WESTERN POWER DISTRIBUTION
INNOVATION

NEXT GENERATION NETWORKS

VOLTAGE CONTROL SYSTEM DEMONSTRATION PROJECT

CLOSEDOWN REPORT

Report Title	:	Voltage Control System Demonstrations Project Closedown Report
Report Status	:	Final
Project Ref	:	WPD_NIA_002
Date	:	29/07/2016

Document Control

	Name	Date
Prepared by:	Steven Gough	Western Power Distribution
Reviewed by:	Roger Hey	Western Power Distribution
Approved by:	Roger Hey	Western Power Distribution

Revision History

Date	Issue	Status
15/7/16	V1	15/7/16
29/7/16	V1.1	29/7/16

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DISCLAIMER

Glossary

Abbreviation	Term
D-SVC	Static VAr Compensator for Distribution Networks
D-VQC	Hitachi's Voltage and Reactive Power Control System
AVC	Automatic Voltage Control
LRT	Load Ratio Transformer

1. Executive Summary

This project was the successor to the Voltage Control System Demonstration Project which investigated a single Static VAr Compensator (D-SVC). The initial project established that the D-SVC could help control the voltage on the 11kV rural network by marginally reducing the absolute voltage and significantly helping to smooth the voltage profile. The project also highlighted the need of closer integration between the Hitachi systems and WPD's control systems along with the need to consider an innovative, reliable and high band width communication solution.

Phase 2 was intended to explore how multiple D-SVCs could be operated on the same HV network while still being optimised by a central control system, the D-VQC. This is an Hitachi system(Voltage and Reactive Power Control System) that it was planned would take data from multiple remote points of the network, process the state of the network through state estimation and dispatch set points to D-SVCs and influence the primary substation's bar voltage through the AVC relay.

There were key areas that needed to be investigated, picking up where Phase 1 finished off. There needed to be further investigation including more closely coupled integration with PowerOn within the overall system. Also the demonstration of multiple D-SVCs would enable WPD to show how coordinated reactive power sources functioned alongside each other. This in turn would demonstrate the D-VQC itself and how a closed loop control system could optimise the network

Additional benefits it was hoped would come from understanding the impact of a specific transformer on the D-SVC in terms of its performance, along with the demonstration of a novel communication system which could be effective for rural 11kV networks.

The project was terminated early for a number of reasons which are discussed within this report. First and foremost the D-SVC did not have a significant impact on the HV voltage, and even a specific transformer only had limited impact. This points clearly to the implementation of STATCOMs being concentrated on the higher voltage levels were there is more reactance in the network.

2. Project Background

As the integration of Distributed Generation (DG) onto the distribution network becomes more common, the growing number of connections to distribution networks can cause voltage problems.

These problems are either caused by high voltage during periods of high DG or low voltage during times of high demand. The majority of DG is renewable and hence output can change rapidly due to weather.

Both of these circumstances can cause the voltage to move outside statutory voltage limits but also cause large variation in voltage profiles which may be noticeable to customers. In turn this can affect the efficiency and capacity of the distribution network to connect further DG or demand. There are several different ways that the voltage on rural network can be controlled to reduce this variation. However, some traditional solutions are unable to cope with the rapidly varying output of renewables such as wind turbines and photovoltaics (PV).

The project hypothesis was that D-SVCs could be deployed across various locations of the 11kV network to optimise the voltage closer to the problem. This combined with the ability to influence primary bar voltage from remote measurements, the entire system voltage could be control within tighter limits.

In this project we intended to build on the learning of the first project undertaken under the Low Carbon Network Fund by increasing the number of D-SVCs connected into to the same 11kV network and integrated their control with a D-VQC. This would have allowed voltage optimisation across that entire 11kV network. To do this effectively multiple measurement points needed to be introduced onto the system. Therefore an effective, high bandwidth communication network to connect the measurement points and control the D-SVCs would be needed to cover remote spread of the 11kV network. The D-VQC was to be integrated with a more sophisticated tap changer relay at the primary substation which would aid the voltage optimisation by changing the bar voltage to ensure that there was not voltage infringements on all of the feeders. This would take account of the generation output of individual feeders but also the level of demand on the others.

The project had two phases, a design and Model phase or “Discovery” and a Build and Test phase which include both lab and site tests.

One of the key learning points from the LCNF project was that WPD's standard transformer which was used to connect the D-SVC, demonstrated performance limitations because the two units were not impedance matched. In this second project there was additional work to ascertain the ideal transformer impedance and how much of an impact this had on the effectiveness of the D-SVC to control the 11kV voltage. It would then be tested in lab conditions to reduce the effect of other factors and a network deployment would then follow.

3. Scope

The scope of the project was to take the learning from the first SVC LCNF project and extend it to include multiple devices on the WPD 11kV network. This was to be trialled within a rural area determined within the discovery phase, with the trials taking place over 24 months. It was expected that this trial would provide the following insights:

- Optimise multiple networked D-SVCs on the distribution network
- Identify the appropriate impedance transformer and establish its sensitivity to the voltage control
- Develop a communication system for rural 11kV networks
- Implement a pole top sensor that measures real power, reactive power and voltage
- Integrate control and data from the D-VQC and D-SVC systems into ENMAC/PowerOn
- Develop a tap changer relay scheme that integrates with the D-VQC

4. Objectives

The objective of this project was to determine the effectiveness of D-SVCs controlled by the D-VQC, used in conjunction with an advanced tap changer relay, to control voltage on an 11kV rural network.

The first phase was the discovery phase where the intention was to model and design the requirements of the project.

In this second phase, 3 D-SVCs were intended to be connected across the 11kV network of a single primary substation; 2 D-SVCs on the same feeder where there were multiple generators, the 3rd on another feeder adjacent to a larger generator. This would test the ability of the D-VQC to optimise two D-SVCs in close proximity while using all three along with the tap changer relay to keep the voltage stable across the network.

These objectives were supported by a series of success criteria to measure the results. It is disappointing that the project was unable to proceed beyond the discovery phase.

5. Success criteria

The project had a series of measurable success criteria, as follows:

Criteria	Evidence	Success
Optimise multiple networked D-SVCs on the distribution network	Design/Modelling proved the theory of using D-SVCs, however the business case was low.	✓
Identify the appropriate impedance transformer and establish its sensitivity to the voltage control	Detailed design completed and indicated that a low impedance transformer would help with the impact of the D-SVCs. However, the impact was insufficient to make a significant difference due to the high impedance of the connected network and the relatively low reactance.	✓
Develop a communication system for rural 11kV networks	As part of the communication design a system was designed. The Wood and Douglas radios were selected as they were able to communicate over the two channels; our traditional SCADA and the meshed high speed IP based protocol required for the D-VQC real time control loop.	✓
Implement a pole top sensor that measures real power, reactive power and voltage	Pole Top Sensors were selected but not installed.	✓
Integrate control and data from the D-VQC and D-SVC systems into ENMAC/PowerOn	Not progressed	×
Develop a tap changer relay scheme that integrates with the D-VQC.	An innovative design was developed at part of the project but this was not progressed.	✓

Table 1: Project Success Criteria and evidence at project closure

6. Details of the Work Carried Out

6.1 Site Selection

The primary objective of the trial, was to investigate the voltage control of an 11kV rural network with an intermittent, distributed generator connected. As the D-SVCwas able to respond quickly to voltage fluctuations it was capable of reacting to the fast ramp rates created by solar generation. To achieve this we needed to identify a suitable location which had significant generating towards the end of a long feeder and was close to its voltage limits. This proved challenging as most DG developers tend to actively avoid feeder ends due to the potential high reinforcement cost associated with voltage rise. This is particularly true for solar developments due to the relatively small restrictions in planning during the solar boom due to the feed in tariff and rush to connect 5MW sites on the 11kV.

The original intention was to find a site in South Wales however Cornwall offered more sites with a high density of 11kV generators on the same network. The Fraddon network is one of the networks have seen significant generation. This is partly due to the rural but industrial landscape and it being part of the China Clay mining area of Cornwall. The primary substation is also adjacent to the Bulk Supply Point (BSP) removing the need for 33kV reinforcement works in many cases. These factors made it reasonably difficult to find many locations were we could locate the trial.

The generation on the Fraddon network is predominantly small to medium wind sites, a large diesel generation run for Short Term Operating Reserve (STOR) and a large Photovoltaic (PV) farm. As shown in the table 2 below, Feeder 41 has 11 wind turbines and 2 small PV arrays along the feeder, varying from 40kW to 225kW totalling an installed capacity of 965kW, which rises to 1136kW once the small generation is considered.

HV Feeder	Generator Type	Number of Phases	Installed capacity
437380/0041	Onshore Wind	Three Phase	50
437380/0041	Photovoltaic	Three Phase	40
437380/0041	Onshore Wind	Split Phase	40
437380/0041	Photovoltaic	Three Phase	40
437380/0041	Onshore Wind	Three Phase	80
437380/0041	Onshore Wind	Three Phase	80
437380/0041	Onshore Wind	Three Phase	80
437380/0041	Onshore Wind	Three Phase	55
437380/0041	Onshore Wind	Three Phase	55

437380/0041	Onshore Wind	Three Phase	80
437380/0041	Onshore Wind	Three Phase	80
437380/0041	Onshore Wind	Three Phase	225
437380/0041	Onshore Wind	Three Phase	80

Table 2: Generation Types connected to Feeder 41

The generation is spread along the length of the feeder with the largest 225kW wind turbine connection roughly in the middle and the most distant almost 10.5km from the primary substation.

On the other feeders there were also a significant number of generators however the most significant was a larger site closer to the primary. For example, Feeder 45 had a 500kW wind turbine 6.3kM from the primary substation.

In addition to the selecting the network on the installed capacity and spread of the generation, there couple of additional factors that helped confirm the decision. These were communication related as we needed to have good integration with PowerOn (WPD's control system) and to be able to test the novel communication solution for the project. Firstly, Fraddon primary substation is adjacent to Fraddon BSP which has a high bandwidth fibre link back to PowerOn and the corporate network. This would have allowed close integration with the D-VQC and the WPD's other corporate systems.

Secondly we wanted to test the communication solution we were going to install so needed some relatively challenging terrain to do this with. Fraddon is a hilly area, with some spoil heaps from the mining work in the area, along with many wind turbines; all of which are challenging for wireless communication. This would have allowed us to put the communications solution through the rigorous testing required.

6.2 Transformer Design

For this project the project partner, Hitachi, supplied a D-SVC (Distribution Static VAr Compensator) STATCOM, connected at 11kV through a transformer. However in the first LCNF project it was identified that the D-SVC was not having a significant impact on 11kV voltage. This was partly put down to the standard 11kV distribution transformer which was used to connect the D-SVC. One of the key objectives of this project was to design and test an impedance matched transformer to improve the performance of the D-SVC. This would follow a similar methodology to the designing of a transformer for the 33kV connected D-STATCOM used in the Lincolnshire Low Carbon Hub.

We decided to use the same transformers manufacturer, Ultra, as we had observed good performance from the 33kV D-STATCOM. Although Hitachi aided us with information, we also gained some specialised knowledge from Parsons Brinckerhoff.

The Parsons Brinckerhoff report concluded that the Hitachi's D-SVC was too small to have a significant impact on the 11kV network voltage (the report is included in Appendix E). The report explains that the transformer design is not in fact the critical factor in the performance of the SVC; the key issue is the relative size of the unit relative to the network it is trying to influence. This essentially led us to the decision to not progress the phase 2 part of the delivery as the D-SVC clear was not able to have a significant enough impact for us to get meaningful results from the trial.

6.3 Control System Integration

The control system required a number of key parts to ensure that it had all of the information and data required to carry out its function correctly. The key parts of the system are as follows:

- D-SVCs – these provide the reactive power support
- Wireless communications – links the constituent parts together
- Sensors – these measure the voltage, real power and reactive power at several points in the network
- LRT – the tap change relay, in this case the Supertapp N+
- D-VQC – the control system which models of the electrical parameters as dispatches sets points to the D-SVCs and the Supertapp N+
- ENMAC – WPD's Network Management Software, now upgraded to PowerOn

The diagram below shows the system architecture:

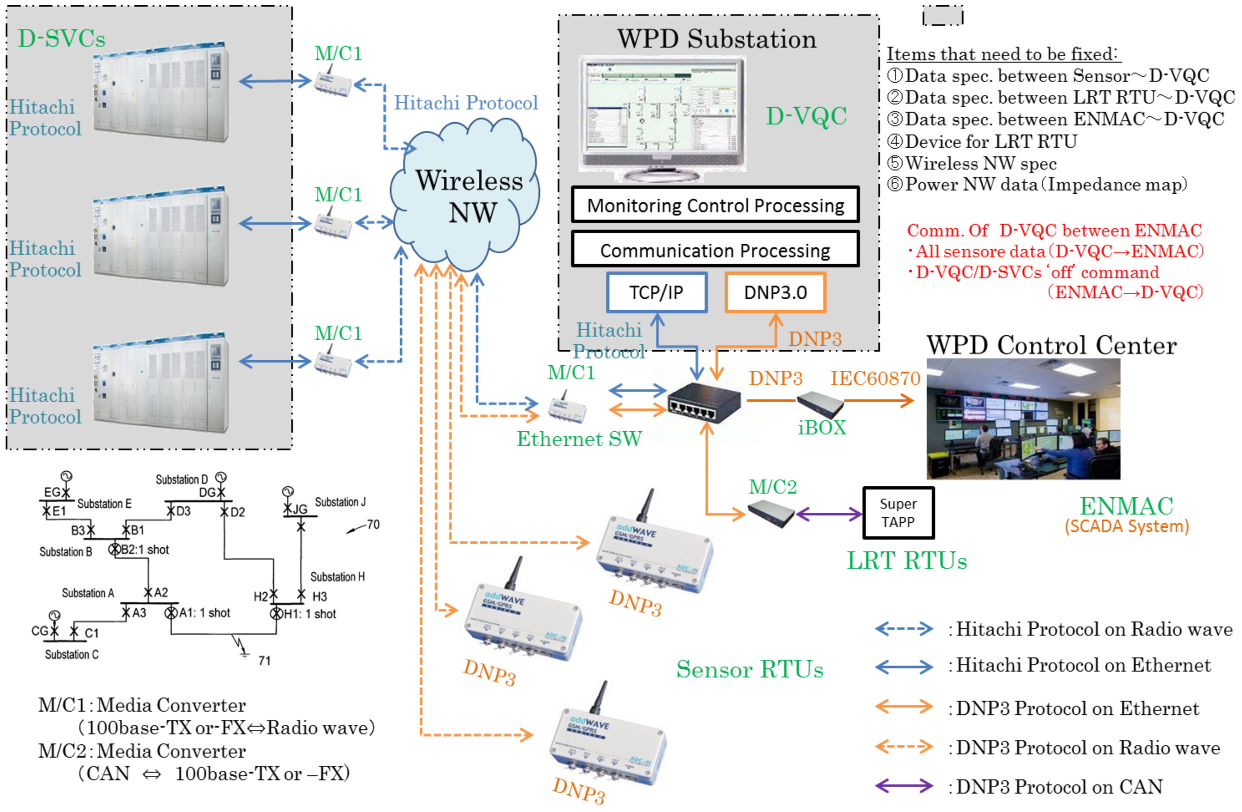


Fig 1: System Architecture

Linking the D-VQC to PowerOn was a key part of the system and Hitachi needed to modify the D-VQC to allow this. The original system only had Hitachi's proprietary protocol so we modified the protocols to include DNP3. This was also important to allow communication with the sensors which were not supplied by Hitachi.

6.4 Network Model

The network model allowed the D-VQC to interrogate the sensor readings from the network and to send the relevant information to the D-SVCs and the tap changer relay to subsequently optimise the voltage. It took this information to run a load flow while using state estimation to estimate the intermediary nodes.

The network model used was taken from an extract of WPD's 11kV modelling systems DINIS. The diagram in Appendix F shows the skeleton schematic on the network loaded into the D-VQC.

The D-VQC (Voltage and Reactive Power (Q) Control System for Distribution Grid) is a centralised supervisory and control system designed for voltage fluctuation suppression and optimal operation of distribution systems. Figure 2 below shows the layout of an installation. The D-VQC controls voltage regulators such as SVCs (Static Var Compensator) and LRTs (Load Ratio Transformer) so that minimum voltage fluctuation and power loss is achieved. The control parameters for such optimal operation are calculated by D-VQC based on monitored data, such as P, Q, V, I from sensor terminals and tap position from primary substation transformers.

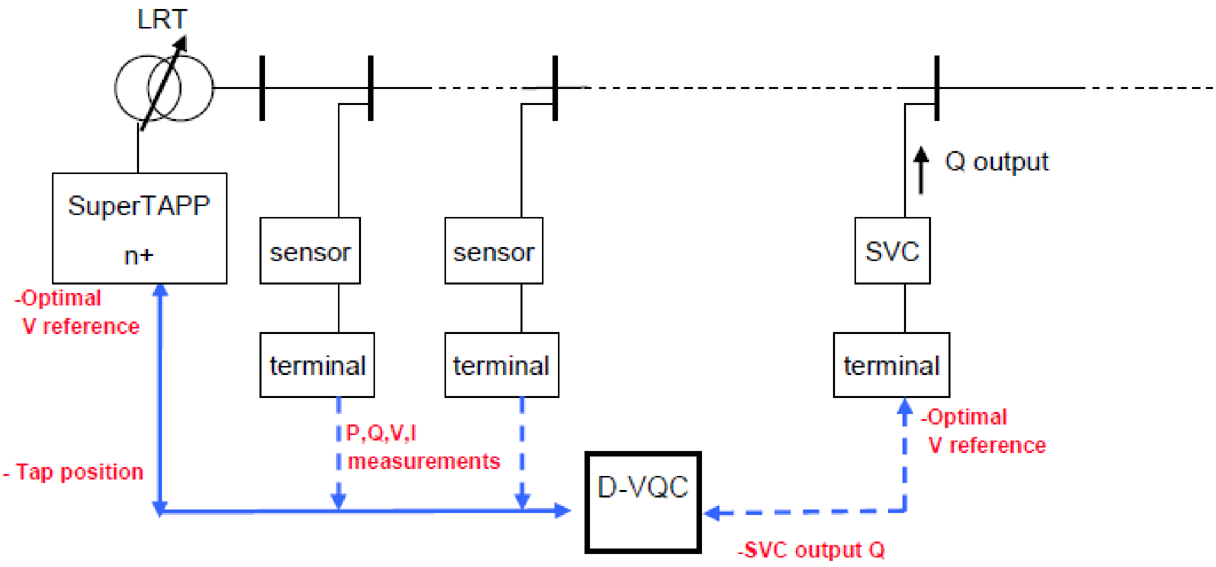


Fig 2: Layout of D-VQC installation

The purpose of applying D-VQC is to solve the following issues with operating multiple, locally controlled SVCs:

1. Each SVC can only control its local system voltage therefore voltage control of the total system is difficult.
2. Voltage regulating equipment cannot operate at maximum performance. For example, when SVC-Q output is already at maximum and a tap change causes the system voltage to rise. The SVC cannot further output reactive power to control system voltage towards the reference voltage.

In order to solve these issues, D-VQC utilises sensor measurement data to efficiently control multiple voltage regulating equipment and effectively reduce voltage fluctuation of the distribution system.

6.5 Network Sensors

One of the key aspects of the project was the sensors that are needed to monitor the data for the D-VQC. The devices were needed to monitor the voltage, real power and reactive power of the network across a number of points in the network, most of which were on pole top locations.

It was important to select a sensor which was easy to install, accurate and reliable to ensure that the project was not disrupted. There were three devices considered:

- Alstom iSTAT 5MT
- Tollgrade Lighthouse power sensor
- Schneider Nulec U-series auto-recloser

Each of the devices had their pros and cons however we decided to use Schneider Nulec U-series auto-recloser for the pole top installations and the Alstom iSTAT 5MT for the ground mounted locations such as the D-SVCs themselves. This was mainly due to internal standards, ease of fit and side benefits.

6.6 D-SVC and Sensor locations

Once the network had been identified, the first stage was to establish the best locations for the D-SVCs. Feeder 41 had already been identified as a high generation feeder, with a significant amount of generation spread along the feeder. This made it an ideal location to place two D-SVCs along it, one midway along close to the largest generator and one adjacent to the final generator along the feeder. This allowed us to test the impact of multiple reactive power sources in close proximity and helped test how optimised the D-VQC actually was.

The third D-SVC was to be located on another feeder which had a medium sized (500kW) wind turbine a moderate way along it. It was the largest generator on Fraddon and was under a kilometre from the substation. This feeder also had the advantage of being able to be configured to feed the larger 5MW PV farm close to the substation. Although the reactive power would have had little effect being so close to the tap changers, it would have been useful to understand the response of the control system to the D-SVC as the PV park quickly ramped up and down.

Once these rough locations were determined, WPD along with the local planner and wayleave officer, agreed the sites with the respective land owners. This site design took account of access and the electric works required to connect the site.

The selected D-SVC sites are shown below:

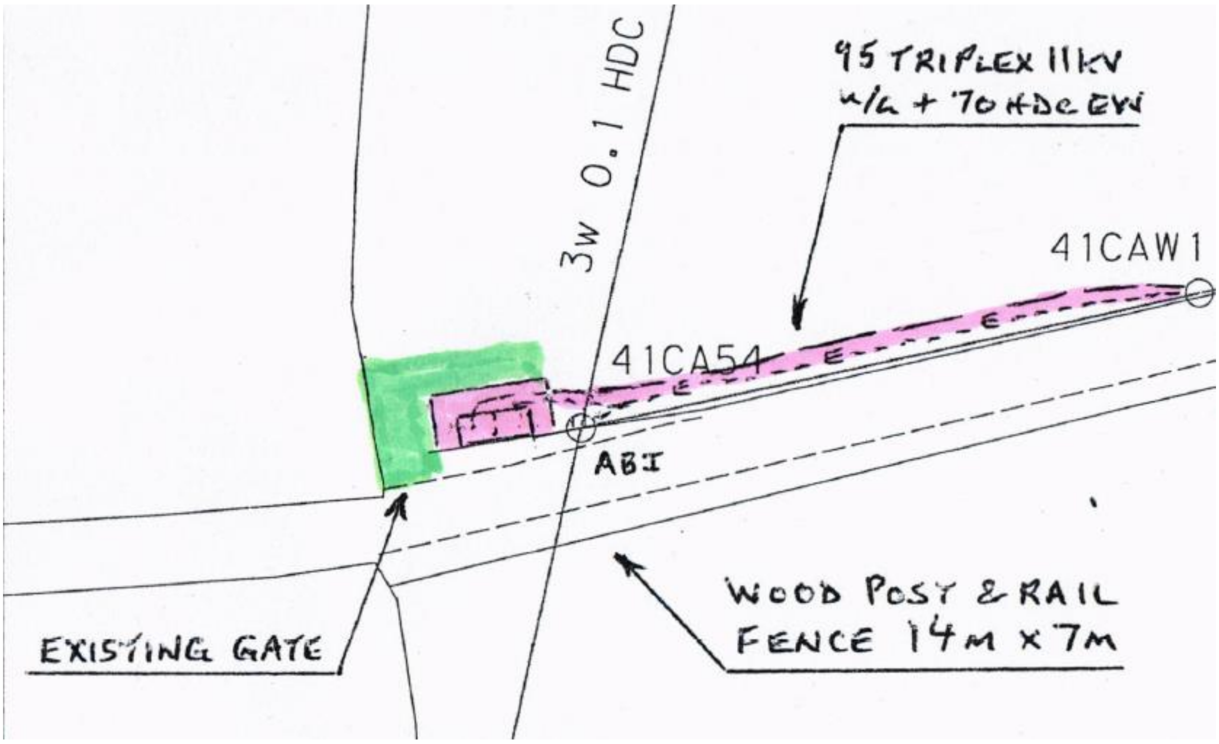


Fig 3: Grampound D-SVC site

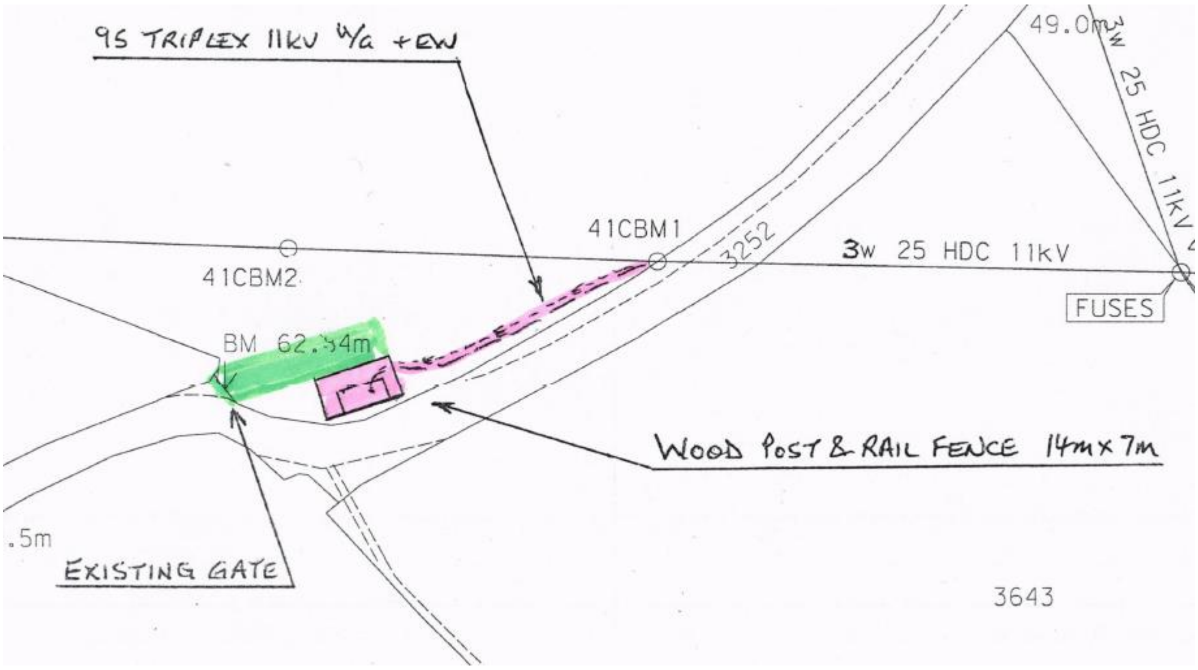


Fig 4: Ladock D-SVC site

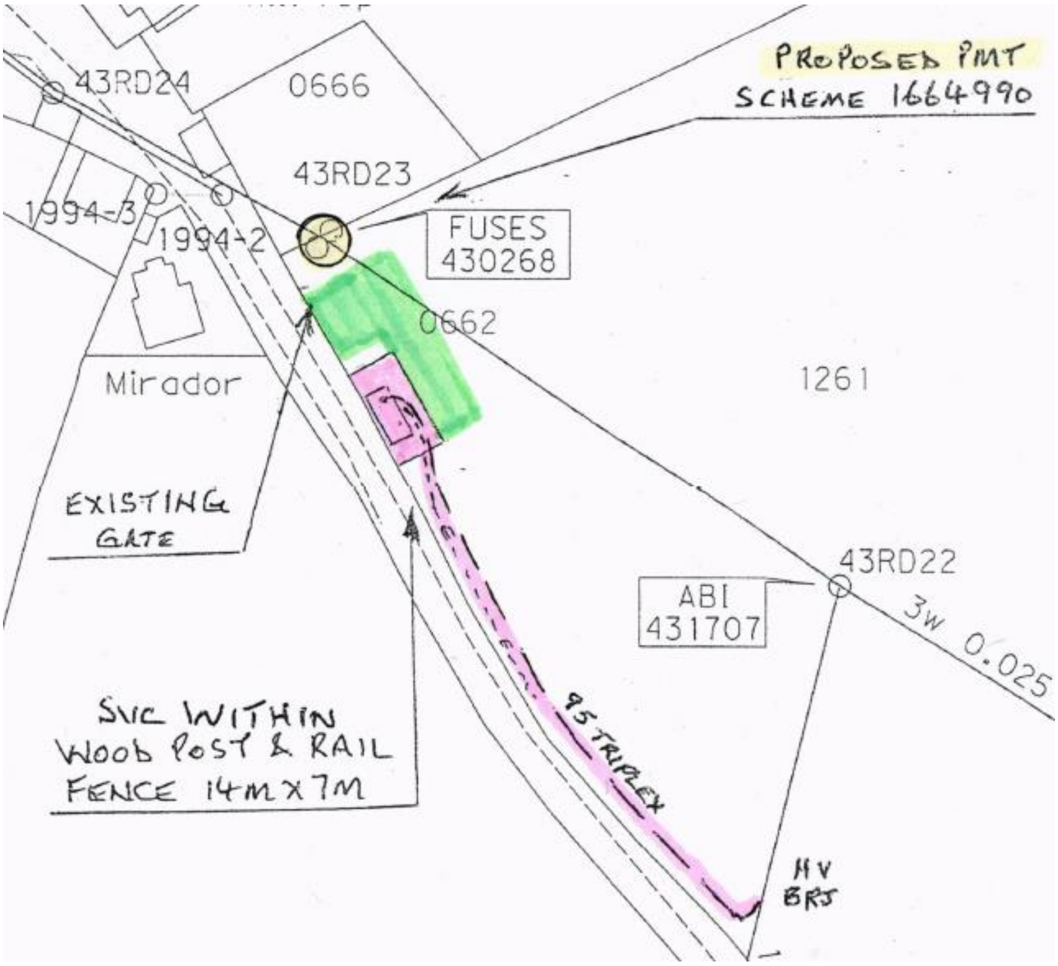


Fig 5: White Cross D-SVC site

The sensor locations were more numerous however and they needed less space and did not require any additional wayleave. Hitachi gave us indicative locations to site the sensors and WPD's Wayleaves Officer went out to locate the best specific poles. They identified several spans within the network topology which fitted within Hitachi's impedance preferences which had reasonable access. WPD Project staff then went to site with the local overhead line technician, who helped identify the specific poles.   We selected these poles with the local knowledge of the land owners, access considerations and where we could replace older manual or gas operated ABIs. This would have had the side benefit of increasing the amount of tele-control the network would have, making it quicker to restore customers during a fault.

6.7 Tap Changer Relay

The tapchange relay needed to have an IP interface to communicate with the D-VQC. This meant there were two options at the beginning of the project, either the Supertapp N+ or the Microtapp. The Supertapp N+ had more versatile outputs to drive the D-VQC and thus we selected this relay.

The new AVC relay relay needed to carry out the same function as the legacy relay however it would need to able to be influenced by the D-VQC to optimise the primary bar voltage to allow the optimal amount of headroom for the prevailing conditions. This was eventually decided to be in the form of a percentage difference on the existing set point.

We needed monitoring at the feeders and extra equipment to communicate with D-VQC as indicated in the architecture diagram below:

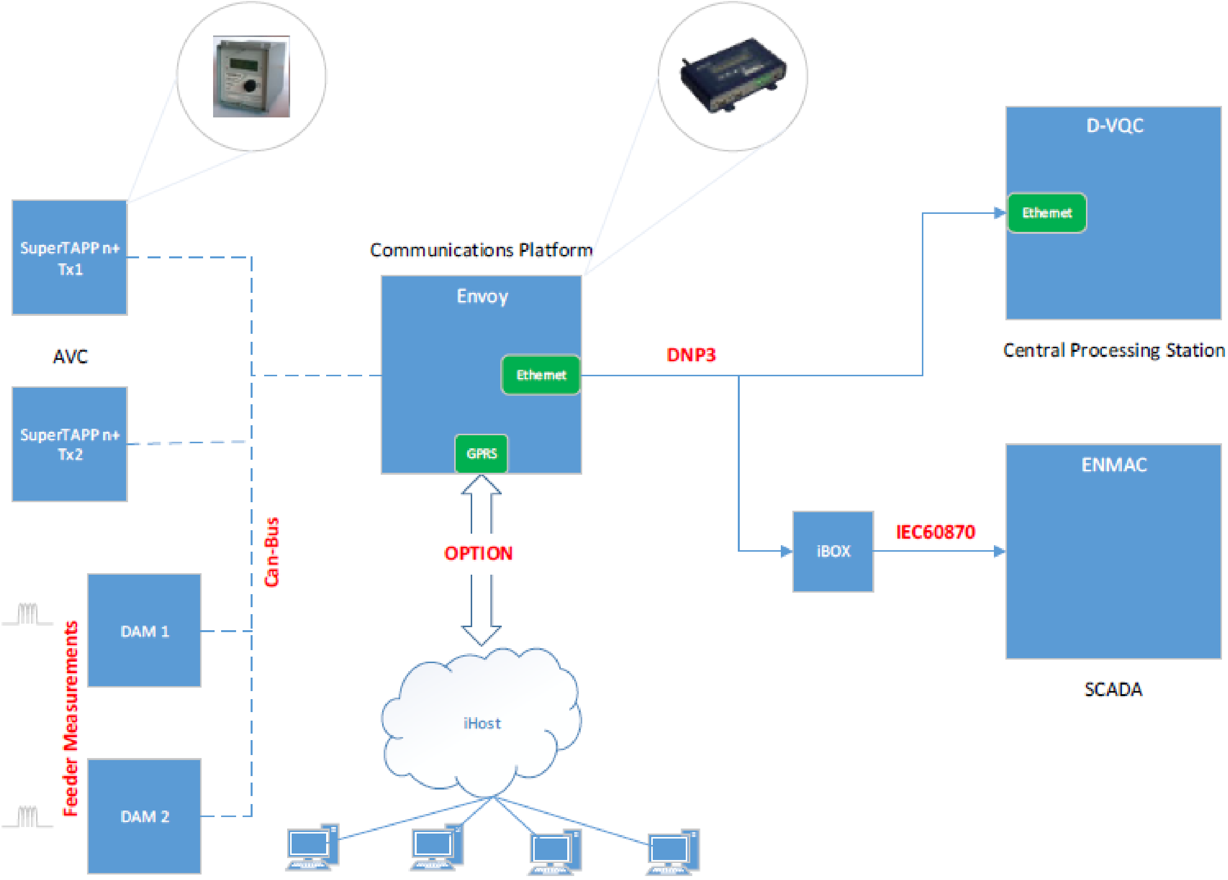


Fig 6: Communications Architecture Diagram for Tapchange relay

The overall AVC specification was:

- D-VQC voltage target command via DNP3 analogue to SuperTAPP n+ units.
- Periodic update rather than continuous update of voltage target to limit tap operations. D-VQC to confirm voltage target change to correct value after each command and before a subsequent command.
- Voltage target values to be limited by D-VQC. Limitation also possible through blocking contacts.
- SuperTAPP n+ actual voltage target(s) analogue measurement via DNP3 to D-VQC and PowerOn.
- Substation feeder measurements via DNP3 analogues to D-VQC and PowerOn.
- Polling of analogues recommended every 10s.
- DNP3 control enable/disable command via DNP3 digital from PowerOn.
- DNP3 control enable/disable indication via DNP3 digital to D-VQC and PowerOn.
- Voltage reduction facility (3% and 6%) can be provided via hardwired or DNP3.

6.8 Communications

The original wireless communications design was given to Silverspring as their meshed network solution was deemed well suited to the distances and density of measurement points of the 11kV network.

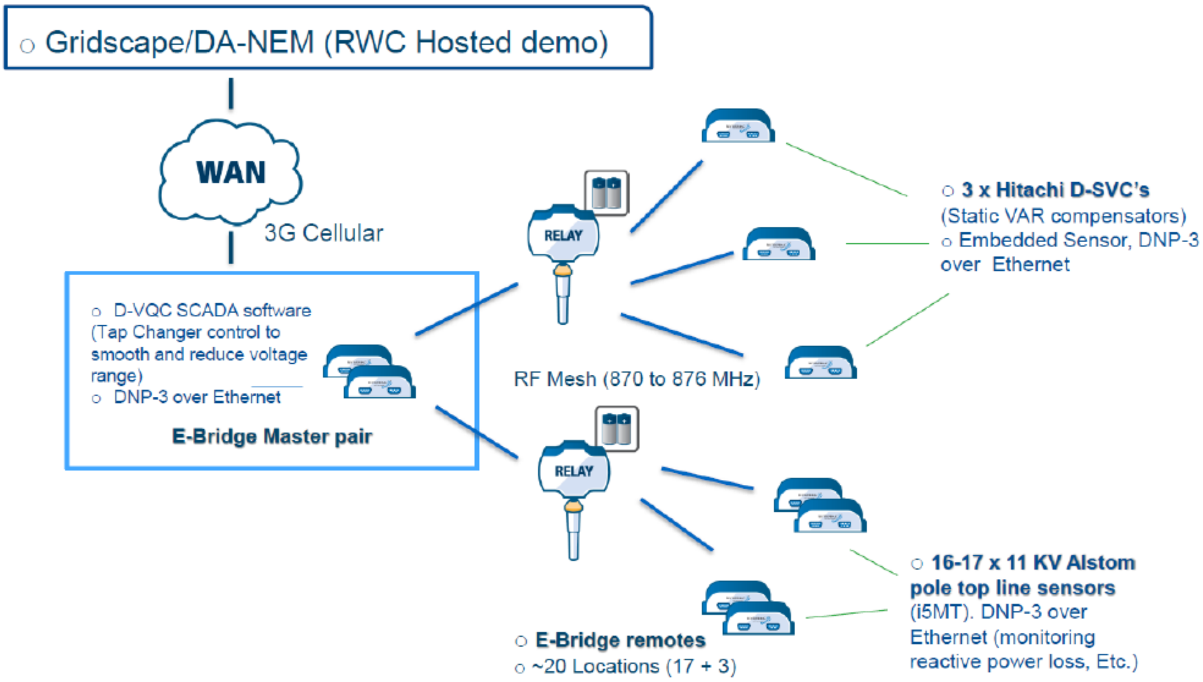


Fig 7: Silverspring Meshed Network architecture

Their solution was relatively simple having the high numbers of sensors in a small area meant the sensors meshed well and were well suited to the difficult terrain as shown in the Figure 8 below.

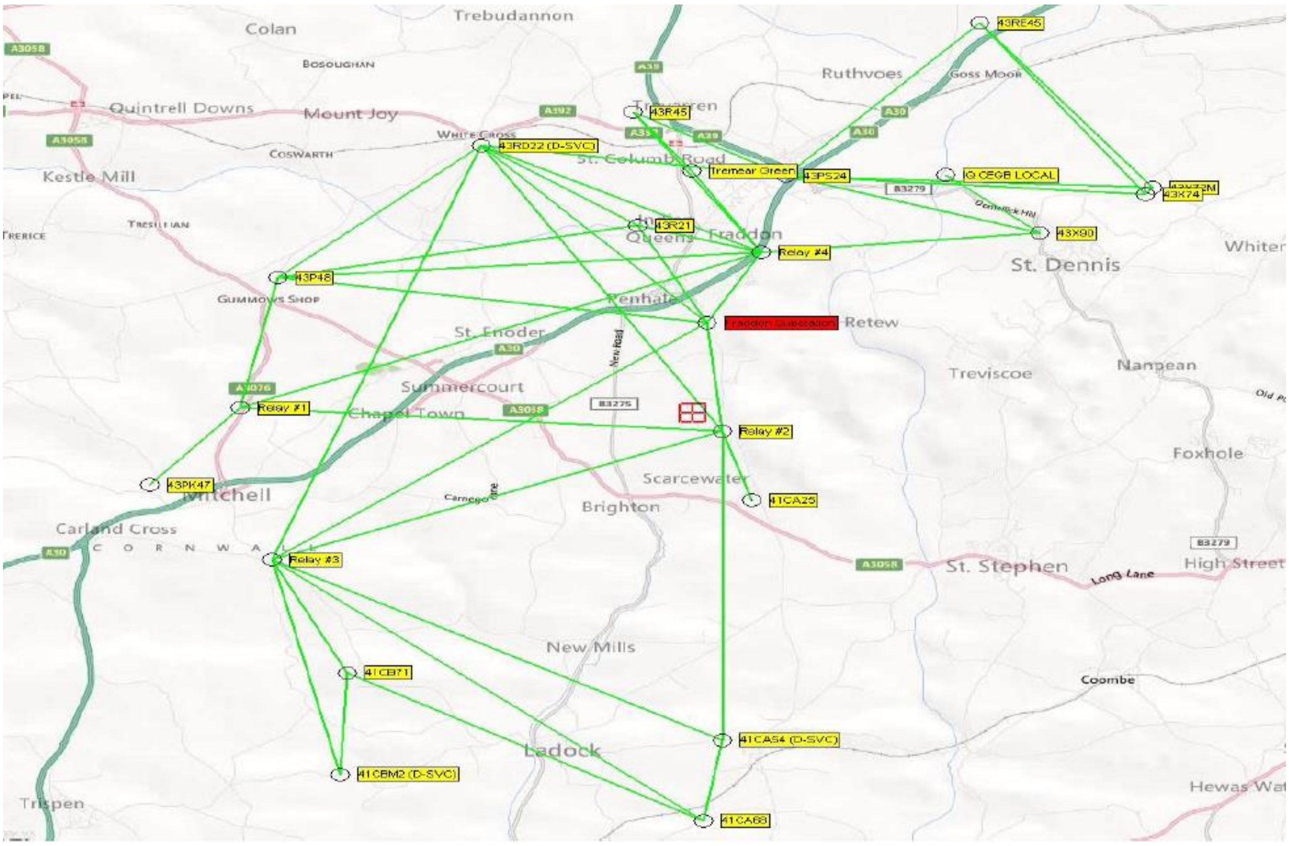


Fig 8: Silverspring meshed telecoms network over trials area

There were difficulties with the solution, the trial radios were difficult to configure and they only had limited success on the test bench. The configuration software proved to be quite challenging. It was decided not to proceed with the Silverspring solution.

The alternative solution was selected based on the Wood and Douglas J-series radios. These were originally manufactured by Trio and now distributed by Schneider so were well suited to be used alongside the Schneider Nulecs. These radios worked on the same frequency of 2.4 GHz as the Silverspring radios however they were not a meshed system. They were purely configured as a point to point system, but they were able to have predefined alternative routes if a path lost its integrity. They were high bandwidth able to run at 512kb/s, a substantial improvement over SCADA. It was however a non licensed solution so needed to hop frequencies to avoid interference and would have had some latency issues.

6.9 PNDC Testing

It was decided that the Power Network Demonstration Centre (PNDC) in Cumbernauld would carry out the lab testing phase of the project. The intention was to test both the standard transformer and the newly ordered impedance matched transformer back to back to establish the difference between the transformers. We were also going to test the transient performance of the D-SVC to establish its responsiveness.

The diagram below shows the suggested network configuration for the testing:

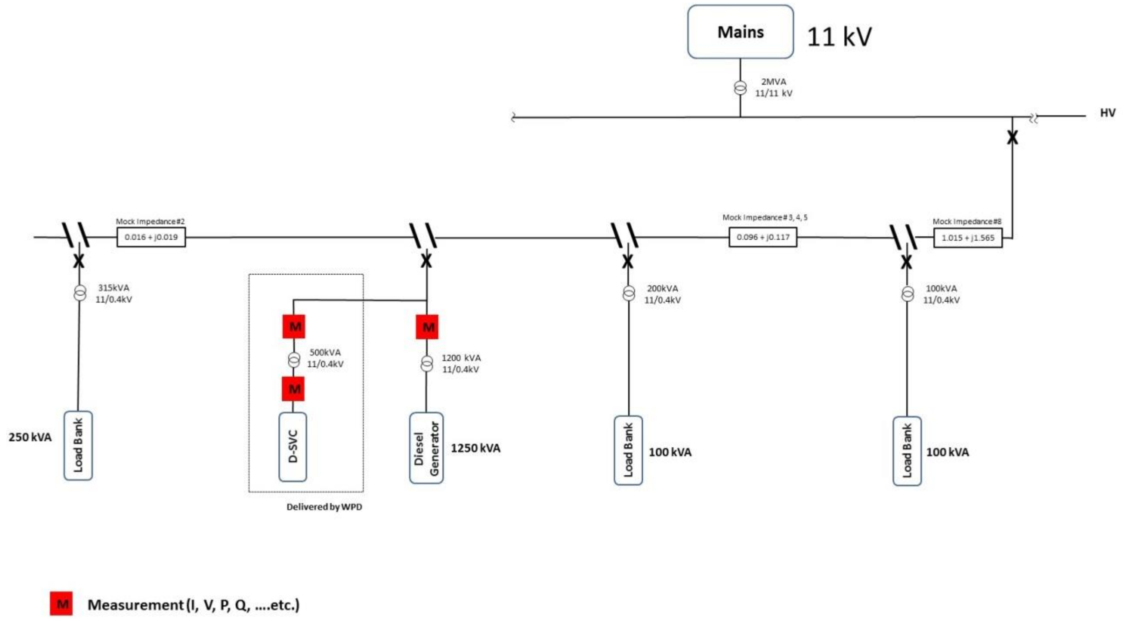


Fig 9: Suggested network configuration for testing

The following tests would be performed at the PNDC.

Delivery and Connection:

- Delivery of diesel generator
- Connection of the diesel generator and communications test
- Delivery of the D-SVC system
- Connection of the D-SVC system

Commissioning of System under Test:

- Commissioning of the complete system (with its 2 transformers) for testing, including both the generator and the D-SVC system
- Simple load and generation profiles will be applied for the commissioning
- WPD to share operational experience during commissioning

Test–1 Verify the Voltage-Current (V-I) Characteristics of D-SVC with Transformer 1:

- Voltage Control mode
- Motor Generator set and load banks impose different terminal voltages
- Measure the steady-state D-SVC current, reactive power, harmonics and voltage
- Test carried out at 11 kV and 50 Hz
- Record parameters both at LV and HV

Test–2 Voltage Control to a Set-point and Flicker Reduction with Transformer 1:

- Voltage Control mode
- Adaptation of pre-recorded (wind farm/PV) generation and load profiles for test
- Diesel Generator and load banks follow adapted generation and load profiles respectively
- Measure voltage, flicker and harmonics with and without the D-SVC operation
- Test carried out at 11 kV and 50 Hz
- Record parameters both at LV and HV

Test–3 Reduction of Step Changes in Voltage with Transformer 1:

- Voltage Averaging mode
- Load banks to create large load steps leading to large voltage steps
- Measure voltage and harmonics with and without the D-SVC operation
- Test carried out at 11 kV and 50 Hz
- Record parameters both at LV and HV

Test–4 Reduction of Spikes in Voltage with Transformer 1:

- Short-term Fluctuation mode
- Use the fault-thrower or (an adjacent) transformer in-rush current to create short-duration voltage dip (2 in number) at the point of connection of D-SVC to the HV network
- Measure terminal voltage with and without the D-SVC operation
- Test carried out at 11 kV and 50 Hz
- Record parameters both at LV and HV

Test –5 Synchronous Operation under Abnormal Conditions with Transformer 1:

- Voltage Control mode
- Test under different fault conditions using the fault-thrower
- Test at variable voltage and variable frequency using the MG-set
- Measure the steady-state D-SVC current, reactive power, harmonics and voltage
- Record parameters both at LV and HV

Test–6 Verify the Voltage-Current (V-I) Characteristics of D-SVC with Transformer 2:

- Voltage Control mode
- Motor Generator set and load banks impose different terminal voltages
- Measure the steady-state D-SVC current, reactive power, harmonics and voltage
- Test carried out at 11 kV and 50 Hz
- Record parameters both at LV and HV

Test–7 Voltage Control to a Set-point and Flicker Reduction with Transformer 2:

- Voltage Control mode
- Adaptation of pre-recorded (wind farm/PV) generation and load profiles for test (WPD to provide recorded profiles in required format)
- Diesel Generator and load banks follow adapted generation and load profiles respectively
- Measure voltage, flicker and harmonics with and without the D-SVC operation
- Test carried out at 11 kV and 50 Hz
- Record parameters both at LV and HV

Test–8 Reduction of Step Changes in Voltage with Transformer 2:

- Voltage Averaging mode
- Load banks to create large load steps leading to large voltage steps
- Measure voltage and harmonics with and without the D-SVC operation
- Test carried out at 11 kV and 50 Hz
- Record parameters both at LV and HV

Test–9 Reduction of Spikes in Voltage with Transformer 2:

- Short-term Fluctuation mode
- Use the fault-thrower or (an adjacent) transformer in-rush current to create short-duration voltage dip (2 in number) at the point of connection of D-SVC to the HV network
- Measure terminal voltage with and without the D-SVC operation
- Test carried out at 11 kV and 50 Hz
- Record parameters both at LV and HV

Test –10 Synchronous Operation under Abnormal Conditions with Transformer 2:

- Voltage Control mode
- Test under different fault conditions using the fault-thrower
- Test at variable voltage and variable frequency using the MG-set
- Measure the steady-state D-SVC current, reactive power, harmonics and voltage
- Record parameters both at LV and HV

7. The Outcomes of the Project

7.1 Transformer Design

WPD developed a specification for the D-SVC transformer that are specifically matched to the D-SVC’s characteristics to optimise its performance. The D-SVCs had already been delivered and had been in storage while the control system which was being programmed in Japan. The transformers were on critical path and need to be ordered as soon as possible not to delay the project even further.

Hitachi had carried out some sensitivity calculations to help establish the basic parameters and suggested that the network impedance was the overriding factor, the results are detailed within Appendix G.

From this information WPD asked Parson Brinckerhoff to do some detailed modelling to verify this and provide a specification for the D-SVCs which would better optimise their performance compared to the standard WPD transformer which was used in the first phase.

From this specification WPD planned to procure 4 transformers, 3 of which would go to Fraddon in Cornwall for use in phase two, the demonstration phase, of the project. They would have been used to connect 3 D-SVCs at remote locations of the 11kV network. The 4th would have been sent to the PNDC to be tested alongside a standard WPD specified transformer to test their relative performance on an identical network for a number of performance tests.

Parsons Brinkerhoff did some additional modelling and the report is provided within Appendix E.

The report concluded that the Hitachi unit was too small to have a significant impact on the 11kV network voltage. Moreover, the transformer design was not a critical factor in the performance of the SVC; the key issue was the relative size of the unit relative to the network it was attempting to influence. This essentially led us to the decision to terminate the project as the D-SVC would not be able to have a significant or measurable enough impact for us to get meaningful results from the demonstration phase.

7.2 System Integration

One of the key challenges to integrating D-SVC and D-VQC with PowerOn was changing the protocols and interaction between the systems with these new protocols. The Hitachi implementation of the DNP3 protocol had not included the ability to act as a client. This became problematic when sending data to the D-VQC from PowerOn such as an inhibit signal to turn the system off. This is an important function which allows the control engineer to turn off the D-VQC and the D-SVCs from the PowerOn diagram in the event of a fault. It is important for them to not require additional systems to do this and it must be native within the PowerOn diagram.

There was some difficulty configuring PowerOn without the D-VQC performing as a client and it would have required bespoke development to include this functionality and this made it cost prohibitive.

7.3 Network Model

To allow Hitachi to model the network, WPD needed to extract data from its 11kV power flow modelling software. WPD uses DINIS for 11kV design and WPD was able to provide an acceptable extract.

A fault analysis was carried out at set points on the network which calculated the X and R for the network up to this point. This gave the basic impedances at several points along the line. To do a full model, more comprehensive data was required listing the section of the network. This data needed to be accessed through the back end of DINIS, this was much more time consuming and required specialist resources. Once the data was extracted it required some work to get the data into a usable form for Hitachi. One of the key aspects was to index link the lines to the nodes as this was not done automatically. This allowed the connectivity of the model to be established more readily. To allow the impedance of each section to be identified extra data needed to be exported on the line types. As the line types are only identified in the export rather than the impedance data itself, this needed to be cross referenced from a line type impedance table for Hitachi's impedance model.

To improve this for the future an automated script would need to be developed to allow the information to the extracted more easily for third parties. Several other pieces of power flow modelling software have DINIS conversion scripts for importing DINIS data into their file format. These can be acquired from the software developers so the data can then be manipulated and transferred from this software.

Once the network was installed the D-VQC operated in the following way.

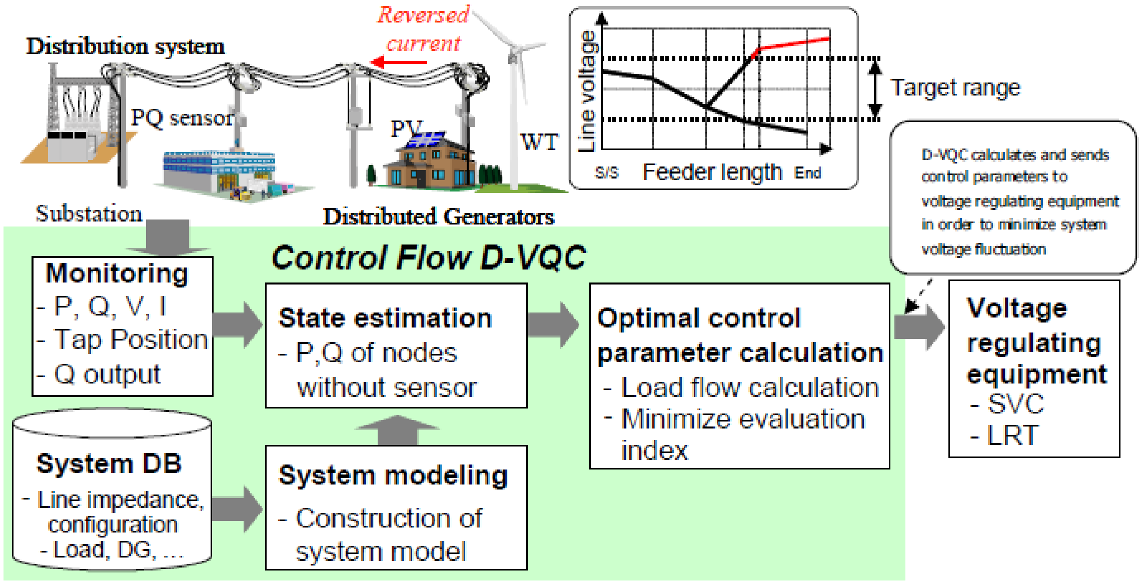


Fig 10: Operational Flow of the System

The key function of the D-VQC was to be able to carry out state estimation. Optimal control parameter calculation includes flow calculation which requires either a set of P,Q or P,V values for each node. However not all nodes in the system have sensors installed. In order to perform the load flow calculation, D-VQC estimates the state of nodes without sensors based on the measurement values from sensors and ratio of rated load at each node. State estimation follows the procedure shown in Appendix H.

7.4 Sensor selection

As discussed above in Section 6 there were three types of sensors considered:

- Alstom iSTAT 5MT
- Tollgrade Lighthouse power sensor
- Schneider Nulec U-series auto-recloser

It was important that all the sensors were easy to install, reliable and accurate. The Tollgrade sensor was the easiest to discount as although we had previously installed the current measurement only variant of this device, we had some concerns around the trailing earthing point required to give the sensor a voltage reference point making it non-compliant with WPD policy. Also the device is set up to monitor data to be logged rather than to be used in close loop logic, the sensors power down when currents are too low to power the device making it unsuitable for the D-VQC.

The Alstom iSTAT is the standard transducer used in switch gear in WPD. They are well understood and often installed, they are very flexible and measured all the parameters we needed. However, they are well suited for ground mounted substations where they can be fitted easily alongside switch gear but are more difficult to use for the pole top installations. This would need a three phase pole top transformer to be installed and a weather proof enclosure. It was decided that these would be the choice for the ground mounted sites: for example if future D-SVC installations were at large 11kV customers.

The vast majority of sensors needed to be pole-top devices and neither of the first two devices were well suited to our needs. The Nulec was well suited, it was a pole top device which is well known and often installed by WPD. Although its primary function is to act as auto-recloser, it has CTs and a capacitive VT natively within the device. These measurements could be used to derive the voltage, real power and reactive power where required. Moreover its standard build comes with a control cabinet with standard SCADA radio and space for an additional radio if required.

The Nulecs had an added benefit when arranging installation. As they are an auto-recloser, they have tele-control built into the device making it an ideal replacement for manual or older ABIs. While selecting the locations of the exact poles it was agreed that we would replace several of these devices. This made it easier to remotely sectionalise that part of the network during faults, thus making it easier to restore customers.

7.5 Device locations

The location of both the D-SVCs and the sensors required two distinctive approaches. Initially the locating of the devices relied on an analysis of the network to establish the technical best locations and in the case of the sensors which needed to be rationalised down to a number which was not cost prohibitive. This then was checked using the load flow tool that would be running in the D-VQC to ensure the system would indeed have enough information to model effectively.

The outcome of this analysis gave us some flexibility when considering local onsite factors. First of all there was communications; a WPD Surf engineer visited the proposed D-SVC sites to check communication paths. This information was used to do a detailed communication path model for these sites and indicated areas of the feeders which may be problematic in terms of the sensor locations.

The other considerations were the physical onsite limitations. As discussed above we worked closely with our operational team to find the best locations of the sites.

Hitachi's proposed site locations for the sensors for feeder 41:

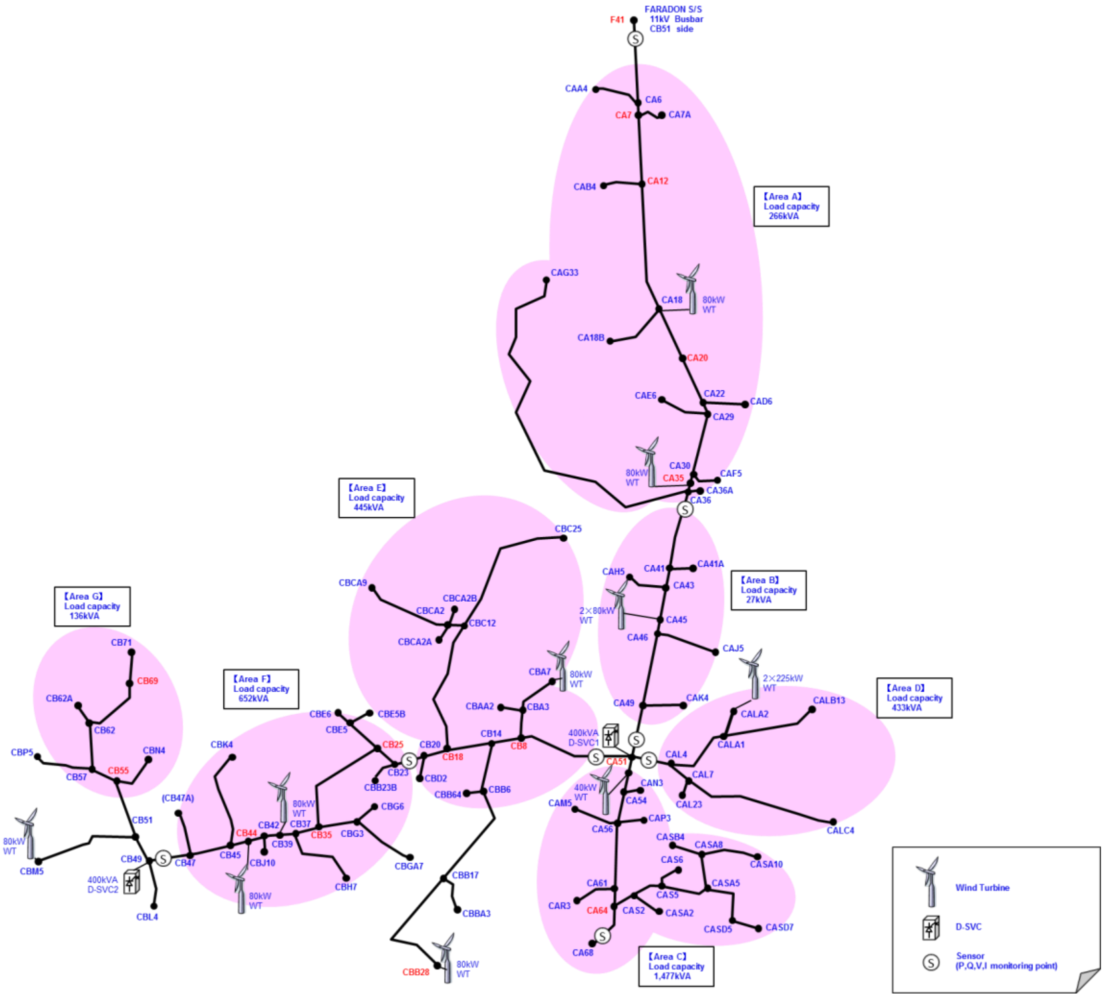


Fig 11: Feeder 41 sensor locations

And the suggested sensor locations for feeder 45:

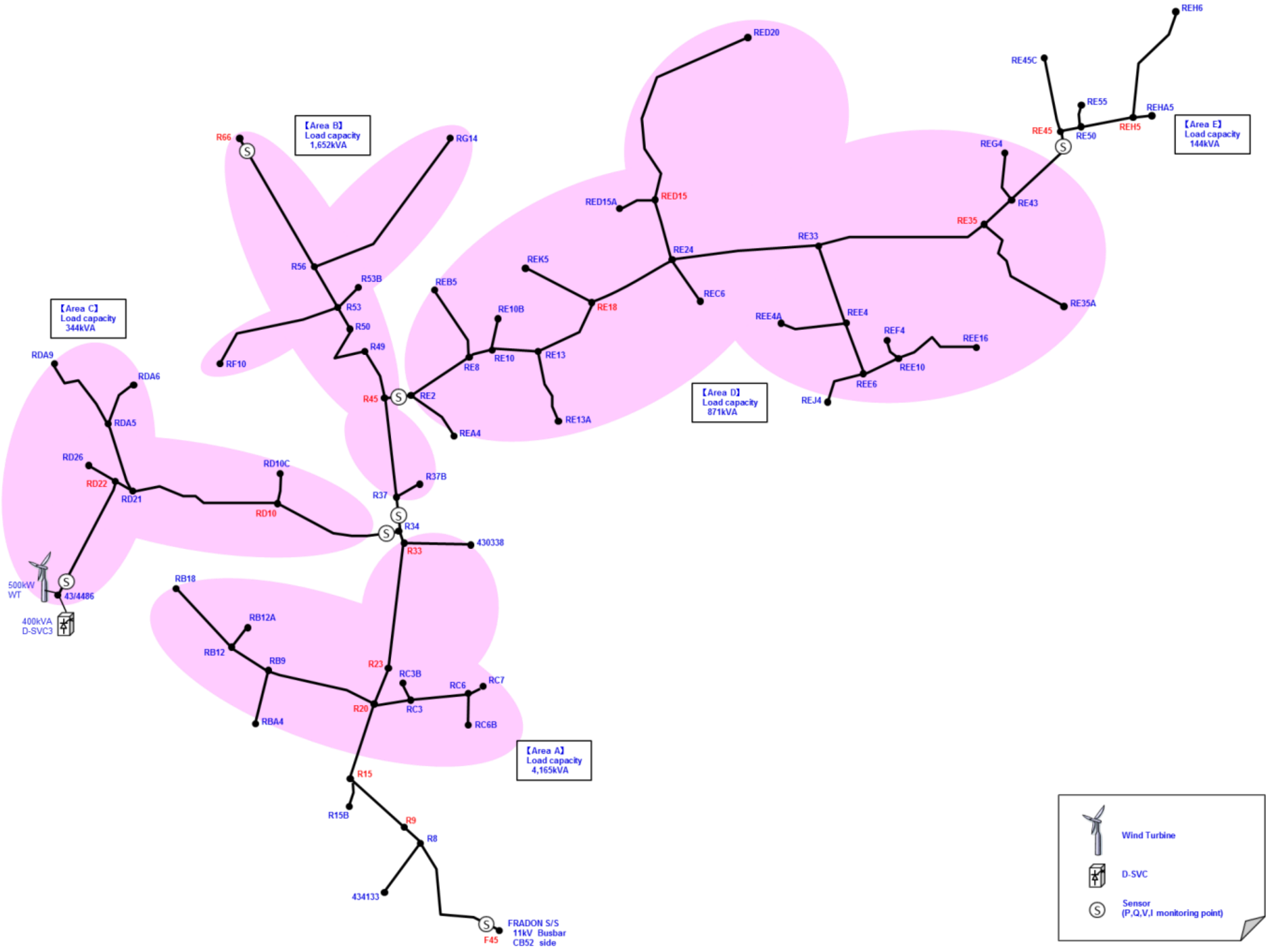


Fig 12: Feeder 45 sensor locations

For the remaining feeders we only needed to identify a midpoint and endpoint sensor so the control system could ensure the feeders without D-SVCs were not out of voltage limits.

For the exact locations of each sensor please see Appendices A to D.

7.6 Tap change scheme

In Hitachi's original design the D-VQC was initially envisaged as being able to control the tapchangers directly by moving the taps up or down. In reality an AVC scheme is more sophisticated as it ensures the voltage is well matched to the demand and that the tapchangers do not tap apart. The decision was made that rather than allowing direct control of the tapchangers, the D-VQC scheme would use the percentage raise and lower functionally that some tapchange relays have for voltage reduction. It was decided that a relay that had this functionality and was controllable via DNP3 would be an ideal choice to allow the D-VQC, a less familiar device, to influence the 11kV primary bar voltage without taking direct control. This also allows the D-VQC to be disabled if necessary which impacts on the AVC scheme.

Another key aspect was presenting data to the D-VQC, the Supertapp N+ has monitors on each of the feeder breakers which can be presented back to the DNP3 interface for the D-VQC to poll alongside the remote sensors. These are particularly useful as the current measurement is natively converted onto real and reactive power measurements from the measured voltage as well. This allows the data to be directly presented to the D-VQC.

The D-VQC would use this information to calculate the set point which would be presented as a percentage set point for the Supertapp N+ to target. As this varied with the prevailing conditions of the demand and embedded generation this was updated. The D-VQC would always ensure that the neither the upper or lower voltage limit are breached. This would be done with the AVC scheme still running in the background, responding to the demand, bar voltage and circulating currents as normal.

Several options were evaluated over which control was best to present to the relay from the D-VQC. Initially a percentage was favoured from the standard percentage drops used for National Grid. However if the D-VQC has already reduced voltage and National Grid called on this function, should another 3% should be knocked off? This meant that we would need to implement a 9% drop in total. It was decided to stay with a percentage set point which was easier to manage overall.

8. Performance Compared to the Original Project Aims, Objectives and Success Criteria

8.1 Issues Investigated from NIA Project Registration Pro-forma

The project aimed to determine whether using these D-SVC devices could alleviate voltage issues that can arise on networks that have large amounts of connected distributed generation. This is a particular issue within WPD’s more rural areas such as the far South West and the farther reaches of the East Midlands.

The project was had two distinct phases with stage gates at key points along the way. Phase 1 being the discovery phase, and Phase 2 being the test and build in lab and field conditions. The project had a stage gate after the Discovery phase.

8.2 Performance Relative to its Aims, Objectives and Success Criteria

The project was terminated early after phase one after it showed that the D-SVC was not capable of making significant differences to the network voltage on typical 11kV rural networks even with specifically designed transformers.

Within Phase 1 we were still able to deliver the learning and demonstrate some of the objectives around integration and communications. The project performed against each success criteria as below.

- *Optimise multiple networked D-SVCs on the distribution network*: we were able to model and design and prove the concept at 33kV and above
- *Identify the appropriate impedance transformer and establish its sensitivity to the voltage control:* the detailed design was done and moreover indicated that a low impedance transformer would indeed help with the impact of the D-SVCs. However, there was not enough impact to make a significant difference due to the high impedance of the connected network and the relatively low reactance.
- *Develop a communication system for rural 11kV networks:* A detailed design was achieved for a rural 11kV network. As part of the communication design a system was derived. Initially a solution from Silverspring was considered however due to some operation issues, another solution was designed. Wood and Douglas radios were selected as they were able to communicate over two channels; our traditional SCADA and the meshed high speed IP based protocol required for the D-VQC real time control loop. This would have worked well by retaining reliable, traditional control to the devices for safety critical functions.
- *Implement a pole top sensor that measures real power, reactive power and voltage:* It was decided, to use the Nulecs for the pole top installations as they are well known and often installed.
- *Integrate control and data from the D-VQC and D-SVC systems into ENMAC/PowerOn Fusion:* the design included a DNP3 interface with PowerOn which presented the data from the D-VQC. The intention was that PowerOn would also have simple controls to completely stop and inhibit certain functionality of the system as part of the PowerOn diagram. However, the interface designed by Hitachi could only act as a server and not a client. The assessment was achieved but the build could not be done.
- *Develop a tap changer relay scheme that integrates with the D-VQC:* the design was achieved and we were going to implement the Supertapp N+ as it is able to receive controls over IP. This was going to be in the form of a percentage target from the D-VQC while maintaining all the traditional control functionally of the existing scheme.

9. Required modifications to the planned approach during the course of the project

The project was terminated. The project was terminated as the business case was compromised as it was established during the design phase that the D-SVCs do not control 11kV voltage.

The D-SVCs would not give a measurable voltage difference on the 11kV network even after a specific impedance transformer was designed for it. This was due to a combination of the D-SVC not being large enough and the network X/R ratio being too resistive.

In addition the interface developed by Hitachi for communication with PowerOn had the limitation that they were unable to act as a client to receive instructions from PowerOn.

We considered locating the D-SVCs at parts of the network with higher reactance such as adjacent to a primary transform however as all primary bars are controlled by tap changers this negates the impact of the D-SVC.

10. Significant variance in expected costs and benefits

The costs and benefits have a significant variance due to the decision to terminate the project early. Therefore only some of the budget has been spent. This is detailed below for reference.

Allocated budget and DNO contribution:

Project NIA Budget	£889,910.10
DNO Contribution	£98,878.90
Total Budget	£988,789.00

In terms of the expenditure it is detailed below:

Description	Forecast	Actual	Variation (%)
WPD Labour	£328,789.00	£21,341.90	-94%
Contractors	£176,000.00	£9,692.48	-94%
Equipment	£379,000.00	£141,465.01	-63%
Payments to Suppliers	£105,000.00	£77,750.00	-26%
Full Project Total	**£988,789.00**	**£250,249.39**	-75%

The labour and contractors were largely left unspent as the project did not get to the installation phase. The largest payment was to Hitachi, when we terminated the vast majority of the development work had been completed which was the majority of their costs. The D-SVC kit is to be donated to UK universities for educational purposes.

11. Lessons learnt for future Projects

The project showed that there is limited impact in deploying STATCOMs on the 11kV network due to their low reactance. Therefore it is suggested that implementation of this technology is concentrated on the 33kV, 66kV and 132kV networks.

The other elements of the project such as more sophisticated control of tapchangers, novel communication options and closer integration of third party equipment into PowerOn is now being investigated by other projects.

Coordinated system learning is relevant to more sophisticated control of 33kV, 66kV and 132kV connection systems similar to the designs on this project. From a broader perspective, a detailed investigation of the wider impact of reactive control is required considering reactive power support from generators. This would help to understand what capability these assets provide and the wider implications on tap changers, circuit breakers and overall network control(i.e. lots of big DG may be better than one SVC) .

It also enabled some potential for exploring the practicalities of controlling the Supertapp N+ over an IP protocol and prompted more detailed research into radios that can provide high bandwidth communications with IP support. This has been taken forward on Equilibrium, our most recent Tier 2 project.

A key learning has been the provision of stage gates during projects with key design/discovery phases. This enabled us to reflect and review the whole project at the end of a key stage and determine the progress and potential outcomes based on the original hypothesis. This key learning is being taken forward.

In addition we a reflecting on third party projects where there is a key piece of equipment that is procured as part of the project lifecycle at a point before the equipment has been properly assessed.

12. Planned implementation

The project showed the limitation of D-SVC at 11kV.

The project recommends that STATCOMs are connected at higher voltage levels which may offer more favourable X/R ratios and this is borne out by the Lincolnshire Low Carbon Hub project.

13. Facilitate Replication

Replication is not expected to occur.

13.3 Project IPR

No IPR was generated.

The D-SVC and the D-VQC control system are based on Background IPR owned by Hitachi. As part of the project the D-VQC has an open protocol developed to allow the system to communicate to non-Hitachi devices. The knowledge learnt from trying into incorporate this equipment into the DNO's systems is listed in the key learning outcomes in Sections six and seven.

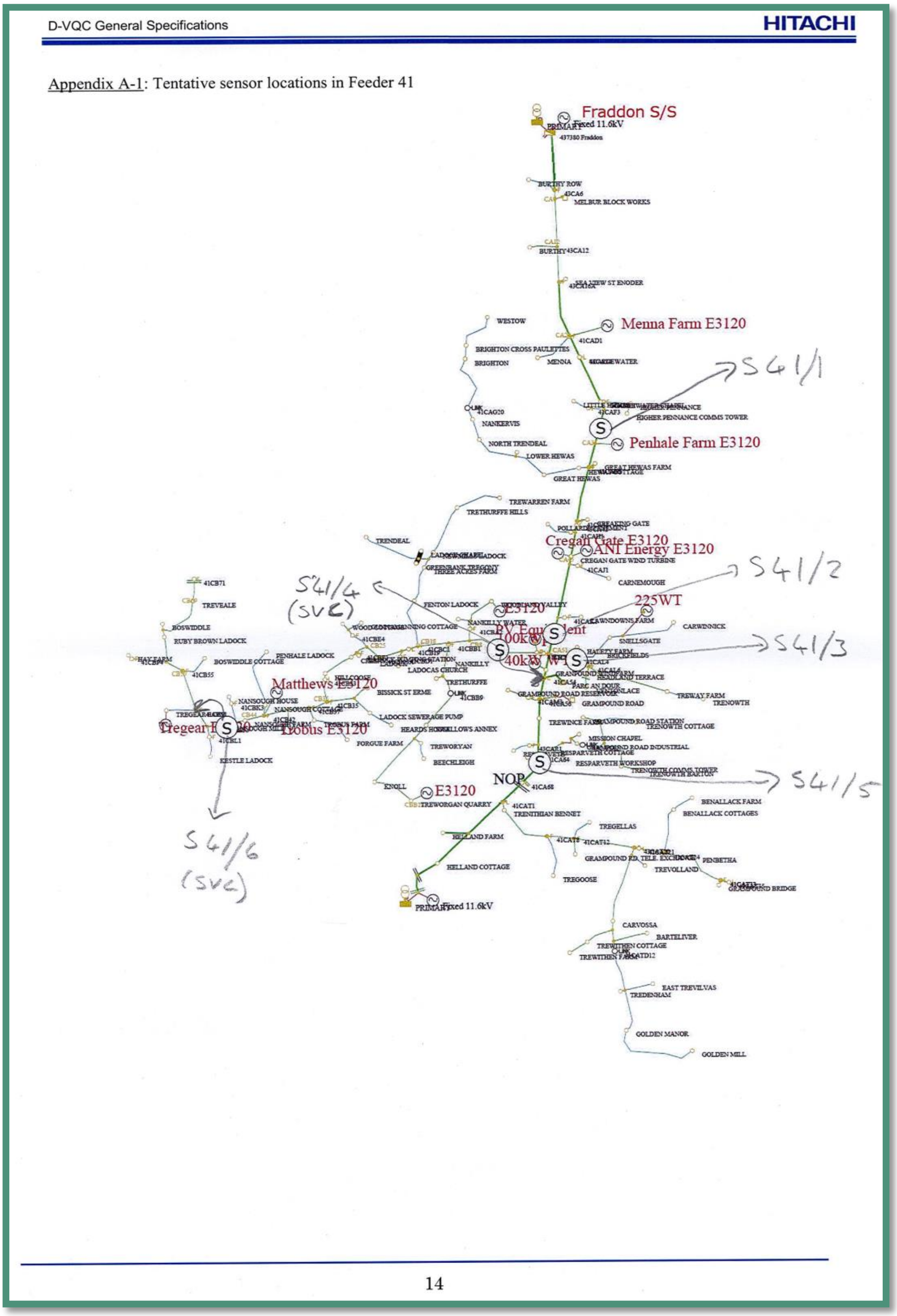
13.4 Points of Contact

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

- Future Networks Team, Western Power Distribution, Pegasus Business Park, Herald Way, Castle Donington, Derbyshire, DE74 2TU Email: wpdinnovation@westernpower.co.uk

Appendices

13.3.1 Appendix A: Feeder 41 Sensor Locations.pdf

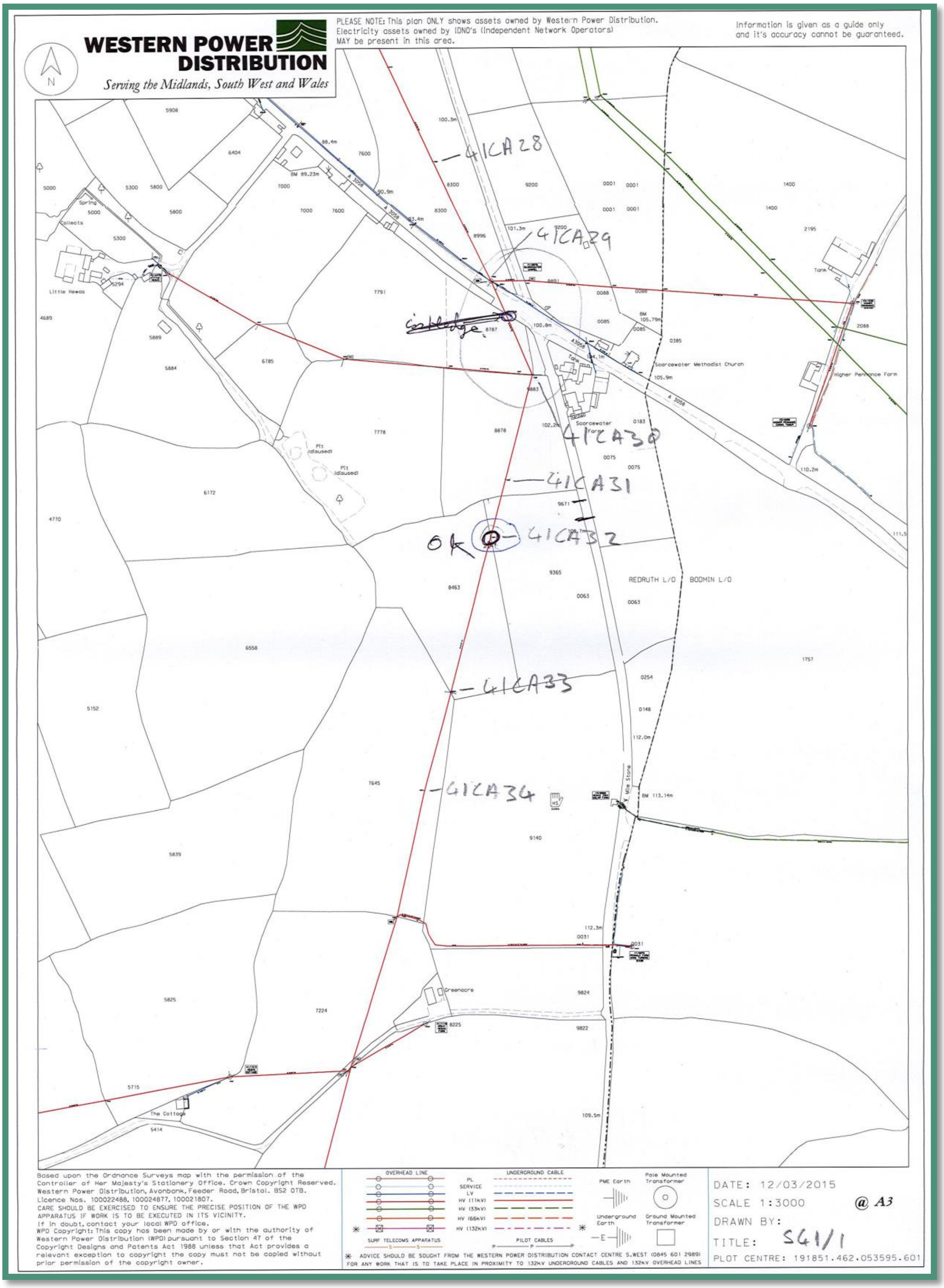


D-VQC General Specifications

HITACHI

Appendix A-1: Tentative sensor locations in Feeder 41

14



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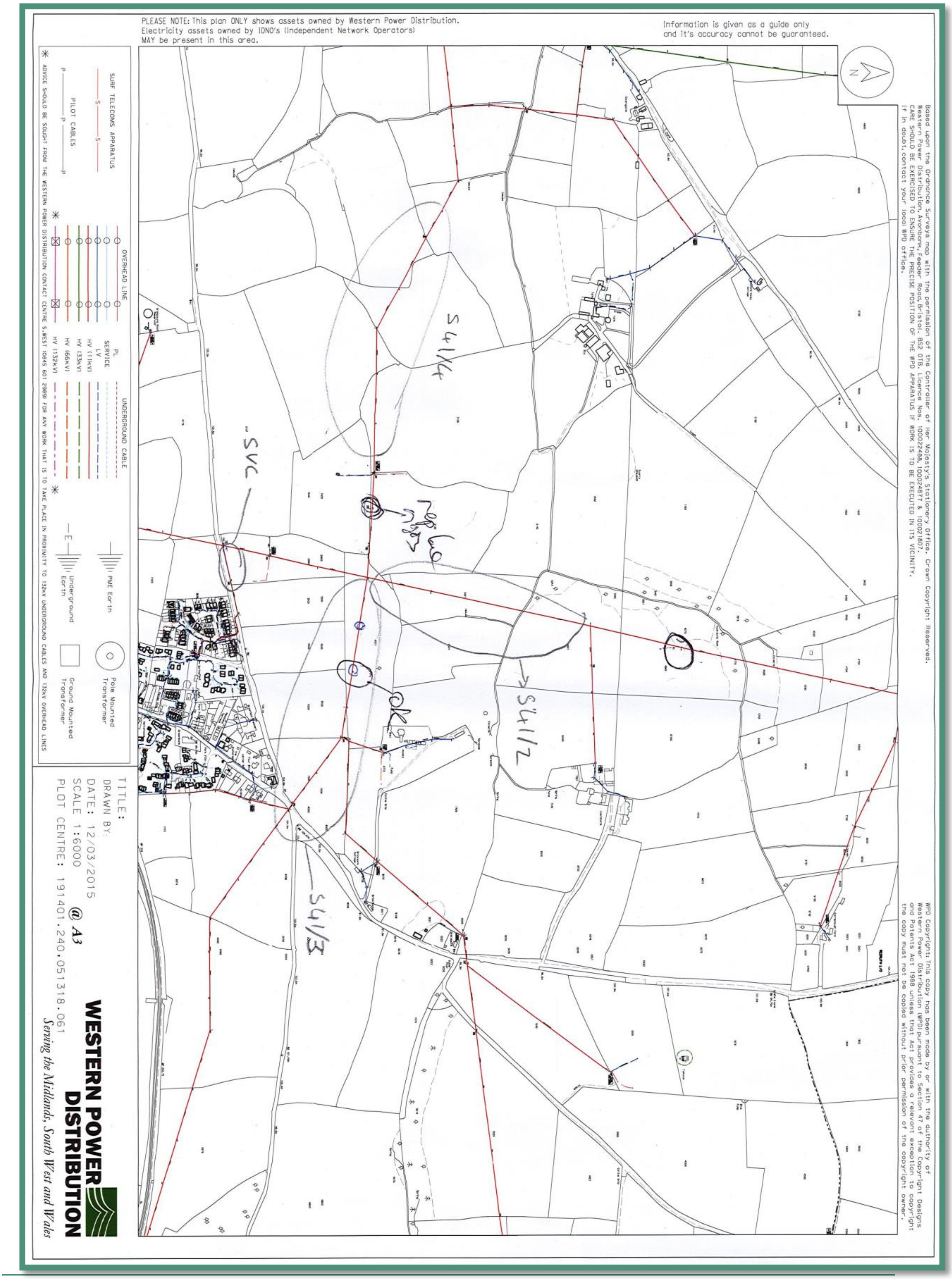
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OVERHEAD LINE
UNDERGROUND CABLE
PL
SERVICE
LV
HV (11kV)
HV (33kV)
HV (66kV)
HV (132kV)
SURF TELECOMS APPARATUS
PILOT CABLES
PME Earth
Underground Earth
Pole Mounted Transformer
Ground Mounted Transformer
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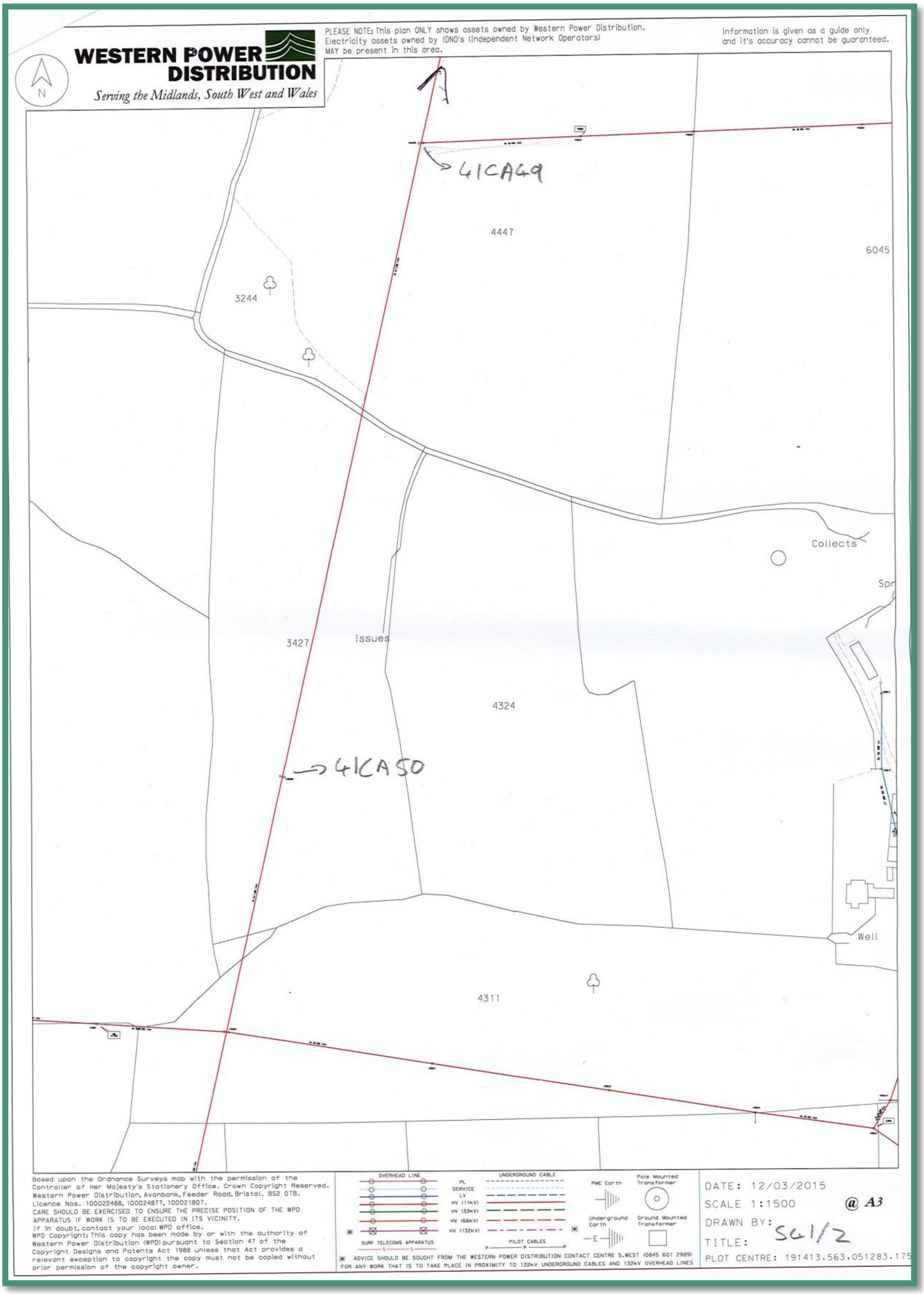
SVC
S41/4
S41/2
S41/3
OK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WESTERN POWER DISTRIBUTION
Serving the Midlands, South West and Wales
41CA49
4447
6045
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Collects
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Issues
4324
41CA50
Well
4311
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OVERHEAD LINE
UNDERGROUND CABLE
PL
SERVICE
LV
HV (11kV)
HV (33kV)
HV (66kV)
HV (132kV)
SURF TELECOMS APPARATUS
PILOT CABLES
PME Earth
Pole Mounted Transformer
Underground Earth
Ground Mounted Transformer
✳ ADVICE SHOULD BE SOUGHT FROM THE WESTERN POWER DISTRIBUTION CONTACT CENTRE S.WEST (0845 601 2989) FOR ANY WORK THAT IS TO TAKE PLACE IN PROXIMITY TO 132kV UNDERGROUND CABLES AND 132kV OVERHEAD LINES
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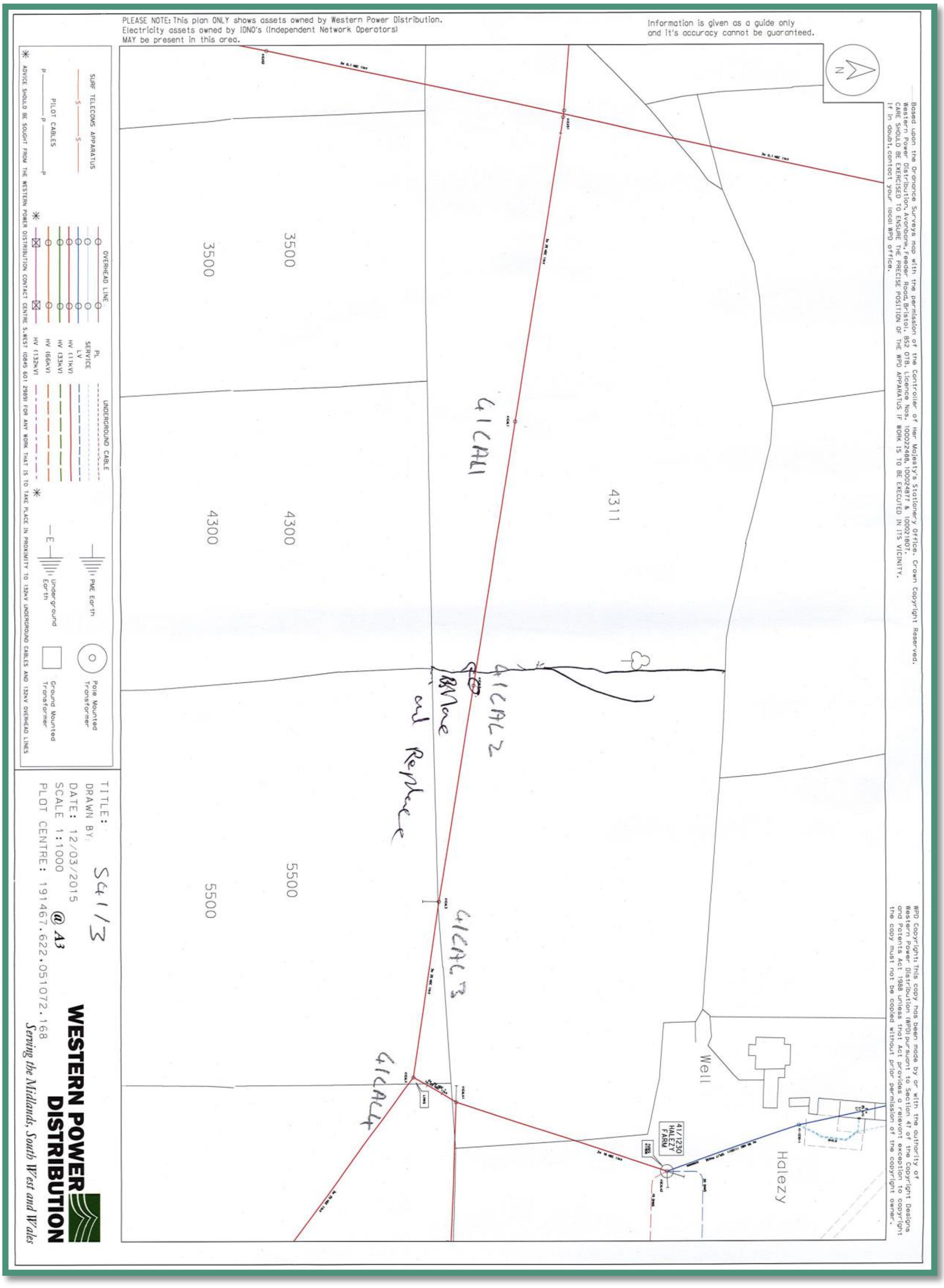
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N
SURF TELECOMS APPARATUS
PILOT CABLES
OVERHEAD LINE
UNDERGROUND CABLE
PL
SERVICE
LV
HV (11kV)
HV (33kV)
HV (66kV)
HV (132kV)
PME Earth
Underground Earth
Pole Mounted Transformer
Ground Mounted Transformer
* ADVICE SHOULD BE SOUGHT FROM THE WESTERN POWER DISTRIBUTION CONTACT CENTRE S.WEST (0845 601 2989) FOR ANY WORK THAT IS TO TAKE PLACE IN PROXIMITY TO 132kV UNDERGROUND CABLES AND 132kV OVERHEAD LINES
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3500
3500
4300
4300
4311
5500
5500
41CAL1
41CAL2
41CAL3
41CAL4
Remove and Replace
Well
Halezy
41/1230 HALEZY FARM
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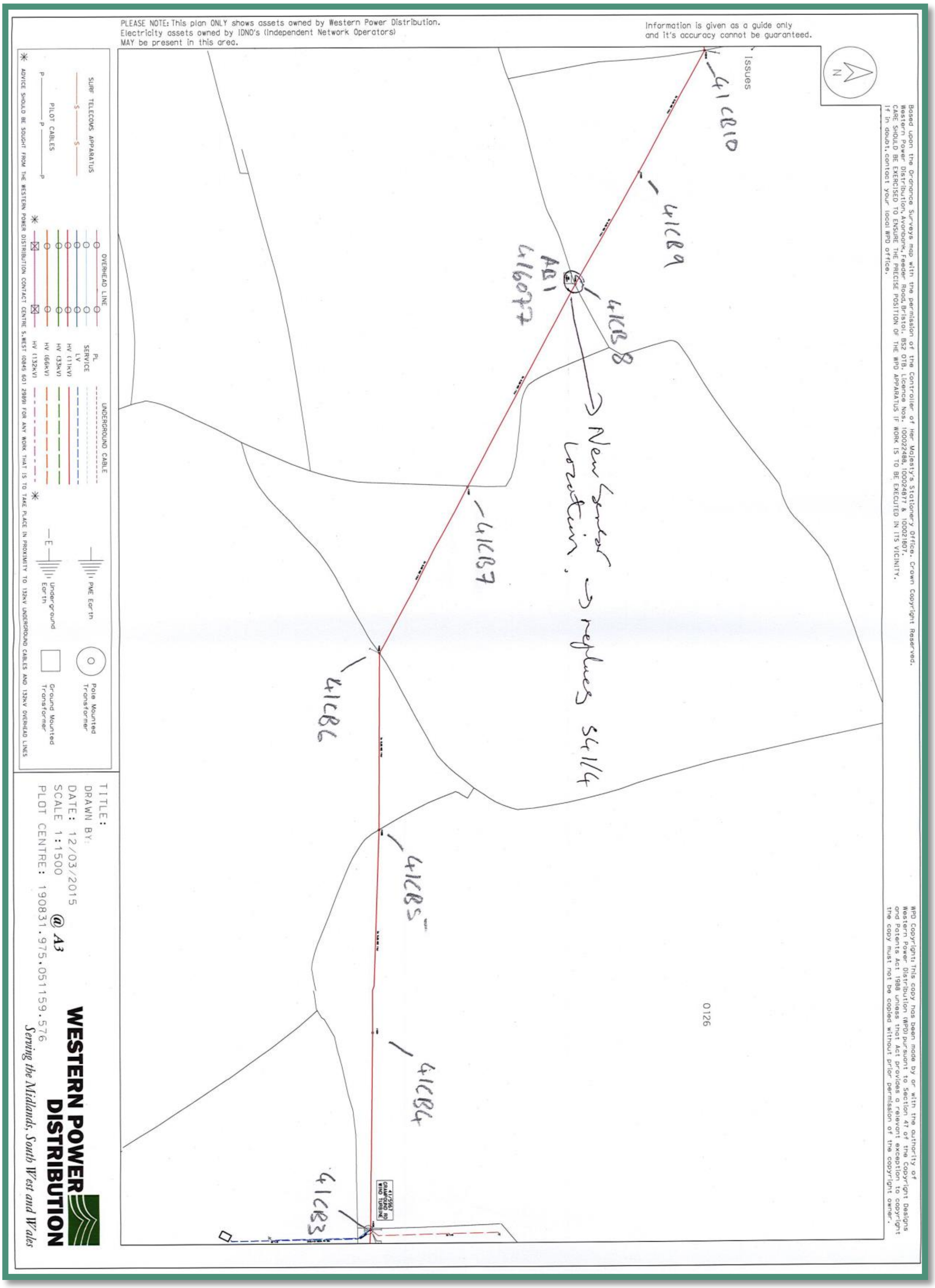
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41CB9
AB1
416077
41CB8
New Sensor location, replaces 54/1/4
41CB7
41CB6
41CB5
41CB4
41CB3
0126
OVERHEAD LINE
UNDERGROUND CABLE
PL
SERVICE
LV
HV (11kV)
HV (33kV)
HV (66kV)
HV (132kV)
SURF TELECOMS APPARATUS
PILOT CABLES
PME Earth
Underground Earth
Pole Mounted Transformer
Ground Mounted Transformer
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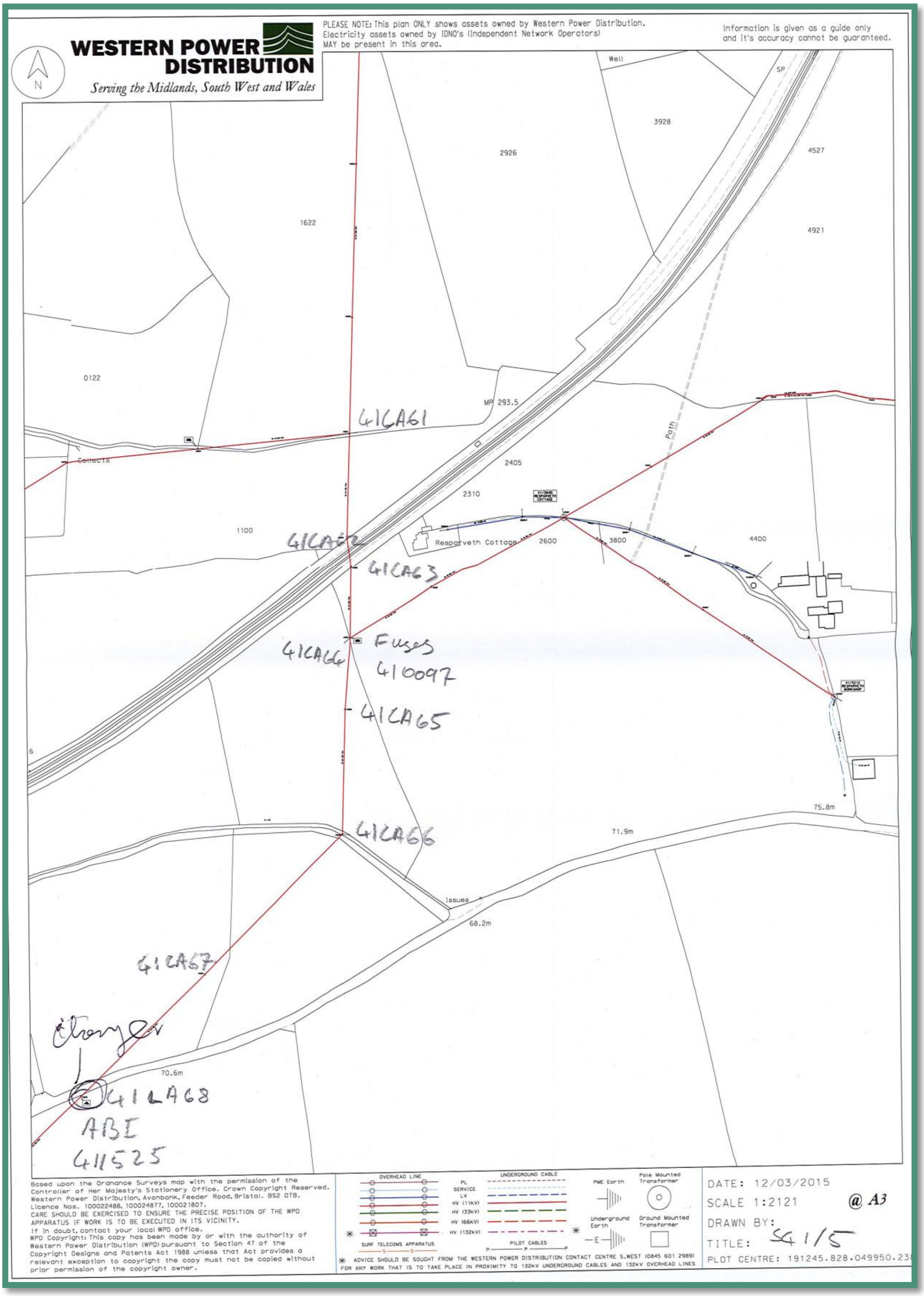

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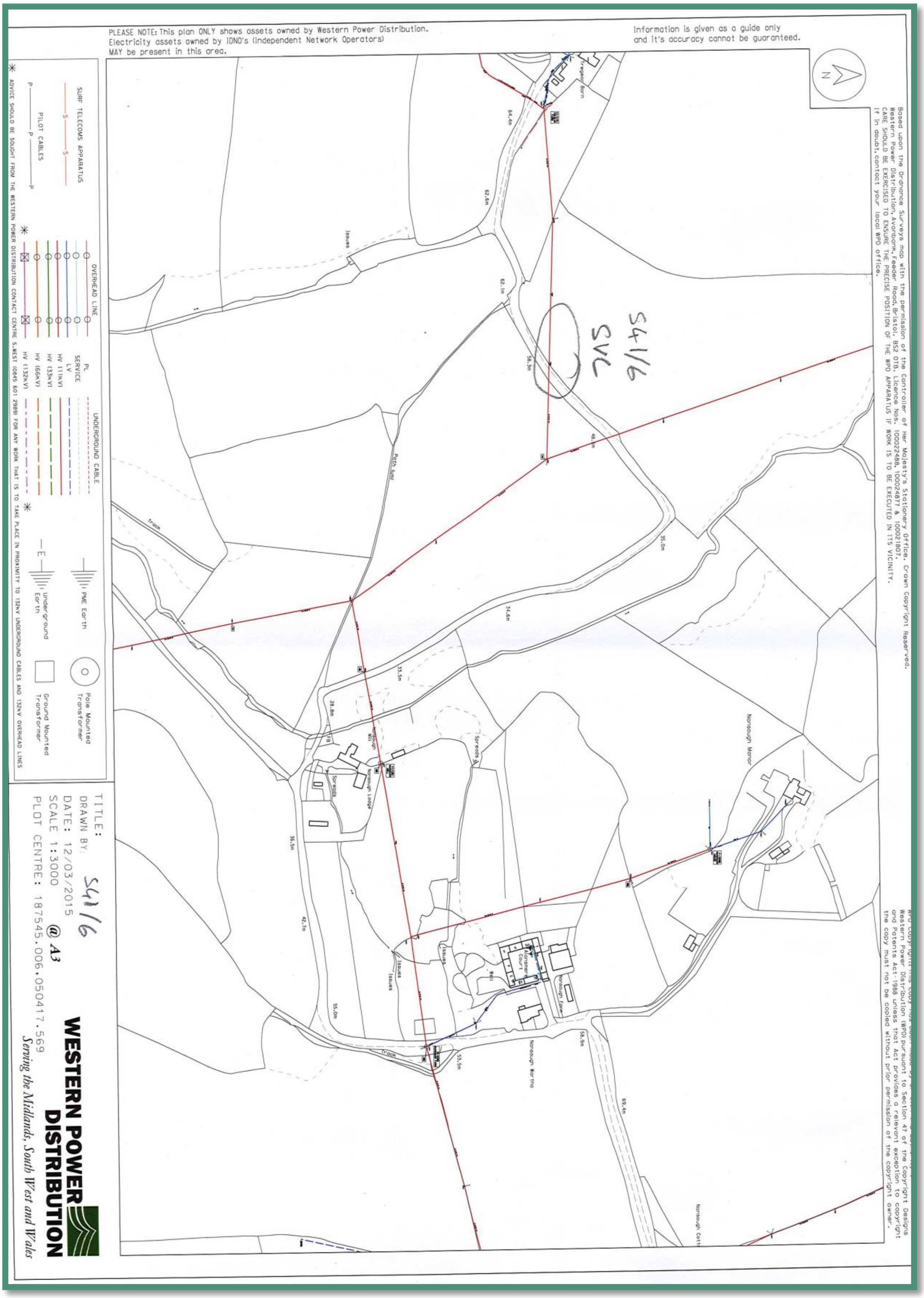
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PILOT CABLES
OVERHEAD LINE
UNDERGROUND CABLE
PL
SERVICE
LV
HV (11kV)
HV (33kV)
HV (66kV)
HV (132kV)
PME Earth
Underground Earth
Pole Mounted Transformer
Ground Mounted Transformer
* ADVICE SHOULD BE SOUGHT FROM THE WESTERN POWER DISTRIBUTION CONTACT CENTRE S.WEST (0845 601 2989) FOR ANY WORK THAT IS TO TAKE PLACE IN PROXIMITY TO 132kV UNDERGROUND CABLES AND 132kV OVERHEAD LINES
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Serving the Midlands, South West and Wales
S41/6
SVC
Nansough Manor
Nansough Farm
Nansough Lodge
Issues
Track
Path (um)
Spreads
64.4m
62.6m
62.1m
58.3m
35.0m
34.6m
33.5m
28.8m
36.5m
42.1m
55.0m
58.9m
69.4m
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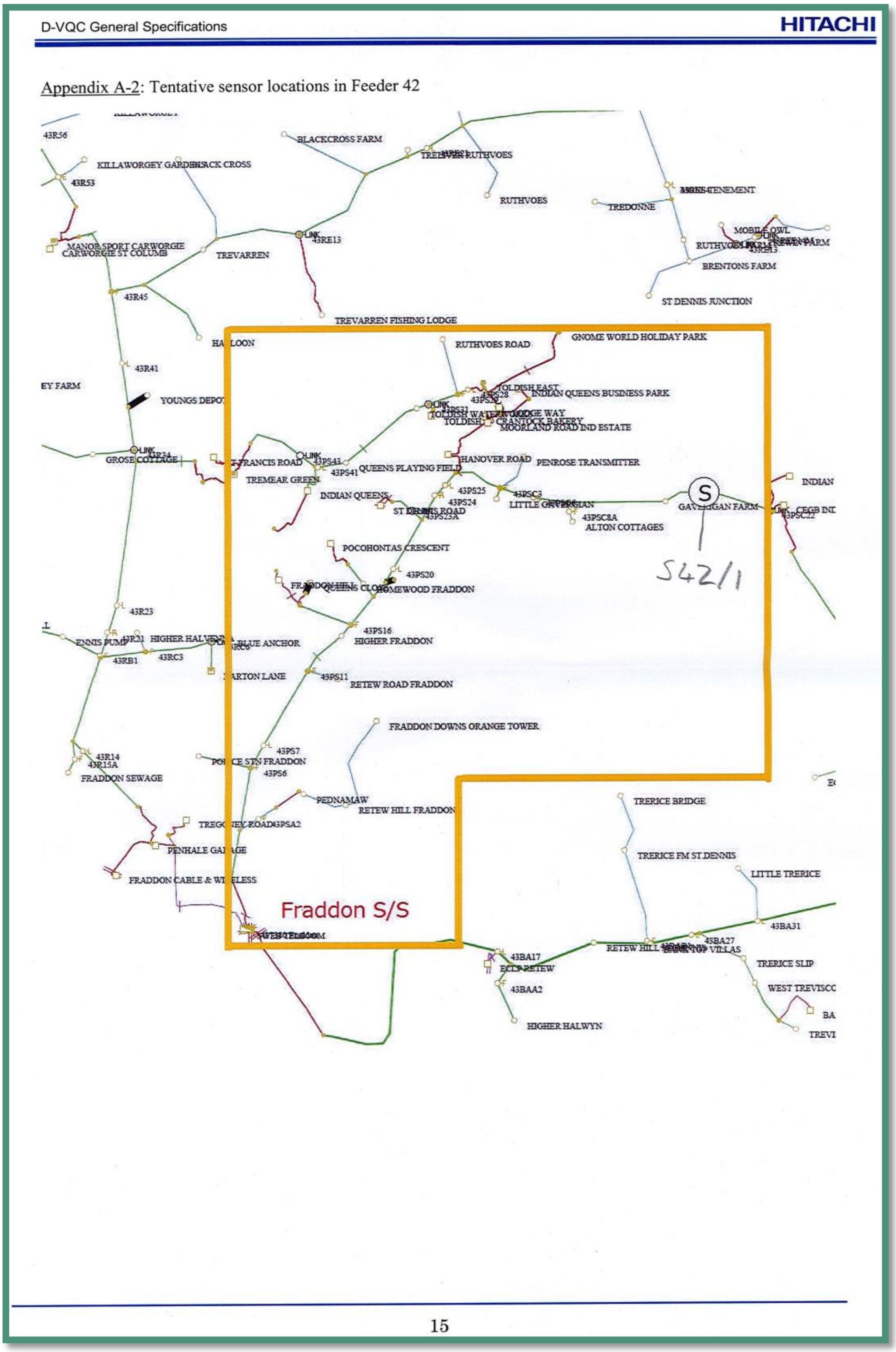
13.3.2 Appendix B: Feeder 42 Sensor Locations.pdf

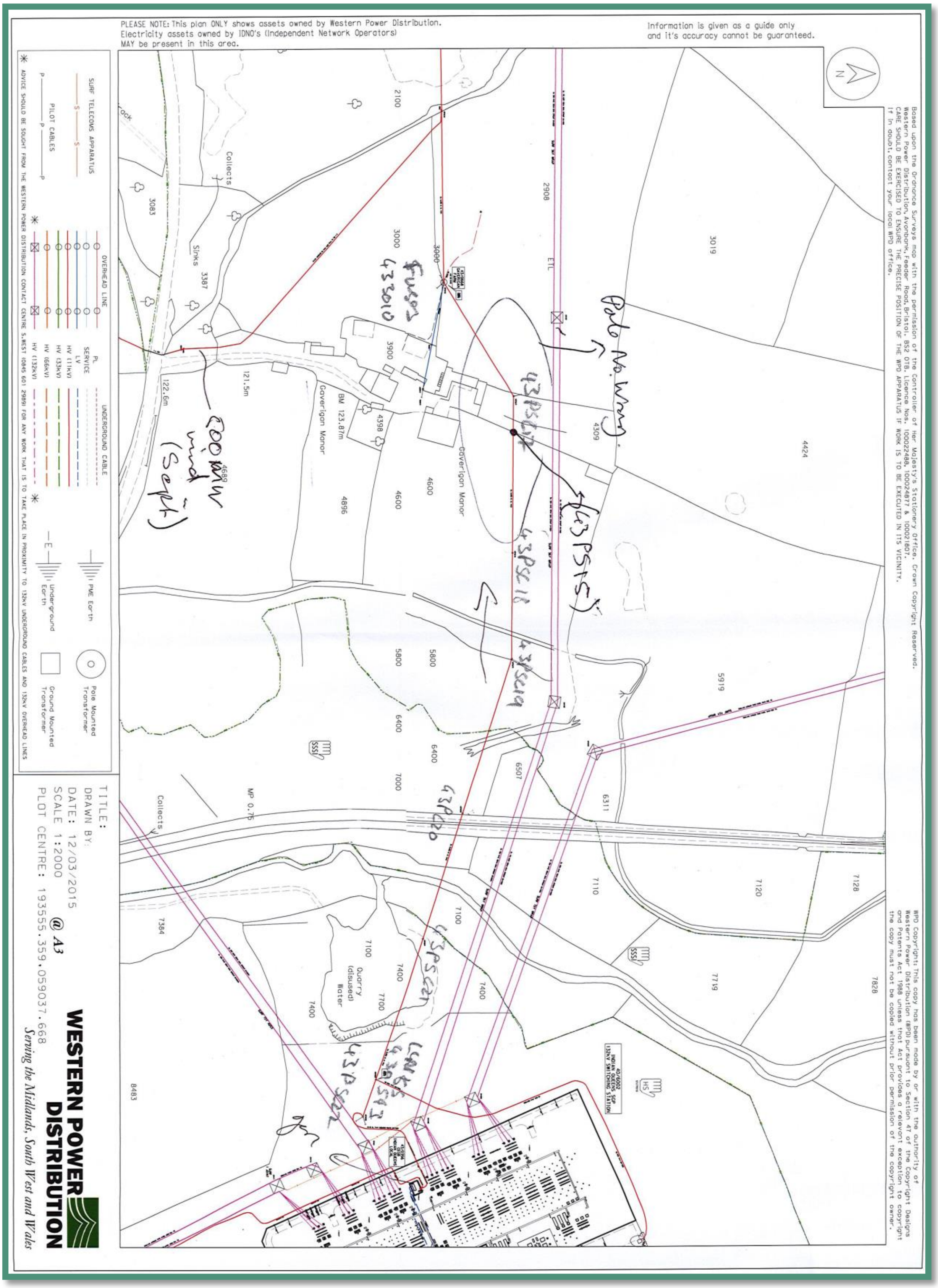
D-VQC General Specifications

HITACHI

Appendix A-2: Tentative sensor locations in Feeder 42



15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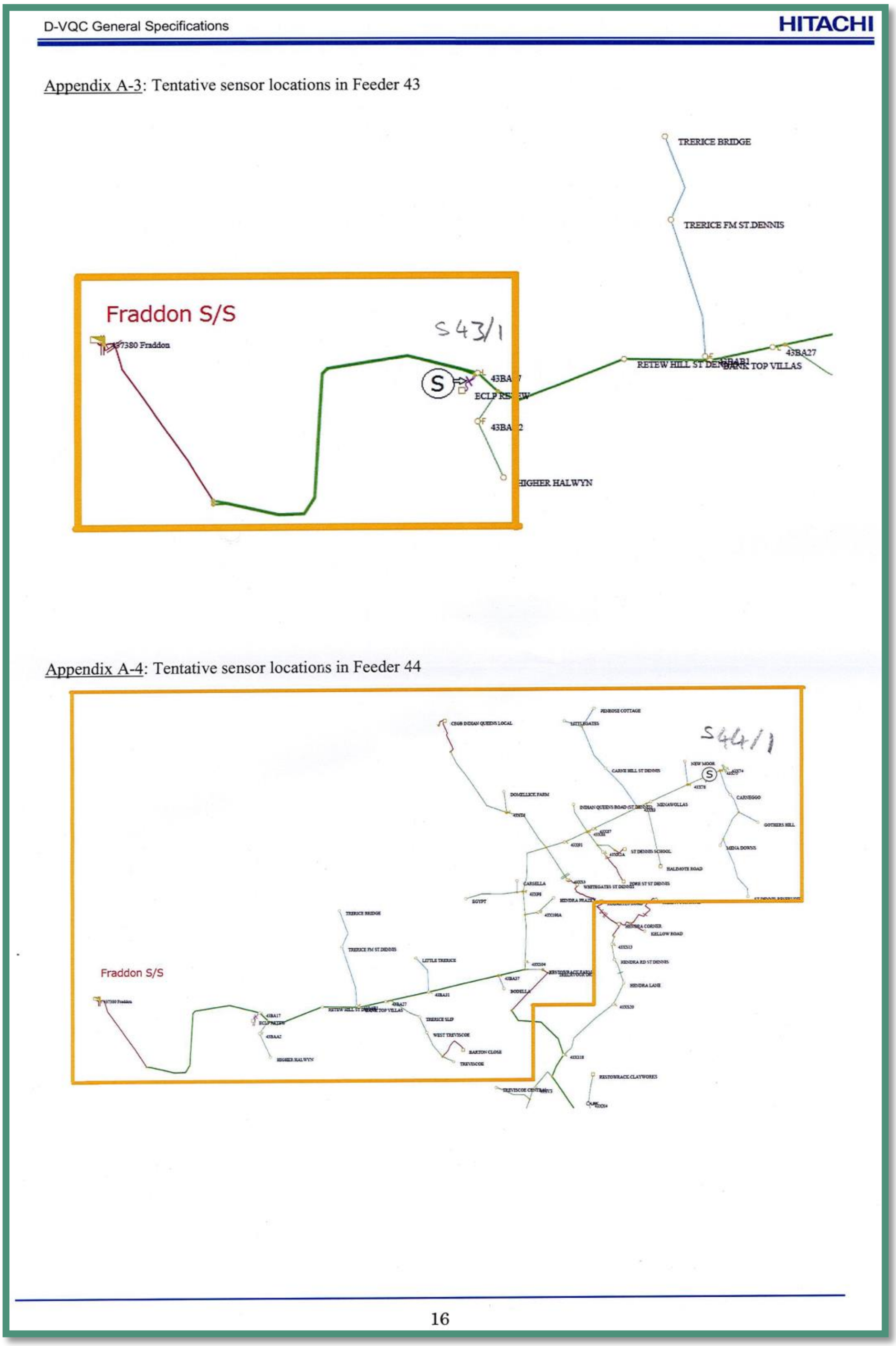
OVERHEAD LINE
UNDERGROUND CABLE
PL
SERVICE
LV
HV (11kV)
HV (33kV)
HV (66kV)
HV (132kV)
SWBF TELECOMS APPARATUS
PILOT CABLES
PME Earth
Underground Earth
Pole Mounted Transformer
Ground Mounted Transformer
ADVICE SHOULD BE SOUGHT FROM THE WESTERN POWER DISTRIBUTION CONTACT CENTRE S.WEST (0845 601 2989) FOR ANY WORK THAT IS TO TAKE PLACE IN PROXIMITY TO 132kV UNDERGROUND CABLES AND 132kV OVERHEAD LINES
TITLE:
DRAWN BY:
DATE: 12/03/2015
SCALE 1:2000 @ A3
PLOT CENTRE: 193555.359,059037.668
WESTERN POWER DISTRIBUTION
Serving the Midlands, South West and Wales
Gaverigan Manor
Collects
Sinks
Quarry (disused) Water
Pole No. Wray
Fuses 432010
43PS17
(43PS15)
43PS18
43PS19
43P20
43PS21
Links 43PS41
43PS22
200kW mid (Sept)

13.3.3 Appendix C: Feeder 43 and 44 Sensor Locations.pdf



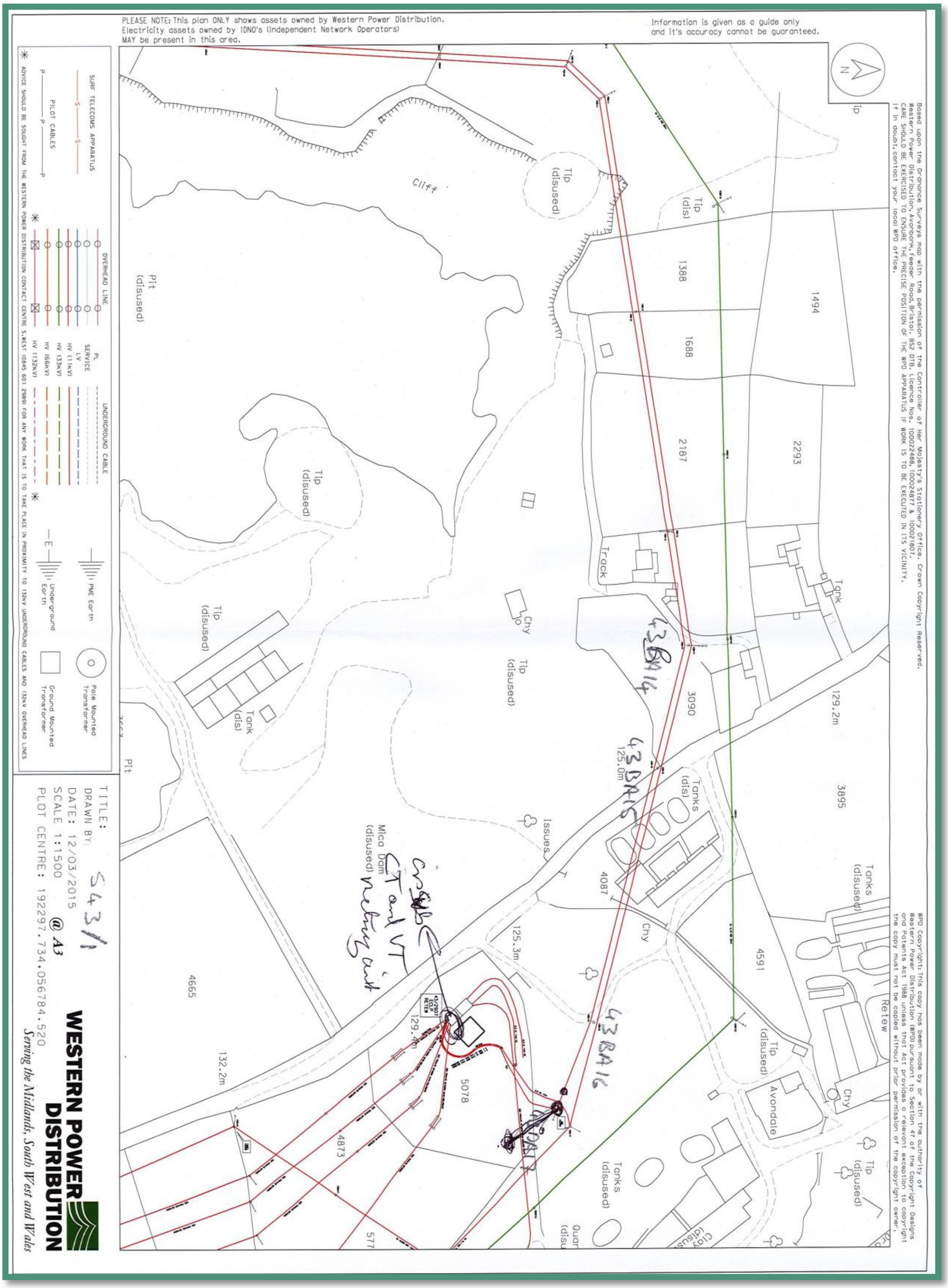
D-VQC General Specifications

HITACHI

Appendix A-3: Tentative sensor locations in Feeder 43

Appendix A-4: Tentative sensor locations in Feeder 44

16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OVERHEAD LINE
UNDERGROUND CABLE
PL
SERVICE
LV
HV (11kV)
HV (33kV)
HV (66kV)
HV (132kV)
SURF TELECOMS APPARATUS
PILOT CABLES
PME Earth
Underground Earth
Pole Mounted Transformer
Ground Mounted Transformer
* ADVICE SHOULD BE SOUGHT FROM THE WESTERN POWER DISTRIBUTION CONTACT CENTRE S.WEST (0845 601 2989) FOR ANY WORK THAT IS TO TAKE PLACE IN PROXIMITY TO 132kV UNDERGROUND CABLES AND 132kV OVERHEAD LINES
TITLE: S43/1
DRAWN BY:
DATE: 12/03/2015
SCALE 1:1500 @ A3
PLOT CENTRE: 192297.734,056784.520
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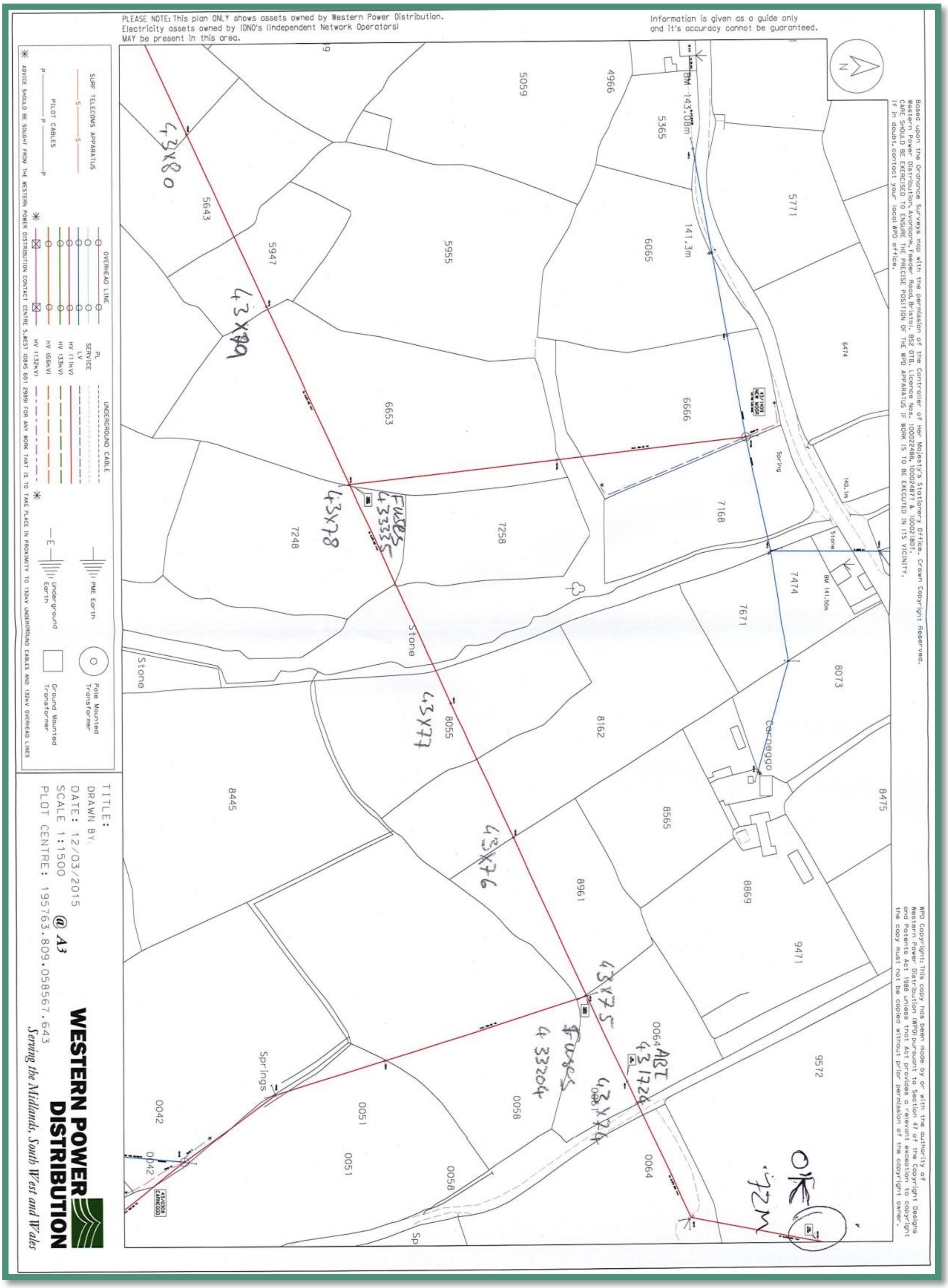
Cliff
Tip (disused)
Pit (disused)
1388
1494
1688
2187
2293
Track
Tank
Chy
3090
129.2m
125.0m
Tanks (dis)
3895
Issues
4087
Tanks (disused)
4591
125.3m
4665
Mica Dam (disused)
129.4m
5078
132.2m
4873
Avondale
Retew
43BA14
43BA15
43BA16
cable CT and VT metering unit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OVERHEAD LINE
UNDERGROUND CABLE
PL
SERVICE
LV
HV (11kV)
HV (33kV)
HV (66kV)
HV (132kV)
SURF TELECOMS APPARATUS
PILOT CABLES
PME Earth
Underground Earth
Pole Mounted Transformer
Ground Mounted Transformer
ADVICE SHOULD BE SOUGHT FROM THE WESTERN POWER DISTRIBUTION CONTACT CENTRE S.WEST (0845 601 2989) FOR ANY WORK THAT IS TO TAKE PLACE IN PROXIMITY TO 132kV UNDERGROUND CABLES AND 132kV OVERHEAD LINES
TITLE:
DRAWN BY:
DATE: 12/03/2015
SCALE 1:1500 @ A3
PLOT CENTRE: 195763.809.058567.643
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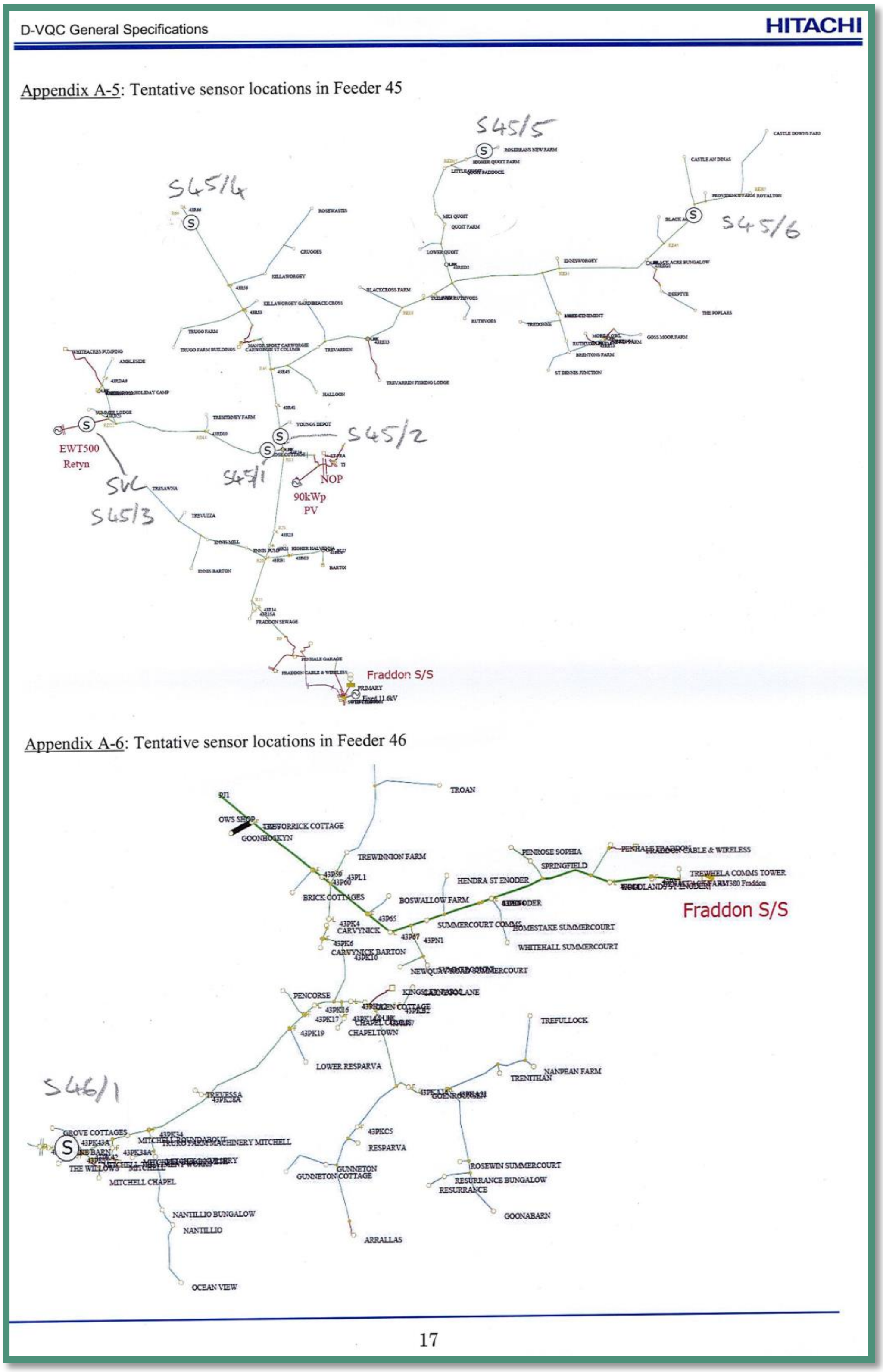
BM 143.08m
141.3m
140.1m
BM 141.50m
Spring
Stone
Springs
Carnego
43X80
43X79
43X78
Fuses 4 33335
43X77
43X76
43X75
Fuses 4 33204
ABT 43 1726
43X74
OK
72M

13.3.4 Appendix D: Feeder 45 and 46 Sensor Locations.pdf



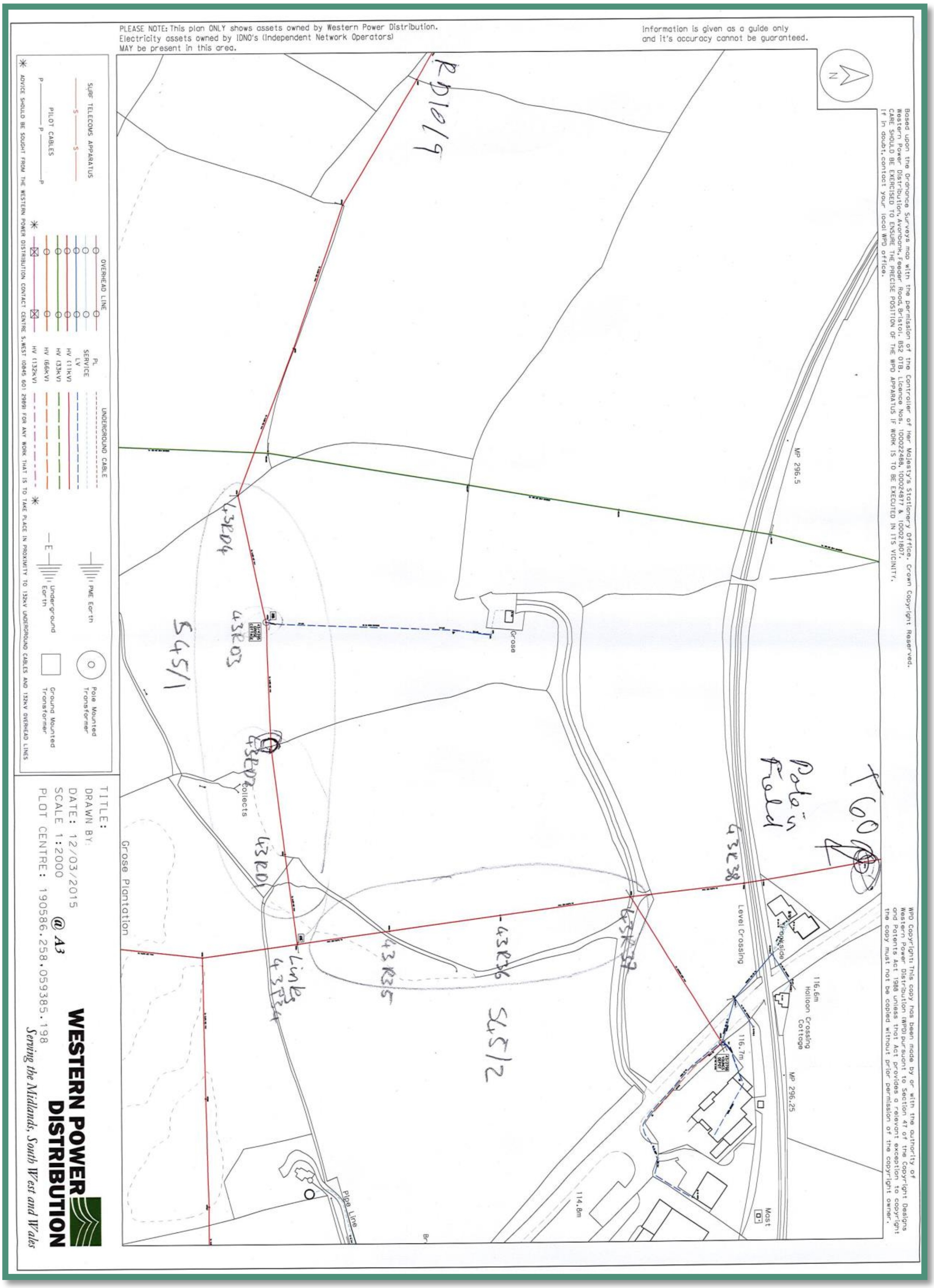
D-VQC General Specifications

HITACHI

Appendix A-5: Tentative sensor locations in Feeder 45

Appendix A-6: Tentative sensor locations in Feeder 46

17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If in doubt, contact your local WPD office.
RD1019
43R04
43R03
S45/1
43R02
Collects
43R01
Link
43R34
43R35
43R36
43R37
S45/2
43R38
Pole in Field
T60
Grose
Grose Plantation
Level Crossing
MP 296.5
MP 296.25
116.6m
116.7m
114.8m
Halloon Crossing Cottage
Mast
Pipe Line
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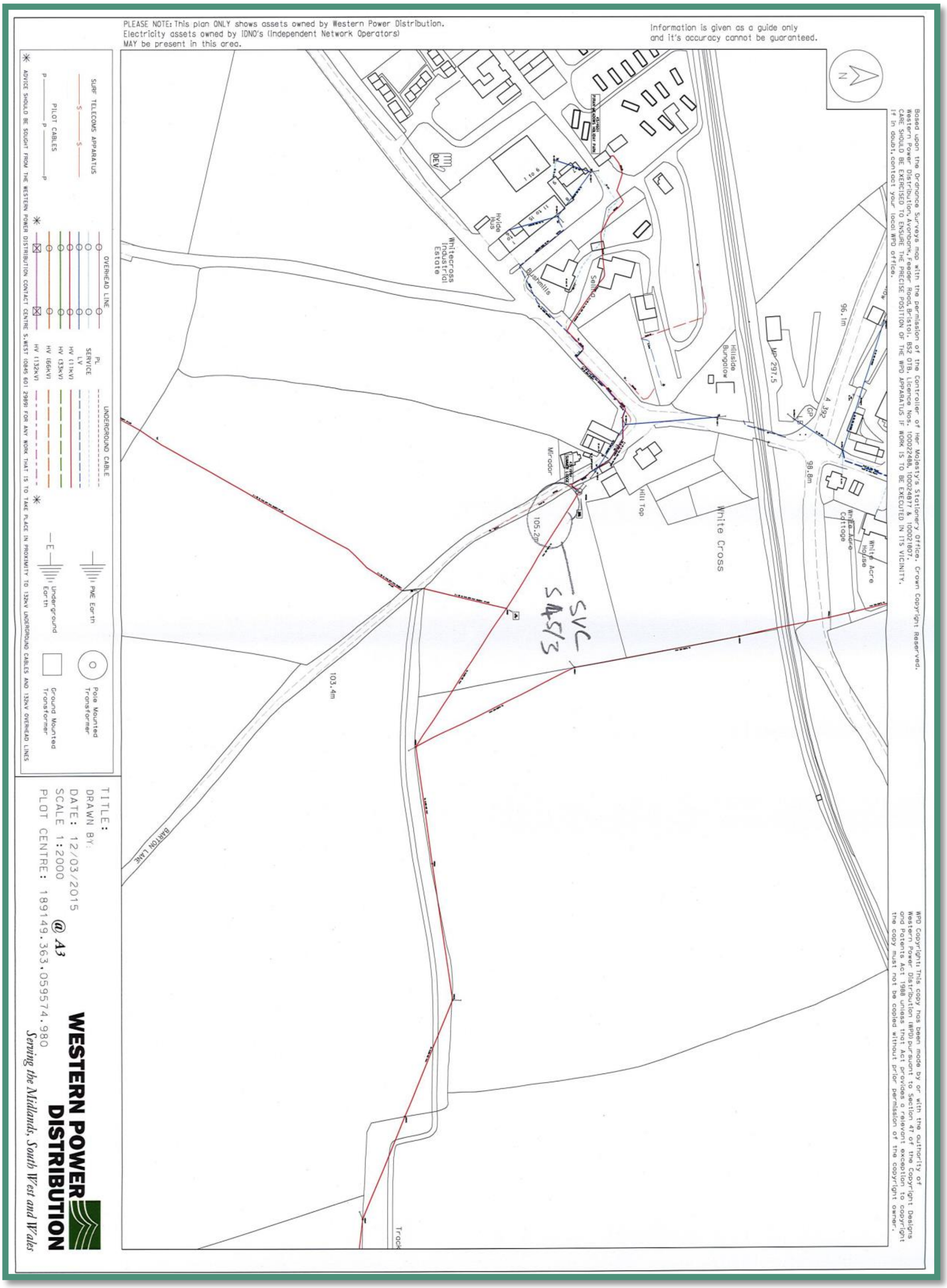
OVERHEAD LINE
UNDERGROUND CABLE
PL
SERVICE
LV
HV (11kV)
HV (33kV)
HV (66kV)
HV (132kV)
SURF TELECOMS APPARATUS
PILOT CABLES
PME Earth
Underground Earth
Pole Mounted Transformer
Ground Mounted Transformer
ADVICE SHOULD BE SOUGHT FROM THE WESTERN POWER DISTRIBUTION CONTACT CENTRE S.WEST (0845 601 2989) FOR ANY WORK THAT IS TO TAKE PLACE IN PROXIMITY TO 132kV UNDERGROUND CABLES AND 132kV OVERHEAD LINES
TITLE:
DRAWN BY:
DATE: 12/03/2015
SCALE 1:2000 @ A3
PLOT CENTRE: 190586.258.059385.198
WESTERN POWER DISTRIBUTION
Serving the Midlands, South West and Wales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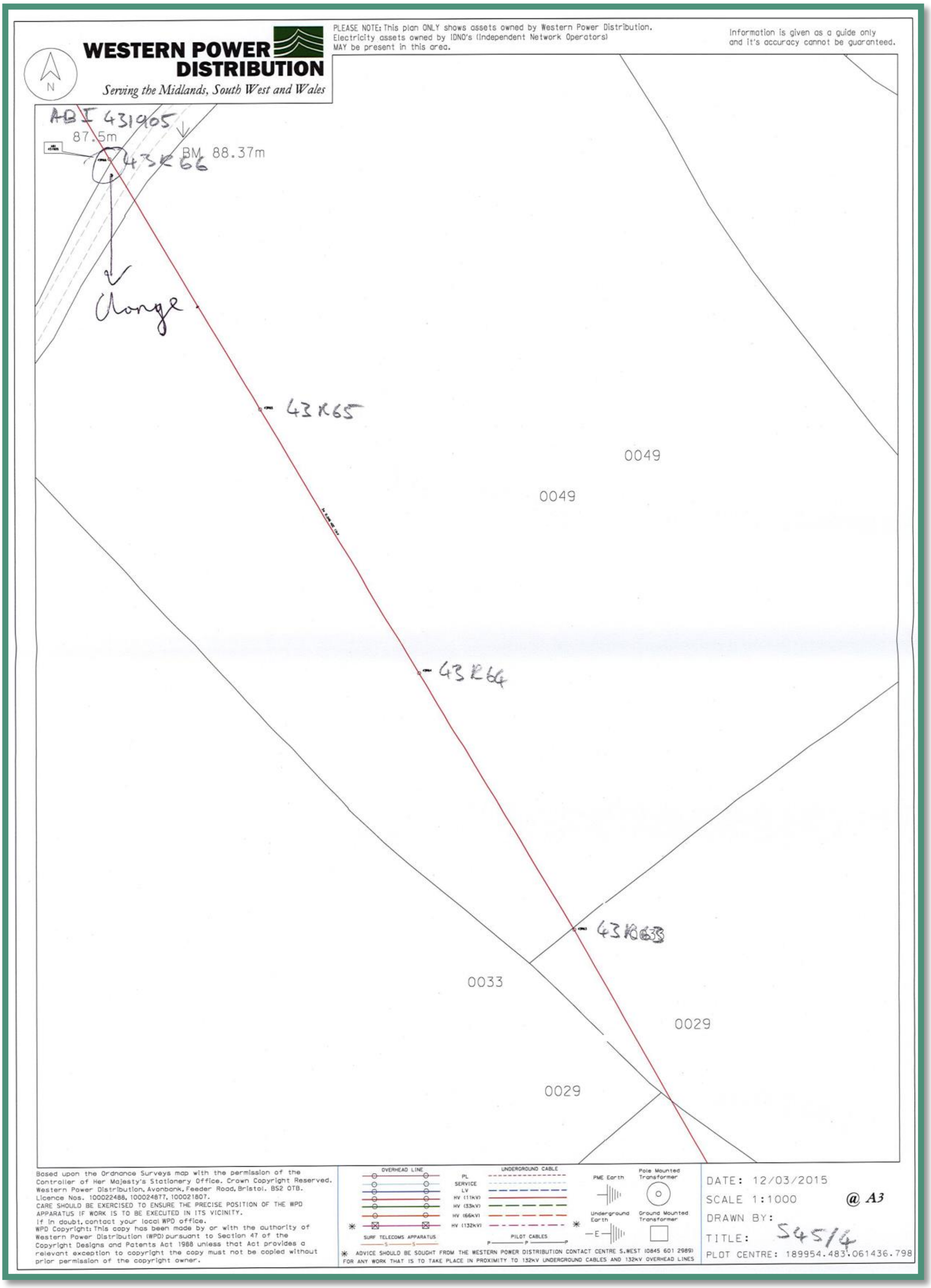
SURF TELECOMS APPARATUS
PILOT CABLES
OVERHEAD LINE
UNDERGROUND CABLE
PL
SERVICE
LV
HV (11kV)
HV (33kV)
HV (66kV)
HV (132kV)
ADVICE SHOULD BE SOUGHT FROM THE WESTERN POWER DISTRIBUTION CONTACT CENTRE S.WEST (0845 601 2989) FOR ANY WORK THAT IS TO TAKE PLACE IN PROXIMITY TO 132kV UNDERGROUND CABLES AND 132kV OVERHEAD LINES
PME Earth
Underground Earth
Pole Mounted Transformer
Ground Mounted Transformer
TITLE:
DRAWN BY:
DATE: 12/03/2015
SCALE 1:2000 @ A3
PLOT CENTRE: 189149.363,059574.980
WESTERN POWER DISTRIBUTION
Serving the Midlands, South West and Wales
Whitecross Industrial Estate
Hillside Bungalow
Mirador
Hill Top
White Cross
White Acre Cottage
White Acre House
A 392
MP 297.5
96.1m
98.8m
105.2m
103.4m
BARTON LANE
Track
SVC S45/3



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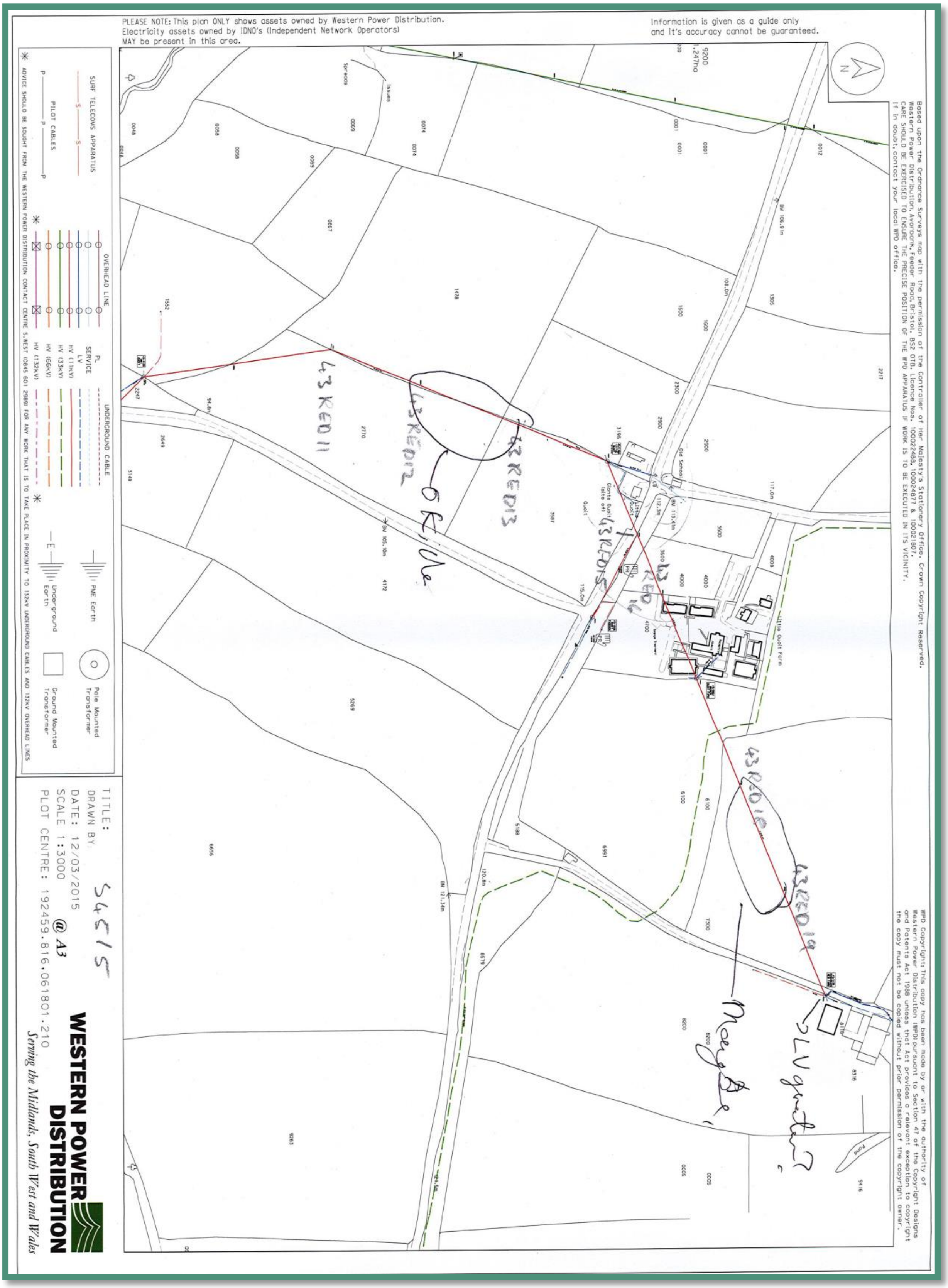
DATE: 12/03/2015
SCALE 1:1000 @ A3
DRAWN BY:
TITLE: S45/4
PLOT CENTRE: 189954.483,061436.798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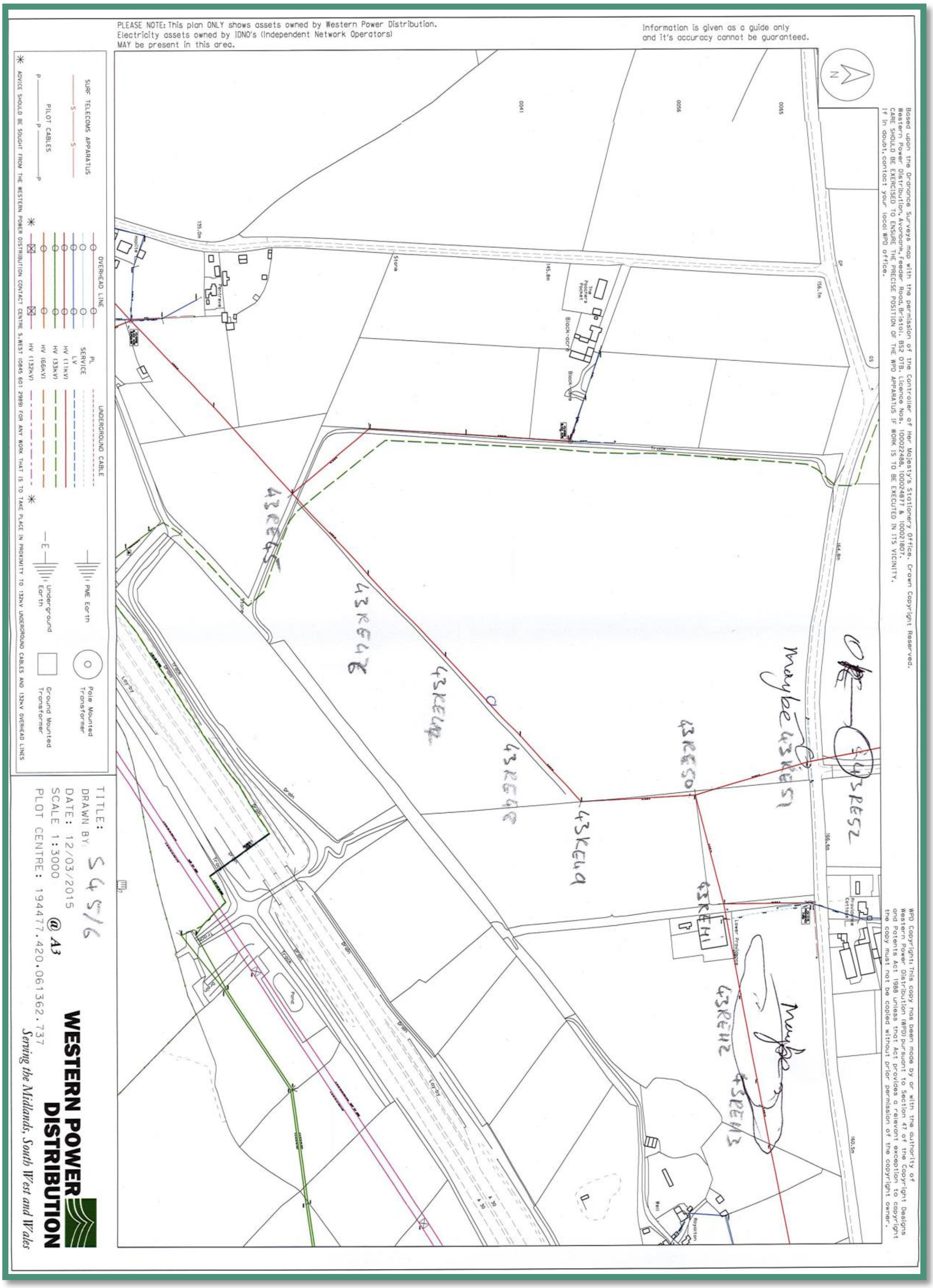
OVERHEAD LINE
UNDERGROUND CABLE
PL
SERVICE
LV
HV (11kV)
HV (33kV)
HV (66kV)
HV (132kV)
SURF TELECOMS APPARATUS
PILOT CABLES
PME Earth
Underground Earth
Pole Mounted Transformer
Ground Mounted Transformer
TITLE:
DRAWN BY:
DATE: 12/03/2015
SCALE 1:3000 @ A3
PLOT CENTRE: 192459.816.061801.210
S4515
WESTERN POWER DISTRIBUTION
Serving the Midlands, South West and Wales
43REO11
43REO12
43REO13
OK/ide
43REO15
43REO16
43REO18
43REO19
LV quota?
Maybe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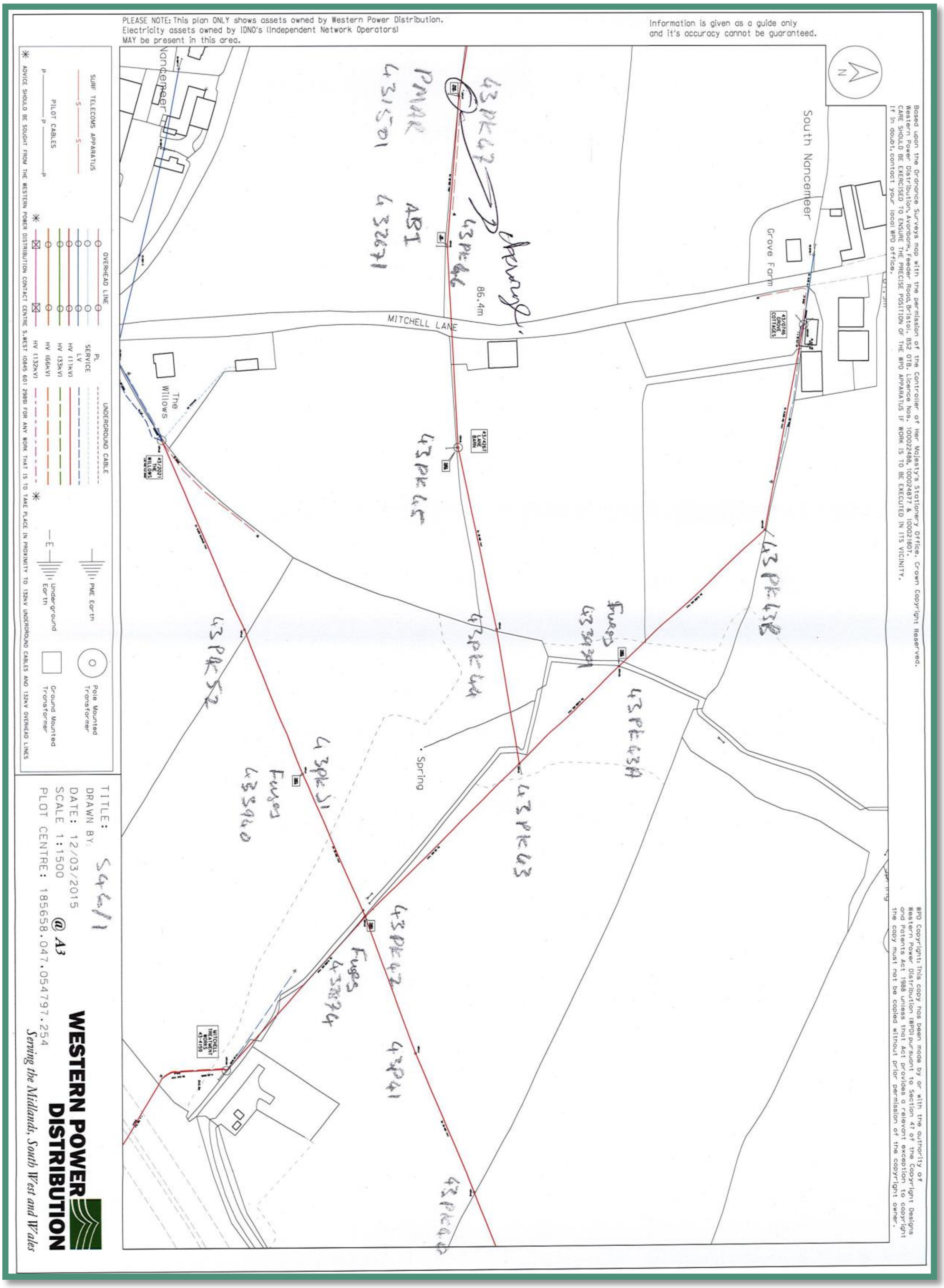
OVERHEAD LINE
UNDERGROUND CABLE
PL
SERVICE
LV
HV (11kV)
HV (33kV)
HV (66kV)
HV (132kV)
SURF TELECOMS APPARATUS
PILOT CABLES
PME Earth
Underground Earth
Pole Mounted Transformer
Ground Mounted Transformer
ADVICE SHOULD BE SOUGHT FROM THE WESTERN POWER DISTRIBUTION CONTACT CENTRE S.WEST (0845 601 2989) FOR ANY WORK THAT IS TO TAKE PLACE IN PROXIMITY TO 132kV UNDERGROUND CABLES AND 132kV OVERHEAD LINES
TITLE:
DRAWN BY: S4 S/6
DATE: 12/03/2015
SCALE 1:3000 @ A3
PLOT CENTRE: 194477.420.061362.737
WESTERN POWER DISTRIBUTION
Serving the Midlands, South West and Wales
Track
Store
Drain
Lay-by
Pond
Providence Cottage
Lower Providence
Royston
Well
135.0m
145.8m
156.1m
164.8m
166.4m
160.5m
43KE45
43KE46
43KE47
43KE48
43KE49
43KE50
Maybe 43KE51
OK
43KE52
43KE41
43KE42
Maybe 43KE43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SURF TELECOMS APPARATUS
PILOT CABLES
OVERHEAD LINE
UNDERGROUND CABLE
PL
SERVICE
LV
HV (11kV)
HV (33kV)
HV (66kV)
HV (132kV)
PME Earth
Underground Earth
Pole Mounted Transformer
Ground Mounted Transformer
ADVICE SHOULD BE SOUGHT FROM THE WESTERN POWER DISTRIBUTION CONTACT CENTRE S.WEST (0845 601 2989) FOR ANY WORK THAT IS TO TAKE PLACE IN PROXIMITY TO 132kV UNDERGROUND CABLES AND 132kV OVERHEAD LINES
TITLE: Sq Eu/1
DRAWN BY:
DATE: 12/03/2015
SCALE 1:1500 @ A3
PLOT CENTRE: 185658.047,054797.254
WESTERN POWER DISTRIBUTION
Serving the Midlands, South West and Wales
South Nancemeer
Nancemeer
Grove Farm
MITCHELL LANE
86.4m
The Willows
Spring
43PK47
PMAR
431501
change
43PK46
ABI
432671
43PK45
43PK44
43PK43
43PK43A
43PK43B
Fuses
433424
43PK52
43PK51
Fuses
433940
43PK42
Fuses
433874
43PK41
43PK40

13.3.5 Appendix E : Extract from Parsons Brinckerhoff report

Introduction

This modelling was considering impact which the device can have on the bus voltage at the Point of Connection (POC). The following key data is used in the evaluation.

D – SVC, one off unit

- Manufacturer; Hitachi
- Connection voltage; 415V
- Operating range (at 415V); ±400kvar.

11kV network

- Short Circuit Level (SCL); assumed range 50 – 150MVA
- X/R ratio very large

SVC transformer

- Voltage ratio: 11/0.415kV
- Rating; 1000kVA
- Impedance; assumed range 5 – 15% on unit rating
- Losses, assumed to be negligible

Methodology

A simple electrical circuit was evaluated, which consisted of four components,

- A voltage source (at 1pu) behind a network impedance
- A network reactance derived from the range of SCL
- A transformer reactance, derived from the range of impedances assumed
- A SVC reactive power output, at 400kvar (inductive) or 400kvar (capacitive)

All data was modelled in pu on 100MVA base. The evaluation considered the impact which network SCL and transformer impedance would have on the controlled voltage at the 415V SVC bus and the 11kV bus. For ease of calculation the resistance inherent in the distribution network and the losses in the transformer were neglected, i.e. for both the X/R ratio is assume to be very large.

Study Results

The following table presents the results of the study, showing the impact that varying the SCL and transformer impedance has on the voltage at the 415V SVC bus and the 11kV bus. At the maximum inductive output from the SVC, the bus voltage is reduced and at the maximum capacitive output from the SVC the bus voltage is increased.

SCL (MVA)	Transformer impedance (%)	SVC bus voltage range (pu)	11kV bus voltage range (pu)
50	5	0.973 – 1.029	0.992 – 1.008
50	10	0.954 – 1.050	0.992 – 1.008
50	15	0.936 – 1.073	0.993 – 1.009
100	5	0.977 – 1.025	0.996 – 1.004
100	10	0.958 - 1.046	0.996 – 1.004
100	15	0.940 – 1.068	0.996 – 1.004
150	5	0.978 – 1.023	0.997 – 1.003
150	10	0.959 – 1.045	0.997 – 1.003
150	15	0.941 – 1.067	0.997 – 1.003

As may have been anticipated, the impact of the SVC is greatest on the weakest system, i.e. the lowest SCL and the highest transformer impedance.

For a nominal system SCL of 100MVA, increasing the transformer impedance from 5% to 15% gives a greater voltage range at the SVC bus, but has no impact on the 11kV bus voltage, where the voltage range is only ±0.4% of nominal.

Even under the weakest system SCL considered (50MVA), the SVC’s impact on the 11kV bus voltage is minimal, ±0.8% (average).

Based on the declared operating range of the SVC given by Hitachi, the maximum capacitive output is controlled to 400kvar at 1pu voltage. In the inductive range of its characteristic, the SVC can operate at 1.1pu voltage and 1.1pu current, i.e. 1.21pu reactive power, or 484kvar, but based on the present analysis, the impact on the 11kV bus would be negligible.

As a sensitivity study the rating of the SVC was doubled to ±800kvar, i.e. considering two units connected at the same location. This is within the capability of the 1000kVA step-down transformer. The impact for a nominal system SCL of 100MVA is shown in the following table.

SCL (MVA)	Transformer impedance (%)	SVC bus voltage range (pu)	11kV bus voltage range (pu)
100	5	0.954 – 1.050	0.992 – 1.008

100	10	0.919 – 1.096	0.993 – 1.009
100	15	0.887 – 1.147	0.993 – 1.009

Doubling the rating of the SVC doubles the impact on the 11kV bus voltage, but this is still less than ±1% of the nominal voltage.

Conclusions

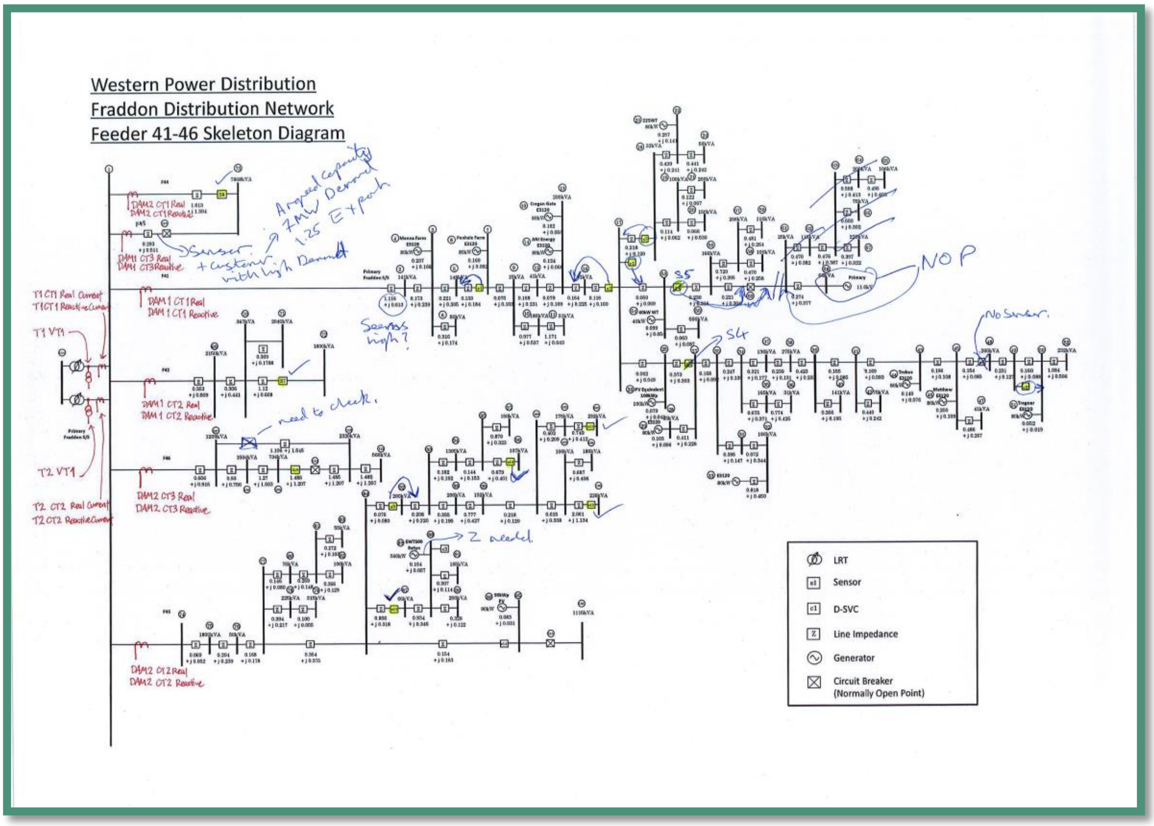
At a rating of ±400kvar the SVC is too small to exert any significant influence on the 11kV bus voltage at the POC, assuming a typical SCL of 100MVA.

Doubling the rating of the SVC has limited impact at the 11kV bus.

The choice of the impedance of the transformer does not significantly influence the capability of the SVC to support the 11kV bus voltage. The transformer impedance may be chosen to limit fault currents into the power electronic converter and/or to achieve the most economic design.

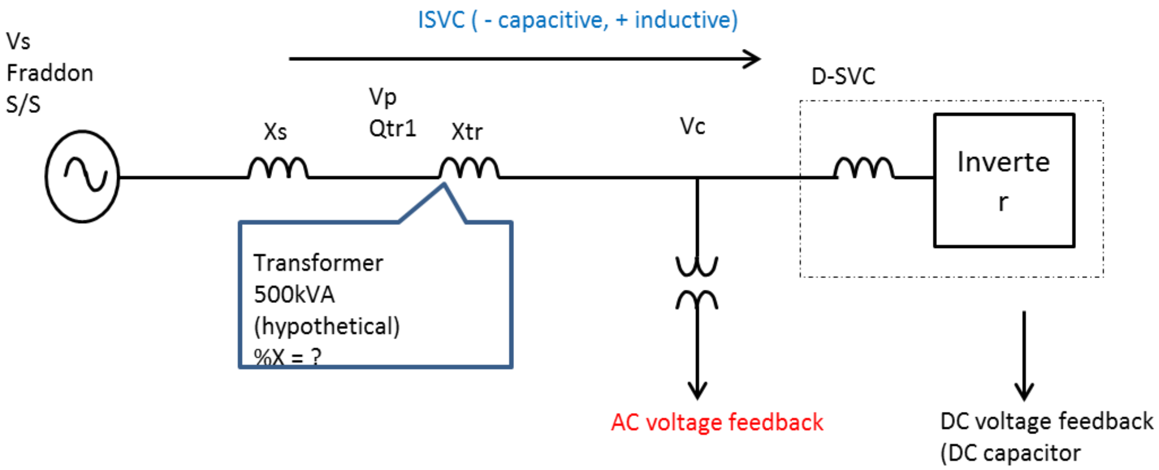
A range of system SCL of 50 – 150MVA has been assumed for this evaluation. The impact for other SCL levels may be linearly interpolated or extrapolated, for a given transformer impedance.

13.3.6 Appendix F – Skeleton Diagram



13.3.7 Appendix G- Hitachi Sensitivity Calculations

Fig 1: Schematic of D-SVC



Xs: Network impedance

Xtr: Transformer impedance

Vc: AC feedback voltage (network equivalent)

Vs: Network voltage at S/S

Vp: Voltage at network side of transformer

Qsvc: SVC output reactive power

Qtr1: Reactive power at network side of transformer

In the equation below, current flowing through the network may be shown in two different ways:

1) by taking the voltage difference between Vs and Vp and dividing by the network impedance, or 2) by taking the voltage difference between Vp and Vc and dividing by the transformer impedance. 1) and 2) must give the same results:

$$\frac{V_s - V_p}{X_S} = \frac{V_p - V_c}{X_{tr}}$$

The above equation leads to the following expression for Vp:

$$V_p = \frac{X_S V_c - X_{tr} V_S}{X_S + X_{tr}}$$

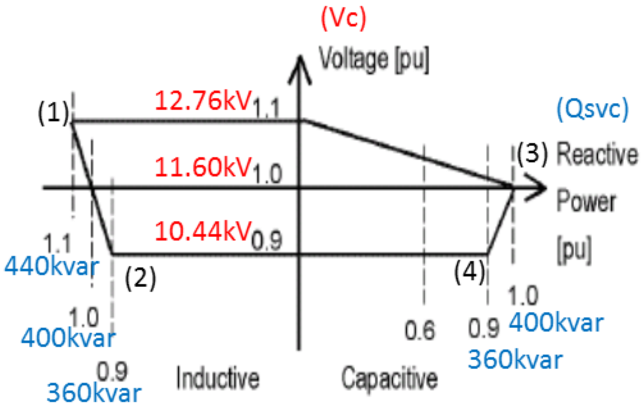


Fig 2: Operational Range of D-SVC

In the following tables, Vs and Vp is calculated under four conditions (1) - (4) shown in the diagram "Operational Range of D-SVC"above (Fig. 12). The SVC is at maximum var output (i.e. maximum current) in these conditions.

The worked example below shows this:

Network

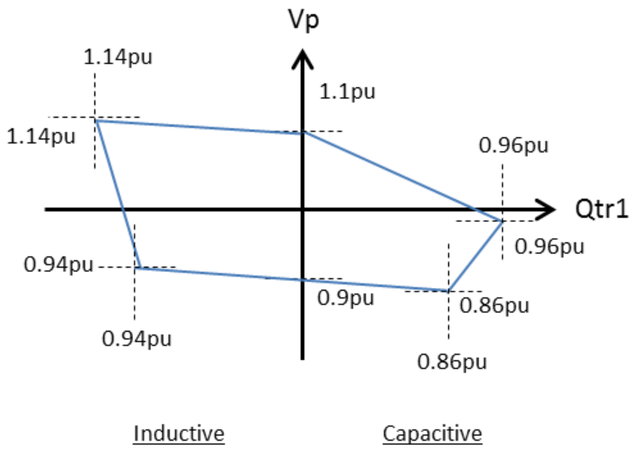
Sbase	4.0E+05	VA
Vbase	11600	V
Xbase	336.4	ohm

Transformer

Sbase	5.0E+05	VA
Vbase	11600	V
Xbase	2.7E+02	ohm

SVC

Sbase	4.00E+05	VA	
Vbase	415	V	
Ibase	556.5	A	@415V
	19.9	A	@11.6kV



Impedance

%Xs	1.85	%	Xs	6.223	ohm
%Xtr	5.00	%	Xtr	13.456	ohm

(1)Inductive, above rated voltage					
Vc(*)	12765.534	V	1.100	pu	
Vs	13443.840	V	1.159	pu	Vs-Vp
Vp	13229	V	1.140	pu	**-214.51** V
Itr	19.9	A			
Qsvc	4.4E+05	var	1.100	pu	
Qtr1	4.6E+05	var	1.140	pu	

(2)Inductive, below rated voltage					
Vc(*)	10444.527	V	0.900	pu	
Vs	11122.833	V	0.959	pu	Vs-Vp
Vp	10908	V	0.940	pu	**-214.51** V
Itr	19.9	A			
Qsvc	3.6E+05	var	0.900	pu	
Qtr1	3.8E+05	var	0.940	pu	

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(3)Capacitive, above rated voltage					
Vc(*)	11605.031	V	1.000	pu	
Vs	10926.725	V	0.942	pu	Vs-Vp
Vp	11141	V	0.960	pu	**214.51** V
Itr	-19.9	A			
Qsvc	-4.0E+05	var	-1.000	pu	
Qtr1	-3.8E+05	var	-0.960	pu	

(4)Capacitive, below rated voltage					
Vc(*)	10444.527	V	0.900	pu	
Vs	9766.222	V	0.842	pu	Vs-Vp
Vp	9981	V	0.860	pu	**214.51** V
Itr	-19.9	A			
Qsvc	-3.6E+05	var	-0.900	pu	
Qtr1	-3.4E+05	var	-0.860	pu	

13.3.8 Appendix H: State Estimation Process

The state estimation process is shown in the diagram below and explained in detail within this appendix.

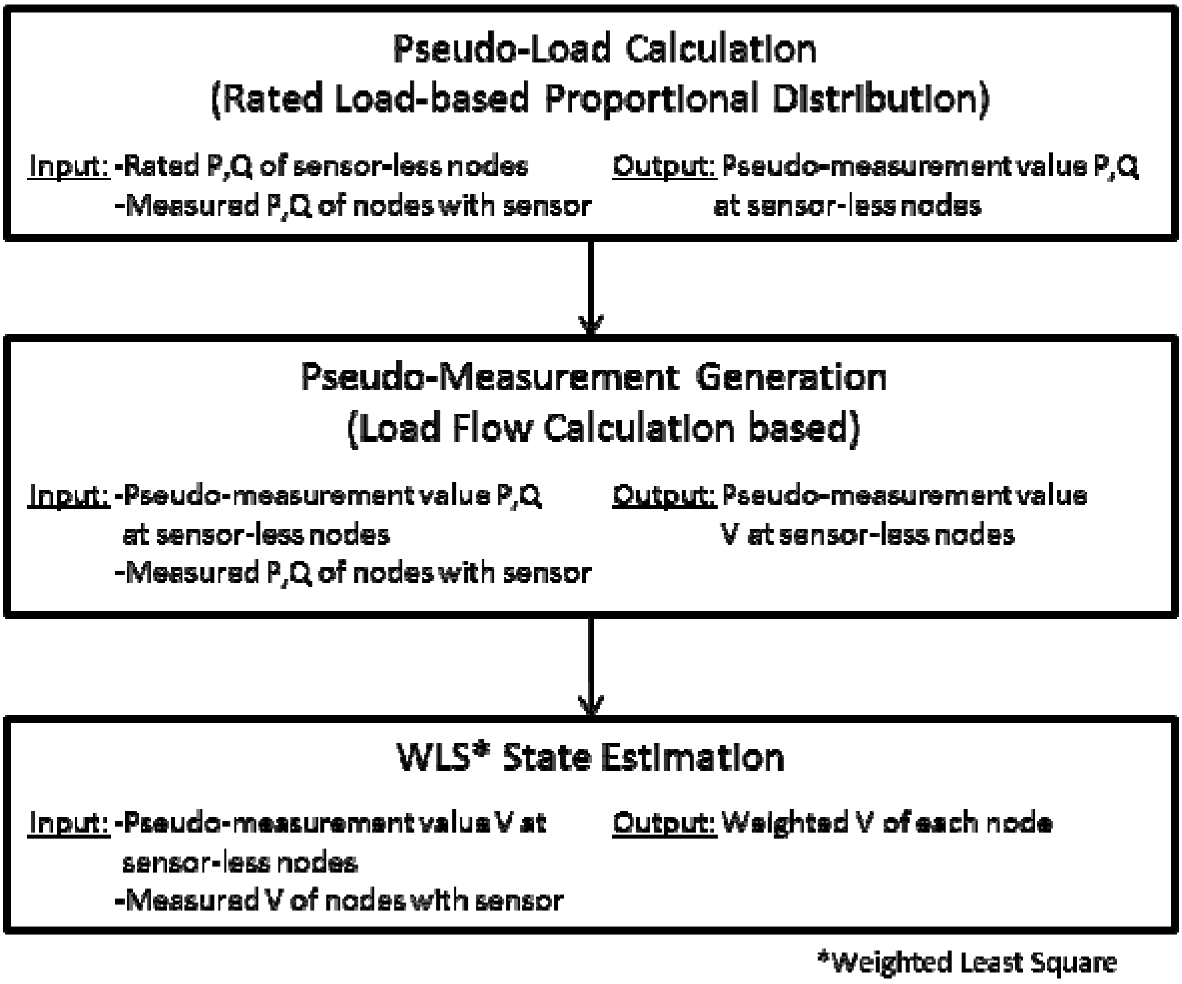
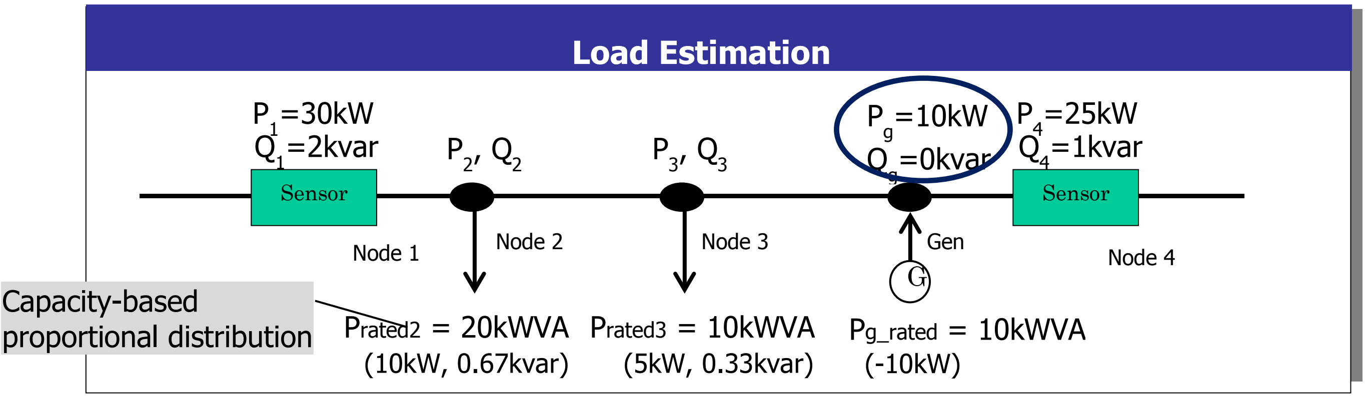


Fig 1: State Estimation process

A good way to explain this in detail is by a worked example:



P_{in}, Q_{in} : Active and reactive power between sensors

P_i, Q_i : Active and reactive power at each node number *i*

In the above example, sensors are only installed at Node 1 and 4. An embedded generator also provides power between the sensors. P_2, Q_2, P_3 and Q_3 at Node 2 and 3 are unknown because there are no sensors installed. Load estimation aims to solve these P_2, Q_2, P_3 and Q_3 by the sensor measurements P_1, Q_1, P_4, Q_4.

Here, P and Q between sensors are:

$P_{in} = P_1 + P_g - P_4 = 15\text{kW}$

$Q_{in} = Q_1 + Q_g - Q_4 = 1\text{kvar}$

P_{in} is then distributed to Node 2 and 3 based on the ratio of rated load.

$P_2 = P_{in} * P_{rated2} / (P_{rated2} + P_{rated\,3}) = 10\text{kW}$

$P_3 = P_{in} * P_{rated3} / (P_{rated2} + P_{rated\,3}) = 5\text{kW}$

Q_{in} is also distributed based on their rated load, provided that the power factor at each node is equivalent.

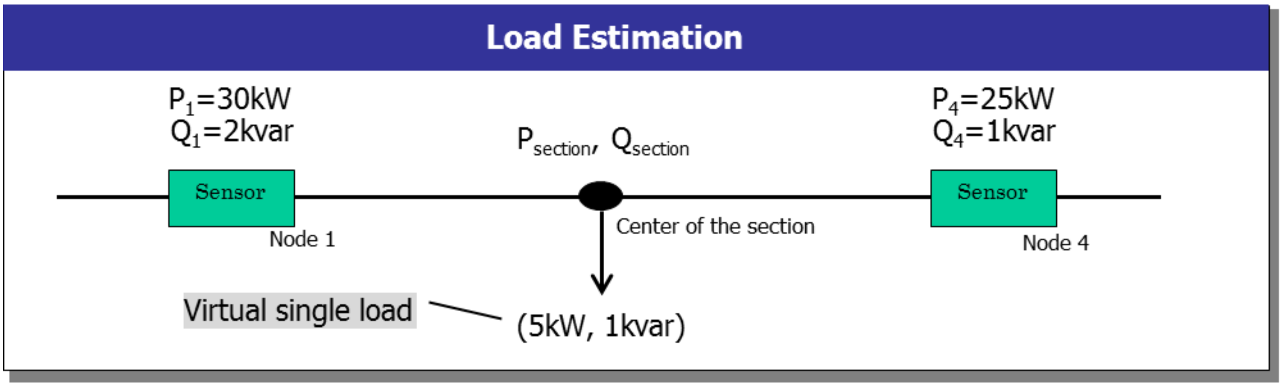
$Q_2 = Q_{in} * Q_{rated2} / (Q_{rated2} + Q_{rated\,3}) = 0.67\text{kvar}$

$Q_3 = Q_{in} * Q_{rated3} / (Q_{rated2} + Q_{rated\,3}) = 0.33\text{kvar}$

P_{rated} is treated as a fixed value in load estimation.

The calculated P and Q values are treated as pseudo-measurements in the following steps.

The next stage is a load flow based state estimation using the pseudo-measurements. The pseudo-measurement generation is performed using the P, Q pseudo-measurement values obtained by load Estimation. This calculation outputs the voltage V at each node without sensors. The output is treated as pseudo-measurement values of V. The voltage V at each node without sensors is then weighted based on the difference between pseudo-measured V and actual measured V at nodes with sensors installed.



In the case of not-acquiring the generator's output, here, the section load ($P_{section}$, $Q_{section}$) is regarded as a virtual single load. And the position of the section load is simply supposed to be the centre of the section (or the centre of all the load nodes).

An example of voltage profile by the approximate approach is shown in Figure 2 below:

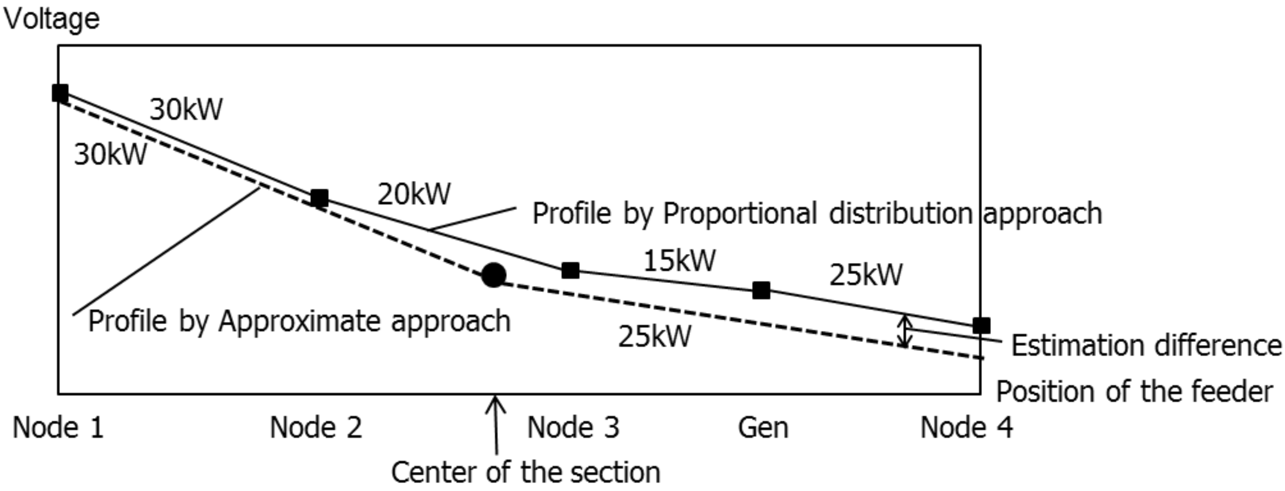


Fig 2: Voltage profile

From this, an optimal control parameter calculation is carried out. The goal of this calculation is to find the optimal set of control parameters (V_{ref} of LRT, V_{ref} or Q_{ref} of each SVC) so that system voltage fluctuation and power loss is minimal. This iterative process follows the steps listed below:

1) Set initial control parameters (Q_{ref}, V_{ref}) to the current values

2) Incrementally change the control parameters

3) Perform load flow calculation based on the changed control parameters

4) Calculate the evaluation index (based on power loss, utilization factor, system voltage level)

5) Repeats the load flow calculation until minimum evaluation index is achieved.

This process applies Taboo search method, which is a method of elimination to minimise the number of iterations. For example, if the Q_{ref} of SVC is increased and the resulting evaluation index is larger than that of the previous iteration, any larger value of Q_{ref} will be avoided in the following iterations. The flow of Optimal Control Parameter Calculation is shown in Figure 3 below:

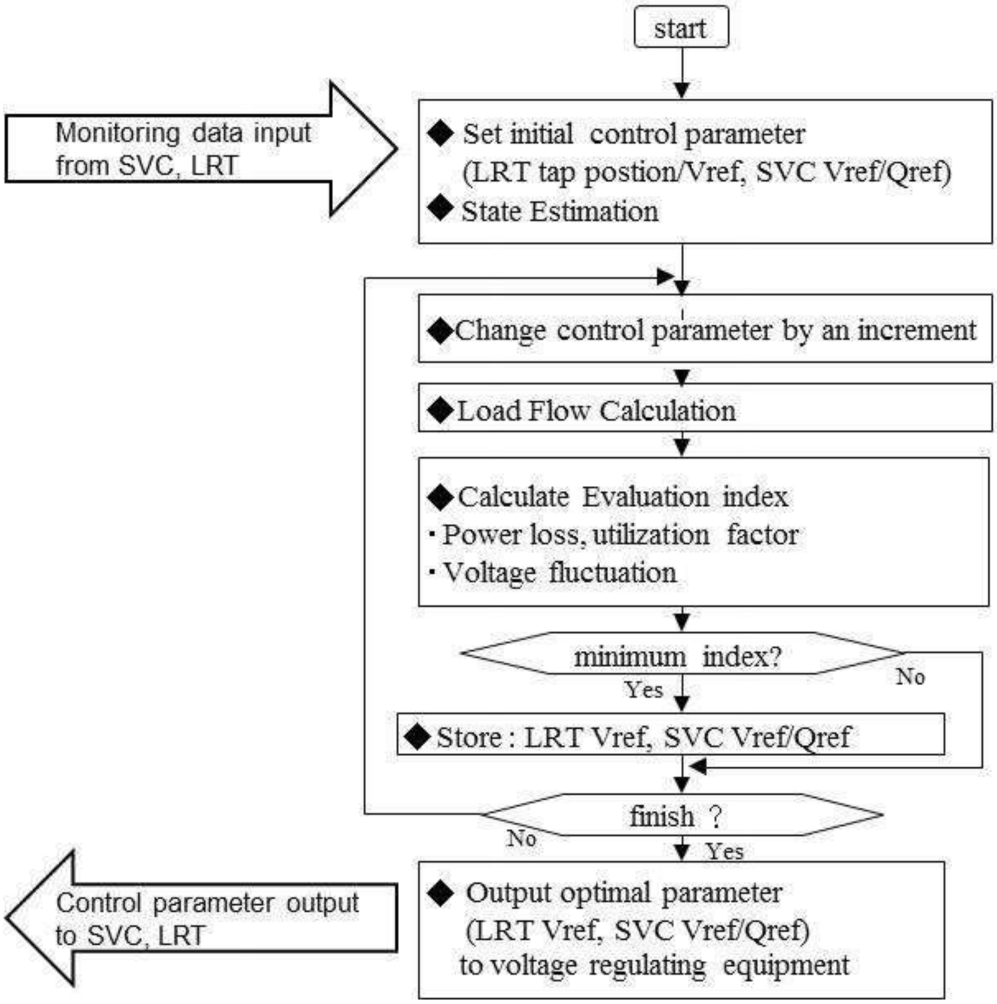


Fig 3: Flow of Optimal Control Parameter Calculation

The system database includes the topology of the distribution system, rated load P and power factor values at each pole-mounted substation and line impedance between each node. The D-VQC does not automatically recognise any variations of system topology (e.g. opening/closing of a Normal Open Point.). The D-VQC is programmed with a number of topology patterns that the user can choose from when system topology changes. The topology patterns will be based on maps and DINIS data provided by WPD.