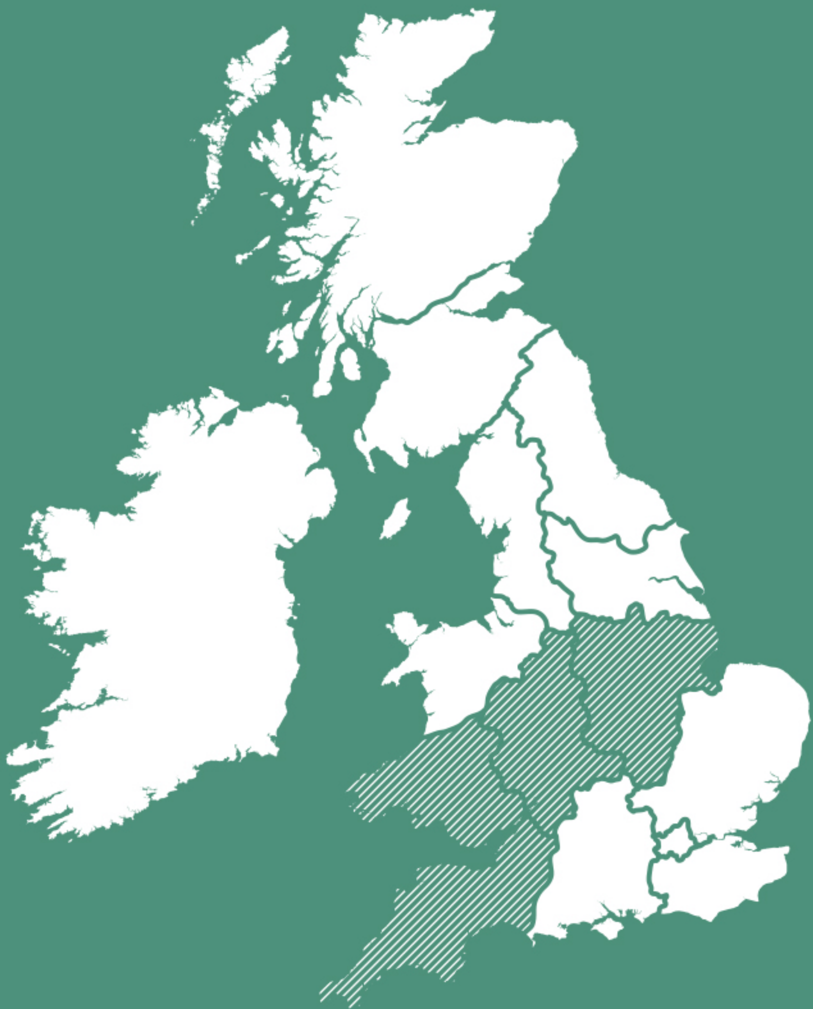
WESTERN POWER DISTRIBUTION

INNOVATION

# NEXT GENERATION NETWORKS

## LV CURRENT SENSOR TECHNOLOGY EVALUATION

## CLOSEDOWN REPORT



LCN Fund
Low Carbon Networks

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# Contents

# Glossary

| Abbreviation | Term |
|---|---|
| WPD | Western Power Distribution |
| UKPN | UK Power Networks |
| DNO | Distribution Network Operator |
| LV | Low Voltage |
| LCTs | Low Carbon Technologies |
| NPL | National Physical Laboratory |
| ENA | Energy Network Association |
| OJEC | Official Journal of the European Community |
| CIs | Customer Interruptions |
| CMLs | Customer Minutes Lost |
| DSR | Distribution Safety Rules |

# Executive Summary

As UK distribution networks migrate to a Smarter Grid, there is an increasing requirement to improve the visibility of the Low Voltage (LV) network. There is currently limited monitoring of the low voltage distribution network and as customers change their usage habits and more renewable generation connects to the network it is imperative that we are aware of and understand the impact it will have.

This project was developed in response to a consultation issued by Western Power Distribution (WPD) and linked to the Tier 2 Network Templates project. At the time of starting the Network Templates scheme, there were no off-the-shelf LV monitoring solutions on the market. WPD took the step to develop a solution with GE based on fixed ring CTs. However, installation of these monitors required an interruption to electricity supplies. As a condition of continuing with the installations, Ofgem placed a dependency on the project that a consultation be undertaken to assess the market for alternative solutions that avoided the need for supply interruptions

The responses to this consultation proved very constructive, but no products were identified that could adequately replace the use of fixed ring CTs in the timescales of the project. The alternatives were either too costly, or were not available in the quantities required for the Network Templates project. Subsequently the LV Current Sensor Technology Evaluation project was developed to conduct a detail assessment of the market as it stood and to inform the wider DNO community of its findings.

UK Power Networks (UKPN) was separately investigating commercially available LV monitoring solutions that do not require customers to be interrupted during installation.

The two DNOs decided to collaborate to evaluate a range of LV monitoring solutions under laboratory conditions at the National Physical Laboratory and in the field on their low voltage networks, equipping at total of 28 substations with sensors from 7 different manufacturers. This report details the findings of both the field and laboratory test, along with practical learnings based around installation practices.

### Project Scope

In order to make well informed Low Voltage (LV) network planning and operational decisions, there is an increasing need to improve our visibility of distribution substation performance. A growing uptake of low carbon technologies (LCTs), such as micro generation and electrification of transport, intensifies this need further. Many existing substation sites currently utilise low cost low accuracy maximum demand indicators with no remote reporting functionality. It is expected that greater visibility of LV network loads and voltage will be required and substation monitoring solutions will play a vital role in future network management.

The scope of the LV Sensor Evaluation project was to compare off-the shelf LV monitoring technologies that can be retrofitted to exiting distribution substation equipment. It was also intended to develop safe systems of work to allow equipment to be installed live and to identify monitoring solutions that would provide accurate and detailed information to allow the DNO to assess the performance of the LV network.

### Aims

The project aimed to evaluate various current sensor technologies in both controlled laboratory and operational field environments. This project was done as a collaborative project between UK Power Networks (UKPN) and Western Power Distribution (WPD) allowing a greater range of installation scenarios to be assessed. The project also aimed to generate knowledge around the wider roll out of these monitoring technologies in the low carbon future.

### Activities

The project involved working with manufacturers of LV monitoring solutions whose equipment had met the project requirements. The monitoring equipment needed to be capable of measuring the current flow in individual LV ways of an LV distribution board or cabinet. In that regard, a joint tender was completed from which 7 different monitoring solution manufacturers were selected to participate in the project.

A range of laboratory tests have been carried out at National Physical Laboratory (NPL) to assess a range of accuracy scenarios. A test bench was built at NPL using an LV cabinet ensuring that the test facilities would mimic as closely as possible the real life situation encountered in field installations. A side by side comparison was then completed using the results. A summary report of the laboratory tests can be found in Appendix A.

Another key focus of the project was the safe installation of monitoring equipment. Installation training for each manufacturer's equipment was carried out at UKPN's Sundridge Training Centre. Following the development of installation methodologies, equipment was installed at 14 outdoor substations in Market Harborough by WPD and 14 indoor sites in central London by UKPN.

### Outcomes of the Project and Key Learning

The project has led to the development of installation policies to enable LV monitoring equipment to be installed safely and without the need for an outage on the substation. An example policy is included in Appendix C.

Several methods of making voltage connections were trialled and a hierarchy of preferred methods was developed. These included the use of existing voltage take off points, insulated and fused busbar clamp and modified fuse carriers. The transmission of data via GPRS was also demonstrated but no data integration with the DNO SCADA system was attempted as it was out of scope for the project.

Basic current and voltage measurements were provided by the equipment from all manufacturers along with the apparent, real and reactive power and power factor. A number of manufacturer's equipment offered more advanced monitoring functionality which included the measurement of neutral current, power frequency, harmonics, substation air temperature, disturbance recorder functionality and network event alarms.

The key learning from this project was firstly around the safe installation of monitoring equipment in a diverse range of substations and how the mitigation of constraints that each of these might present to the installer. Secondly, how accuracy of various monitoring solutions is impacted under different environmental conditions and installation scenarios. These assessments were carried out in laboratory testing by NPL.

The knowledge generated will allow DNOs to make more informed decisions as monitoring of the LV Network increases.

### Conclusions and Future Work

The project led to a comprehensive evaluation of seven commercially available LV monitoring solutions and the development of installation policies to allow wider scale deployment on the LV network. The learning from the installations will also benefit any further LCNF projects involving LV monitoring.

The project demonstrated that the current generation of monitoring solutions are mature enough to allow sufficient data to be collected by DNOs to assess the performance of LV networks. Monitoring solutions can provide network load measurement with accuracies of around 2.5% for Rogowski coils, and 1% or better for solid state sensors, such as split core CTs.

As a result of the field and laboratory trials feedback was provided to manufacturers, leading to improvements in their products. The product improvements made by each manufacturer are detailed in the individual product assessments section in Appendix B.

The table below outlines the overall conclusions from the assessments carried out of the products from the seven participating manufacturers. It should be pointed out here that these conclusions reflect the performance and functionality of systems tested in this trial and not necessarily of the current iteration of products.

| Manufacturer | Overall Rating | NPL Test | Ease of Installation | Installation time per site (mins) | Relative Cost | Positive | Negative | Monitoring type |
|---|---|---|---|---|---|---|---|---|
| GMC i-Prosys | Excellent | Average | Easy | 35-45 | £ | Plug and Play | Bulky metrology unit | Advanced |
| Sentec/Selex (Gridkey) | Excellent | Good | Easy | 40-50 | £ | Plug and Play | Hard to access internal electronics | Advanced |
| Current | Good | Good | Easy | 45-60 | £££ | Plug and Play | Case not fully weather proof | Advanced |
| PowerSense | Good | Average | Medium | 60-90 | ££ | Back up battery, robust case | Time consuming sensor connection | Advanced |
| Ambient | Good | Good | Easy | 45-60 | £££ | Plug and Play | No commissioning indicators. One unit per feeder | Advanced |
| Haysys | Satisfactory | Average | Hard | 90-100 | £ | Large sensor aperture | Time consuming sensor connection | Basic |
| Locamation | Satisfactory | Good | Easy | 45-60 | ££ | Plug and Play | Electronics prone to failure | Advanced |

**Table 1: Overall project conclusions for all seven manufacturers.**

# 1. Project Background

As UK distribution networks migrate to a Smarter Grid, there is an increasing requirement to improve the visibility of the Low Voltage (LV) network. There is currently limited monitoring of the low voltage distribution network and as customers change their usage habits and more renewable generation connects to the network it is imperative that we are aware of and understand the impact it will have.

The Project Direction from Ofgem for Western Power Distribution's (WPD) Tier 2 Network Templates project resulted in a consultation with the other DNOs to see if there were alternative methods of obtaining current measurements without the need for customer interruption. The responses to this consultation were all very constructive, but there were no products identified which could adequately replace the use of fixed ring CTs in the timescales of the project. The alternatives were either too costly, or were not available in the quantities required for this project.

UK Power Networks (UKPN) was separately investigating commercially available LV monitoring solutions that do not require customers to be interrupted during installation.

The two DNOs decided to collaborate to evaluate a range of LV monitoring solutions under laboratory conditions at the National Physical Laboratory and in the field on their low voltage networks, equipping at total of 28 substations with sensors from 7 different manufacturers.

# 2. Scope and Objectives

1. The project aims to evaluate innovative current sensor technologies in a controlled laboratory environment and field situations.
2. The project will evaluate sensors from 7 manufacturers and the field trials will last for 12 months.
3. The objective is to generate knowledge of LV monitoring techniques enabling wider roll-outs to facilitate a low carbon future and minimising disruption to customers.
4. A full report detailing the results of individual tests, and a comparative assessment will be produced.

# 3. Success Criteria

| Success Criteria | Status |
|---|---|
| DNOs approve safe installation procedures. | ✓ |
| Testing and report of lab evaluation is completed by NPL. | ✓× (TBC) |
| A 12 month field trial is completed. | ✓× (TBC) |
| A full project report has been written - evaluating and comparing sensor results from laboratory and field trials. | ✓ |
| The results of the project influence DNO LV monitoring policies. | ✓ |

# 4. Details of Work Carried Out

This section aims to give an overview of the principle components of LV substation monitoring, the evaluation methodology used and what considerations were taken when choosing trial.

## 4.1. Substation Monitoring Overview

Distribution substation low voltage monitoring equipment is generally composed of a number of fundamental components to assess a range of metrics.

- Power connection – 3 phase voltage input to provide power and voltage monitoring point
- LV Sensors – Usually a current transformer or Rogowski coil to measure currents. Generally one sensor per phase per LV way.
- Interface – a unit that can take the sensor measurements and translate them into current and voltage readings.
- Central processing unit – Computing power to be able to make an initial assessment of the data collected and process for further consumption.
- Communications module – remote communications unit to send measurement for storage in a database.

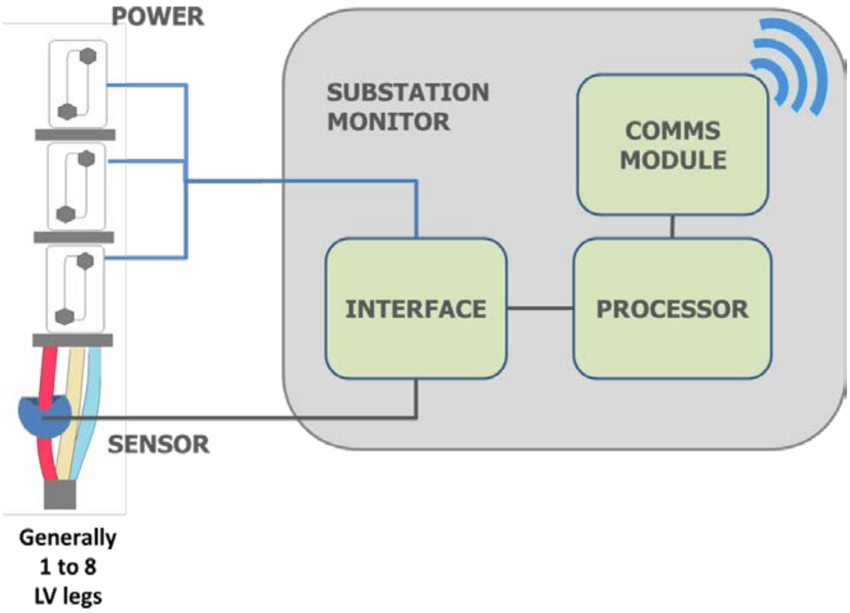


Figure 1: Fundamental components of a LV Substation Monitor.

This project was intended to test substation monitoring solutions as a whole, while paying additional attention to the current sensors being used by each manufacturer.

## 4.2. Method trialled

A two stage evaluation was carried out:

1. The first stage evaluation was a laboratory comparison of monitoring solutions at the National Physical Laboratory (NPL). This compared the solution's technical capabilities such as accuracy, temperature coefficient, reaction to humidity, reaction to fault current, effect of orientation and proximity to other conductors, under controlled conditions.
2. The second stage compared the monitoring solutions during a 12 month live trial. Each manufacturer equipped 4 substations, two at WPD outdoor substation sites and two further installations at UKPN indoor substations (a total of 28 substations). The live trial evaluated the engineer training required, ease of installation and maintenance, data collection, software provided, day-to-day usage and accessibility of results.

The systems provided by each manufacturer varied in their design. They ranged from full solutions (sensors, communications and software tools etc.) to sensors only with a conditioned box (amps output only). When required WPD and UKPN provided remote communication systems to enable data collection.

### 4.2.1. Product Selection

The sensors being evaluated were selected following a call for proposals issued through the Energy Networks Association (ENA) and Official Journal of the European Community (OJEC) notification processes. All solutions selected featured either Rogowski coils or split-core current transformers with a central processing unit and GPRS communications The minimum measurements required were 3 phase current and voltage, total, real and reactive power and power factor.

The companies selected through the tender process were:

1. GMC i-Prosys
2. Sentec/Selex (GridKey)
3. Current Group
4. PowerSense
5. Locamation
6. Ambient
7. Haysys

One further organisation did tender for the trial, but were not taken through to the project as the equipment was significantly more expensive and required a separate monitor for each phase of each LV way.

The premise for carrying out these trials was to test out various non-invasive monitoring solutions whose installation would require no outage on the substation; thus having no impact on Customer Interruptions (CIs) and Customer Minutes Lost (CMLs). The mechanism for monitoring was the same across the solutions tested:

- A sensor was placed around the low voltage (LV) conductor to measure the current flowing through.
- An additional connection made to the LV board or pillar to obtain the voltage measurement along with the power for the monitoring unit.
- The voltage and current sensors were connected to a control box which contained the metrology and communication electronics.

#### 4.2.2. Laboratory Tests Selection

A selection of laboratory tests were undertaken so that a comparative study could be carried out between the different monitoring solutions. For the tests, a LV sensor was fitted to a vertical conductor representative of an individual phase core of an LV cable as found in a typical secondary substation (Figure 2). Tests were made against a national standard current transformer with amplitude accuracy better than 0.01 %. Each manufacturer's equipment was tested as a complete unit to ascertain the accuracy of the system, rather than an Individual component level.

**Figure 2: Laboratory test setup at NPL**

The following laboratory tests were selected for carrying out this comparative study and assess the current measuring capability of the solutions

1. *Full scale amplitude accuracy and drift*. To compare the full accuracy of a sensor, a measurement was made at 500A at least 5 times with at least 1-day gaps between the measurements. These tests will be performed in a temperature-controlled environment. During this test the sensors were not being moved.
2. *Linearity*. A linearity test was performed at 1%, 5%, 10%, 20%, 30%, 50%, 75% and 100% of 500 A.
3. *Positional sensitivity*. The sensor was rotated and/or inverted depending on its shape. It was being moved around the conductor to a number of positions in order to assess its sensitivity to position.
4. *Conductor end effects.* The sensor was moved to the end of the horizontal section of the conductor to the point where the conductor bends away. The end effect was assessed.
5. *Proximity of adjacent conductors (stray fields).* The sensor was tested at a current level of 20A in the presence of a parallel vertical conductor carrying 20A, 50Hz with a phase displacement of a nominal 120 degrees. The distance between the horizontal conductors was 12 cm.
6. *Frequency Response.* The sensor amplitude frequency response was tested at 20A at several frequencies up to 2 kHz.
7. *Temperature Coefficient.* The sensor was tested at 2.5°C, 21°C, 39°C at 20A, 50Hz. This test was not performed on a vertical conductor due to the configuration of the temperature cabinet.

Many of the units tested as part of the trial featured additional functionality including temperature sensors, voltage, harmonics and neutral current measurement. None of these functions were tested as part of the NPL assessments as these were over and above the specification used for procurement.

### 4.2.3. Installation Site Selection

A number of factors were considered when selecting the indoor substation locations for UKPN and outdoor locations by WPD.

The UKPN sites were located in the London Power Network (LPN) area. The purpose behind selecting sites in LPN was to test out the sensors suitability for installation in brick built indoor distribution substations. Within the LPN area the selected sites were fed from Carnaby Street Primary Substation. This primary substation feeds the area in and around Leicester Square which is a highly commercialised area and has seen high load growth over the years. A number of site surveys were then carried out to short list suitable sites for installation. The majority of sites had open LV boards or wall mounted open LV frames with 5 LV ways with some sites having their LV board extended to accommodate another transformer at site. The LV boards were either top entry (Figure 3) or bottom entry with respect to the LV cable connections. Sites identified during surveys where the gap between the individual phase cores of the LV cable was a few millimetres were discounted as it would not have been possible to place sensors, either CTs or Rogowskis, around all three cores. This was the main consideration during the selection of sites in the Carnaby Street primary substation area.

The second factor considered was the GSM (2G) signal strength in the substation as a majority were inside basements of commercial buildings. The signal strength was recorded during site surveys and used in the selection of suitable sites.

A third factor considered in the selection process was the availability of space near the LV board where the metrology unit could be placed. This would help with cable management and ensure that maximum number of LV ways can be monitored given the reach of sensor cables in some cases. There were no issues foreseen with obtaining voltage reference or power for the monitoring units as there were several options available which included the use of modified fuse carriers, Remote Terminal Unit (RTU) fuses and fused G-clamps. More detailed on these is provided in the next section.

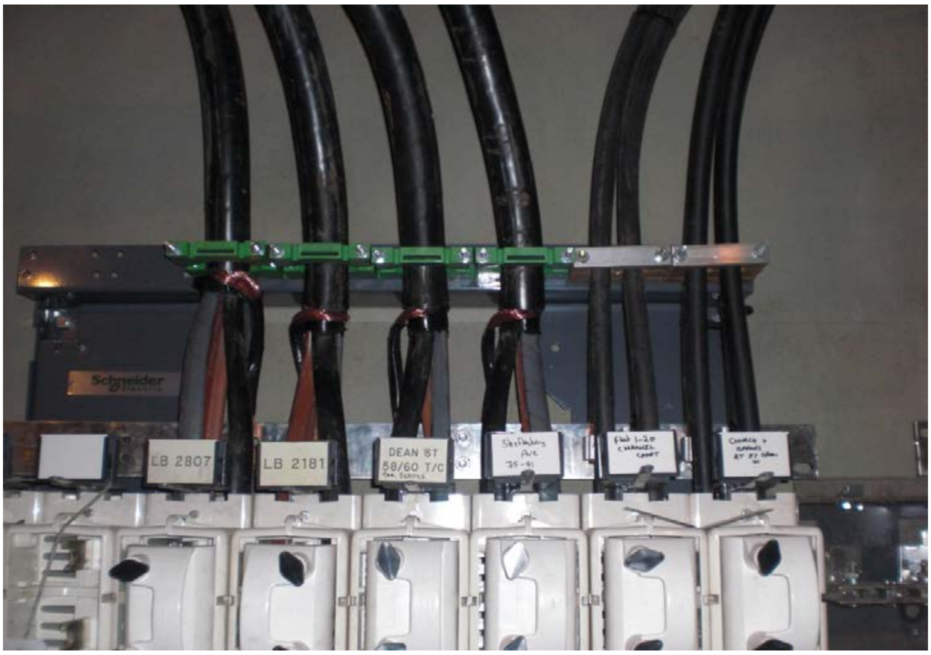


**Figure 3: Top entry Schneider LV board showing separation of individual phase cores. (UKPN)**

For the purposes of the WPD trial, detailed site surveys were conducted to establish appropriate locations in Market Harborough. This included sites with a maximum of 5 LV feeders, in either outdoor compounds or GRP housings. A number of sites were discounted due to the makeup of the LV pillar. The example below (Figure 4) which is quite common, was deemed unsuitable for a range of reasons.

**Figure 4: LV cast iron cabinet with compound filled tiered cable terminations.**

Firstly, there were 6 LV feeder ways and while some manufacturers could accommodate this scale, it would have required modification.  Modifications of the monitoring equipment were outside the scope of the trial, so sites with 6 or more LV feeder ways were discounted. Secondly, the cabinet was constructed out of cast iron and set on a solid brick plinth. This presented a problem in getting cables out of the cabinet to the control box. It is recognised that for a wider deployment this could be achieved by excavating around the pillar and bringing cables out of the base of the unit. However for the purposes of the trial it presented additional challenges that could be avoided by a different site choice. Where possible, sites were chosen where existing openings were available to allow sensor cables to be fed out of the cabinet without the need for creating additional holes.

One further consideration was the cable terminations. In this case, as the cable enters the pillar it is terminated in a metal compound filled tiered box as shown in Figure 5. This meant that it was not possible to access the cable cores and therefore the LV sensors could not be installed around the conductors. If monitoring was required at this pillar it could be achieved using a flexible Rogowski coil, either around the transformer links to gain a whole substation view, or around the fuse carrier handles if a feeder by feeder view was required. However it is recognised that this presents further operational challenges as the each coil would need to be removed should the fuses require removal. The following photos show a tiered box with enclosed cores (Figure 5), and a more open termination with each core accessible (Figure 6).

**Figure 5 & 6: Tiered cable termination (left) and accessible individual cores (right).**

### 4.2.4. Safe Installation Procedure

Before installation of equipment could begin a safe system of working and installation had to be developed. In order to do this each manufacturer was invited to the UK Power Networks training centre, located at Sundridge, and asked to bring one complete unit consisting of sensors, metrology unit and accessories. The manufacturers demonstrated the installation and commissioning procedure to representatives from both DNOs. The representatives included the project managers, the installation personnel and a health of safety advisor. Mock installation of the sensors were carried out in indoor and outdoor substations which were part of the training network. This was done to highlight any potential issues that could be encountered during installation.

Additional precautions had to be taken when installing CTs based sensors, especially in variants with the lack of a shorting pin between the CT terminals. The CTs had to be connected to the metrology unit before being installed on the LV board or pillar to prevent a dangerous voltage appearing between the terminal wires of the CT. This could cause damage to the device and lead to the risk of an electric shock to the installer.

As a result of these meetings and further discussions with manufacturers installation policies were developed and approved. An example installation policy can be found in Appendix C. Before the installations could begin, field staff were provided with a Work Method Statement along with specific task instruction sheets for each site. Once installations were complete, local operational staff were made aware of the installations and contact details left at each site should further information be required. All safe working procedures as laid out in the DNO Distribution Safety Rules (DSR) and operational policies were followed during the installations.

#### 4.2.5. Voltage Connections

For each manufacturer a 3 phase voltage connection was required to allow monitoring of the voltage on the live busbars while a single phase connection was sufficient to power the unit. A range of solutions had to be developed, primarily driven by the design of cabinet, but also by operational requirements. The aim was to keep the interaction with daily operations down to a minimum by not impeding the removal of fuse carrier handles. The following order of preference was therefore developed for WPD and UKPN.

1. Use of existing voltage reference points (RTU power source/ Test point- Figure 7)
2. Approved Insulated busbar G clamps (with inline fuse – Figures 9 and 10)
3. Modified fuse carrier handles on a spare LV Leg (Figure 11)
4. Modified fuse carrier handles on a live LV Leg

A number of pillars and LV cabinets have existing voltage test points which can be utilised to provide power and a voltage reference point for testing. These can be utilised to provide a three phase reference point and supply voltage for the cabinets. In some of the newer package substations, this will be a test block with live terminals. Older pillars (such as the one pictured in Figure 7 below) provide an alternative take off point that can be utilised. This required some modifications to the monitoring power leads. Where test points are present, it is recommended that a check is made during the pre-installation surveys to ensure that the terminals are live.

Figure 7: LV Cabinet with 3 phase test point

In a number of sites, the LV pillar / board will have exposed busbars that can be utilised to get a voltage reference. If terminals are not available, an approved nylon voltage clamp can be utilised with the appropriate fused leads.  The following photograph (Figure 8) shows an open pillar where the voltage clamp may be appropriate. In this scenario it would be recommended to install the clamps to the side of the end set of fuses, so as not to interfere with any future operations on the boards.

Figure 8: LV Cabinet with open busbar design

There are a number of voltage clamps which can be attached over the top of the busbars and tightened using an approved tool or integral screw. Prior to install a risk assessment should be made as to whether the clamps can be installed safely. Particular consideration should be made as to the location on insulated phase barriers and access to the bars. Full PPE should be worn for such activity in accordance with Distribution Safety Rules.

Figure 9 & 10: Voltage clamps manufactured by 1047 (left) and Martindale (right)

Should none of the above methods prove practicable, an alternative method is to replace a fuse carrier handle with a modified Schneider unit with a voltage terminal (Figure 11). These replacement fuse holders are ideal for enclosed boards although special consideration should be made as to their location. The disadvantage with such as solution is that trailing leads will be left down the front of the board and these will require unplugging before any operations can take place on that cable leg. Where possible, a spare leg should be utilised and the voltage take off point kept at the top to give a voltage for the bus bar. At present, these replacement carriers are only available for JS fuses with 3 5/8” spacing. Where a spare LV leg is not available, an alternative leg can be back fed, the fuse carriers replaced and the back feed removed.

Figure 11: Modified fuse carrier handles installed on spare leg in pillar

#### 4.2.6. Data Transmission

Data from the metrology units was transmitted back to each manufacturer’s database via GPRS. The majority of manufacturers used the widely adopted DNP3 protocol to transmit data over GPRS while some used their own proprietary protocol. The majority of manufacturers provided their own SIM cards for the trial with the exception of PowerSense and Locamation for whom the SIM cards were provided by the DNOs. The data transmitted from each unit was accessible via the manufacturer’s own proprietary web based data visualisation portal.

For the purpose of this project any data integration activity was discounted due to the effort and cost required to integrate data from 7 different manufacturer’s equipment into each DNO’s own database. This activity would have been considered for a much larger roll out of monitoring equipment from one single manufacturer.

# 5. The Outcomes of the Project

This section outlines the findings of both the laboratory and field trials for each of the monitoring solutions tested. While the principles used to install the equipment has not varied much between vendors, the practicalities, ergonomics, functionality and reliability of equipment vary from one solution to another. Detailed results from the laboratory testing can be found in the NPL report (Appendix A), with a detailed company by company assessment of equipment in Appendix B.

As a market, substation monitoring equipment is evolving at a rapid pace. In less than 3 years, some high specification, lower cost units have been developed by a range of companies. This pace of change is continuing with new models and functions becoming available all the time. While each of the manufacturers involved have made improvements to the equipment in response to the learning demonstrated through this project, it should be stressed that the results and conclusion published in this paper are based upon the versions of equipment supplied in July 2012 for the purpose of the trial. Additional information is presented on the developments that have been made by each manufacturer in Appendix B. For details of current equipment specifications, vendors can be contacted directly.

## 5.1. Monitoring solution measurement capability comparison

Through the tender process, the focus was to procure a replacement for a fixed-ring CT solution, with the ability to measure total LV substation demand for a three phase transformer. In addition the sensors were to be capable of being fitted without the need for an interruption to electricity supplies, of accuracy class 0.5S or better and able to be fitted to a range of LV boards. What the project did not specify was the functionality of any accompanying metrology unit other than the use of GPRS communications.

Subsequently, the range of solutions that were proposed for the project was varied and included some advanced functionalities such as harmonic monitoring, system alarms and temperature measurement. These were not tested as part of the project as they were deemed to be over and above the core current measuring specification that was requested in the project, but demonstrates functionality that is becoming more common with such solutions. The functionalities of the solutions trialled are summarised in table 2.

While communications have not been tested in this scheme, it is worth noting that many of the units included an Ethernet communications port that would allow the connection of additional communications options such as radio, internet, or wired links.

| | LV Ways Per System | Maximum LV ways in a single unit | 3 Phase Current (A) | 3 Phase Voltage (V) | S (kVA) | P (kW) | Q (kVar) | Power Factor | Neutral Curreny | Frequency (hz) | Temperature Sensor | THD Current | THD Voltage | Fundamental Harmonics | Configurable Alarms | Alarms | Battery | Ethernet Comms Port | Minimum Reporting Resolution | Solid State Data Storage |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gridkey** | 5 | 5 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | Internal sensor | ✓ | ✓ | - | ✓ | All parameters programmable | - | ✓ | 1 min | ✓ |
| **GMC i-Prosys / Nortech** | 4 | 9 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | 2 - 1 x ambient and 1 x patch | ✓ | ✓ | Up to 21st | ✓ | Threshold alarms on a range of parameters | - | ✓ | 1 sec | ✓ |
| **Current** | 4 | 6 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | 1 per LV Way | ✓ | ✓ | Up to 50th | ✓ | All data types set as % change or absolute values. | 20 sec last gasp | ✓ | 100ms | ✓ |
| **Ambient** | 1 | 1 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | - | - | - | ✓ | ✓ | Up to 50th | ✓ | All parameters programmable | Optional | ✓ | 1 min | ✓ |
| **Haysys** | 4 | 16 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | - | - | Up to 8 probes | ✓ | ✓ | Can be calculated | ✓ | All parameters programmable | Optional | ✓ | 1s | ✓ |
| **Powersense** | 4 | 8 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | - | ✓ | Up To 4 | ✓ | ✓ | Up to 50th | ✓ | Under / Overvoltage<br>No volts<br>Over Current<br>Blown Fuse<br>Health | 8 Hours + | ✓ | 200ms | ✓ |
| **Locamation** | 5 | 5 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | - | - | - | ✓ | ✓ | Up to 25th | ✓ | All parameters programmable | - | - | Continuous | ✓ |

**Table 2 – Functionality of tested solutions**

What became apparent through this trial is that the functionality available from these off-the-shelf monitoring solutions is becoming increasingly advanced and in many cases in line with what could be expected from power quality monitoring devices. Many units are now capable of assessing total harmonic distortion and individual fundamental harmonics. Additional flexibility is also provided with some units catering for battery backup, temperature probes and in some cases the ability to monitor neutral currents.

While specific product costs cannot be disclosed due to commercial sensitivity, a relative cost comparison has been included in Table 6. It is recognised that in a wider deployment, economies of scale could be gained from the purchase of larger quantities. In addition the costs incurred within the project are skewed by software licencing, while in a full procurement the total cost of ownership should also be reflected by considering the installation and on-going running costs. This project was not conducted at a scale that would allow a fair reflection of actual cost, especially in light of the on-going developments in the market. Therefore no conclusions should be drawn on this indication.

Another area that has not been considered during the testing is that of system earthing. In a number of substation sites, significant rises in potential can be experienced on the earth in the event of a fault. The “hot sites”[1] require separation of the site earth and neutral. Where a metal cases unit would be utilised it would have both a connection to the site earth and neutral. No testing has been completed as part of this trial to evaluate what would occur to a unit in the event of a fault. It is therefore recommended that further risk assessments are carried out by DNOs facing this situation.

## 5.2. NPL laboratory testing summary

As detailed in section 4.2.2, a range of laboratory tests were undertaken to assess the accuracy of current measurements in a range of scenarios. NPL have produced a detailed report that outlines the findings from the entire laboratory testing which is included in Appendix A of this document.

The following table outlines the specification of the individual sensors tested including the resolution of current measurement and the size of the sensor aperture. This represents the maximum diameter of cable that the sensor could be attached around. It was generally found that the flexible Rogowski sensors were the easiest to connect and remove, with a couple of the solid sensors proving more difficult to use. This assessment was based on laboratory experience only where the sensors were attached and removed with great regularity. Further findings on the practicality of each of the sensors can be found later in this document and in Appendix B.

| Characteristics of Sensors | | | | | | |
|---|---|---|---|---|---|---|
| Manufacturer | Sensor In NPL Report | Resolution (A) | Rated Current (A) | Approximate Aperture Size (cm) | Flexible or Solid Sensor | Ease of connect /reconnect |

[1] If the earth potential rise is greater than 430V, a Secondary substation is designated a Hot Site.

| | | | | | | |
|---|---|---|---|---|---|---|
| Ambient | Sensor A | ±0.001 | 600 | 3 | Solid | Difficult |
| Current | Sensor B | ±0.001 | Not Marked | 5 | Solid | Easy |
| Haysys | Sensor C | ±0.1 | Not Marked | 14 | Flexible | Easy |
| GMC i-Prosys | Sensor D | ±0.01 | Not Marked | 7.5 | Flexible | Easy |
| Locamation | Sensor E | ±0.001 | 600 | 3.5 | Solid | OK |
| PowerSense | Sensor F | ±1 | 600 | 5 | Solid | Difficult |
| Sentec/Selex (Gridkey) | Sensor G | ±0.01 | 600 | 2.5 | Solid | OK |

**Table 3: Sensor characteristics**

Some of the initially scoped out laboratory tests were not carried out:

- For the linearity test it was envisioned that an assessment of the hysteresis performance would be carried out but it was later concluded that this was not necessary as the repeatability of the sensors at all levels was good.
- For the conductor end effects test, the conductor orientation was initially going to be vertical, as you would find in distribution substations, but it was later decided that for ease of testing a horizontal conductor would be used as it was not easily possible to position the sensor accurately at the 3 positions on a vertical bus bar.
- For the stray fields test it was initially scoped to test at current levels of 5% and 100% of 500A in the presence of another conductor carrying 500A but it was later decided that 20A flowing in both conductors was sufficient to study the effects of stray fields and a typical conductor spacing of 12 cm as found in LV cabinets and pillars would be used.
- Finally, for the temperature coefficient test, it was later decided to test in temperatures of 2.5°C, 21°C and 39°C to see the impact on sensor operation in low, medium and high temperatures that could be experience in substations as opposed to the initially chosen temperatures of 10°C, 20°C and 30°C. Due to restrictions with the temperature cabinet, 2.5°C and 39°C were the 2 extremes possible. Due to time constraints, 21°C was chosen being equivalent to the laboratory temperature used for all of the other tests.

While a range of tests were undertaken, the linearity tests were of particular interest. These demonstrated the ability of the systems to measure known currents across a range of common operating currents as found in many UK substations. The findings from these tests are summaries in tables 4 and 5.

| Table 1a - Error, % of Nominal Applied Current | | | | | | | |
|---|---|---|---|---|---|---|---|
| Nominal Applied Current | Current Reading | | | | | | |
| | Sensor A | Sensor B | Sensor C | Sensor D | Sensor E | Sensor F | Sensor G |
| (A) | (%) | (%) | (%) | (%) | (%) | (%) | (%) |
| 5 | | 2.251 | | -2.26 | -0.020 | -19 | -1.89 |
| 25 | -1.877 | -0.062 | -1.2 | -1.47 | -0.118 | -4 | -0.50 |
| 50 | -1.063 | -0.094 | -1.9 | -1.90 | -0.122 | -2 | -0.47 |
| 100 | -0.406 | -0.111 | -2.2 | -1.95 | -0.204 | -1 | -0.48 |
| 150 | -0.139 | -0.120 | -2.1 | -1.98 | -0.209 | -1 | -0.47 |
| 250 | 0.193 | -0.115 | -2.1 | -2.11 | -0.204 | -1 | -0.43 |
| 375 | 0.627 | -0.087 | -2.1 | -2.17 | -0.210 | 0 | -0.41 |
| 500 | 0.887 | -0.049 | -2.1 | -2.35 | -0.221 | 0 | -0.27 |

**Table 4: Accuracy and Linearity Test Results from NPL report (Table 1)**

| Accuracy and Linearity Tests | | | | | | | |
|---|---|---|---|---|---|---|---|
| Nominal Applied Current | Current Reading | | | | | | |
| | Sensor A | Sensor B | Sensor C | Sensor D | Sensor E | Sensor F | Sensor G |
| | Ambient | Current | Haysys | GMC i_Prosys | Locamation | Powersense | Gridkey |
| (A) | (A) | (A) | (A) | (A) | (A) | (A) | (A) |
| 5 | | 5.113 | | 4.89 | 4.999 | 4 | 4.91 |
| 25 | 24.531 | 24.984 | 24.7 | 24.63 | 24.970 | 24 | 24.88 |
| 50 | 49.469 | 49.953 | 49.1 | 49.05 | 49.939 | 49 | 49.76 |
| 100 | 99.594 | 99.889 | 97.8 | 98.05 | 99.796 | 99 | 99.52 |
| 150 | 149.791 | 149.821 | 146.8 | 147.03 | 149.687 | 149 | 149.29 |
| 250 | 250.483 | 249.712 | 244.8 | 244.72 | 249.489 | 249 | 248.93 |
| 375 | 377.352 | 374.675 | 367.0 | 366.87 | 374.213 | 373 | 373.47 |
| 500 | 504.436 | 499.756 | 489.6 | 488.24 | 498.893 | 498 | 498.67 |

**Table 5: Error % Accuracy and Linearity Test Results from NPL report (Table 1a)**

Sensor F (Powersense) had a number of accuracy issues at lower currents, although this was generally attributed to the resolution of the monitoring unit. As the design was based on a split core CT, the accuracy generally improved as the current increased. Sensors C (Haysys) and D (GMC i-Prosys) were both flexible Rogowski coil designs. It can be concluded from these results that this design of sensor will generally provide accuracy in the region of 2% through the range of currents tested.

The laboratory results showed that the solutions provided by Current and Locamation proved to be the most accurate across the range of tests, with good performances from the Gridkey and Ambient sensors.

## 5.3. Installation Experience

During the 28 installations, it became clear that a number of practical considerations in the designs would have a bearing on the simplicity and practicality of installation. This included the size of the units, cable terminations, and sensor design.

Several solutions featured plug in or screw in fittings, allowing a simple attachment of the sensors to the monitoring unit. This significantly reduced the installation time compared with sensors provided with bare ended cables, and also reduced the chance of connection error. The best solutions were provided by GMC-iProsys and Locamation where by sensors were grouped into one connector for each LV way, meaning that sensors could be connected in under 5 minutes.  In contrast, one solution took over an hour to wire in individual sensors, as cables required extending and bare ends each were attached to a wiring loom.

During installations it became clear that flexibility was important and that no manufacturer had a one size fits all solution. Some manufacturers therefore offered sensors with a range of cable lengths and in some cases sensor types.  This was particularity important and in some cases the monitoring unit had to be placed 4-5m from the LV board due to space restrictions.

The design of the sensor also had a bearing on the ease of installation. While not the most accurate in the laboratory tests, the flexible Rogowski coils proved to be the easiest to install. Some of the more rigid sensors were at times difficult to install due to the diameter of cables and spacing between cable cores. This was a particular problem with some of the more bulky sensors such as the Ambient sensor, and split core CT design from Locamation. Current provided both a flexible and solid sensor, which allowed some additional flexibility, although it was considered that the solid sensor was extremely bulky and difficult to connect in tight spaces. A number of manufacturers have now recognised the limitations of solid sensors and offer both solid and flexible sensor types. There is however a trade-off between installation ease and accuracy as the laboratory tests has shown.

The trials were conducted in both indoor and outdoor substations, to represent the full range of ground mounted substations found in the UK. Most monitoring units came in metal or plastic housings that were appropriate for both indoor and outdoor applications, with the exception of monitors by Current. The Current monitoring units were housed in aluminium cases with open vents at the back, which would easily allow moisture into the case. For outdoor applications, these would need to be housed in additional enclosures to prevent damage from the elements. From a practical perspective, plastic housings offered the greatest flexibility due to the non-conductive nature of the material. For example, it was possible to install the Gridkey unit inside an LV cabinet as the unit was extremely shallow and plastic.

From a commissioning perspective, a number of units featured indicator lights to confirm correct installation and setup. The best examples of these were provided by Gridkey and Powersense. An additional cover was also provided by Gridkey, to cover indication lights once installation was completed. Units provided by Ambient featured no indication and the correct installation could only be confirmed by checking to see if the units had registered with the server.

Cases for the monitoring units came in either metal or plastic. From a practical perspective, plastic housings offered the greatest flexibility due to the non-conductive nature of the material. For example, it was possible to install the Gridkey unit inside an LV cabinet as the unit was extremely shallow and plastic.

## 5.4. Overall Product Conclusion

The following table summarises the findings from both the field and laboratory testing for all the monitoring solutions assessed as part of the trial.

| Manufacturer | Overall Rating | NPL Test | Ease of Installation | Installation time per site (mins) | Relative Cost | Positive | Negative | Monitoring type |
|---|---|---|---|---|---|---|---|---|
| GMC i-Prosys | Excellent | Average | Easy | 35-45 | £ | Plug and Play | Bulky metrology unit | Advanced |
| Sentec/Selex (Gridkey) | Excellent | Good | Easy | 40-50 | £ | Plug and Play | Hard to access internal electronics | Advanced |
| Current | Good | Good | Easy | 45-60 | £££ | Plug and Play | Case not fully weather proof | Advanced |
| PowerSense | Good | Average | Medium | 60-90 | ££ | Back up battery, robust case | Time consuming sensor connection | Advanced |
| Ambient | Good | Good | Easy | 45-60 | £££ | Plug and Play | No commissioning indicators. One unit per feeder | Advanced |
| Haysys | Satisfactory | Average | Hard | 90-100 | £ | Large sensor aperture | Time consuming sensor connection | Basic |
| Locamation | Satisfactory | Good | Easy | 45-60 | ££ | Plug and Play | Electronics prone to failure | Advanced |

Table 6: Product Conclusions

Taking all elements into consideration the GMC i-Prosys and Gridkey units proved to be the best units tested. In both cases they proved easy to install, reliable and met the required standards in the laboratory testing.

Since this trial started, further developments have taken place with all products tested, and further details of the improvements can be found in Appendix B.

# 6. Performance compared with Project aims, objectives and success criteria

This joint UKPN and WPD Tier 1 project has successfully demonstrated the safe and relatively inexpensive installation of LV monitoring equipment in typical Distribution Substations. The project has also demonstrated the measurement capability of the monitoring solutions in tests against different measurement parameters in a laboratory environment.

## 6.1. Project Aims & Objectives

The performance against the original aims and objectives is summarised below.

**The project aims to evaluate innovative current sensor technologies in a controlled laboratory environment and field situations.**

The monitoring equipment provided by seven different manufacturers was successfully evaluated in both a controlled laboratory and field environment.

A range of sensors based on Current Transformer and Rogowski coil technologies were tested along with the metrology units provided. A safe installation policy and report detailing the test results have been written.

**The project will evaluate sensors from 7 manufacturers and the field trials will last for 12 months.**

The field installations were started in July 2012 as opposed to April 2012 due to unavailability of the DNO training centres to carry out installation training. A number of devices have therefore been in place for the 12 month. Those in UKPN were started and completed in February 2013 due to the delay in approval of the installation policy and unavailability of field staff. However it is considered that the core learning associated with functionality and installation practice has been gathered within this shorter timeframe.

Despite these delays, with sensors of each manufacturer installed in at least one location for between nine and twelve months, it is believed that evaluation of the engineer training required, ease of installation and maintenance, day-to-day usage, accessibility of results and reliability could be adequately assessed. With one exception, all the reliability issues were identified and resolved within a short period of their commissioning. It is considered that the core learning associated with the sensors' functionality and installation practice was gathered during the initial activities of the various field trials and was therefore unaffected by the shorter timeframe.

**The objective is to generate knowledge of LV monitoring techniques enabling wider roll-outs to facilitate a low carbon future and minimising disruption to customers.**

Significant learning was generated through the installation of different monitoring technologies on the diverse networks of Britain's two largest DNOs. Different installations scenarios were encountered and the close down report expands on these. This will allow the DNOs to prepare for a wider roll out of monitoring equipment. Learning has also been generated through the laboratory testing of these technologies which will allow the manufacturers to improve their products further.

Also, any further innovation projects involving the installation of LV monitoring equipment or business as usual larger roll-out will be able to use the learning from this project.

**A full report detailing the results of individual tests and a comparative assessment will be produced.**

Following the successful completion of laboratory tests by NPL a report has been prepared expanding on the individual performance of the sensors along with a comparative assessment. This is included in Appendix A

## 6.2. Success Criteria

The performance against the original success criteria is summarised below.

**DNOs approve safe installation procedures.**

Each monitoring solution manufacturer demonstrated the installation and operation of their equipment to the DNOs at the UK Power Networks Sundridge Training Centre. The learning from these meetings was incorporated into a comprehensive policy that UK Power Networks wrote on the installation of LV monitoring equipment in distribution substations. It was approved by the different business departments and shared with Western Power Distribution. A copy of this can be found in Appendix C. WPD have also developed a number of installation guides and draft policy which is currently being developed for business as usual application.

**Testing and report of lab evaluation is completed by NPL.**

The manufacturers of monitoring equipment delivered three sensors and a metrology unit to NPL while WPD delivered the LV cabinet that would act as the test bench. Some modifications had to be made to the LV cabinet before it was suitable for testing the sensors.

This led to a delay in the start of the tests. Once the modifications had been implemented the tests agreed were completed for the majority of sensors. Some tests could not be conducted on a few sensors due to either the size of their aperture or their measurement resolution. The report detailing the test results has been written by NPL and approved by both DNOs (see Appendix A).

**A 12 month field trial is completed.**

There was a delay in the start of the field installations as the installation training sessions could not be conducted due to non-availability of the DNO training centres. Once the training of installation staff was completed in three sessions spread over June and July 2012, at the UKPN training centre in

Sundridge the installations commenced. WPD started installation work in July 2012, completing all the installations by October 2012. The UKPN installations were completed in February 2013. UKPN had to wait for the installation policy to be approved before any installations could be carried out and this led to a further delay in their installations.

**A full project report has been written - evaluating and comparing sensor results from laboratory and field trials.**

This close down report along with the NPL testing report have been completed.

**The results of the project influence DNO LV monitoring policies.**

The learning from the project will be disseminated internally and externally via learning events such as the LCNF conference (Brighton, November 2013), and through other events such as the LV Monitoring Knowledge Sharing event run at the National Space Centre in July 2013 by WPD.

UKPN are currently developing a Remote Terminal Unit specification for substation monitoring and the learning from the project will feed into that specification.

# 7. Required modifications to the planned approach during the Project

Two modifications were made to the approach of the project during the duration of the project. As part of the project governance, internal change mandates were completed. These can be found in Appendix D

## 7.1. Success Criteria - 12 month field trial period.

One of the project success criteria was to carry out a 12 months field trial. The installations could not be started until July 2012 because of the delay in finding suitable dates at the DNO training centres to hold the installation training sessions. This meant that only some of the equipment was installed for the full 12 month. WPD successfully completed their installations by October 2012 which meant that the field trial actually lasted for only 10 months for some units. With a number of WPD's monitoring equipment installed in outdoor substations it was envisaged that 10 months would be a sufficient time period to assess the equipment's performance in outdoor conditions where they would be exposed to the elements. The challenge of the UKPN installations was around the installation of sensors around the LV cable cores due to limited spacing between them. The main learning from those installations related to the type of sensors and different types of LV boards found in indoor brick built substations and outdoor substations with LV cabinets or pillars.  It is considered that the delay in the UKPN installations did not affect the overall learning from the project.

## 7.2. Change of LV Sensors.

At the time of the installation training, all the manufacturers were given a chance to demonstrate their product. It came to the attention of the DNOs that a number of sensors which were being tested by NPL might not be suitable for installation on either live LV equipment due to the safety risk they presented, or there would not be sufficient space to fit them around the cable cores (this point was more relevant for UKPN's substations). In particular, one design of CT featured an exposed metal split core that was held in place with a rubber strap. This was deemed to be unsafe due to the exposed parts and insecure fitting methodology. The manufacturers who were informed of the DNOs concerns were able to provide alternatives especially where the sensor presented a safety risk.

# 8. Significant variance in expected costs and benefits

## 8.1. Project cost and variance

| Cost Item | UKPN Predicted (£k) | UKPN Actual (£k) | WPD Predicted (£k) | WPD Actual (£k) | Total Predicted (£k) | Total Actual (£k) | Variance (£k) | Variance (%) |
|---|---|---|---|---|---|---|---|---|
| Equipment Cost | 100.0 | 76.4 | 100.0 | 76.6 | 200.0 | 153.0 | 47.0 | 23% |
| Project Management and Installation | 99.4 | 26.2 | 99.4 | 28.3 | 198.8 | 54.5 | 144.3 | 73% |
| NPL testing and report | 34.2 | 17.1 | 34.2 | 17.1 | 68.4 | 34.2 | 34.2 | 50% |
| **Total** | **233.6** | **119.7** | **233.6** | **122.1** | **467.2** | **241.8** | **225.4** | **48%** |

Table 7: Project cost and variances.

When the project was initially developed, costs were estimated based on prior experience from other Tier 1 and Tier 2 project with elements of monitoring. The tender process revealed off-the-shelf solutions that were at a lower price than initially anticipated. In addition, live installations practices significantly reduced the installation and project management costs. These two factors account for the significant level of underspend on the project.

## 8.2. Project benefits

The project has resulted in a number of key benefits to all parties involved. From a DNO perspective, UKPN and WPD have developed a detailed knowledge of some of the challenges faced when deploying substation monitoring across a number of sites. This has led to the development of policies that will allow further installations to be completed.  It has also allowed greater knowledge regarding the required specification of equipment, and will support future procurement processes.

The laboratory testing has allowed increased confidence around the level of accuracy available for current measurement. It is generally considered that all the solutions tested were able to produce a satisfactory level of measurement on site.

A further benefit from the project has been the feedback loop created by the project to the suppliers. The practical learning from the installations has led to all manufacturers making improvements to their systems in response to feedback from the project. This has allowed the market to continue to develop, while increasing competition and choice.

### 8.3. Financial Benefits

This project was developed to ensure that the DNO community would be better informed on the technical issues associated with the purchase of monitoring equipment. At present, the majority of DNO benefits of substation monitoring are not directly measurable; substation monitoring is currently a facilitating technology that is allowing data to be gathered to support a range of research and development projects.

The financial benefits that could be realised would come from the wider roll out of monitoring equipment, and the use of the data to make smarter network reconfiguration or reinforcement decisions. There would also be financial benefits for customers as a better visibility of the LV network would allow the connection of additional Distributed Generation without the need for reinforcement. The extent of financial benefits would depend upon the scale of a roll out by DNOs.

This project has ensured that the DNO community will be better informed when it comes to procurement of equipment, generating the maximum benefit from future installations. It is therefore considered that a limited targeted deployment of substation monitoring could be continued where individual projects call for additional data or a specific business case is identified.

## 9. Lessons learnt for future Projects

### 9.1. LV Monitoring Products

The project demonstrated that there are now a number of commercially available LV monitoring solutions which meet the DNO requirements. This shows that manufacturers understand the DNO requirements more and more around LV monitoring and are responding by developing a wide range of solutions. The project also showed that manufacturers were willing to develop their products further in order to increase their flexibility and suitability to overcome any installation constraints that could be encountered at site. The manufacturers also learnt about the technical performance of their equipment via the laboratory test conducted by NPL. This will help them to further improve their products.

### 9.2. LV Sensor Safe Installation Procedure

This project demonstrated that it is possible to safely retrofit monitoring equipment on live LV board, LV cabinets and pillars. A safe installation procedure was produced by UKPN and shared with WPD to enable wider roll out of monitoring equipment.

### 9.3. Communication

The communication method adopted for this project was GPRS. Due to the diverse landscape of the GB DNOs, it was concluded that the reach of GPRS/3G/4G would be limited in certain situations and this would mean using other communication technologies to bring back the data. For example in cases where the substations are located indoor in basements the mobile signal strength would be weak and would require a BT line or Power Line Communications to be used.

For this trial a range of standard and company specific protocols were used by the manufacturers. It was concluded that to allow the DNO to easily integrate the equipment into their SCADA system, the manufacturers should adopt communications protocols that would allow interoperability across different hardware (e.g. IEC 61850). These developments could be encouraged through the specifying of standard protocols through further DNO procurement processes, along with working with the industry to promote interoperability.

## 9.4. Large Scale Deployment

The project has shown that is it possible to monitor individual LV ways in a distribution substation without interrupting customers paving the way for wide scale roll out of monitoring equipment at the LV voltage level. Further Tier 2 projects being planned by DNO involving LV monitoring would be able to use the installation policy and lessons learnt in the close down report to plan out their installations.

The manufacturer equipment, which has further developed over the course of the project, would now be available to DNOs for use in their business as usual processes.

## 9.5. Dissemination

UKPN and WPD along with NPL held meetings with the manufacturers before the end of the project to disseminate the learning from the testing and installations to help them improve their products. Some manufacturers demonstrated how they had improved their products after taking on initial feedback at the installation training sessions at Sundridge Training Centre.

UKPN have also carried out an internal dissemination meeting to share lessons learnt with the Future Network, Operational Telecommunications, Network Strategy and Engineering Standards departments, which was well received.

WPD hosted a substation monitoring knowledge sharing event on 11$^{th}$ July 2013 at the National Space Centre in Leicester. The day shared learning from six LCNF projects, but in particular the LV Sensor Evaluation trial. The day was attended by over 80 people, with representatives from universities, vendors, DNOs, government and blue chip organisations. Ten companies exhibited substation monitoring equipment, including the seven organisations taking part in this trial. This was seen as a key opportunity to share the practical learning from this trial, while providing a hands-on experience with some of the commercially available solutions on the market.

## 9.6. Intellectual property

The project trialled existing commercially available monitoring products and did not look to change their main functionality or their configuration. No relevant Foreground Intellectual Property (IP) has been generated for the project.

The knowledge creation from this project is around solution requirement, safe retrofit installation, operation and communication of LV monitoring equipment. Through this project manufacturers were able to better understand the DNO requirements for LV monitoring equipment. Learning to allow other GB DNOs to replicate this project is set out in this close-down report

## 9.7. Laboratory Testing

When the project was initially scoped, LV substation monitoring was in its infancy. As the procurement process progressed, it became apparent that the equipment being supplied was generally of a higher specification and functionality than expected.  The testing schedule that was drawn up at NPL focused on a small number of tests around current and frequency.

Should this project be repeated, it is suggested that there should be additional laboratory tests undertaken with modifications to some of the methods applied.

In particular it is suggested that tests could be undertaken to look at some of the core electrical and power quality measurements, such as voltage accuracy and aspects related to harmonics.

In addition, tests made to examine the effects of stray fields that should be modified if repeated. Following further review, it is considered that method utilised did not fully replicate the circumstances faced in a typical LV cabinet. In field installations the spacing of conductors with different phase angles can be barely a few mm, whereas the laboratory test undertaken to replicate this used a much larger spacing. In addition the 20A used for the test is generally much lower than the average current carried by cables in live substations.

## 9.8. Data

The project aims were specifically focused on examining the available hardware, installation processes and system accuracy. However, a significant amount of data has been collected from the 28 test sites. Further analysis has shown that the sites monitored are performing within expected boundaries, and no major network performance issues exist.

The load profile on Figure 12 is typical of some of the sites monitored serving primarily domestic areas. It shows the average current in each of the three individual phases of one LV feeder way measured over 15 minute intervals across a 24 hour period in August 2012. The current peaks at 6pm in the evening and again at 8 am in the morning. Knowing the load profiles on the feeders of individual substations allows a better assessment to be made of a substations utilisation. This is useful when considering the connection of additional load or identification of overloaded assets.

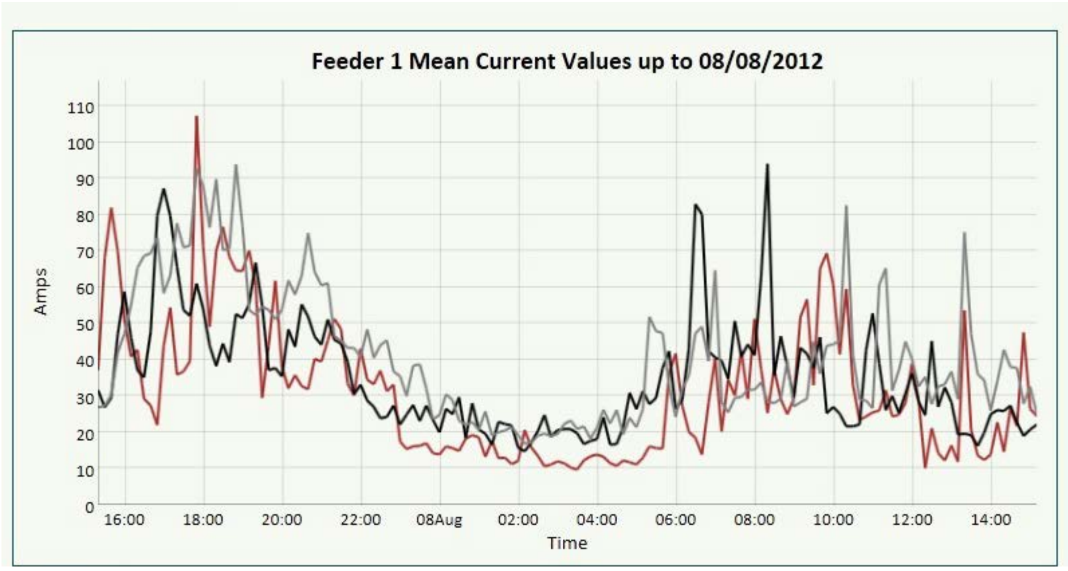


**Fig 12 – Typical Load Profile – Ritchie Gdns (WPD) -Gridkey**

The voltage profile of the same substation site for the same period (Figure 13) demonstrated that the site was operating within the expected statutory voltage limits. The voltage would be expected to drop during periods of high current draw, but it is managed by voltage control equipment, which monitors and adjusts the voltage between set limits. This equipment has not traditionally been located at secondary substation sites, but at the associate primary substation, which supplies electricity to a number of secondary sites. Clusters of LV connected generation and/or large loads can have a significant impact on voltage and monitoring sites will allow the standards of supply to be maintained.

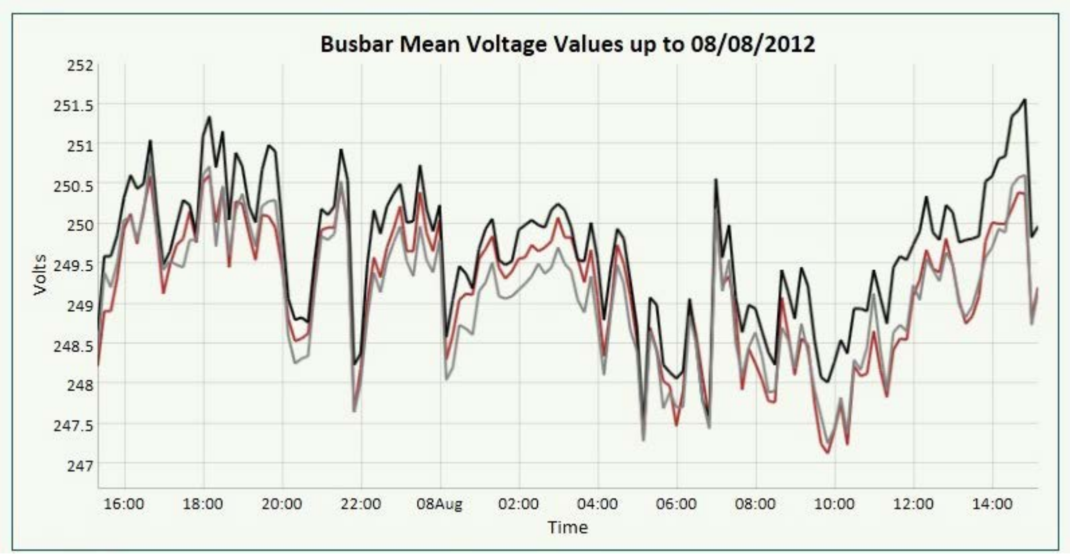


Fig 13 – Typical voltage profile – Ritchie Gdns (WPD) –Gridkey

One thing the monitoring of this site did identify was the presence of relatively large neutral currents (Figure 14). This is primarily due to imbalance in the loading on the individual phases on the network. While not posing a significant operational risk, it does contribute to the system losses experienced in the area.

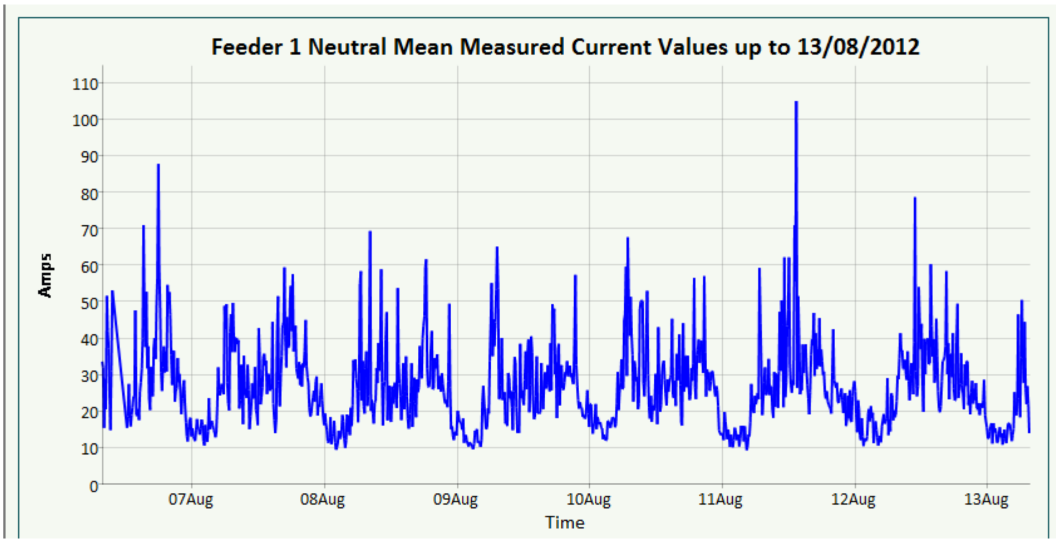


Fig 14 – Neutral Current from network imbalance – Ritchie Gdns (WPD) -Gridkey

Given that for the majority of the time substations operate within expected parameters, they still produce large amounts of data while being monitored. This has led to the development of a number of analytical tools to help visualise data. Figure 15 outlines the load duration for the Dean Street Substation (UKPN). This summarisation of data shows, not only that the site is not overloaded, but also how heavy loaded the site is and for what percentage of time.

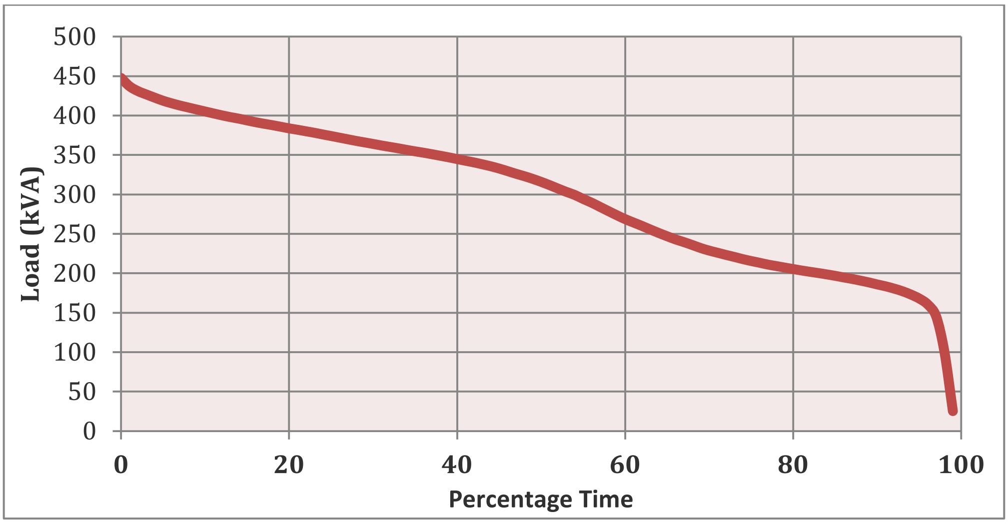


Fig 15 – Load Duration Curve –Dean Street (UKPN) – GMC-iProsys / Nortech

Another important factor is being able to pin-point anomalies that may occur in small time bands. Simply sifting through the data is a very labour intensive, and often means that some of the finer details are missed. The use of alarms and triggers to direct towards periods of abnormal operation is therefore vital. Figure 16 shows the current trace that was recorded on operation of an LV fuse at the Swiss Centre substation (UKPN).

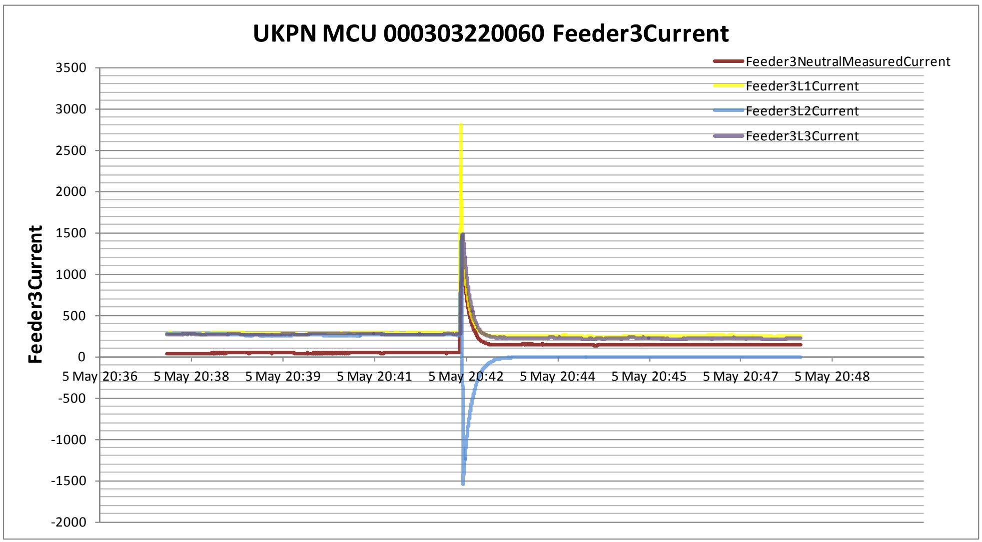


Fig 16 – Trace of current from blown fuse at Swiss Centre (UKPN) –Gridkey

In summary, even the limited amount of data produced by this trial is too much to rely on manual analysis. It is therefore vital that for any wider deployment, suitable analytical tools are utilised to summarise every-day running arrangements into meaningful metrics, and allow the automated identification of abnormal situations.

# 10. Planned implementation

Substation monitoring will inevitably become a vital part of the electricity network, to help support the understanding of how the LV system is performing. However, at this stage, retrofitting monitoring will be driven by trial projects rather than wide-scale rollout. This is primarily down to the whole life cost of installations and no immediate need for ubiquitous monitoring for safe network operation. The outputs of this project will therefore focus the choice and installation techniques where monitoring is required to support further trial projects. It has also helped to drive further innovation with vendors as they have responded to feedback and develop improved products.

During the site selection process for the demonstration project, it was identified that some substation arrangements would present increased installation challenges. These sites were specifically avoided to ensure that a fair evaluation of the monitoring equipment was not compromised by individual site conditions. It is believed that with two exceptions the identified issues could be resolved by providing features such as; extended connections, a waterproof enclosure for the metrology unit or an alternative communications system.

Areas requiring further considerations are locations where the LV equipment has either; insufficient space between individual phases to install sensors or compound filled tiered cable terminations. In both of these cases a possible solution is to use Rogowski coils around the fuse carriers, but this has operational implications and would restrict the monitoring solutions. Alternatively, sensors could be deployed around the LV busbars or transformer links allowing monitoring of the substation load as a whole, rather than by individual LV feeder. The proportion of substation sites affected by these issues is unlikely to exceed 15% of the total population.

# 11. Facilitate Replication

The main body of text in this report outlines the learning from this project and will help other businesses develop their own installation processes. From and Intellectual Property (IP) perspective, this report and appendices focus on the on-site and practical learning from the project. Developments by the manufacturers are considered as background IP, and therefore not available in the public domain.

Appendix A is the NPL report. Appendix B provides a description and the results of the tests undertaken on the seven individual products. Appendix C is an example of the installation procedure developed, which also contains the details and technical specifications of each of the individual sensors used in the field tests. Both WPD and UKPN are keen to share with other companies their installation procedures. Further information on the current product ranges from manufacturers can be found at the following website addresses.

| Name | Website |
|---|---|
| Locamation | www.locamation.nl |

| | |
|---|---|
| Nortech | nortechonline.co.uk |
| GMC i-Prosys | www.i-prosys.com |
| Current | www.currentgrid.com |
| Ambient | www.ambientcorp.com |
| Haysys | www.haysys.co.uk |
| Gridkey (Sentec / Selex) | www.gridkey.co.uk |
| Powersense | www.powersense.com |

# 12. Contacts

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

Future Networks Team

Western Power Distribution,

Pegasus Business Park,

Herald Way,

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# Appendices

Appendix A - NPL Laboratory Reporting

Appendix B - Individual Manufactur

Appendix C - Example Installation F

Appendix D - Tier 1 Proforma LV current s