LCNF Tier 1 Close-Down Report

Demonstrating the Benefits of Monitoring LV Networks with embedded PV Panels and EV Charging Point

SSET1002

Prepared By

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Electric vehicles (EVs) and photovoltaic (PV) tiles are increasingly being adopted by consumers, and are generally connected to a Distribution Network Operator's (DNO's) low voltage (LV) network via existing connection points without need for permission, and likely without prior notification. The potential impacts of these low carbon technologies (LCTs) on the LV network are of some concern; to understand these impacts, if any, some kind of network monitoring is required. As increasing quantities of LCTs are connected, consideration needs to be given to the potential requirement for large scale deployment of monitoring to enable DNOs to make informed decisions.

Monitoring of distribution substations already occurs on LV networks elsewhere in the world, but at the start of this project, had not been deployed by UK DNOs. Today, typical DNO distribution substation monitoring is still limited to a low cost low-accuracy Maximum Demand Indicator (MDI) capable of recording the peak current, aggregated over a 30 minute period, on each of the transformer's three LV phases. The MDI does not include any communications options and requires a manual reading or reset. If planning, investment or operational decisions are to be made effectively when the LV network is undergoing pressure to allow connection of LCTs, more accurate data is required regarding the resulting impacts on the network. At least in part, this data will need to come from detailed, accurate substation monitoring.

The scope of this project was to demonstrate that appropriate substation monitoring can be installed retrospectively and provide meaningful electrical information, and to assess the network impacts of PV and EV uptake at a development of ten low carbon homes, built by SSE at Chalvey, near Slough.

Aims

This project introduced distribution substation monitoring to obtain detailed and accurate current, voltage, power and directional energy usage data, and to develop an understanding of how DNOs might pursue such deployments in the future using monitoring devices installed at substations. It provided the opportunity to monitor the LV feeder circuit to which SSE's low carbon homes are connected to gain insight into the impact on the low voltage network. Consideration was given to the monitoring requirements of the Low Carbon Networks Fund (LCNF) Tier 2 New Thames Valley Vision[1] (NTVV) project so that monitoring can be deployed with certainty on a larger scale through this project.

Activities

[1] This project has now been funded, for further details see www.thamesvalleyvision.co.uk

This project focussed on establishment of a meaningful schedule of parameters to be measured or calculated, assessment of products available or to be developed to provide the parameters, and identification of the modes of operation for monitoring systems that will allow provision of data in a manner that can be used by a DNO.

Of primary concern was the ability to fit monitoring equipment safely and efficiently without taking customers off supply. This is crucial if larger scale deployments are to be implemented without adversely affecting existing customers and allow the benefits of monitoring to be obtained.

At the start of the project, no manufacturer was able to offer a complete monitoring system that could be installed as required and integrated with a DNO's information management system to provide a DNO with a full suite of electrical parameters as specified. The project involved work with three manufacturers to help them fully understand the requirement (they understand how to make products, but lack awareness of how a DNO interacts with products) and allow them the opportunity to configure their solutions for trial on the network.

While not a major focus of the project, the ability of the monitoring systems to transmit data back to a DNO was considered, and mainstream GPRS communications used.

Outcomes of the project and key learning

The project developed a work instruction by which monitoring equipment can be installed safely and efficiently without taking customers off supply. This is included in Appendix II for use by any DNO.

Manufacturers identified existing current sensors that are easy to fit, and work with their data aggregators to give a system accuracy that met DNO expectations. A G clamp was selected for direct live connection onto low voltage busbars to obtain a voltage reference. The modes of operation to which a monitoring system would be expected to operate were established, and transmission of data by GPRS was demonstrated.

All manufacturers provided voltage and current information from their equipment. Two manufacturers reconfigured their data aggregators during the project to enable provision of measured and calculated electrical parameters including power, reactive power, energy, reactive energy and harmonic content, all in line with DNO expectations.

The data obtained was reviewed and particular observations were made about the performance of the LV network. In particular, significant feeder phase current imbalance was observed; busbar voltages were seen to exceed the specified voltage limits that would apply at the point of connection, real and reactive power flows were measured on the circuit to which PV is connected, and the harmonic content of the same feeder was observed to be low. At this level of PV connection to a low voltage feeder (10 houses) in an urban environment, no net detrimental impact on the LV network was observed.

Detailed outcomes are described in Table 7.

Conclusions and future work

This project facilitated the selection and configuration of monitoring equipment for retrospective and live installation, and the development of procedures that will allow larger scale deployment. This will bring immediate benefit to the Tier 2 NTVV project and wider DNO deployment. It has already provided benefit to other DNOs that have purchased the components and equipment.

The sample networks monitored were observed to have characteristics (large current imbalance, low levels of harmonics) typical at distribution substations. While observations showed no further action was required at this location at this time, the project showed sufficiently detailed and accurate data can be obtained for a DNO to assess the impacts of LCTs and develop a rigorous business case for modification of the LV network.

Future work to understand the implications of handling large volumes of data, optimise the communications, and optimise the requirement for monitoring substations (identify the minimum number of substations requiring monitoring, and which substations bring most benefit) will be considered in the NTVV project. Separately, alternative communications solutions should be further considered as the use of GPRS / GSM communications technology may not be suitable in all DNO locations.

Intellectual property

This project informed the configuration of existing products by manufacturers (current sensors, voltage clamp, data aggregators). It did not change core functionality of any products, and all products used are available to other network operators as existing commercial products. As such no Relevant Foreground Intellectual Property (IP) has been registered for this project.

The main benefits and knowledge delivered by the project relate to learning around requirements for monitoring systems and their procurement, live and retrospective deployment, operations and communications. In particular, manufacturers' understanding of DNO requirements and how they can be met has increased. Details necessary to allow the project to be replicated by other GB DNOs are set out in this close-down report. Any additional information required can be requested through jenny.1.rogers@sse.com.

1 Project Background

Previous work: SSE has funded a development of ten zero carbon homes at Slough. Each property has photovoltaic (PV) tiles installed with 63kW output in total. An all-electric Ford car will also be shared between residents. Domestic monitoring devices have been installed to monitor the energy performance of the homes for 24 months. The findings will contribute to studies being carried out by University of Reading, NHBC (National House-Building Council) and BRE (Building Research Establishment).

This Tier 1 project will introduce 11kV/LV substation monitoring to obtain directional energy usage data over a period of 12 months. The substation monitoring will make use of air-gap CTs, intended for retro-fit involving no (or low) CML impact. These current transformers (CT) sensors have not previously been deployed in UK but the technology has been deployed in North America.

2 Scope and Objectives

The scope of the project is to assess the impact of the PV panels and EV charging point on the LV network by utilising a first installation of retro-fit 11kV/LV substation monitoring solution. This project also aims to gain insight into the actual impact on the network of PV and EVs and hence demonstrate the benefits of LV network monitoring on the operation of the Distribution System.

The objectives are:
1 - Demonstrate a "no/low CML" retro-fit 11kV/LV substation monitoring solution
2 - Analyse the data on LV feeders to understand the performance of the LV network
3 - Assess the impact of PV system and EV charging behaviour on the network
4 - Identify the additional capacity of connecting PV panels and EV charging points on the LV feeder.
5 - Assessment of multiple (eg 3 off) different monitoring products
6 - Develop modes of operation for the transmission of data to suit a control room requirement

The installation includes:
1 - Deploy suitable current and voltage sensors at 11kV/LV substation with capablility of expansion to accept temperature, solar radiation, wind speed and direction inputs etc
2 - Deploy suitable methods for data collection and storage allowing future communications installation

3 Success Criteria

The following success criteria have been identified:

- Installation of sensors at distribution substations involving zero, or minimal, CML impact.
- Monitor a range of measurements (V, A, kW, kVAr) on LV feeders
- Demonstrate presentation and dissemination of monitored data via existing business systems to appropriate DNO user community (operations, network planning).
- Produce accurate documentation and reports through the project for learning and dissemination between industry and public.

Proposed Milestones:
- Milestone 1: First sensing devices installed and active local monitoring.
- Milestone 2: Collecting the measurements over a 12 month period
- Milestone 3: Determine additional capacity (or headroom) for the future connection of PV/EV charging point available on an LV feeder.

See Section 6, page 56 for an overview of the extent to which Objectives and Success Criteria were met

See the following sections for details of the outcomes related to the Success Criteria:

- Sensor installation - Section 5.1, page 21
- Range of data monitored – Section 5.2, page 28
- Presentation of monitored data – Section 5.5, page 50
- Documentation of outputs – Appendices I, II and III

4 Details of the work carried out

4.1 Method trialled

This project sought to identify monitoring equipment that could be retro-fitted to the LV network at one or more distribution substations (11kV/LV) to facilitate assessment of the actual impact on the network of PV and EVs, and hence to demonstrate the benefits of LV network monitoring on the operation of the Distribution System. Monitoring of distribution substations already occurs on low voltage networks elsewhere in the world, but has not been deployed in the UK by DNOs. To date, typical DNO distribution substation monitoring is limited to a low cost but low-accuracy Maximum Demand Indicator (MDI) capable of recording the peak current, aggregated over a 30 minute period, on each of the transformer's LV phases. The MDI does not include any communications options and requires a manual reading and reset. This is typically carried out on an annual basis. If planning, investment or operational decisions are to be made effectively when the low voltage network is undergoing pressure to allow connection of low carbon technologies such as PV and EV charging, more accurate and timely data is required, and it is believed that at least in part this will need to come from substation monitoring.

This project aimed to trial a more accurate and timely method of monitoring current, voltage and a range of other parameters including automated collation and transfer of monitoring data to the DNO.

4.2 Trialling methodology

The methodology for this trial involved five steps listed below, each is described in detail in sections 4.2.1 – 4.2.5.

1) Identification of suitable products from different manufacturers that could be deployed to measure network parameters and capture data;
2) Development of a safe installation procedure, installation of monitoring equipment at selected locations and assessment of performance against expectations.
3) Identification and development of modes of operation for the transmission of data to suit a control room environment or planning environment.
4) Collation and analysis of the measured data.
5) Assessment of the impact of PV systems and EV charging behaviour on the network based on data analysis.

4.2.1 Product Selection

4.2.1.1 Current Sensors

The use of traditional CTs was considered, but rejected, as our assessment concluded that traditional CTs would not be suitable for retrofit installation without LV shutdowns involving customers. At best, fitting would have been labour intensive, and at worst, would have incurred substantial unnecessary costs due to the replacement of large quantities of cable terminations onto distribution equipment along with associated extensive disruption to customers' electricity supply. These concerns triggered initial discussions with manufacturers regarding use of alternative current sensing technologies.

Traditional Rogowski coils were offered by some vendors (CURRENT Group and GE). These were trialled at SSEPD's training and test facility at Thatcham in order to ensure a safe method of live installation could be identified and to confirm measurement accuracy.

Figure 1 CURRENT Group Rogowski Coils (blue) 'live installed' at two LV feeders

One vendor , GridKey (a collaboration between Sentec Ltd and Selex Galileo) identified a small rigid type Rogowski sensor, with a hinged face suitable for retrofitting on a range of typical DNO cable tails. This was trialled following discussions regarding the maximum and minimum cable core sizes, and space limitations between cable cores. Gridkey discussed their expectations for accuracy and how this could be achieved in a device that has the rigidity of a traditional (CT) combined with the flexibility of deployment more associated with a traditional Rogowski coil. This device was trialled at SSEPD's Thatcham facility.

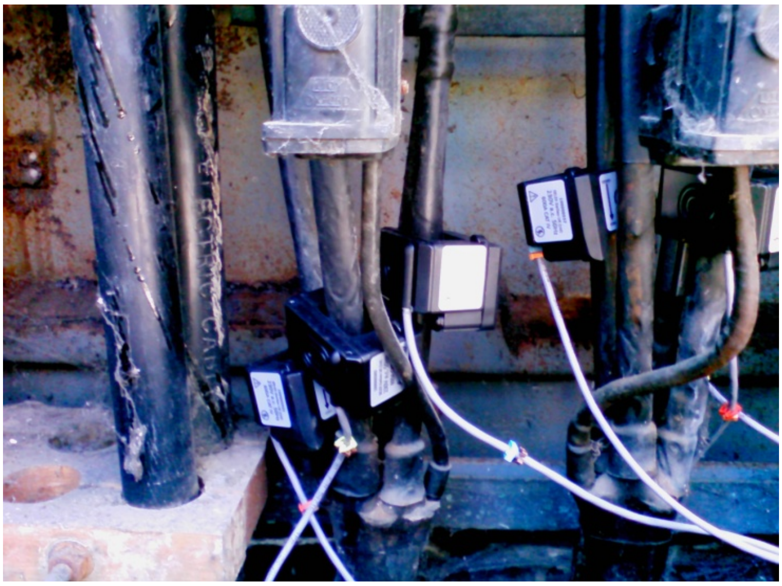

Figure 2 GridKey CURRENT transducers installed on LV feeder cables

In both cases (flexible Rogowski coils and rigid GridKey devices), these current sensors are suitable for live installation around the LV cable tails below any existing shrouding and above ground level.

The trial did not include any outdoor Pole Mounted Transformer (PMT) locations. These are considered easier for current monitoring, typically involving between one and three sensors (at single, double or three phase transformers) with adequate clear safe working access adjacent to the existing LV "PC 400" pole mounted fuse holders. Naturally, an outdoor environment will involve harsher environmental conditions and each manufacturer's device includes the optional provision of a weather-proof enclosure suitable for installation at a PMT.

4.2.1.2 Voltage Connections

Two methods of accessing live LV phase voltages were trialled in this project:

Modern shrouded LV cabinets:

Figure 3 Modern shrouded/screened type LV cabinets

Voltage connections are available on modern Lucy Trifca type distribution cabinets by means of access to small wiring connections on the existing terminal block. These cabinets are typical of those installed throughout GB in recent years and include significant shrouding of all live metalwork while giving ready access for the testing and replacement of fuses. In this case, the electrical connection could be regarded as straightforward involving small wiring only; however the safe routing of wiring from the terminal block to the monitoring device (which is necessarily mounted external to the distribution cabinet) was more of a challenge.

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Traditional open LV pillars:

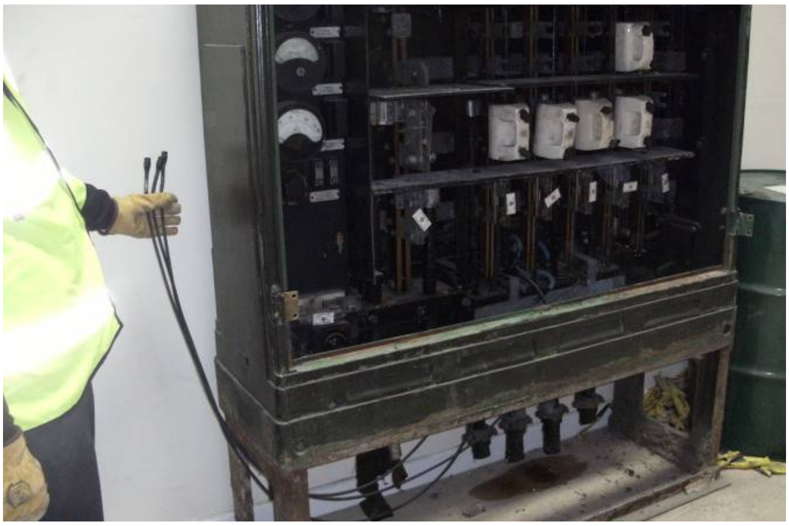

Figure 4 Traditional open LV pillar

It was recognised that a separate trial would be required for more traditional distribution pillars with exposed busbars and cable connections; these predate the Trifca pattern shrouded cabinet and there are many thousands of such pillars still in service throughout GB (accurate quantities are not known but are estimated to be no less than the number of shrouded cabinets). Such open pillars do not include any small wiring terminal block suitable for Voltage monitoring, and a direct electrical connection would be required onto the busbars (or cable connectors). It was accepted that existing rules prohibit live electrical works inside distribution cabinets and pillars, and the development of an acceptable connection method would be necessary if the retrofitting of voltage monitoring equipment at the large proportion of distribution substations containing exposed busbar pillars and no small wiring terminal blocks is required.

The requirement to develop a connector for connection to live busbars has already been addressed by SSEPD in recent power line carrier trial activities with the assistance of Martindale Electric Ltd. This insulated LV clamp connector (known as a “G Clamp”) is commercially available and it was proposed that this should be assessed in this project for use in substation monitoring.

4.2.1.3 Data Aggregation and Transmission

The manufacturers approached generally offered combined current sensor, data aggregation and data transmission solutions. It was understood that the components work together to form an integrated solution of specified accuracy.

SSEPD specified the parameters that were believed to be required to be measured or calculated for the assessment of the network, and challenged the manufacturers to propose their most compliant data aggregator. The specified requirements are shown in Appendix I.

4.2.2 Safe Installation Procedure

4.2.2.1 *Current Sensors*

To test for suitability, each current sensor supplied was taken to SSEPD's training centre and workshop at Thatcham; at this location typical pillars and cabinets are available for trial activities in a safe environment. The sensors were fitted using existing techniques for safe installation (e.g. operator wearing electrically insulating gloves), and consideration was give to electrical clearances, ease of fitting, requirement for tooling, cable routing, access and working space.

4.2.2.2 Voltage Sensors

Voltage information is generally obtained by voltage transformers on the high voltage network, but these are not necessary on the low voltage network where a direct electrical connection with small wiring is suitable for the provision of a voltage signal. The challenge was to find a safe way of connecting small wiring onto the low voltage busbars or associated cables and fittings. This is the primary safety consideration; secondary safety considerations of cable routing and consequential hazards to operatives are no different in principle to those described for current sensors.

4.2.2.3 Work Instruction WI-PS-912

Both current and voltage sensors need to be able to be installed safely while keeping the low voltage network live. The outcomes of the techniques considered for the sensors were written down as a work instruction.

4.2.2.4 Locations for Live Installations

With installation principles established in an electrically safe workshop environment, and a suitable work instruction written, a contractor was engaged to carry out a number of individual installations at live substations, using each of the sensors and monitoring devices considered acceptable, and to develop the work instruction from live experience and feedback from the contractor.

It was originally intended to carry out the trial at Chalvey Local Substation to allow the low voltage cable that feeds the SSE's low carbon homes (including EV charging points and multiple PV installations) to be monitored, but taking into account the different types of low voltage cabinets, pillars, and overall substation layouts, it was decided that additional locations would also be required so that a more comprehensive understanding of potential issues relating to installation could be obtained.

The project therefore funded trial installations at three other substations in the Bracknell area. This area was chosen because it is the location for the NTVV project, hence it was appropriate to run this pilot study in the same area. Equipment was supplied by GE Energy, CURRENT Group, GridKey and Martindale Electrical.

The locations chosen and equipment fitted are summarised in Table 1.

Table 1 - Summary of trial sites involved in this project

Location	Context	Type of Pillar	Equipment Fitted	Scope of Trial
Thatcham Training Centre	Training centre with typical equipment in a safe environment (electrically disconnected)	Cabinet with shrouded busbars and a small wiring terminal block AND pillar with exposed busbars	All current and voltage sensors tried out at this location before being used in a live substation	Initial testing only and opportunity to develop a safe working installation procedure appropriate for all future locations
Chalvey Local Substation	Live enclosed substation – feeds the Low Carbon Homes	Cabinet with shrouded busbars and a small wiring terminal block	CURRENT Group LVA (Low Voltage Analytics) / Open Grid monitoring equipment with Rogowski coils	Small wiring connection methodology; Low carbon technology impact on network
Worlds End Hill Substation	Live substation – brick enclosure	fully exposed wall mounted busbars (no pillar)	GE C650 Relay with Rogowski coils AND GridKey monitoring Equipment and sensors	Exposed busbar connection methodology
Service Yard D Substation	Live substation – brick enclosure	pillar with exposed busbars	GE C650 Relay with Rogowski coils/transducers	Exposed busbar connection methodology
Keldholm Substation	Live substation – brick walls only – outdoor environment	pillar with exposed busbars	GridKey monitoring Equipment and sensors	Effect of outdoor environment on monitoring equipment.

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4.2.3 Data transmission

Without communications to enable data transmission, monitoring data would be left stored in the data aggregator at the substation. While the data could be captured by visiting the substations and downloading data to a laptop computer, this approach is not suitable for anything other than a small trial. While this project did not seek to analyse different communications technologies (eg GPRS / GSM, Wimax, Radio etc), it was clear that it was important to develop an understanding of the types of data, the expected use for the data, and the ultimate transfer and storage requirement as these will influence the design of a monitoring system for any wider roll out.

Two parameters were measured (i.e. current and voltage) and these can be used to calculate real and reactive power, and the harmonic content. These values are all real time values, and they are likely to be useful in a DNO control room environment, but serve little value in a network planning context. Other calculated values include maximum, minimum and mean values of voltage and current, and real and reactive energy. These are very relevant in a network planning context. In recognising the importance of including such data as a routine part of the DNO's planning and operations teams' policies and procedures, these two types of data were described as streamed (Mode 1) and half hour calculated (Mode 2).

It was considered relevant to ensure that the monitoring devices could be easily integrated with existing SSEPD operational and data storage systems. As a prerequisite for the NTVV project, this project included consideration of the means of integrating LV monitoring devices into SSEPD's existing operational Data Acquisition (the 'DA' in 'SCADA') systems. In a large scale roll out, any monitoring device will be required to provide remote data access via openly available communications channel protocols, e.g. Distributed Network Protocol (DNP3) which is also already used at SSEPD's operations centre. Hence a template was created to clearly identify the data points, their DNP3 reference and the respective Mode of Operation. The template is shown in Appendix III.

In practice, most monitoring equipment manufacturers offer a number of communications solutions and protocols as options with their products, and those involved in the trial were willing to work with SSEPD to integrate DNP3 based communication from their device into SSEPD's control room system (ENMAC) for storage in PI historian. However, SSEPD was undergoing significant coincidental upgrades to its control system, and the resources (skilled real time systems engineers) could not be made available to adequately support the project in carrying out this integration, and further, it was agreed that commissioning of equipment by means of DNP3 into ENMAC was an established practice that would provide minimal new learning.

Consequently it was agreed that for the purpose of this trial, data would be stored in the substation data aggregator, and either manually downloaded by connection of a laptop (applied to GE Energy's C650 relay), or transferred to the manufacturer's host system (OpenGrid for CURRENT Group and the GridKey Data Centre web portal) via GPRS. Data was typically made available by CSV (comma separated values) file upon request.

4.2.4 Analysis of Captured Data

This project gave the opportunity to review the data made available by each sensing and measuring solution through installations at a number of substations over a period of several months. The initial focus was on assessing the capability of the monitoring systems to capture, calculate and store a range of electrical parameters. The required parameters were specified as shown in Appendix I. A summary is shown below.

- Voltage (measured)
- Directional current (measured)
- Neutral current (calculated)
- Real power (calculated)
- Energy (calculated)
- Reactive energy (calculated)
- Harmonic content (calculated)
- Alarms

Sample data received from the substations was reviewed, and findings are reported in Section 5 (Outcomes of the project).

4.2.5 Technical Impact on Network of EV / PV

There are two primary considerations when assessing the impact of connecting EV and PV to the network, one being capacity, which is a measure of current, and the other being a measure of performance, which is a measure of voltage and power quality.

4.2.5.1 Network Capacity

Current was measured and half hour maximum, mean and minimum values identified on each phase of each feeder and at the busbar to allow consideration of network capacity. Phase currents were measured with full regard to phase angle compared to the voltage.

4.2.5.2 Network Performance

Voltage was measured and half hour maximum, mean and minimum values identified on each at the busbar to allow consideration of the network performance. Where possible the harmonic content will also be identified.

5 The outcomes of the project

5.1 Demonstration that substation monitoring including Sensors can be retrofitted with no/low CMLs

5.1.1 Work Instruction WI-PS-912

A Work Instruction for live installation of monitoring systems was developed through initial trialling of each system at SSEPD's training centre and refined on the basis of feedback from contractors carrying out substation installations. The installation of small wiring, whether for current sensors or voltage connections, was seen as the most hazardous aspect of monitoring installation. From a risk assessment perspective, it was necessary to ensure that the hazards associated with retrofitting could be controlled and mitigated adequately to demonstrate that all retrofit installations can be achieved safely. A work instruction was drafted to describe at an appropriate level of detail the method, constraints and precautions required to be adopted by an installation team. This work instruction has been demonstrated to the SSEPD policy team and subsequently approved. See Appendix II.

Key features of the work instruction include:

- Visual assessment of equipment prior to start of work
- All works to be carried out wearing PPE applicable to live LV working
- Current sensors to be fitted around cable cores without disturbance to insulation
- Voltage connections to be made by connection to an existing terminal block if available; where no terminal block available, voltage connections to be made using an approved connector, and fitted by hand
- Voltage connection small wiring to be fused at source
- Small wiring to be routed away from power cable fuses to a predetermined route
- Disturbance and vibration of panels to be avoided (drilling is a last resort)
- Drilling of cast iron pillar panels is not permitted

The work instruction includes appendices for the types of pillar and cabinet commonly found in the Southern Electric Power Distribution area. The principles of live connection established are applicable to other pillar types, and further appendicies will be added for other types and situations when the need arises in the future (after completion of the project). It is anticipated that the fitting of current sensors at pole mounted transformer locations will be straightforward subject to due consideration of high voltage electrical safety clearances and working at height considerations. For voltage monitoring SSEPD already has appropriate insulated piercing clamps which are suitable for use on overhead line conductors and it was not considered that these devices required any further testing as a part of this project.

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5.1.2 Installation Experience

Monitoring equipment from each of three vendors was installed using the work instruction developed at SSEPD

5.1.2.1 CURRENT Group

CURRENT Group provided flexible Rogowski coil sensors, and their modular based CCE (communications chassis) and LVA / OpenGrid monitoring equipment. These were fitted at Chalvey Local substation and connected to a Lucy Trifca distribution cabinet. The fitting of Rogowski coils was straightforward as there was adequate space between the cable cores, and voltage connections were easily achieved using the small wiring terminal block. The routing of cables out of the cabinet was more challenging as the cabinet was sat on a concrete base with power cables exiting through ducts. It was agreed that the cabinet would have holes drilled to provide a small wiring route to the data aggregator; it was demonstrated that this could be done safely, although this remains a method of last resort on account of the residual hazards (e.g. vibration, use of power tools in a live environment).

The data aggregator was mounted in a cabinet with legs to allow it to be moved by operational staff if necessary. All small wiring was contained in flexible plastic conduit for protection.

Figure 5 CURRENT Group Rogowski Coils (blue) 'live installed' at two LV feeders

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Figure 6 CURRENT Group Site Monitor

Figure 7 CURRENT Group equipment (unit at left of picture) as installed at Chalvey S/S

The size and weight of the data aggregator was found to be reasonable for fitting in the majority of substations, and the free standing portable approach was designed with use in typical glass reinforced plastic (GRP) kiosk style substation enclosures in mind.

5.1.2.2 GE Energy

GE Energy also provided flexible Rogowski coils for use with their C650 relay (provided as an interim and available solution). These were fitted at Worlds End Hill and Service Yard D substations in 0.5m by 0.5m cabinets. The Rogowski coils were easy to fit, although lead length became more apparent as a constraint due to the limitations of mounting positions for the data aggregator cabinet. At Worlds End Hill substitution a skeleton LV distribution board is fixed to a wall and the live busbars are fully exposed, although the whole substation is enclosed in a secure brick walled building with pitched roof. Connection of small wiring for voltage reference was achieved by live connection of G clamps with fused leads. These were fitted without difficulty, and followed up by tidying of small wiring with cable ties.

Figure 8 G Clamp and fully insulated connect plug and lead

Figure 9 GE Monitoring Unit (brochure photo)

Figure 10 GE C650 Relay Installed in Protective Cabinet

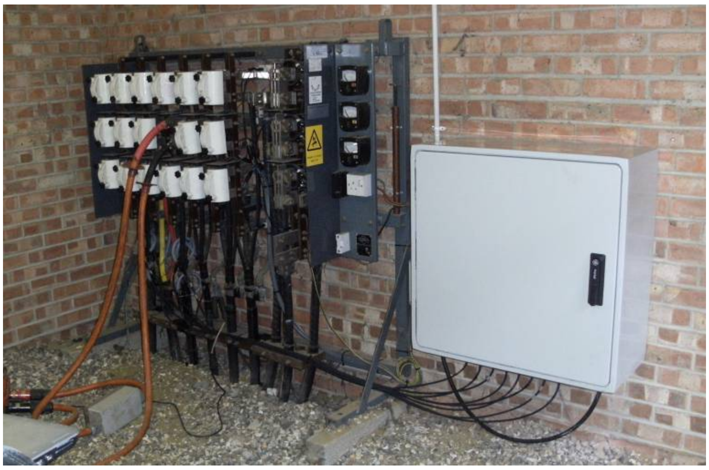

Figure 11 GE Cabinet Mounted at Worlds End Hill Substation

A similar installation was achieved at Service Yard D substation, although at this location the live exposed busbars were contained in a traditional cast iron pillar. This required additional work to access the pillar with small wiring, but the electrical connections are identical.

Figure 12 GE Cabinet Mounted at Service Yard D Substation

5.1.2.3 GridKey

Gridkey provided their current sensors and associated data aggregator, and these were also installed at Worlds End Hill substation. The sensors were easy to fit, and gave installers intuitive confidence of accuracy by virtue of their rigid nature and clear direction arrow. The sensors “click shut” when firmly engaged around the conductor giving the installer confidence of a correct installation. However, more care is needed in handling these sensors around cable cores as the risk of damage to core insulation is greater than with the fully flexible Rogowski coils. No instances of damaged insulation occurred on the project.

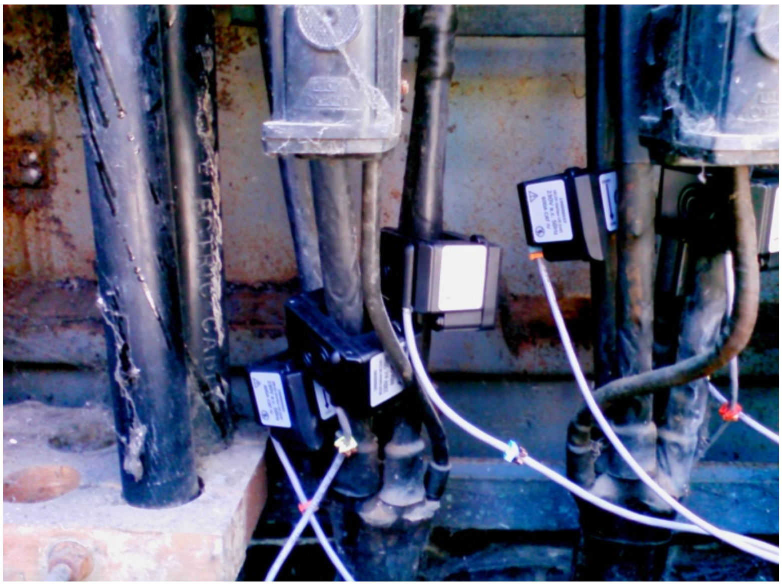

Figure 13 GridKey current transducers installed on LV feeder cables

Figure 14 GridKey MCU520 Data Aggregator

The GridKey data aggregator is clearly colour coded for small wiring connections, and has dimensions and weight that could clearly be installed by a single operative (although the risk assessment process concluded that a two man team should always be used where work is carried out in close proximity to live exposed equipment).

5.1.2.4 Feedback from installation contractor

The contractor carried out the site installations on behalf of SSEPD, and consistently reported their preference for devices that are small and light weight for ease of handling. With regard to electrical connection activities, each site was different, but what was common was the need for a standardised approach and avoidance of tasks associated with higher risks (e.g. the drilling of panels). Their feedback significantly influenced the drafting of Work Instruction WI-PS-912. With clarity of approach, it was observed that a typical site installation should take no more than four hours, i.e. it should be possible to complete two in a working day.

The contractor drew attention to the fact that one of the current sensors had a small multi-pin plug socket arrangement which could impede any subsequent replacement or relocation activities. This feedback was passed on to the manufacturer to allow for subsequent component selections to be best suited to the needs of a DNO.

5.1.3 Key points:

- Work Instruction WI-PS-912 has been written and approved. This facilitates the retrofit of monitoring equipment without taking customers off supply at substations that contain equipment of the common types identified..
- Earlier in-house development of an insulated voltage G-clamp (supplied by Martindale Electrical) was put to good use in this trial, demonstrating effective re-use of learning. These clamps were supplied by Martindale Electric for use at three of the four installations.
- CURRENT Group and GridKey demonstrated rapid learning regarding DNO requirements and offered alternative current sensors so as to ensure that live installation could proceed where previously difficult or impossible (due to narrow clearances between live insulated cable tails).
- GE Energy made use of an existing MV protection relay with appropriate 3rd party current sensors. While this arrangement was easy to fit at Worlds End Hill substation lessons were learnt regarding the need for the monitoring device to be kept as small and light as possible to assist the ease of handling.
- CURRENT Group's LVA is a modular solution, and must be installed in a suitably sized and IP rated cabinet. There are advantages to modularity, and the use of standard USB and power connections may be favourable when used in an indoor environment
- The GridKey MCU520 solution is a fixed five feeder design with colour coded cable connections designed for easy connection of GH600-D sensors and voltage connections. As supplied this also required installation in a suitably sized and IP rated outer cabinet for outdoor use.
- All on-site work was carried out by suitably authorised contract staff. Taking into account the diversity of current sensors and data aggregators supplied by the manufacturers, the learning point from the contractor was the importance of keeping the data aggregator as small and lightweight as possible for safe and easy handling, and to keep the cable connections as clear and easy to connect as possible to minimise installation time.

5.2 Analysis of measured voltage, current and power quality data

For each monitoring solution trialled vendors' data was supplied for review using comma-separated values (.csv) or Excel spreadsheet format. For comparison, the existing maximum demand indicator (MDI) data available at the substation sites was obtained from the local depot team. This is limited to a single value for each electrical phase at the substation busbar, collected at best once every three months.

Table 2 below shows actual MDI parameters as taken from site by the depot team responsible for substation inspections. Clearly every site has different types of MDI and it is necessary to read both the actual reading from the instrument and the scale factor to be applied; correct readings are dependent upon the knowledge and experience of the operative as well as correct form filling and data capture in a remote office.

Table 2 - Maximum demand indicator survey information

Site Information	WORLDS END HILL	KELDHOLME	SERVICE YARD D
Site Barcode	1641660	1626021	1626630
Site Type	Indoor	Outdoor	Integral
Survey Date/Time	12/04/2012 07:40	10/04/2012 10:01	13/04/2012 10:56
LV Housing ID	M1	M1	M1
Overload Flag Status	80	36	28.8
MDI Red Phase	500	1	1.2
MDI Yellow Phase	600	1	1.2
MDI Blue Phase	500	1	1.2
MDI Multiplier	1	240	160
MDI Calculated Amps	1600	720	576
Surveyed KVA (Transformer Rating)	500	500	500
Placar kVA (Transformer Rating)	500	500	500
Depot	BRAC	BRAC	BRAC
Inspector	GR10	GR10	RK13
Comment	73% loaded at peak demand	33% loaded at peak demand	12% loaded at peak demand

The MDI information can reasonably be interpreted to allow a DNO to decide if additional traditional load can be connected at the substation. It does not provide any information about the loading of individual feeders, or about the timing of individual peaks on each phase or other constraints related to power factor, neutral currents or harmonic content.

By comparison, the monitoring solutions used in the project could all readily provide basic information about the substation busbar and feeder loading at half hourly intervals. In the early stages of the project all devices could measure current and voltage with minimal configuration. Calculation of the more complex parameters (e.g. reactive power and harmonic content) required much more configuration for some of the devices.

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5.2.1 Parameters Measured

The data items reported by each manufacturer's device are summarised in Table 3.

Table 3 - Data items reported by manufacturers' devices

Monitoring – Distribution Substation LV Feeder					
Parameter	**Required Phases**	**Unit**	**Worlds End Hill S/S data (GridKey)**	**Chalvey Local S/S data (CURRENT Group)**	**Worlds End Hill and Service Yard D S/S data (GE Energy)**
Voltage (V) max	all	Volts		All Phases	
Voltage (V) min				All Phases	
Voltage (V) mean				All Phases	
Measured Current	All and neutral	Amps		Ia	ANALOG_INP_F_01
				Ib	ANALOG_INP_F_02
				Ic	ANALOG_INP_F_03
				In	ANALOG_INP_F_04
Phase current (I) max	all	Amps	Feeder1L1 Current Maximum	All phases	
			Feeder1L2 Current Maximum		
			Feeder1L3 Current Maximum		
Phase current (I) min	all	Amps	Feeder1L1 Current Minimum	All phases	
			Feeder1L2 Current Minimum		
			Feeder1L3 Current Minimum		
Phase current (I) mean rms	all	Amps	Feeder1L1 Current Mean	All phases	
			Feeder1L2 Current Mean		
			Feeder1L3 Current Mean		
Neutral current (I) max	Neutral	Amps	Feeder1 Neutral Current Maximum	In max	
Neutral current (I) min			Feeder1 Neutral Current Minimum	In min	
Neutral current (I) mean			Feeder1 Neutral Current Mean	In avg	
Power (P)	all	kW	Feeder1L14 Quadrant Power Mean	Real Power A(kWatts)	
			Feeder1L24 Quadrant Power Mean	Real Power B(kWatts)	
			Feeder1L34 Quadrant Power Mean	Real Power C(kWatts)	

Table 3 continued - Data items reported by manufacturers' devices

Monitoring – Distribution Substation LV Feeder					
Parameter	**Required Phases**	**Unit**	**Worlds End Hill S/S data (GridKey)**	**Chalvey Local S/S data (CURRENT Group)**	**Worlds End Hill and Service Yard D S/S data (GE Energy)**
Reactive Power (Q)	all	Var	Feeder1L14 Quadrant Reactive Power Mean	Reactive Power A(kVArs)	
			Feeder1L24 Quadrant Reactive Power Mean	Reactive Power B(kVArs)	
			Feeder1L34 Quadrant Reactive Power Mean	Reactive Power C(kVArs)	
Energy	all	kWhr	Feeder1L1Active Energy	All phases	
			Feeder1L2 Active Energy		
			Feeder1L3 Active Energy		
Reactive energy	all	kVArh	Feeder1L1 Reactive Energy	All phases	
			Feeder1L2 Reactive Energy		
			Feeder1L3 Reactive Energy		
Harmonic content	all	% harmonic content	Feeder1L1 Total Active Harmonic Content	Voltage THD A(%)	
			Feeder1L2 Total Active Harmonic Content	Voltage THD B(%)	
			Feeder1L3 Total Active Harmonic Content	Voltage THD C(%)	
Measured Voltage	all	Volts		Voltage A	Vab Primary
				Voltage B	Vbc Primary
				Voltage C	Vca Primary
Voltage (V) max	all	Volts	BusbarL1 Voltage Maximum	All phases, all xfmrs	
Voltage (V) min	all	Volts	BusbarL1 Voltage Minimum	All phases, all xfmrs	
Voltage (V) mean	all	Volts	BusbarL1 Voltage Mean	All phases, all xfmrs	
Measured Current	all	Amps		Current A	
				Current B	
				Current C	

Table 3 continued - Data items reported by manufacturers' devices

Monitoring – Summated Distribution Substation Transformer LV Output (or Input)					
Parameter	**Required Phases**	**Unit**	**Worlds End Hill S/S data (GridKey)**	**Chalvey Local S/S data (CURRENT Group)**	**Worlds End Hill and Service Yard D S/S data (GE Energy)**
Phase current (I) max	all	Amps	BusbarL1 Current Maximum	All phases, all xfmrs	
Phase current (I) min	all	Amps	BusbarL1 Current Minimum	All phases, all xfmrs	
Phase current (I) mean rms	all	Amps	BusbarL1 Current Mean	All phases, all xfmrs	
Neutral current (I) max	Neutral	Amps	Busbar Neutral Current Maximum	All xfmrs	
Neutral current (I) min			Busbar Neutral Current Minimum	All xfmrs	
Neutral current (I) mean			Busbar Neutral Current Mean	All xfmrs	
Power (P)	all	kW	BusbarL14QuadrantPower Mean	All xfmrs	
Reactive Power (Q)	all	Var	BusbarL1Cur4Quadrant Reactive Power Mean	All xfmrs	
Energy	all	kWhr	BusbarL1ActiveEnergy	All xfmrs	
Reactive Energy	all	kVArh	BusbarL1ReactiveEnergy	All xfmrs	

Table 3 continued - Data items reported by manufacturers' devices

Additional Parameters					
			Worlds End Hill S/S data (GridKey)	**Chalvey Local S/S data (CURRENT Group)**	**Worlds End Hill and Service Yard D S/S data (GE Energy)**
			Feeder1L1 Phase Angle	Frequency(Hz)	
			Feeder1L2 Phase Angle	K-Factor Current A	
			Feeder1L3 Phase Angle	K-Factor Current B	
			Feeder1L1 Total Reactive Harmonic Content	K-Factor Current C	
			Feeder1L2 Total Reactive Harmonic Content	Crest Factor Voltage A	
			Feeder1L3 Total Reactive Harmonic Content	Crest Factor Voltage B	
				Crest Factor Voltage C	
				Crest Factor Current A	
				Crest Factor Current B	
				Crest Factor Current C	
				Crest Factor Neutral Current	
				Current THD A(%)	
				Current THD B(%)	
				Current THD C(%)	
				Neutral Current THD(%)	
				Apparent Power A(kVAs)	
				Apparent Power B(kVAs)	
				Apparent Power C(kVAs)	

5.2.2 Data Measured

Samples of data were obtained from equipment at each substation:

- **CURRENT Group:**
  Monitoring equipment installed at Chalvey Local s/s
  Comprehensive data was provided for each LV feeder included for analysis.

- **GridKey:**
  Monitoring equipment installed at World's End Hill s/s
  Comprehensive data was provided for each LV feeder included for analysis.

- **GE Energy:**
  Monitoring equipment installed at World's End Hill s/s and Service Yard D s/s
  Configured to provide specific data for transformer monitoring..

For each manufacturer, the data collected can be analysed using Excel or similar tools (statistical analysis and advanced graphing tools are usefully available in 'R' a free software tool[2].

The subsequent sections review the data obtained with regard to the ability of the equipment to provide meaningful measurements in the categories of voltage, current, power and harmonic content.

5.2.2.1 Voltage Measurements

Each manufacturer's monitoring equipment was able to measure voltage. Graphs of voltage are shown below for each site:

[2] The R Project homepage: http://www.r-project.org/ R is available as Free Software under the terms of the Free Software Foundation's GNU General Public License in source code form.

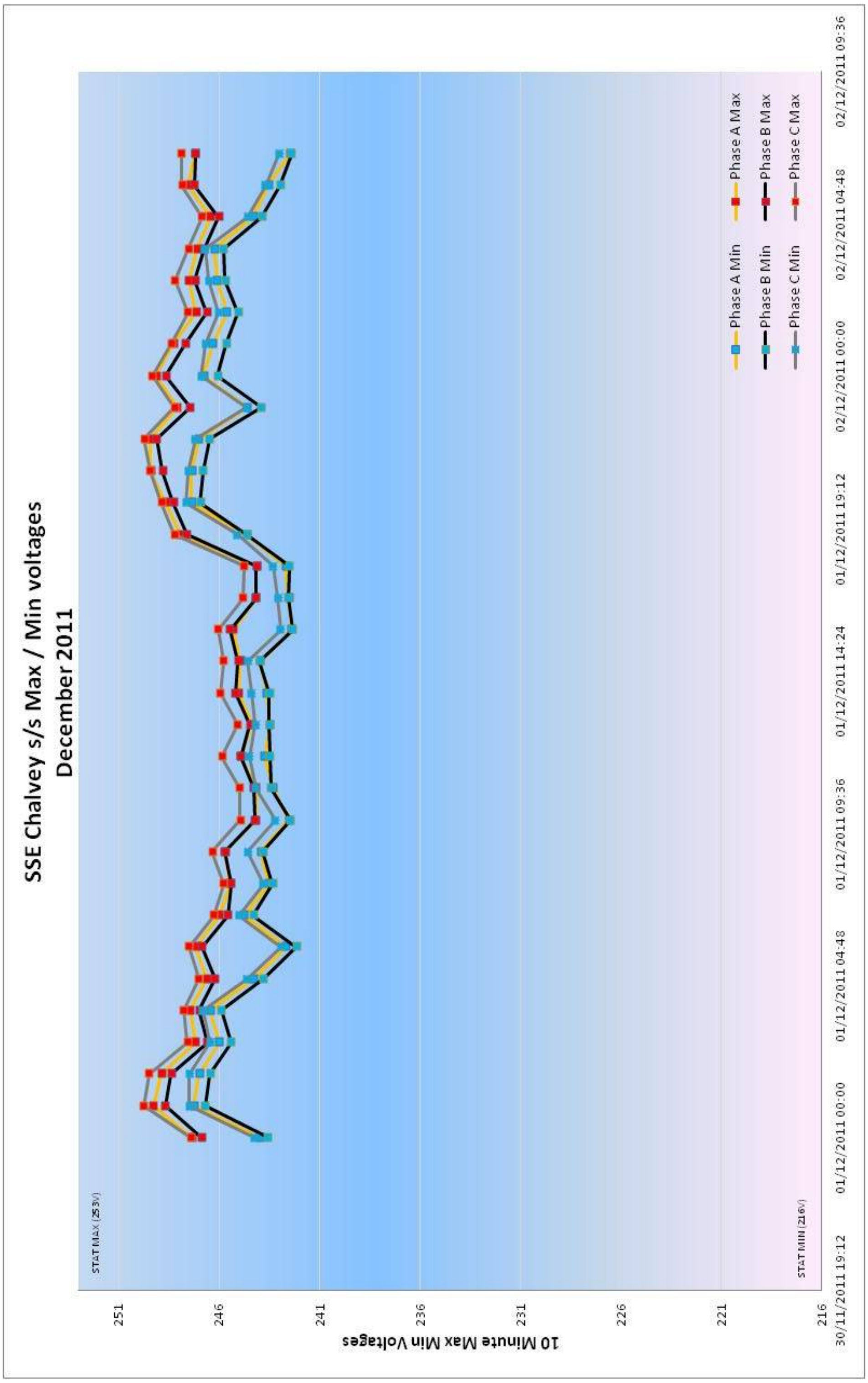

Figure 15 CURRENT Group Voltage data from Chalvey Local S/S

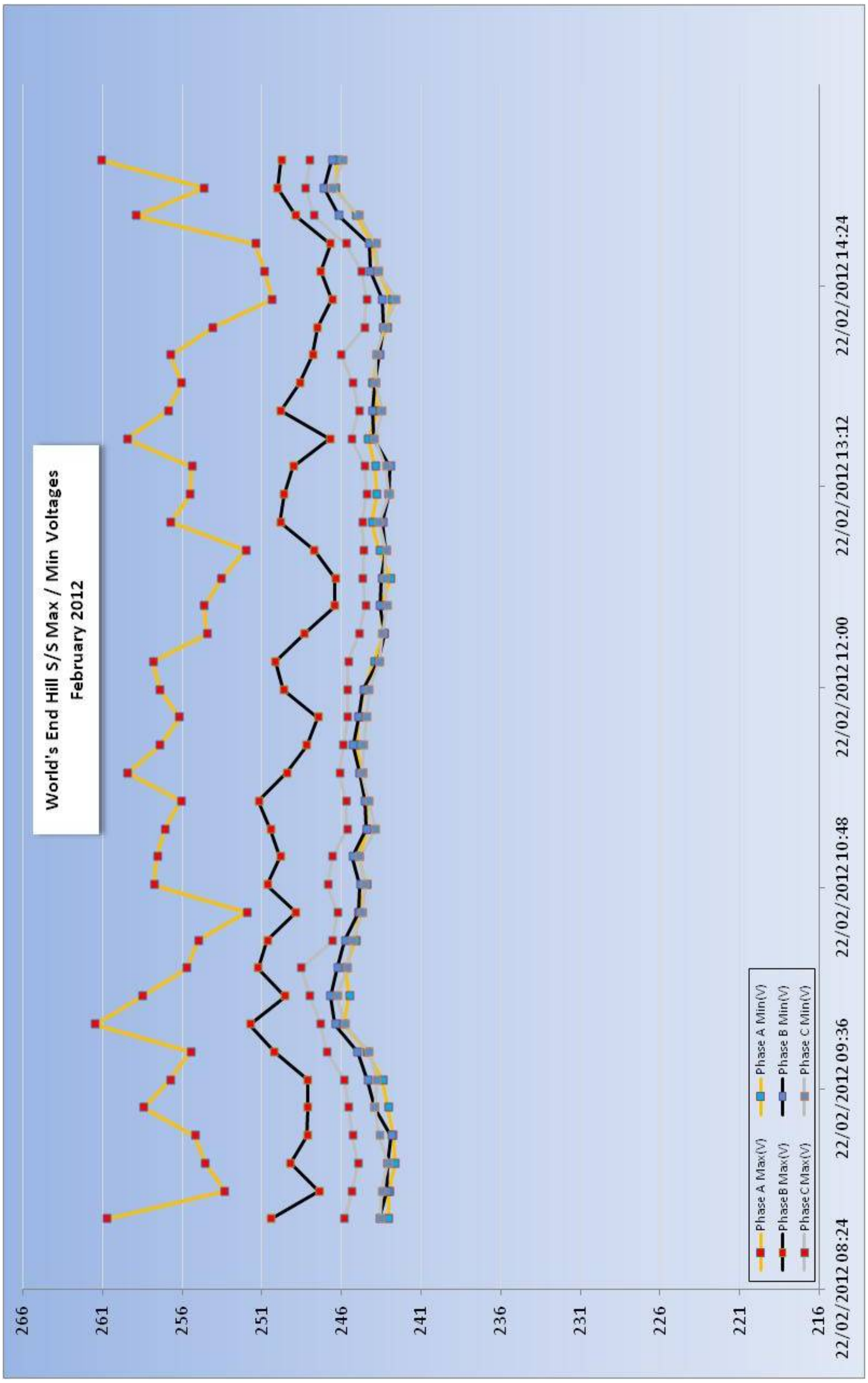

Figure 16 GridKey Voltage data from Worlds End Hill S/S

Both the above graphs provide visibility of maximum and minimum values; this is very useful as it is the excursions to the upper and lower voltage limits that will be useful in any analysis. In the case of Worlds End Hill Substation, it can be seen that the maximum voltage identified exceeds the upper threshold of 254V (230+10%); this has been drawn to the attention of the local depot team for a more detailed investigation.

GE Energy's device at Worlds End Hill Substation also measured voltage. See graph below.

Figure 17 GE Voltage data at WorldsEnd Hill S/S

The voltage data collected using a C650 relay in this case only shows phase-phase voltages and indicates that each is static at 400V. GE Energy advised that this is likely to be due to an issue with the configuration of the unit (if not an error in the downloading process). This was identified too late to be resolved during the operational phase of this project but is noted for any subsequent deployment.

5.2.2.2 Current Measurements

Each manufacturer was able to provide data for current.

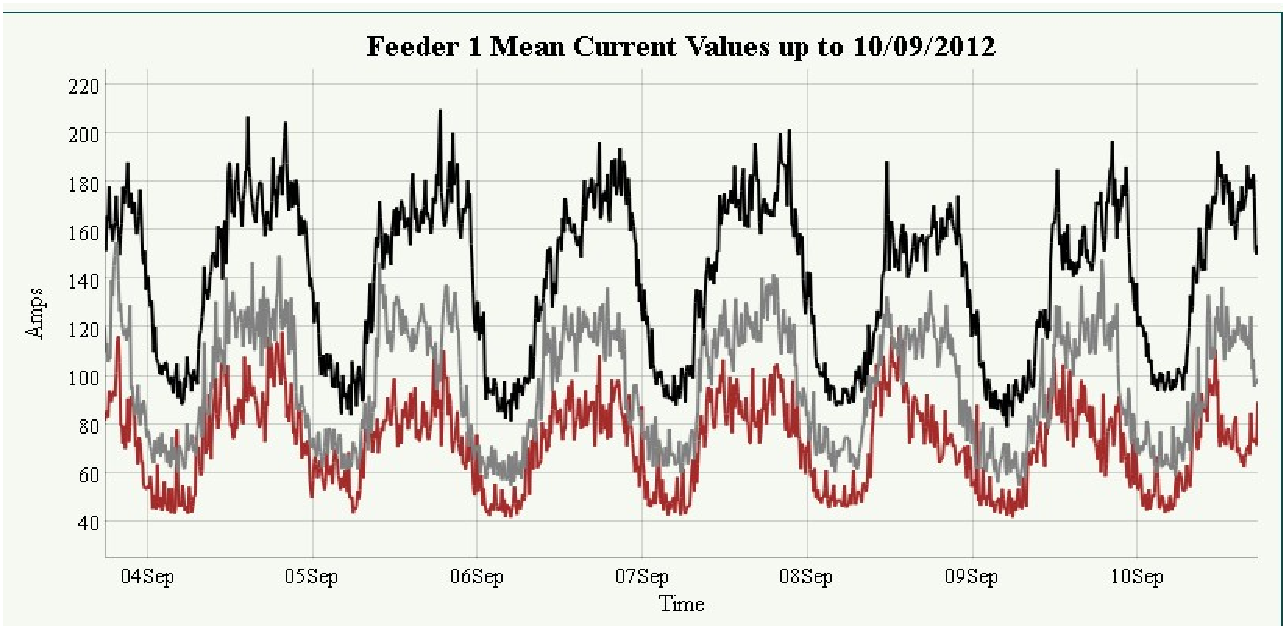

Figure 18 GridKey current data at Worlds End Hill S/S

It can be seen that the black phase current peaks at about double the value of the brown phase current. A similar level of imbalance was observed at the other substations, and is characteristic of low voltage networks. The more balanced a network is the better able it will be to accept additional load (e.g. from EV) and the more resilient it will be to the effect of additional PV. In this case, while the level of balance may be described as poor, the total peak load on the network was observed from the MDIs (Table 2) to be approximately 73% of capacity. There is no short term problem, but the detailed information about individual phase loading as seen above will be useful in enabling a DNO to improve the level of balance by transferring one or more customer connections between phases to increase the effective available capacity of the network (the headroom). This would cost significantly less than full circuit reinforcement.

5.2.2.3 Power, Reactive Power and Power Factor

Both CURRENT Group and GridKey's equipment were able to measure Power and Reactive Power. CURRENT Group data from Chalvey Local substation is shown below.

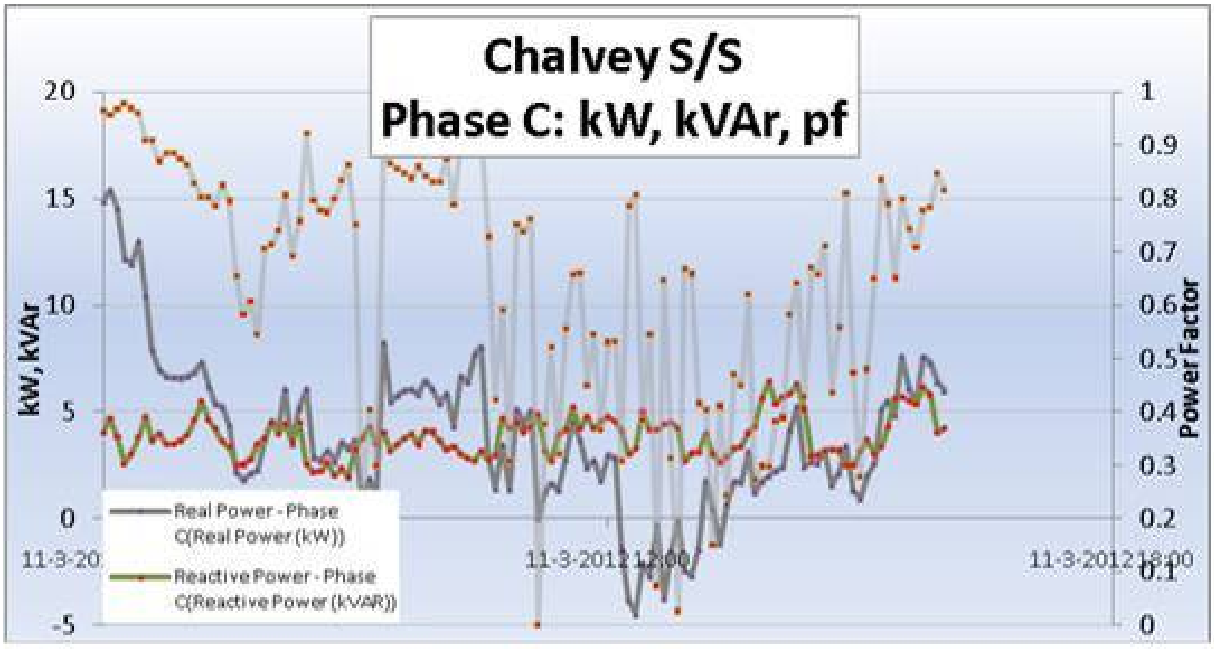

Figure 19 CURRENT Group - power, reactive power and power factor at Chalvey Local S/S

A graphical presentation of data relating to power related parameters is helpful in understanding the impacts of EV and PV on network capacity. These are discussed further below.

5.2.2.4 Total Harmonic Content

Both CURRENT Group and GridKey's equipment were able to measure Harmonic Content. Note that it is the harmonic content of the voltage for which a DNO is responsible, and of greatest interest for measurement. A DNO is responsible for ensuring that the voltage waveform provided to customers is within specified limits for harmonic content. The provision of accurate harmonic content information is crucial for resolving problems associated with harmonic content, and prior to accepting further new connections to the network. A DNO has no control over the current on the network, and measurement of current harmonics is not routinely required.

CURRENT Group's data from Chalvey Local Substation is shown in the graphs below. One graph is shown for each electrical phase, the x axis is the day, the y axis is the half hour (1 to 48) and the colour represents the total harmonic distortion (THD) as a percentage (blue / green lowest, red / purple highest up to 5%).

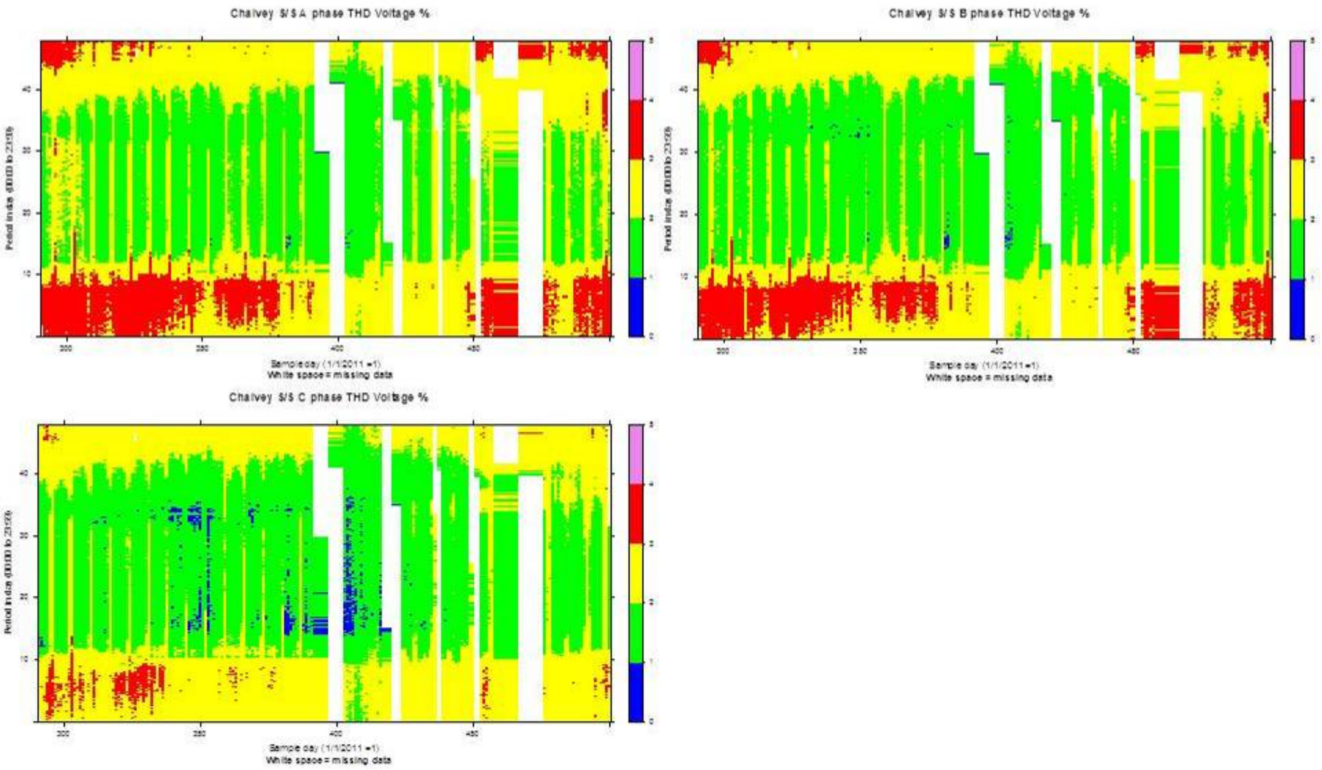

Figure 20 THD Voltages % for Chalvey Local Substation (full page copies included in Appendix IV)

The THD Voltage measurements at Chalvey indicate headroom against existing limits (ENA G5/4-1 5% planning level; EN 50160 8% Compatibility Level). As a percentage against fundamental Voltage, these THD measurements indicate a quiescent level of harmonics which appears lower during periods of higher load (day time, weekdays).

5.2.3 Key points:

- All manufacturers can measure voltage and current with their equipment.
- Monitoring systems can accurately calculate power, reactive power, power factor, energy, reactive energy and total harmonic content from measurements of current and voltage; some manufacturers require refinements to their equipment to calculate all parameters fully.
- Measured and calculated data can be presented graphically for easiest interpretation.

- The data collected at each site and from each vendor's equipment will enable SSEPD to identify any load-related or power-quality related issues at the earliest opportunity.

- The data collected indicated that the brown (red) phase voltages at Worlds End Hill S/S exceed Statutory Limits (253V maximum) and has prompted an SSEPD investigation and remedial work before any customer complaints. There may not be a problem at the customer's point of connection at this time, but the network is still operating abnormally due to either a defect or equipment setting, and left unresolved will inevitably result in further network problems and customer complaints. The clear information available from the network monitoring is very helpful to the depot team for the resolution of such problems as part of business as usual.

5.3 Technical and Capacity Impact on the Low Voltage Network of EV / PV

Some additional questions were considered during this project directed at identifying the opportunity to identify the impact of new low-carbon technologies on DNO networks. Impacts were assessed through analysis of representative snapshots of data.

5.3.1 Impact of power factor and harmonics on network losses

5.3.1.1 Power Factor

The graphs below show the power, reactive power and power factor for a few hours on a sunny winter day on two feeders (phases) at the same substation with and without a significant level of PV connected.

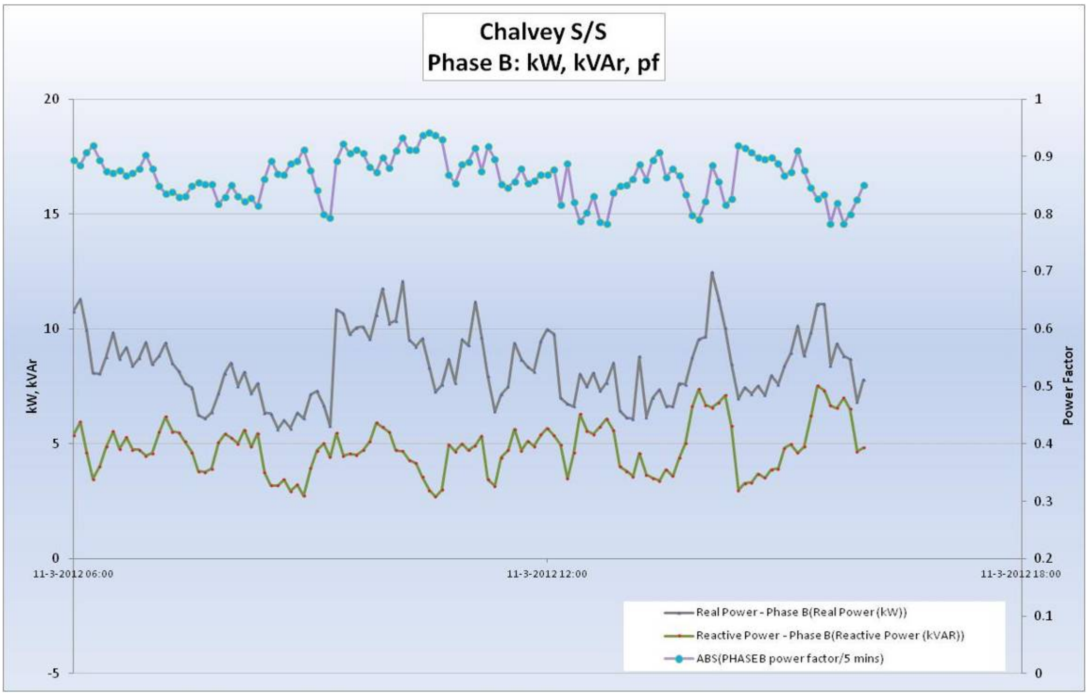

Figure 21 Feeder (phase) with low/no solar PV

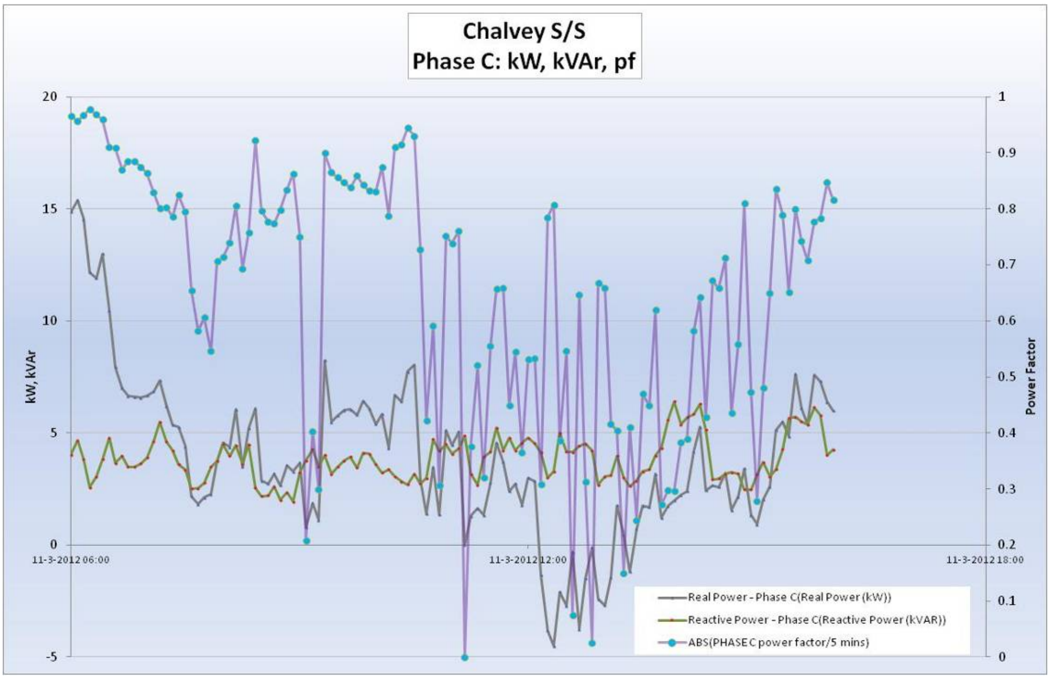

Figure 22 Feeder (phase) with significant solar PV

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Figure 22 (high PV), indicates connected PV has a visible impact on real power and power factor.

In general, non-linear loads[3] increase power losses due to the harmonic voltages and currents they produce. Solar PV may be regarded as being similar to a non-linear load.

When considering a pure sinusoidal case the true power factor is the ratio of average power to apparent power. When harmonics are present (non-sinusoidal case), the average power has harmonic components that may make either positive or negative contributions and hence there is a difference between the power factor calculated and the true power factor. The former sometimes is referred to as displacement power factor. It is known to be difficult to correct the overall power factor distorted this way by adding shunt capacitors as they will only improve the displacement power factor. In such cases, filtering is regarded as the best approach to reduce higher harmonic level.

During solar PV generation the impact on the network is a reduction in real (kW) demand while reactive (kVAr) demand remains unaffected. This is most evident in the power factor which appears very poor throughout the day on Phase C compared with Phase B – the actual data reveals a drop in power factor from a daily median of 0.92 to 0.89. This would imply an increase in network losses of about 0.3% but in reality the losses have decreased because the kW loading has reduced by about 20%.

Outcome: The connection of solar PV results in increased support to the network for real power, but the network continues to be relied upon to provide reactive power support. Substation monitoring that can record this reactive power can provide information over time to support a review of domestic charging assumptions (how should this reactive power be paid for?) It is possible that smart meters that also have the capability to measure reactive power at the customer's point of connection may introduce the opportunity to charge domestic customers for poor power factors.

5.3.1.2 Harmonic Content

The measured Voltage THD % for each of the feeders and phases appear similar and in the region of 1% during daytime, rising to 2% to 4% over night. These are low and compliant values, and it is known that the solar PV generation on the circuit being monitored is small compared with the load on the feeder. It follows that the contribution to THD by the Solar PV is indistinguishable in this case, and this is typical of small solar PV installations embedded in an urban LV network. It is likely that the larger THD values appearing overnight (definitely not solar PV) are explained by HV and EHV system disturbances (e.g. transformer tap changes)

[3] Non-linear loads change the shape of the current waveform from a sine wave to some other form. Non-linear loads create harmonic currents in addition to the original (fundamental frequency) AC current.

impressing harmonics on the LV system; these would not be seen during the day with the increased load on the network.

While EV load may also affect THD, only one EV was on charge at Chalvey and no harmonic data measured on the feeder could be attributed to this single source. No problems would be anticipated for small numbers of EV chargers on a low voltage feeder that is already subjected to a large domestic, commercial and industrial mixed load (like the one at Chalvey). However the monitoring solution would be capable of assessing impacts of larger concentrations. SSEPD's LCNF Tier 2 project I^2EV[4] will present opportunities to explore these effects more robustly.

Outcome: The LV monitoring solution provides a means of tracking trends in background harmonics over time. Harmonics are present in the voltage due to all the non-linear loads connected to the network, one of which may be solar PV. Where there are large quantities of solar PV compared to other non-linear loads the specific impact on THD from Solar PV could be assessed using this equipment.

5.3.2 Impact of phase balance on network capacity and losses

An analysis of 5-minute sample data from World's End Hill s/s for February indicates that if phase balance could be maintained precisely the losses may be reduced by about 2%. It is likely that the imbalance present in the network will remain due to variability in customer activities so that the only option for phase balance may involve a Z-wound voltage balancer as typically used on LV overhead networks. It is not clear that the financial benefits would outweigh costs (based on loss reduction) and there will be issues in physical location of such a device on an underground LV network.

At Worlds End Hill substation, the maximum notional capacity available (limited by standard sized fuses) is 400 Amps per phase. The peak current on the most heavily loaded phase (black) is slightly over 200 Amps whereas the least loaded phase (brown) is peaking at around 110 Amps. If the three phases were consistently balanced this would be equivalent to 155 Amps per phase, so the headroom could be described as increasing from 200 Amps (400 less 200) to 245 Amps (400 less 155); this represents an increase of 23%.

Outcome: Phase balance can be easily identified with substation monitoring, and where it is poor (large imbalance) a DNO is then better armed to make a decision as to what to do. Where the total demand on any one phase is significantly lower than the capacity of that phase, there is unlikely to be a case to correct or improve the situation. If however, the demand on one phase is close to the capacity of that phase, the subsequent consequence of the use of EV charging by customers at peak times is likely to result in overload, disruptive fuse

[4] http://www.ofgem.gov.uk/Networks/ElecDist/lcnf/stlcnp/year3/innovation-squared/Pages/index.aspx

failures and customer complaints. In that scenario, armed with information about phase balance, a DNO could make the decision to reconnect one or more customers from the heavily loaded phase to the least loaded phase. While not cheap or easy on an underground cable network, this would be considerably cheaper than overlaying the feeder with a larger cable.

The opportunity to deploy 3-phase services with 3-phase cut-outs at new and upgraded domestic customers should be reviewed as a means of achieving LV network phase rebalancing at a lower cost than the alternative need for excavation, re-jointing and reinstatement.

5.3.3 Capacity available for additional connection of EVs and PV to LV feeder at Chalvey

Monitoring feeder 1 at the Chalvey substation (with low carbon homes connected) enabled quantification of the headroom available for additional EVs. Connection of additional EVs is essentially a question of capacity. From the data obtained the maximum loading available on each phase was confirmed (Table 4). Each phase is capable of carrying 435A on a continuous basis in summer conditions (the worst case rating for 300sqmm Wavecon Cable). It can be seen that in the summer each phase has headroom as shown below. This is the worst case with summer ratings and assuming the load from EV coincided with the peak loading of the network. The emerging standard rating for EV chargers is 7kW[5], or 30A. On this basis, the number of additional EVs which could be accommodated on each phase was estimated, showing nearly 30 additional EV chargers could be operated before there would be a detrimental impact on the network (Table 4). This includes consideration of voltage drop – calculations based on informed assumptions regarding current distribution indicated this level of additional connections would not breach voltage limits, even if they were at feeder extremities.

Table 4 - Available headroom and estimated potential for additional 7kW EV connections on Chalvey LV feeder

Phase	Maximum loading (A)	Available headroom (A)	Estimated no. of additional EVs
L1	185	250	8
L2	112	323	10
L3	101	334	11

However, the most important point about the substation monitoring regarding estimation of available capacity for EVs is that it provides visibility of the load curve on each feeder for each day. This would inform a DNO of the headroom throughout the day, hence with appropriate customer engagement/incentives it may be possible to

[5] Based on consultation with Nissan, manufacturers of Nissan Leaf, which will be produced in UK and aimed at UK mass market

either achieve a reduction in peak load or to influence the timing when EV charging might be encouraged (or discouraged). SSEPD's LCNF Tier 2 I^2EV project will explore this further and demonstrate the potential for additional connections when methods to stimulate non-concurrent charging are employed.

No data were obtained that would provide any quantification about the headroom that might limit the connection of PV. The substation monitoring indicated that PV was not seen at the substation except on very rare occasions, and this is a reflection of the fact that PV generation is typically absorbed by the load on the feeder. No problem would be expected unless the PV generation is large compared with the load on the feeder during daylight hours

5.4 Product Assessment

Findings from the review of each vendor's equipment in terms of standards compliance are summarised below.

Table 5 - Summary of product standards compliance

Requirement	Reference Standard	CURRENT Group	GE Energy	GridKey MCU520
Voltage accuracy		35V-350V +/-0.5%	0.5% (60 – 300V)	0.25% : 80 – 264Vac (3-phase operation); 20 – 285Vac (1-phase operation)
Current accuracy		50A-1200A +/-0.5%	0.5% (0.2 – 1.5 x CT)	Nominally 0.5%-1% accuracy from 20-720A; 2% up to 900A; 1400A max
Metering Standards	EN50470 EN62053-21 (active) EN62053-23 (reactive)			Class B Class 1 Class 2
Harmonic accuracy		30th harmonic @ 50Hz, Magnitude accuracy better than +/-1.5% Phase accuracy better than +/- 2.5°	NA	NA
Transformer K-factor	IEEE 1100-1992	Included	Not Included	Not Included
Calibration Factory or On-site		No on- site calibration required	On-site calibration required	No on- site calibration required
On-site storage capacity		In general, data storage capacity can be provided to suit DNO specifications, once determined, because of the continuing falling price of solid-state storage and flexibility during manufacturing of these monitoring devices.		
Dielectric Voltage Withstand	EN60255-5	2.3KV	2.3KV	EN61010-1 3.3kV
Impulse Voltage Withstand	EN60255-5	5KV	5KV	EN61010-1 6kV

Table 5 continued - Summary of product standards compliance

Requirement	Reference Standard	CURRENT Group	GE Energy	GridKey MCU520
Insulation Resistance Test	EN60255-5	500 VDC	500 VDC	EN61010-1 1.5kVac
Damped Oscillatory	IEC61000-4-18IEC60255-22-1	NA	2.5KV CM, 1kV DM	NA
Electrostatic Discharge	EN61000-4-2/IEC60255-22-2	Level 4	Level 4	8kV air; 4kV contact
RF Immunity	EN61000-4-3/IEC60255-22-3	Level 3	Level 3	Level 3
Fast Transient Disturbance	EN61000-4-4/IEC60255-22-4	Level 3	Class A and B	Level 3
Surge Immunity	EN61000-4-5/IEC60255-22-5	Level 3 & 4	Level 3 & 4	Level 4
Conducted RF Immunity	EN61000-4-6/IEC60255-22-6	Level 3	Level 3	Level 3
Radiated & Conducted Emissions	CISPR11 /CISPR22/ IEC60255-25	Class B	Class A	Class A
Sinusoidal Vibration	IEC60255-21-1	NA	Class 1	NA
Shock & Bump	IEC60255-21-2	NA	Class 1	EN62262 IK06
Siesmic	IEC60255-21-3	NA	Class 2	NA
Power Magnetic Immunity	IEC61000-4-8	Level 3	Level 5	NA
Voltage Dip & interruption	IEC61000-4-11	0, 30, 60 95% dips 300 cycle interrupts	0, 40, 70, 80% dips 250/300 cycle interrupts	NA
Environmental (Cold)	IEC60068-2-1	-40C	-20C 16 hrs	-20C
Environmental (Cold Storage)	IEC60068-2-1	-40C	-40C 16 hrs	-25C
Environmental (Dry heat)	IEC60068-2-2	70C, Test Be	85C 16hrs	70C, Test Bd
Relative Humidity Cyclic	IEC60068-2-30	NA	6day variant 2	6 day Variant 1
RF Immunity	IEEE/ANSIC37.90.2	80-1Ghz 10V 80%AM(1khz)	20V/m 80-1Ghz	NA
Degree of Protection (IP Rating)	EN60529	NA	NA	IP65

A DNO is primarily concerned that monitoring devices can be installed and operated safely (i.e. do not create a hazard to staff or the public and does not adversely affect supply reliability), and that the data collected is of sufficient accuracy for the purpose for which it is to be used. Safety compliance is reflected with standards of impulse voltage withstand and insulation resistance (all three manufacturers comply). Accuracy of measurement for voltage and current in the region of +/- 0.5% is symbolic of accuracy comparable to tariff metering, which is adequate for majority of requirements (all three manufacturers comply). Note that it is the overall accuracy of the monitoring system that is important, but clearly this cannot be better than the accuracy of the sensors used. All three manufacturers achieve this standard, and it is apparent that given the solutions offered by the three manufacturers, a DNO would expect compliance with these standards and make a product selection based on functionality.

Ingress protection (IP) rating is a key consideration for devices installed in outdoor situations, although this can be selected by the DNO and achieved by any manufacturer simply by supplying their device in an outer cabinet supplied to the specified standard. IP55 is accepted as appropriate for a typical outdoor environment in terms of ingress by solids and liquids. IP65 provides enhanced protection from solids which may be necessary in smoke filled environments.

5.4.1 Functionality

The functionality achieved by each manufacturer at the end of the project after taking into account actual DNO requirements, selecting appropriate sensors, and adjusting their data aggregator firmware is summarised below.

Table 6 - Summary of product functionality observed

Parameter	CURRENT Group OpenGrid	GE Energy C650	GridKey MCU520
Voltage (measured)	yes	yes	Yes
Directional Current (measured)	yes	no	Yes
Neutral Current (measured or calculated)	yes	yes	Yes
Real Power (calculated)	yes	no	Yes
Reactive Power (calculated)	yes	no	Yes
Energy (calculated)	yes	no	Yes
Reactive Energy (calculated)	yes	no	Yes
Harmonic Content (calculated)	yes	no	yes
Number of Feeders monitored	2	2	5
Alarms	yes	yes	yes
Communications (GPRS option)	yes	yes	yes
Period of Data obtained	14/10/2011 to 23/10/2011	1/12/2011 to 14/12/2011	9/3/2012 to 16/4/2012

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The table is a reflection of the data values obtained in the project and all products had additional functionality that was either unseen on the project, or additional to the parameters listed above.

CURRENT Group's LVA / OpenGrid and GridKey's monitoring solutions are both capable of measuring the majority of parameters that a DNO is likely to require. Where a parameter is not available, both companies demonstrated the capability to upgrade firmware in their devices to achieve the required additional functionality. CURRENT Group's solution could be extended by adding more feeder measurement cards; GridKey's solution is designed to measure up to five feeders.

GE Energy provided a C650 relay which is a feeder protection and bay controller relay. According to the product brochure it has the capability to measure current and voltage, and to calculate power, reactive power, active energy and reactive energy. It is however designed to work with 1A and 5A current transformers and required modifications to be able to work with Rogowski coils suitable for retrofitting in distribution pillars. As can be seen from the table above only current and voltage were measured during the project. Two feeders could be monitored with one relay.

The cost of a protection and control relay is likely to be prohibitive for widespread use in distribution substation monitoring; the provision of such a device allowed GE Energy to understand better a DNO's requirement and to influence the configuration of their Multilin DGCM monitoring solution (not tested on this project).

Other non-functional requirements including size and weight were considered. Safe and efficient installation require the monitoring device to be capable of being handled by a single operative, leaving a second operative free to focus on the fitting of current and voltage sensors (if working as a two man team). Both OpenGrid and GridKey solutions fulfilled this expectation; GE Energy's C650 was supplied in a large cabinet containing a separate power supply, terminal block and modem. The design information offered for the existing DGCM product suggests that this could be handled by a single operative.

Where more detailed harmonic measurements are required (individual harmonics rather than total harmonic content), some devices can already supply this, but they are typically limited (e.g. no greater than the 25^{th} harmonic). It is suggested that the routine measurement, calculation, transmission and storage of such harmonic data is not routinely required by a DNO. Where a problem is identified by a high harmonic content it is possible to temporarily install a portable power quality monitor that is compliant with the appropriate standards and capable of measuring to the desired maximum harmonic value.

Manufacturers advise that the functionality requested for SSEPD's trials differs from that seen deployed elsewhere in the world. This is likely due to differences in network configuration, e.g. minimal LV network in North America, and a lower focus on customer quality of supply in much of the rest of the world.

5.4.2 Key points:

- Manufacturers have responded to DNO requirements for LV monitoring devices and it is possible to obtain suitable equipment from a number of different vendors. The measurement of basic parameters, and calculation of more complex parameters is possible for a five feeder substation.

- If a DNO has specific non functional requirements relating to the installation (retrofitting) of equipment, these need to be specified. It cannot be assumed that the manufacturers will provide these features by default.

5.5 Modes of Operation / Transmission of Data

5.5.1 Modes of Operation

It would be uneconomic both in terms of communications bandwidth and cost to stream all data continuously, and it would bring little benefit to a DNO. With that in mind, some modes of operation were identified that would give the DNO reasonable choices about communications. The modes of operation were defined as follows:

- **Mode 1**: In this mode, measured data and instantaneously calculated data are streamed, and parameters include:
    - Current
    - Voltage
    - Power
    - Reactive Power
    - Harmonic Content

- **Mode 2**: In this mode, calculated (half hour) average values are sent, and parameters include:
    - Current (Max, Min, Mean)
    - Voltage (Max, Min, Mean)
    - Energy
    - Reactive Energy
    - Harmonic Content (mean)

- **Mode 3**: In this mode, Alarms are transmitted to the head end system.

Mode 3 is generally always on in the back ground, and Mode 2 is on most of the time to supply the DNO with useful network data for medium and long term planning. The more communications intensive (and therefore expensive) Mode 1 is likely to be routinely left disabled, and would only be expected to be enabled by a network controller in response to an alarm.

5.5.2 Transmission of Data

A template to map each parameter to a DNP3 data point was created (see Appendix III) and shared with the manufacturers. GE Energy were able to apply this directly to their device, and would have been able to transmit data directly to the SSEPD control system had the Real Time Systems resources been available to support the necessary configuration issues. Commissioning of equipment by means of DNP3 into ENMAC (PowerOn Fusion) is not new or innovative; it is the development of a generic substation monitoring template that is important and new.

Data from GE Energy’s C650 relay was manually downloaded using a laptop computer for this project although it is accepted that for any future business as usual deployment full transmission of data would be required.

Both CURRENT Group and GridKey’s products transmited data directly into their own head end systems (OpenGrid and GridKey) respectively, although both advised that they could transmit data direct to SSEPD, including by DNP3 if required, subject to further configuration. In the absence of SSEPD resources as per comments above, data was transmitted to OpenGrid and the Gridkey Data Centre from where SSEPD had access to the data via a web portal.

Each manufacturer included a GSM / GPRS modem in or with their equipment and both CURRENT Group and GridKey were able to transmit data after modifications to their aerials. It was quickly found that signal strength inside enclosed substations (Chalvey Local and Worlds End Hill) was too low for successful communications, and aerial extensions were required; in both cases the aerial was positioned close to the door of the substation. The use of a roaming SIM card was found to work effectively and minimise the risk of coincidentally poor signal strength attributed to any one mobile network operator affecting communications.

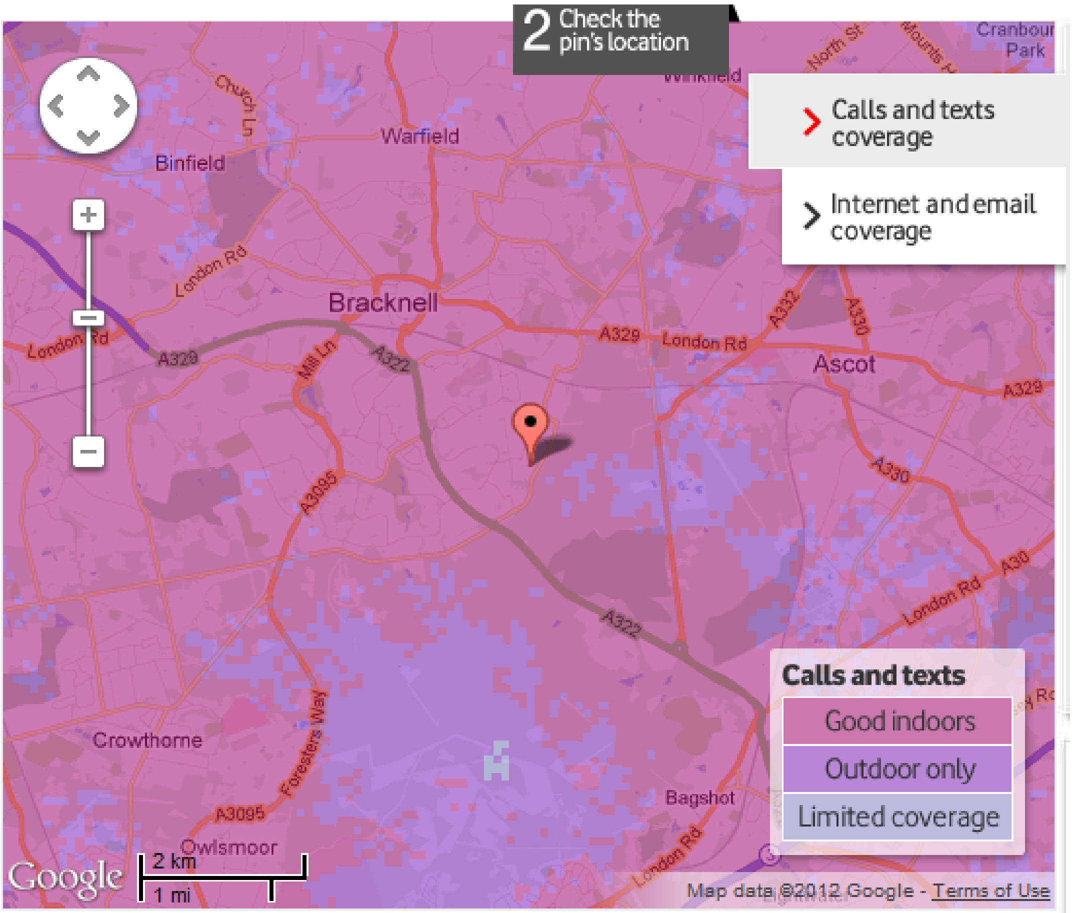

Figure 23 GSM / GPRS Coverage Map (Vodafone) (centred on Worlds End Hill Substation)

The above Vodafone coverage map (above, accessed via Vodafone Coverage Checker[6]) indicates 'good indoors' coverage at the selected site, World's End Hill substation. The poor communications success found prior to the installation of the aerial extension may reasonably be explained by the close proximity of other substation equipment (transformer and 11kV switchgear) either as a physical obstruction (large metal box close to data aggregator modem) or as a source of significant electromagnetic interference. Either way, while indoor signal strength may be adequate in general, the need for a signal strength assessment prior to fit out is necessary.

Cellular signal coverage varies across the region and it is also possible that the coverage indicated above could be affected by other local factors, e.g. building shading, time of day. It may therefore be prudent to budget for the fitting of aerial extensions at all indoor substations.

[6] http://www.vodafone.co.uk/our-network-and-coverage/uk-coverage-map/index.htm

Where data was collected via remote communications, CURRENT Group and GridKey have identified how they can deliver data in a suitable format such as a Comma Separated Value (CSV) file for continued use at SSEPD. Further development work would be required to achieve full integration with SSEPD's existing network management system (ENMAC) and with SSEPD's existing data historian (PI).

If the data is integrated within SSEPD's existing ENMAC demand management system it will be possible to include overload, low voltage and any temperature events and alarms with existing SSEPD operational procedures.

If the data is integrated within SSEPD's existing PI data historian, it will be possible to enhance the network planning processes so that substation and LV cable overloads can be predicted earlier and with greater precision.

This project did not seek to understand the actual costs of data transmission; emphasis was placed on achieving a monitoring system design that is efficient with regard to communications (no more data sent than necessary), and where the choices that a DNO can make are clear.

5.5.3 Storage and Usage of Data

The storage of data within the data aggregator is an important aspect of the equipment functionality, and is linked to the modes of operation. Mode 2 data needs to be stored in the data aggregator until such time as it has been transmitted successfully (minimum of 30 minutes). A minimum storage period of 14 days was specified; this was intended to allow for power outages and communications failures, any of which could require an operative to attend site and resolve site problems.

All manufacturers achieved this with their equipment, based on the volume of data being collected. CURRENT Group and GridKey indicated that their actual equipment capability would be no less than 30 days, and could be significantly longer if required by a DNO.

Storage of the data at the DNO head end was not investigated in this project, other than to ensure that the data would be compatible with SSEPD's operational data store, Pi Historian. Ultimately best use of data may be through detailed correlation of measurements with other existing IT systems and databases including:

- SSEPD DMS/OMS/SCADA (eg ENMAC) and Customer-Network Link (MPAN) systems to enhance 11kV network modelling and any LV outage response and reporting

- PLACAR asset register so as to improve identification of assets exposed to above average load, harmonics, or other factors likely to require enhanced maintenance or accelerated end-of-life.

- Operational data historian (e.g. Pi Historian) – storage of LV data and analysis of data including extrapolation to cover DNO region and assist with improved tariff modelling.

Populated with monitored data these systems will support the provision of information for RIIO-ED1, and this is likely to support the drive for further LV monitoring of substations where MPAN data shows a larger than average population of solar PV installations or EV charging.

5.5.4 Key points

- A DNP3 data point template is now available for the transmission of data with regard to the three modes of operation: streamed, aggregated and alarms.
- These trials have confirmed that GSM/GPRS data collection is possible, provided that public wireless network coverage is available. This is a reasonable assumption for the majority of urban areas.
- Localised signal strength issues can be overcome by means of aerial extensions.
- Other communications technologies such as radio or Wimax are options. These may be useful if a DNO already has infrastructure in place for such systems, or if it can be shown that the total cost of data transmission is less. This is subject to commercial negotiation with communication providers.

5.6 Technology Readiness Level

The Technology Readiness Level (TRL) of each of the components of substation monitoring based on DNO requirements for retrofitting of substation monitoring was already well advanced at the project outset. The TRL of DNO monitoring systems has increased from 8 to 9 as manufacturers have become more aware of how to configure their products for use on the live LV network[7].

Table 7 - TRL Levels at start and end of project

Component	TRL at Project start	TRL at Project end	Comments
Current sensors	9 (in service)	9 (in service)	Rogowski coils are in use in other applications.
Voltage Sensors	9 (in service)	9 (in service)	G Clamps are in use in other applications.
Data Aggregators	8 (completed system)	9 (in service)	Data aggregators provided are in use in other applications, but had not been configured to measure or calculate data in the format required for use on a UK DNO LV network.
Complete Integrated Monitoring System	8 (completed system)	9 (in service)	A complete monitoring system that can be retrofitted to an existing LV network requires appropriate sensors to be selected and integrated with the data aggregator, and the complete system configured for use by a DNO. The DNO needs to have a procedure in place to allow such equipment to be installed to the live LV network.

[7] The starting TRL before the project was originally estimated at 5. Internal understanding of monitoring systems was relatively low at this time and this original estimate reflects this – a more informed estimate of the staring TRL (8) is used here, based on our improved understanding of components and systems gained through the project.

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6 Performance compared to original project aims, objectives and success criteria

This SSEPD Tier 1 project has successfully demonstrated that relatively inexpensive suitable LV monitoring equipment can be installed at typical LV substations without interruptions to consumers' supplies. The extent to which specific objectives and success criteria have been met is summarised below.

Table 8 - Extent to which project objectives have been met

Objectives	Commentary
Demonstrate a "no/low CML" retro-fit 11kV/LV substation monitoring solution. The installation should include: • Deployment of suitable current and voltage sensors at 11kV/LV substation with capability of expansion to accept temperature, solar radiation, wind speed and direction inputs etc • Deployment of suitable methods for data collection and storage allowing future communications installation.	Three different manufacturers' monitoring devices were supplied and live-installed at three different 11kV/LV substations. Three different types of current sensors were fitted (all based on Rogowski coil technology) and voltage connections were made, both through small wiring connections and by means of a G clamp connection onto live busbars. Three different data aggregators were fitted and connected to the current and voltage sensors. A number of electrical parameters were successfully measured and stored.
Analyse the data on LV feeders to understand the performance of the LV network	Accurate data relating to voltage, current, power and reactive power were captured (including maximums, minimums and means). Energy and harmonic content were also successfully recorded. It was demonstrated that the phase currents on feeders could be measured, and the imbalance was clearly visible. It was demonstrated that the voltages at the busbars could be measured, and analysis identified that there may be a network problem with the voltage being set too high at Worlds End Hill substation.

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Table 8 continued - Extent to which project objectives have been met

Objectives	Commentary
Assess the impact of PV system and EV charging behaviour on the network	Data analysis identified the presence of PV and showed the monitoring systems would also assist with identifying any load increase due to EV charging, where present. It was apparent that the amount of Solar PV and EV charging present were small, and at this level, no detrimental effect on the low voltage network was observed. The data obtained during this project did not suggest any additional impacts of greater concentrations of PV or other LCT connections The monitoring solutions will enable a comprehensive assessment of the impact of new 'low-carbon' devices, including PV and EVs.
Identify the additional capacity of connecting PV panels and EV charging points on the LV feeder.	Data analysis showed there is capacity for additional connection of around 30 EVs on the feeder to which the low carbon homes are connected, but did not enable quantification of additional PV which could be connected (see Section 5.3.3). Access to detailed annual loading and voltage profile data will enable network operators to better identify available 'headroom'. The accuracy of the monitored data is such that confidence can be gained with regard to knowledge of current loading.
Assessment of multiple (suggest 3 of) different monitoring products;	Three different manufacturers' monitoring devices were included in these trials. CURRENT Group provided their LVA / OpenGrid solution. This provided all electrical parameters specified. GE Energy provided their C650 Relay. This was configured to monitor phase current and voltage. Their more advanced DGCM LV data monitor takes into account their increased understanding of DNO requirements. GridKey provided their MCU520 and GH600-D sensor solution. This provided all electrical parameters specified.

Table 8 continued - Extent to which project objectives have been met

Objectives	**Commentary**
Develop modes of operation for the transmission of the data to suit a control room requirement.	Three modes of operation were developed (streamed, aggregated and alarms) and presented as a DNP3 data point template. CURRENT Group and GridKey monitoring solutions included and demonstrated remote communications via GPRS.
Detailed Expectations	
Connection issues (installation achieved without interrupting supplies to customers (zero CML) using a safe procedure.	A safe installation procedure has been written and approved, and installation teams reported their satisfaction with the deployment of the current and voltage sensors. The importance of minimising size and weight of the data aggregator was recognised to ensure that handling issues do not inhibit efficient installation.
Equipment functionality (parameters measured, accuracy, storage capability in device)	The electrical parameters required to be monitored and specified to the manufacturers were successfully captured by two manufacturers. The third manufacturer is currently developing a device to fulfil these expectations. Actual parameters reported by each manufacturer are listed in section 5.2.1.
Equipment Standards (IECs to which the equipment does / should comply)	Each manufacturer's product complies with the desired safety, environmental and accuracy standards as identified in the table in Section 5.4.1.
Actual Data (format, presentation, user control, use of vendor's portal)	All the data obtained was received in CSV or Excel format, and could be manipulated in a spreadsheet environment. The vendor's web portals were user friendly to a regular user for the purpose of observing real time data.

Table 8 continued - Extent to which project objectives have been met

Detailed Expectations	
Observations relating to the network (issues, interpretations, consequences, proposals)	Feeder current was observed to be unbalanced and meaningful maximum values could be seen so that current usage could be assessed. Busbar voltages were observed and actual network voltage issues reported. Real and reactive power could be observed and linked to Solar PV connected to the network. The harmonic content was observed and noted as background level. For a given feeder, access to information as above will be invaluable in making judgements regarding the capacity and technical capability of the network in accepting future Solar PV and EV charging, and this will allow more informed investment decisions to be made.
Communications (choices, learning points)	With modes of operation established detailed design of a communications infrastructure can proceed. For the trials, good use was made of existing mobile phone cellular networks, and concerns regarding signal strength resolved (they can be overcome by extending the aerial).
Environment (consideration of criteria to apply for outdoor use, EMC)	All the products had been tested by the manufacturer for compliance with environmental standards (as per table in Section 5.4.1). IP rating is an important aspect and it was accepted that the manufacturers could achieve a typical IP rating of IP55 by installing their data aggregator in an IP55 rated enclosure to suit the DNO.

Table 8 continued - Extent to which project objectives have been met

Detailed Expectations	
Product assessment	All the components used were existing well developed products and systems. It is important to note that the project allowed the manufacturers to better understand the issues associated with retrofitting equipment to the DNO's existing live LV network, and this enabled them to make the most appropriate component selections, and subsequent configuration and integration to provide a complete and effective monitoring solution for a DNO. CURRENT Group supported SSEPD's project in their response to space limitations by providing their LVA / OpenGrid solution including the introduction of flexible Rogowski CTs. GE Energy has demonstrated how an MV protection and control relay can be used, albeit with limited success, for LV monitoring. GridKey has successfully integrated a novel current sensor (GH600-D) which can be live-installed and delivers good measurement precision, accuracy and range into their MCU520 solution.

Table 9 - Extent to which project success criteria have been met

Success Criteria	Commentary
Installation of sensors at distribution substations involving zero, or minimal, CML impact.	This project successfully demonstrated that current and voltage sensors could be installed without interrupting supplies to customers using three different manufacturers' products,
Monitor a range of measurements (V, A, kW, kVAr) on LV feeders	This project succeeded in monitoring and remotely collecting a wide range of voltage, current and power quality measurements from each phase of a number of LV feeders.
Demonstrate presentation and dissemination of monitored data via existing business systems to appropriate DNO user community (operations, network planning).	The modes of operation developed allow the monitored data to be presented to the appropriate DNO user community. Mode 3 Alarms would go direct to an Operational Control Room, and Mode 1 Streamed data would be made available to a Control Room upon request. Mode 2 aggregated data would be sent to a DNOs data storage system (PI Historian in SSEPD) for use by planning engineers, new connections team etc.
Produce accurate documentation and reports through the project for learning and dissemination between industry and public.	The SSEPD team had numerous discussions with the manufacturers during the project to provide feedback and clarification of requirements and specifications. The installation procedure and DNP3 templates developed have been directly shared with other DNOs (ENW, Scottish Power and WPD). The key findings have been presented at the LCNF Conference (Cardiff, October 2012). The findings from this project are being fed directly into the Tier 2 New Thames Valley Vision Project.

7 Required modifications to the planned approach during the course of the Project

The project underwent one project change consisting of two additional objectives, the rationale for each is explained below.

7.1 Objective 5 - Product Assessment

Early discussions with manufacturers during the project scoping stage indicated market availability of suitable devices. However, detailed investigation following the requirements specification stage revealed that no device then available would provide the complete integrated and fully configured solution for monitoring the low voltage network at Chalvey Local substation (to which the Low Carbon Homes with PV and EV chargers were connected). It became apparent that one manufacturer's proposed solution would struggle to provide meaningful measurement of directional current, and this would inhibit calculation of real and reactive power, energy and harmonic content. There were further constraints relating to equipment dimensions.

Other manufacturers, when approached, were quick to advise that their products were already capable of measuring directional current, and the other calculated values (if not already available), could be provided with minimal further configuration.

No one manufacturer could provide a solution to all requirements at the outset, but it was clear that the desire to fully understand the DNO requirement and to configure a solution that would fully meet that requirement was strong. SSEPD accepted that manufacturers would be unable to meet the requirement without access to a DNO network, supported with guidance from the DNO as to what the requirement actually was. With that in mind, it became necessary to assess the equipment offered by multiple manufacturers. It was therefore agreed to pursue the discussions with three manufacturers (CURRENT Group, GE Energy and GridKey), and to add the product assessment objective to the planned approach of the project.

7.2 Objective 6 - Modes of Operation / Transmission of Data

It was recognised that any scaled up substation monitoring deployment would fundamentally depend on the efficient and economic transmission of data from substations to the DNO's systems, and for data to be available to the relevant user community.

The requirements of the user community (short term real time information in a control room versus continuously available aggregated data for planning requirements) are diverse, and a single "mode" of transmission was clearly going to be inefficient and potentially uneconomic given the volume of data. These considerations led to the conclusion that the actual modes needed to be identified, discussed with users and developed into meaningful data strategies.

With modes of operation identified, the link with an actual data transmission protocol (DNP3 for SSEPD) was seen as a crucial development that would facilitate efficient data transmission in a scaled up monitoring deployment.

The development of modes of operation and a DNP3 template were therefore seen as important objectives that should be included in the project objectives.

7.3 Impacts of change on original objectives

The original objectives were set based on the assumption that suitable monitoring systems were commercially available and could be easily procured, installed and operated. As described above, this was not the case and the objectives above were defined to reflect the additional preliminary work required to develop specifications and protocols for installation and data transmission. This meant data collection could not be established as early as expected and assessing the basic functionality of monitoring systems became the main focus of data collection. As a result the emphasis on data analysis to understand the performance of the LV network and impacts of PV and EV charging behaviour became a lower priority and was achieved by analysing representative snapshots of data as opposed to systematic review of continuous data over a 12 month period.

8 Significant variance in expected costs and benefits

8.1 Project costs and variances

Table 10 shows the overall cost of this project was significantly lower than estimated. The reasons for the lower costs are explained below.

Table 10 - Project cost elements

Cost	Predicted £k	Actual £k	Variance £k	Variance (%)
Manufacturers	220	110	-110	-50
Installation Contractors	30	15	-15	-50
Consultants	10	7	-3	-30
Project Management	60	59	-1	-2
Total	**320**	**191**	**-129**	**-40**

Manufacturers

The budget was based on a quotation from one manufacturer; other manufacturers subsequently took a different view about the actual cost to be charged to SSEPD, taking into account the benefit that they would gain by being given access to a DNO network, and the prospect of subsequent scaled up substation monitoring deployment. The outcome was that actual costs were significantly lower than the predicted costs.

Installation Contractors

There is some provision for the dismantlement of the monitoring equipment; the equipment has not yet been dismantled so these costs have not yet been charged.

Consultants

A provision was made for the use one or more consultants to provide advice or witnessing of tests by a manufacturer if necessary. Only one consultant was engaged.

8.2 Benefits of Project

8.2.1 Connection of substation monitoring equipment without disrupting supplies to customers

At the start of the project, awareness of the required features of products that would allow for retrofitting to the live LV network was limited, and there was no approved procedure for the live installation of monitoring equipment.

The project has resulted in clarity by manufacturers regarding appropriate sensor selection for integration into their complete monitoring solution, and a work instruction has been approved for the live connection of monitoring equipment.

8.2.2 Monitoring a large range of electrical parameters on LV Feeders

At the start of the project, no one product was available that could monitor the range of electrical parameters specified. The project has resulted in the configuration of data aggregators from different manufacturers that can measure and calculate all the electrical parameters specified.

8.2.3 Review of the impact of PV and EV charging on the LV Network

At the start of the project there was no data available for assessment of the impact of PV and EV charging. The Project has resulted in data being available that can allow a full assessment of the network at the monitored location, so that the impact of PV and EV charging can be understood. Being able to understand the impact on the network is key to being able to make choices about the need for, and urgency of reinforcement, or alternative solutions.

8.2.4 Financial Benefits

The project outcomes demonstrate that there is a wide range of potential financial benefits that could be realised through wider deployment of LV monitoring solutions. The value of these benefits will depend on the nature and scale of any wider roll out.

Table 11 – Summary of financial benefits

ID	Benefit	Estimated Value
1	Provide clear specification and allow manufacturers to better understand a DNO's requirements for substation monitoring allows the manufacturers to select the most appropriate sensors and data aggregation equipment and to integrate these to give the best data output and lowest equipment costs and installation costs.	Correct solution configured and deployed; the value gained is a reflection of the wasted equipment and effort avoided.
2	Early medium scale deployments can proceed, and manufacturers can standardise their solutions.	Advantages of scale; value depends upon quantities deployed
3	Clarity of requirements combined with standardisation allows multiple manufacturers to supply equivalent equipment providing a competitive market for the DNOs	Value depends upon quantities deployed
4	Disruption to customers from shutdowns avoided by being able to fit monitoring equipment to live LV networks	Each customer will value their continuous electricity supply differently and the costs of any shutdown to DNOs would vary by licence area. As an indication of value to a DNO, penalties for supply interruptions in the Southern Electric Power Distribution licence area are: Customer Interruption (> 3 minutes) £4.38 per customer; and Customer Minutes Lost, £9.50 per customer per hour. On average, substations in residential areas of the Tier 2 NTVV project area have around 140 customer connections. Avoiding a four hour interruption at a substation in this type of area would therefore avoid a cost of around £6k.
5	Labour saved by a DNO in not having to arrange a shutdown for each monitoring installation	Labour saved will be 4 hours minimum (including production of letters, identification of customers affected, dispatch of letters, electrical isolation and restoration, responding to customer queries etc.) At an average hourly rate of £78.43 (fully on-costed), avoided cost would be £313.72 per installation.

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Table 11 continued – Summary of financial benefits

ID	Benefit	Estimated Value
6	Opportunity to benefit from enhanced reliability and security of supply resulting from a proactive DNO approach to Power Quality issues as an alternative to existing business practices which are necessarily driven by customer complaints after significant problems arise.	A DNO will be able to target investment in the low voltage network more accurately.
7	Allow customers to connect new low carbon technology without significant constraints or requirements for large scale low voltage network reinforcement. This is being explored more fully in SSEPD's Tier 2 New Thames Valley Vision project.	WPD's LV Templates project has calculated potential savings (assuming large scale deployment by all DNOs) in the range £12M to £159M.

Table 11 continued – Summary of financial benefits

ID	Benefit	Estimated Value
8	Potential for DNOs to identify opportunities for cost savings where balancing across phases could avoid need for reinforcement	The potential cost savings will vary enormously according to individual situations, however, an example of the potential saving is illustrated by the following scenario: assume a low voltage 250 metre long feeder cable has 50 services connected to it, and the loading ratio is 30% / 50% / 20% with the 50% phase loaded to the maximum capacity of the cable. To achieve a balanced scenario (33/33/34) would require 27 percent of services (14 out of 50) to be reallocated assuming all services represent the same load. Taken literally, this would mean excavation and rejointing for 14 services, at an estimated cost of c.£14,000. The alternative scenario for reinforcing the network to pick up additional load would typically involve laying a second cable from the substation and selectively transferring some of the services from the existing feeder (assume 14 again); This feeder may be half the length of the existing one to achieve the requirement, at an estimated cost of c.£28,000. The traditional reinforcement method is in this instance is around 50% higher. In reality, DNOs will target the most cost effective service transfers – and make greater percentage savings – by identifying the least cost implementation opportunities, minimising the actual quantity of transfers involved and also staging transfers in batches, i.e. a second batch would only be confirmed once it is known if there is still a problem after transfer of a first batch.

9 Lessons learnt for future projects

9.1 Products

Substation monitoring equipment capable of retrofitting to a very large proportion[8] of the existing DNO substation sites has now become available from a number of manufacturers, partly at least as a result of this project. Manufacturers initially struggled to believe that traditional CTs could not be fitted to achieve the project goals. Direct experience of working with a DNO as an informed end user with access to a DNO network along with feedback and guidance from a DNO team with experience of operating on a live LV network was an important contributor to the successful evolution of products and systems to meet the requirements of the end users. A DNO team must not assume that manufacturers fully understand their requirement until they have appropriate requirement specifications that take into account the environment in which the equipment will be required to operate.

While manufacturers may sometimes be accused of overstating product capability and/or readiness, all manufacturers involved in this project demonstrated a willingness to support the project objectives so as to achieve a positive outcome.

9.2 Safe Installation

A safe working procedure for the retrofitting of substation monitoring equipment at live LV pillars and cabinets has been drafted and has SSEPD internal approval. This worked effectively for a handful of single installation scenarios, but is it efficient if applied to a large volume of sites? Further experience will be gained and learning identified on the Tier 2 NTVV project.

9.3 Communications

Effective communications are crucial to any monitoring activity proposed to be scaled up, and to make this happen in a DNO environment requires significant input from a number of DNO functions including Real Time Systems, IT, Control and Network Planning. The level of engagement required is very difficult to achieve on a small project. The Tier 2 NTVV project will provide the scale (over 300 substations) to justify the level of engagement required, and to help identify actual communications issues linked to volume of data, and data categorisation by mode.

[8] It is possible that a very few sites may require some further attention although we are not yet aware of these sites. NB: SSEPD has about 98,000 HV/LV substations and Pole Mounted Transformers.

9.4 Large Scale Deployment

This project has demonstrated that substation monitoring can be done and provides real value in terms of information gained about the LV network. The Tier 2 Thames Valley Vision Project will deploy monitoring at more than 300 substations from which further direct learning will be derived, and then develop a much deeper understanding about the ways in which the data can be used to bring value to a DNO. It is the outcome of this Tier 2 project that will much more directly influence the justification for a true large scale deployment.

It is noted that other DNOs (ENW in particular) have already procured equipment configured by manufacturers on this project for deployment for business as usual activities. This may be considered a medium scale deployment (hundreds) rather than large scale deployment (thousands), but the manufacturer will undoubtedly gain further experience leading to product improvements and cost reductions.

9.5 Dissemination

SSEPD has already shared learning from this project with other DNOs via one-to-one site visits, including demonstrations of data transfer capabilities. The learning relating to retrofitting monitoring with zero customer interruptions was identified as new knowledge relevant to the industry and the method of dissemination was chosen following initial discussion of learning from the project with Ofgem, as an efficient, relatively low-cost method which would enable in-depth discussion of the technical aspects.

Initial discussions with other DNOs indicated that dissemination on the monitoring project was not sufficient alone to attract significant interest – a site visit including tour of SSE's Low Carbon Homes as well as the monitoring systems at Chalvey Local substation was therefore offered.

One-to-one visits were arranged with UK Power Networks, Scottish Power, and Electricity North West (ENW). Most participants were Future Networks/Low Carbon team members. Visits lasted 2-3 hours and followed the general agenda below, participants left with contact details and a copy of the presentations.

Agenda

- Introductory presentation on Low Carbon Homes and Tier 1 monitoring project
- Viewing of low carbon homes - discussion of network impacts compared to traditional homes
- Viewing of Chalvey substation monitoring equipment - discussion of design and practicalities
- Viewing of live data feed on CURRENT Group OpenGrid head-end system - led by CURRENT Group, discussion of options for streaming, viewing, access
- Open discussion of SSEPD's and visiting DNO's monitoring experience and projects

The format worked well; visiting DNOs were very open in sharing their challenges and plans, typically they had monitoring projects of their own and discussion enabled differences of approach to be identified and put into context. These productive discussions may have been the result of the small numbers involved. The Energy Storage Operators Forum (ESOF) was also used as a dissemination channel; the 12 September 2012 meeting, hosted by SSEPD at the Low Carbon Homes, included a viewing of the Chalvey monitoring installation. All DNOs participated.

Lessons learnt regarding dissemination activities include the following:

- Listen to feedback – Ofgem provided excellent realistic advice re getting the learning out into the marketplace;
- Be open and honest and share both successes and problems;
- Anticipate areas of interest and time dissemination accordingly – in this case, questions on testing, validation of results and the safety case were most common, dissemination occurred once initial results were available.
- Be prepared and allow time for visitors to take lots of photos and ask plenty of questions;
- Do not wait for large conferences - arranging small meetings can be more effective, particularly for technical knowledge exchange;
- Consider use of additional incentives to attract target audiences;

9.6 Future opportunities

This project has demonstrated that a rich variety of LV network data can be collected. It is likely that greater value may be gained from this data if it can easily be correlated with other DNO data sources, including smart meter data (when available) and Customer-Network Link (CNL) connectivity data so that analysis can include correlation between different data sources. This may assist with data modelling as an alternative to monitoring a large population of substations; this is one aim of the New Thames Valley Vision LCNF Tier 2 project.

The project has focussed on the monitoring of electrical parameters of the LV network, but with additional equipment deployed at distribution substations, it should be possible to measure and report transformer temperature and ambient temperature. This would assist with identifying distressed transformers before failure and may lead to more effective problem resolution.

Further trials of alternative communications solutions are recommended so that cellular radio coverage does not restrict any larger scale deployment plans. This could include other existing licensed radio schemes and satellite communications.

10 Planned implementation

This project has been carried out with an underlying desire to support the Tier 2 NTVV project which requires the deployment of sensors and data aggregation equipment at up to 300 substations without disrupting supplies to customers, and to transmit this data for analysis by SSEPD and its partners (specifically the University of Reading). The Tier 2 NTVV project is focused on the usage of the data (specifically energy usage behaviour of customers and the consequential impact on the LV network), not on the means by which the data is obtained. The fitting of monitoring equipment is a means to an end, but will serve to highlight issues with a medium scale retrofit substation monitoring deployment.

The NTVV project has directly benefited from this Tier 1 project in the following areas:

- Current Sensors identified, application ready
- Voltage connection methodology established
- Monitoring equipment capable of measuring relevant parameters
- Monitoring equipment capable of being fitted safely and efficiently
- Installation procedure drafted and approved within SSEPD
- Modes of operation recognised in terms of the usage of the data
- DNP3 data point mapping template established
- Communication is possible by means of GPRS

The information gathered to date demonstrates that meaningful information can be retrieved with monitoring, but it does not make a case that the information is crucial on a large scale. The NTVV project will provide learning outcomes regarding the scalability and actual usefulness of the data in allowing a DNO to make improved investment, planning and operational decisions, and it will seek to understand the optimum scaled up monitoring deployment (i.e. the percentage of sites, or types of sites, where monitoring is justified). It is the outcome of the Tier 2 project that is expected to directly influence SSEPD and other DNOs' approach to business as usual.

Knowledge and awareness of the monitoring possibilities by existing operational and planning teams is growing, and interest has been expressed in further small scale deployments. These are possible and subject to management consideration within SSEPD, but no decisions have been taken at this stage.

At this point in time SSEPD expects substation monitoring to play a part in it's RIIO ED1 programme, in particular this monitoring will focus on those areas where networks are particularly stressed to allow operation of existing assets as close to their full capacity as is reasonably possible. SSEPD does not intend to roll out monitoring to all substations at this point pending better understanding of the value that Smart metering could make to LV network visibility. This is a key output of the NTVV project and will directly inform SSEPD's long term monitoring strategy.

There have been wider industry moves towards implementation, which may be a result of the dissemination activities described above (9.5). Business as usual medium scale deployment is now in progress at ENW, one of the DNOs attending a one-to-one visit.

11 Project replication guidelines and intellectual property

The following tables list all physical components and knowledge required to replicate the outcomes of this project, showing how the required intellectual property (IP) can be accessed by other GB DNOs. Further detail relating to any knowledge item is available from SSEPD on request through jenny.1.rogers@sse.com

Table 12 – Components required for project replication

Component	Products used in project or commercially available equivalents
Monitoring system including current sensors, data aggregator and communications	GE Energy C650 Protection and Control Relay (including Rogowski coils) which are existing commercially available products.
	CURRENT Group LVA / Open Grid monitoring equipment (including Rogowski Coils) which are existing commercially available products.
	GridKey monitoring equipment (including GH600-D current sensors) which are existing commercially available products.
Voltage measurement	Martindale G Clamp including fused leads which are existing commercially available products

Table 13 – Knowledge products required for project replication

Knowledge item	Application	IP ownership and availability
Monitoring Requirements Document	Procurement of substation monitoring equipment	SSEPD Close-Down report Appendix I
Installation Work Instruction WI-PS-912	Installation of substation monitoring equipment without disrupting supplies to customers.	SSEPD Closedown Report Appendix II
Modes of Operation	Development of internal strategy and protocols for use of substation monitoring systems, may also be used in developing procurement specifications and business processes	SSEPD Closedown Report
Data point allocation table for DNP3 Communications	The DNP3 template has been developed to reflect modes of operation and the diversity of data points to be transmitted	SSEPD Closedown Report Appendix III
Methodology for voltage connection onto live low voltage busbars	Installation of equipment to monitor voltage signal in substations where this requires a connection to be made directly onto the busbars using an appropriate G clamp.	SSEPD Closedown Report