WESTERN POWER DISTRIBUTION

INNOVATION

NEXT GENERATION NETWORKS

DEDUCE

CLOSEDOWN REPORT

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Contents

Glossary

Abbreviation	Term
AC	Alternating Current
CREST	Centre for Renewable Energy Systems Technology at Loughborough University
EV	Electric Vehicle
IP	Intellectual Property
LU	Loughborough University
LV	Low Voltage
MEMS	Micro Electronic Mechanical System
DNO	Distribution Network Operator
MDI	Maximum Demand Indicator
NIA	Network Innovation Allowance
PCB	Printed Circuit Board
PV	Photovoltaic
RMS	Root Mean Square
SCADA	Supervisory Control and Data Acquisition

Executive Summary

Recent growth in embedded generation and the anticipated consumer uptake of EVs and heat pumps present new challenges for WPD. Data from maximum demand indicators in distribution substations is inadequate to understand the spread of demand over time. Retro-fit data logging solutions are available for substation monitoring, but typically cost over £1200. This NIA research project on network analogues was conducted by CREST in conjunction with WPD. The aim of the project was 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 had tightly defined cost requirement and loose technical requirements.

CREST have designed, built and coded 8 different sensors using three different control platforms with the following high level results:

- The majority of the sensors and platforms for communication came within the target budget.
- There were three sensors that could give a good indication of substation loading and one more where results were inconclusive.
- There is capability to get at least eight useable input/output channels on most platforms and many more on others.
- The best resolution found was data logging to a server at an average of 7ms resolution using a Raspberry Pi. Typically 10s resolution was felt to be useful.
- All the solutions can communicate via Wi-Fi or over the mobile Network (and in some cases through wired connections).

In addition a university competition was carried out to seek alternative solutions. This involved engaging with universities and students across the UK. However despite the engagement and support, a limited number of projects were received and limited learning was generated.

1 Project 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 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 Rogoswki 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 looked to develop a low cost (sub £100) distribution substation monitor based on indirect loading measures (temperature, noise, vibration…). At a minimum this should 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 were utilised:

- 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

The trial of existing low-cost sensors and investigation of disruptive technology was undertaken at Loughborough University where a number of different sensors were designed, built, tested and characterised in the laboratory and followed through to testing on University owned 11kV/400V facilities.

The university competition was organised through Loughborough University and targeted all UK University students. It was launched in November and followed a three stage process.

1. Students submitted their ideas for measurement along with costing
2. The top teams are invited to build and submit a hardware prototype for testing and provided a budget of up to £500
3. The prototypes are tested and characterised. With a top prize going to the highest scored project.

2 Scope and Objectives

To meet the aims the following scope of work was developed.

Scope	Status
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	✓

The following objective was set.

Objective	Status
To develop, characterise and test sensors that could be used for indirect measurement for substation monitoring. The project is expected to develop a whole systems methodology from reading sensor data through inferring loading profiles from this measurement leading delivery of such data to the DNO.	✓

3 Success Criteria

The following success criteria were put forward. Full details on performance can be found in section 5.

Success Criteria	Status
Development of 6-8 sensors at Loughborough.	✓
Entries from 8 Universities.	✗ There were 5 entries
5 University student entries taken forward to prototype.	✗ 3 projects shortlisted
Characterised performance of researched sensors.	✓
Business case for trial based deployment.	✓

4 Details of Work Carried Out

The work was split into 3 areas. A literatures review to determine which sensors to test, testing of the relevant sensors, and a University competition.

4.1 Low Cost Sensor Literature Review

The initial piece of work was a literature review carried out by LU to assess what sensors would be worthwhile testing. Full details are available in the comprehensive Low Cost Sensors Literature Review report.

This involved carrying out research on a variety of sensors across a range of parameters as shown below.

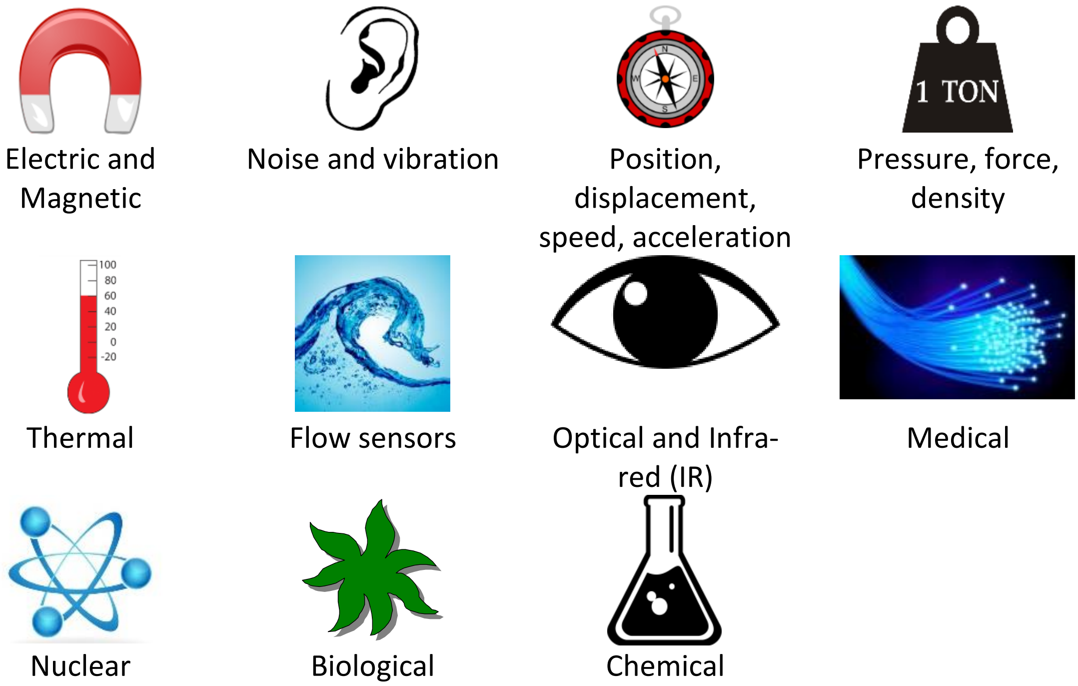

Figure 1 : Types of sensor detection

For each of the sensing parameters, a range of sensors was investigated, looking into the measurement path and then assessing the suitability for LV substation monitoring.

Alongside the review of sensors, existing sensing packages such as smart phones and Arduinos were also reviewed to investigate any simple routes to operable sensors.

This initial work led to the following sensors being chosen for further testing.

Table 1 : Summary of sensors and platforms to be tested

ID	Sensor type	Variable measured
A	MEMS Magnetometer	Magnetic field
B	Hall effect chip	Magnetic field
C	Novel magnetic field coil sensor	Magnetic field
D	Accelerometer	Vibration
E	Audio microphone	Noise
F	Strain gauge	Strain through a Wheatstone bridge

G1	Temperature labels	Temperature
G2	Thermistor remote alarm	Temperature
H	Thermal imaging	Temperature
ID	**Platform type**	**Variable measured**
I	Android phone	Magnetic field
J	IOIO interface unit	With a sensor above
K	Arduino	With sensors above
L	Raspberry Pi	With a sensor above

It should be noted that not all the sensors can measure loading on all types of cable. Usually, sensors only measure single core or three core cable types.

4.2 Low Cost Sensor Testing

Following the initial literature review, a range of sensors across a range of platforms were tested. Full details can be found in the Low Cost Sensor Testing Report. In theory, each sensor could be connected through to each platform. However, the reality is that it is easier to connect certain sensors with associated platforms. The figure below highlights the combinations tested.

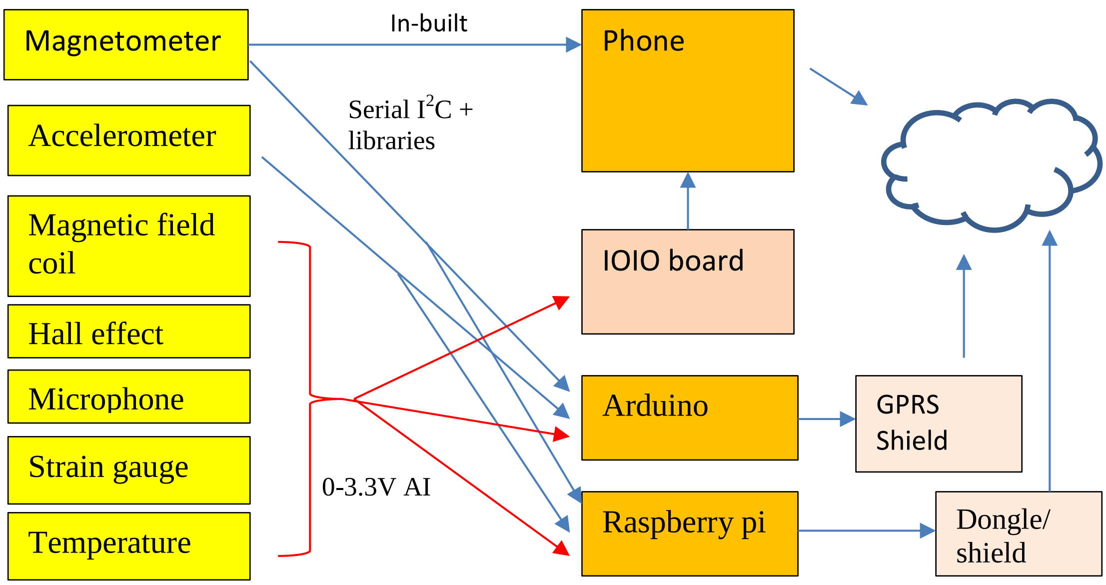

Figure 2: Sensor - platform interface options

Each combination was built and tested following the methodology below:

1) Design sensor system
2) Manufacture sensor system
3) Conduct detailed tests on the test rig
4) Modify design following 3
5) If Appropriate - Conduct tests on active 11:0.4kV substation
6) Document results & plan any potential further testing

4.2.1 Lab Test Rig

For initial testing, a simulated substation was setup to recreate many of the characteristics of an LV substation.
There were two main aspects of the lab facility:

1) A 3 phase, 45kVA air cooled transformer with variable voltage supply
2) A high current, low voltage power supply which could supply up to 150A into a shorted 3 phase cable as shown in Figure 3. This meant that any DNO 1,2, 3 or 4 core cables could be connected, and their electromagnetic field measured with sensors under test. It could also be used for other tests such as temperature and strain.

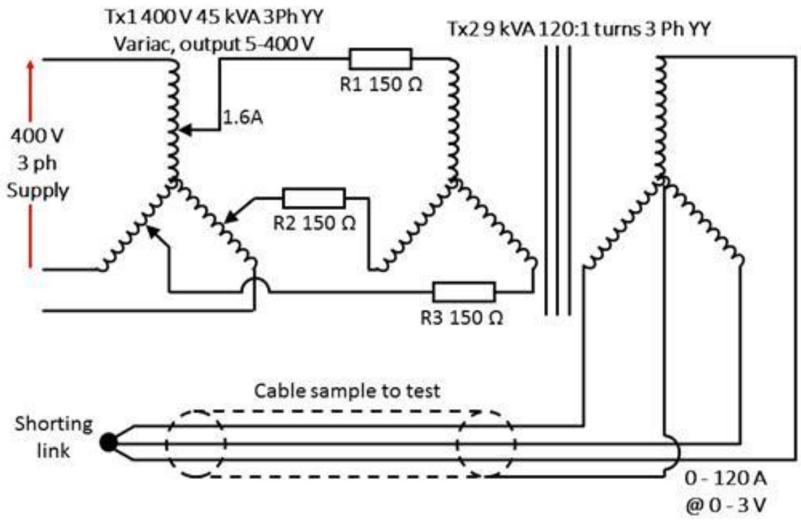

Figure 3: Simplified schematic of the test system used at Loughborough University. Note that earthing and protection is omitted in this drawing.

The following systems were used to validate current sensor measurements:

- Fluke 435 II Power Quality Analyser (PQA).
- Fluke i430 Flex-TF-II Rogowski Coil
- Teledyne Lecroy HDO6104 High Definition Oscilloscope
- CP0150 Current Probe

The Fluke 435 and i430 were internally checked by LU for accuracy, linearity and response to harmonics and reactive power with a calibrated Fluke 9100 multifunction calibrator.

The cables used in the test rig included a small selection of LV and HV cable types based on availability and could be used to represent some typical cable specifications found in secondary substations

The following cables (Figure 4-Figure 6 and Table 4-2) were used for testing in the Loughborough Test Rig.

Figure 4: single phase welding cable

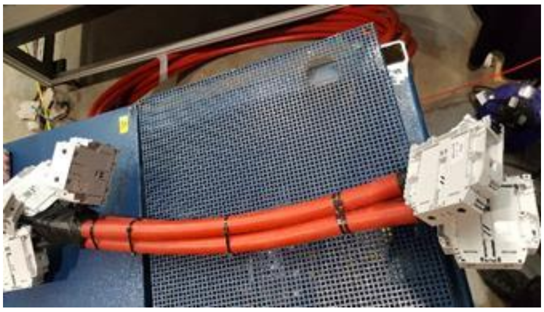

Figure 5: 11kV 3-core Trefoil XLPE cable

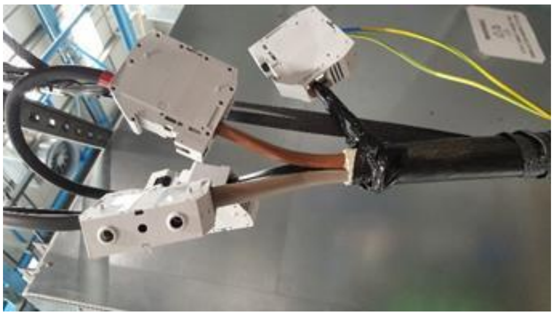

Figure 6: 11kV 3-core Waveform PVC cable

Table 4-2 : Cable types used in the testing

Type	Voltage rating [kV]	Conductor	Screen / Sheath	Cores	Cross sectional area [mm2]	Outside diameter [mm]
Waveform	11	Al	Al	3	95	33.5-35.3
Trefoil	11	Al	Al	3 (singles)	95	31-33*
Welder	0.4	Cu	Rubber	1	16	11.8

*Diameter given is of an individual core of the trefoil formation – outside diameter of the bundle is about 66.8mm

Loughborough developed several measurement criteria to test against requirements. These were undertaken in the laboratory at Loughborough under controlled conditions which were then extended to substation facilities at Loughborough University under real world conditions.

The table below shows a summary of tests that were considered.

Table 4-3 : Key tests identified in scoping document

Test	
Range of values	Test for linearity between min and max expected values
	Test for measurement factors; saturation, impact of temperature, and other tests as determined appropriate
Accuracy	Test for accuracy, sensitivity and repeatability
Data Storage	Test for data capture and communication

4.2.2 Substation testing

Tests were conducted at Holywell Building substation 8. This substation was convenient because it was close to the laboratory and the University Wi-Fi Network could be used. However, the building was recently emptied and there was low load on the substation. This made it difficult to get very accurate results. In particular the current on the 11kV side of the transformer was calculated to be approximately 3A.

The cables in the substation are SWA XLPE cables. There was also access to the 11kV cable in two places Access to the LV cables is straightforward – but there are a number of feeders leaving the transformer and to calculate the total loading accurately on the 11kV cable couldn't be accurately done using conventional measurements with the equipment available at Loughborough. This was therefore approximated by using a fluke to measure the red phase current on each LV feeder and then assuming the currents are balanced – add these together to determine the total current. Multiply this by the 433V (rating of the transformer) and √3 to get the approximate LV apparent power and then assuming that this is supplied by the primary and the transformer is lossless and dividing by √3 x 11kV to get an estimate of the primary current.

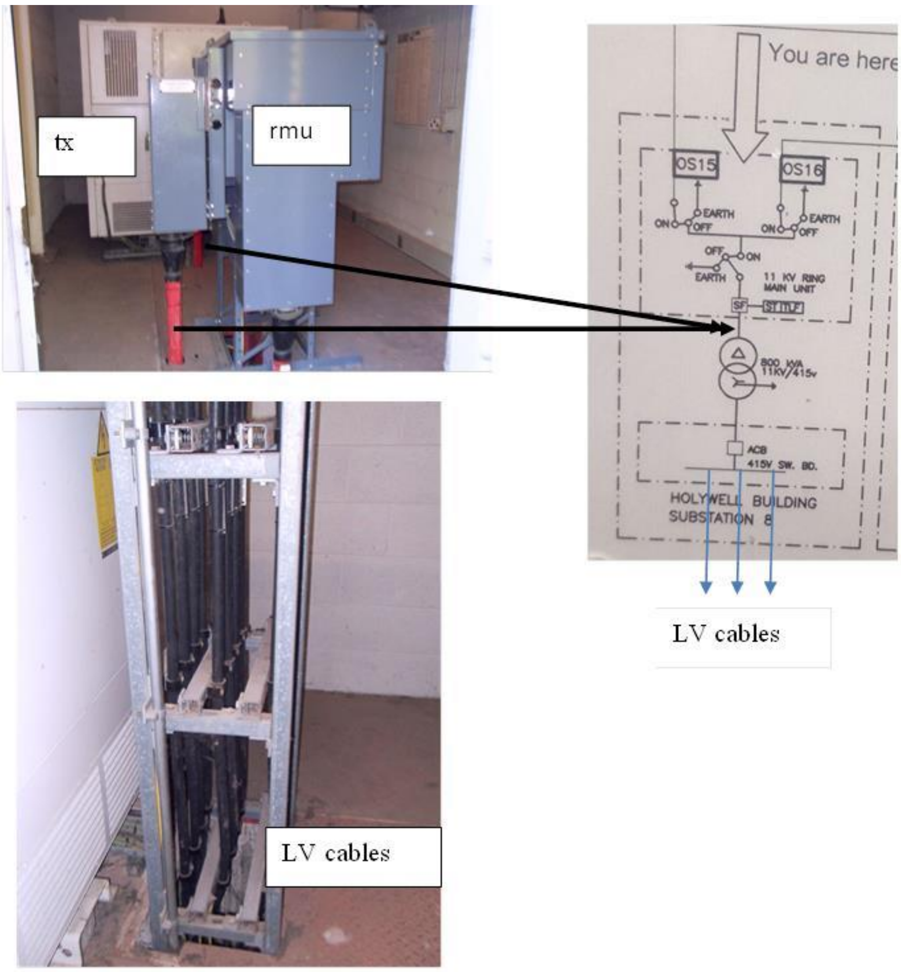

Figure 7: Substation, Holywell Building, Substation 8, schematic and photo

Table 4-4 : Cable types in the substation testing

Type	Voltage rating [kV]	Conductor	Screen / Sheath	Cores	Cross sectional area [mm2]	Outside diameter [mm]
XLPE	11	Cu	SWA	3	185	75
XLPE	0.4	Cu	SWA	1	185	27.14

Another issue with the substation is that the transformer was not directly available as this had been enclosed in a stainless steel covering. This impacted efforts to measure the noise, vibration and temperature of the transformer as there was a gap between housing and transformer.

4.2.3 Results

Full details of the results can be found in the Low Cost Sensor Testing Report. This includes the theory behind how each sensor works as well as the specific challenges associated with the testing.
A summary of the sensors tested are as follows:

Table 4-5 : Summary table

Sensor	Advantages	Disadvantages
Magnetometer	Already exists on a mobile phone platform	May need to calculate a "phone factor" prior to installation on site
Hall effect Chip		Unable to get working
I2m coil	Quick to install	Theory around back calculation of current still needs work
Accelerometer		No obvious relationship has been developed. Would require on-site calibration
Microphone		Significant amount of processing and its not clear if the control platforms would be able to log data to sufficient fidelity. Correlation poor and on-site calibration would be needed
Strain gauge		Difficult to get working Fragile to install and Likely to have some drift
Temperature sensors		Previous work suggests that installation on transformers is possible but calibration on site and model tuning would be needed. Results not sufficiently detailed within this work.
Thermal Imaging		Unable to get working
Platform	**Advantages**	**Disadvantages**
Mobile phone	Can connect directly to the Network to upload and download information	No immediate analogue inputs available. Internal magnetometer sensor may be used
IOIO board	Provides the IO ports for the phone	Adds additional cost to the mobile phone platform
Arduino	Easy to use and code	Needs a shield to connect to the mobile network and the lack of memory may be an issue for processing and uploading data securely
Raspberry Pi	Powerful with good onboard storage	Needs an additional IO chip to give analogue inputs. This is not as expensive as that required by the phone. This has the fastest of all the data logging solutions that were tried

4.3 University competition

Alongside the work carried out by researchers at LU, a university competition was carried out to see if new sensors or processes could be determined by university students. Full details are available in the University Competition Report.

4.3.1 Competition brief

The competition brief included a technical description and some photos of substations, along with a summary of why WPD were keen to develop low cost sensors and some terms and conditions.

The description of the competition in the initial publicity material was intentionally loose for two reasons. Firstly, to widen the potential pool of applicants. Secondly to encourage entrants to be imaginative in their approach and not be heavily constrained by existing approaches. It was also decided that it wasn't essential to prescribe every detail of the competition format and requirements in the beginning, but, allow it to evolve in response to initial feedback from entrants and academics.

4.3.2 Promotion

The timing of the competition promotional material was considered to be important to the success of the competition. Materials ideally should reach students just before they pick projects, so they can be guided towards this as an idea. Final year students often have meetings with supervisors in the first or second week of term where they would need to decide the broad theme of their project in order to start on background research. The start of term varies between Universities, in 2017 Autumn term started on the 2nd October at Loughborough, 18th September at Manchester, 11th September at Strathclyde, 3rd October at Cambridge, 23rd September at Bath. The contract for this project was formally signed on the 3rd November, approximately 4 months from initial concept discussions between CREST and WPD in early August.

The competition was launched with a multimedia publicity campaign, including a bespoke website, posters, Facebook as described below.

A following competition website was setup also a QR code was used in marketing material as shown in Figure 8.

Figure 8: QR code 2D barcode used for the competition website

The main feedback from academics at other institutions was that they had already allocated student projects when they heard about the competition. Final year projects tend to be allocated in the first weeks of the autumn term or in the final weeks of the preceding summer term.
Awareness is a key factor and many student and academics hadn't heard about the competition until close to the first deadline, so there is advantage to running a competition as part of a regular annual event, so academics can plan ahead for the next upcoming competition, and future competitions are publicised by the award publicity from preceding competitions.

A forum was also setup for discussion about the competition, firstly to minimise email traffic, and secondly so that information given to any entrant would also be disseminated to all other entrants for fairness. Facebook was used as a quick platform for the forum which is generally popular with students.

A wide range of promotion channels was used to hedge against the limitations for individual channels.

- An email sent to 120 academics at 60 institutions identified from the following sources:
    - IET (institute of Engineering and Technology) Power Academy partners
    - Engineering degrees accredited by the IET for Chartered Engineer status.
    - Attendees at the 2017 Low carbon networks and Innovation (LCNI) conference
    - Academics with an interest in WPD project Falcon
    - Personal contacts of Project staff

  The complete list of Universities approached is given in the appendices.
- Leaflets and posters sent to the above institutions.
- Adverts on various University websites and social media channels –
- CREST website
- CREST facebook group
- CREST LinkedIn
- CREST Twitter feed
- IET student communities
- Engineering at Loughborough Facebook group (13th November)
    - Other Universities which advertised the competition on their news pages
    - Heriot Watt University
    - Nottingham University
- Adverts on display screens in University premises.
- A mailout to all Loughborough University Engineering Students.
- Leaflets given out at Loughborough University careers fairs.
- Messages placed on student social media groups by students working as careers and publicity interns.
- A 16:9 electronic poster displayed on screens in the engineering departments at Cardiff University and Loughborough University.

4.3.3 Shortlisting

Entries were received from the following universities:

- Cardiff
- Liverpool
- Liverpool John Moores
- Loughborough
- Sussex

Of the entries, 40% had joined the Facebook group and 80% had emailed beforehand with questions about the competition. 20% entrants had no prior communication before submitting.

The competition brief was intentionally written to in a way which accurately describes the main components of a distribution substation without describing current monitoring options. Whilst the competition was titled the student sensor competition, the brief didn't specify whether the entrants should focus on the actual sensor or the signal processing and transmission or if they had to deliver a complete system. All the entrants interpreted the brief by proposing a complete system, but different entrants focused on different parts of the system in terms of novelty.

Of the entries received, some of the competitors used off the shelf sensors including CTs but focused on value engineering the signal and data processing and forward communications. Some applicants took existing sensor technologies but proposed modified or value engineered variants of them.

Some entries used bespoke analogue or digital signal processing options. Most entrants used off the shelf microprocessor development boards for some or all of the A-D, control and communications. Development boards proposed included Arduino, Particle.IO, Raspberry PI and Seeduino.

A variety of communications options were proposed including GPRS, WLAN, Zigbee and Powerline communications.

The judges had questions regarding most of the entries, these were sent to the entrants by email for clarification before the final shortlisting decision was made.

Each entry was scored out of 10 against the following eight criteria:

- Background research
- Attention to detail
- Sensor novelty
- Sensor feasibility
- Signal-Data novelty
- Signal-data feasibility
- Communications novelty

- Communications feasibility

Therefore, the maximum possible total score was 80,

There was considerable variation in how generous the judges were in their scoring, with average scores awarded by a judge varying from 23 to 39.
The aggregate scores of the entries varied from 24 to 40.

The development grant was awarded to all successful entries which achieved an aggregate score above 30. It was made clear to those candidates that unless they had hardware available for testing at Loughborough that they would be ineligible to win a prize.

The majority of shortlisted ideas were final year student projects with the remainder PhD teams.

4.3.4 Support and Guidance

The shortlisted students were spread over different Universities and each was offered the support of a member of the CREST team along with an open invitation to visit Loughborough. Only one team came to Loughborough prior to testing to discuss their project.

On the whole, the students were content to work independently (or with a supervisor at their own institution). As the deadline approached for hardware testing, the students were prompted with an email about bringing their hardware to test and arrangements were made for train journeys and hotel accommodation as required.

The students also filled out a questionnaire so that the University could take feedback on the level of support offered and to understand if the students felt any other support was required.

Comments back from the questionnaire are varied and include;

- The majority of students found out about the competition through word of mouth, which made them more aware of the advertising material. One group found out by a displayed poster.
- Timing worked ok with the academic timetable and didn't interfere with exams and coursework.
- Most students liked the two stage process with one team feeling that getting through the first stage made them more committed to seeing the project through to the end.
- Some students would have liked more time for hardware design and development (perhaps by shortlisting earlier)
- A hardware budget of £500 was considered by all to be fine and allowed the students to explore different options while developing their sensors

- Support offered by both Loughborough and WPD was considered to be good
- Some students would have liked access to off-service real equipment to help with testing
- If the competition were to be re-run then one group have suggested including an example case study.

4.3.5 Testing

The students visited Loughborough over a two week period to undertake testing of their hardware. During this time two members of Loughborough personnel were available at all times the students were around to help supervise, mentor, support, set up measurement devices, adjust the test rig as required and witness the testing program.

The testing for each of the shortlisted teams was individual to their requirements and so the test rig and instrumentation required was unique in each case.

As the hardware was different for each entry it was necessary to adapt the rigs. To enable testing of all solutions the following test equipment was required.

1. The Loughborough test rig with single core cable to test loading and additional cabling required to give a measure of voltage at the primary of the transformer
2. A variac connected to a single core cable to test voltage measurements
3. An oscilloscope to look at waveforms with both current and voltage probes. It was necessary to have data capture capability as this was used to check the results
4. A multi-meter to measure voltage
5. Additional PCB based power supplies (some entrants had batteries as part of their set-up)

The entries include solutions around novel powerline communication, current testing using low cost Rogowski coils and voltage testing without contact using capacitor charging and discharging.

All of the entries were tested such that the variable under measurement was varied and the response was noted. Loughborough University witnessed each of the testing. Figure 9 shows a sub set of the results of the testing on the day. In most cases it can be seen that there is a relationship between the measured value and the response and that this is singular such that a value of response may be related back to the measured value. For most of the teams this was not quantified at this time and the measurement device would likely require on-site calibration to produce a look up table.

Other key points to note from the day;

1. Not all the solutions focussed on load measurement
2. None of the solutions were available as a complete solution; for example the use of power supplies, batteries which would need re-charge or intermediate data capture

3. All the solutions had bespoke electronic circuits manufactured on pcb or breadboard
4. A lot of work had gone into developing and manufacturing the prototypes
5. All of the prototype solutions worked with varying degrees of success
6. All of the solutions worked on single core cables and none would have been transferable to three core cables in their current state.
7. Most of the solutions would have worked with screened and earthed cable, but one solution required the cable to have no screen.
8. The costs provided by most teams were lacking key pieces of information as to a total package solution as they focused on the part of their sensor that was relevant.

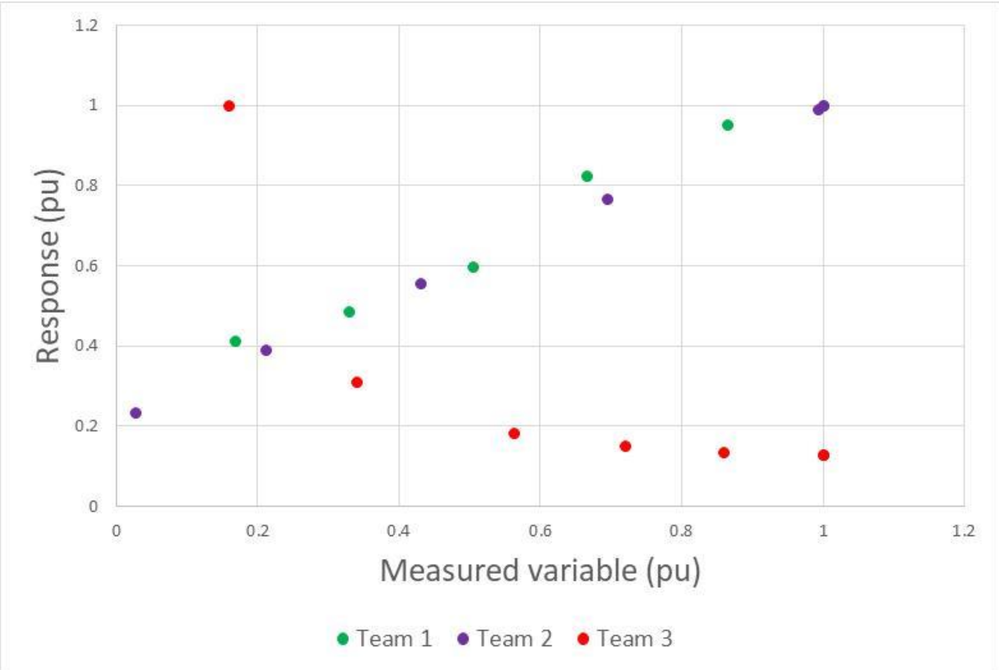

Figure 9: A sub-section of the witness test results normalised for measurement

4.3.6 Judging

Judging was undertaken solely by WPD staff to avoid any bias.

To help with judging each of the teams produced a slide show explaining their solution and some cost figures. A marking sheet was also produced from which to judge the competition.

4.3.7 Conclusions and recommendations

It took a significant amount of effort to run a University based competition and there were issues with timings, ensuring IPR was adequately dealt with and the ability to easily target students.

Entry numbers were lower than expected. However, what was lacking in quantity was present in commitment. In particular, the student teams that were shortlisted worked hard and produced working hardware that provided measurements of potential value.

A University competition is a good mechanism for identifying knowledgeable and committed students from a recruitment perspective, but the ideas were not sufficiently developed to have value of the WPD Network at this time and would require considerable effort before they were ready as a low cost product for field trials on a grid.

5 Performance Compared to Original Aims, Objectives and Success Criteria

To meet the aims the following scope of work was utilised:

Aims	Performance
Investigate existing low cost sensors that can be used for indirect substation loading monitoring.	✓ met through literature review and lab/site testing.
Investigate new disruptive technologies to determine their suitability and accuracy for monitoring	✓ met through literature review and lab/site testing.
Use existing low cost measurement devices or packages (such as a smart phone or raspberry pi) to indirectly provide measurement	✓ met as part of testing
Run a university based competition to enable non-traditional solutions to be explored	✓ met through UK wide university competition

Objective	Status
To main objectives were to develop, characterise and test sensors that could be used for indirect measurement for substation monitoring. The project was expected to develop a whole systems methodology from reading sensor data through inferring loading profiles from this measurement leading delivery of such data to the DNO.	✓ met through the development of the Magnetometer and I2M sensor packages.

Success Criteria	Status
Development of 6-8 sensors at Loughborough	✓ 11 sensor packages under development
Entries from 8 Universities	× Responses from 5 universities received
5 University student entries taken forward to prototype	× 3 entries taken forward to prototype
Characterised performance of those sensors	✓ met in Low Cost Sensor testing report.
Business case for trial based deployment	✓ met in the development of a follow up project.

6 Required Modifications to the Planned Approach during the Course of the Project

There were no modifications to the planned approach.

7 Project Costs

Table 6 shows the project costs.

Table 6: Project Costs

Activity	Budget	Actual
WPD Project Management (including dissemination)	£20,463	£9,852[1]
WPD installation costs	£1,091	£0[2]
Loughborough University contract	£142,594	£142,594
Contingency	£16,414	£0[3]
Total	£180,562	£152,446

[1] WPD project management costs were lower than expected due to the robust sub-management of the project by Loughborough University. Dissemination costs were also limited as learning was shared at the LCNI amongst other projects.
[2] No network installs were carried out as part of the trial.
[3] As the project went relatively straightforwardly, no contingency was required.

8 Lessons Learnt for Future Projects

The key lessons learnt are shown below in Table 7. More detailed lessons are covered in the relevant reports.

Table 7: Learning Points

Topic / Area	Learning generated
Literature review	Sensors to measure current in multicore/trefoil cables are not commercially available and there is no available published literature on measurement solutions. These are the most popular type of cable on the distribution network and measuring these types of cable with a single sensor may be valuable.
MEMs sensors	MEMS sensors are very cheap due to tiny raw material volume and massive production volumes and offer an attractive approach for low cost high volume sensor development.
MEMs sensors	Pre-fabricated MEMs sensor development boards help reduced time scales to development and are set up to easily interface through common platforms. These may also come with libraries which speed development on the coding.
Data Processing	Low cost control platforms for logging data operate at a time span that is comparable to the frequency of the supply. Care is therefore needed to deal with aliasing and post data processing. In particular, it is recommended that traditional calculation of RMS is not used on fast changing signals such as magnetic field. An exponential moving average method with principle component analysis is the most suitable method.
Data Capture	The android phone is designed to be seamless to the user and therefore the rate of data capture of the phone is varied and occurs asynchronously depending on what the rest of the phone is doing. This means that it is difficult to use traditional calculation techniques to get RMS currents. The data can be captured as fast as 10ms intervals and therefore if required this could offer a near real time measurement solution.
Magnetometer	A magnetometer detects magnetic fields on three axes. Saturation on one sensor vector doesn't impact any of the other sensor axes and it's still possible to obtain meaningful relationships between load current and magnetic field. However, Saturation of sensor output even on one axis of a magnetometer compromises the ability to accurately check measurements against theory using principle component analysis.
Magnetometer	The magnetometer field appeared to increase slightly with temperature. This is in keeping with previously published work. In this application the impact is minimal.
Magnetometer	MEMs magnetometers are able to measure fields which can track the loading on a cable.
Magnetometer	Installing the MEMs magnetometers at a substation took less than 5 minutes – attach the device to the cable and provide power to the platform unit. Further work is needed on packaging this solution to give it an appropriate IP rating and allow the connectors to be better developed.
Magnetometer	The cost of the MEM's magnetometer is such that more than one may be applied to different cables and these may be daisy chained on the I^2C bus. The theoretical limit is 127 but this is lower in practice.

Magnetometer	Distance is a factor when turning magnetic field back to an estimate of load current. Therefore, the location of the sensor is important to estimate its distance from the centre of the cable.
Magnetometer	It could be possible to pick up some harmonic content within the system, but the maths needs to be further developed. This is also limited by the processor of the platform device.
Hall Effect sensors	A hall effect measurement device did not provide a suitable measurement reading to allow output to be correlated to load current.
I2M coil	3 phase AC Current can be measured in multicore cables using the new coil design developed at CREST
I2M coil	The new coil designs showed good correlation between measurement and load current in a balanced system.
I2M coil	There are many different methods to produce turns or wire onto something suitable to go round a cable. Material with conductive thread could be best for large scale implementation as the coils may be made to tighter specifications in a manufacturing environment (eg straight sides) and these can be easily overlapped for multi-coil designs and stacked to increase the number of turns. In addition waterproofing and adding suitable fastenings eg Velcro could ensure fast installation.
I2M coil	The coils have to fit 180^{o} around the cable these mean the coils sides have to be a set distance apart. The sewn coil offers the best opportunity for a single design as it can be folded to give the straight edges 180^{o} apart. The PCB and wired coil would need to be made in different sizes for large scale roll out.
I2M coil	Although the coil itself can pick up the harmonics. The platform it is connected to may limit the use of this information through the data logging resolution and also timing.
Vibration	The testing undertaken indicated that it was not going to be possible to accurately relate vibration with loading at the target price point. The calibration process would be too complex and time consuming.
Noise	The testing undertaken indicated that it was not going to be possible to accurately relate noise with loading at the target price point. The calibration process would be too complex and time consuming.
Strain Gauge	Strain gauges are not suitable for measuring loading in distribution substations due to the signal being close to or below the signal noise floor. They are also difficult to install.
Temperature	Thermal stickers are low cost devices that show temperature. However, it is not clear if there is a business case for their use as these would need to be manually observed.
Temperature	A temperature alarm sensor would not to be calibrated on site – as it is not directly looking for a load current – but would look instead at ensuring that the tank temperature (as a proxy for top oil temperature) did not exceed values set by standards (60^{o}C above 20^{o}C ambient BSEN600-76-2_2011).
Temperature	It should be possible to link a temperature measurement device such a thermistor to a transformer to give an indication of loading. However no representative hardware was available to test properly and calibration on site may be needed.

Temperature	Calibrating a temperature measurement in one location with or without Utility found equipment does not guarantee calibration in other locations or with other pieces of equipment.
Temperature	Thermal imaging using an android phone is not going to be suitable as measuring through a conventional camera by changing the filtering couldn't be made to work.
Smartphone as a sensor	A smart phone can be used to measure magnetic field which can be correlated through theory to a load current which ties up well with measured values.
Smartphone as a sensor	Different phones have different sensors, and these may be in different locations within the phone. As distance is a factor when determining the cable loading, a consistent method for installing the phone is needed. This can also help mitigate saturation issues.
Smartphone as a sensor	The Android phone works well as a control platform especially if the internal Magnetometer is being used. However bespoke App software is required to ensure methodology and readings are transparent. Using uncalibrated data avoids many complications.
Smartphone as a sensor	The temporal resolution of measurements on a phone varies from any delay set in code dependent on the processor and other core phone specifications. It is also dependent on what other apps are running and their processor usage.
Smartphone as a sensor	Using a phone to calculated load current is possible. There is a good degree of linearity and correlation. The accuracy of the direct back calculation of current from the phone is less than would be liked. However, a lower magnetometer reading shows a higher value of current than would be obtained in the field and therefore there is an inherent safety margin. To get more accurate results a "phone factor" is suggested which could be used to multiply to the calculated current.
Smartphone as a sensor	Installing the phone was the easiest of the sensor installation options. The phone was cable tied to the cable and the phone clipped into place and then App started. A USB power supply was connected to the phone to ensure it didn't run out of charge.
Smartphone as a sensor	An IOIO board offers a neat solution to turn a mobile phone into a controller with up to 60 I/O. It would allow the phone to be connected to any of the sensors under investigation.
Data logging	The Arduino platform logs data at >10ms and has less memory than would be liked to log data to a server and deal with security. A move was therefore made to investigate a raspberry pi. This has significantly more memory and can log analogue signals at <5ms through an Analogue to Digital chip. The raspberry pi can also log data locally or remotely to a server. A prototype has been set up and will be used on the next substation test.
Student Competition	It is easier to plan a competition and target groups of researchers if the competition is within a common and traditional research theme for which large University groups exist.
Student Competition	For a two-stage competition, it is useful to keep the first stage entry as easy as possible to include as many different ideas as is possible. Requirements for detailed drawings and part lists would put off entrants of interesting out of the box based ideas.

<table>
<tr><td>Student Competition</td><td>It is helpful if competition dates can be tied to common undergraduate University dates:
Initial launch close to when students are picking projects
First stage entry after term 1 exams and before the student gets too busy with project work
Second stage entry after exams and before the student leaves the university (while waiting for results)
This is not so critical for researchers who operate on more flexible timescales but are often tied to specific projects.</td></tr>
<tr><td>Student Competition</td><td>Student competitions need to be disseminated to academics well in advance of the start of term so they can incorporate them into final year projects.</td></tr>
<tr><td>Student Competition</td><td>Students are more receptive to additional activities at the start of the academic year before workload and exam anxiety build up.</td></tr>
<tr><td>Student Competition</td><td>To keep interest among students (for whom we have no access to mailing lists) it is necessary to maintain contact with key University staff to help with distributing publicity material and providing timely prompts.</td></tr>
<tr><td>Student Competition</td><td>Emails sent to lists should be very concise, so a skim reader would get directly to what was on offer (before they have deleted them).They are more likely to be acted on or replied to if they offer something tangible and beneficial to the recipient.</td></tr>
<tr><td>Student Competition</td><td>Giving presentations at institutions as part of their seminar series is a good way to reach and engage with both students and academics, however these are booked up many months in advance and are dormant during exam periods so require considerable advance planning.</td></tr>
<tr><td>Student Competition</td><td>Competition rules should consider how to marry the IP requirements of the project funders/sponsors and the IP rules of the students’ host institutions.</td></tr>
<tr><td>Student Competition</td><td>It was useful to meet with students prior to competition submission and testing to understand what was required from a testing perspective. The test requirements for the teams were very different.</td></tr>
<tr><td>Student Competition</td><td>It was necessary to provide intensive support on the day of testing to modify test rigs and deal with instrumentation to allow witness testing of the hardware. As each student had been developing their solution at different Universities the test facilities that each had access to was slightly different.</td></tr>
<tr><td>Student Competition</td><td>It was very obvious on the days of testing that the students were committed and spent much time and effort on getting their hardware working properly. There was a minimum amount of adjustment to their hardware to allow it to work with our test equipment.</td></tr>
</table>

9 The Outcomes of the Project

9.1 Sensor Testing

As described earlier the sensor testing provided significant learning.

	Sensor Type									Platform			
	Magnetometer	Hall Effect chip	I2m coil sensor	Accelerometer	Audio Microphone	Strain gauge	Thermal stickers	Thermal transducer	Low cost thermal imaging	Android Phone	Sensor with IOIO board and phone	Arduino	Raspberry Pi
Cost	£14	£2	£13	£19	£9	£31	£4	£99	£350	£13 + phone	£35 + phone	£49	£37 dongle
Application													
Monitoring load close to real time < 10s	✓	✗	✓	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓
Load profiling (30min peak)	✓	✗	✓	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓
Exception reporting (> max value)	✓	✗	✓	✗	✗	✗	✗	✓	✗	✓	✓	✓	✓
MDI	✓	✗	✓	✗	✗	✗	?	✓	✗	✓	✓	✓	✓
Data storage													
Uploaded to a server										✓	✓	?	✓
Stored locally										✓	✓	✓	✓
Data form													
Current peak	✓	✗	✓	✗	✗	✗	✗	✗	✗	✓			
Current RMS	✓	✗	✓	✗	✗	?	✗	✗	✗	✓			
1 phase	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓			
3 phase (cable)	✓	✗	✓	✗	✗	✗	✗	✗	✗	✓			
Load from transformer	✗	✗	✗	?	?	✗	?	?	✗	✗			
Data Quality													
Linearity	✓	✗	✓	?	?	✓	?	✓	✗	✓	✓	✓	✓
Correlation with load	> 0.999	✗	> 0.996	0.34	0.48	-0.91	?	?	✗	> 0.999			
Accuracy	> 7.5%	✗	> 10%[1]	?	?	< 25%	?	?	✗	> 7.5%			
Recommend for Field Trial	✓	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓

✓ Tested, satisfactory > better than

✗ Tested, unsuitable < worse than

? Test not conclusive

[1]There is still significant theory needed to back calculate current for distributed windings and this value could be easily improved.

It is recommended that the i2m coils, mobile phone and magnetometer be taken forward for field trials. Possible follow on applications for these low cost sensors are shown over and include benefits already identified by UK Power Network's Distribution Network Visibility project:

- Quick identification of substations where new load is able to be connected.
- Improving the potential to defer costly reinforcement of the network through the use of demand profiles.
- Improving network and asset reliability by monitoring trends.
- Improving the management of substation and network utilisation.
- Providing information on network to better support operational activity.

9.2 University Competition

Whilst the University competition delivered learning on process, the tangible outcome from the project participants provided limited benefit. This highlights the risk associated with student led work.

10 Data Access Details

All sensor testing data is available subject to WPD's data sharing policy.

www.westernpower.co.uk/Innovation/Contact-us-and-more/Project-Data.aspx)

11 Foreground IPR

The following foreground IPR was developed in the project.

Intellectual Property	Ownership
Design of I2M coil	Loughborough University. Open sourced
Deduce App	Loughborough University. Open sourced

12 Planned Implementation

The i2m and magnetometer sensors are ready for field test and they could be an alternative to more traditional ways of measuring in local substations.

Investigations are underway into the appropriate mechanisms to take such trials forward whilst maximising the benefits to customers.

13 Contact

Further details on replicating the project can be made available from the following points of contact:

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