WESTERN POWER DISTRIBUTION

INNOVATION

NEXT GENERATION NETWORKS

DEDUCE
Low Cost Sensors – Literature Review

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Contents

Glossary

Abbreviation	Term
API	Applications programming interface
CCD	Charge coupled device used in light sensors
CO	Carbon Monoxide
CREST	Centre for Renewable Energy Systems Technology at Loughborough University
DB	Distribution board
DNO	Distribution Network Operator
EEPROM	Electrically erasable programmable read only memory
emf	Electromotive force
FOCS	Fibre Optic Current Sensors
GPRS	General packet radio service (mobile data service)
GSM	Global system for mobile communication
HPLC	High Performance liquid Chromatography
I2C	Serial computer bus
InGaAs	Indium Gallium arsenide used in photodiodes
IOT	Internet of things
IR	Infra Red
LCNF	Low Carbon Network Fund
LP	Learning Point
LV	Low voltage (≤11kV)
MEB	Midlands Electricity Board
MEMS	Micro electromechanical systems
PCB	Printed circuit board
POF	Plastic Optical Fibre
RFID	Radio Frequency Identification
rms	Root mean squared
SPI	Serial Peripheral Interface bus
SPL	Sound Pressure Level
UART	Universal asynchronous receiver-transmitter (for asynchronous serial communication)
UV	Ultra violet

1 Executive Summary

Recent growth in embedded generation such as wind and solar photovoltaic (PV) systems and the anticipated consumer uptake of electric vehicles (EVs) and heat pumps present new challenges for Western Power Distribution (WPD) to develop and operate its network which will experience greater fluctuation in electricity demand.

Data from maximum demand indicators in distribution substations is inadequate to understand the spread of demand over time. Retro-fit datalogging solutions are available for substation monitoring, but cost typically >£1200, which would be difficult to justify for all of WPDs 40,000 distribution substations.

This NIA (Network Innovation Allowance) research project on network analogues is being conducted by CREST (Centre for Renewable Energy Systems Technology) at Loughborough University in conjunction with Aston University and WPD.

The aim of the project is to identify and develop a novel low-cost monitoring approach with a target cost of £100 per substation.

Engineering projects usually capture the requirements first then identify the best solutions for those requirements. This project intentionally has a tightly defined cost requirement and loose technical requirements, which are as follows:

- The solution shall cost £100 or less excluding installation and operation costs.
- The solution should give an indication of substation loading.
- The solution should act as a replacement for existing MDIs (maximum demand indicator).
- The solution should provide as many channels of useful data at the highest feasible resolution within the cost requirement.
- The solution should consider how data will be transferred to a WPD datacentre or control room.

CREST will design build and test 6-8 different sensors which will be laboratory tested against a set of pre-defined characteristics to determine usefulness and estimate value.

This report is one of a series of reports which focuses on a literature review of existing sensor solutions.

2 Introduction

2.1 Background

DNOs currently have very limited visibility of LV networks. With Supervisory Control and Data Acquisition (SCADA) systems generally limited to 11kV feeders, visibility of LV network loading is restricted to Maximum Demand Indicators (MDI). These manual readings are generally supplemented with industry metering flows to develop an understanding of network loading. MDIs are restricted by their need to be reset periodically as well as the potential for network back-feeds to distort readings.

A number of previous LCNF projects have looked into LV monitoring. This has pushed the market for LV monitoring forward significantly from the custom-built units used for the Low Voltage Network Templates project, to a number of commercially available units available to date. WPD currently has Standard Techniques (STs) for the installation of ground mounted and overhead monitoring as well as a fully tendered framework agreement for the supply of such units.

These units depend primarily on the measurement of voltage and current to determine loading. Voltage is generally measured directly through the use of busbar clamps or modified fuse holders with a voltage take off point. Current is generally measured using Rogowski coils. These units are capable of measuring the detailed loading of each phase on each feeder and provide a significant level of detail and granularity. However, these devices are also costly due to the requirement for multiple sensors. This has limited their roll out to date.

This project looks to develop a low cost (sub £100) distribution substation monitor based on indirect loading measures (temperature, noise, vibration, etcetera). At a minimum this must give access to more granular and less error prone data than is currently acquired through MDIs. The substation monitor is expected to develop a methodology for the acquisition of basic whole substation loading profiles as well as the optimal method for the delivery of such data to planning teams and simplicity of installation.

To meet these aims the following approaches are proposed:

- To investigate existing low-cost sensors that can be used for indirect substation loading monitoring.
- To investigate new disruptive technologies to determine their suitability and accuracy for monitoring
- To use existing low-cost measurement devices or packages (such as a smart phone or raspberry pi) to indirectly provide measurement
- To run a university based competition to enable non-traditional solutions to be explored

The trial of existing low-cost sensors and investigation of disruptive technology will be undertaken at Loughborough University by B Goss under the guidance of D Strickland, A Cross, M Thompson and R Ferris. 6-8 different sensors will be designed, built, tested and characterised in the laboratory with possible follow through to testing on University owned 11kV/400V facilities if applicable.

This document concentrates on the investigation into different types of potential low-cost sensors through a literature review.

2.2 Scope

To meet these aims the following scope of work has been proposed:

- Investigate existing low-cost sensors that can be used for indirect substation loading monitoring.
- Investigate new disruptive technologies to determine their suitability and accuracy for monitoring
- Use existing low-cost measurement devices or packages (such as a smart phone or raspberry pi) to indirectly provide measurement
- Run a university based competition to enable non-traditional solutions to be explored

This document is the literature review into low cost sensors and disruptive technology, to decide on a selection of sensor types to investigate.

The project is aimed at 11kV:400kV 50Hz distribution substations connected to public distribution networks. The project focuses on ground mounted substations on the 11kV distribution network since these account for the bulk of final LV demand. As such pole mounted transformers and substations on legacy 6.6kV networks are not specifically covered since they are a small proportion of overall demand. Likewise, primary substations are not specifically considered since the smaller number of primaries and greater power flow means more accurate and robust solutions are more like to be justified economically. Monitoring at the DNO/meter operator/consumer interface is not considered since a wide range of parameters will be available from smart meters as they are commissioned as part of a national program.

The findings of this project may have relevance for monitoring of 6.6kV substations, pole mounted transformers and primary substations which could be determined as part of a successor project.

2.3 Presentation of learning

Throughout the document, key learning outcomes are presented in a box as follows:

LP x	Brief description of learning.

Each piece of project feedback is referenced as a uniquely numbered Learning Point (LP). All learning points are collected together in the Appendix.

3 Sensor Types

3.1 Introduction

There are many definitions of a sensor. In the context of this report - a sensor is a device which provides an electrical output with respect to a specific physical quantity. Sensors can be further classified in many different ways.

- Explicit or implicit (direct measurement or data collected from physically accessible points and parameters of interest estimated)
- Active and passive (requiring external power or not)
- Means of detection (electrical, biological, chemical)
- Means of conversion (photoelectric, thermoelectric, electrochemical)

Note: the sensor is not just about a sensor type but needs to include

- Primary sensing element
- Excitation control (if needed) – power rating of this
- Amplification
- Analogue filtering
- Data conversion
- Compensation
- Digital information processing
- Digital communication processing
- Communication

Any measurement system designed needs to come in at an appropriate cost in its entirety. Tied up with all measurement is the need to define quality of that measure in terms of accuracy based on bias, variance and confidence. In addition, it is important to understand issues on implied measurement such as calibration.

Figure 1 is a summary of the different types of sensor that are available. The following sub-sections look at each of these sensor detection types in turn and describes briefly how they work, what they can measure, a discussion on whether or not this can be linked to substation loading, what typical ranges they come in and if it is possible to adapt these for use in this project.

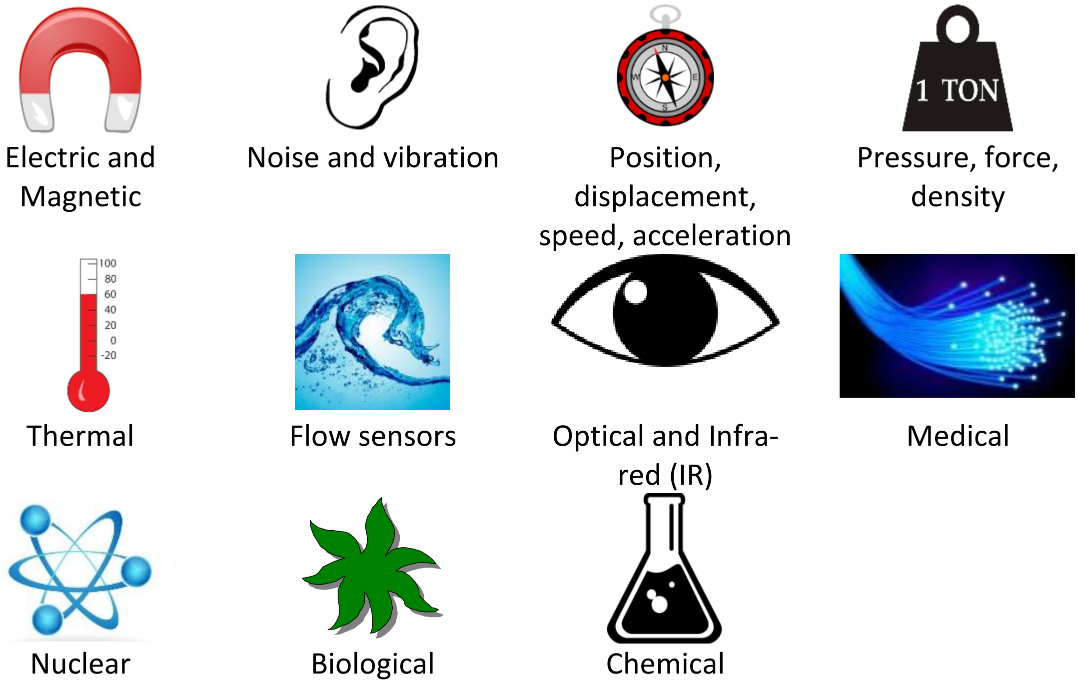


Figure 1 : Types of sensor detection

3.2 Detailed Sensor Review

3.2.1 Electric and Magnetic Transducers

Electrical transducers are normally divided into current and voltage transducers. There are a number of devices around to measure current. These include direct measurement devices such as Current Transformers (CT's) including clamp meters, and devices which measure related parameters such as magnetic field or voltage such as the Hall effect transducers and Rogowski coils. Figure 2 shows the operating principles of these common devices. A CT may be of a split core type to aid installation, while a Rogowski coil is usually easier to install but more expensive. It is uncommon to use a single device to measure the current in a multi-core cable but not unknown.

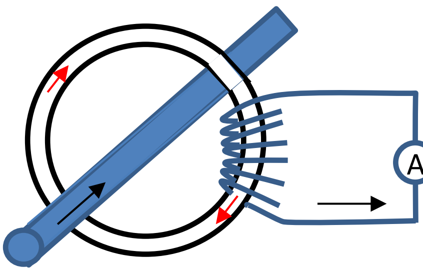
It is typical to measure voltages using voltage transformers (VT's). However, to do so the substation must be taken off-line for installation purposes.

Some low-cost devices of up to 400A, 415V of unknown quality as advertised on the internet are shown in Table 1. The cost in this table is just for the sensor and then on top of this, the conditioning systems, data monitoring, separate power supplies and communication system are required. Therefore, to monitor a LV feed would require 4 CT's and 3VT's, installing, possibly in a panel with testing and commissioning. It is likely that this will give a cost of well over several thousand pounds. The lack of information on loading on LV substations has been reported as increasing costs for new connections as a worst case loading scenario is assumed if there is no up-to-date MDI figure [1]. Some attempt at low cost version of these devices have been published including versions of Rogowski coils [2] and current sensors [3].

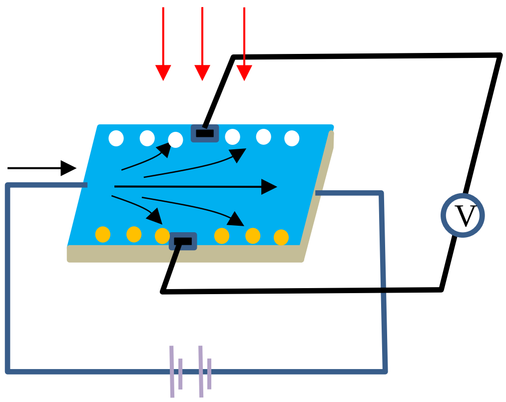
Table 1 Current and voltage measurement devices

Device	Reported approximate cost
Single phase, split core, 35mm aperture [4]	£20 each ex VAT
Single phase, split core, 40mm aperture [5]	£30 each ex VAT
Single phase current clamp meter	£22 each ex VAT
Single phase Rogowski coil [6]	£212 each ex VAT
Single phase, through core, Hall effect Transducer [7]	£20 each ex VAT
415V transformer to 24V per phase	£40 approx.

Current transformer – The current in the wire produces a magnetic field which links to the secondary winding causing a current to flow which is then measured.



Hall effect transducer – A semiconductor material passes a constant current. When the device is placed in a magnetic field, the field deflects the holes and electrons sideways, generating a voltage



Rogowski coils – A flexible coil that can be wrapped around a cable giving a voltage proportional to rate of change of current. An integrator is needed to give a voltage proportional to current

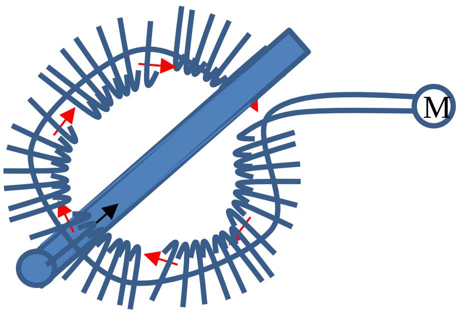


Figure 2 : Current transducers

There are some publications available on a limited number of devices which allow multi-core measurement. An example would be the patented Suparule Flexiclamp as shown in Figure 3. The sensor uses up to 7 planar coils placed around a multicore cable to measure magnetic field. If the sensor-conductor distance is known and the spacing between conductors then the magnetic field components of each conductor can be measured [8]. This sensor was used in the Megger MMC850 multicore current sensor which is now discontinued. The meter had 5 settings for different flat and round 1, 2 & 3 core cables, it could measure up to 16mm^2 & up to 100A in multicore mode. A similar current sensor is used in the Fluke T6 open jaw current sensor which can only be used on single core cables. It is unclear why the Megger instrument was discontinued; the most likely scenarios are:

- Lack of demand, as the instrument can only be used on a limited number of cable types, and electricians might not want to carry equipment unless they use it regularly.
- Electricians may prefer using single core instruments inside DBs if they get more accurate measurements.

No other articles, patents or web pages for devices to measure the current in multicore screened cables were found.

Figure 3 Suparule Flexiclamp sensor technology [8]

Figure 4: Megger MMC850 multicore clamp meter

Any current carrying conductor produces a magnetic field. The magnetic field strength B at a distance r from the centre of a conductor can be calculated as

$$B = \frac{\mu I}{2\pi r}$$ Equation 3-1

Where I is the current in the conductor and $\mu = \mu_r \mu_o$ is the magnetic permeability of the medium between the conductor and sensor measured in Henrys per metre (H/m). With the exception of iron/steel, all other materials can be assumed to have a value of permeability of $4\pi \times 10^{-7}$ H/m with a relative permeability μ_r=1. This equation provides a link between load current and the measurement of the magnetic field.

The magnetic field can be measured using a magnetometer of which a hall effect device is one example. Other examples include a fluxgate magnetometer (used in space to look at 3D flux density). This works by using a drive coil to saturate an iron core into saturation as shown in Figure 5. This can be toroidal, or rod based.

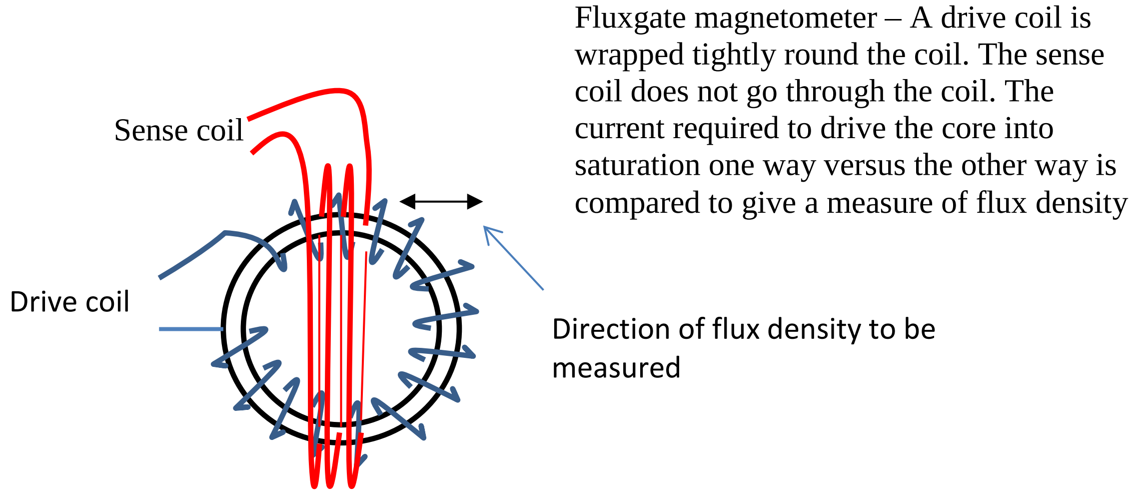


Figure 5 : Fluxgate sensor

Taking an example of a conductor carrying 400A rms current and a sensor at a distance of 50mm, the peak magnetic field strength would be 0.0023 Tesla which is close to the 0.002T measurement range of a typical Android magnetometer (for example the Yamaha YAS537), as listed in Table 2.

Extending this example to look at three phase balanced currents gives a flux density at a point distant to the red phase as shown in Figure 6 of +/-0.0014T pk.

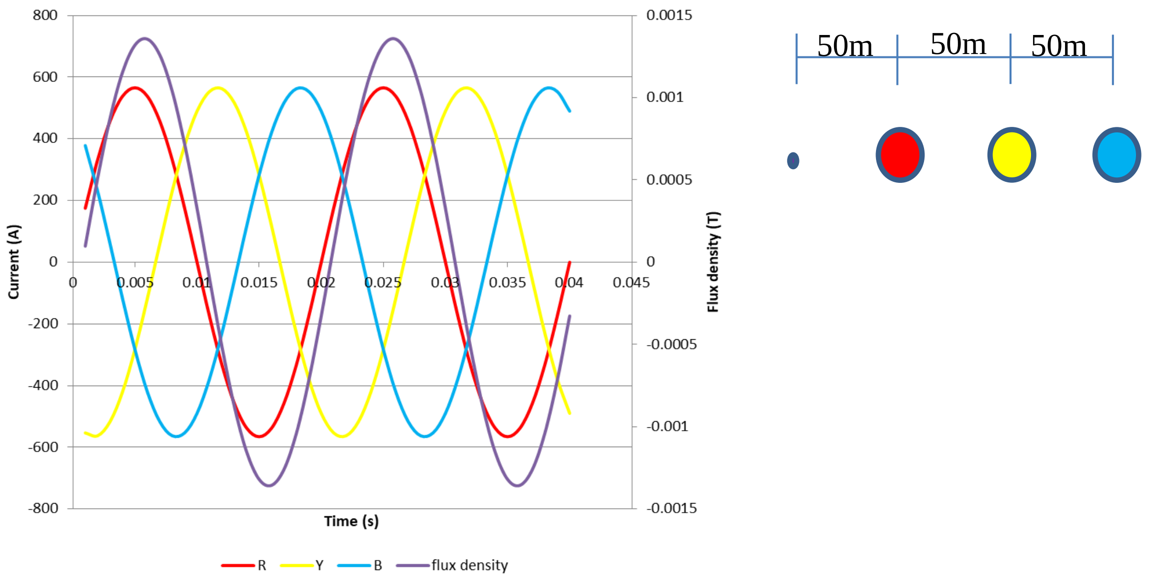


Figure 6 : Flux density in the presence of 3 balanced single core cables

Table 2: Comparison of Magnetometer / Linear hall effect chips

Sensor	Range	Sensitivity	Noise	Sample rate	Notes
Freescale MAG3110	+/-1mT	0.1uT	0.25uT	80Hz	Prototype PCBs
Yamaha YAS537	2mT	0.3uT	0.25uT	1.6ms	Samsung S6
Honeywell SS39ET/ SS49E/ SS59ET	+/-10,000G = +/- 10T	1.4mV/Gauss		3us	
Analog devices AD22151	13950G =13.9T	0.4mV/G			

NB 1 Tesla = 10,000 Gauss

However, the presence of other conductors in the area will alter the magnetic field. This is particularly the case in a three-core cable. Any metallic sheath around the cores will have eddy current induced into it which will produce a field of its own. Figure 7 shows the flux plot produced by finite element analysis of a 3-core cable with lead sheath carrying a 400A balanced current.

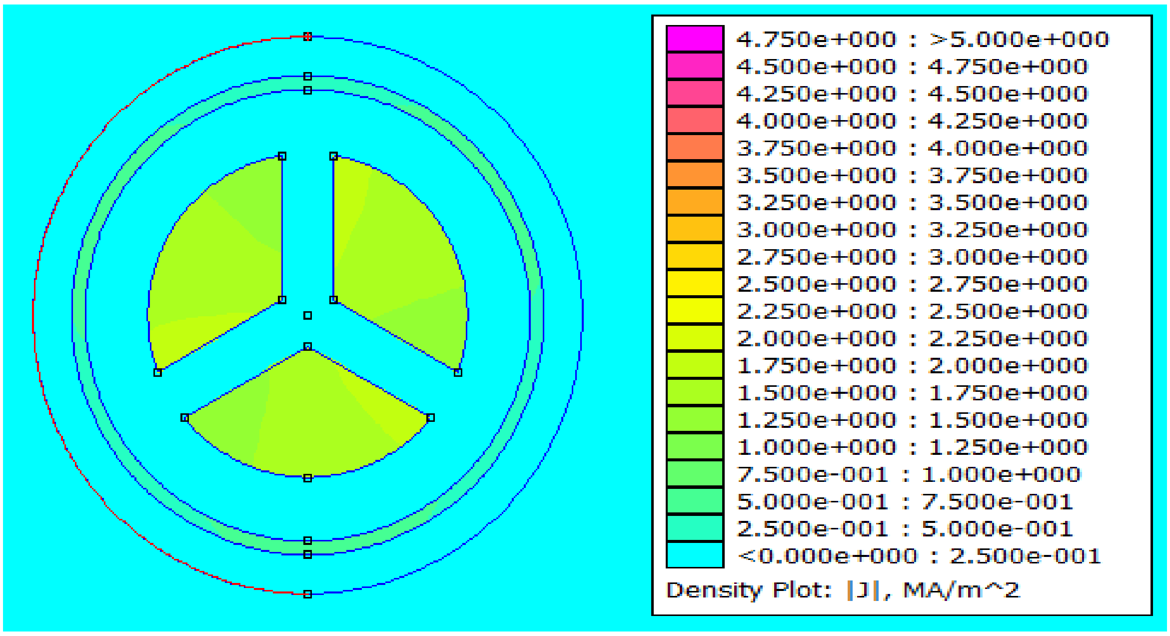


Figure 7 : Theoretical flux in a 3-core cable

The normal magnetic field (B) along left-hand outer contour of insulation (can just be seen as red in the above plot) shows a classical sinusoidal type pattern as shown in Figure 8 of the order of magnitude of approximately 0.001 to 0.0017T.

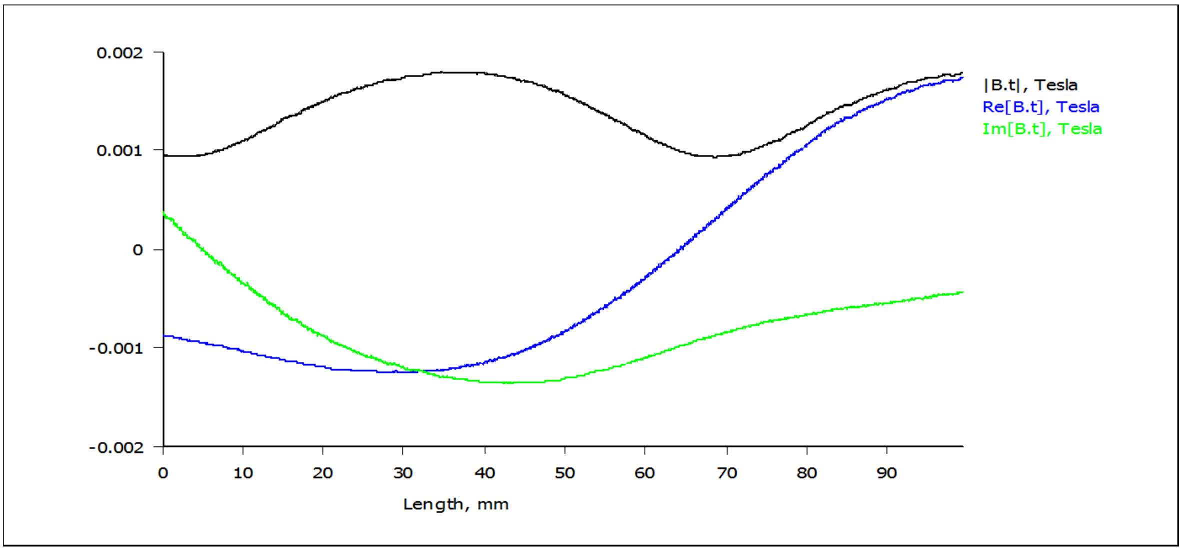


Figure 8 : Theoretical normal component of flux around the outside of a 3-core cable

The lowest cost current transformers found on the internet to measure current >100A cost upwards of £20 per sensor, whereas a magnetometer chip is available for ~£1 or on a development PCB for £10-15.

In addition to magnetic field, there is the opportunity to look at electric field. An example of an electric field measurement includes using capacitance to detect the presence of voltage in a conductor by non-contact 'voltage sticks' (Figure 9). Until recently these only provided a binary on/off visible indication.

The Fluke T6 meter (Figure 10) now gives a voltage reading with a non-contact option. Non-contact voltage sensors rely on the user providing continuity to ground in order to function – however a separate bespoke ground connection may be needed if the user is wearing insulated boots. Because of the large measurement uncertainty non-contact sensors are not approved by the health and safety executive under guidance note GS38 to prove LV circuits are dead prior to working on them. However, this does not mean that this type of measurement isn't available for looking into voltage. These sensors work by detecting the steady state electrostatic field produced by ac voltage through insulation without requiring contact to the bare conductor.

Figure 9: Fluke VoltAlert non contact voltage detector pen

Figure 10: Rear view of Fluke T6 meter with non contact voltage detection

Summary

Measurement path is as follows:

Load current in cable → magnetic field → measured using magnetometer

It may be possible to back calculate the current directly from the magnetometer reading. However, the complexity of a substation lay out means that indirect measurement and on-site calibration will probably be required.

Expected range of measurement 0 – 0.002T

Recommendation – to try this device as part of the project.

3.2.2 Sound and vibration transducers

A substation is not normally a silent place of work. Sound and vibration around the transformer can come from different sources including but not limited to;

- A combination of magnetostrictive deformation of the core and electromagnetic forces in the windings, tank walls and magnetic components. The vibrations produced from the forces causes sound to be radiated.
- Additional noise from partial discharge during insulation breakdown emits sound at specific frequencies which it is claimed can be isolated from other noise using a band pass filter [9].
- People and switching activity

It is not untypical to assume that the noise produced by the transformer has a no-load component and a load component. It is only where these values are different that it may be possible to detect the influence of the load current on the noise.

Vibration originates in the core, windings (and, in the unlikely event that it is present, an on-load tap changer). The sound and vibration can propagate through the oil to the transformer walls, where the vibration signature can be measured. Tank vibration signals may have a relationship with the condition of the transformer's core and windings providing claimed diagnosis information [10]. Load based vibration in transformer windings is due to the Lorenz electrodynamic forces caused by the interaction of the current circulating in the windings with the leakage flux. These forces are proportional to the current squared and have axial and radial components. In the simple case of a two-winding transformer, radial forces tend to compress the internal winding and to expand the external one, since currents in the windings have opposite senses. Vibration depends on the square of the current which is a 50Hz sinusoid, so the main harmonic is 100 Hz, but some harmonics at other multiples of 50 Hz may be present due to magnetising current or residual harmonic currents.[9] Additional “off load and on-load” vibrations in the transformer core are caused by changes in its dimensions of about few parts per million due to the magnetic field, called magnetostriction and excitation generated at air gaps. Magnetostriction is a deformation of magnetic materials due to magnetisation and is defined in Equation 3-2 as follows:

$$\lambda = \frac{\Delta l}{l}$$

Equation 3-2

where Δl is the change in length, l is the length of the material. [11].

Vibration due to magnetostriction is proportional to the voltage squared. The voltage is proportional to the Magnetic Flux Density in Equation 3-3 which in turn is related to load current. However, this relationship is dependent on the cross-sectional area that the flux travels through. As this is not information that is readily available from transformer manufacturers, it is not possible to directly calculate this.

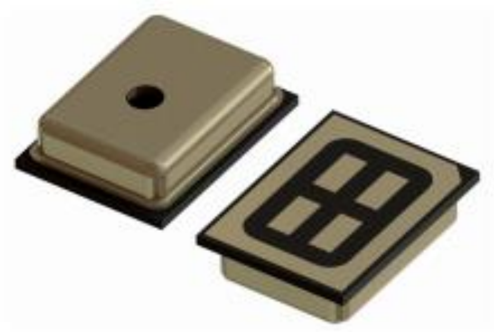
$$\mathrm{E} = 4.44\mathrm{fNBA}$$

Equation 3-3

Where: E is the voltage, N is the number of winding turns; B is the maximum flux density in the core; f is the supply frequency and A is the core cross-sectional area. [12]

Since core vibration is related to voltage and winding vibration is related to current, the former is present during no load conditions, but both are present under load. Some analytical expressions for noise level due to loading have been reported [13].This lack of a straightforward direct relationship between vibration and current loading means that a complex calibration process may be needed to relate the noise measured against the loading current.

The sound caused by the vibration can be detected with a microphone. These are classified by the type of electrical transducer they use. Some of the most common types of microphones are: Carbon microphone, Moving Iron microphone, Moving Coil microphone, Ribbon microphone, piezoelectric microphone and capacitor microphone. Some of these are pressure operated and some velocity operated. The microphones can be omni-directional or multi-directional. All but the Piezo electric microphones are used in air. The piezoelectric microphone can be immersed in non-conducting liquid. When the crystal is strained by sound waves, the ions of the crystal displace in an asymmetrical way and generate a voltage. Most modern devices use a capacitor microphone as a base and are an example of a MEMS (Micro-electrical mechanical) device. These can be around 3-4mm in size as shown in Figure 11.



Used in speech recognition, gaming and VR devices, Digital and video cameras.
Detects acoustic noise up to 120 dB SPL and costs £2.33 from Farnell

Figure 11 : An example of a MEMS audio sensor microphone

Summary

Measurement path is as follows:

Load current and voltage in transformer→ Lorenz forces and magnetostriction → vibration and noise → measured using a microphone or accelerometer

The complexity of the process means that direct measurement is not possible and initial investigations will determine how complex calibration processes are and the extent of on-site calibration.

Expected range of measurement: noise 20 – 20kHz, accelerometer 0-10mV/g

Recommendation – to try this device as part of the project.

3.2.3 Position and displacement transducers

Displacement sensors are concerned with the measurement of the amount by which some object has moved. Position sensors are concerned with the determination of the position of some object with respect to a reference point. Proximity sensors are a form of position sensors. They are used to determine when an object has moved to within some particular critical distance of the sensor.

These sensors can be contact or non-contact. In a contact system, movement of the sensor causes a change in one of the following; voltage, resistance, capacitance or inductance. Non-contacting sensors make use of a change of air pressure, inductance or capacitance in air.

- Capacitive based displacement looks at plate overlap area, separation distance or dielectric position in a capacitor.
- Differential transformers look at displacement of a core in a three-winding system, where the central winding is the excitation source and the difference between the other windings gives an indication of position of the transformer core.
- Eddy current proximity sensors look use a field to generate an eddy current in any close metallic object which in term produces its own opposite field and changing the impedance in the excitation supply coil.
- Inductive proximity sensor. This is a coil wound on a core – which if it comes close to a metal object changes its inductance. This impact can be monitored by its effect on a resonant circuit and can be used for detection of metals.

Optical, pneumatic and mechanical devices are also able to give indication of position and displacement.
Velocity and rotational motion can be measured using tachogenerators (variable reluctance or ac generator) which pick up the changes in magnetic field due to a rotating body.

Summary

At this time, it is not clear how these may be used to measure loading. They are included for completeness.

3.2.4 Pressure and force transducers

Although there are various types of transducers to measure pressure, the most common is the strain-gauge contained in a Wheatstone bridge circuit to convert pressure into an electrical signal. The strain gauge will produce an electrical resistance change proportional to the pressure. The most common type of strain gauge consists of an insulated flexible backing which supports a metallic foil pattern. (known as a foil strain gauge).

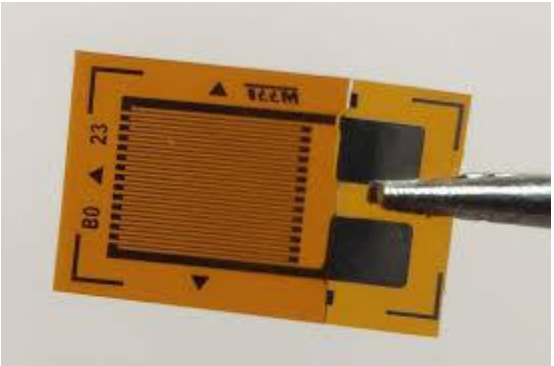


Figure 12: Example of a strain gauge

Strain gauge measurement may also be impacted by temperature so a dummy strain gauge close by can be used within the Wheatstone bridge to negate this effect. The gauge can be used to measure axial or bending strain.

Within a substation environment, loading of cables causes them to increase in temperature and this then causes their length to increase in accordance with the following equation.

$$\Delta L = \alpha \Delta T L \quad \text{Equation 3-4}$$

Where ΔT is the change in temperature, L is the original length and α is the co-efficient of thermal expansion. If the cable is prevented from moving this results in stresses developing forcing the cable to buckle slightly.

Measurements in literature indicate that the change in length is up to 2% (or 20 mε or 20,000$\mu\varepsilon$) on a temperature rise from 20^{o}C to 80^{o}C as shown below.

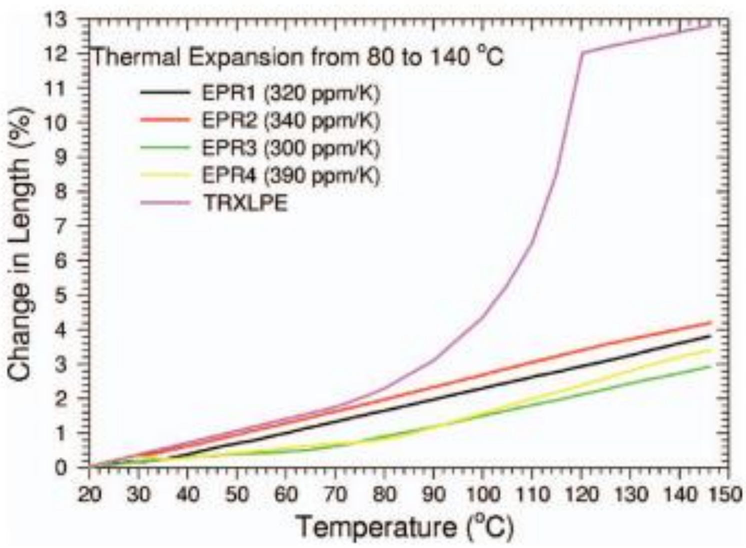


Figure 13: Change in length with temperature reproduced from Xiaoguang Qi and Steven Boggs "Thermal and Mechanical Properties of EPR and XLPE Cable Compounds" [14]

The stress in the wire is due to the force, P (restraining force preventing the cable expanding naturally)

$$f = \frac{P}{A} = E\varepsilon \quad \text{Equation 3-5}$$

Where A is the cross-sectional area. The stress is also a product of the modulus of elasticity, E and the strain, ε.

A strain gauge can be complex to set up and calibrate. Several factors can affect the measurement performance of a strain gauge, including signal conditioning issues, electrical noise, temperature fluctuations, and improper calibration. The strain gauge works on the ratio of fractional change in resistance to the fractional change in length:

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\varepsilon}$$ Equation 3-6

Sensitivity at 1000$\mu\varepsilon$ is anything from 0.5mV/V to 1.3mV/V in the Wheatstone bridge and amplification may be needed. Typically, 3-10V are used to excite the circuit. The higher the excitation the easier it should be to measure the change in voltage due to strain however, it may result in self-heating. This is especially true if the strain gauge is mounted on an insulator. Long leads may also need to be compensated for as their change in impedance due to carrying current may be of a comparable order of magnitude.

In the case of the cable, with say an increase from 20^{o}C to 40^{o}C this results in a strain of 2000$\mu\varepsilon$ resulting in a change in voltage in the Wheatstone bridge of 1mV. Difficult to measure but not impossible.

Other types of strain gauge include variations on this such as wire based resistance element, semiconductor strain gauges and thin film strain gauges. The gauge factor for a semiconductor strain gauge is many times that of a foil or wire based system (100 compared to 2) – however these are non-linear devices.

They key to using a strain gauge is to determine in advance the likely pressure and change in length and match this to the device. Other transducers which measure pressure or force include piezoelectric crystals. The electric charge on a piezoelectric crystal changes with force. A force of 10kN results in a transducer deflection of 0.001mm. It is common to use these as a bolt for use in a mechanical structure and they should be used with a matched cable.

Other devices which exist include hydraulic and pressure based transducers which are typically for large systems and act to balance the force with another equal and opposite force. More obscure devices such as elastic devices exist whose length changes subject to a force. The length is then measured. Strain can also be measured through the use of a capacitive type system where the gap between parallel plates is measured. Or through an optical fibre type system where the phase angle of a reflected wave is compared between two test pieces one of which is subject to a force.

Vibrating systems that rely on movement such as tuning fork or vibrating wire transducer or surface wave resonator could also be used but are unlikely to be practical in this application. Dynamic movement and balancing devices such as a gyroscopic load cell look at timing of rotations to detect forces.

Measurement devices which use electrical/magnetic properties within this type of system include;

- Inductance and reluctance load celsl also related to Magneto-elastic devices which work by relying on the knowledge that a ferromagnetic material changes its magnetic properties when under stress.
- Electrical force balancing devices which use an electric current passed through a coil to generate a restoring force in opposition to the applied force. The coil current to achieve this balance is proportional to the applied force and is measured as a voltage sensed across a resistor in series with the coil.

Summary

Measurement path is as follows:

Load current in cable → temperature increase → change in length → strain gauge

It may be possible to back calculate the current directly from the strain gauge reading, depending on access to data and the correlation between theory and practical. However, strain gauges are difficult to setup and calibration is required as part of this along with temperature compensation.

Initial investigations will determine how complex calibration processes are and the extent of on-site calibration.

Expected range of measurement: 0 – 10mV

Recommendation – to try this device as part of the project.

3.2.5 Flow transducers

Flow transducers are usually used to measure the passage of gas or fluid through pipework at a rate per second. There are many types of flow meters and these vary if the substance to be measured is open to air or within an enclosed pipe. The most common types of in-flow measurement are:

- Mechanical flow sensors – This looks at how much physical volume passes through in time and can use pistons, blades or vanes, floats or gears which “count” how much fluid passes.
- Pressure based flow sensors- These operate on Bernoulli’s equation principles (conservation of energy) and look for pressure drops in the system which can then be related to fluid velocity. These devices may restrict flow in some cases. Vortex flow measurements also restrict flow but cause small vortexes which can be used to look at flow rate.
- Thermal flow sensors – introduce a source of heat upstream of the flow and then the temperature measured downstream at the sensor is related to the mass flow rate of the fluid.
- Optical based flow sensors – These look for light scattering off particles in the flow and the same light scattering signature downstream and then use distance over time to get the velocity of the fluid.

- Magnetic flow meters – A magnetic field is applied to the measuring tube which forms a voltage in a conducting fluid which is detected by two electrodes perpendicular to the flow and the magnetic field. The magnetic field is pulsed to cancel any stray voltages in the piping system

None of these offer a direct carry through to a substation environment. There are also a number of external measurements based outside of the pipework which include;

- Sonar and ultrasonic flow measurement – uses an array of sonar sensors to detect sonar waves travelling in the fluid. In the ultrasonic version the difference in time between ultrasonic waves flowing upstream and downstream with the fluid can be compared to give a measure of fluid flow.
- Lorentz flow meters – These are non-contact magnetic flow meters that look at the force produced from an interaction with a magnetic field and a conductive fluid moving at speed as shown below. There are transverse and longitudinal versions of the meter [15].

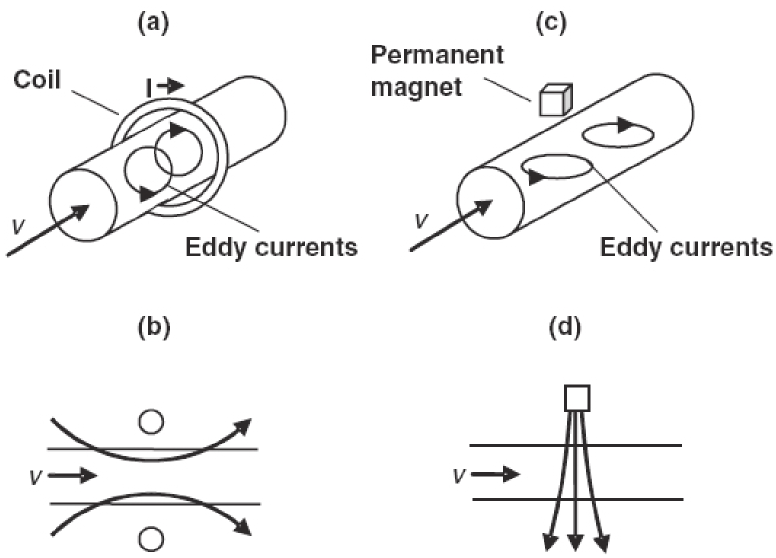


Figure 14: Lorentz flow meters – operating principle [15], and b are longitudinal and c and d are transvers methods

Summary

At this time, it is not clear how these may be used to measure loading. They are included for completeness.

3.2.6 Chemical sensors

Chemical sensors consist of a chemical (molecular) recognition system (receptor) and a physicochemical transducer. In the majority of chemical sensors, the receptor interacts with

chemical under test. As a result, its physical properties are changed in such a way that an electrical signal is produced.
Examples include;

- Carbon monoxide: A semiconductor that changes resistance in the presence of CO or colour change devices
- Glucose: A test strip is mixed with glucose oxidase, which reacts to create gluconic acid. Another chemical within the test strip, called ferricyanide, then reacts with the gluconic acid to create ferrocyanide. The electrode within the test strip then runs a current through this and the ferrocyanide changes this current to give a measure of glucose (used in blood testing)
- Lateral testing is a type of chemical analysis test which is commonly used to test liquids for the presence of a specific substance, such as drugs, hard water chemicals or hormones (e.g. in a pregnancy test kit). As a mixture moves up a test strip in reacts to chemicals on that strip to form bands of colour which can be visually seen.
- Nano sensors: Still in its infancy, nanotechnology can be used to fabricate sensors that detect very small amounts of chemical vapours. Detecting elements, such as carbon nanotubes change their electrical characteristics, such as resistance or capacitance, when they absorb a gas molecule. Due to the small size of such nanotubes, nanowires, or nanoparticles, a few gas molecules are sufficient to change the electrical properties of the sensing elements. This allows the detection of a very low concentration of chemical vapours.

There are a couple of cases of chemical transducers being used within a substation environment already. These are primarily to detect by products around insulation breakdown. It is not clear how these types of sensors may be used to produce meaningful results cheaply in this application.

Furan detection

Furan gas is discharged during paper insulation de-polymerization, this is normally identified by performing High Performance Liquid Chromatography (HPLC) on samples of transformer oil. An optic fibre based Furan detection sensor has been tested against HPLC in a laboratory [16]. Of the 22 citations for the paper most were in other fields or generic biochemical work, there were a small number of similar papers on transformer monitoring. The authors went on to develop a D-shaped plastic optical fibre (POF) sensor for furan detection from a Research Fund for use with the Italian Electrical System [17].

The main challenge of the approach described is that it requires a custom fibre optic sensor to be commercialised. If there is also demand from other industries such as brewing there may be some economies of scale, though it wouldn't be a low-cost sensor in the same magnitude as smartphone sensors for example.

Dissolved Gas Analysis (DGA)

Gases dissolved in oil are analysed by gas Chromatography. Monitoring systems which use dissolved gas analysis are already commercially available, for example the Kelvatek Totus system kelvatek.com/totus.php.

Summary

Load current in transformer→ furan gas increase → gas detection

At this time, it is difficult and expensive to get the equipment needed to look into this and correlation between gas emissions and loading is likely to be highly influenced by aging and less by loading, resulting in difficulties in correlating load current.

3.2.7 Thermal transducers

These can be grouped as
• Bimetallic strips – two different metals have different co-efficients of expansion and bend into a curved switch – primarily used as a temperature switch
• Thermocouples - are based on the fact that a potential difference occurs across the junction of two dissimilar metals if this is heated. A thermocouple contains two such junctions and if both junctions are at the same temperature there is no net emf. A difference in temperature t results in an emf, V as follows.

$$V = aT + bT^2$$ Equation 3-7

Where a and b are constants and T is the temperature. Thermocouples are very cheap, but the same dissimilar metals must be used for all cables and connectors from the sensor to the measuring circuit. Whilst suitable cables are available they are more suited to laboratory than industrial environments.

• Resistance Temperature Detectors (RTD) – resistive elements in the forms of coils of wires whose resistance changes by the standard formula – usually platinum or nickel copper alloys.

$$R_T = R_0(1 + \alpha\Delta T)$$ Equation 3-8

where $\Delta T = T_T - T_0$ the difference between a reference temperature and the measured temperature and R_o is the resistance at that reference temperature. RTDs are generally more expensive than thermocouples, but they are better suited to industrial and outdoor environments since any multicore cable and connector can be used.

• Thermistors –resistance changes with temperature, but may have positive or negative coefficients and are typically crystalline in structure. They follow a change of resistance with temperature of

$$R_T = ke^{B/T}$$ Equation 3-9

Where k and B are constants and T the temperature being measures.

• Thermo-diodes & transistors

• Temperature sensitive labels

Temperature sensitive labels incorporate a liquid crystal layer behind a front graphics layer. The labels can be manufactured with different temperature ranges and sensitivity. They are sold for £0.8 to £1.20 each in small retail quantities, so could be procured at a substantially lower cost in large orders direct from the manufacturer. Installation is very quick and requires very little training.

The basic type of temperature sensitive label would be of limited use in substations because they only display the present temperature and a camera based device would be needed to observe and record.

However, Irreversible temperature labels are widely used for example to display if operating theatre trays have been autoclaved (to the required temperature) for patient safety. These labels could be custom designed to a DNO specification. If a 'date installed' section was included it would be known since when the overtemperature event occurred, and if additional labels were added at the same location in subsequent visits it would be known the high temperature event re-occurred.
Time duration temperature sensitive labels are also available which show how long a temperature has been exceeded for, this would help to discriminate between short duration events (for example unusual circuit switching arrangements during upgrades) and ongoing overload on a particular feeder.

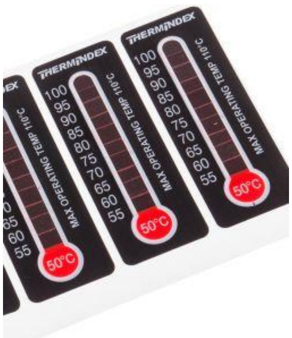


Figure 15: Basic temperature sensitive label which shows present temperature from uk.rs-online.com

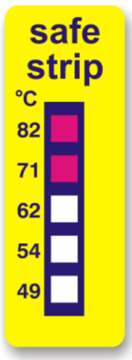


Figure 16: Irreversible indicator label from temperature-indicators.co.uk

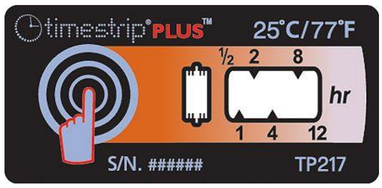


Figure 17: Timestrip label from uk.rs-online.com or Timestrip.com

It may be possible to incorporate the present temperature, maximum temperature and setpoint exceeded duration features into a single label. The labels could be applied for example to cables with additional cable ties for robustness. They could also be applied to bolted terminals by fixing them to a metallic tab with insulated cover.

The choice of operating range for any temperature sensor depends on the normal operating temperature range of the equipment. A list of equipment temperature ratings for common cable types is given in the table below.

Table 3: Comparison of Cable maximum temperatures

Component	Maximum temperature
XLPE/MDPE 1/3 core 11kV cable ELAND rating	90
XLPE/MDPE 1/3 core 11kV cable SPEN rating	60
XLPE/MDPE 1/3 core 11kV cable Central Networks rating	60
PILC cable	70
PVC SWA 600/1000V	70
Bitumen, softening point, varies according to composition*	30-150

* BS EN 1427

Any temperature measurements would require an informed decision to be made as to where the temperature sensor should be placed and on which pieces of equipment, since any temperature measured will be a function of several variables including:

- Conductor current.
- Thermal conductivity of materials.
- Radiative emissivity of materials.
- Convective movement of air and transformer oil.
- Outside ambient temperature.
- Solar irradiance.
- Wind.

Numerous transformer thermal models exist, some of these are complex physical models that require detailed physical data about transformer materials such as the viscosity and specific heat capacity of the oil [23][19] [20]. The only data which is generally available for transformers in secondary substations is the power rating, manufacturer and volume of oil. More common models include the IEC 60076 model which also requires transformer specific data such as the ratio of load losses at rated current to no-load losses. This complicates the measurement and to undertake thermal measurements to predict load current forces on-site calibration (as discussed later in the report)

A thermal imaging survey was conducted at Church Hill substation, Woodhouse Eaves, Leicestershire. This substation consists of an outdoor ring main unit, transformer and LV panel in separate enclosures linked by underground cables.

Figure 18 Photograph showing overall layout of substation used in thermal survey

The survey was conducted in winter and the temperature of the adjacent ground and stone walls was in the range 8.1-8.6. The images were taken at 16.00 on a weekday, it was not possible to get current loading data at the same time, therefore the thermal images shown here give an impression of the relative temperature of different parts of the substation but cannot be used to infer any meaning from the absolute values of temperature.

The temperatures of the 11kV ring main unit (9.3°C) were only slightly higher than the outdoor ambient temperature. The switchgear enclosure at the top was slightly warmer than the cable termination boxes below.

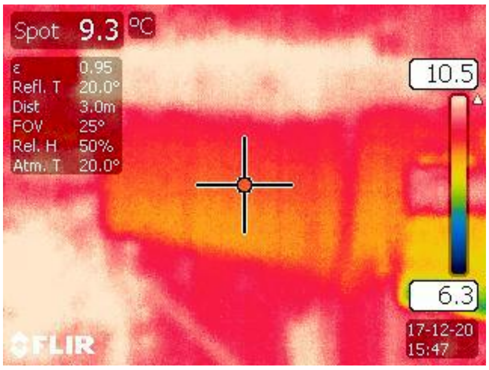


Figure 19 Thermal image of ring main unit

Figure 20 Photograph of ring main unit

The transformer is the hottest device in the substation with an outer case temperature of 20.6. The hottest part of the transformer are the pipes at the top of the cooling radiators.

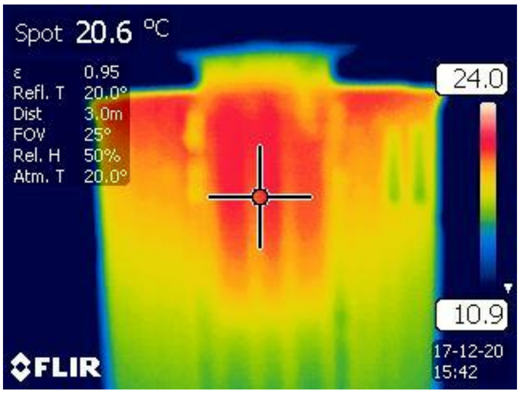


Figure 21 Thermal image of transformer (rear view)

Figure 22 Photograph of transformer (front view)

The LV panel case was in the range 13-14° with the top of the panel being the hottest part. A thermal hot spot can be seen at the bottom right of the panel, this is likely to be due a loose or corroded connection.

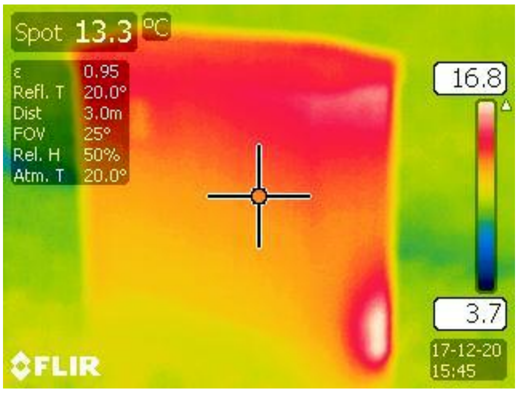


Figure 23 Thermal image of LV fuse board (rear view)

Figure 24 Photograph of LV fuse board (rear view)

Summary

The measurement path is as follows:

Load current in cable or transformer → temperature increase → thermocouple/temperature label

Some work has been undertaken on monitoring top oil temperature of transformers on the outside of the tank. It is difficult to tie this back to loading without calibration. However, just monitoring for a top oil temperature close to limits could be adequate and would offer a low-cost solution of showing when further investigation was needed without the expense of callibration.

Expected range of measurement: -20°C to +100°C

Recommendation – to try this device as part of the project.

3.2.8 Optical and IR transducers

Power lines give off UV flashes that can be detected by animals such as Reindeer. These occur as irregular flashes are insulators and within the corona discharge. These typically occur at higher voltage than is found is an 11kV substation. In addition, Neon lights will glow in the presence of a magnetic field. It is not clear if the visible glow from a bulb will be sufficiently high and variable to detect within a substation environment.
The electromagnetic field around a conductor can be measured optically using the Faraday effect. Fibre optic current sensors (FOCS) are used to measure current in substations from 245 to 800kV AC, where traditional current transformers were very costly due to the quantity of copper and insulation[18].

Summary

Load current in cable→ electromagnetic field → fibre optic sensor

The quality of optical components required for this type of sensor mean that it is unlikely to be possible to reduce the costs to the extent that FOCS become cheaper than CTs for secondary substation applications.

3.2.9 Optical, infra-red and thermal imaging sensors

The quality of CCTV sensors has improved to the extent that automatic facial recognition and recognition of suspicious objects is possible. A similar approach can be applied to infra-red and thermal images as a real-time fault diagnosis approach and this is used already in substations on national networks[19].

Infra-red imaging uses the same CCD or In GaAs sensors as high quality digital cameras, but a visible light blocking filter is used instead of the infra-red blocking filter normally used in digital cameras. Some digital cameras can be dismantled and modified. IR imaging is successfully used in photovoltaic systems to identify micro cracks in solar cells, as shown in Figure 25 and Figure 26 where the dark areas identify lower current due to micro cracks. However, the materials used as electrical conductors (copper, aluminium and occasionally brass) are much more ductile than silicon solar cells and therefore unlikely to suffer micro-cracks.

Figure 25: Infra-red image of a solar panel at night with no current flowing.

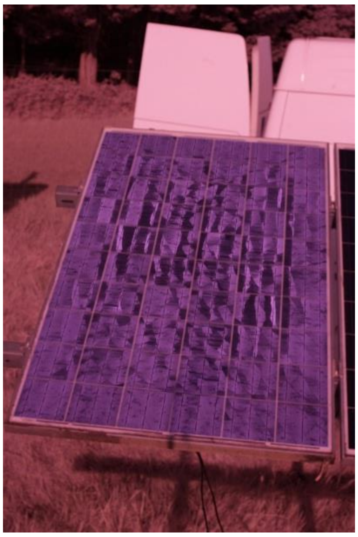


Figure 26: Infra-red image of a solar panel with reverse current applied at night.

The disadvantage of infra-red imaging as opposed to thermal imaging is that it shows the amount of energy being emitted rather than the absolute temperature of a surface. Therefore, thermal imaging may be more suitable for substation diagnostics. A thermal image of an LV feeder pillar is shown in Figure 27, the hot spot to the bottom of the image may indicate and overloaded feeder or high resistance connection.

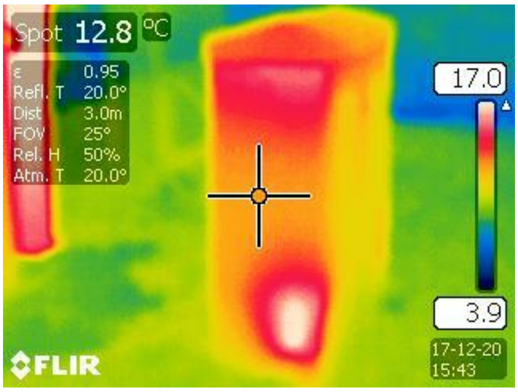


Figure 27: Thermal image of an LV feeder pillar.

Summary

Measurement path is as follows:

Load current in cable or transformer → temperature increase → thermal image capture →analysis of image

Some work has been undertaken on monitoring top oil temperature of transformers on the outside of the tank. It is difficult to tie this back to loading without calibration. However, just monitoring for a top oil temperature close to limits could be adequate and would offer a low-cost solution.

Expected range of measurement: -20°C to +100°C

Recommendation – to try this device as part of the project along with thermal stickers.

3.2.10 Biological transducers

A biosensor is a chemical sensing device in which a biological agent is coupled to a transducer, to allow the quantitative measurement of some complex biochemical parameter. Bio sensors typical comprise

- A biological element that acts as a sensor
- An electronic component that detects and transmits the signal

Most examples of biological sensors are around production of chemical components including; nucleic acid, proteins, lectins and microorganisms.

However, there is some recent published work on using magnetic fields to speed up the process of detection of super para-magnetic particles, to speed up biological sensing [20]. It may be possible for this to work in reverse – i.e. using a fixed biological agent to identify the magnetic field.

It is also possible for some biological system to fluoresce in the presence of a magnetic field [21] which provides an alternative approach. These bio-sensors are still in an R&D environment and as the focus is on the accuracy of detecting a biological element, it is not-known yet if these could be used to detect the magnetic element with any degree of accuracy. Until the bio-sensors leave the lab and become commercial products it is unlikely that this could be investigated with any degree of accuracy. Current literature indicates that these will appear as very small micro / nano chips in the future.

Summary

Load current in cable→ magnetic field → bio-luminescence → optical transducer

At this time, it is difficult and expensive to get the equipment needed to look into this and the measurement setup is complex and unlikely to be a viable alternative to measuring magnetic field directly.

3.2.11 Nuclear sensors

Nuclear sensors include

- Geiger counters which work by applying a high voltage across an inert gas in a sealed tube and measuring pulses in current when ionisation occurs.
- CCD camera sensors which can measure radiation like a Geiger counter if the lense is covered, various android radiation counter apps use this principle.
- MEMS radiation sensors use a photodiode with an opaque cover and operate on the same principle as CCD radiation sensors above.

Summary

At this time, it is not clear how these may be used to measure loading. They are included for completeness.

3.3 Sensor summary

A review of commercially available sensors identified a number of key findings. Commercially available current sensors of suitable current and voltage ratings for substation use all exceeded £20 in cost. The cost factors are likely to be quantity and commodity cost of raw materials (typically copper windings and polymer insulation) also the cost of design testing and accreditation.

Micro Electro Mechanical Systems (MEMS) sensors are often very compact devices measuring less than 10 cubic millimetres which are surface mounted onto circuit boards. These sensors often costed less than 1p each even in small quantities. The low cost of MEMS sensors is likely to be due to two main factors:

- Very low materials cost due to their small size
- Development cost per sensor is very low due to the very large volumes manufactured for smartphones, tablets and other mobile devices.

Therefore, the application of MEMS sensors in a substation environment was identified as a priority area for this project. As these sensors are found primarily in consumer electronics they consist of those measurement devices in the next section.

LP 1	MEMS sensors are very cheap due to tiny raw material volume and massive production volumes.

It is not clear if reverse engineering a measurement device using a fixed magnetic field which measures another quantity can be used to reverse calculate a variable magnetic field under a fixed condition However, it is unlikely that these would offer any benefit above a magnetometer in the first instance.

LP 2	Many different types of sensors use a fixed magnetic field to give another type of measurement. It’s not yet clear if these are more or less accurate than a magnetometer.

The sensors to be trialled are as follows:

Table 4 : Summary of sensor types to be tested

Sensor Type	Measurement	Range
Magnetometer	Magnetic field	0-0.002T
Hall effect chip	Magnetic field	0-0.0025T
Planar magnetic current sensing	Magnetic field	0-0.002T (to be designed)
Accelerometer	Vibration	0-10mV/g
Audio microphone	Noise	20-20kHz
Strain gauge	Strain through a Wheatstone bridge	0-10mV
Thermal stickers/transducers	Temperature	-20 to 100^{o}C
Thermal imaging	Temperature	-20 to 100^{o}C

4 Existing Packaged Solutions

There are many pre-packaged consumer devices which include sensors as part of their functionality. This section looks at some of these and considers their suitability for looking into substation measurement. A summary of these is shown below.

Table 5: Prototyping & development platforms, see Appendix for the complete list.

System	Sensors	CPU / OS	Native language
Android phone	Camera, Accelerometer, Ambient temperature, Magnetic Field, Fingerprint, Gyroscope, Heart Rate, Light, Pedometer, Proximity, Pressure, Relative humidity, Radiation	Android	Java / C++ / Go / Kotlin
iPhone	Camera, Accelerometer, Ambient light, Barometer, Compass Gyroscope, Pressure sensitive display, Proximity, Fingerprint	iOS	Ajax (Java + XML)
IOIO	A board that connects to an Android device via USB or blue tooth and allows the phone (Android 1.5 or later) to be connected to 46 I/O devices	Android	As Android
Raspberry PI	plug-in PCBs available with wide ranges of sensors including cameras	Many including Linux	C
Arduino	built in analogue ports	Microcontroller	Machine code via C/C++
Ni MyRIO	Accelerometer	ARM processor	LabVIEW
Lego Mindstorm	Plug & play Sensors include ultrasonic, IR, gyro		
Fitbits	steps, movement, sleep, heart rate, altitude, GPS.		

There are many different devices on the market which may be used. Some of these have open source platforms for helping with developing code and code user support websites. This should be considered when choosing a platform as it then correlates to the amount of time required for development.

LP 3	The choice of prototyping & development platform should consider temporal and amplitude resolution, ease of programming, compatibility of communication.

4.1 Low cost consumer devices

- USB temperature loggers

USB temperature data loggers cost from £25 to £60 for a unit which also measures humidity. They can store up to 16,000 temperature readings at up to 0.1Hz resolution. They are powered with non-rechargeable ½ AA batteries so can last several years in service. They are used for example to monitor the temperature in containers of bananas in transit.

Figure 28: Lascar USB temperature logger

Summary

Load current→ Temperature → stored measurement

The method of use would be similar to a thermocouple connected to a data logging device. It is unlikely to offer additional benefit over investigating temperature capture directly so will not be considered.

4.2 Smartphones

Many instrument manufacturers now use the smartphone as the processing & display interface for their sensors, as a means to provide a detailed graphical user interface (GUI) without the additional cost, an example would be hand held anemometers, current clamps and flow meters [22].

Given that Smartphones include sensors, processing, memory and GSM/GPRS data transmission capability they have been used as complete dataloggers in previous research projects. However, even if smartphones are not found to be suitable after testing & appraisal, they provide a useful platform to conduct initial tests on sensors to assess their suitability without the need to build full prototype systems.

A list of base (actual physical) sensors found in android phones is given in Table 6. Not all phones include all sensors, the last column shows which phones feature the more unusual sensors. Previous versions of the Android operating system didn't support all the sensors found in current handsets.

Most high-end Android phones include a gyroscope and/or magnetometer which are used for Navigation, Virtual Reality (VR) and Augmented Reality (AR) apps. Mid/low end devices usually only have basic sensors such as an accelerometer. Mid-range android phones which include a gyroscope and magnetometer include Lenovo vibe k4 / k5; Asus Zenfone 2; Xiami Redmi note 3 pro; Moto G4 / G4 plus; Asus Zenfone 3; OnePlus One / OnePlus 2;

Table 6 :Base sensors found in android phones

	Units	Min delay (us)	Resolution	Max	Current consumption (mA)	Phone including this sensor
Accelerometer	m/s^2	5000	0.00119	39.23	0.25	most
Ambient temperature	°C					Samsung Galaxy S4
Magnetic Field	uTesla	5000	0.01	2000		most
Fingerprint						iPhone 5s; Galaxy S5; HTC one max;
Gyroscope	°/s	5000	0.001 rad/s	34.9 rad/s	6.1	most
Heart Rate	beats/minute					Galaxy S5
Light	Lux	200000	1	60000	0.75	
Pedometer						Google Nexus 5
Proximity	cm	0	8	8	0.75	
Pressure	mbar	200000	1	1260	1	
Relative humidity	%					
Radiation						only on Sharp Softbank Pantone 5 107SH

The accelerometer, magnetometer and gyroscope sensors return data in 3 axes as shown in Figure 29

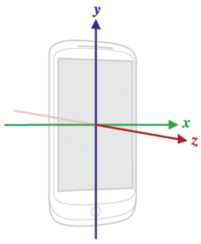


Figure 29: Position system used for handheld apps

Figure 30: Position system used for automotive apps

This is important because the magnetic field is measured in three dimensions and it is necessary to make sure that the phone is aligned to the field that needs measuring. For example, connecting the phone to a cable along the y axis would mean magnetic field in the x and z axis would recorded.

Many of the sensors ported in the Android API, are not actually physical sensors but variables derived from them via algorithms, these include the following:

- Game rotation vector
- Geomagnetic rotation vector
- Glance gesture
- Gravity
- Gyroscope calibrated
- Linear acceleration
- Magnetic field calibrated
- Orientation (deprecated)
- Pick up gesture
- Rotation vector
- Significant motion
- Step counter
- Step detector
- Tilt detector
- Wake up gesture

The calibrated magnetic field for example includes the effect of the earth's magnetic field in its calculation. The uncalibrated value (which is available) is different from the calibrated. It will be necessary to investigate which is the most appropriate to use for this application.

Most android apps are written in the native Java using the Android Studio Integrated Development Environment (IDE). Other languages such as Python and Delphi support Android, but don't necessarily port all the methods available in Java, so Java is the only language which would be guaranteed to access all sensor related features.

A few open source sensor datalogging apps have been reportedly published as working on open-source websites such as Github, but in some cases, the code tested was found to be broken could require significant testing & debugging work.

A number of such available apps were tested including 'Sensor Box', 'Gauss Meter' and two apps both called 'Sensor Datalogger'. Most of these apps showed data from several sensors on screen, but the only app which had the capability to save sensor data to file was called 'Sensor Logger' by i-realitysoft. The app can save data from all axes and overall magnitude of any sensor to text or csv file. The measurement interval varies from 3ms to 12ms so is presumably dependent on other processor activities. The average interval is 10ms which should be adequate for this project. A complete list of the apps tested, and their capability is given in the Appendix.

A list of sensors in Apple iPhone/iPad/iPod devices is also given in the Appendix

LP 4	Smartphones provide a useful environment for initial testing of MEMS sensors when sensor datalogging apps are used.

LP 5	Data from Android MEMS sensors can be accessed using free apps available on the Google Play Store. If more flexible measurements are required, then custom apps could be used with the Android API (Application programming interface).

Summary

Load current → Magnetic field or temperature → Phone measurement device

This provides one of the most promising sensor solutions for low cost substation monitoring. The use of the phone to measure magnetic field and report this will be trialled.

4.3 Raspberry Pi, Arduino and Lego Mindstorm

The processors of all these devices are all different but the sensors available can work across all platforms. Some of these sensors are expensive but there is a large range of possible sensors including but not limited to;

- Compass
- GPS
- Miniscope
- RFID transponder
- Light sensor
- Accelerometer
- Tilt sensor
- Angle sensor
- Barometric sensor
- Pneumatic pressure sensor
- Infrared sensor
- Thermal probe
- Vision subsystem
- Gyroscope
- IR sensors
- Ultrasonic sensor
- Colour sensor
- Optical proximity sensor
- Force sensor

In particular the Lego Mindstorm offers an expensive platform for investigating sensors that are available as discrete units at much lower cost. The Raspberry Pi and Arduino offer processor capability that can be utilised with sensors that has more flexibility in being able to use prototype systems and to store and analyse results.

Summary

Load current → Magnetic field, noise or temperature etc→ Arduino (or other)

The Lego Mindstorm is an expensive solution so won't be used. The Raspberry PI and Arduino offer alternative platforms to a mobile phone but without the necessary communications. It is recommended that these devices are only used if the mobile phone proves to be a difficult platform for testing.

4.4 National instruments - MyRIO

National Instruments produces a range of controllers with configurable Input and output. My Rio is a student type application on an embedded PCB with configurable I/O which allows multiple concepts to be tested. These are fairly expensive devices and are unlikely to be useful in a substation environment, but may be used to test and analyse sensors. The I/O sensors includes more sophisticated options such as;

- oscilloscope
- logic analyser functionality
- digital pattern and waveform generator
- Digital I/O,
- Voltmeter up to 25V
- Spectrum analyser

Along with more standard options such as a mechatronics kit;

- Geared motor 19:1 (includes encoder for rotation and speed, 12 V)
- Ultrasonic range finder (accurate readings of 0 in. to 255 in. or 6.45 m)
- Compass
- Servo motor: standard (215 degrees rotation)
- Servo motor: continuous rotation
- Accelerometer (3 axis, digital - SPI and I2C)
- Digilent Motor Adapter for MyRIO (compatible with gear motor and servos)
- Gyroscope (3 axis, digital - SPI and I2C)
- Infrared proximity sensor (10 cm to 80 cm)
- Ambient light sensor (SPI),

Accessory kit

- Mechanical rotary encoder
- Photo interrupter (light sensor with LED)
- Small DC motor (1 VDC to 3 VDC, no load speed: 6600 rpm)
- Microphone with audio jack
- Potentiometer (500 kΩ)
- Piezoelectric sensor
- Photocell
- 2 Hall effect sensors (latch and switch)
- Thermistor (NTC: 10 kΩ, 25 degrees)
- Force sensing resistor

And the embedded kit

Keypad

- Digital temperature sensor (I2C)
- Character LCD (I2C, SPI, and UART)
- Digital potentiometer (SPI)
- Bluetooth interface (UART)
- EEPROM (SPI)
- LED matrix

Although this is a nice development kit it offers an expensive option for investigating substation sensors.

Summary

Load current → Magnetic field, noise, temperature etc →MyRio

Expensive alternative to the other platforms. We recommend not using this unless there are issues with cheaper platforms.

4.5 Fitbits and other health tracking monitors

Fitbits and other health tracking devices include a range of features. This can include for example, step tracking, sleep monitoring and heart rate monitoring. The range of sensors in this type of technology include;

- 3 axis accelerometers – used for counting steps
- GPS – location and tracking a run
- Altimeter
- Optical heart rate monitor - An LED shines through the skin, and an optical sensor examines the light that bounces back. Since blood absorbs more light, fluctuations in light level can be translated into heart rate – a process called photo plethysmography.
- Galvanic skin response sensor - measures electrical connectivity of the skin, some more complex variations on this include a bio-impedance sensor that uses a 4-wire method to inject a small signal and look at the impedance changes while can allow respiration, heart rate and electrical connectivity to be measured in one go.
- Thermometers – Looking at skin temperature (e.g. identifying if temperature increases with heart rate to look for illness)
- Ambient light sensors – for changing screen luminescence
- UV sensors – measuring UV radiation

Summary

With the exception of the thermometer and possibly UV detector, it is difficult to see how the other health and fitness related measurement devices could be used around a substation environment. These are not recommended for further investigation.

4.6 Summary

Pre-packaged solutions within development environments offer a user-friendly method of looking into sensors – however this comes at a cost. There is usually some form of data logging functionality associated with this.

The most promising solution would be to use the sensors inherent with a mobile phone solution, running an android operating system. In the event that this creates problems then either an Arduino or raspberry pi could be used with discrete sensors to test sensor solutions. A summary of the techniques to trial are shown below.

Table 7 : Summary of sensor types to be tested

Package Type	Measurement
Android phone	Magnetic field, audio, temperature, camera
IOIO interface unit	With sensors from Table 4
Arduino	With sensors from Table 4

LP 6	Development kits such as NI offer a comprehensive list of generic sensors that they can be used with. However, all of these can be manufactured at significantly lower cost on a part by part basis

5 Communications

5.1 Introduction

DNOs operate their own private radio network for some applications for which bandwidth is licensed directly from OFCOM. Using this network doesn't incur data charges to a third-party network provider, but all the costs are loaded into the equipment and installation which is very costly and only justified for critical infrastructure where the public cellular telephone network would not be considered adequately robust.
Likewise, private bandwidth can be licensed from OFCOM but would incur significant new infrastructure costs.

5.2 Cellular telephone (mobile) networks

Primary, secondary and generation substations do not generally have a fixed telecoms service. Metering, etcetera data is therefore usually transmitted from the substation to the datacentre using the GSM (Global System for Mobile Communications) and/or GPRS cellular telephone network. GSM/GPRS offers relatively good signal strength and bandwidth for low cost, due to the extensive network of local masts with the costs spread between a very large number of consumers.
Mobile networks can be subdivided by generation as shown in Table 8.

Table 8: generations of cellular mobile telecommunication

Generation	Base protocol	Data transmission layer	Actual data rate (when stationary)	Security	Year introduced
1G					1981
2G	GSM	GPRS /	40 kbit/s	A5/1	1992
'2.5G'	GSM	Edge over GPRS 'EGPRS'	500 kbit/s	A5/1	
3G	UMTS	WCDMA	384kbit/s	Kasumi	2001
3G	UMTS	HSPA	7.2Mbit/sec	Kasumi	
3.5G	UMTS	HSPA+	21.6 Mbit/s	Kasumi	
4G	LTE / IEEE 802.16m	N/A all transmission in packets	Up to 1Gbit/s urban		2011
5G	To be confirmed	N/A all transmission in packets	Up to 1Gbit/s urban	To be confirmed	2020?

GSM/GPRS is used for many other applications including

- Building management systems (BMS)
- Scada systems (Supervisory control and data acquisition
- Scientific and meteorological dataloggers

- Passenger information displays at rail and bus stops
- Energy metering

A specific variant of GSM is used in the railway industry called GSM-R (GSM-Rail). It uses similar protocols and equipment allowing standardisation, but requires a private network of masts along railway lines to provide a highly reliable connection to trains.

The widespread use of GSM/GPRS in industry and commerce means that modems to interface systems with the network are manufactured in large quantities by a number of manufacturers at competitive prices. Older dataloggers and meters tended to use a Siemens TC35 or equivalent GSM modems (Figure 31 at around £30). Newer systems would use a Siemens MD720 or equivalent GSM/GPRS modem (Figure 32 closer to £350), since GPRS allows faster transmission speed and may have better signal strength in some areas. Modem functionality may be incorporated within a datalogger by including a GSM/GPRS chip on the circuit board.

Figure 31: Siemens TC35 modem

Figure 32: Siemens Sinaut MD720 modem

GPRS/GSM modems and chips all require a specific data SIM card to be used. For GPRS data communications a special APN (Access Point Name) must be registered with the mobile network as a gateway from the network to the datacentre. GSM data transmission is somewhat simpler as the modem can dial a dialup modem connected to the Public Switched Telephone Network (PSTN) or vice versa.

GSM/GPRS data hardware is relatively inexpensive, but any logging system needs to be carefully coded to control the cost of charges from the network provider depending on the quantity of data. There are two main contractual options to provide SIM cards for secondary substations:

- IoT style contracts with low monthly costs (costs range from 4-50p/month).
- Addition to existing corporate data contracts which have inclusive monthly data and unlimited number of SIM cards. As such the costs of maintaining a sim card which only reports by exception is cheap.

Both options favour designing a device with minimal data transmission to minimise data transfer costs.

6 Data Management

The data management strategy will need to satisfy a number of requirements

- Records to have a timestamp with an agreed accuracy.
- Gaps in data to be minimised.
- Error checking of incoming data, for example erroneous or incomplete records.
- Ability to query the database for a variety of purposes.
- Data to be secure from intrusion.
- Raw data to be recorded by measuring devices in a standard format which is readily viewable for diagnostics purposes, for example comma or tab separated ascii text.
- It is likely that the volume of data collected from secondary substations will require data to be stored in a database for ease of access.
- The database should use an industry standard platform to minimise training and administration costs.
- Where possible, raw data should be recorded in a simple tabular format which allows rapid bulk importing into a database without the need for pre-processing scripts.
- The above requirements also facilitate direct analysis of raw data using maths software.

7 Test sites

7.1 Substation details

This project is geared towards monitoring of an 11kV ground mounted substation. This typically consists of the following components;

An incoming 11kV cable connected to an 11kV RMU. The output of which goes to an 11kV/400V transformer. The LV circuit then goes off to different circuits via fuses.
The different locations which may be available and can therefore be used for measurement purposes include:

- Incoming HV cable (multicore / trefoil)
- HV cable switchgear - transformer
- LV transformer bushings (requires outage)
- LV cable transformer – fuse panel (small number of older subs <1960s)
- LV busbar (requires outage except <1960s) disconnect accessible.
- LV disconnect accessible behind Perspex panel
- LV fuse holders
- LV Feeder wires
- LV feeder multicore

A typical substation is shown in Figure 18.

The following list were identified as quantities in a substation which might be measured:
- Electric current
- Magnetic field
- Electric field
- Conductor temperature
- Gas discharge (e.g. Furan discharge during paper insulation de-polymerization), normally done using gas Chromatography)
- Oil temperature
- Oil breakdown
- Tank pressure
- Tank temperature
- Conductor displacement
- Vibration (of conductor / transformer core / other structure)
- Strain (of conductor / transformer core / other structure)
- Noise

Tank pressure was discounted, as the transformer tanks are at atmospheric pressure & vented via an inverted J-tube.

The transformers in secondary substations are typically in the size range 300-1000kVA. Pole mounted transformers smaller than 300kVA as used in rural areas are outside the scope of this project as are transformers greater than 1000kVA used for connections to industrial users and embedded generation. Transformers greater than 1000kV aren't used in substations on the public network due to the large number of consumers which would be affected by a fault at this single point of failure. Transformer data from all WPD regions (South West, South Wales, West Midlands, East Midlands and Eastern) was collated and binned by transformer size as shown in the histogram in Figure 33. 500kVA is by far the most common transformer size, 300, 315, 800 and 1000kVA are also common, very few 750kVA are found and less than 10 each at 350, 375, 400 and 630 kVA.

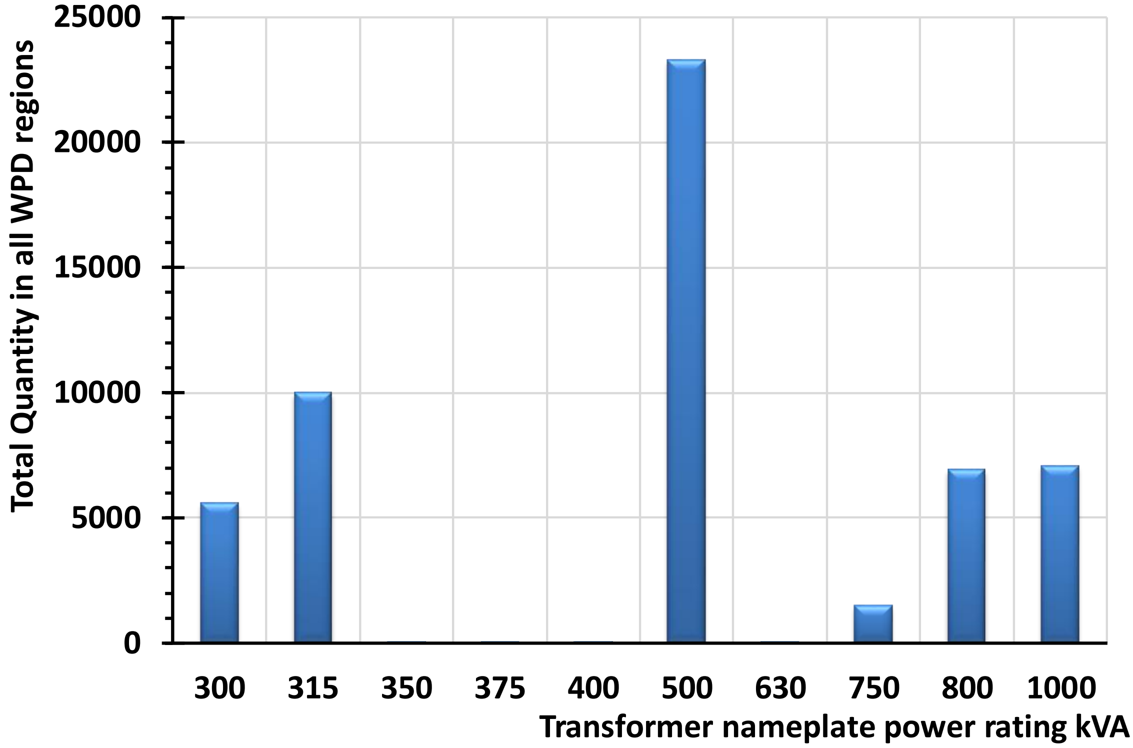


Figure 33: Histogram showing the distribution of transformer sizes across all WPD regions.

Pole mounted transformers and private substations are less popular.

7.2 Previous substation monitoring projects by DNO's

There have been several related LCNF projects undertaken by UK Utilities around sub-station monitoring. These include;

UKPN - Distribution Network Visibility (DNV) Project [26].

Most DNOs have limited monitoring at lower voltage levels. The UK Power Networks' London network is different as it has an extensive and widespread monitoring capability, with Remote Terminal Units (RTUs) deployed in approximately 60% of the distribution substations primarily for the purposes of HV switching. These RTUs had a range of unused features around data captured, which were not being fully utilised. The Distribution Network Visibility LCNF Tier 1 project looked at using the hardware to collect network data.

The project then assessed the possibility of manipulating, updating (and where necessary cleanse this data) to automatically detect network performance and issues and produce useful information such as available capacity.
Some of the RTU's were upgraded, but the majority were in-situ prior to project commencement.

The project also trialled some optical fibre sensors as a means of measuring current. The Powersense optical phase sensors were tested under the following conditions.

Cable type	Reported results
Triplex Cable (Single core and plain lead)	ok
PILSWA Cable (Steel Wire Armour)	Unsatisfactory
Unbalance System (currents in cores sum to zero)	ok
Unbalanced System (separate phase loops)	Unsatisfactory

Unfortunately, the technology was bought out by Landis and Gyr and seems to be unavailable as a product. Recently ABB have launched the fibre-optic current sensor - FOCS in 2014. However, FOCS is aimed at >100kV systems and is not clear what the price of these devices is. Without the benefit of the already installed RTU units. This may not offer a low-cost monitoring option.

SP Energy Networks – Enhanced substation monitoring project [27]

SP Energy identified that they required data for

- Dynamic Ratings – Asset loading, temperature and weather data
- Flexible Network Control – Power flows and voltages across the network
- Energy Efficiency – Energy consumption and power flows at substations
- Voltage Optimisation – Voltage profiles across the 11kV and LV network

As such determined a set of data to be collected at choice substations of:

- Voltage (1min interval)
- Current (10min interval)
- Temperature (of selected transformers)
- Weather information (at selected sites) including:
    - Ambient temperature
    - Wind speed and direction
    - Solar radiation

To capture the current and voltage – 3 phase current and voltage monitoring devices were used at both primary and secondary substations. SP Energy Networks used Subnet monitoring, GridKey monitoring (similar to the WPD Falcon project) and Landis and Gyr.

The typical cost quoted by SP Energy Networks is between £1400 and £2400 per substation with installation and removal costs of £100 - £200.

The voltage measurement was facilitated using a Drummond bus-bar clamp, of which a pack of four cost around £175 [28], and the current measurements were reportedly undertaken with Rogowski coils or Selex Gridhound clip-on CT's.

Their conclusions were that a low-cost replacement for the existing MDI's which is permanently fitted with a captured-data communication function would probably give a greater cost/benefit. Should there be less predictable loads or generation which may give rise to the need for more detailed data information, then a more expensive monitor could be fitted to measure all the circuit phase loads as necessary.

Northern Power Grid – CLNR Enhanced Network Monitoring [29]

At substation level this was primarily undertaken as 3 phase monitoring of current and voltage on either HV or LV side whichever was most convenient. These were monitored at half hourly and 10minute intervals as average quantities (for design and control purposes) requested to be 0.5% accuracy and power quality data where required with changed values sent to control within 15s (for control). In terms of quoted costs, these were summarised as:

"The cost of the monitoring system, comprising more than 150 monitoring points performing over 3million measurements per day, was £850k, of which £336k was the capital cost of the monitoring equipment. It should be noted that the principal use of much of this monitoring equipment was for the purposes of advanced network control.
The maximum cost for a secondary substation monitor to provide data for planning purposes, if all secondary substations were to be monitored instead of using smart meter data, is £78. This figure excludes the cost of CTs on the LV Board for the incoming supply (as these will already be fitted), providing that they are sufficiently accurate."

Earlier Projects

A list of earlier projects (pre-2014) which include some form of substation monitoring include.

Project	Utility
Demonstrating the benefits of monitoring LV network with embedded PV panels and EV charging points	SSEPD
Assessing Substation Measuring Equipment	WPD/UKPN
LV Network Templates	WPD
Network Management on the Isles of Scilly	WPD
Ashton Hayes Smart Village	SPEN
Hook Norton Low Carbon Community Smart Grid	WPD
Low Voltage Network solutions	ENWL

These projects all relied on commercial current and voltage transducers and were therefore costly to roll out over many substations. This work is different as it aims to be low cost to roll out.

LP 7	Utilities are used to traditional forms of measurements where equipment comes with certification declaring it fit for purpose. Therefore, the introduction of new methodology requires careful planning and management especially in early stages when certification issues are not clear cut and may be missing altogether.

8 Testing, validation and calibration

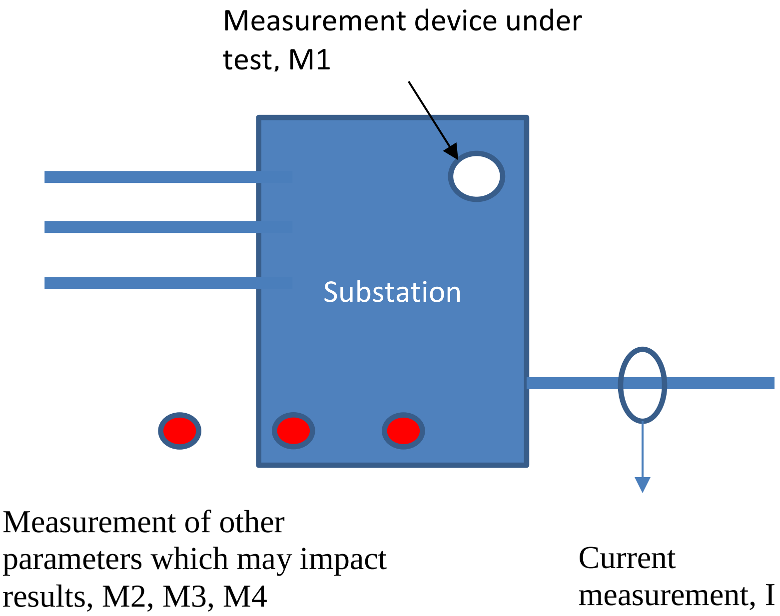
There are several issues that are important to consider when developing a measurement strategy. In many cases an indirect measurement leading to an inferred value may not be directly portable between different substation environments because of changes to hardware and other parameters that may be present in the system. An example of this is inferring transformer loading through transformer top oil temperature.
In the FALCON project a number of distribution transformers were monitored over a year and the parameters used to tune a model of each transformer which could then be used to infer the loading on the basis of the measured transformer top oil temperature and ambient temperature

This process is complicated for a number of different reasons;

- There is a large variety in transformer size, type, manufacturer, year of manufacture etc so very few transformers are the same
- There are three different models of a transformer that can be used. In FALCON the IEC60076 model provided a better correlation to the measured data, and was deemed the most appropriate for use with the Distribution transformers under study.
- The models rely on information which if not given (almost certainly not available) needs to be estimated through a calibration tuning process. This information includes; R (ratio of load losses at rated current to no load losses), $\Delta\theta_{or}$ the top oil temperature at rated load, $\tau_o$the oil time constant.
- Fixing R to a typical value based on transformer size allows a real value of load to be used to tune the other two parameters using a weighted regression method
- The method needed to be applied over the period of a week in order to tune the parameters, but was then sufficiently accurate across the seasons.
- The accuracy with which each top oil parameter could be calculated from loading data and ambient air temperature to check the tuned parameters was variable from <1% up to >5%

This then results in an onerous process of calibrating each transformer temperature measurement in situ. The data needs to be stored for a week and then analysed to allow the parameters to be tuned before being updated into a processor to allow for data values to be inferred. Any changes to the transformer (e.g. adding additional cooling) will result in the need for re-calibration. The measurement system is dependent on the ambient temperature, so this also needs to be recorded and used in the calculation. Wind and solar effects were indicated in work by EA Technology [30] to be negligible.

As direct physical models are complex to produce, and many rely on detailed layout information, it may not be practical to develop the sensors based purely on a theoretical approach as the time necessary, for example, to calculate the magnetic field at any point due to 3D current flows is complex and time consuming and not likely to be accurate Therefore, a practical method of calibrating sensors will be used as shown in Figure 34.



Statistics will be used to determine the function that relates I to measurement
I(t) = f (M1, M2, M3, M4)

The device will be moved to the university substation and the pre-determined function tested. If this holds true, then it means the devices can be pre-tested and tuned in the laboratory

Otherwise, a method of on-line tuning as a function of location will be developed to allow tuning to be automatic and low cost and ensure that calibration in-line is available

Figure 34: Calibration procedure

LP 8	Calibrating a measurement in one location with or without Utility found equipment does not guarantee calibration in other locations or with other pieces of equipment.

LP 9	Calibration may change due to external influences such as temperature or over time. It is important to try and pre-determine both factors as part of this project.

8.1 CREST Electrical Sensor testing Environment

For initial testing, a simulated substation has been setup which recreates many of the characteristics of an LV substation without requiring high voltages to be used.
There are two main aspects of the lab facility:

1) A 3 phase, 45kVA air coiled transformer with variable voltage supply to test vibration and noise based sensors.
2) A high current, low voltage power supply which can supply up to 200A into a shorted 3 phase cable as shown in Figure 35. This means that any DNO 2, 3 or 4 core cables can be connected, and its electromagnetic field measured with sensors under test. It could also be used for other tests such as temperature and strain.

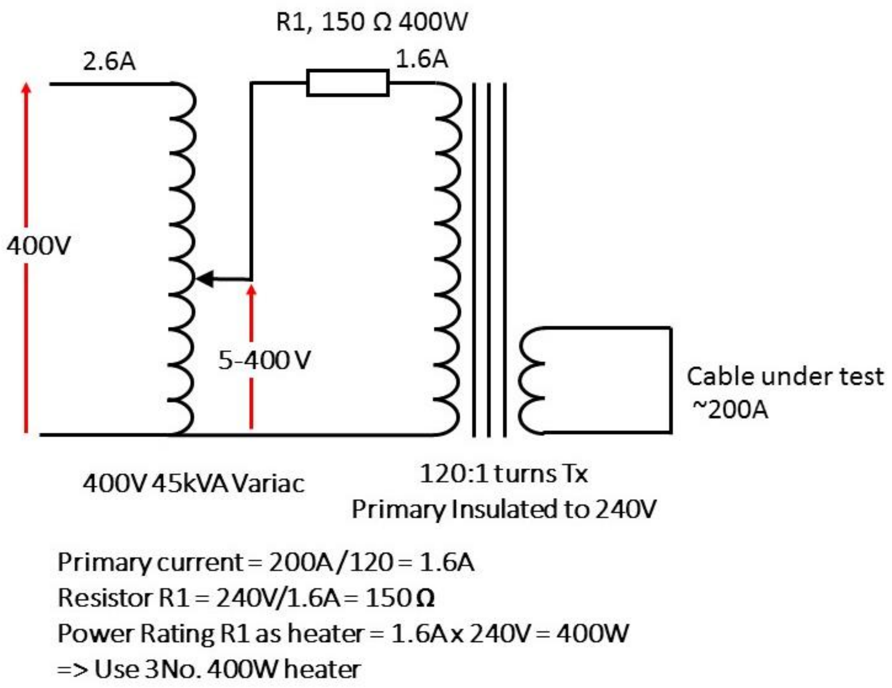


Figure 35: Simplified schematic of the test system used at Loughborough University. Note that earthing and protection is omitted in this drawing.

The cables used in the test rig will include a selection of contemporary and legacy LV and HV cable types based on typical cable specifications found in secondary substations as described in the network design manual [31] as follows:

1) for LV cables:

The majority of existing underground cables are paper insulated, lead covered, steel tape armoured construction. Most cables have 4 cores (3 phase + neutral) but areas of 5 core (3 phase + street light + neutral), 2 cores (1 phase + neutral) and 3 cores (2 phase + neutral) also exist. In some locations plain lead or steel wire armoured cables exist and some of the older cables may be of concentric construction.

Wavecon Cables were also used, for example, in the MEB (see attached photograph taken in Milton Keynes in 2009 as part of a Power Line Carrier trial, which is why there are fuse carriers attached to piecing connectors on some of the LV cable cores). There were at least three types of Wavecon cables listed in chronological order:
1) Oil impregnated paper insulated cores with aluminium wire concentric combined neutral earth (three cables on the left with heat shrink over the paper insulation)
2) Plastic insulated cores with aluminium wire concentric combined neutral earth (cable on the right with coloured plastic cores)
Both these types suffered from oxidation of the aluminium wires, in a similar way as CONSAC cable.
3) Plastic insulated cores with copper wire concentric combined neutral earth. On the mains records these were identified as Wavecon (Cu)

Figure 36: Wavecon cable terminating at fuse board

2) For 11kV cables:

New ring main cables are XLPE Triplex (Al/Cu conductor, copper wire screen). Legacy cables include: PICAS (Al conductor, paper insulation, corrugated aluminium tubular sheath). PILC (Cu conductor, paper insulation, lead sheath).[32].

The cables under test are suspended in free air to minimise interference from adjacent magnetic materials whilst testing magnetic field sensors. Adjacent steelwork can then be added to measure field around the cable with and without an adjoining steel structure.

LP 10	Many of the characteristics of substations can be synthesised using high current low voltage power supplies.

It is intended that sensors which have passed initial testing in the labs at CREST will be tested in an active 11kV:400V substation on campus.

8.2 Prototyping systems

Many of the sensors identified are supplied in very small packages and come under the category of micro electro mechanical systems (MEMS) sensors, these are very challenging to solder onto circuit boards without automated soldering machines, however most MEMS sensors are supplied on prototyping or development PCBs with essential outboard components included. EMES sensors are usually designed to communicate with a microcontroller or processor using the I2C bus, which is used by Arduino, Raspberry Pi, smartphones etc. Therefore, one of these prototyping systems is a logical platform with which to test MEMS sensors.

The sensor solutions will be compared against the lists of possible advantages of substation monitoring to check functionality.

What does the data give us?

	Data
1	Real time load for control purposes for DNR
2	Reporting that helps with restoration (On/off conditions of substation/feeders/phases, FPI)
3	Exception reporting (Overloads, THD, trespassers for example)
4	Load profile every season for planning purposes
5	MDI
6	Maintenance information

Where does the information from the sensor go?

	Location
1	Locally at the substation and remotely to anyone in the company
2	Locally at the substation and remotely in the control room
3	Locally at the substation and remotely for planning purposes
4	Locally at the substation
5	Other

What time span does the data come in?

	Data fidelity
1	Near real time (<15s)
2	10-minute intervals
3	30-minute intervals
4	Daily
5	3 months/occasional

What back up is available?

	Data logging
1	Near real time logging
2	10-minute interval logging
3	30-minute interval logging
4	Daily log
5	3 months/occasional logs

In what form does the data come in?

	Data form
1	Waveform capture (resolution/trigger?)
2	Including harmonics and angles
3	Phase angles for real/reactive power
4	Peak/RMS/ over different intervals
5	True RMS
6	Time average RMS using peak/root 2

Failure mode – is it safe to deploy in a substation.

8.3 Information from testing

Loughborough will look to develop a number of measurement systems to be tested against requirements. In addition to the key requirements listed above, it is also necessary to characterise the measurement devices over the full range of operation. This will be undertaken in the laboratory at Loughborough under controlled conditions which could be extended to facilities at Loughborough University under real world conditions.

The substation chosen should have accurate measurement to contrast and calibrate the measurement systems under test. The table below shows a summary of tests that will be considered.

Test	Notes
Range of values	Test for linearity between min and max expected values
	Test for measurement factors; saturation, impact of temperature, losses, time constants, harmonics and other Network conditions
Accuracy	Test for accuracy, sensitivity and repeatability
Data Storage	Test for data capture and communication

Any measurement solution will also need to be scalable to deal with the whole Network. Data storage, analysis and monitoring will need to be considered in relation to this;
The trial will also look to quantify any other benefits e.g. safety, environmental and reliability.

To get MD indication, a power or current measurement is required directly or to be implied through indirect measurement. The number of measurements available will depend on the cost and methodology.

Note: the sensing circuit is not just the sensor but will include

- Primary sensing element
- Excitation control (if needed) – power?
- Amplification
- Analogue filtering
- Data conversion
- Compensation
- Digital information processing
- Digital communication processing
- Communication

9 Conclusions and recommendations

The following sensors were identified as being worthy of further investigation

Table 9 : Summary of sensors and platforms to be tested

	Measurement
Magnetometer	Magnetic field
Hall effect chip	Magnetic field
Planar magnetic current sensing	Magnetic field
Accelerometer	Vibration
Audio microphone	Noise
Strain gauge	Strain through a Wheatstone bridge
Thermal stickers/transducers	Temperature
Thermal imaging	Temperature
Android phone	Magnetic field, audio, temperature, camera
IOIO interface unit	With sensors above
Raspberry Pi	With sensors above

It is planned that low-cost MEMS versions of these are developed and tested on the test rig at Loughborough University. Where, these sensor types are available in a mobile phone or other pre-package solution – this will also be tested in conjunction with the MEMS prototype so calibration and internal processing which may occur within the pre-package device may be analysed. The ability of these to characterise a current measurement will be undertaken.

It is planned that this process of characterisation is finalised prior to the end of the University competition so that a clear testing plan is determined and has been fully tested against the sensors listed above and available in a timely manner.

10 Appendix

10.1 Summary of learning points

No	Learning
LP 1	MEMS sensors are very cheap due to tiny raw material volume and massive production volumes.
LP 2	Many different types of sensors use a fixed magnetic field to give another type of measurement. It's not yet clear if these are more or less accurate than a magnetometer.
LP 3	The choice of prototyping & development platform should consider temporal and amplitude resolution, ease of programming, compatibility of communication.
LP 4	Smartphones provide a useful environment for initial testing of MEMS sensors when sensor datalogging apps are used.
LP 5	Data from Android MEMS sensors can be accessed using free apps available on the Google Play Store. If more flexible measurements are required, then custom apps could be used with the Android API (Application programming interface).
LP 6	Development kits such as NI offer a comprehensive list of generic sensors that they can be used with. However, all of these can be manufactured at significantly lower cost on a part by part basis
LP 7	Utilities are used to traditional forms of measurements where equipment comes with certification declaring it fit for purpose. Therefore, the introduction of new methodology requires careful planning and management especially in early stages when certification issues are not clear cut and may be missing altogether.
LP 8	Calibrating a measurement in one location with or without Utility found equipment does not guarantee calibration in other locations or with other pieces of equipment.
LP 9	Calibration may change due to external influences such as temperature or over time. It is important to try and pre-determine both factors as part of this project.
LP 10	Many of the characteristics of substations can be synthesised using high current low voltage power supplies.

10.2 Current commercially available measurement systems

Manufacturer	Product	Description	URL
Kelvatek	Bidoyng smart LV fuse	Modified LV fuse carrier, includes 2 fuses for single shot auto-reclose. Includes current & voltage monitoring	www.kelvatek.com/bidoyng.php
Lucy Electric GridKey UK	MCU318		
	EMC		
Fluke	T6-600 / T6-1000	Contactless ammeter/voltmeter	http://www.fluke.com/fluke/uken/electrical-testers/Electrical-Testers/T6-1000-Electrical-Tester.htm?PID=81966
Megger	MMC850	Multicore clamp meter, measure up to 100A & 16mm2 for specific cable specs	
Suparule	Flexiclamp	Multicore current sensor, patented? Not developed.	http://www.suparule.com/docs/Flexiclamp_technology_datasheet.PDF

10.3 Table of sensors investigated

The following sensors were identified as worthy of further investigation as to their possible use to measure a physical quantity in a substation:

Sensor type	Examples	Cost range	Parameter [Unit]	Range	Resolution	Package	Typical applications	Comments	Include in trials? Why / why not?
Electric and magnetic	MEM/AMR Magnetometer	£1 RS	Magnetic field strength [Tesla]	0-2000uT		3x3mm SMT	Electronic compass in satnavs, smartphones, etc.	Combined magnetometer/accel chips £5-15 RS	Yes, cheap & useful readings on android
	Magnetoresistive angular sensors	£3.30 Farnell	Angular position [°]	0-360°	0.1°	6x5mm SMT	KMT32B Contactless angular position sensors	Measures magnetic field direction independently of strength[33]	
	Hall effect sensor							Can detect static M fields, available with Boolean or floating output.	
	capacitance						Touchscreens, taps, liquid level, voltage detector pens	Ground reference required	
	Metal detector principle							AC/pulse applied to emitter coil induces eddy current in metal object which is detected by receiver coil.	
	Electromechanical film						Microphones, pressure/force sensors,	thin membrane, thickness is related to an electric	

							speakers	voltage.	
Acoustic Sensors	microphone	<£1							
Position Sensors	Resistive strain gauge							e.g. change in position along cable bend radii. Transformer vibration	
	Piezoelectric strain gauge							ditto	
	Fibre optic strain gauge								
	Fibre optic flex sensor								
	Capacitive flex sensor								
	Vibrating wire strain gauge							Strain calculated from resonant frequency of wire	
Imagining, optical, light Sensors	CCD/InGaAs etc						CCTV, smartphones, etc	Could use visible blocking filter to image IR	
	Thermal imaging camera								
	Passive infra-red						Movement sensors for lighting & intruder alarms		No, there are cheaper & easier ways to detect temperature

									increase
	Photodiode		Irradiance [W/m^2]	0-1000	1		Smoke detectors, CD players, remote control	Is a tiny solar cell.	No, too convoluted
	Photo resistor /light dependent resistor (LDR)						Lux meters, daylight sensors,		No, too convoluted
	Heat flux sensor (thermopile)		Heat flux [W/m^2]				Conductive heat flux - Building physics. Radiative heat flux density – pyranometer (solar irradiance). Agro-meteorological studies		
	Bolometer		Electromagnetic radiation (Power of)			Through hole	Astro-physics, particle physics, thermal cameras, microwave measurement		No, too expensive
	Thermocouples /							Cheap but	

	thermopile							restrictive re connector	
	RTD							More expensive, reliable to measure	
	Silicon bandgap								
	thermistor								
	Golay cell		Infra-red radiation				infrared spectroscopy.		No, too expensive
Chemical / Biological	Dissolved gas analysis							e.g. Kelvatek TOTUS	
	Photoionization								No, too convoluted
Other	Tactile sensors (touch) Bio-chip and nano-sensors Digital sensors looking at pH, oxygen content Lab on a chip – also micro-electro-mechanical systems (MEMS) micro total analysis system (uTAS) RFID [21]							Not clear yet what and how these could work in a Utility environment.	

10.4 List of potential prototyping / development systems

System	Sensors	OS	Native language	Notes
Android phone	Camera, Accelerometer, Ambient temperature, Magnetic Field, Fingerprint, Gyroscope, Heart Rate, Light, Pedometer, Proximity, Pressure, Relative humidity, Radiation	Android	Java / C++ / Go / Kotlin	
iPhone	Camera, Accelerometer, Ambient light, Barometer, Compass Gyroscope, Pressure sensitive display, Proximity, Fingerprint	iOS	Ajax (Java + XML)	
IOIO		Android	As Android	USB I/O breakout board for Android AKA super-Arduino
raspberry PI	plug-in PCBs available with wide ranges of sensors including cameras	Many including Linux	C	
Arduino	built in analogue ports	Microcontroller	Machine code via C/C++	
Ni MyRIO	Accelerometer	ARM processor	LabVIEW	
Lego Mindstorm	Plug & play Sensors include ultrasonic, IR, gyro			Expensive at £27/sensor, sensor outputs are
Fitbits	steps, movement, sleep, heart rate, altitude, GPS.			Wearable sensors which connect to a smartphone app via Bluetooth

10.5 Android sensor apps tested in the project

Data from sensors can be retrieved in code with methods like

```
getDefaultSensor(SENSOR_TYPE_GYROSCOPE)
```

However, the values given are not the raw sensor measurements, but are compensated for bias and temperature. It would not be possible to access raw data using the android firmware shipped with the handset. Whilst the android operating system is released as open source, support for third party firmware varies between manufacturers and always invalidates the warranty of the handset, unlike the use of custom coded apps which doesn't invalidate the warranty.
Sensor accuracy can be interrogated using e.g.

```
sensors_event_t.acceleration.status
```

Name	Developer	Magnet-ometer	Acceler-ometer	physical sensors *	derived sensors *	Total sensors	graph	Numeric display	Save to file	notes
Sensor Data Logger	Stepschuh	y	y	8	11	19	y	n	n	nice graphs shame it doesn't save data
Sensor Data Logger	Alfredo Prades	y	y	2	0	2	n	y	n	alphanumeric display no graph no logging
Sensor Logger	i-Realitysoft	y	y	8	0	8	y	y	y	measures every 10mSec (varies from 3-12 mSec)
Gauss Meter	Keuwlsoft	y	n	1	0	1	y	y	n	nice 1min min max average feature & flux calculations but no logging
Sensor Box		y	y	8	0	8	y	y	n	basic app with nice visuals

* as counted on Samsung Galaxy S6

10.6 List of Apple iPhone/iPod/iPad devices and their sensors

	iPhone 3GS	iPhone 4/4S/5/5C/5S	iPhone 6/6plus	iPhone 6S / 6S plus	iPhone SE	iPad 1	iPad 2/3/4/air	iPad Pro	iPad Mini 1/2	iPad Mini 3	iPad Mini 4	iPod Touch 1/2/3	iPod Touch 4/5/6
Camera (Mp)	3.15	5/8	8	12	12	none	0.7/5	08-Dec	5	5	8	none	0.7/5/8
Accelerometer	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Ambient light sensor	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Barometer			Y	Y	Y		Y	Y			Y		
Compass	Y	Y	Y	Y	Y		Y	Y	Y	Y	Y		
Gyroscope		Y	Y	Y	Y		Y	Y	Y	Y	Y		Y
NFC for Apple Pay			Y	Y	Y								
Pressure sensitive display				Y									
Proximity sensor	Y	Y	Y	Y	Y								
Touch ID fingerprint scanner			Y	Y	Y			Y		Y	Y		
Others								True-tone display					

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11.1 Experts consulted during the project

- Dr Robert Edwards, Reader in Mobile Communications, Loughborough University. Consulted about low sensors & use of antennae for electrical measurements.
- Dr Andrew Urquhart, Research Associate on CREST/WPD losses project. Consulted about typical LV feeder configuration & loadings, signal processing.
- Prof Massimiliano Zecca, Professor of Healthcare Technology, consulted about application of healthcare sensors in substations