

**DEVELOPMENT OF REMOTE MONITORING TECHNIQUES USING
ELECTRICAL IMPEDANCE SPECTROSCOPY AND FIBRE OPTICS**

By

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LIST OF ABBREVIATIONS

AC	Alternating current
BPM	BP/heart-rate monitor
CCCs	Cryogenic current comparators
CK-based	Correlated-k based
CMOS	Complementary metal-oxide semiconductor
CT	Current transformer
CVC	Current voltage converter
DC	Direct current
DSP	Digital signal processor
EIS	Electrical impedance spectroscopy
F O	Fibre optic
FBG	Fibre Bragg grating
FFPI	Fibre-optic Fabry–Perot interferometer
FTIR	Fourier transform infrared
GaAs	Gallium Arsenide
GC	Gas chromatography
GMI	Giant magneto impedance
HPLC	High performance liquid chromatography
IR	Infrared
L	Length
LCD	Liquid crystal display
LED	Light emitting diode
LHPG	Laser heated pedestal growth
MCU	Micro-Controller Unit
MOS	Metal-oxide semiconductor
NIR	Near infrared
NMR	Nuclear magnetic resonance
OPCT	Optically powered current transducer
PCA	Principal component analysis
PCB	Printed circuit board

PIC	Peripheral Interface Controller
PRT	Platinum resistance thermometer
Pt	Platinum
PZQ	Piezoelectric quartz
PZT	Piezoelectric transducers
RBF	Radial basis function
SAW	Surface acoustic wave
SQUID	Superconducting quantum interference device
SRS	Spectral remote sensing
STS	Stainless steel
TGG	Terbium gallium garnet
WHO	World Health Organization
WNB	Wide narrow band

LIST OF SYMBOLS

R_F	Feedback resistance
B_z	Flux density in sensor
C_P	Parallel capacitance
I_D	Photo diode current
I_L	Drive current through LED
I_X	Current through the sensor
I_m	Current under measurement
I_t	Current through transistor
K_e	Constant emitted light
K_t	Constant value of responsivity of the photo diode
P_e	Emitted optical power
P_{int}	Power internally generated in LED
R_E	Total resistance of the emitter circuit
R_{HC}	Hall coefficient
R_P	Parallel resistance
V_{03}	Output voltage of the summer
V_B	Base voltage
V_F	Forward voltage
V_H	Hall voltage
V_{inph}	In-phase voltage component
V_o	Output voltage of the op amp
V_{quad}	Quadrature voltage component
V_s	Supply voltage
n_x	Refractive index of material of LED
η_{int}	LED Internal quantum efficiency

μ	Micro
C_{ef}	Effective capacitance
h	Plank constant
\mathfrak{R}	Responsivity of the photo diode
R_{ef}	Effective resistance
t	Temperature
Z_{ef}	Effective impedance
Z_p	Impedance of the fruit
α	Temperature coefficient of resistance
Ω	Ohm
F	Transmission factor of the semiconductor-external interface
R	Resistance
T	Plate thickness
c	Velocity of light
e	Charge of an electron
f	Frequency of the incident light
n	Refractive index of the optical fibre refractive index of the optical fibre
η	Quantum efficiency of the diode
λ	Wavelength
W	Width

PEMBANGUNAN TEKNIK-TEKNIK PEMANTAUAN BERCAPAIAN JAUH MENGUNAKAN SPEKTROSKOPI GALANGAN ELEKTRIK DAN GENTIAN OPTIK

ABSTRAK

Kajian ini adalah berkaitan dengan pembangunan beberapa pengesan berasaskan bidang opto-mekatronik dan agro-elektronik bagi pengukuran kuantiti elektrik dan bukan elektrik. Pembangunan ini bertujuan menghasilkan pengesan yang berkos rendah dan mempunyai rekabentuk ringkas, dengan ketepatan dan kejituan yang baik serta dapat digunakan di tempat yang terpencil. Pengesan pertama dibangunkan berasaskan bidang opto-mekatronik untuk penyukat suhu dari jauh. Ia memainkan peranan penting dalam penilaian keselamatan dan kestabilan pelbagai sistem. Pengesan yang dibangunkan mempunyai ketepatan 1% atau lebih baik dan dapat mengukur suhu sehingga 30°C. Pengesan kedua dibangunkan untuk pengukuran arus elektrik dari jarak jauh menggunakan peranti magneto-optik. Ia telah digunakan dengan jayanya untuk pengukuran arus sehingga 60 A. Pengesan ketiga menggunakan teknik haba-optik yang sesuai untuk pengukuran arus dari jauh. Output yang diperolehi menunjukkan bahawa pengesan yang dibangunkan memberikan sisihan piawai sebanyak 0.5% atau lebih baik dalam situasi berbahaya. Seterusnya, dalam bidang agro elektronik, spektrometri galangan telah digunakan bagi pencirian buah-buahan dan sayur-sayuran tanpa memusnahkannya. Pengesan asas yang digunakan untuk aplikasi ini ialah sistem kuar yang dapat membantu pengukuran galangan secara tak invasif. Akhir sekali, pengesan gentian optik telah dibangunkan untuk mengesan ketulenan minyak masak dengan menentukan takat awan minyak yang diuji. Sistem optik ini bersama-sama dengan pengesan suhu dan mikropengawal digunakan untuk memperolehi bacaan takat awan. Ia dapat digunakan secara ekonomi untuk menganalisis kualiti ketulenan pelbagai jenis minyak dalam jeda masa yang singkat.

DEVELOPMENT OF REMOTE MONITORING TECHNIQUES USING ELECTRICAL IMPEDANCE SPECTROSCOPY AND FIBRE OPTICS

ABSTRACT

The research work deals with the development of sensors in the field of opto-mechatronics and agro-electronics to measure electrical and nonelectrical quantities. The development aims to produce sensors that are low in cost and have simple design with good order of accuracy, precision and can be used in remote places. The first sensor employs electro-optic technique for the remote measurement of temperature to assess the safety and stability of different types of systems. It has an accuracy better than 1%, and is able to measure temperature up to 30°C. The second sensor has been developed for the remote measurement of electrical current using magneto-optic devices. It has been successfully used for the measurement of currents up to 60 A. The third sensor, using the thermo-optic technique, has been constructed for the remote measurement of current. The output has been shown to have a standard deviation better than 0.5% under hazardous conditions. Next, in the field of agro electronics, impedance spectrometry has been used to characterize fruits and vegetables non-destructively. The basic sensor used for this application is a probe system developed to aid the measurement of impedance non-invasively. Finally, a fibre-optic sensor has been developed for detection of adulteration in edible oils by determining the cloud point of the oil under test. The optical sensor together with the temperature sensor and microcontroller is used to obtain the cloud point measurement. It can be used economically for qualitative analysis of adulterated oils in a short interval of time.

CHAPTER ONE

INTRODUCTION

1.1 Introduction

Sensors have revolutionized the modern world. Their applications have produced advancements in devices, machines, processes and systems by enhancing their performances. There has been integration among sensors, electronic hardware, and computers to give new dimensions to the old technology based on conventional systems. In recent years sensor technology has been increasingly incorporated at an accelerated rate into modern equipments to provide new solutions to complex problems by achieving a desirable function or performance which was not possible by conventional systems. It has enhanced the state of precision, reduced the size, and greater intelligence and autonomy. In the future this trend will continue to map out the direction of next generation technologies.

1.2 Problems and Motivations to Research Work

Research work presented in this thesis deals with the development of some simple low cost sensors which would be able to measure physical quantities with high degree of accuracy, precision and at a remote place. The measurement and control of temperature are important everyday applications of transducers in the industries. Its measurement and control play important role in a wide variety of consumer products. The industrial and medical applications cover a wide range of temperatures of interest. Its importance further increases when it has to be made under hazardous conditions where the conventional methods fail. One of the burning topics of the latest requirements of the power systems is the measurement of

temperature of high potential parts of the transmission system like high voltage transmission conductors, power transformers; switch gears which play important role in the stable operation of power supply system (Youssef, 2001; Abdulhalim and Moors, 2004; Seki et al., 1978). Sometimes, increase in temperature is beyond the safe limits which are due to over loading, friction and sparking inside the machine or chip. Under such situations, devices may be damaged. To avoid this damage, proper sensors, should be employed to warn timely. The system, to be used for the purpose, must be capable of operating under extreme conditions, without affecting the real temperature, as well as must have the added feature of remote sensing with continuous monitoring, at low cost.

Although, remote measurement of temperature is not a new thing because it has been done with other techniques in the past (Chrzanowski, 1996; Moghavvemi et al., 2005), the presented technique is an integration of highly accurate platinum resistance temperature sensor with fibre optic transmission technique. Similarly fibre optic transmission system is integrated with the magnetic and thermal sensors for D.C current measurement. It will help in the repair of measuring systems without closing the main circuit which is a crucial requirement of supply system.

There is another successful integration among the electrical and optical sensors, electronic hardware, microcontrollers and software to solve difficult problems of agriculture. It could give new dimensions to the field of agro electronics by solving very genuine problems associated with the characterization of the raw and ripe fruits and vegetables. It has been done previously with the help of impedance

spectrometry, at higher frequencies, and mostly employing invasive techniques (Harker and Dunlop, 1994). The developed technique works at low voltage and frequency, to avoid self heating of the fruit under test which was not given any importance in the past (Harker and Forbes, 1997). However, a new impedance bridge is designed to be able remotely measuring impedance which is based on a novel circuit developed under this scheme.

1.3 Research Objectives

The techniques developed have applications in day to day life to solve a number of difficult tasks. Remote measurement and analog sensors are the main threads among the different subjects of this research work. Following are the main objectives of the research work carried over in this thesis.

1. To develop scheme, to measure the temperature rise of the hot bodies, which are the parts of the high voltage and high current systems, safely, by providing isolation through optical fibre.
2. To develop the schemes for the remote measurement of direct electrical currents, in power systems, using magnetic and thermal techniques, with good order of accuracy and isolation.
3. To explore the feasibility of the application of the electrical impedance spectroscopy, in the monitoring of the fruits, during the ripening process, with the help of fibre optic remote measurement technique.

4. To develop an accurate microcontroller based impedance measuring system to monitor the impedance of the fruits at low cost.
5. To develop microcontroller based schemes to detect the order of adulteration, in different types of edible oils, using fibre optic technique through cloud point determination.

1.4 Thesis Organization

The thesis has been divided into six chapters, the introduction highlights the importance of the presented research work in the background of the problems encountered by the consumers as well as researchers in the field of remote measurement of physical quantities as well as in the remote assessment of the quality of fruits at low cost together with the main objectives of the research work.

Chapter 2 deals with the survey of the available literature on different topics covered in this thesis. Mainly, the literature was surveyed on the topics of remote measurement of electrical and non-electrical quantities, the assessment of the quality of fruits using impedance spectroscopy and detection of adulteration in edible oils using different techniques.

Chapter 3 contains the details of the development of the three techniques for the remote measurement of temperature and electric current. The first technique deals with the remote measurement of temperature rise and the second scheme deals with the development of a novel system for the measurement of large values of electric currents using the Hall sensor (ACS750xCA-075) developed by Allegro Micro Systems, electro-optic converting circuit based on transistor, LED, fibre optic

transmission system, optical detector, microcontroller and LCD display, without making direct contact with the main power circuit. Finally, the third scheme deals with the development of a low cost, thermo-optic technique for the remote measurement of electric current under hazardous conditions.

Chapter 4 presents the development of an electrical impedance spectroscopy based technique for the Non-destructive assessment of the quality of the Fruits and vegetables. This technique is further developed to remotely assess the quality of the fruits.

Chapter 5 deals with the development of a novel fibre optic technique for the detection of adulteration in different edible oils by determining the cloud point of the oil under test.

Chapter 6 concludes the achievements of the research work carried out in this research work. It gives the scope of future work by highlighting the limitations of the completed work.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter deals with the survey of the available literature on the remote measurement of electrical and non-electrical quantities, on the assessment of the quality of fruits using impedance spectroscopy and detection of adulteration in eatables with special reference to edible oils using different techniques.

2.2 Remote Measurement of Temperature

Remote measurement of physical quantities plays an essential role in many of the scientific research as well as everyday applications. These techniques vary in their complexity and capabilities according to their applications. However, most of them share a common operating procedure. This procedure starts with connecting instruments to the devices under test, followed by a sequence of actions to set up and operate the instruments, monitor the system for abnormal or exceptional conditions, collect, and analyze the measured data from a remote place.

One of the most important non- electrical quantities which plays important role in any kind of research is temperature as it helps in the assessment of safety and stability of the different types of systems. It plays a very important role in the working of an item from a small chip to big rotating, static machines, airplanes etc. The remote measurement of any physical quantity has two major components i.e. the sensing part and the transmitting part. Variations may be targeted for accuracy,

precision, linearity, economy, simplicity and distance of observation. Some of the important techniques, recently published, are surveyed here.

The remote measurement of temperature, with dual spectral IR systems, has been reported in the book written by Chrzanowski (1996). The system is based upon determining the temperature on the basis of the ratio between two radiometric signals registered in two different spectral bands. The results show that the accuracy of remote temperature measurement depends on the measurement conditions and the system parameters. In another paper, spectral remote sensing method has been used in the measurement of a temperature profile of a hot gas in a furnace by Kim and Song (2002). The measurement of temperature profile of a hot gas is determined by using the Spectral Remote Sensing (SRS) method. Emphasis is placed on the accuracy of the SRS method in a test furnace with intense radiation emerging from the gas as well as from the rear wall. Kerosene is used as the fuel and a 2 m long stainless steel (STS) tube is employed as the test furnace. In calculating spectral intensity, the CK-based WNB model is used. The CO₂ 4.3 μ m wide band is used as the sensing spectra because this band does not overlap with other wide bands of CO or H₂O and CO₂ is always a product of hydrocarbon combustion likely which is utilized in most practical energy systems. The method proves to be applicable in determining the temperature distribution of the gas with a reasonable accuracy whether the rear wall is hot or cold. To demonstrate the SRS method, the recovered temperatures are compared with measured temperatures using thermocouples. The recovered temperature profile and measured temperatures are in good agreement within an error of 4%. For further study, the SRS method deserves more research regarding the effects of particle scattering and concentration of error.

Another remote sensing system for temperature and relative humidity has been investigated by Moghavvemi et al., (2005). The analogue signal of the sensor is applied to a microcontroller based data logger for storage purposes. The data is then transferred to the computer through standard RS232 serial port using the user interface program. The program also allows the user to input some of the important parameters such as sampling interval as well as the starting date and time for the logging operation. It is a low-cost product but has a large memory capacity. This is an added advantage when compared to other data loggers of the same type. However it can be used for small distances only.

Optical fibre temperature sensors that have been successfully used for the remote measurement of temperatures can be classified into extrinsic and intrinsic temperature sensors. Extrinsic sensing thermometers, also termed, indirect temperature sensors use the optical fibre for transmission of the electromagnetic waves between the sensor and the electronic temperature indicating system. In these sensing systems the light itself is modulated by some process outside the optical transmission system. Intrinsic sensing thermometers also, referred to as direct use thermometers, where the optical fibre itself is used as the temperature sensor. In these sensors a light transmitting property of the optical fibre is modulated by the temperature. They indicate either the average temperature of the fibre or the temperature distribution along its length.

Operating principle of extrinsic sensing thermometers is based on the dependence of the absorption coefficient of a semiconductor material upon its temperature and upon the frequency of the incident radiation. An early *extrinsic*

optical fibre sensor by Wang and Luo (2004) used a semiconductor material as the sensing element. The sensor is based on the temperature dependence of band gap edge absorption of infrared light in semiconductor, and made of multimode optical fibre in light reflected from a GaAs semiconductor platelet configuration. A light emitting diode is used as source of analytical and reference radiations, which eliminates the influence of intensity fluctuation of the light source and that of the coupling and connecting loss of optical fibres. Likewise, Kyuma et al.(1982) introduced a practical fibre-optic measurement instrument for temperature which consists of a small sensor responding to optical absorption change in a semiconductor, and a unique signal processing system with two different-wavelength light emitting diodes (LED's). The sensor's absorption of light at one wavelength changed as a function of temperature, and the light of the second wavelength was used as a reference. An accuracy of ± 1 °C was obtained for the temperature range of -10 to 300 °C. The sensor had a response time of 2 seconds.

Another type of thermometer uses fluorescent material, which is placed at the end of the light guide, and excited by the radiation of a given wavelength. The fluorescent radiation and the exciting radiation are subjected to monochromatic filtering, which allows easy separation of the radiation from the two sources, and causes the sensor to fluoresce at a different wavelength from the exciting light source.

The first generation fluorescent thermometers were based on temperature dependence of monochromatic repartition of emitted radiation. The GaAs sensor, which is placed at the end of the light guide, is excited by a LED modulated light

when it emits fluorescent radiation. The combined light from the visible fluorescent light emitted by the sensor and the exciting light is transmitted by the same light guide to an optical bifurcator which splits the light into two beams (Michalski et al., 2002). Each beam then passes through a filter. The output signal of the each filter, which is proportional to the respective intensities of light are applied to detecting Photodiodes, before being amplified. Taking the ratio gives a signal which is a function of the measured temperature. The readings are independent of the exciting radiation intensity; nevertheless they may be influenced by bending of the light guide (Augousti et al., 1987).

The second generation of fluorescent thermometers which are based on the decay-time concept of a periodically excited probe was developed by Shen et al., (1998), he found that the emitted intensity of radiation is a function of time and the decay time is the function of temperature. Moreover, a novel sapphire fibre thermometer, using fluorescent decay, was developed. The thermal probe is simply a sapphire fibre grown from the Laser Heated Pedestal Growth (LHPG) method. The relationship between the fluorescent lifetime of the intensity and the temperature, for the doped sapphire fibre, was carefully measured. Experimental result shows that the thermometer has an average temperature resolution of 1°C between 20 to 450°C. It can be used for remote measurement of temperature.

Seki and Noda (1987) theorized that a pseudo-heterodyne detection system using a PZT (piezoelectric transducers) light phase modulator and an analog switch can be applied to detect a phase difference of the Fabry-Perot interferometer with low reflectivity. A helium-neon laser is used as a light source. An object lens of 10

magnifications focuses the laser light on the fibre core. A 1-m-long nylon-coated single-mode optical fibre whose cutoff wavelength is 0.6 μm is used for the Fabry-Perot interferometer. The phase modulator is introduced to a part of this fibre, an optical fibre connector is employed at the output end of the fibre to achieve light coupling efficiency to the photo-detector. By this system, a temperature sensor using a fibre-optic Fabry-Perot interferometer has been developed.

As well as dual fibre-optic Fabry-Perot interferometer (FFPI) sensor system, with a low-coherence communication-system light emitting diode (LED), as a light source, have been investigated by Wang et al.,(2008) to detect temperature variation signals. In this system, there are two FFPIs: the sensing and reference FFPIs, and the light which reflected from the sensor is demodulated by the reference FFPI to extract the measurand. A low-power optical signal is converted into an electrical signal and processed by a designed optical receiver. This setup is applied in biosensors to compensate the temperature variation in a sensing environment or sense the temperature effect in a certain measurement on an interior local site.

Fibre-optic Raman scattering temperature sensors were produced by Iida et al., (1994), making it possible to measure temperature distributions up to 500°C. Laser pulses are passed through the optical fibre, then the laser beam is scattered in the fibre, consequently Raman scattering light is generated and measured on its return to the point of origin. The intensity of the Raman scattering light depends on the temperature of the optical medium. By measuring the intensity of the Raman scattering light, the temperature in the portion of the optical fibre where the scattered light was generated can be determined. This sensor is used in steel works to measure

the temperature of the steel shell of a hot stove and to detect potential molten steel leaks in the continuous casting from a remote place.

In another application, temperature dependence of the refractive index of optical fibres is used for the direct measurement of temperature. Gottlieb and Brandt (1981) described the theoretical and experimental study of a method of sensing temperature with optical fibres with the radiations thermally generated within the fibre. By using quartz fibres it is possible to read temperatures in the range from room temperature to over 1000°C. The method also allows the determination of the location and length of a hot spot along the fibre. The purpose of this type of sensor is to monitor the development of hot spots in electrical machinery, such as generators and transformers, where conventional measurement techniques cannot be effectively applied.

Moreover, remote health care system based on wireless sensor network has been investigated (Zhang and Chen, 2008). This remote health care system consists of sink nodes and sensor nodes. The MCU (Micro-Controller Unit) on the sensor node controls the sensors collecting and dealing with the data of the patients and transmitting the collected data through the multi-hop wireless network to the Web Server (sink node), consequently sink node deals with the data transmitted from the sensor node and transmits the fused data to the remote central server, then the medical staff or scientist can deal with the data and come to some conclusion.

Likewise, wireless sensor networks for monitoring patient vital sign data in a hospital setting have been designed by Hande et al., (2006). Commercial BP/heart-

rate monitor (BPM) was interfaced to a wireless sensor. The sensor node controls the BPM to initiate a reading, then collects the data and forwards it to the base station.

Literature review presents different designs and development of many configurable remote access measurement techniques. Many new methods, achievements, additions and developments, as well as literature references, are included to review many different applications. The developed systems are not limited to a specific application domain, it offers a generic architecture that can be easily maintained and extended.

2.3 Remote Measurement of Electric Current

Electric current remote sensing and monitoring is a basic and important technology for control, protection, and supervision in most of the facilities sustaining industry and community, such as power facility. A number of devices are employed to transform the current to be measured into a form suitable for further processing at safe limits. The remote measurement of alternating current is simple and generally done with the help of current transformers generally. However remote measurement and control of direct current is a difficult job and is accomplished with the help of modern devices with good order of accuracy. Generally, Hall effect sensors and electro-optic sensors are used for the remote measurement of direct Electric current.

2.3.1 Hall Effect Sensing System

The Hall effect was discovered by Dr. Edwin Hall in 1879 while he was a doctoral candidate at Johns Hopkins University in Baltimore (Areny and Webster, 2000). Hall was attempting to verify the theory of electron flow proposed by Kelvin some 30 years earlier. Hall Found, when a magnet was placed so that its field was perpendicular to one face of a thin rectangle of gold through which current was flowing, a difference in potential appeared at the opposite edges. He found that this voltage was proportional to the current flowing through the conductor, and the flux density or magnetic induction perpendicular to the conductor.

The Hall effect is an ideal sensing mechanism. The Hall element is constructed from a thin sheet of conductive material with output connections perpendicular to the direction of current flow. When subjected to a magnetic field, it responds with an output voltage proportional to the magnetic field strength. The output voltage is very small (μV) and requires additional electronics to achieve useful voltage levels. When the Hall element is combined with the associated electronics, it forms a Hall effect sensor. The heart of every MICRO SWITCH Hall effect device is the integrated circuit chip that contains the Hall element and the signal conditioning circuits.

Although Hall's experiments were successful and well received at the time, no applications outside of the realm of theoretical physics were found for over 70 years. With the advent of semiconducting materials in the 1950s, the Hall Effect found its first applications.

However, these were severely limited by cost. In 1965, Everett vorthman and Joe Maupin, MICRO SWITCH sensing and control senior development engineers, teamed up to find a practical, low-cost solid state sensor. Many different concepts were examined, but they chose the Hall Effect for one basic reason that it could be entirely integrated on a single silicon chip. This breakthrough resulted in the first low-cost, high-volume application of the Hall effect. MICRO SWITCH Sensing and Control has produced and delivered nearly a billion Hall effect devices in keyboards and sensor products.

2.3.2 D.C. Electric Current Measurement using Magnetic and Semiconductor Devices

A simple circuit for the measurement of direct current (D.C.), using a transformer, has been presented by Pejovic (1998). The circuit is based on nonlinear effects in the transformer ferromagnetic core, and it provides information about the current magnitude and polarity. The circuit is analyzed by applying piecewise-linear model of the core magnetization curve. An average circuit model and the circuit transfer function are also given. Experimental verification of the proposed circuit has been made and good linearity as well as wide measurement range is obtained. Design guide lines for the reduction of the output voltage ripple are given. Authors claimed accuracy is within 0.25% of the full scale.

Developed network studied the accuracy of dc busbar current measurement up to 50 A (Bera and Chattopadhyay, 2003), and output signal is used to send a feedback current through a winding in order to nullify the magnetisation component of the dc flux, the measurement assumed to be more accurate with respect to other similar conventional single core or two core saturable reactor or transductor, which

has been used for dc busbar current measurement. The conventional method may suffer from errors due to the magnetization component of the dc flux and the asymmetry of the core materials.

Isolated current transducer has been used (Pross et al., 1999) for the measurement of direct electric current with the help of a device which employed a Hall Effect sensor to sense magnetic flux in a core as the basic sensing element. The transducer uses a carrier signal produced by the closed loop structure as a high frequency limit cycle to provide DC transmission from the input signal to galvanically isolated output.

Different magnetic field sensors are based on Hall Effect which exploit the deflection of moving electrical charge carriers due to the Lorentz force in the presence of a magnetic field. Performance of this current sensor based on giant magneto impedance (GMI) effect in amorphous ribbon has been tested (Rheem et al., 2003). DC current direction can be determined due to the asymmetric characteristics of GMI effect. The sensor output voltage increases with applied current up to 1A with a good linearity.

Furthermore, Semiconductor industry increased the importance of accurate measurement and control of very small current. Cryogenic current comparators (CCCs) and superconducting quantum interference device (SQUID) sensor are developed in the field of precision electrical measurement (Rietveld et al., 2000). In an international co-operation project, a special CCC system is being developed,

optimized for the measurement of extremely small currents to less 1 pA (10^{-12} A) with high sensitivity, accuracy, and best current resolution due to inductance matching of the CCC and SQUID.

New current measurement circuit for measuring DC current has been investigated using CMOS chip (Tam and Roberts, 2003). The circuit consists largely of digital electronics except for a comparator and a passive RC filter. Experimental results show that the circuit could measure currents with 9-bits of resolution, and minimum current step of 78.1 nA.

2.3.3 Electric Current Measurement using Electro-Optical Sensors

Optical sensors and transducers have risen to a performance level exceeding conventional magnetic devices, and optical current sensors are achieving increased acceptance and use in high voltage substations due to their superior accuracy, bandwidth, and dynamic range. Developing different prototypes of commercial optical current sensors based on different schemes are still the challenge, which will be reviewed below:

A fibre-optic current sensor for aerospace applications has been developed by Patterson et al., (1990). The sensor uses the Faraday effect in optical fibre and standard polarimetric measurements to sense electrical current. The primary component of the sensor is a specially treated coil of single-mode optical fibre, through which the current carrying conductor passes. Since the integral of the magnetic field around a conductor is proportional to the current flowing through it, the rotation of the plane of polarization is proportional to the current and independent

of stray fields. A robust, accurate, broad-band, alternating current sensor using fibre-optics is being developed for space applications at power frequencies as high as 20 kHz. It can also be used in low and high voltage 60 Hz for terrestrial power systems and 400 Hz in aircraft systems, respectively.

Cruden et al. (1993) developed and tested an optical crystal based current sensor for use on medium and high voltage power networks. The sensor uses a Terbium Gallium Garnet (TGG) magneto-optic crystal and is of an unlinked nature, with the sensing head consisting entirely of dielectric materials. A schematic diagram of the optical system is used, An 850nm light emitting diode (LED) light source is used with a corresponding PIN photodiode as the detector. Testing is reported at voltage levels up to 300kV and current levels of 75kA.

In another research work a transducer has been developed with a capability of measuring current up to 50 kA (Hasegawa et al., 1994), which is composed of a current measuring unit, an insulator with integral optical fibres. The current measuring unit combines a winding with a magnetic iron core and a solenoid coil containing a Faraday sensor. Prototype optical current transducers have satisfactory target performance requirements and have maintained that level of performance in field applications also.

A novel all-fibre, magneto-optic current transformer is reported (Dawson et al., 1995). Changes of the optical system response to current with temperature have been measured to be linear with a slope of $6.9 \times 10^{-5}/^{\circ}\text{C}$ with an error bar of less than 0.2% over the temperature range of -40 to +80°C. This temperature dependence can

be entirely attributed to the change in the Verdet constant of the glass. This is, to our knowledge, the first report of a birefringence free fibre-optic current sensor with Verdet constant limited performance. The sensor's response to current is linear to within 0.3% from less than one amp up to 110 amp, the limit of our measurement capability. With an optically powered data link and a transducer, direct current, voltage and temperature measurements have been successfully made by Werthen et al. (1996).

This paper presents a high bandwidth, optically powered current transducer (OPCT), and based on shunt technology. This OPCT replaces a conventional current transformer (CT), eliminating its disadvantages such as non-linearity, overvoltage coupling and risk of explosion and fire. Due to the compact design of the shunt in combination with the optically powered data transmission, the OPCT is ideal in seismically active areas. The system includes two modules connected by optical fibre up to 1 km in length. This remote module converts the optical power into electrical power for the electronic circuitry.

Robles and Giannetti (2000) have also presented a method based on thin cobalt films which will be eventually developed as a current sensor. Two magneto-optic effects are considered in this design, namely (Faraday and Kerr effects). Measurements have been taken in both cases to decide which may be more interesting in the design. They have concluded that the Faraday effect gives larger polarization angle rotation. Different electronic schemes are also studied to attain the most accurate and noiseless output signal. Magneto-optic sensors allow to measure currents through high voltage lines with considerable advantages.

In a similar way, current sensors based on the Faraday effect have been successfully demonstrated with both interferometric and polarimetric configurations (Ferrari et al., 2000). The sensing element is a piece of material of high Verdet constant placed between polarizers. The aim of this study is to describe a novel ac current sensor that uses an optical signal of twice the frequency of the ac signal, which is generated in addition to the usual signal with the same frequency as the current, these signals travel along the same optical path and are measured at the sensor output. The experimental results, demonstrating the practicality of the procedure, are presented.

In another development work, an optical method for the simultaneous measurement of current and voltage has been theoretically proposed and experimentally verified by Li and Yoshino (2002). An optical fibre sensor allows current and voltage to be measured simultaneously by the use of only one block of bismuth germinate crystal. The polarized light from the sensing crystal is split into two light beams; one beam is utilized for current measurement based on the Faraday effect, and the other one is utilized for voltage measurement based on the Pockels effect. The simultaneous measurements of a.c electric current from 0.05 to 10 A, voltage from 1 to 235 V, and power from 2 to 1000W have been attained with good linear-response characteristics.

A new approach for the measurement of A.C. current at high-voltage system has been proposed by Millan et al. (2002). Their sensor exploits the magnetostriction of the ferromagnetic core of a standard current transformer, which is wound by a length of single-mode fibre onto it and a Mach–Zehnder interferometer. The

deformation of the core due to the magnetic field generated by the current produces a frequency-modulated output signal. The current is obtained from the frequency features of the optical signal, and so the sensor avoids certain shortcomings of other fibre optic current sensors such as light power fluctuations, phase drift, and polarization sensitivity.

Yi et al. (2002) described an air-gapped ring core type, optical current sensor based on Faraday-effect using a new design of sensing element. The sensing element is a finely polished glass prism with highly reflective coatings on the two end surfaces, which is designed in such a way that the light beam propagating through it undergoes 20 critical-angle reflections at the glass–air interfaces. An experimental sensor based on the new design has been constructed and tested. It has been verified experimentally that the sensor is sensitive with a new design of Faraday sensing element with an improved current sensitivity used in a ring core type optical current sensor.

In another development work for the simultaneous measurement of voltage and current, on high-voltage distribution lines, was developed by Werneck and Abrantes (2004). The sensing heads used a resistive divider and a magnetic pickup for sampling voltage and current, respectively. A self-powered transmitter converts both signals into a pulse-frequency-modulated optical signal for transmission in multimode optical fibre. At remote place the optical signal is received and demodulated back into voltage and current signals. Thereafter a microcontroller calculates voltage and current for the three phases, and stores them in memory.

Dziuda et al. (2005) has demonstrated hybrid fibre-optic current sensor for remote monitoring of electrical submersible plant from multilayer piezoelectric stack and a current transformer, to monitor electrical submersible pumps operating several tens of km away from an oil rig. The sensor can be employed for the simultaneous measurement of ac current and temperature on remotely operated electrical plant.

Current measurement based on signal detection method for demodulation of Fibre Bragg grating (FBG) wavelength shift has been developed by Zhao et al., (2006). Being attached respectively on the upper and lower surface of a pendulum-type cantilever element, only a couple of matched FBGs are used for both current sensing and wavelength shift signal demodulating. So, the received light power will change due to the split of the two reflected spectrum of FBGs, which correspond to the electromagnetic force caused by the measured current.

2.4 Food Quality Assessment Techniques

Assessment of food quality has all along been in terms of wholesomeness, acceptability and adulteration. Many ingenious approaches have been worked out and subjected to comparative investigations, their reproducibility, sensitivity, simplicity and feasibility for routine application have been critically evaluated in collaborative studies and the methods approved have been selected as official.

The problems arising in the area of major food commodities, the application of the new approaches and the direction of future work are indicated in the literature. It is therefore considered appropriate to survey these trends and highlight the novel approaches that are opening up to the analyst and those are sure to help in solving the

new problems that food scientists are likely to face in the future. During the recent past, several new challenges have been posed to the food quality assessment techniques out of which some have been solved and remaining will be solved by the devotion of the new generations.

2.4.1 Physical factors which decide the quality of fruits and vegetables

Quality is defined as meeting the expectations of consumers. Generally, the quality criteria for fresh products are appearance, texture and flavor (Jongen, 1996). Consumer's preferences drive fresh food industry to provide good quality fruit and vegetables (Peneau et al., 2006). Moreover, efforts have been made to enhance their quality using genetic engineering. Quality evaluation techniques have been around for several decades. These techniques started from a single parameter measurement, such as weight, size, firmness measurements etc. Then more complex biochemical and biophysical analysis were applied to observe internal quality changes, such as titrable acidity measurement, nutritional analysis, and enzymes degrade analysis etc. With the development of information technology, quality assessment is in the state of evolution.

2.4.1(a) Colour

Human visual evaluation has been the primary empirical method for the grading and sorting of fruits and vegetables. Appearance comprises colour, shape, size etc. and is the key factor when consumers are purchasing fruits. Many fruits undergo colour changes during ripening, for example in bananas, the chlorophyll content of the peels of bananas reduces with ripening which contributes to peel

colour changes (Li et al., 1997). Thus the fruit colour is considered to be a strong indicator of the ripening process.

2.4.1(b) Firmness

Firmness is also a term for hardness (Hung et al., 1999). It is a very good indicator concerning eating quality products, and it has also been used as a measure of maturity and ripeness of the fruits (Hoehn et al., 2003). It is usually measured by a penetrometer. The disadvantage of this method is that the samples examined are destroyed and cannot be sold. A non-destructive measurement is therefore very much more desirable. Over the past two decades, resonant frequencies, acoustic response, and ultrasonic approaches have been used to investigate the firmness of food (Gunasekaran, 2001).

2.4.1(c) Sweetness and Sourness

Sweetness is normally referred as the total soluble content in Brix (Harker et al., 2002). It is measured with a refractometer. Generally, the refractive index increases with the rise of soluble solids concentration. Additionally, infrared (IR) and NIR methods also have the capabilities to determine total sugar content directly from fruit juice (Rodriguez-Saona et al., 2001).

Acidity is generally determined by a titration approach. Titrable acidity measures total available hydrogen ion in solution. Sweetness, acidity, astringency, and bitterness are the four key taste components. Sugar level is measured on the Brix scale (Harker et al., 2002), which is a hydrometer scale for measuring the concentration of sugar in a solution at a given temperature. The sugar level is usually