Network Innovation Allowance

Summary Report

1 April 2018 to 31 March 2019

Scottish and Southern Electricity Networks

Scottish Hydro Electric Transmission

FOREWORD

This report is a summary of the progress achieved by Scottish Hydro Electric Transmission plc (SHE Transmission) in Network Innovation Allowance (NIA) projects during the period between April 2018 and March 2019. NIA is targeted at smaller innovation projects which can deliver value to network customers and has been running since the onset of RIIO-T1 in April 2013.

SHE Transmission is part of Scottish and Southern Electricity Networks (SSEN) which owns and operates the transmission network in the North of Scotland. The core value of SSEN is to provide the energy people need in a reliable and sustainable way. SHE Transmission views innovation as being central to achieving the foregoing core value. Innovation helps us to improve the management and performance of the transmission network, enabling us to provide energy in a safe, reliable, sustainable and economical way and ensuring that we deliver value to our customers.

As we continue to witness an enduring shift in the composition of our generation mix in Great Britain (GB), together with increased penetration of other low carbon technologies, our ability to maintain the integrity of our network infrastructure is consistently being tested. SHE Transmission continues to closely monitor ongoing developments and takes a dynamic approach to responding to the associated challenges.

SHE Transmission developed an Innovation Strategy as part of the RIIO-T1 submission, which outlined seven overarching objectives driven to address the needs and aspirations of our stakeholders. In March 2017, we published an updated Innovation Strategy which affirms our adaptability and commitment to value-driven innovation. It streamlines our innovation activities into five focus areas, which reflect the current sentiments of our stakeholders and readies us to respond to the changing demands of future requirements.

As of 31 March 2019, we have a portfolio of eight SHE Transmission-led NIA projects at various stages in their lifecycles. Within the project portfolio, each of the project addresses at least one of the five focus areas which are summarised in this report in Chapter 2 and covered in greater detail in our updated 2017 Innovation Strategy.

Since April 2018, we have registered three NIA projects. We deem our approach to be consistent with our core purpose and our need to prioritise the relevant challenges faced by our networks as well as those of the entire GB electricity sector. Whilst our projects make progress, we keep a lookout for any learning that can quickly be implemented. We also learn from our peers in the industry and engage with our stakeholders and other interested parties in the energy supply chain to ensure that our combined efforts can deliver the best possible value to GB customers.

Stewart A Reid
Head of Future Networks Scottish and Southern Electricity Networks plc

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1 Update to the SHE Transmission Innovation Strategy

As a response to our stakeholders' evolving challenges and priorities, we published our updated Transmission Innovation Strategy in March 2017. The realigned strategy outlines our vision for a value driven innovation culture, whilst also confirming our intention to be able to respond to the changing demands of future requirements. A link to this new strategy is provided at the end of this report.

Our updated innovation strategy is driven by our overarching corporate values: Safety, Service, Efficiency, Sustainability, Excellence and Teamwork. These values and our business drivers have led us to identify five key themes and priority areas for innovations, which are outlined below:

1.1 Asset health and Productivity (Service, Safety)

- A more complete and holistic understanding of the life cycle of our network assets
- Completing the implementation and exploitation of Condition-Based Risk Management and delivery of the benefits
- Cost-effective asset monitoring and accurate knowledge of the state of our assets
- New methods of asset health assessment
- Optimising the timing and nature of interventions

1.2 Network Reliability/Availability and Efficiency (Service, Efficiency)

- Network Performance according to operational targets and contractual obligations
- Voltage Control
- Reliability of supply, reduction of outages and faults, rapid and effective response to faults
- Maintaining high system availability and the optimum level of redundancy
- Interface with System Operator(s)

1.3 Commercial Innovations (Service, Excellence, Teamwork)

- Constraint Management
- Disintermediation, cyber security, blockchain transactions
- Big data analytics, machine learning and automation
- Service provision and supply chain evolution; identification of hidden costs
- Improved decision-making, procurement, standardisation, and policy
- Optimised planning, timing and sizing of load-related investments

1.4 Environmental and Safety Impact (Safety, Sustainability)

- Reduction/Elimination of SF_6
- Health and safety performance improvement
- Impact reduction of site access
- Flood protection

1.5 Management of losses (Service, Efficiency)

- Understanding where losses occur
- Optimising loads for efficiency
- Asset security, protection, and countering metal theft

The five focus areas will be dealt with mostly by devising and developing ways to address the associated listed challenges. Additionally, there will be trials and evaluations of solutions already developed by others, or the fast-follower adoption of ideas tested by our peer organisations. We will continue to scan the horizon for new possibilities, by working with our supply chain to find solutions to our immediate problems, and through calls for innovation via the Energy Innovation Centre (EIC) and the Energy Networks Association (ENA).

2 NIA Project Portfolio

In the year to 31st March 2019, under SHE Transmission's NIA funding stream eight projects were supported; three of which were new registrations and four projects were successfully concluded.

Table 1 below shows all the registered NIA projects for this reporting year, illustrating how each map onto the up-dated 2017 Innovation Strategy focus areas.

Project No.	Name	Asset Health & Productivity	Network Reliability/ Availability & Efficiency	Commercial Innovations	Environmental & Safety Impact	Management of Losses
NIA_SHET_0014	Partial Discharge Monitoring to Reduce Safety Criticality	■	▲		▲	
NIA_SHET_0018	Transformer Intrascope Phase 2	■				
NIA_SHET_0020	Remote Asset INertial Monitoring & Alerting Network (RAINMAN)		■	▲		
NIA_SHET_0021	Composite Core (ACCC) Inspection	■			▲	
NIA_SHET_0022	Transmission System Fault Level Monitoring	▲	■			
NIA_SHET_0023	Line Inspection by Semi-Autonomous Systems (LISAS)	■	▲		▲	
NIA_SHET_0024	Partial Discharge in HVDC Cables	▲			▲	■
NIA_SHET_0025	Zero Missing Phenomenon (ZMP)			■		▲

KEY: ■ **Primary Objective** ▲ **Secondary Objectives**

Table 1. NIA Project mapped onto the 2017 Innovation Strategy focus areas

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3 Summary of Progress

3.1 NIA_SHET_0014 Partial Discharge Monitoring to Reduce Safety Criticality

Start Date: January 2015

Duration: 63 months

Description:
The scope of this project is to install online trial Partial Discharge (PD) monitoring systems incorporating alternative technologies and suppliers at selected sites and integrate with SHE Transmission's SCADA system in order to collect, store and analyse output PD event data to establish if this can be used to improve the management of safety critical plant. Learning from this project will also be used for further work to incorporate PD failure precursors into control and protection schemes.

Expected Benefits:
The most significant benefit from this project is safety. If equipment is isolated from the network prior to disruptive failure, then the risk to safety will be minimised. Furthermore, where assets have been earmarked for replacement as a result of being identified as having high safety criticality, deferring their replacement through the continuous monitoring method proposed in this project will have a financial benefit.

Progress:
Following on from a years' worth of PD monitoring at two substations locations, PD notification alarms have been set and the field data is now viewable in the Supervisory Control and Data Acquisition (SCADA) system.

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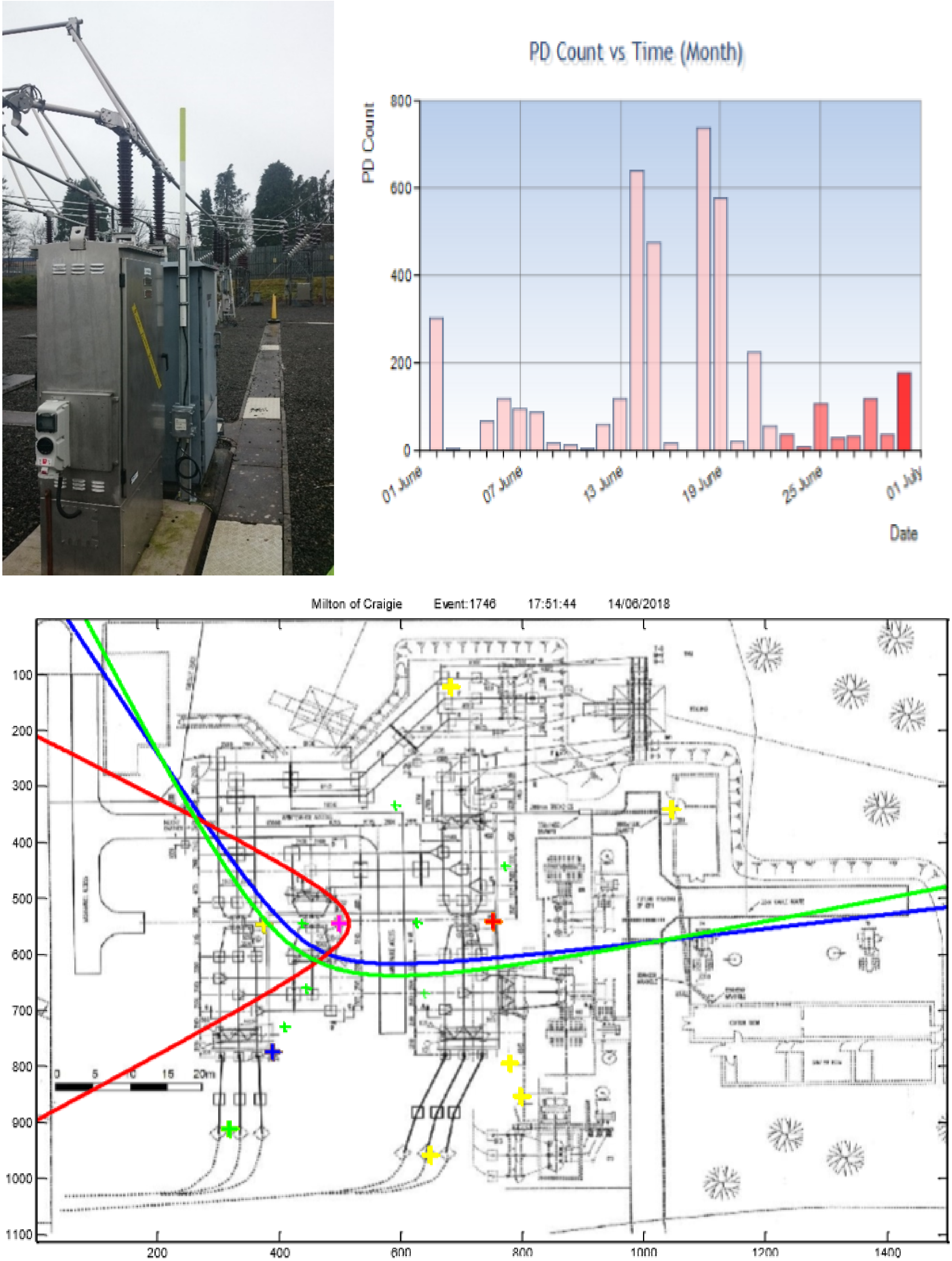

Figure 1. Aerial (white and yellow brush pole) monitoring PD (top left), PD count during June 2018 (top right), mapping the events to pin-point equipment emitting PD (bottom)

3.2 NIA_SHET_0018 Transformer Intrascope Phase 2

Start Date: November 2015

Duration: 37 months

Description:
The transformer intrascope system has been developed in phase 1 of this project as an asset management tool to assist with the condition assessment of internal paper winding insulation within electrical power transformers. It is in the form of a controllable probe which can be inserted through the hatch of a defective transformer to analyse the chemical composition of the Kraft paper insulation to assess the health of the asset in situ.

This project seeks to improve upon and overcome the limitations of the phase 1 design to allow for better access, physical range, positional control and visual imaging capability, whilst accepting any improvements that can also be made to spectroscopic measurements. The scope of the project is to have a fully refined, assembled and functional intrascope probe system which has been both mechanically and functionally proven within a laboratory-based environment and via field trials.

Expected Benefits:
- Correlation with and increased confidence in using existing methods such as dissolved gas analysis of insulation oil for condition assessment of power transformers;
- Maximising the operation of existing transformer assets by delaying expensive asset replacement;
- Collection and storage of retrievable, reliable and potentially improved condition information of our existing fleet of transformer assets;
- The system can be used as a lower cost tool for investigation of commissioned, faulted and decommissioned out-of-service transformer assets compared with conventional off-site transformer de-tanking;
- Increased confidence in the condition of transformer assets connected to the network.

Progress:
The project has progressed with the completion of field trials and closedown. The field trials identified that further development of the intrascope launch mechanism and articulation methods is required in order to progress to BAU deployment. Further details can be found in the closedown report.

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Figure 2. Accessing transformer windings with Phase 2 intrascope prototype

3.3 NIA_SHET_0020 Remote Asset INertial Monitoring & Alerting Network (RAINMAN)

Start Date: July 2016

Duration: 44 months

Description:
This project is trialling a new alert system to establish if timely, reliable and accurate warnings can be provided for sudden and small incremental movements of wooden poles. The project also aims to demonstrate the viability of low power wide area wireless communications for hostile, hard to reach areas. In addition, a resilient autonomous power source will be developed to provide lasting power for the sensors installed on the poles.

Expected Benefits:
This project has the potential to address the challenges associated with pin-pointing deteriorating poles and also significantly off-centre poles following a storm, in hard to access locations. The 132kV Trident line which runs across Skye was chosen to trial RAINMAN as it is very representative of the rural and mountainous terrain of the SSEN network. Being able to monitor the poles for signs of flexing and lean distortion will help focus mitigation measures therefore preventing permanent failure. In addition, where

sudden pole movement is detected and needs immediate intervention, response teams will be able to quickly identify which poles are affected and get to them quickly, rather than relying on walking foot patrols to identify problem poles. There is potential to significantly reduce the time associated with pole damage faults which cause circuit outages.

Progress:
During 2018/19 additional data collection gateways have been installed, unfortunately this has not increased the movement notifications being received from the pole mounted units. The communication medium LoRaWAN which is a wireless low power wide area principle works well, however it's the pole mounted monitoring units which are susceptible to water ingress that are increasingly becoming intermittent in responding. Modification to the pole mounted units has incurred and monitoring is underway to determine their life span.

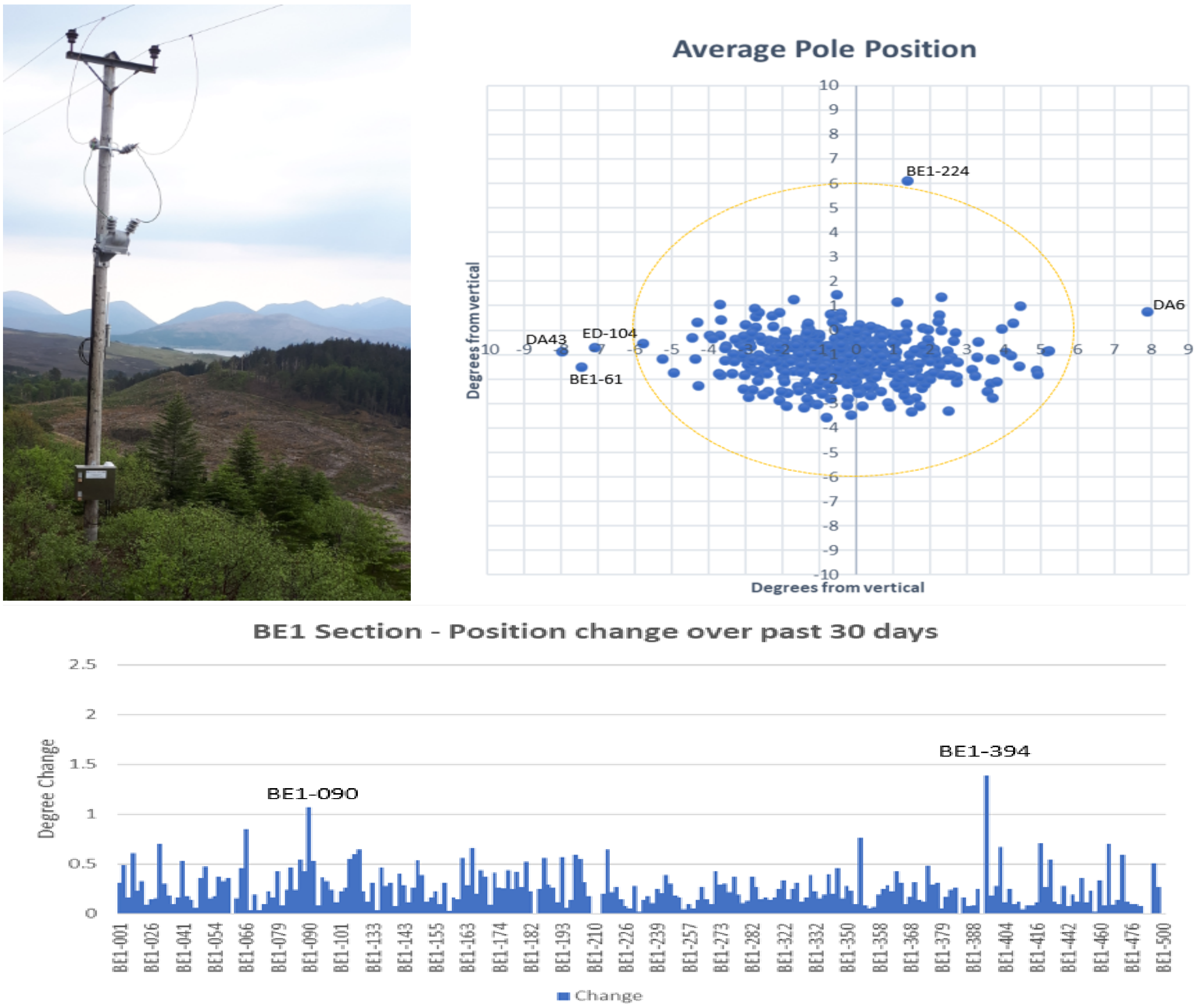

Figure 3. Pole mounted gateway install on Raasay (top left), monthly summary of pole movement (top right) and a summary of the change in pole position over the month (bottom)

3.4 NIA_SHET_0021 Composite Core (ACCC) Inspection

Start Date: December 2016

Duration: 24 months

Description:
This project is a technical method to develop a carbon fibre inspection prototype. This is the first stage in the eventual development of a tool that can be incorporated into on-conductor travelling devices for routine inspection of strung Aluminium Conductor Composite Core (ACCC) in commission.

Expected Benefits:
A tool for validating the integrity of the ACCC composite core at commissioning and in service with the main benefit being the wider adoption of ACCC, which will enable more current to flow in the circuit without the requirement for new tower infrastructure.

Progress:
The project has concluded that non-destructive testing (NDT) technique known as Laser Shearography has been identified as the most effective technique for detecting defects on the ACCC conductor. The equipment developed so far as part of this project would be of greatest benefit situated prior to the carbon fibre being stranded with metal, as it could easily be integrated into such systems in its current form. More work would be needed to package the sensing developed into in-service inspection devices. Further details about the approach and the outcomes of this project can be found under the highlights of the year section of this report.

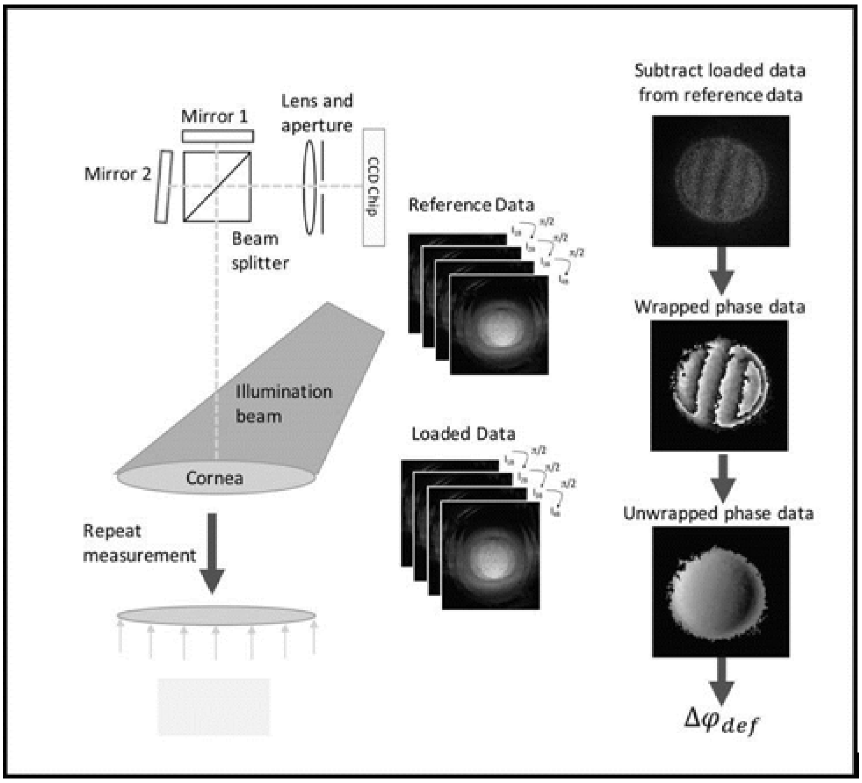

Figure 4. Shows how the raw data and processed data will be collected from the object

3.5 NIA_SHET_0022 Transmission System Fault Level Monitoring

Start Date: June 2017

Duration: 18 months

Description:
This project will explore passive fault level monitoring via comparing actual transmission fault current calculations and observed fault current values.

Expected Benefits:
With the natural developments of the electricity network, initial investigation suggests that the amplitude of fault current will reduce, however our present protection instrumentation which trips the electricity supply is set to respond to a sudden high spike in current. Monitoring the network for intermediary rises in current will help determine as to whether the amplitude of fault current is reducing and if so will provide data to help formulate mitigation measures.

Progress:
Specially designed power quality monitoring equipment was successfully installed in two substations. Evaluating the data collected positively identified infrequent low-level current raises, however when viewed against other forms of fault level monitoring there are consistency concerns associated with the power quality monitoring and repeatability. On reviewing the material, it was concluded that there was insufficient justification to procure further power quality meters.

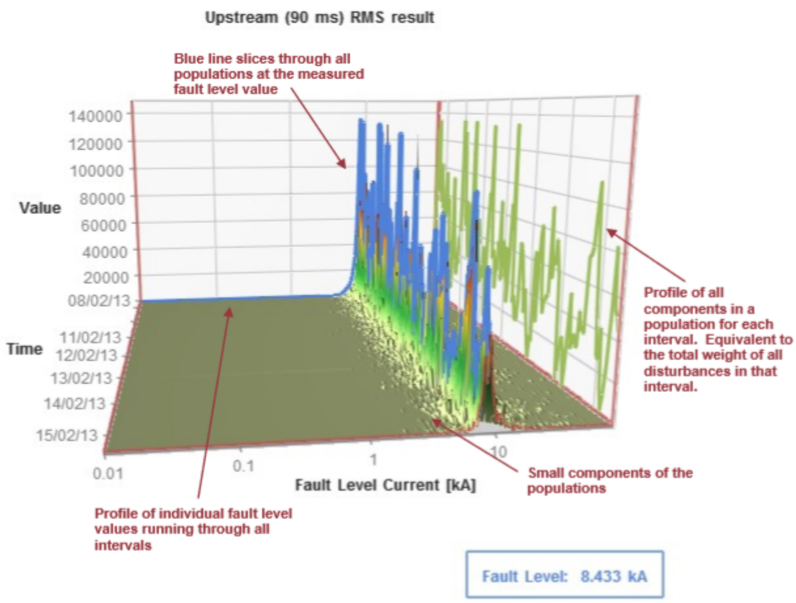

Figure 5. Power Quality low-level current raises

3.6 NIA_SHET_0023 Line Inspection by Semi-Autonomous Systems (LISAS)

Start Date: June 2018

Duration: 23 months

Description:
Accurate and consistent Overhead Line (OHL) Conductor and Lower Insulator condition data is difficult to obtain. Frequently, gathering this data requires climbing and working at height and, can be very costly in both operations and outage requirements. Present methods of testing and sampling can provide unrepresentative data. While drone and flight technology is providing increasing levels of data quality and quantity on Towers, Poles and fittings; the conductors cannot be monitored with this technology at present.

This project addresses the present challenges by investigating the use of a robotic device with onboard monitoring equipment, which can travel along the OHL without requiring continual human interfacing allowing the conductor to be accurately monitored with substantially more coverage. The SSEN networks have a high proportion of tension towers which prevents several of the monitoring devices presently in use in GB from operating as intended. Furthermore, the remote locations in which SSEN operates puts further constraints on any potential robotic technology, in that the device weight and support systems must be minimized and considered.

Expected Benefits:
- Proof of robotic devices traversing the electricity network assets in the GB electricity system
- Reduction in the personnel need for OHL inspection
- Increased frequency of inspection for OHL assets
- Reduction in customer interruptions due to better monitoring of assets
- Reduction in need for planned interruptions for line inspections

Progress:
The project has developed a functional specification for robotic devices that will be tendered for in the coming reporting period. Internal teams have been engaged in order to ensure that the specification will work for a range of use cases and in locations across the GB electricity network. A testing strategy has been developed and approved internally.

3.7 NIA_SHET_0024 Partial Discharge in HVDC Cables

Start Date: August 2018

Duration: 6 months

Description:
SSEN is investing significantly in High Voltage Direct Current (HVDC) cables and the trend is being replicated by the rest of GB industry. Like in Alternating Current (AC) cables, HVDC cables are susceptible to partial discharge (PD), which is the breakdown of a small part of insulation under high voltage stress. PD mechanisms in AC cables are well understood and mitigation techniques are largely mature. There is limited knowledge on PD in HVDC cables thereby necessitating this research to prepare for the growing use of HVDC.

Expected Benefits:

- Development in fundamental knowledge about how to detect PD under HVDC conditions
- Provision of a starting point for the development of monitoring techniques to protect high value HVDC investments from PD induced failures

Progress:
The laboratory investigations have been successfully completed with the accumulation of PD characteristics in HVDC cables. These have led to the presentation of five conference papers and one published journal paper with two datasets available from the laboratory experiments.

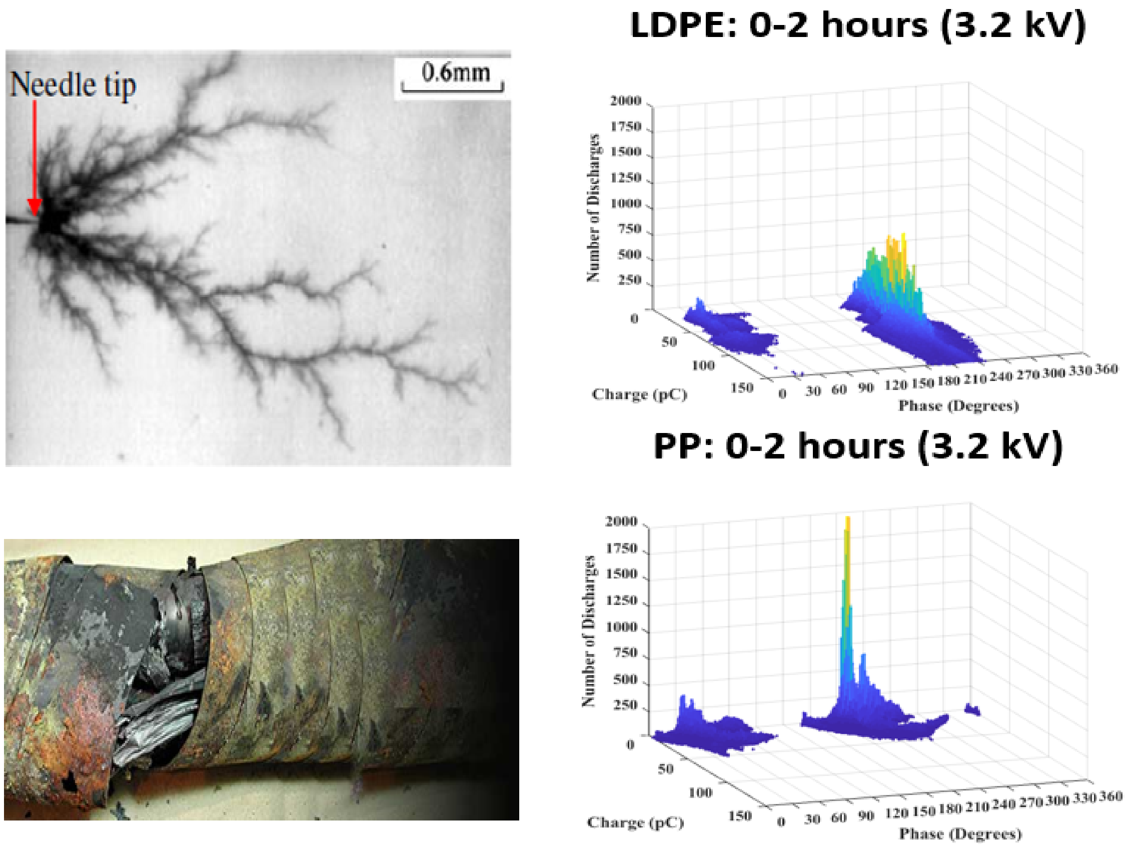

Figure 6. Electrical breakdown of a polymer (top left) and the resulting cable damage if left untreated (bottom left). Measuring PD in two different polymer insulation mediums via artificial voids (right)

3.8 NIA_SHET_0025 Zero Missing Phenomenon

Start Date: October 2018

Duration: 13 months

Description:
The use of shunt reactors in certain configurations to control voltage in networks with falling fault levels is leading to decaying zero missing phenomenon (ZMP) DC current problems. This happens when the fault current flowing through switchgear primary contacts fails to drop in amplitude to zero, the point at which switchgear contacts are designed to open to extinguish current safely. Since this phenomenon is

new and mainly arising from the evolution of the generation mix, its impact as well as potential mitigation are not yet fully understood. This project proposes a technical method that will involve engaging consultants to investigate the ZMP and produce conclusions that can impact the future of circuit breaker design

Expected Benefits:

- Improved understanding of the ZMP due to shunt reactor switching and the problems associated with it
- Gaining an understanding of the viability of technological and operational mitigation options for these problems

Progress:
A consultant has been appointed through a competitive process which saw various power systems experts in GB offering proposals for addressing the problem. Compilation of the findings from literature review is in progress.

3.9 Collaboration Projects

SSEN participates in the ENA Collaborative TO/SO quarterly meetings, this is an opportunity to obtain contacts and learning from existing NIA projects undertaken by others and if possible, offer support. SHE Transmission and Scottish Power Transmission (SPT) are collaborating on the ZMP and the SPT led Transient Recovery Voltage Investigation projects. In addition, this year SSEN has been supporting SPT by providing access to transmission pylons and climbing resource for the installation and on-going monitoring of the Elimpus Power Harvester. This project is of particular interest as a potential means of charging remote field mounted monitoring equipment, other than by batteries and solar cells.

Figure 7. Power Harvester installed (left) and the box transmitting temperature data which is also installed on the tower (right)

SSEN continually seeks out opportunities to collaborate with peers and captures knowledge with the potential to deliver value.

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4 Highlights of the year: Areas of Significant New Learning

SSEN Transmission have closed four projects in this reporting year:

- Transformer Intrascope Phase 2;
- Composite Core (ACCC) Inspection;
- Transmission System Fault Level Monitoring and
- Partial Discharge in HVDC Cables.

Three of projects where associated with testing monitoring equipment, in all cases the prototype devices have been further developed and learning gained from the trials undertaken. Unfortunately, none of the solutions will be progressed to business as usual presently, however disseminating the findings from the projects has created a platform to engage with the user community and gain an insight into pressing areas of concern and challenges associated with maintaining the system.

The partial discharge project associated with HVDC cables has produced key datasheets which will support further development of knowledge into this subject matter. SSEN in the future will be installing large quantities of HVDC cable and the learning from this project will inform operation and maintenance procedures.

Positively also, with the ongoing work looking forwards to RIIO-T2 the NIA Team have been asked about learning and opportunities from several older closed projects, as SSEN gears up for the new investment phase.

In the next sections, more details are provided on some of the significant learning which has been generated in the previous year by both closed and in-flight projects.

4.1 Looking outside the Utility Industry for Answers

The changing network make-up in GB is throwing new challenges for network operators. Demand for energy is growing and the pressure to connect unconventional generation sources is continuing unabated. However, there is also growing public sentiment against introduction of new infrastructure to support the requisite increases in capacity. Confronted by this conundrum, it has become pivotal for network operators to find a compromise through the optimisation of the existing power corridors for delivery of power where needed. SHE Transmission and their peers in GB have been looking at different options to increase power flows on existing circuits using methods such as dynamic line ratings, insulated crossarms, high temperature low sag conductors etc. The greatest attraction to each of the foregoing methods is the potential for capacity increases without complete rebuilding of network infrastructure, an obvious preference to address public concerns. Of those methods, one of the most effective ways of providing a step change in network capacity is the reconductoring of circuits with new higher capacity conductors on existing structures. Amongst the conductors on the market, there has been gradual increase in the use of Aluminium Conductor Composite Core (ACCC). SHE Transmission first trialled the Oslo variant of ACCC in an Innovation Funding Incentive (IFI) project in 2010. Subsequently, a few projects have now been completed in business as usual using other ACCC conductor variants. This growing use of ACCC, and the potential to leverage its benefits in future projects, have motivated SHE Transmission to embark on the just completed project ‘ACCC Composite Core Inspection’. This project was necessitated by a limitation which may discourage wider adoption of ACCC, which is the lack of a non-intrusive means of inspecting the integrity of the conductor strength element once it’s installed. SHE Transmission’s aim is to have tools for managing the life cycle of ACCC which work in a like-for-like way to the ones on conventional conductor types already in existence. The rest of this highlight provides greater detail into how SHE Transmission and the rest of the industry have been managing the existing conventional conductors and how that experience has been shaping the development of methods to manage ACCC, which is significantly different in its form.

Conventional overhead line conductors and their management

Traditionally, transmission overhead line towers have been strung with Aluminium conductors of different varieties. Aluminium is used because of favourable cost and low weight compared to copper. In addition, it is generally stable against corrosion as it tends to undergo corrosion passivation which provides it with a protective layer that shields it from further deterioration. However, aluminium is too soft to provide the required tensile strength when strung and for that reason, a strength member of a different material is usually added to it for strength and stiffness. The combined conductor has both high conductivity and mechanical strength to withstand the elements. An increase of tensile strength and associated reduced sags enables use of fewer structures and longer spans. Probably the most commonly used conductor in transmission networks to date is Aluminium Conductor Steel Reinforced (ACSR). ACSR is a concentric-lay-stranded conductor. Stranded conductors consist of a straight centre core surrounded by one or more layers of helically wound wires. ACSR has a steel core for strength, surrounded by several concentric layers of round wire, as shown in the image below:

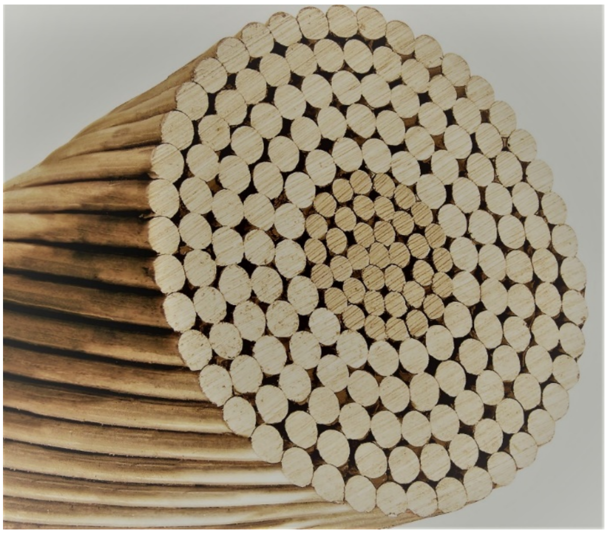

Figure 8. Cross-sectional view of the ACSR conductor

ACSR is a popular conductor but it is not immune to degradation modes such as broken strands, deterioration of joints and loss of material strength. The sources of degradation include mechanical loads, electrical loads, corrosion and vandalism resulting in broken conductor, conductor which does not maintain required safety clearances or a conductor with excessive electrical losses. However, the major limiting factor to the life of ACSR is internal corrosion. Steel, the material used to provide tensile strength in ACSR, has low resistance to corrosion. To mitigate this, steel strands are therefore typically galvanised with a layer of zinc to provide protection. ACSR can deteriorate very quickly due to loss of zinc on the steel core strands. This is usually caused by galvanic corrosion which occurs when two dissimilar metals are brought together in the presence of moisture and an electric potential. One metal becomes an anode while the other becomes a cathode. An anode, in contact with a non-metallic material (the electrolyte) easily gives up electrons to the cathode. Once this relationship commences, the corrosion of the anode takes place very quickly whilst that of the cathode all but stops. In ACSR conductor, under no ingress of moisture and with the galvanising intact, the zinc layer is the anode and the aluminium is the cathode. However, when an aqueous solution with ions manages to penetrate between the aluminium strands it can then attack the galvanising on the steel core. This corrosion of the galvanising ultimately reveals the steel substrate thereby forming a galvanic couple between aluminium and the steel strands. This coupling creates an anode-cathode relationship which rapidly corrodes aluminium into Aluminium Hydroxide, a whitish powdery substance. This usually causes strand breakage, reduced ampacity and eventual loss of mechanical strength.

Although the challenges just stated above affect ACSR conductor, there are ways of mitigating them. For instance, to reduce the chances of zinc galvanising loss, a conductor may be greased within the strands up to the penultimate layer to provide additional protection. Grease keeps out corrosive contaminants and foreign materials which may exacerbate the degradation of zinc. It is important to point out that the grease is only put up to the penultimate layer to stop it leaking outside the strands and becoming a trap for dusty particulates which may cause problems such as corona on the conductor on the conductor surface.

While in service, there are several inspection methods that can be deployed to establish the integrity of the ACSR conductor. Visual inspection can take place either from the ground or from an aerial vehicle such as a helicopter or drone. The most common defects detected by this method are:

- Bird caging
- Raised strands
- Burn marks
- Surface discolouration
- Excessive sag
- Broken strands
- Joint or connector deformities

There are limits to the extent to which defects can be detected via visual inspection. For instance, corrosion is only detectable if it's advanced to a point at which aluminium hydroxide powder is visible on the surface. In most cases, corrosion would either be detected via a form of non-destructive testing (NDT) or the removal of a representative jumper from a strain point on the line for lab inspection. The latter method assumes that adjacent sections of the conductor are likely to be exposed to the same prevailing conditions and would therefore be susceptible to the same degradation sources. This way of assessing condition is invasive and costly for network operators. In mitigation, it is widely deemed that a more optimal solution is the use of NDT. NDT is an examination carried out in a way that that does not change or destroy the subject component's usefulness. It is a useful tool for cost reduction, improvement of component reliability, accident prevention, a means of determining acceptance for given requirement and provision of information on repair criteria. It can take different forms including visual, thermography or other waveform-based methods. NDT tools can be used as predictive tools which quantify the extent of defects or screening tools for identifying defects without specifically quantifying them. For ACSR, one of the most common NDT approaches is the use of devices that travel along the conductor continuously assessing the entire length of the conductor section covered. These devices are based on different principles, but the most commonly used device in SHE Transmission is based on eddy current testing.

Eddy current testing exploits the electromagnetic induction principle for the detection and characterisation of surface or sub-surface flaws, conductivity measurements and coating thickness measurements. In this testing, a coil of conductive wire is excited by connecting it to a source of alternating electric current. This causes the coil to produce an alternating magnetic flux which oscillates at the same frequency as the current flowing through it. If such a coil is placed near a conductive material, circulating eddy currents are induced in that material. Eddy currents tend to oppose the current causing them (in the coil) and the interaction between the two currents reflects on the electrical parameters of the coil. The flow of eddy currents is dependent on a material's conductivity, permeability and dimensions. If the material to which the eddy currents are induced is homogeneous, then a constant impedance can be measured in the electrical coil. Conversely, any imperfections on the subject material will cause a change in the phase and amplitude of the eddy currents which can be quantified through the measurement of impedance on the coil. Due to the skin effect phenomenon associated with alternating current, eddy current testing is only effective at small sub-surface depths thereby limiting the range of testing applications. It is however much suited for detecting galvanic corrosion where the galvanising is only a very thin layer on the outer surface of the steel core. In ACSR, this technique has over the years mainly been implemented through the CORMON overhead line corrosion detector.

The Cormon device travels along the conductor and consists of an electronic unit and a split-hollow cylinder sensing head which clamps around the conductor. The sensing head is made up of two pairs of coils. The first coil is supplied with a high frequency current which produces a magnetic field that penetrates the conductor and induces eddy currents on the strands. The high frequency flux generated is picked up by the second coil as an induced voltage. The electronic unit splits up the induced voltage in the pick-up coil into its in-phase and quadrature components. A change in the phase and amplitude of the sensing coil output is detected for any slight loss in the layer of zinc galvanising on the conductor core. The only limitation of this technology is that it is deemed to be one-dimensional since all it shows is the loss of zinc. Another version of eddy current based detector from Shannon Technology, the conductor corrosion assessment system (CCAS), goes a little further than just loss of zinc to support overall conductor condition and remaining service life which can be used to make investment decisions for overhead lines.

The section above highlights the maturity of ACSR conductor, and similar conductor types, and their life cycle management. However, the same properties which gives the conductor the stated maturity also makes it less than ideal for addressing the challenges introduced by the evolution of electricity generation sources. Addressing these challenges has driven adoption of alternative conductor types such as ACCC. The remaining section in this highlight covers in more detail why ACCC has become a preferred conductor of the future, how its make-up renders the roving device NDT described in the foregoing paragraphs unfeasible and what has been done in the 'ACCC Composite Core Inspection' project to establish a bespoke solution.

New conductor approaches

ACCC is a new type of overhead line high capacity low sag (HCLS) conductor. As stated already, this conductor is addressing the challenges brought about by changes in the way energy is delivered. These new challenges require conductors that can operate at higher capacities combined with reduced sagging to maintain statutory clearances from ground. Over the years, most newly introduced conductors have mainly been high temperature low sag (HTLS). By operating at higher temperatures, they were able to increase network capacity without a penalty on clearances, but they have had the slight disadvantage of increasing line losses. Unlike ACSR described previously, ACCC uses rather complex materials for its tensile strength as can be seen in the image of the cross section of an ACCC conductor.

Figure 9. Cross-sectional view of the ACCC conductor

Some of the elements visible in Figure 9 and the engineering of the conductor give the ACCC conductor the following attributes:

- The conductor has a hollow composite core of glass and carbon fibre with a high strength to weight ratio and low coefficient of thermal expansion (four times lower than steel). The core has 1.3 times the tensile strength of steel. These attributes give the conductor the low thermal sag properties even at significantly high temperatures. The thin glass fibre/epoxy composite sheath at the core-conductor interface isolates the aluminium from the carbon to prevent galvanic reaction.
- The light weight of the ACCC core allows more conductor for the same weight thereby enabling lines to be reconductored without the need to reinforce structures
- ACCC strands are trapezoidal which packs and increases the cross-sectional area of aluminium, unlike conductors with round strands which have interstitial gaps between strands. For a like-for-like conventional conductor diameter, this increases ampacity while maintaining a diameter without a corresponding increase in potential wind loading
- The strands are made of annealed Typed 1350-O Aluminium. Annealing improves conductivity leading to greater efficiency which enables cooler conductor operation under high load conditions. This confers the conductor with the ‘high capacity’ attribute and is responsible for the minimal line losses associated with the conductor.

The advantages of ACCC can be leveraged to support the connection of renewable generation sources. However, the lifecycle management of overhead lines strung with ACCC is currently challenged by the lack of a means to verify the integrity of the carbon core after stringing. The NDT tests which are possible on conventional conductors such as ACSR are not feasible on ACCC’s non-metallic carbon core. Although to date, most ACCC faults appear to be linked with poor installation technique, there is a growing interest for situational awareness of assets which makes the need for a retrospective system of inspecting ACCC essential. To get the quoted life expectancy of the cable, understanding of the structural deterioration with time is essential. It was therefore crucial for SHE Transmission to participate in the identification of a solution that would be comparable to solutions in existence for inspection of conventional conductors. To address the problem, SHE Transmission worked with Transmission and Distribution Innovations Ltd and Laser Optical Engineering (LOE) to develop a potential solution that took learning from the shipping industry. In the project that ensued, there was controlled staging of the work to enable close monitoring of concept viability. The first stage was to develop the sensor which would be able to detect defects on the exposed carbon core. The output of that stage would have the potential to be used by the core manufacturer to ascertain the quality of the conductor or by the stranding organisations to ensure that the core was fit for purpose prior to stranding. That would then be followed by developing the ability to detect defects on a stranded conductor. The output of the work would ultimately be integrated into travelling devices to enable assessment of the conductor in service. The project has so far successfully achieved the aims of the two stages demonstrated by laboratory prototypes. Future work will be required to integrate the sensing into travelling devices. In the following paragraphs, further details about the work and the project outcomes are shared, starting with a look at the anticipated failures which the developed method was looking to prevent.

Anticipated ACCC failure modes

The first, and most crucial stage in identifying ways to address the detection of defects on ACCC was to first understand the failure modes and mechanisms of ACCC. Potential issues on the carbon core's integrity are likely to be introduced in transportation, handling as well as poor artisanship. Carbon fibre defects are almost undetectable and can easily propagate due to mode of loading, service environment and fibre interfacial bond strength. Carbon fibre can also suffer from delamination, whereby cracks occur between adjacent plies, usually from an impact. Delamination can occur several plies beneath the surface thereby making it go unnoticed. One potential source of ACCC failure is bending the core below the critical bend radius which can lead to fibre kinking and potential splitting. All these issues may not be conspicuous at installation thereby potentially causing issues once the conductor is in service. Once in service, the conductor may be susceptible to failure because of low frequency Aeolian vibration at mechanical connections. This is most likely to be caused by improper attachment of terminations thereby introducing new bending stresses. All the foregoing point to the need to inspect the conductor in service. Although ACCC is rated at 180 degrees C, some lab testing has indicated some degradation under sustained operation at such high temperatures. This issue may require a de-rating policy to prevent the degradation. Furthermore, the annealing process, while advantageous for conductivity and sag performance, makes aluminium rather too soft and difficult to handle. In addition, the ductility from annealing means that any failure of the core would result in conductor breakage since the aluminium is entirely dependent on the core for tensile strength. The solutions developed in this project so far tended to focus on the defects that are likely to result from handling or installation issues that can be detected at the commissioning. The next section looks at this solution, called Laser Shearography.

Laser Shearography

This project used Electronic Speckle Pattern Shearing Interferometry (ESPSI), also known as Laser Speckle Interferometry (LSI). In this project, this technique is simply named 'Laser Shearography' and is a technique for measuring the rate of change of displacement, or strain on the ACCC core. The full ESPSI naming of the technique helps to be more descriptive of how this method works in practice and a look at different words in the phrase demonstrates that. A speckle is a spot or mark that is distinct from the surface or background on which it exists. Shearing takes place when something breaks off owing to a structural strain. The physics definition of interference is the superposition of two or more waves to form a resultant wave of greater, lower or similar amplitude. Interferometry is therefore a technique of superimposing electromagnetic waves, thereby causing interference which is used for extracting information.

When the rough surface of an object is illuminated by an expanded laser beam, a granular pattern, or laser speckle, can be discerned through an observation lens. This pattern is unique to the object surface and will vary if either the object, the illuminating beam or the observation lens are moved. If an object being illuminated undergoes some deformation, with the illumination source and observation lens unchanged, then a new unique speckle pattern is generated. Through continuous monitoring of performance of an object under loading and evaluating it against expected performance, a structural defect can be highlighted immediately. Historically, the method involved first recording an object's speckle pattern thereby creating a reference image. The speckle pattern of the deformed image would then be electronically combined with the reference image to produce computer generated fringes. As the object's loading changes, each subsequent speckle pattern (data point) would be digitally compared with the reference image in real time such that changes in displacement could be observed as movements in the fringes across the object. With the initial load known, the difference from the initial status could be quantified to ascertain the severity of a deformity. This approach, known as the Electronic Speckle Pattern Interferometry (ESPI) had some limitations. The fringe numbers were too great and there was less usefulness in deciphering displacement maps as opposed to rates of change of displacement. This is because obtaining information from numerical differentiation of interferometric data is inherently susceptible to noise.

To address some of the ESPI technique's issues raised above, LOE exploit laser Shearography using a set-up they call Defect Dtect which mitigates the issues by optically differentiating the data prior to digital imaging. The image below shows this set-up.

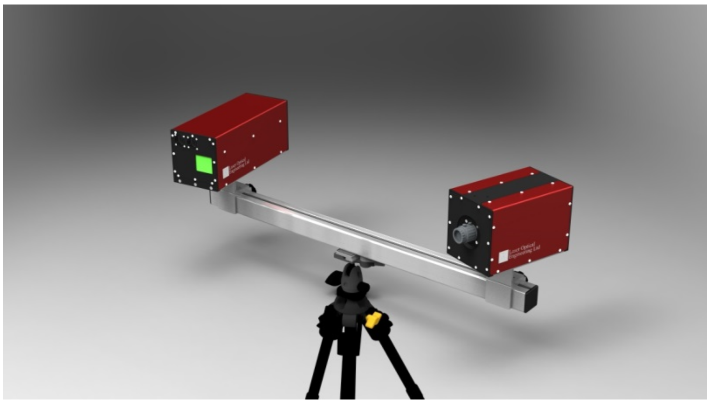

Figure 10. LOE Standard Defect Dtect set-up

As can be seen in the figure above, the unit on the left is the laser source which illuminates the test object and the unit on the right is the interferometer which captures the reflected image. Using this set-up, the wavefront of the test object is split into two parts, one part of which is transformed before the two wavefronts are recombined to give a specific speckle interference pattern in the reference state. This reduces sensitivity to environmental or background noise since such noise is registered in both the image and its transformed copy. To map the strain information, this process is repeated with some load applied to the test object and the images are then digitally subtracted from one another to give an interferogram which contains the fringes that reflect the strain contours from the loading. The interferograms show the rate of change of displacement (strain), although, if of interest, displacement can also be obtained through the integration of the shearing fringe pattern results.

The information from the interferograms would require significant expertise to interpret. However, using appropriate software, the results can be displayed in a readable format. Such formats may include images and graphical plots where strain can be exhibited by a steep rate of change of displacement. For homogeneous objects which retain uniformity in different orientations, it is inherent that the strain manifested in response to a load in a certain direction is uniform. Any loss of such uniformity suggests damage to an object and that's what is inferred from the interferograms. It is this improved method which has been used to demonstrate the detection of damage on exposed carbon core. During the test of the core, defects were simulated in the lab and the Defect Dtect used to identify them. The defects introduced included thermal loading, impact, crush and torsion damage. The pictures below show a couple of the results from the tests displayed visually for ease of interpretation.

Figure 11. Images of the results of detected impact damage induced by a hammer strike on the core.

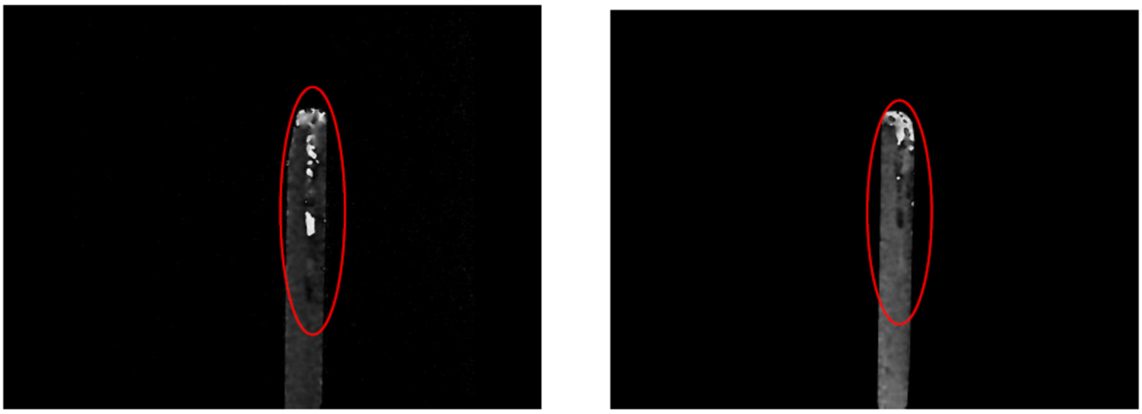

Figure 12. Images of results of detected crush damage induced by vice grip along the core centreline

This stage of work was able to conclude that local structural damage from thermal or mechanical loading could be found using Laser Shearography. The damage simulated was visible on the epoxy coating of the core but also created internal damage. This was identified as a limitation in the technique since any minor damage on the surface with minimal impact on the strength of the core would show up as a damaged area. A quantification of impact of this on the tensile strength of the core was deemed to be a more useful metric for making investment decisions. However, being outside the scope of the current project, after the first stage completed, the project moved on to look at the complete conductor i.e. core with aluminium stranding.

Experience was drawn from tests performed in the marine, aerospace and automotive carbon composites. The basic premise of the follow-on work was that since the carbon core is the sole tensile strength component of the cable, any weakness manifesting on the core would be transferred to the outer surface of the carbon core-soft tempered aluminium interface. This was supported by the view that the core and the aluminium strands have a physical intimacy that would reflect a defect on the core on the aluminium strands. To demonstrate this, a test rig was set up to be used with the Defect Dtect system. The following image is the artist impression of the experimental set up.

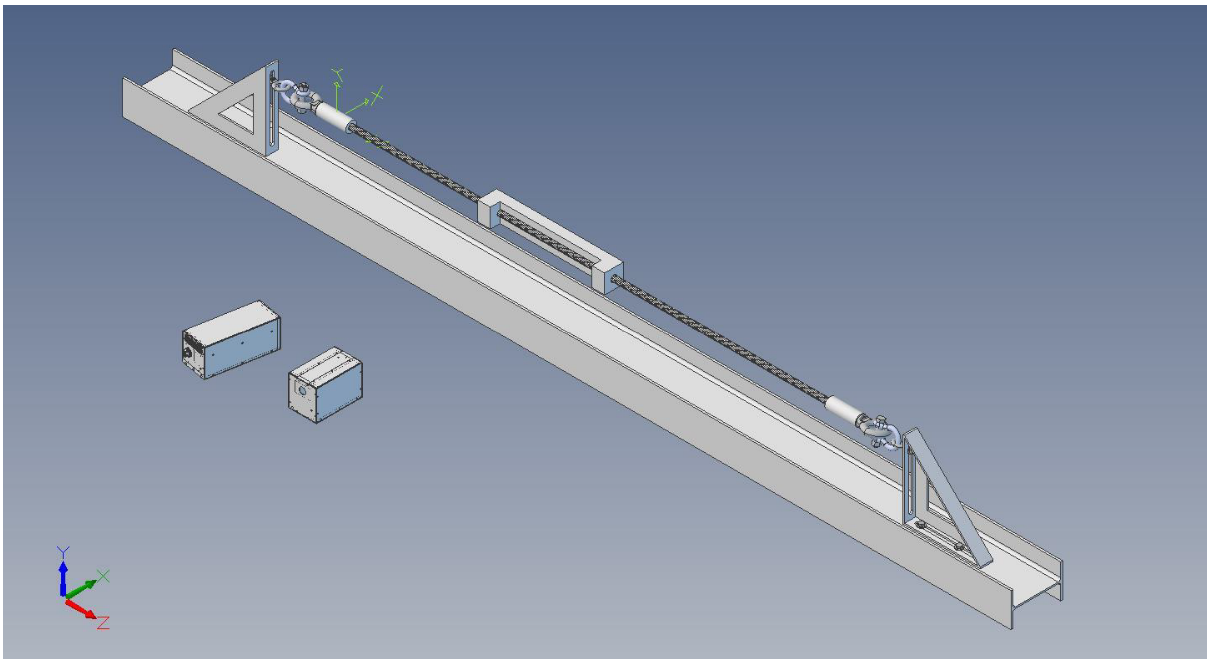

Figure 13. Drawing of the test rig for testing composite ACCC conductor

The approach to the rig was to simulate an ACCC conductor tensioned as anticipated in the real field between structures. The prototype inspection device (Defect Dtect) would then be mounted on a travelling frame that could be moved along performing inspections of the conductor at different points between the two ends. The frame housing the Dtect would also incorporate a means of performing the three-point bend test to apply some load onto the conductor. This was achieved by putting the conductor through two nylon rollers (two bends) with a central piezoelectric actuator applying an 9-micrometre displacement to the conductor during the test. The image below shows the picture of the actual prototype set-up.

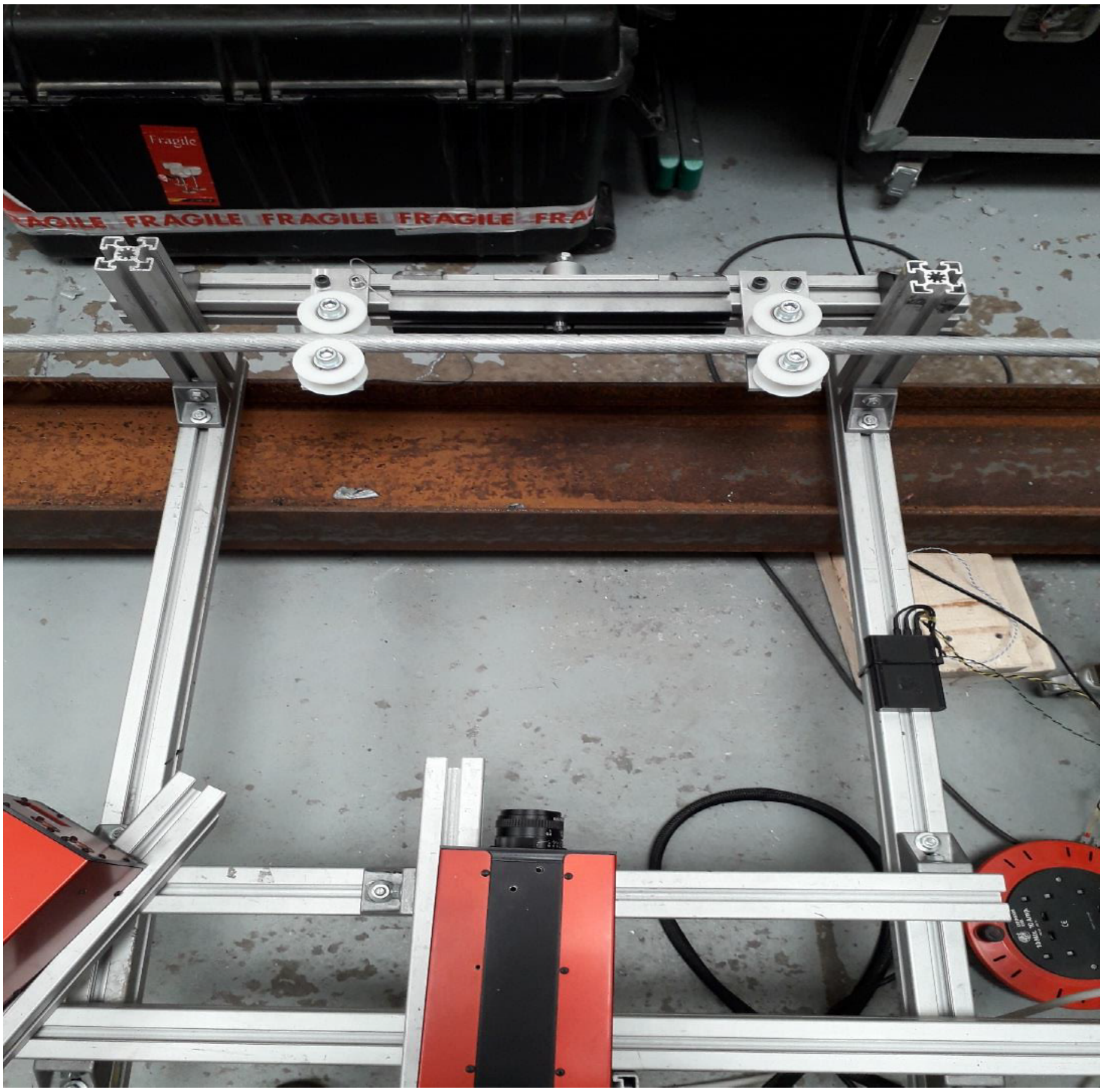

Figure 14. Image of the Defect Dtect with simulated ACCC conductor sample under three-point bending set-up

Once the rig had been set up, defects were deliberately introduced in the carbon core of the ACCC conductor samples before being replaced into the conductor.

The tests concluded that the damage introduced in the core of the 8m length conductor could be detected by the roving device prototype. The following are two images which show the visual outputs of an undamaged core versus those of a damaged one.

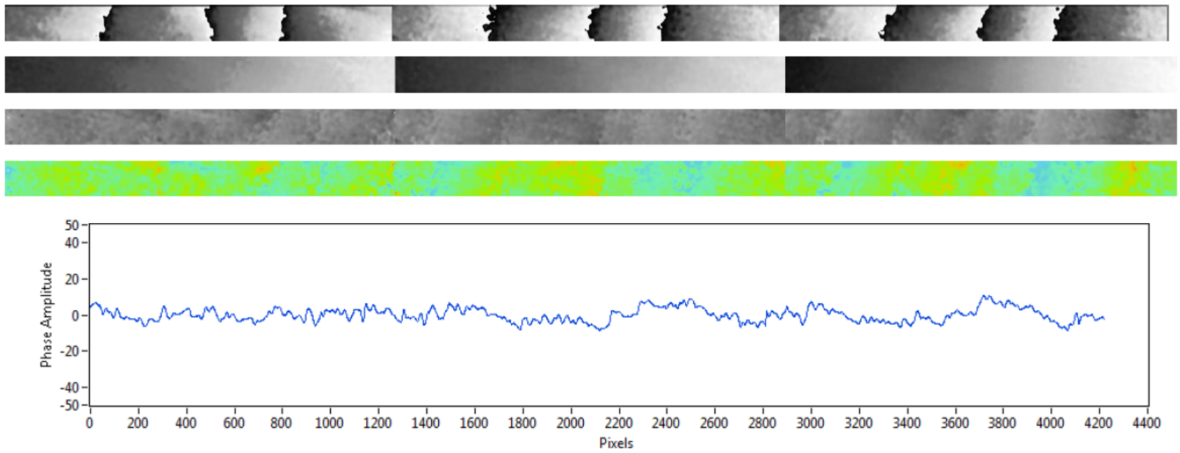

Figure 15. Results of the detection of ACCC conductor with an undamaged sample of carbon core

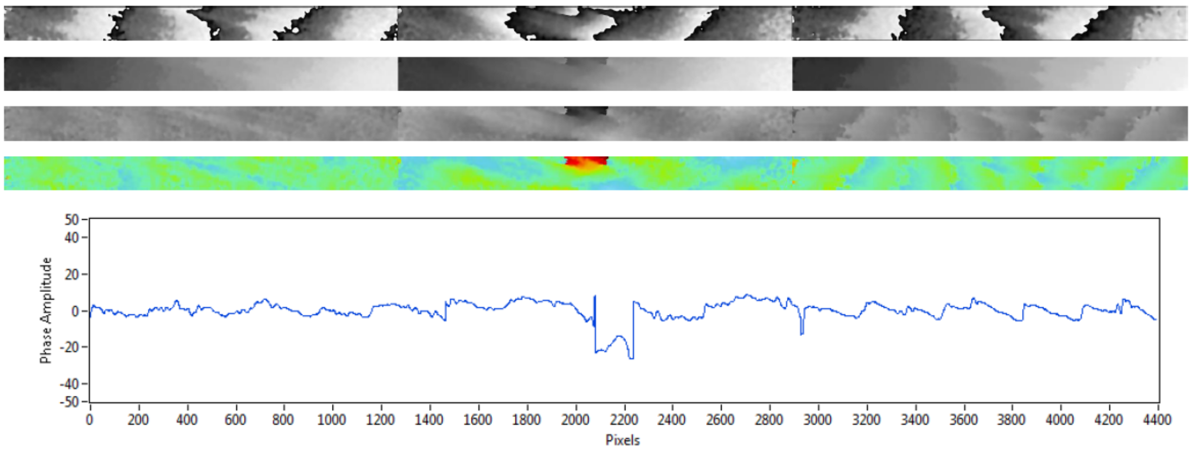

Figure 16. Results of the detection of an ACCC conductor with a core cut to a quarter depth and bent around radius approximately 800mm

Conclusions

The project has demonstrated that most of the defects on the core of the ACCC conductors can be detected on both the exposed core and on a stranded conductor. The project has successfully moved the technology to a higher technology readiness level. However, to get to a business as usual stage, more work is still necessary. The requirements for a travelling device have been established in the completed phase but the developed sensors will need to be packaged onto either an existing device or a bespoke robot. In addition, to glean more meaningful information regarding conductor condition at inspection, more research is needed to corelate the different damages with reduction in the ultimate tensile strength of the conductor. All these activities are likely to form part of future work on this subject.

4.2 The realities of ‘being on trend’

Over the last year event flyers have often made reference to the ‘Internet of Things’ or ‘IoT’ for short, as an up-coming technology. SSEN’s RainMan project is leading the way with the placement of 800 IoT units on the 132kV Skye Wood Pole Trident line. The IoT is simply a field mounted monitoring sensor and in the case of RainMan the aim was to create an early warning movement detection system for a pole snap.

The Skye Trident line was selected as it is SSENs longest 132kV wooden pole line covering 70km, crossing mountainous terrain which makes physically walking the line a time-consuming challenge. On average, once every three years there is a pole snap on the Skye 132kV Trident line, therefore trialling a system that could pin-point the pole snap has potential benefits, such as highlighting sections of overhead line to be visited first based on movement detection.
RainMan is on trend, but with that comes significant learning and knowledge sharing opportunities alongside a mountain of challenges.

The IoT

It uses the same technology as a mobile phone to detect changes in the movement, within a protype being housed in an IP67 rated box, with a 5.6 Ah lithium battery and 2-watt solar cell. **Figure 17**. shows several pictures of the pole mounted box. In isolation, the box and each element worked previously with impeccable reliability, interestingly combining the elements has introduced hurdles and after 18month plus of operation 35% of the boxes correspond intermittently.

Figure 17. Shows the RainMan prototype IoT

Communication between IoT & Gateways

Traditional information between remote locations and a collection point can be sent cheaply by using radio; this has limitations as a communication licence is required and the signal can only travel up to 8km in line-of-sight. At the start of the RainMan project, a significant amount of time was invested into looking at other forms of communication, which led to the selection of LoRaWAN, a Low Power, Wide Area networking protocol. LoRaWAN does not require a transmission licence for small packages of data transfer, it's capable of bi-directional communications, it uses a very small amount of energy to send the data and the information can be encrypted end-to-end. **Figure 18**. illustrates the LoRaWAN network.

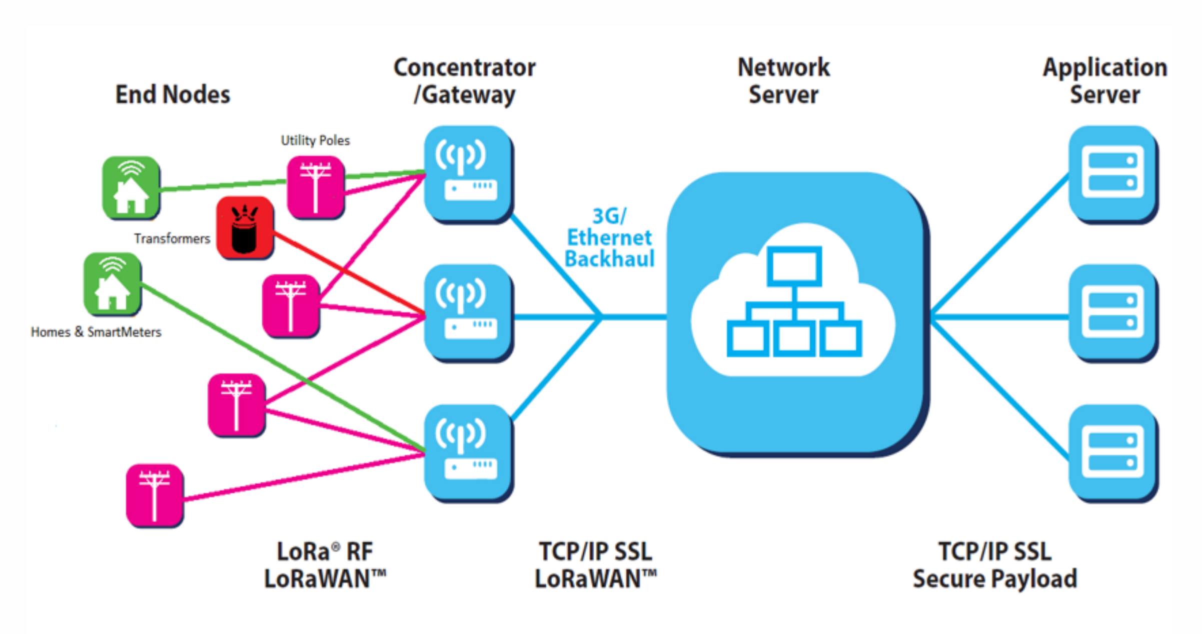

Figure 18. LoRaWAN topology

RainMan is the first IoT system in GB to utilise LoRaWAN, the 800 IoT units transfer their data via LoRaWAN initially to six LoRaWAN collection gateways. The furthest transmission of data has been 52km, below in Figure 19. Highlights the signals pathways being received at the Applecross collection gateway which is 25km from Broadford, Isle of Skye.

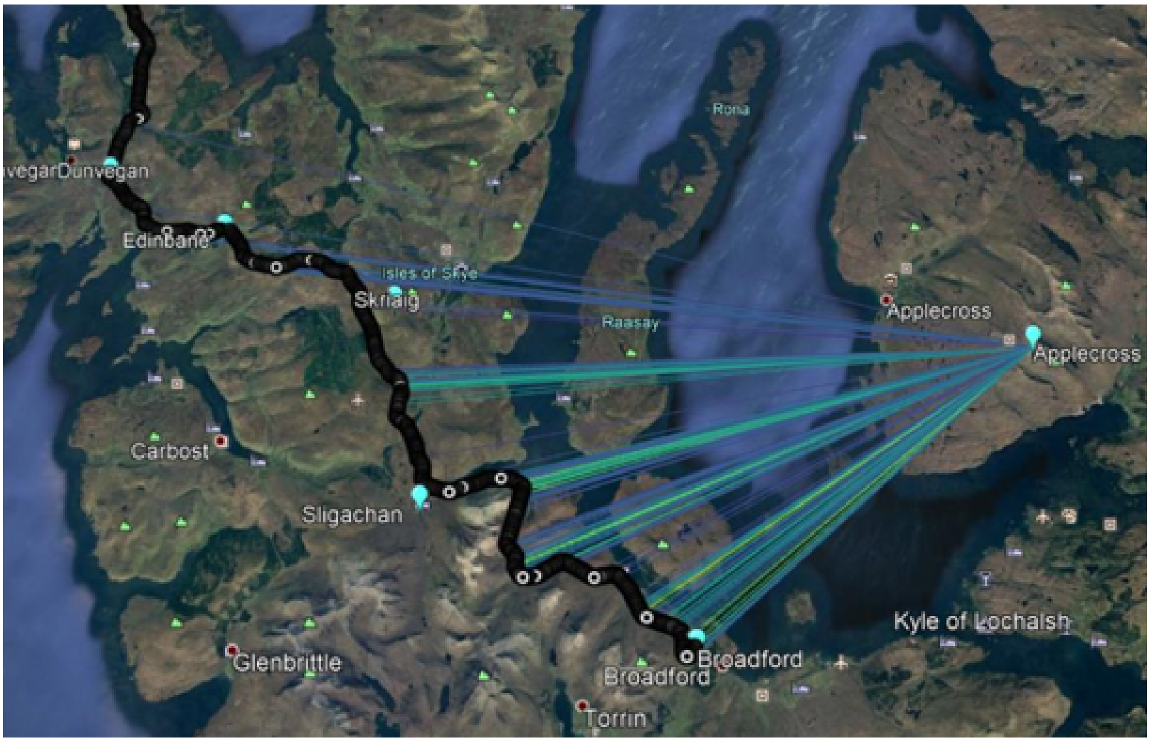

Figure 19. Signal being received at Applecross

LoRaWAN is proving to be a reliable communications medium, its low power requirements mean that the IoT can be fitted remotely with no maintenance requirements for a period up to 10 years.

Auxiliary Power Source for Gateways

The collection gateways require a constant form of auxiliary power and two of the more unusual ways this has been achieved is a stand-alone combined renewable and battery powered solution and power tapped form an 11kV overhead line, shown below in **Figure 20**.

Scottish & Southern Electricity Networks

Figure 20. Left-hand picture is the stand-alone gateway powered by a solar panel, a vertical wind turbine and a car battery and the right-hand picture shows power tapped using a voltage transformer to feed a pole mounted gateway.

The Things Network

The 'things network' is the way in which the remote field information from the pole mounted IoT movement sensors is viewable on the internet. At a glance it is possible to see the pole status;

- Green – information has been received in the last 24hrs, the pole is healthy
- Yellow – information within the last 24hrs indicates that the pole is leaning between 10-25 degrees
- Red – information within the last 24hrs indicates that the pole is leaning greater than 25 degrees
- Black – no information has been received in the last 24hrs

The 'things network' is a helpful tool which enables information from the IoT pole data to be displayed; it also allows the battery life or position and lean of the pole to be viewed by selecting an active pin. The way in which the information is stored, and the viewing platform means that access to the web-viewer can be specifically assigned, there are positives as it presently by-passes internal hurdles associated with external information being incorporated within internal systems. Looking to the future, it's not practical to have a standalone web-viewer therefore investigation is underway with the SSEN Geographic Information System (GIS) Team to determine how the RainMan information could be displayed on their systems.

Figure 21. The 'Things Network' displaying the IoT pole mounted status

Incoming Volume of Data

The RainMan project primary goal is to pin-point the location of a broken pole, therefore within the pole mounted IoT the movement parameters have been set and if the motion exceeds the set parameters the device automatically records its status and sends in a notification. Given the trial nature of the RainMan project, the remote field IoT have also been set-up to transmit an hourly status report. On a calm weather day on average 19,000 data packages of information are sent, this can rise to above 500,000 data packages during a high wind event.
Given the volume of information coming in, work has been undertaken to evaluate what if any of the data is useful, the main findings are outlined below;

- It has been possible to monitor the trending lean of the poles over a year and identify the poles that do not self-correct;
- During high winds the poles move towards and away from each other and not side to side;
- The range of movement from a pole that has been 'back-stayed' (which is a wire support to reduce its movement) can be characterised, this can help identify were and what type of 'back-staying' would best suit presently 'non-back-stayed' poles;
- There is no movement correlation between the visual inspection grading of the pole and monitored motion, in other words a pole that is showing significant visual signs of aging does not mean the associated strength has been compromised; and
- Poles that have water logged footings record high volumes of up and down movement.

The Lightning Strike

On the 2nd March 2018, at 23.52 pole ED-043 was struck by lightning, the results of which can been seen in **Figure 22**. The pole that failed was not the one that had the pole mounted IoT attached. However, in assessing the movement information prior to and post the event, it was observed that the pitch of the pole (the orange dots in **Figure 23**.) were out of character. This event has been pivotal in the direction of the RainMan Project as it shows that pole snaps can occur and monitoring the lean of the pole alone may not correctly identify a broken pole. Work is now ongoing into building a data analytic tool that will compare movement information prior to and after an event.

Figure 22. The aftermath of a lightning strike

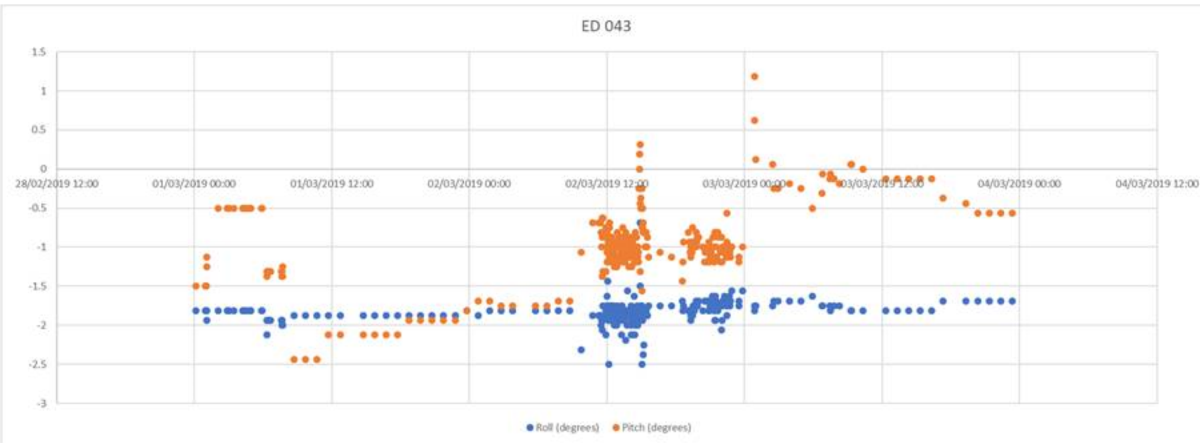

Figure 23. Pole movement before and after the lightning strike, the orange dots are out of character

5 Further Information

The complete SHE Transmission Innovation Strategy can be found on the link below:

2013 Transmission Innovation Strategy

The new SHE Transmission Innovation Strategy, published in March 2017 can be found on the link below:

[2017 Transmission Innovation Strategy]

Further details of all the NIA projects summarised above can be accessed through the following link:

[ENA Smarter Networks Portal - SSEN Projects]

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