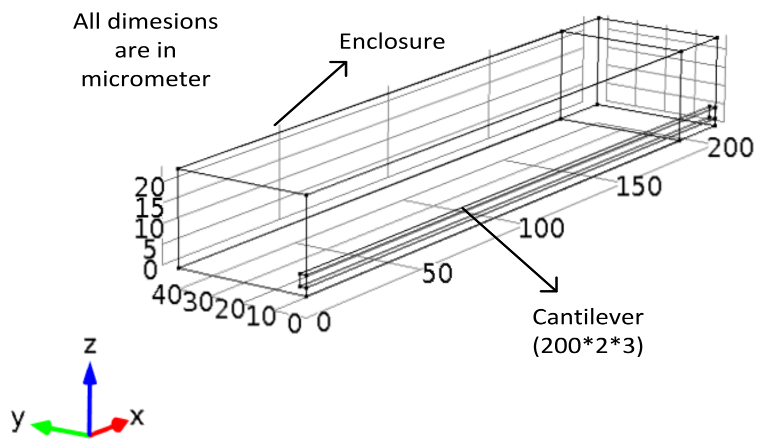
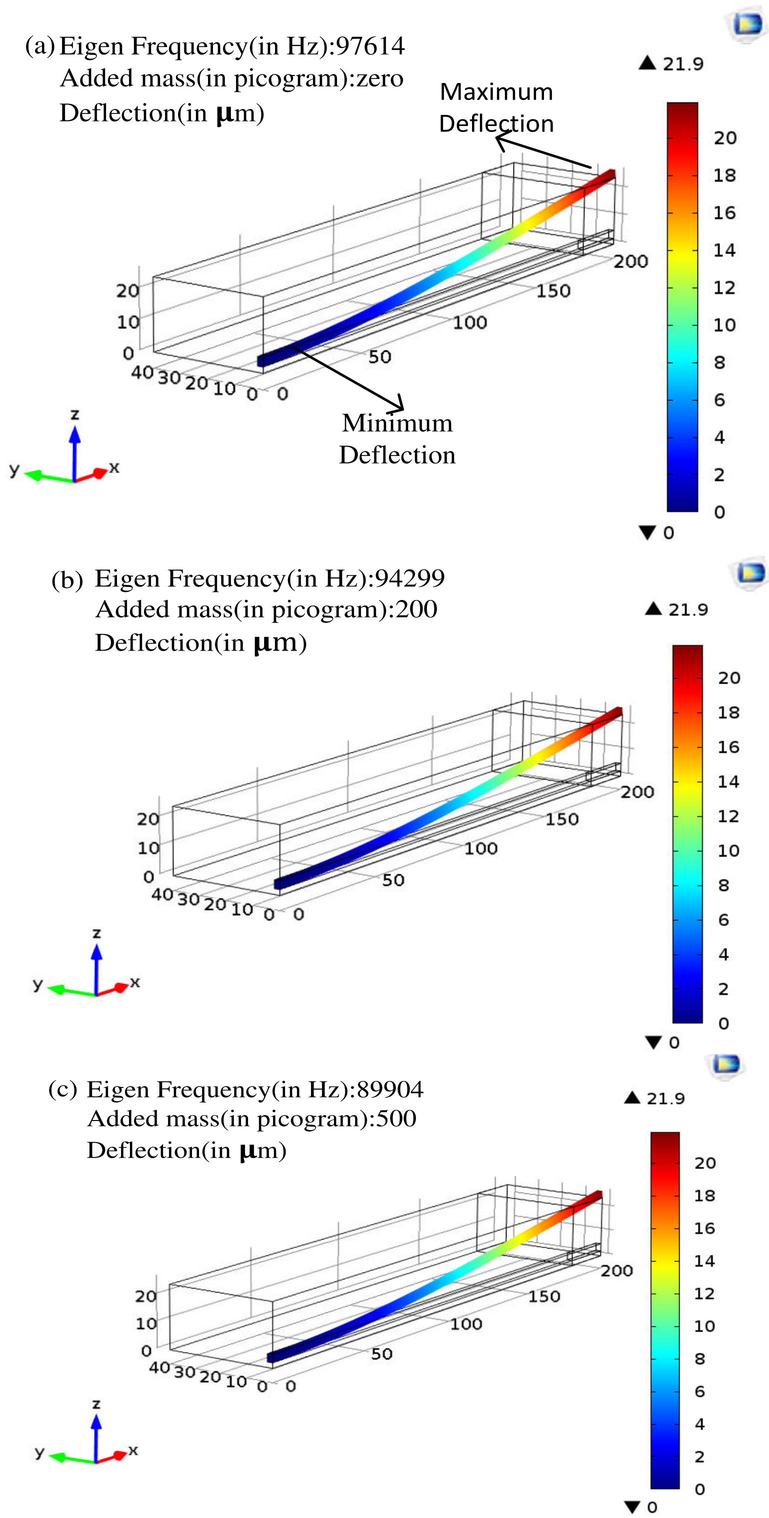


Fig. 4: COMSOL geometry for the Micro-cantilever

Fig.4 shows the COMSOL geometry of the proposed microcantilevers used for simulation. The modeling of the system was done for both Taut String model and Euler Bernoulli model and then a comparison is done with the COMSOL simulations. In COMSOL, the micro-cantilever is modeled as an electrostatically actuated cantilever made of Silicon substrate. An added mass over the cantilever was deposited to simulate the added moisture on the surface of the cantilever. When a DC voltage bias is applied to the microcantilever along with an AC voltage, the microcantilevers resonates in different modes with different resonant frequency for each mode. Vibrational modes are a property of a particular piece of material, with a particular size and a particular shape, and held in a particular way. The mode is the shape of the vibration. In principle every object has a near infinity of different modes, of successively higher frequency, although in practice the higher ones die away too quickly to be detectable. Each mode has its own resonant frequency. The fundamental mode of vibration is considered here for resonant frequency measurement in dynamic mode.



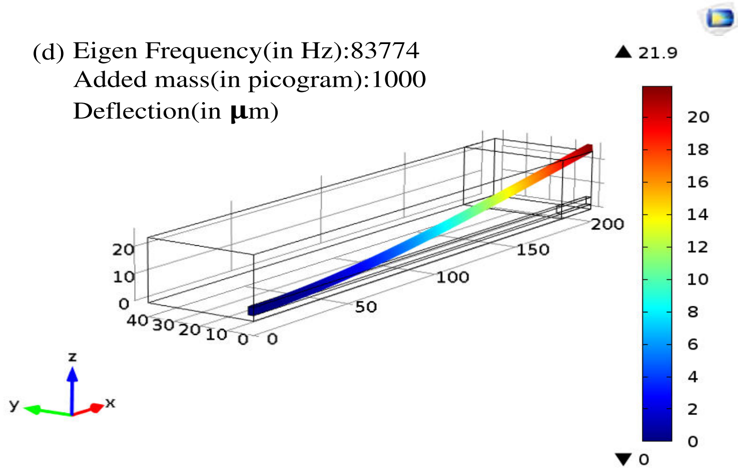


Fig.5: COMSOL results for different added masses of (a) Zero, (b) 200 picogram, (c) 500 picogram, and (d) 1000picogram

Fig. 5 shows the results of the COMSOL simulations done for various added masses. The results are discussed in detail in later sections.

2.4 Experimental Validation using Polyimide Microcantilever

For validation purposes, a Polyimide cantilever of (l*w*t*) = (200µm*2µm*0.1µm) is used. As established in previous sections, Q-factor of the microcantilever is required to detect resonant frequency change and the added mass on the cantilever. Thus, it is necessary to detect a change in Q-factor of the cantilever beam to detect moisture. The proposed microcantilever made of silicon substrate, has a very high Young's modulus (165-GPa) in comparison to the Polyimide cantilever (3-GPa). A lower Young's modulus implies that the polyimide cantilever is be more sensitive to any stress (caused by addition of moisture on the surface), and thus showing more deflection. A greater deflection allows for easier detection of output strain from the strain gauge attached to the cantilever. Thus, the use of polyimide cantilever makes the system more sensitive to moisture. Since, the polyimide cantilever is uncoated; the greater sensitivity makes the moisture detection convenient in absence of standard testing facilities.

It must be pointed out that the given setup is a self-engineered setup due to the lack of a proper test bench and laboratory setup. It is only able to detect moisture and not quantify it. Best efforts have been made to make the system least susceptible to any external disturbances other than the moisture introduced.

The experimental setup and the schematic are well demonstrated in Fig.6 and Fig.7. In the used setup, the strain gauge is fixed to the stationary end of the cantilever. A copper strip is attached to the bottom of the cantilever assembly such that there is a small gap between the cantilever and strip. The whole cantilever assembly is enclosed in an air tight box with an opening for moisture (A). The moisture is introduced through a pipe using a vaporizer (B). The vaporizer is a simple device used to deliver steam and is available easily. A pipe used for medical purposed is attached to its opening and to the box opening to allow moisture to move inside. Excitation was provided to the cantilever using a Function Generator available in the Instrumentation Lab (C). The output of the strain gauge is given to an Instrumentation amplifier connected to a Bridge circuit (D).

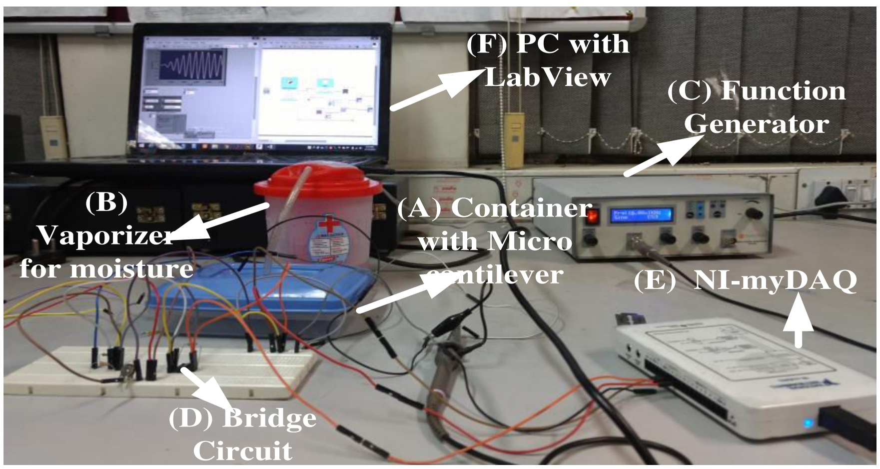


Fig. 6: Experimental Setup used for Moisture detection

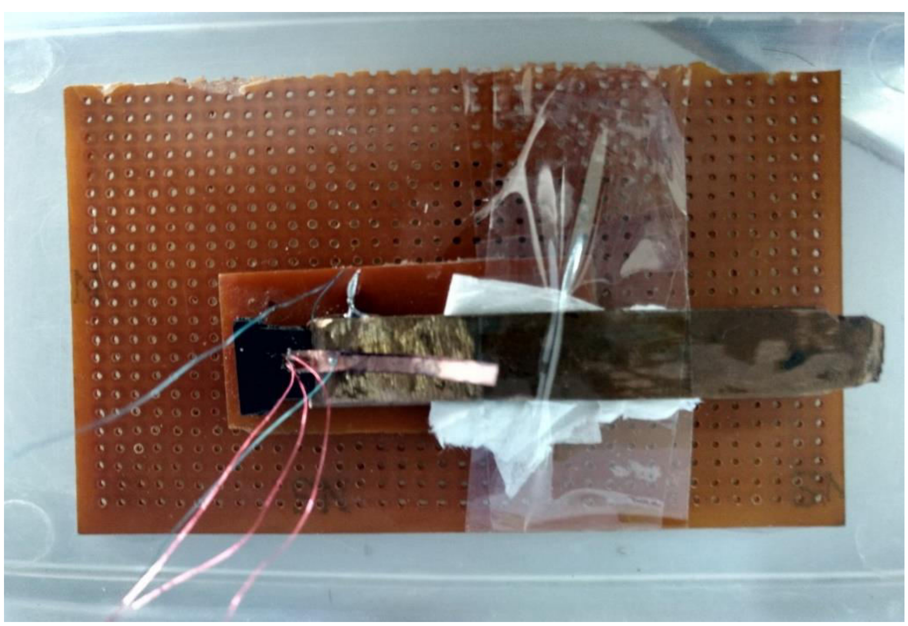


Fig.7: Microcantilever used in the experimental setup

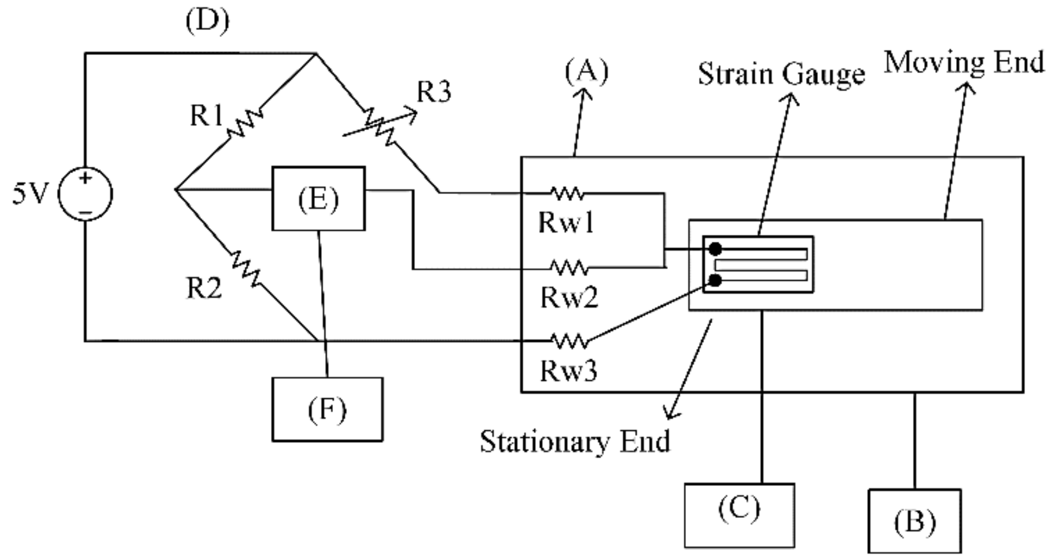


Fig.8: Block diagram representation of the experimental setup

The arms of the bridge circuit consist of two 120-Ω resistor, a 200-Ω potentiometer, and the micro strain gauge of 120-Ω resistance (specified by the manufacturer). AD620AN instrumentation amplifier is used for further amplification of the output of the bridge circuit. The 5-V supply to AD620AN is provided by the NI-MyDAQ connected with the USB port of the PC. The output of Instrumentation amplifier is viewed in a PC with LabVIEW (F) through NI-MyDAQ (E). NI-MyDAQ is a data acquisition board that allows connection to sensors to acquire and analyze signals in various supported platforms. Express VIs in LabVIEW are used for acquisition, display and filtering of the output from the circuit. The output voltage of the strain gauge is related to the strain gauge in the following way:

$$\frac{V_0}{V_{ex}} = -\frac{GF.\varepsilon}{4}\left(\frac{1}{1+\frac{GF.\varepsilon}{2}}\right) \tag{19}$$

Where; Vo= output voltage of the bridge circuit Vex=Bridge Voltage=5V,GF=Gauge Factor of Strain Gauge which is a constant, and ϵ=Strain on strain gauge.

As moisture is introduced into the box, the damping of the Microcantilever must decrease which implies less deflection and hence less strain. Lesser strain would result in lesser output voltage of the strain gauge. Since the microcantilever is continuously vibrating and deflection is not static, the output voltage also varies continuously. Data samples are acquired into a spreadsheet file using another express VI. Further processing on the data samples is done in MS-Excel. After acquiring the data the Raspberry Pi is setup to make the system IoT enabled. The data samples acquired in the spreadsheet files are used to dispay on the html web page created.

2.5 Monitoring the Data using Raspberry Pi

IoT can be defined as a network of multiple interconnected intelligent objects with the capacity to share information using sensors as well as auto organize and analyze data and resources using appropriate software tools. IoT enabled devices are also capable of reacting and acting to the changes in their environment. Thus, making a system IoT enabled enhances the operational efficiency of the overall system while decreasing the requirements of size and cost. The Raspberry Pi is a popular device to implement IoT because it offers a complete Linux server in a tiny platform for a very low cost. It has multitude of capabilities similar to a mini computer which make it the ideal platform for IoT.

A server is setup on the Raspberry Pi to enable it to receive and send data to a local html page created using PHP scripts as well as to a remote server setup at some distant location from the system. The GPIO (General Purpose Input Output) pins of the Raspberry Pi board are used to input sensor data into the board. The use of Cloud services is suggested for enhanced data storage and analysis capabilities. To remotely monitor the sensor data using Raspberry Pi, we require a router along with our moisture sensor and the Raspberry Pi board as hardware. Python programming language is used as the main programming language with the support for BBC Basic, Java Perl and Ruby. The software requirements include the Raspbian Jessie (OS) installed on the Pi board, Apache server and PHP.

For the present work, the Raspberry Pi-3 board is used. The sensor output is connected to the GPIO pins on the board. The Apache Server Application is used to setup the server on the Raspberry Pi board. PHP scripts are written to activate the GPIOs. PHP is installed on the Raspberry Pi to run the PHP output. A user interface is developed using HTML and can be checked by typing “local-host” command in the URL of the browser. To access data on the local network “ipconfig” command is used which outputs an IP address designed by the router. This IP can be used to access the page hosted on the Raspberry Pi on another local device. For remote accession of data, the router is configured using “port forwarding technique”. After configuring the router, the Public IP address of the router is obtained using Google search for “What is my

IP”. This public IP address is used to remotely access the webpage hosted on the Raspberry Pi board.

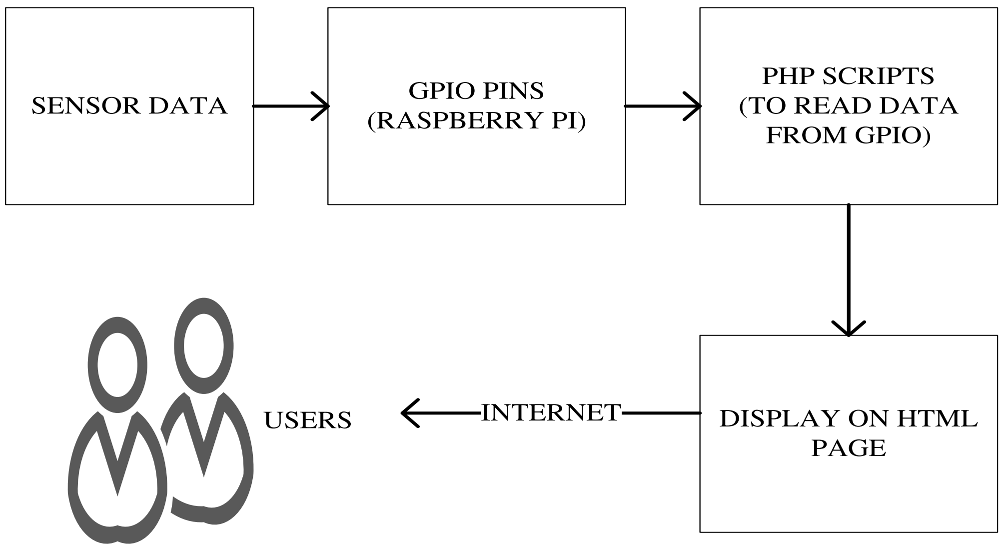


Fig. 9: Flowchart of the working of Raspberry Pi Setup

The above figure (Fig.9) shows the working of the Raspberry Pi Setup. The sensor data is fed into the GPIO pins of the Raspberry Pi board, from where it is read using the developed PHP scripts. It is then displayed on an HTML page for easy access. The results are further discussed in detail in Section VI.

2.6 Results and Discussions

The modelling and simulation results presented here establish the efficacy of the microcantilever sensor for enhanced accuracy and sensitivity in trace moisture measurement. The experimental setup used is an attempt to validate the possibility of implementation of the microcantilever as a sensor in the system. Due to the lack of proper setup, the experimental part is limited to the detection of moisture. Furthermore, enabling the system with an IoT module introduces smart capabilities into the Smart grid environment such as remote and local access, computational abilities, compactness and the possibility of development of a handheld device for easy monitoring.

Two mathematical models are studied for calculating the resonant frequency of the micro cantilever namely: Taut string Model and the Euler Bernoulli Beam model. Resonant frequency is calculated for both models for different added masses.

Table I: MATLAB calculation results for various mathematical models with and without surface stress

Added Mass (in picogram)	Resonant Frequency Taut String Model(in Hz)	Resonant Frequency for Euler Bernoulli Beam Model(in Hz)
Zero	50224.47	99359.14
200	49798.83	95975.24
500	49180.19	91503.24
1000	48198.45	85264.25

From Table I, it is observed that the difference in the resonant frequencies of the beam calculated using the two models is large. So, one model is to be chosen which closely agrees with the simulation results. It is also be noted that the change in resonant frequency due to added mass is more for the Euler Bernoulli Beam model as compared to the Taut Sting Model.

In this work, the effect of surface stress on resonant frequency is analyzed. The taut string model assumes that the surface stress is large and sufficiently positive but no such assumptions are made in the Euler Bernoulli Beam Model. So, the surface stress effects are to be calculated separately. A sufficiently large arbitrary axial force of 10^{-3}N is assumed to be applied to account for the surface stress. The dimensionless number Π_1 whose value determines the contribution of surface stress is calculated. It is found to be $\Pi_1 = 3.4778*10^{-6}$.

As mentioned in Section-II, the value of Π_1 (<<1) indicates that surface stress has negligible effect on the resonant frequency of the microcantilever. It is concluded that almost all the contribution in the resonant frequency change is due to mass loading on the cantilever. The dimension of the cantilever simulated is (l*w*t)=(200µm*2µm*3µm). Pre stressed Eigen frequency analysis is done with a DC bias voltage of 5-V. The microcantilever is loaded with different masses to simulated added moisture in the surface of the microcantilver. The change in the resonant frequency of the cantilever for the first mode is observed.

Table II: COMSOL results for different added masses on the micro cantilever

Added mass (in picograms)	Resonant frequency (Hz)
Zero	97614
200	94299
500	89904
1000	83774

Table II shows that while the change in resonance frequency due to added mass is clearly noticeable but the deflection of the cantilever is not .It is observed that the change in resonant frequency can be easily detected. The results of the simulation are in close agreement with the Euler Bernoulli beam model. So this model is selected for further analysis of the proposed microcantilever.

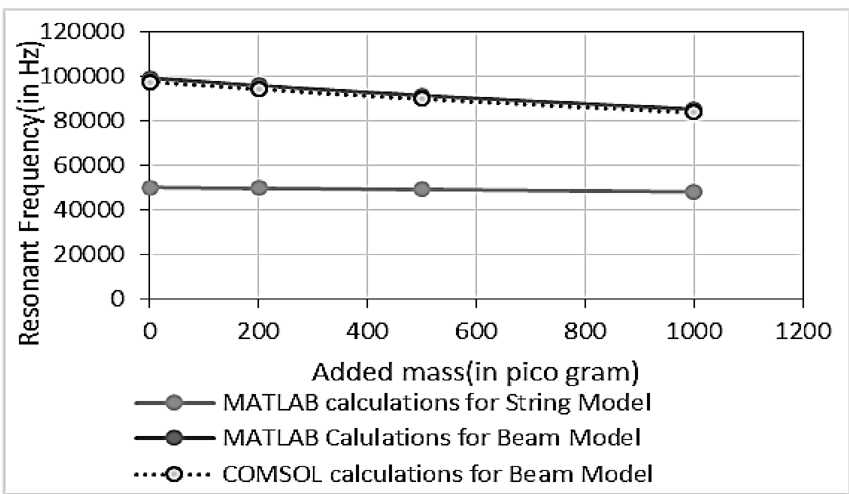


Fig. 10: MATLAB calculation and COMSOL results for the Euler Bernoulli Beam model and -String model

Fig.10 is a graphical representation of the results obtained from MATLAB calculations and COMSOL simulations. It can be easily observed that the Euler Bernoullli Beam Model agrees with the COMSOL simulations. Q-factor is independent of temperature. However, the resonant frequency may vary with temperature but the variation is very small and negligible in comparison to the change in resonant frequency obtained from the simulations performed in the present work.

NI-MyDAQ is used to acquire the voltage output from the instrumentation amplifier connected with the bridge circuit. The incoming signal is filtered with a bandpass filter express VI to obtain the filtered output of the polyamide micro-cantilever. 500 continuous samples were taken from a number of at a sampling rate of 10-kHz. 10 samples are taken in each sampling period. The data samples are taken for both conditions that is, with and without moisture. Standard deviation of the 500 readings for each case is calculated. As stated above, since the output voltage of the strain gauge decreases due to damping, the standard must also show the same behavior. It is observed that when there is no moisture (air damping) the standard deviation of output voltage is 426μV.When moisture is introduced the damping increases and the Standard deviation of output voltage reduces to 407μV.Since the box is airtight and left undisturbed it can be concluded that the increased damping of the microcantilever is due to the additional moisture introduced in the container. A change in damping is easily implicated as a change in Q-factor and is related to the resonant frequency and added mass as mentioned in the above sections. Hence, this gives us a method to measure the trace moisture content continuously in the required SF_6 environment.

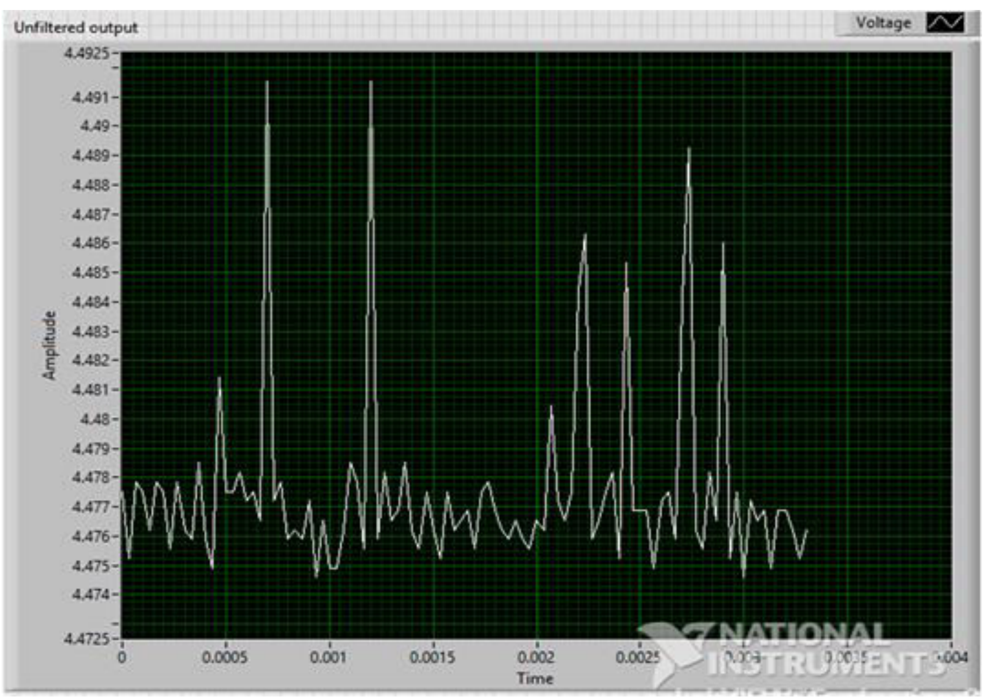


Fig.11: Acquired unfiltered waveforms from Instrument Amplifier using LabVIEW X-axis: Time (in ms) Y-axis: Amplitude (in Volts)

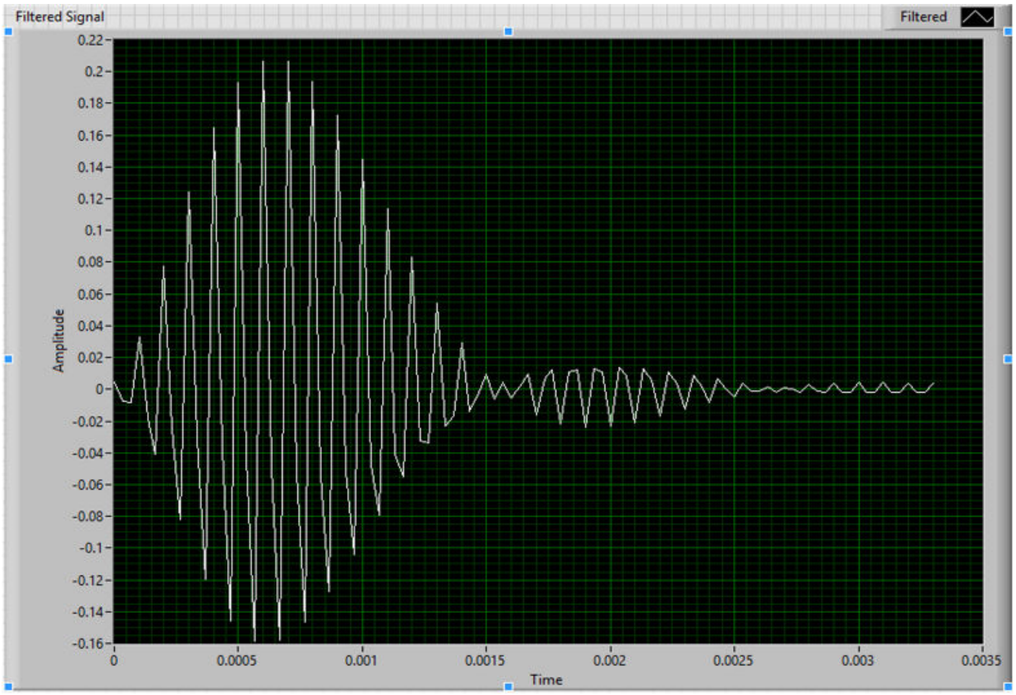


Fig.12: Acquired filtered waveforms from Instrument Amplifier using LabVIEW. X-axis: Time (in ms) Y-axis: Amplitude (in Volts)

.Fig 12 shows a waveform recorded after filtering of the output signal of the Instrumentation amplifier. The damping of the voltage output can be clearly seen with time which is also the expected response. Excessive noise in the original signal from the instrumentation amplifier (Fig.11) makes it necessary to filter the signal around the excitation frequency. The sensor data is acquired using NI MyDAQ and LabVIEW platform, which is further sent to a web page which displays the present value of sensor data.

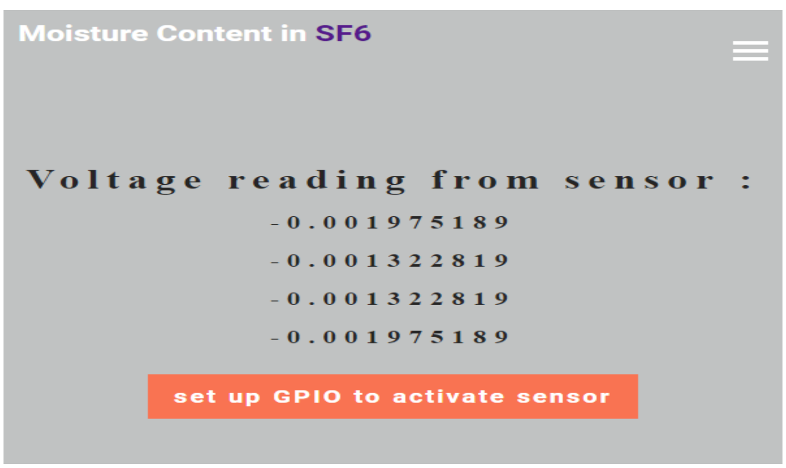


Fig.13: HTML web page created to display Sensor data

In the Fig.13, we display the voltage output of the instrumentation amplifier on an html page hosted on the Raspberry Pi board. This gives a method to continuously monitor the sensor data at any point of time. Also, the GPIOs can be turned on and off from the HTML page itself. Enabling the system with IoT has made the system more connected, efficient and accessible in the smart city scenario. It allows for the design of a compact and smart condition monitoring system capable monitoring, analyzing and storing the moisture sensor data in the SF_6 based GIS.

2.7 Conclusion

A micro-cantilever sensor based system is proposed to monitor the presence of trace level moisture in SF_6 based GIS. It is capable of detection of trace moisture levels by monitoring changes in Q-factor and therefore resonant frequency and added mass. The experimental validation indicates that the cantilever shows increased damping in presence of moisture, and thus, a change in Q-factor. The continuous measurement of Q-factor is suggested by the use of an Amplitude Locked Loop that makes measurement system more compact and cost-effective. An IoT enabled system for local and remote access of data is created and is used to display the sensor data of the used sensor. It has resulted in the design of an IoT enabled condition monitoring system capable of operating in the smart city environment. The proposed system is cost effective, compact, easy to install, integrate, and use in the GIS as compared to the earlier proposed systems.

The proposed system encourages the condition based monitoring approach instead of the traditional time based monitoring. Condition based monitoring helps us to analyze operational data rather than just maintenance data leading to better asset management. Hence, this system is a useful addition for monitoring trace moisture in SF6 based GIS in Smart Grid Environment.

Chapter 3

IOT BASED MONITORING SYSTEM FOR SUBSTATION AUTOMATION

3.1 Introduction

The Internet of things has taken the industry by storm in the past few years and it is touted to be even more popular in the coming future. IoT is penetrating almost each and every industry lately and there are still industries left to be influenced by it. Smart grid is one technology that can benefit greatly by the use of it as IoT complements many if not all the objectives aimed by the smart grid. If we go further, then substation is one of the most important part of the grid that need to be optimized and connected on the generation end as well as the consumer end, and thus, the need of more efficient and connected Substation Automation systems. The following work tries to present a possible design to build a connected sensor system using IoT for substation automation needs to complement the existing systems. The design proposes the uses of a lightweight messaging protocol MQTT for communication and open source hardware such as Arduino and Raspberry Pi for the system.

3.2 System Description

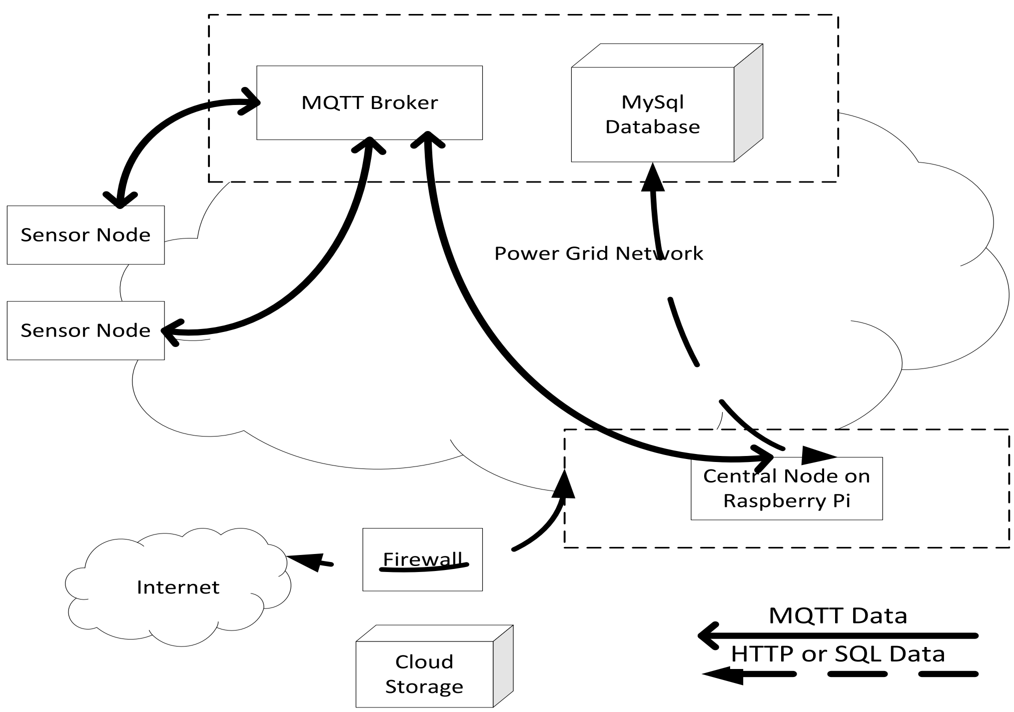


Fig. 14: Overall architecture of the proposed sensing system

Figure 14 shows the network and hardware setup and the data streams.

The hardware setup includes:

- The central node which can be implemented using a Raspberry Pi device.
- A 24/7 active server which can run a Mosquitto MQTT broker and a MySQL database.
- An Arduino sensor node capable of transferring the sensor data wirelessly to the MQTT broker and the central node.

The data streams are:

- Sensor Data: MQTT messages from sensors node to central node over MQTT broker
- Processed measurement data from the central node to MySQL database and Cloud storage.

The various parts of the system are described as follows:

3.2.1 Sensors and sensor interfacing:

The substation environment consists of a variety of sensors for monitoring a number of parameters such as temperature, pressure, humidity, vibration, gas density, leakage current etc. The output of these sensors is generally expressed in the 4-20mA signaling standard due to its proven robustness. Other type of sensors can be RF sensors and Fiber optic sensors. It is required to properly interface these sensors to make them compatible for the IoT environment.

The 4-20mA sensors can be easily interface using current loops to provide a voltage output which can be used as an input to the IoT device such as Arduino. Using current loops for data transmission is ideal because they are inherently insensitive to electrical noise. Figure 15 shows the schematic of a basic 4-20mA current loop. There are mainly four components:

1. A DC power supply
2. A 2-wire transmitter: It converts the real world signal such as temperature, pressure etc. into the necessary control signal for the current loop.
3. A receiver resistor that converts the current signal to a voltage: It is more convenient and easier to measure voltage than current and so it is used to produce a voltage that is easily measured by analog input of the controlling device.
4. The interconnecting wire

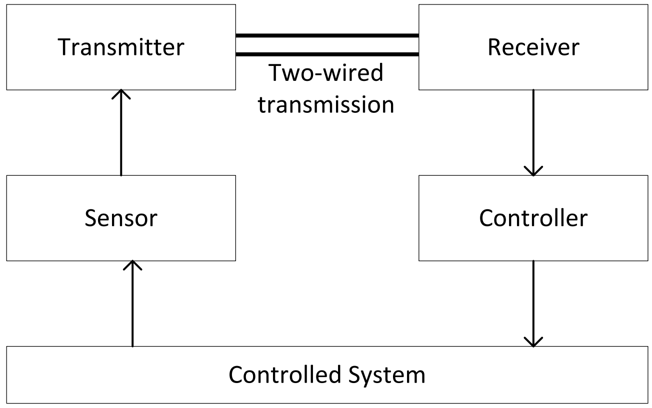


Fig. 15: A basic 4-20mA current loop

The RF sensors and Fiber optic sensors can be interfaced with the IoT hardware such as the Arduino using RF shields and fiber optic connectors that are easily available. There are a diverse set of adapters and connector that can connect to machines, SCADA and DCS. Thus, the IoT devices can be conveniently interfaced with the sensors using appropriate hardware which can be procured or built easily using simple hardware.

3.2.2 Sensor nodes

A sensor node is a small and inexpensive device with on board capabilities to process, power and communicate sensor data wirelessly. It also contains limited memory and power resources. Here a sensor node using an Arduino Uno and ESP8266 Wi-Fi chip is suggested. Both of the suggested hardware are cost effective, small in size and provide multi-functionality to transfer the sensor data wirelessly with good reliability. Figure 16 shows a schematic for a sensor node.

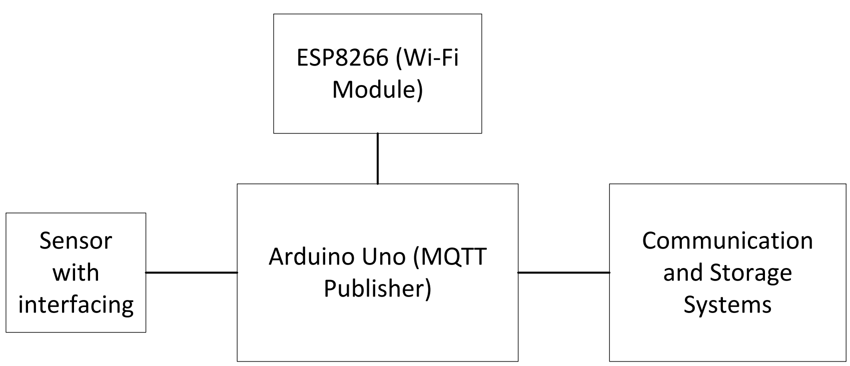


Fig.16: Schematic diagram of the sensor node

The Arduino Uno is an open source micro-controller board based on the ATmega328. It comes with both analog and digital input/output pins and can be easily powered using a USB connection. It can be conveniently programmed using the Arduino IDE. It is a widely used board with ample support available. The raw sensor data can also be processed up to some extent at the sensor node itself before further transmission [14].

The ESP8266 is a very small and cheap Wi-Fi module which can be easily programmed to send sensor data wirelessly with low power consumption. It can double as an application processor using its Built-in-low power 32 bit CPU. It means that it can function as a standalone device once it has been programmed. Although, here it is recommended to use ESP8266 in conjunction with the Arduino for better robustness and reliability in the substation environment.

The sensor node based on Arduino supports the MQTT messaging protocol and hence can send MQTT data wirelessly over the TCP/IP protocol.

3.2.3 MQ Telemetry Transport (MQTT)

MQTT is a Client Server publish/subscribe protocol. It is ideal for use in constrained environments with low processing requirements and /or the network bandwidth is at premium. It is an ideal for industries, machine to machine communication, power grids where the data to be transferred is generally small and time sensitive [15].

Fig.17 shows the MQTT publish/subscribe model. It uses publish and subscribe pattern (pub/sub) is an alternative to the conventional client server model. In MQTT, the client, who is sending a message (Publisher) and the client who is receiving a message (Subscriber) is decoupled by Pub/Sub unlike the Client Server model where the client communicated directly with an end point. A third component called broker connects both publisher and subscriber and filter all the incoming messages and distributes them accordingly. In this way, the publisher and subscriber are unaware of each other’s existence. The MQTT protocol embodies all the aspects of the Pub/Sub model and consists of two components the Client and the Broker. It is based on top of TCP/IP and both client and broker must have a TCP/IP stack.

It has three Quality of Service (QoS) agreement levels between the receiver and sender regarding the guarantees of delivering a message. They are: QoS 0, QoS1 and QoS 2 referring to at most once, at least once and exactly once respectively. QoS is important because it provides greater reliability in communication and guarantees the delivery of data regardless of the how unreliable the underlying transport is.

MQTT is an ideal protocol for communication in Substation environment for sensing data where reliability is a priority.

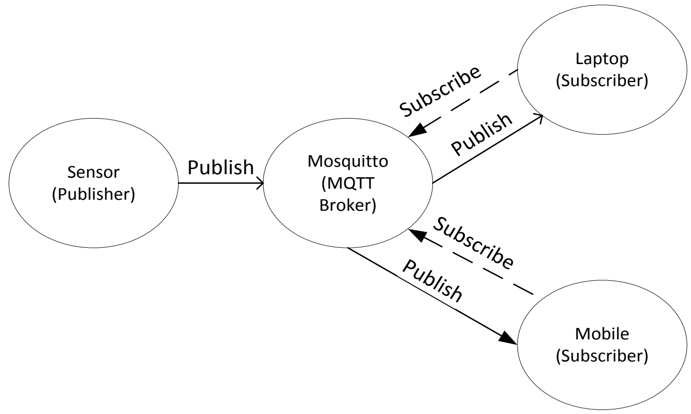


Fig. 17: Publisher/ Subscriber model for MQTT protocol

MQTT Broker:

The MQTT broker is a server device that can host any one of the several MQTT clients available to facilitate the transfer of MQTT data as and when requested by the subscribers. The size of the server depends on the number of clients it is expected to serve. Mosquitto is a reliable and frequently used MQTT client available on a variety of platforms. For test purposes Mosquitto can be hosted on a Raspberry Pi. Although for Substation environments dedicated servers can be used to host the broker client as well as for storing the data.

Data Storage:

The data can be stored locally in a MySQL database as well sent to a Cloud server where interactive visualization of the data can do. This allows remote access of data as well as condition monitoring of data from a remote location.

3.2.4 The Central Node

It is responsible for processing and storing the incoming MQTT messages from the sensor node. The central node decides the behavior of the MQTT data as to how the measurements are to be sent, processed and where the processed data should be stored. Raspberry Pi is the recommended hardware for the central node since it is a small and powerful processing device with low power consumption and supports many programming languages making it easier and efficient to handle the data. Data processing is done to reduce and to retain the minimum data points required for further analysis of the data as well as to save the storage space. Thus, a cost effective decentralized sensing system with remote access to data for analysis within the substation has been developed.

3.3 Additional aspects of the IoT System Architecture

Furthermore, the reliability and accessibility of the system can be enhanced by:

- Selecting a suitable network topology for the sensor nodes
- Bridging the MQTT brokers to establish communication between various substations
- Selecting a suitable network for the Substation
- Implementing proper security protocols

The above objectives can be achieved as described below:

3.3.1 Selecting a suitable network topology:

The Substation is spread over a large area and hence the sensors are distributed all over the substation so a suitable network topology must be selected to ensure complete and reliable coverage. To achieve this Star topology network can be beneficial in which Sensor subsystems can be deployed. The sensor subsystem can serve a dedicated number of sensor nodes distributed around the MQTT broker server and the Central node as shown in Fig. 18(a). This will allow a particular sensor node to be located in the range of the broker and central node as well as distribute the network load. The various central nodes can then send their data to a common Master node as shown in Fig. 18(b). For the Sensor subsystems the Broker devices used can be relatively smaller and hence cheaper to make the system cost effective. Also, similar type of sensors can be grouped to in the same sensor subsystem to allow easier setup.

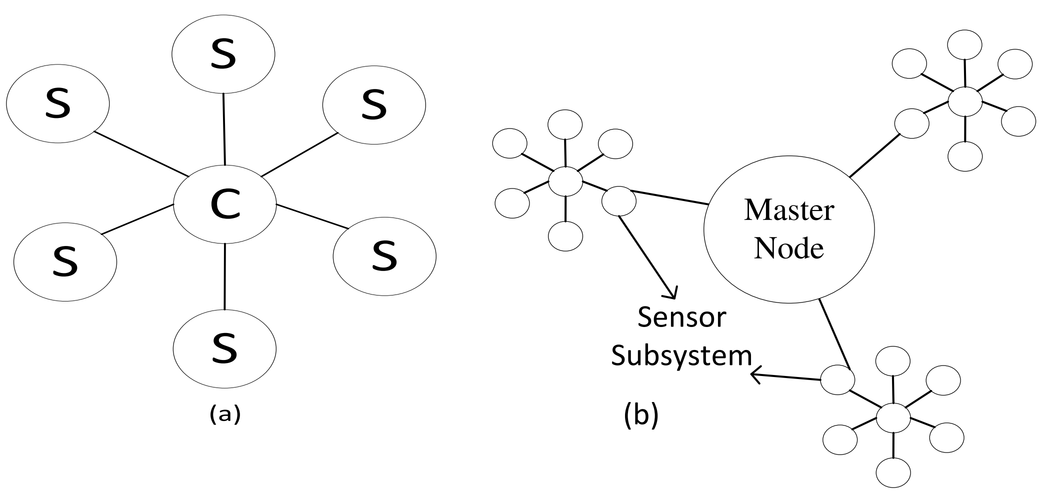


Fig. 18: (a) Suggested network topology for the sensor nodes C=Central Node with MQTT broker S=Sensor Node (b) Suggested network topology for the sensor subsystems.

3.3.2 Bridging MQTT Brokers

Mosquitto (and some other MQTT brokers) lets you connect two or more brokers together using a feature called Bridging. Fig. 19 shows how bridging is done. If we want to share information while maintaining the privacy on both sides then it can be achieved by bridging. Using this feature; only relevant information allowed by a broker can be easily and securely accessed. This feature uses Transport layer Security (TLS) to protect credentials and data in transit. The sharing of data can be controlled using an Access Control List (ACL) setup by the broker. ACLs ensure only that data is shared which is agreed upon. Using user authentication on both sided requested data can be shared.

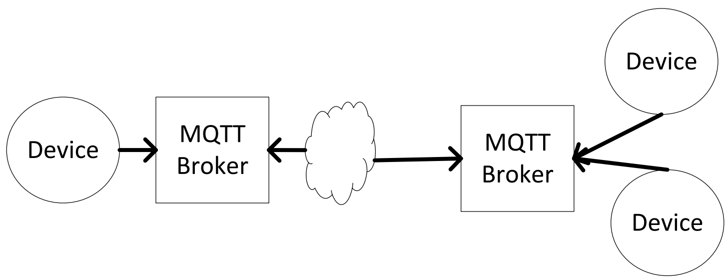


Fig. 19: Bridging of two MQTT brokers

This feature can prove to be useful when there are a lot of Distributed Energy Resources (DER) present. Since the Smart Grid technology encourages the integration of Non-conventional energy resources, Distributed Energy resources have become very common and integral to the Smart Grid Environment. It is not be possible to setup separate Substations for each of the DERs so bridging of MQTT brokers can prover very useful to share information between DERs and substations provided the DERs are enabled by the MQTT protocols.

3.3.3 Selecting a suitable wireless network

Wireless communication technologies such as Public Wireless Network, Power Private Network, Wireless Mesh Network and Low Power Wide Area Network are widely used in power grid communication. However, a single technology cannot suffice all the requirements of the power grid and the same can be said for substations. Due to a variety of application principles, different technologies must be appropriately and used in the substation.

The Public Wireless Communication has low cost but is also low on reliability and hence it must not be used for transfer of critical. Although, it can be used for remote access and transfer of time insensitive and non-critical data to save costs. The Power Private Wireless network is a dedicated network for the Power grid enterprises and provides high reliability. However, the signal coverage is limited to the area in the substation. This network can be effectively used for communication within the substation. The Wireless Mesh Network has the self-healing network ability but its planning and installation is a complex task for the complete substation environment. This network can be used to connect the various central nodes of the sensor subsystems in the system described in Figure 17. The Low Power Wide Area network can be used to connect the various sensor nodes in a sensor subsystem as it has low power consumption, increase the signal coverage. The LPWAN must be tested first for suitability of the sensor node in use as it as low throughput and high time delay. Thus, multiple type of communication networks suitably selected can optimize the overall communication network of the substation.

3.3.4 Implementing proper security protocols

The communication infrastructure of any Substation Automation System is prone to security threats at various levels. The security protocols must be implemented in the development phase itself to validate the authenticity of messages and prevent intrusions. The main concern of the IED (Intelligent Electronic Device) developed is that the microprocessors deployed have little processing capabilities and hence are potentially open to threats. The MQTT protocol used in the proposed system has an authentication function at the client broker level. It employs a Transport Layer Security (TLS) protocol to protect the integrity of the data in transit. TLS has many methods of encrypting data and authenticating message integrity.

A detailed system design approach is hence discussed in this section which can be tested in real time using smaller prototypes.

3.4 Experimental Setup

Arduino based Sensor Node Prototype:

Implementation of the system described in the previous section is in progress. As of now an Arduino sensor node was tested to control an LED using Internet as a prototype to control a sensor. The Arduino node consists of an Arduino Uno, ESP8266 and interfacing circuit for the ESP8266. Figure shows the circuit developed of the developed node. The ESP8266 requires a

3.3V power supply which was obtained using AMS1117 and 2 capacitors (470µF each) from a 9V DC battery. To connect the TX and Digital Out pin two voltage dividers are used. They were made using 10kΩ and 20kΩ resistors to shift the 5V logic to 3.3V. The ESP8266 was then connected to the Arduino and a simple code was written to setup an internet gateway on the home Wi-Fi network to display the status of the LED and change its state. The code is written and flashed using Arduino IDE. The Raspberry Pi was setup and an MQTT broker is successfully tested to publish and subscribe using a simple test routine. Further work includes connecting the Raspberry Pi with the Arduino sensor node and using it to obtain the sensor data wirelessly using the MQTT protocol and publish the data to various devices as well as store and visualize the data on the cloud and a MySQL database. The system can also be tested using multiple sensor nodes to check the reliability and range. After the testing of the prototype of the system, an attempt will be made to test the system in real time in Substation environment subject to availability of resources.

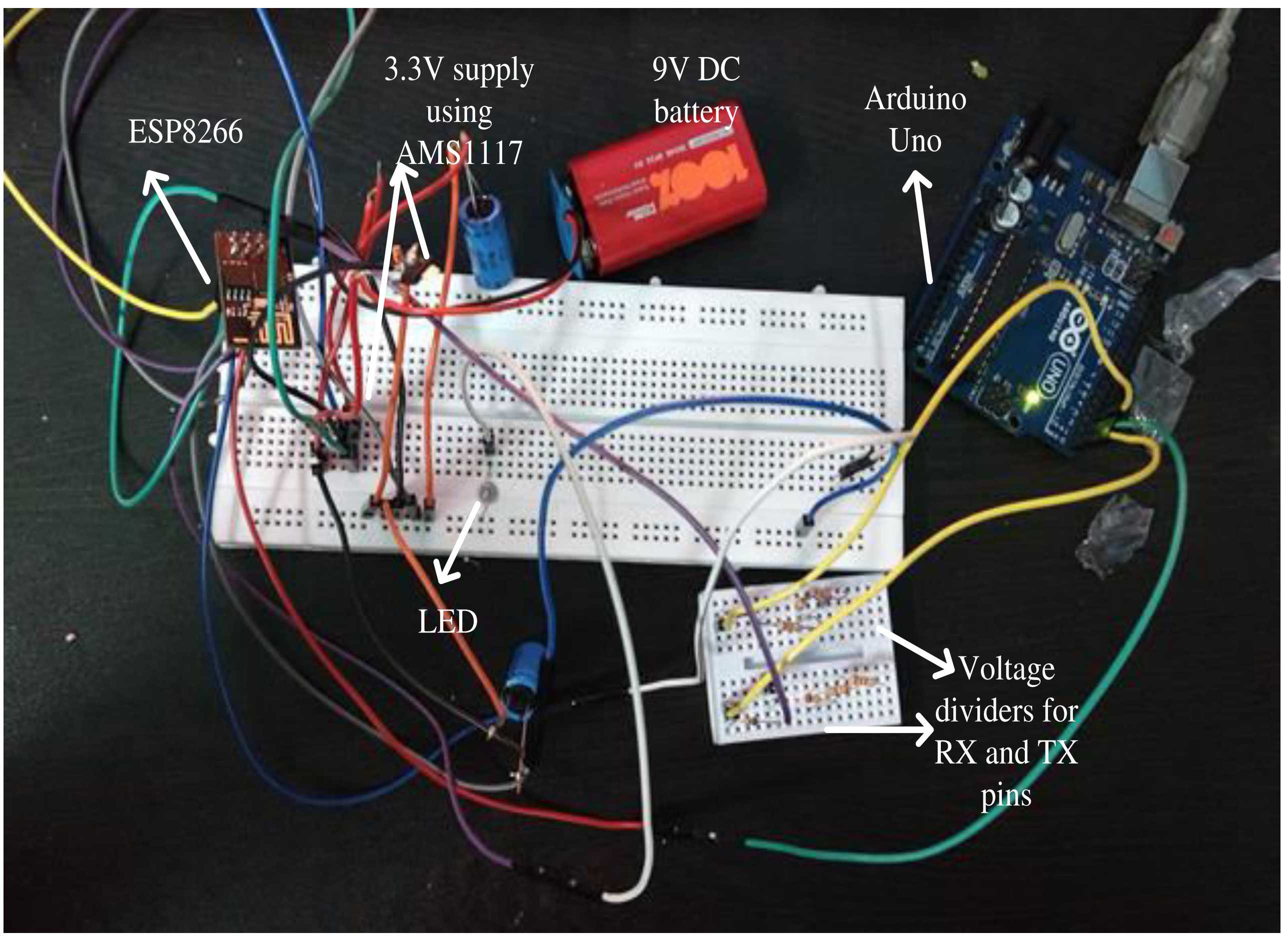


Fig. 20: Arduino sensor node test circuit

Fig. 21: Screenshot of the developed internet interface for the Arduino sensor node test circuit

3.5 Results

A complete IoT based sensing system is proposed for Substation automation application in Smart Grid environment. Various parts of the system are discussed in detail along with their possibility of application alongside the present substation automation systems. An overall implementation of the system including network topologies, wireless communication networks and secure communication with other parts of the power grid is also discussed. The MQTT protocol suggested in the proposed system is relevant to the substation environment and provides a reliable and secure way to communicate sensor data to a large audience. The system design is cost effective and easy to implement and configure. It provides a new approach to monitor, store, visualize and communicate the sensor data using IoT in the substation environment. The proposed system is currently under implementation and an Arduino sensor node prototype has been tested as a part of it. Remaining implementation of the work is expected to be completed soon and presented in further research.

3.6 Conclusion

IoT is expected to become a major enabling technology in the Smart Grid environment and substation automation is not expected to remain untouched. The present work is one of the many possibilities to integrate IoT in substation automation. It presents an Open Source based system which provides a versatile platform for development of unique application that can be used in the Smart grid environment.

CHAPTER 4

CONCLUSION

In this thesis, contributions towards sub-station automation are claimed at two-front sides, namely, (i) design of MEMS micro-cantilever moisture sensor and (ii) interfacing of sensor and its enabling with the Internet-of-Things (IoT) for the purpose of condition monitoring.

In the first part of the presented work, MEMS micro-cantilever based measurement system has been proposed for application in SF_6 based GIS in the Substations. The system measures trace level moisture using a micro-cantilever by measuring the change in resonance frequency of the sensor upon addition of moisture. The idea is supported by mathematical modelling as well as simulation of the microcantilevers in MATLAB and COMSOL. Two mathematical model for the cantilever are described and resonance frequency has been calculated for each case. A suitable model is then selected by comparing the results of mathematical modelling with the simulation results. The effect of surface stress on the resonance frequency has also been discussed and analyzed. A relation between the resonance frequency of the cantilever and its Q-factor has been established and an ALL based approach is suggested to measure the Q-factor of the micro-cantilever. The Q-factor can be then used to find the change in resonant frequency using the mathematical relation established. This provides a simpler method to detect the change resonant frequency as opposed to the present methods which use large and costly equipment to measure resonant frequency. An elementary experimental setup to detect the presence of moisture using a Polyimide cantilever was performed. Raspberry Pi was used to connect he sensor to the internet and send data to a website. The resulting system has several advantages over the existing systems. It enables continuous condition monitoring instead of time based monitoring. It proposes a system for in-situ measurement of the moisture levels unlike other systems which require the sample to be taken out and pumped back into the Switchgear which might be a risky exercise. It aims to provide the measurements in ppm levels directly unlike present systems which use dew point measurements along with temperature to measure the ppm levels. It has a compact construction and can be easily integrated with the present systems.

The second part of the work proposes a design of an IoT based monitoring system for Substation Automation environment. It attempts to present an approach to connect the sensors present in the substation using IoT. MQTT has been suggested as the communication protocol to be used as it is lightweight and uses low bandwidth. It also provides better reliability in the Substation environment. The work describes the design of the system in detail. All aspects of the system and the possibility of the implementation has been discussed. The system is currently in implementation stage and initial prototyping has been done. The complete implementation is being performed as a continuation of the work described here.

Hence, this work is an attempt towards the design and implementation of Sensors and IoT together in the Substation environment. Substation is an important part of any grid from the point of view of the generation end as well as the consumer end. In the smart grid, it is expected that the substation automation systems will have to be smarter and more efficient. The work tries to contribute to the current research in the Smart grid environment and eventually to the vision of a smarter and better world around us.

CHAPTER 5

FUTURE SCOPE OF WORK

Some of the recent developments in the line of this thesis work that can be considered as future scope of works are:

- Development of the Amplitude Locked Loop for use with the proposed moisture sensor.
- Integration of sensors mounted in substation with automation tools such as Programmable Logic Controller (PLC) / Programmable Automation Controller (PAC) to increased robustness of the system.
- Integration of cloud services for data storage and real time analysis to make the system more efficient and robust.
- Enabling Wireless Sensor Networks (WSNs) and Internet-of-Things (IoT) with IEC 61850 Complaint Sub-station Automation.
- Reliability analysis and security testing of the system to assess the scalability and robustness of the system.

LIST OF PUBLICATIONS

- <u>Referred Journal Publications</u>:

1. **Yashdeep**, Gyan Ranjan Biswal, T. Choudhury, T. Islam, S. Mukhopadhyay, and V. Vashisht, "Design and Modeling of MEMS based Trace-level Moisture Measurement System for GIS Applications in Smart Grid Environment," *IEEE Sensors Journal*, pp. 01 – 08, May 2017. {Accepted}
   Indexed by: SCI; ISI; Inspec; Scopus   Current Impact Factor: 1.889

2. **Yashdeep**, Gyan Ranjan Biswal, and T. Choudhury, "Internet of Things based Sensing System for Substation Automation in Smart Grid Environment," *Res. J. Computer and IT Sci.*, Int. Sci. Commu. Assoc., Vol. 5, No. 3, pp. 01-05, May 2017.

- <u>Peer Reviewed Conference Publication(s):</u>

1. **Yashdeep**, Gyan Ranjan Biswal, and T. Choudhury, "Internet of Things based Sensing System for Substation Automation in Smart Grid Environment," *BITCON-2017* (Research Challenges in Applications of Computing Towards Digitization of India), Durg, pp. 01 – 12, Mar. 28, 2017.
   {upgraded version is selected for Research Journal of Computer and Information Technology Sciences, International Science Community Association }

REFERENCES

[1] Zanella, A, “Internet of Things for Smart Cities” .*IEEE Internet of Things Journal*, vol. 1, no. 1, pp. 22 – 32, 2014.

[2] Bush,S. F. , Goel,S. and Simard,G..”IEEE Vision for Smart Grid Communications: 2030 and Beyond Roadmap”, pp. 1-19, 2013.

[3] Molderink, A.,Bakker,V., Bosman,M. G. C., Hurink,J. L. and Smit,G. J. M., “Management and Control of Domestic Smart Grid Technology”. *IEEE Transactions on Smart Grid*, vol. 1, no. 2, pp. 109-119, 2010.

[4] Ingram, M. and Ehlers,R.. ”Toward effective substation automation”. *IEEE Power and Energy Magazine*, vol. 5, no. 3, pp. 67-73, 2007.

[5] “IEEE Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems”. *IEEE Std 1547.3-2007*, pp.1-160, 2007.

[6] Nielsen, J.J., Ganem, H., Jorguseski, L.,”Secure Real-Time Monitoring and Management of Smart Distribution Grid using Shared Cellular Networks”,*eprint arXiv:1701.03666*, 2017.

[7] “IEEE Standard for Exchanging Information Between Networks Implementing IEC 61850 and IEEE Std 1815(TM) [Distributed Network Protocol (DNP3)]”, *IEEE Std 1815.1-2015 (Incorporates IEEE Std 1815.1-2015/Cor 1-2016)*, vol., no., pp.1-358,2016.

[8] Kelly,S. D. T. , Suryadevara,N. K. and Mukhopadhyay,S. C..”Towards the Implementation of IoT for Environmental Condition Monitoring in Homes”, *IEEE Sensors Journal*, vol. 13, no. 10, pp. 3846-3853, 2013.

[9] Sajid, A., Abbas, H. and Saleem, K. “Cloud-Assisted IoT-Based SCADA Systems Security: A Review of the State of the Art and Future Challenges”, *IEEE Access*, vol. 4, no. , pp. 1375-1384, 2016.

[10] Papageorgas,P. , Piromalis,D. , Iliopoulou, T., Agavanakis, K., Barbarosou1, M., Prekas,K., Antonakoglou.”Wireless Sensor Networking architecture of Polytropon: An open source scalable platform for the smart grid”, *The International Conference on Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES14,Energy Procedia* 50 ,270 – 276, 2014.

[11] Ahmim, A., Le,T.,Ososanya,E. and Haghani,S., “Design and implementation of a home automation system for smart grid applications”,*2016 IEEE International Conference on Consumer Electronics (ICCE), Las Vegas, NV*, pp. 538-539, 2016.

[12] Hunkeler, U., Truong, H. L. and Stanford-Clark,A.. “MQTT-S — A publish/subscribe protocol for Wireless Sensor Networks”, *3rd Int. Conf. Commun. Syst. Softw.* , 2008.

[13] Robert L. Szabo and Farkas, K.,” Publish/Subscribe Communication for Crowd-sourcing Based Smart City Applications”, *ICTIC - Proceedings in Conference of Informatics and Management Sciences, no. 1*, 2013.

[14] Arduino.[Online]. Available: *http://www.arduino.cc/*

[15] Message queue telemetry transport (mqtt). [Online]. Available: *http://mqtt.org/*

[16] Frechette, M. F., Sakakibara, T., Goyette, J. and Errais, A.,"Development of a Differential Microwave System to Measure Traces of Water in SF6," *IEEE/PES Transmission & Distribution Conf. and Exposition: Latin America*, Caracas, pp. 1-4, 2006.

[17] IEEE Guide for Moisture Measurement and Control in SF6 Gas-Insulated Equipment, 2013.

[18] Kamei, M. and Takai, O. "Influence of Sensor Information Accuracy on Condition-Based Maintenance Strategy for GIS/GCB Maintenance," in *IEEE Trans. Power Delivery*, vol. 26, no. 2, pp. 625-631, Apr. 2011.

[19] Golders, K. M., Colton, J. S. and Bottomley, L. A. "Microcantilevers: Sensing chemical interactions via mechanical motion" *Chemical Reviews*, vol. 108, no. 2, pp. 522–542, 2008.

[20] Ziegler, C. "Cantilever-based biosensors," *Analytical and Bioanalytical Chemistry*, vol. 379, no. 7-8, pp. 946–959, 2004.

[21] Shi, X., Chen, Q., Fang, J., Varahramyan, K. and Ji, H. F. "Al2O3-coated micro cantilevers for detection of moisture at ppm level," *Sensors and Actuators, B: Chemical*, vol. 129, no. 1, pp. 241–245, 2008.

[22] Kapa, P., Pan, L., Bandhanadham, A., Fang, J., Varahramyan, K., Davis, W., Ji, H. F. "Moisture measurement using porous aluminum oxide coated microcantilevers," *Sensors and Actuators, B: Chemical*, vol. 134, no. 2, pp. 390–395, 2008.

[23] Bouchaala, A., Nayfeh, A. H. and Younis, M. I. "Frequency Shifts of Micro and Nano Cantilever Beam Resonators Due to Added Masses," *J. Dynamic Systems, Measurement, and Control*, vol. 138, no. 9, pp. 1002-1009, 2016.

[24] Islam, T., Mahboob, R. and Khan, S. A. "A Simple MOX Vapor Sensor on Polyimide Substrate for Measuring Humidity in ppm Level," *IEEE Sensors Journal*, vol. 5, pp. 3004–3013, 2015.

[25] Mahboob, R., Zargar, Z. H. and Islam, T. "A sensitive and highly linear capacitive thin film sensor for trace moisture measurement in gases," *Sensors and Actuators, B: Chemical*, vol. 228, pp. 658–664, 2016.

[26] Mittal, U. , Islam, T., Nimal, A. T. and Sharma, M. U. "A Novel Sol–Gel -Al_2O_3 Thin-Film-Based Rapid SAW Humidity Sensor," *IEEE Trans. Electron Devices*, vol. 62, no. 12, pp. 4242-4250, 2015.

[27] Mertens, J., Finot, E., Thundat T., Fabre , A., Nadal, M.H., Eyraud , V., Bourillot, E. "Effects of temperature and pressure on microcantilever resonance response." *Ultramicroscopy,* vol. 97(1-4) pp.119-126, 2003.

[28] Sandberg, R, Svendsen, W, Mølhave, K and Boisen, A, "Temperature and pressure dependence of resonance in multi-layer microcantilevers",*Journal of Micromechanics and Microengineering,* vol. 15,pp.1454-1458,2005.

[29] Thundat, G. Y., Wachter, E. A. and Warmack, R. J. "Adsorption induced surface stress and its effects on resonance frequency of microcantilevers," *J. Applied Physics*, vol. 77, no. 8, pp. 3618–3622, 1995.

[30] Ren, Q. and Zhao, Y. P. "Influence of surface stress on frequency of microcantilever-based biosensors," *Microsystem Technologies*, vol. 10, no. 4, pp. 307–314, 2004.

[31] Sebastien, T., Caillard, B., Menil, F., Debeda, H. and Lucat, C., "Modeling and performance of uncoated microcantilever-based chemical sensors," *Sensors and Actuators B: Chemical,* vol. 143, pp. 555-560, 2010.

[32] Fadel, L., Dufour, I., Francais, O. "Microcantilever : a chemical resonant sensor," 2008.

[33] Dufour, I., Josse, F., Heinrich, S., Lucat, C. and Ayela, C., "Unconventional uses of microcantilevers as chemical sensors in gas and liquid media," *Sensors and Actuators B: Chemical,* vol. 170, pp.115-121, 2012.

[34] Moir, T. J., "Analysis of an amplitude-locked loop," *IET Electronics letters*, 1995.

[35] Smith, N. D., “A technique for continuous measurement of the quality factor of mechanical oscillators,” *Review of Scientific Instruments*, vol. 86, no. 5, 2015.

[36] Stankovic, J. A., "Research Directions for the Internet of Things,"*IEEE Internet of Things Journal*, vol. 1, no. 1, pp. 3-9, Feb. 2014.

[37] Jin, J., Gubbi, J., Marusic, S. and Palaniswami, M. "An Information Framework for Creating a Smart City Through Internet of Things," *IEEE Internet of Things Journal*, vol. 1, no. 2, pp. 112-121, Apr. 2014.

[38] Asadi, A. A., Bagheri, S., Imam, A., Jalayeri, E., Kinsner, W. and Sepehri, N. "A data acquisition system based on Raspberry Pi: Design, construction and evaluation," *IEEE 7th Annual Info. Tech. Electro.and Mobile Commun. Conf. (IEMCON)*, Vancouver, pp. 1-5, 2016.

[39] Nag, A., Zia, A. I. , Li, X., Mukhopadhyay, S. C. and Kosel, J. “Novel Sensing Approach for LPG Leakage Detection—Part II: Effects of Particle Size, Composition, and Coating Layer Thickness,” *IEEE Sensors Journal*, vol. 16, no. 4, pp. 1088-1094, Feb. 2015.

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ORIGINALITY REPORT

%6	%1	%5	%2
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	GONDA, Jora Mangala and DAVID, Sumam. "Real-time implementation of an amplitude-locked loop: a validation on the dSPACE DS1006-based platform", TÜBİTAK, 2013. Publication	%1
2	Zhang, Wen-Ming, Kai-Ming Hu, Zhi-Ke Peng, and Guang Meng. "Tunable Micro- and Nanomechanical Resonators", Sensors, 2015. Publication	%1
3	Q. Ren. "Influence of surface stress on frequency of microcantilever-based biosensors", Microsystem Technologies, 05/01/2004 Publication	<%1
4	Christiane Ziegler. "Cantilever-based biosensors", Analytical and Bioanalytical Chemistry, 08/2004 Publication	<%1
5	Manjunath, T.C. Bandyopadhyay, B.. "Multivariable control of smart Timoshenko	<%1