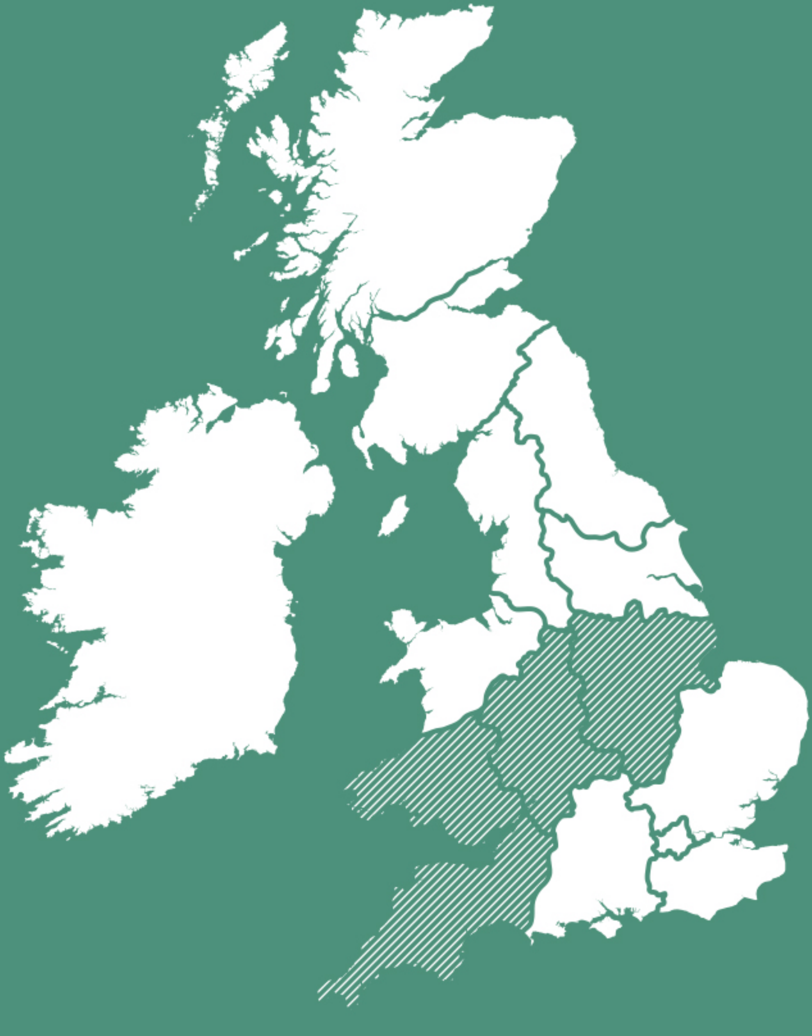
WESTERN POWER DISTRIBUTION
INNOVATION

NEXT GENERATION NETWORKS

VOLTAGE CONTROL SYSTEM DEMONSTRATION PROJECT

CLOSEDOWN REPORT



LCN Fund
Low Carbon Networks

Report Title	:	Closedown Report
Report Status	:	FINAL
Project Ref	:	WPD_NIA_011(WPDT1011)
Date	:	01.12.2016

Document Control

	Name	Date
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Revision History

Date	Issue	Status
01.12.2016	v2.0	Rebrand and updated

Contents

DISCLAIMER

Executive Summary

As more distributed generation connects to the 11kV rural network, the adverse impact is becoming more apparent. Across large areas of this network, generation is triggering high costs of reinforcement often driven by voltage issues. Predominantly this reinforcement is required for voltage rise but voltage step change is also becoming a concern in some areas. Intermittent generation installed towards the end of the feeder on rural networks is often the worst affected by both of these issues. There are several ways that these issues can be addressed, using reactive power from a D-SVC is one of the more innovative ways.

Therefore this project aimed to address the issue of fluctuations seen in long distribution lines in a rural area with Distributed Generation (DG) in the form of wind turbines. The objective was to determine the effectiveness of D-SVCs (Static VAr Compensator for Distribution Networks) as a system to control voltage on 11kV rural networks.

This project was originally scoped to run in two phases.

- Phase 1 - Trial a single installation of Hitachi's D-SVC on the 11kV network for 18 months
- Phase 2 - Optimisation of multiple D-SVCs across two primary substation for a further 24 months

For the first phase of the project, a D-SVC was installed 4.3km away from Falmouth Bickland Hill Primary adjacent to Roskrow wind farm. We also installed monitoring at certain points along the length of the feeder. Once the D-SVC was appropriately set up, including modifications to the under and over voltage protection, it was set to run in its various operational modes. These operations were logged and analysed to establish the best settings for the D-SVC. The device was also integrated into WPDs control system (PowerOn), allowing basic control and status data to be returned.

This 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.

1. Project Background

As Distributed Generation (DG) becomes more common, the growing number of connections to distribution lines can cause voltage problems (specifically high or low voltage) due to the variable power output of DG (the majority of DG is weather-dependent).

In turn this can affect the efficiency and capacity of the distribution network. There are several different solutions and devices available in the market that can help reduce voltage variation. However, some traditional solutions are unable to cope with the rapidly varying output of renewables such as wind turbines and photovoltaics (PV).

Because this is a relatively new phenomenon, potential solutions are unproven within the UK and so this in itself adds to the risk and uncertainty in trialling new and creative ideas.

This project sought to address this over a two phased delivery with Phase 2 being wholly dependent on the successful outcome of Phase 1. We chose a two phase delivery because we were uncertain that the technology could be proven at the scale that is potentially required so trialling one D-SVC installation ahead of a multiple installation seemed to be the most practical and pragmatic way forward given the level of uncertainty and the level of innovation under trial. Moreover as the solution, if proven viable, would require a level of integration into a DNO’s IT estate it was deemed sensible to trial it in “bite size” chunks first.

2. Scope and objectives

This project aimed to address the issue of fluctuations seen in long distribution lines in a rural area with DG (in the form of Wind Turbines) connected. The objective was to determine the effectiveness of D-SVCs (Static VAr Compensator for Distribution Networks) as a system to control voltage on 11kV rural networks. Phase 1 comprised the testing of a single D-SVC and, it was anticipated that it would provide feed-back for the development of a D-VQC (Voltage and Reactive Power (Q) Control System) that would be utilised within Phase 2 which would then explore the optimisation of multiple D-SVCs across two primary substations.

3. Success criteria

The success criteria for this project were about gaining an improved understanding of the functioning of D-SVCs and its ability to control voltage variations on rural networks. Specifically, it would:

1. Identify optimum settings for the D-SVCs for a given load and to achieve optimum voltage
2. Use changes in set points & low pass filter to expand understanding of D-SVC performance for a given set of parameters and a given network load.
3. Utilise learning gained from the above items to ensure that a D-VQC can be developed to optimise multiple networked D-SVCs over a wide distribution network.

4. Details of the work carried out

4.1 Site Selection

The primary objective of the trial was to investigate the voltage control of an 11kV rural feeder with an intermittent, distributed generator connected. To achieve this we needed to identify a suitable location which had a fairly large generator 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. However a location in Cornwall connected to Falmouth Bickland Hill primary substation was identified and selected for the project. The generator is a large 1.8MW windfarm near Penryn. It 4.3km from the primary substation on a mixed underground/overhead feeder but predominantly constructed of overhead lines.

4.2 Site Works and Commissioning

For this project the project partner, Hitachi, supplied a D-SVC (Distribution Static VAr Compensator) STATCOM, connected at 11kV through a transformer. The D-SVC helps to regulate the voltage by managing the power factor so that the device is either importing or exporting reactive power. Hitachi originally envisaged the D-SVC to be a standalone system without needing any integration with other operational WPD control systems. However it was important for such a trial that WPD maintained at least a supervisory element and basic control functions to reduce risk to WPD customers.

Following site selection, the impedance data of the network was provided to Hitachi who modelled the performance of the D-SVC. Meanwhile monitoring was installed along the feeder and relevant wayleaves were agreed for the site. The D-SVC was purposely located on land adjacent to a windfarm so the landowner was likely more responsive to our need for land agreements. It also meant that the existing substation earthing arrangements could be combined to reduce touch and step potentials. Figure 1 shows the D-SVC in situ.

Figure 1: The D-SVC in situ

The site consisted of a standard distribution transformer with a ring main unit in a GRP enclosure and another GRP enclosure for the D-SVC (shown later on in the report in Figure 8). Both enclosures were located on the same land as the windfarm and were near the field's entrance, see Figure 2. An additional internal block wall was built to mount the protection panel, battery charger and RTU.

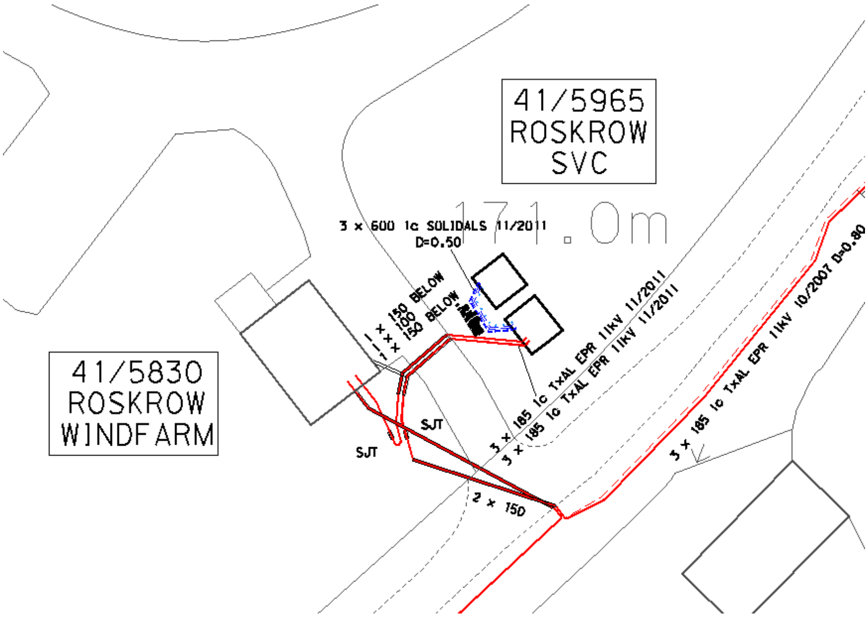


Figure 2: Layout of the site

As part of the on-site commissioning several tests were carried out jointly by WPD and Hitachi engineers. The D-SVC was first thoroughly tested at the factory in Japan to ensure that it performed as expected. Some of these tests were then repeated at site, such as measuring of the insulation resistance and output power to ensure there was no damage during shipping. Several tests were then carried out to check the performance of the D-SVC in its various modes for bench mark purposes later in the project. The initial tests allowed for the optimisation of the D-SVC, including tuning the filters to give the best performance and modifying the set points for each of the modes of operation. These parameters needed to be modified to take account of the system voltage and the measured system impedance on site to ensure the best performance possible. Figure 3 shows the electrical set up of the site with a single line diagram.

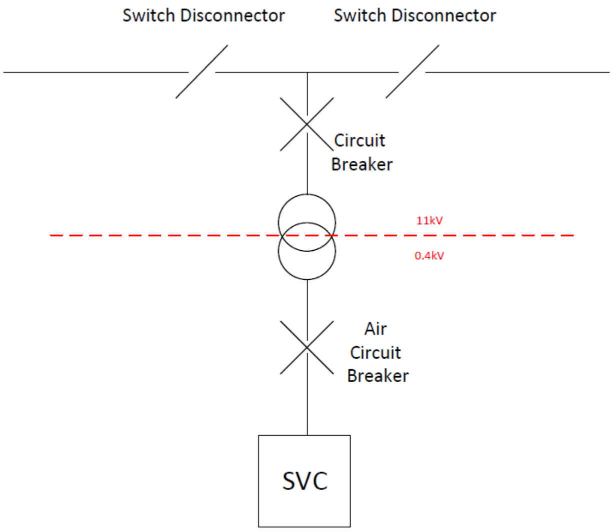


Figure 3: Signal Line Diagram of equipment on site

WPD set up all auxiliary equipment in the substation. This included monitoring and communication equipment to allow basic remote control and monitoring of the D-SVC, an over/under voltage relay to ensure connected customers were protected from any adverse effects of the device and a battery system for contingency in the unlikely event of a network power interruption. This is the device on the right in Figure 4 below.

During the development of operational documentation, and based on a better understanding of the equipment, it was decided that the WPD Control Centre should have a SCADA based remote shut off capability for the D-SVC. This had not previously been envisaged but was relatively simple to implement using several spare contacts on the D-SVCs communication module. WPD's "business as usual" telemetry and communication equipment was used to relay the data to WPD's Control Centre in Cardiff.

Figure 4: Voltage protection relay, battery and battery charger in situ

The installation of a voltage protection relay, shown in Figure 4 on the panel of the left, was not as straightforward as the installation of the SCADA equipment. The D-SVC was connected to the LV side of the transformer via a three phase cable. However, a standard distribution transformer is not fitted with HV voltage transformers meaning over and under voltage protection could not be fitted on the HV side as per standard practice. Relays therefore needed to be connected onto the LV side of the transformer.

When the voltage settings were derived, they were set as a direct ratio of the HV voltage limits. As a consequence of using conservative values there were several occasions where nuisance tripping occurred. The cause was traced to the low voltage which was produced on the LV by the D-SVC exporting reactive power. This was happening even when the HV voltage was within limits.

Our analysis discovered that the export of VArs changes the usually linear relationship between HV and LV voltage across the transformer, this learning is discussed in greater depth in section 6.1.3. To avoid the trips a similar algorithm to the one used in the D-SVC was used to calculate the appropriate LV lower limit setting. The calculation of these limits is detailed in Appendix C. Figure 5 shows the dedicated transformer used to connect the D-SVC to the 11kV network.

Figure 5: The D-SVC's dedicated transformer

To establish the cause of the tripping described above, and to collect more detailed data on the performance and behaviour of the D-SVC, a detailed set of tests were carried out including collection of high resolution 1ms data during May 2012.

During these tests three different operation modes were trialled:

- AVR – Automatic Voltage Regulation mode

In this mode the voltage set point was defined as a target for the system to try to keep the voltage to as close as possible, it also provided voltage smoothing

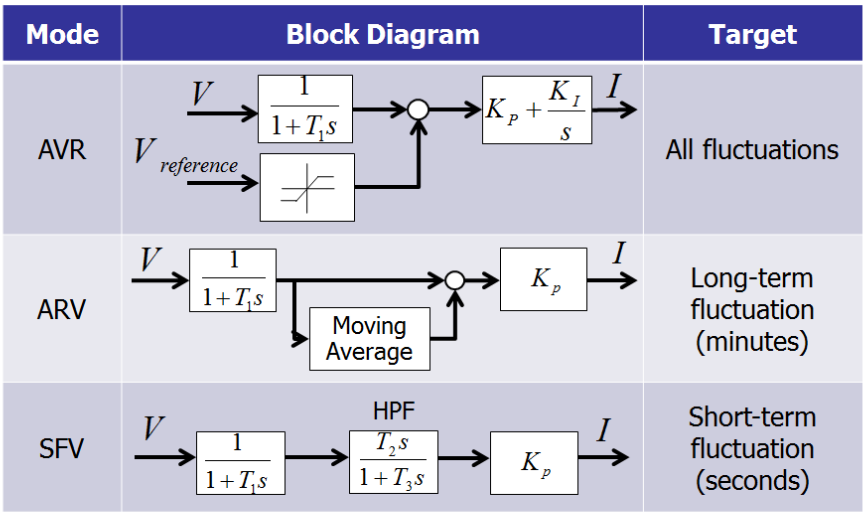
- ARV – Average Reference Voltage mode

This mode also provided voltage smoothing for medium term fluctuations but did not target a particular voltage

- SFV – Short Term Fluctuation of Voltage mode

This mode provided smoothing for faster variations in the voltage profile but did not target a particular voltage

The function block diagrams are described in Figure 6.



AVR : Automatic Voltage Regulation, ARV : Average Reference Voltage
SFV : Short-term Fluctuation of Voltage, VSC : Voltage Source Converter

Figure 6: Description of each of the D-SVC's settings

Each mode of operation has distinct characteristics which the trials aimed to understand the impact of each on the distribution network. Since a substantial amount of data had already been collected with the system running normally, the trials in each operational mode allowed for thorough analysis of the data from monitoring on the LV and HV sides of the transformer as well as the other points along the system

Following the resolution of the nuisance tripping problem, mentioned previously, the D-SVC ran without interruption. Data collection and equipment performance evaluation continued with the D-SVC acting predictably. The revised under voltage settings were proved to be adequate protection tripping the breaker only when there was significant system voltage depression from remote faults.

4.3 Network Monitoring

Along the 11kV feeder there were several locations where advanced monitoring was installed in the form of devices provided by EMS Ltd, an SME based in Northern Ireland (more details of the eMS sub.net product can be found at www.emsni.com). The devices recorded 10 minute averages of current, voltage, power and power quality data, which were then transmitted every 24 hours to a centralised server via mobile phone networks. The units were installed at the primary substation, Kernick Industrial Estate, Summerheath, the windfarm (equivalent to the HV side of the D-SVC transformer due to proximity) and the LV side of the D-SVC transformer shown in Figure 7**: The 11kV feeder with monitoring locations**. Data from the sub.nets was also collected through site visits allowing for high resolution 1ms data to be extracted. Such high resolution data can be stored for 2 weeks in the sub.nets memory after it has been recorded. WPD local teams were trained in the use of sub.net units and carried out regular data downloads as needed for the analysis.

No	Node	Line Impedance from HV side SS (400[kVA] base)	Sub.net Location	Transformer	
				Capacity	Transformation ratio
1	Bickland Hill SS	0.291[%]	LV	No data	11000/433

2	Kernick Ind Est East	0.478[%]	LV	500[kVA]	11000/433
3	Summerheath	0.529[%]	LV	200[kVA]	11000/433
4	Roskrow WF	0.748[%]	MV	None	None
5	D-SVC	0.748[%]	LV	500[kVA]	11000/415

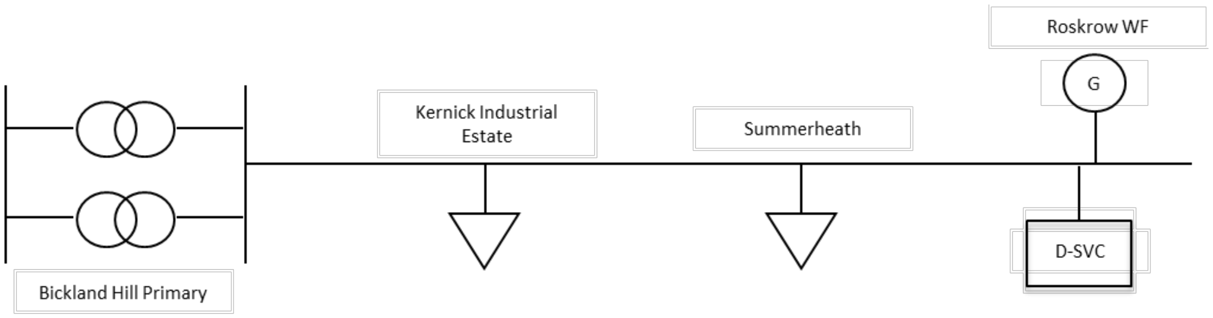


Figure 7: The 11kV feeder with monitoring locations

4.4 Control System Integration

The D-SVC's control system has a communications card which was used for its remote control functionality. From this card the status of the D-SVC could be established and control signals could be sent. The system is similar to many remote/local systems on the network with a selector switch to denote if the device is in remote or local mode. This functionally was extended to the substation remote telemetry unit (RTU) via a hard wire connection, which enabled remote control by the WPD Control Centre using the PowerOn system commonly used by DNOs. The diagrams within PowerOn were updated to provide a simple user interface through a number of on screen buttons and indicators.

4.5 System Testing Schedule

To demonstrate the system's capabilities, performance was monitored through its different operational modes to see how it affected the network. Initially, after monitoring was installed, the network was analysed without the D-SVC being operational to give a base set of data. After this period each of the operational modes was run for two weeks intervals to demonstrate the effect on the network. It was during this period of time when we concluded that the under voltage setting was set too low and resulted in tripping of the unit whilst the 11kV voltage was still inside limits.

This prompted several days of intensive analysis which is documented in the reports in the Appendices A and B. During the intensive tests we recorded 1ms resolution data on the D-SVC performance. This allowed the valuable capture of knowledge related to the D-SVC's characteristics. As previously described the tests included running the D-SVC in each mode under a higher level of scrutiny than originally planned. This facilitated the capture of additional learning on the benefits of D-SVC units, for example programming the unit to output set values of VArs, both leading and lagging to see what effect this had on the network.

After these tests were completed it was concluded that the AVR mode was best for keeping the voltage within limits. The D-SVC monitoring continued while running in this mode, allowing further analysis of the long terms effects of the D-SVC as well as capturing performance during the unusual or sporadic events that happen on the 11kV network.

5. The outcomes of the Project

5.1 Installation and Commissioning

The installation of the D-SVC was carried out early in 2012 and required several Hitachi engineers on site to complete the commissioning. Installation and commissioning revealed a number of key learning points on how best to install the D-SVC. The outcomes highlighted the practical aspects of installation such as importance of appropriate enclosures for the relatively harsh rural hill top sites and the considerations around procuring short term wayleaves. There was significant technical learning around the implementation of voltage protection, the impact of using a standard distribution transformer and the various issues surrounding monitoring.

5.1.1 Enclosure

The enclosure used for the D-SVC was a GRP enclosure which is normally used for 11kV switchgear. The D-SVC is IP rated as indoor equipment so it was important that it was protected from the elements of the windy hill top site adjacent to the windfarm. We selected an older style GRP enclosure (see Figure 8) which is taller to give the D-SVC the required head room for the fan aided convectional air flow to cool the D-SVC. This enclosure should have kept the D-SVC dry as well as sufficiently ventilated.

In reality the wet winter weather and hot summer weather challenged the enclosure. In winter, water pooling on the plinth was observed inside the enclosure as was rain water which had been blown in through the vents. During particularly windy days the blast roof would lift temporally and let additional rain into the enclosure. During the summer the temperatures rose close to the operating temperature of the D-SVC therefore the vents needed to stay operational and open even though water was getting in.

The water ingress was helped by installing two dehumidifiers, which kept the moisture in the air inside the enclosure to a minimum without reducing the ventilation required in summer. This worked, however it did not completely solve the problem with the pooling on the plinth due to the amount of ground water. The roof was unable to be modified at this stage due the enclosure's construction. This is being addressed in the Phase 2 plinth design by including a lip for the enclosure to fit over the plinth and a water resistant seal along the base. To reduce the rain getting into the enclosure the vents will have more inclusive shrouding. To stop the roof lifting, tighter and more substantial split pins will be used to keep it in place. The alternative would be using more costly permanent buildings, which would need to be dismantled at the end of the project.

Figure 8: D-SVC (left) and associated transformer (right) installed on site

5.1.2 D-SVC interface with PowerOn

When the D-SVC installation was designed, there was no intention to have an interface with any WPD systems as it was a pre-defined design by Hitachi. The D-SVC only had an interface to communicate with the D-VQC via a proprietary protocol. The D-SVC would be independent from the wider WPD control systems as this is what had been trialled by Hitachi in Japan at Akagi Testing Centre, Central Research Institute of Electric Power Industry (CRIEPI).

WPD would need to know basic information about the D-SVC and have the ability to control its operation for safety reasons and security of the network. Therefore, it was decided that the ability to operate the device remotely and have a live status for the D-SVC was necessary. This was implemented via a WPD standard Radius RTU. The D-SVC and the Radius RTU were interfaced via hard wire connection and then Radius communicated conventionally with PowerOn via SCADA. There was a special D-SVC diagram designed for PowerOn so that the control engineer could directly control and see the status of the D-SVC as shown in Figure 9.

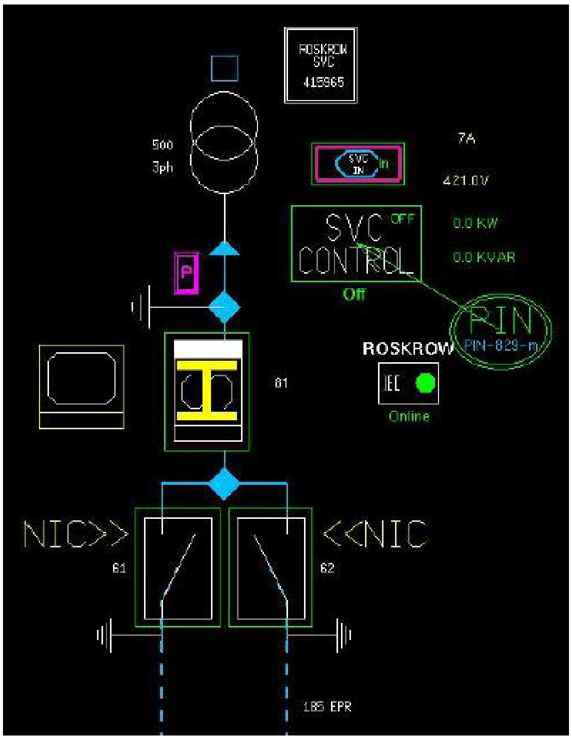


Figure 9: D-SVC diagram in PowerOn

Through the radius RTU installed on site the following analogues, indications and alarms are visible within PowerOn:

Indications

- SVC ON – Indication that the D-SVC is operating
- SVC OFF – Indication that the D-SVC is NOT operating
- SVC Protection IN – Indication that the voltage protection is in operation
- SVC Protection OUT – Indication that the voltage protection is NOT in operation
- Circuit Breaker Status – Indication as to the position of the CB (Open or Closed)

Alarms

- SVC Relay Fail – Alarm to indicate the voltage relay has failed

- SVC Failed Alarm – Alarm to indicate that the D-SVC has switched off due to an internal failure
- SVC System Abnormal – Alarm to indicate that the network the D-SVC is connected to is abnormal and the D-SVC has switched off
- Protection Trip – Alarm to indicate the voltage protection has operated

Analogues

- Voltage – LV voltage analogue at the D-SVC's PCC
- Current, MW and MVAr analogues – from LV connected CTs

Controls

The control functionality availability within PowerOn is:

- SVC Control ON – Control to remotely engage the operation of the D-SVC
- SVC Control OFF – Control to remotely disengage the operation of the D-SVC

When the D-SVC is in remote mode, local operation is not possible – therefore control only can switch the D-SVC on or off.

- SVC Protection IN – Control to remotely switch in the voltage protection functionality
- SVC Protection OUT - Control to remotely switch out the voltage protection functionality

This allowed the functionality required for Control to understand the operation and moreover control the D-SVC under all foreseeable circumstances.

5.1.3 Voltage Protection

To ensure that the D-SVC was not at risk of putting the network out of voltage limits it was decided that under and over voltage protection was required at the D-SVC's location. This would protect WPD's customers from any unexpected operations of the D-SVC during the trials. Due to the fact that there was no HV voltage transformer on the distribution transformer, we could not use the 11kV voltage to drive the protection. To overcome this, LV current transformers where installed and a voltage reference was taken from the LV side of the transformer. The over-voltage setting was 445V (or 263V line voltage) while the under-voltage setting was 395V (or 228V line voltage).

During the initial months (February-May) of operation the voltage relay tripped on several occasions due to under voltage. From the monitoring it revealed that the HV voltage was above the 10.34kV (or 5,970V line voltage) lower limit. As the monitoring only gave 10 minute average data, while accessing remotely, it was difficult to establish exactly what was happening. However, the data indicated that the HV voltage was above the low voltage limit. The LV voltage was tripping at the right voltage despite the monitored HV voltage being higher than equivalent HV protection setting. To investigate this further WPD and Hitachi went to site to do more testing to assess the performance of the D-SVC and establish why the tripping was occurring. The 10ms monitoring data showed with more clarity what was happening. Details of all the results are in Appendices A and B.

As the reactive power was being absorbed by the D-SVC the voltage was being reduced as expected. Looking at the LV graph (Figure 10) the voltage reached the LV trip setting of 228V and promptly trips off shortly after 15:16.

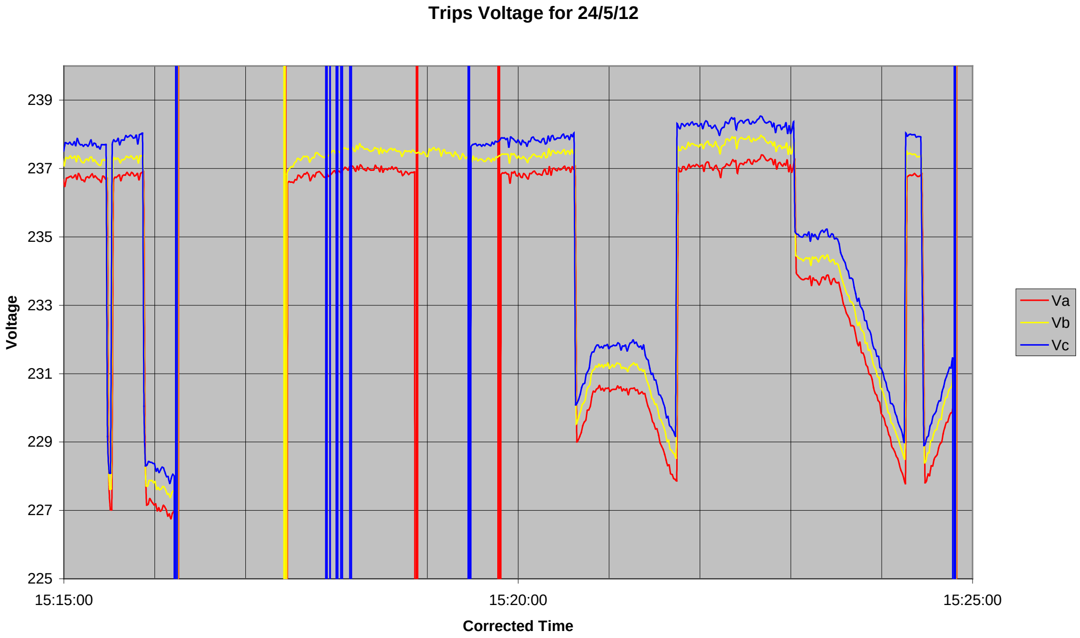


Figure 10: LV voltage during reduction in voltage

This compared to the HV graph of the same time (Figure 11) shows the voltage being reduced in line with the LV voltage. However, at the time of the trip, the voltage was above the 6,150V and therefore well above the 5,970V limit when the relay ought to be tripping.

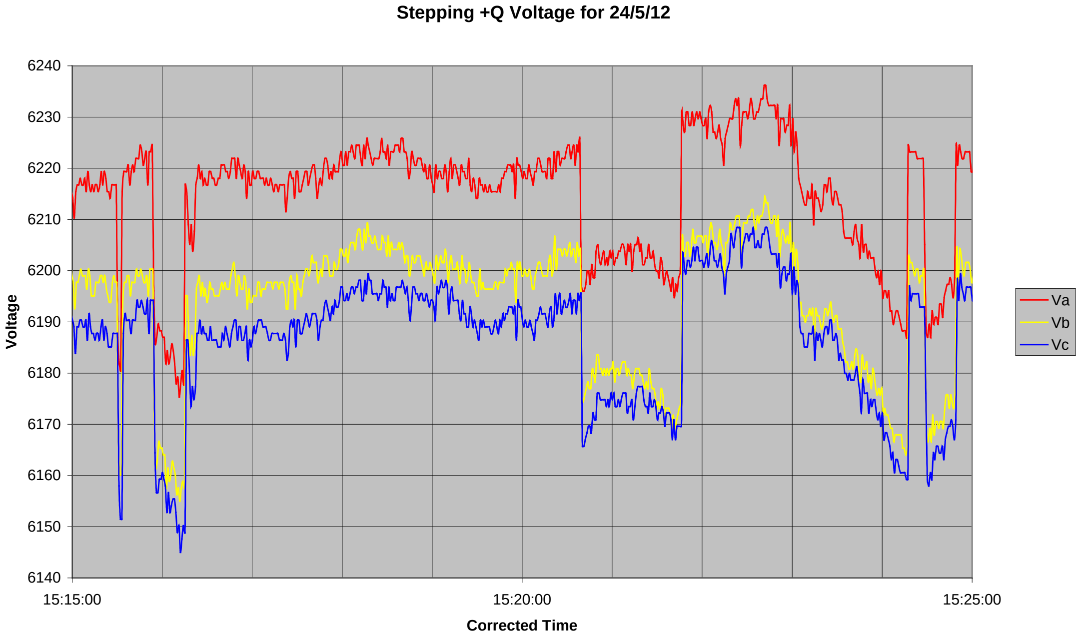


Figure 11: HV voltage during reduction in voltage

Hitachi gave WPD access to a simplified algorithm used by the D-SVC to establish the relationship between the HV and LV voltage which took account of the reactive power flows. This enabled WPD to update the voltage protection settings for undervoltage to 111V and for overvoltage to 251.5V. Details of this derivation can been found in Appendix C. After updating these settings the normal operation of the D-SVC did not trip the protection. The protection did occasionally trip when there was a significant voltage depression on the network. To avoid this problem in the second phase of the project all transformers have been specified with a HV metering unit so a voltage reference can be used from HV voltage transformer to drive the voltage protection.

5.1.4 Transformer Specification

At the design phase of the project the specification of the transformer to connect the D-SVC was considered in detail. WPD consulted Hitachi for guidance on the appropriate considerations for the selection of the transformer. The transformer would be required to be able to operate with 10% over-voltage, 10% over-current and be sized at least 1.21 times greater than the rated capacity of the D-SVC. Harmonic effects and sufficient cooling were also highlighted as areas to consider. For full details of the guidance please see Appendix D.

A standard 500kVA distribution transformer was selected, which met the specifications. This had an extra benefit for WPD as many of these standard transformers are in WPD's stores and purchased in large quantities under frame work agreements making it ideal for any potential roll out.

As discussed in section 6.1.3 the limitation of not having a HV voltage measurement adversely effected the voltage protection. Therefore a key addition to the specification for the future would be a metering unit.

The performance of the D-SVC was not as expected (this is detailed below in Section 6.2). The discrepancy between the effect on the voltage for the LV side of the transformer compared to the HV side of the transformer was noticeable and prompted a revisiting of the transformer specifications. While comparing this to the specifications of the D-STATCOM used on the Lincolnshire Low Carbon Hub project it became clear that significant care was taken to match the D-STATCOM with the impedance of the transformer and the connected network to maximise the effect on the voltage on the HV side of the transformer. One of the key performance limitations for the D-SVC was attributed to the use of a standard transformer with inappropriate impedance.

To correct this for the second phase, transformers would need to be specifically matched with the D-SVC, along with a HV metering unit installed, to help maximise the effect of the D-SVC on the HV voltage. This would have an impact on the cost and time scales due to the lead times on bespoke transformers.

5.1.5 Monitoring

The monitoring equipment was used to gather a full understanding of how the D-SVC affected the network. The eMS sub.nets were installed along the feeder at 5 locations and are detailed in Section 5.3. The monitoring gave a full picture of the impact the D-SVC had along the length of the feeder. At most locations, other than at the windfarm and Falmouth Bickland Hill, the monitoring was connected via the LV side of the distribution transformer, including one pole top transformer at Summerheath. At the windfarm the HV metering unit was used and at Falmouth Bickland Hill Primary, the 11kV board's VT and CTs were used.

The monitors recorded 10 minute averages of voltage, current, real power and reactive power which were sent via a GSM modem to WPD's internal systems. The data then was sent to a sub.net dedicated email inbox. This inbox reached its maximum limit regularly and the data was sorted by substation and transferred to an archive. This process was modified to two way during the course of the project, as the GSM calls were costly and periodically failed. The SIMs were transferred to GPRS, the data was then handled by Nortech's iHost on an internal server where the information was more easily accessible. This improved the communication of the data's reliability and reduced the need to drive to site to extract the data manually.

There were unforeseen reliability issues with several of the sub.nets during the project. The device at Falmouth Bickland Hill required an 'over the air' firmware update from eMS after it stopped working. Another sub.net at the D-SVC stopped functioning unexpectedly and required a replacement device to be installed. A third device at Summerheath stopped communicating and the device also locked up while being interrogated locally. As this device was difficult to access due to its pole top location and the data recorded at this location did not give any additional insight of the D-SVC's performance compared to the remaining monitors, the decision was taken to remove this monitor 18 months after installation.

The monitor at the D-SVC suffered from an additional issue. The transformer tripped several times on under voltage as discussed in Section 6.1.3. Occasionally when this happened the fuse in the fused leads which monitored the voltage would blow. The fuses used in the leads were fast blow fuses and were being blown by the "magnetic inrush" from the transformer when it was being reconnected after a trip. Figure 12 below shows a high resolution graph of the D-SVC tripping on an occasion when the V_c lead fuse blew. The problem was overcome by replacing the fuses with longer blowing fuses which were not affected by this transient phenomenon.

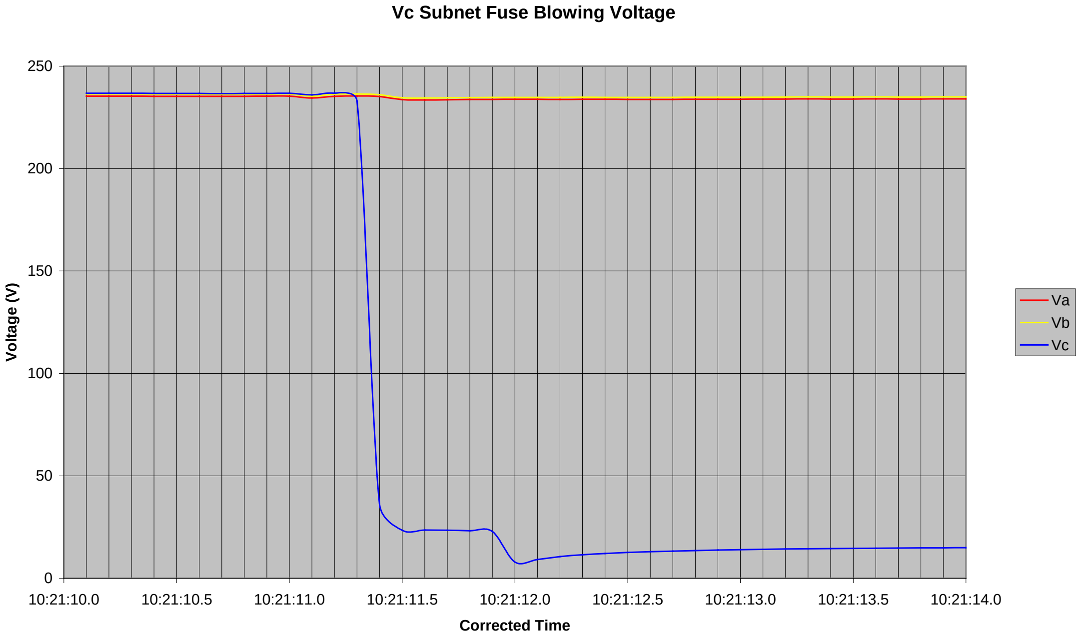


Figure 12: Voltage during a while a lead fuse blew

5.1.6 Mentoring of Harmonics

The harmonics were checked to ensure that the D-SVC did not have an adverse effect on the network's power quality. The sub.nets have power quality measurement capability so this was the data which was looked at first. The sub.net data highlighted that there were high voltage values on the 48th and the 50th harmonic. These were well above the planning limits on the LV side of the transformer but within limits, although high, on the HV side as shown in Figure 13.

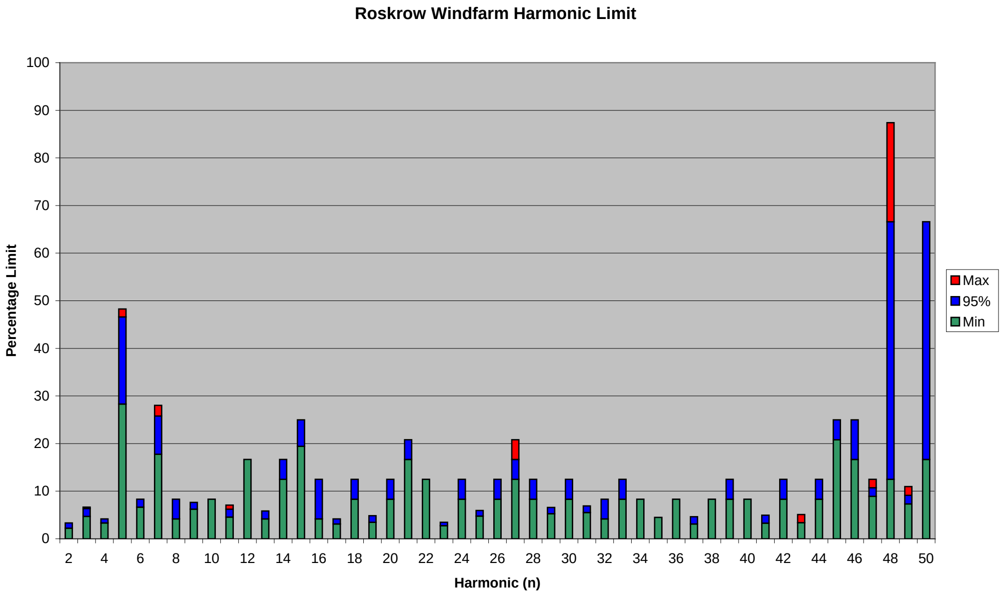


Figure 13: Harmonics on the HV side of the transformer

The results seemed unusual so further tests were carried out to identify if they were indeed correct. Two other instruments were used, the Topas supplied by Fluke and the PM7000 supplied by Outram.

The PM 7000 was able to measure different values compared to the sub.net but did highlight high results for the 48th and 50th harmonics like the sub.net identified in Figure 14. There is a discrepancy in magnitude between the two, however the results of the other high harmonics align well with the 15th and 21st. The 33rd is a high value measured by PM7000 but less so for the sub.net. However the 27th is a higher value for the sub.net but is zero for the PM7000.

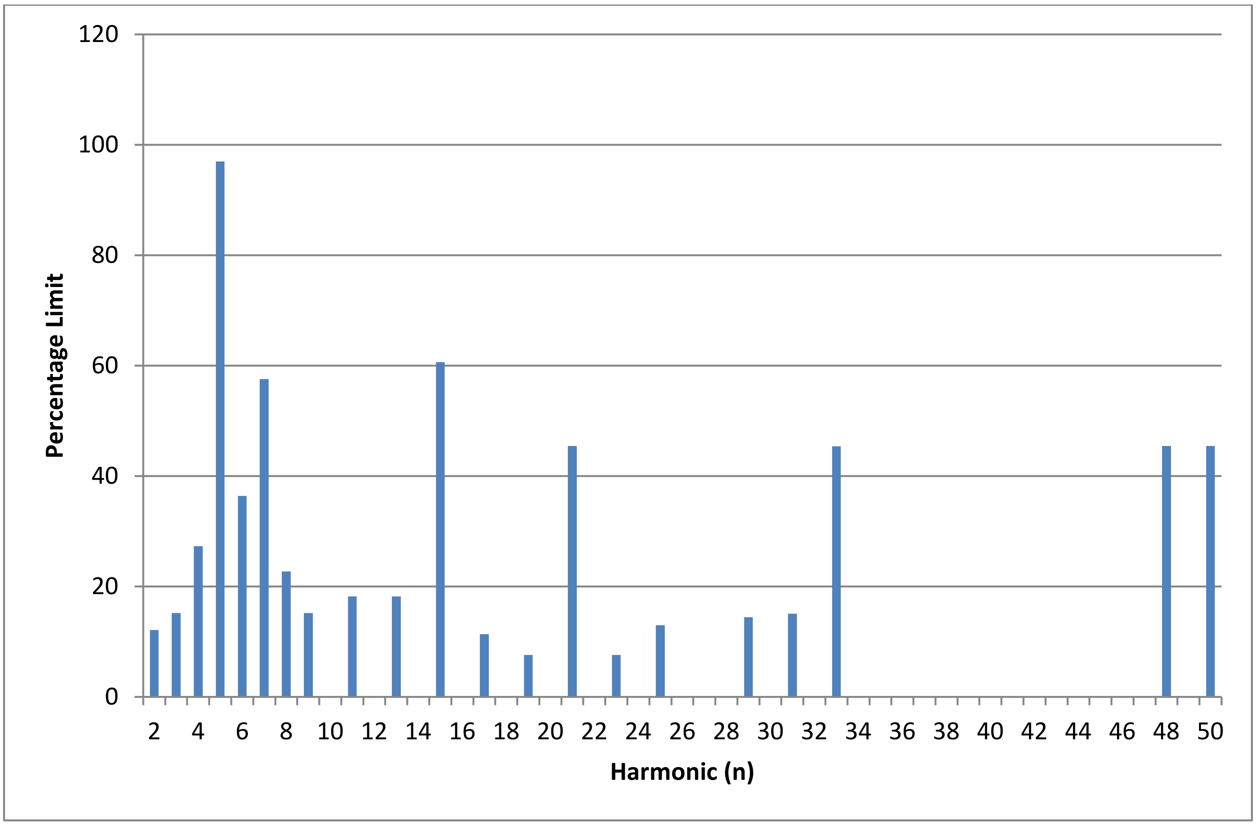


Figure 14: HV Harmonics measured by the PM7000

Some of the discrepancy is due to the data extraction from the PM7000's software. The values are only exported at 1 decimal point and therefore this reduces the sensitivity of the results. The Topas was installed to be a third device to compare the results against. The Topas can only measure the harmonics up to the 25th so could not verify the higher order harmonics. However the Topas acted well as a benchmark for the lower harmonics, the results of this are shown in Figure 15.

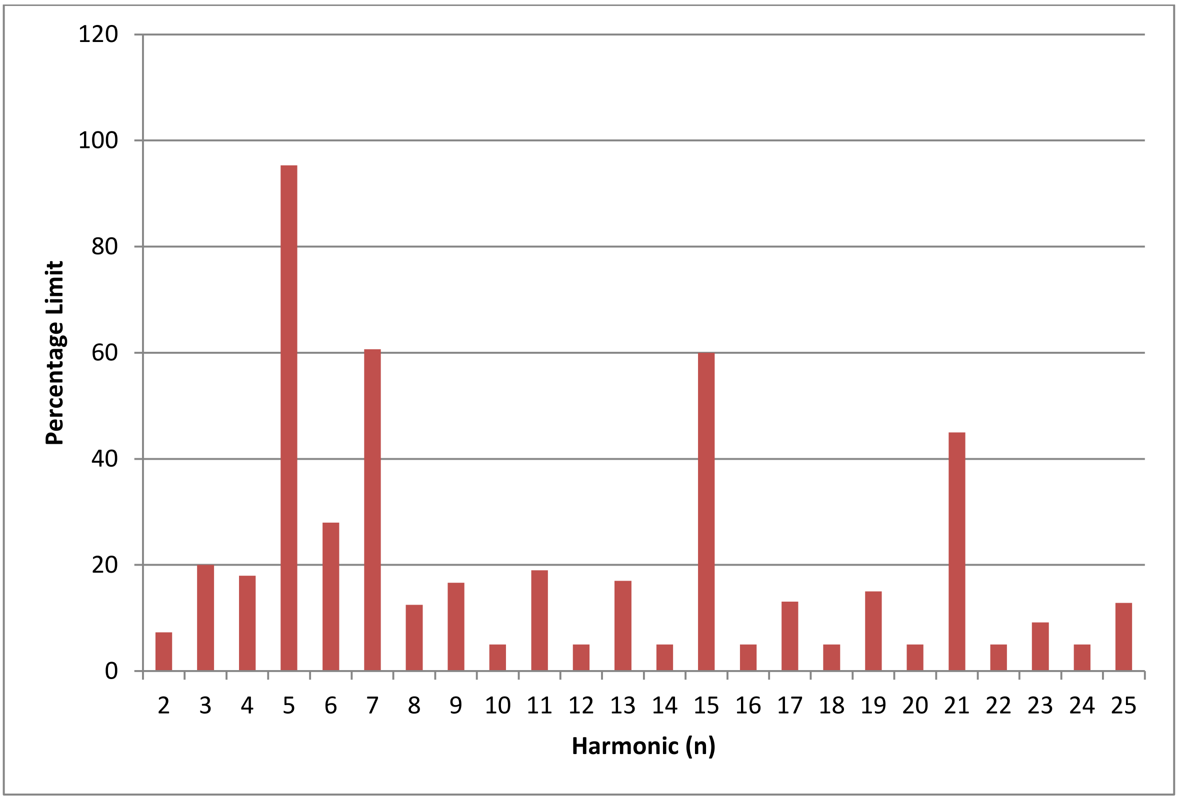


Figure 15: HV Harmonics measured by the Topas

The magnitude is comparable between the PM7000 and the Topas. The same key high values noticeable across all three devices, the 5th, 7th, 15th and 21st.

When the results were queried with Hitachi their engineers explained that the harmonic limits in Japan are up to the 40th therefore the filtering was designed to limit the harmonics below the 40th rather than the 50th. It would be possible to change this filtering for a UK version of the D-SVC. However this would require redesigning the D-SVC and as the HV values were not outside the limits it was decided not to extend the time scales to modify the D-SVC.

5.1.7 Wayleaves

The wayleave for the D-SVC was negotiated with the landowner at the beginning of the project. Even though the land owner had the windfarm on their land already, the wayleave negotiated ended up being more expensive than a conventional substation site but they were accepting of the D-SVC. The wayleave was agreed for 2 years but required to be renegotiated for another year.

For the potential sites for the second phase, sites were located on land where landowners had generation already installed. During initial conversations, the landowners saw the value of the D-SVC and were keen to take negotiations further. From the experience of the first D-SVC it was decided to negotiate a long wayleave period beyond the end of the project with a clause to allow WPD to cancel the wayleave if necessary. This meant that WPD could leave the D-SVC in situ after the project and if the project over ran wayleave negotiation would not incur any additional cost.

5.1.8 Key learning points

- The enclosure required further modification to be properly weather proofed
- The D-SVC and PowerOn could be integrated effectively

- For future reference Voltage protection ought to be installed on HV side of the transformer and Transformers ought to be impedance matched for the second phase

5.2 System Performance

A range of performance characteristics of the D-SVC were analysed over the course of the project. These were established from both 10 minute average data and high resolution 1ms data. The data collected and the analysis helped assess the performance of the D-SVC against its expected performance but also allowed testing of unforeseen behaviours of the D-SVC interacting with a real network.

5.2.1 Data from typical D-SVC operation

The graph below (Figure 16) shows the power output of the wind farm on a day with variable windspeeds.

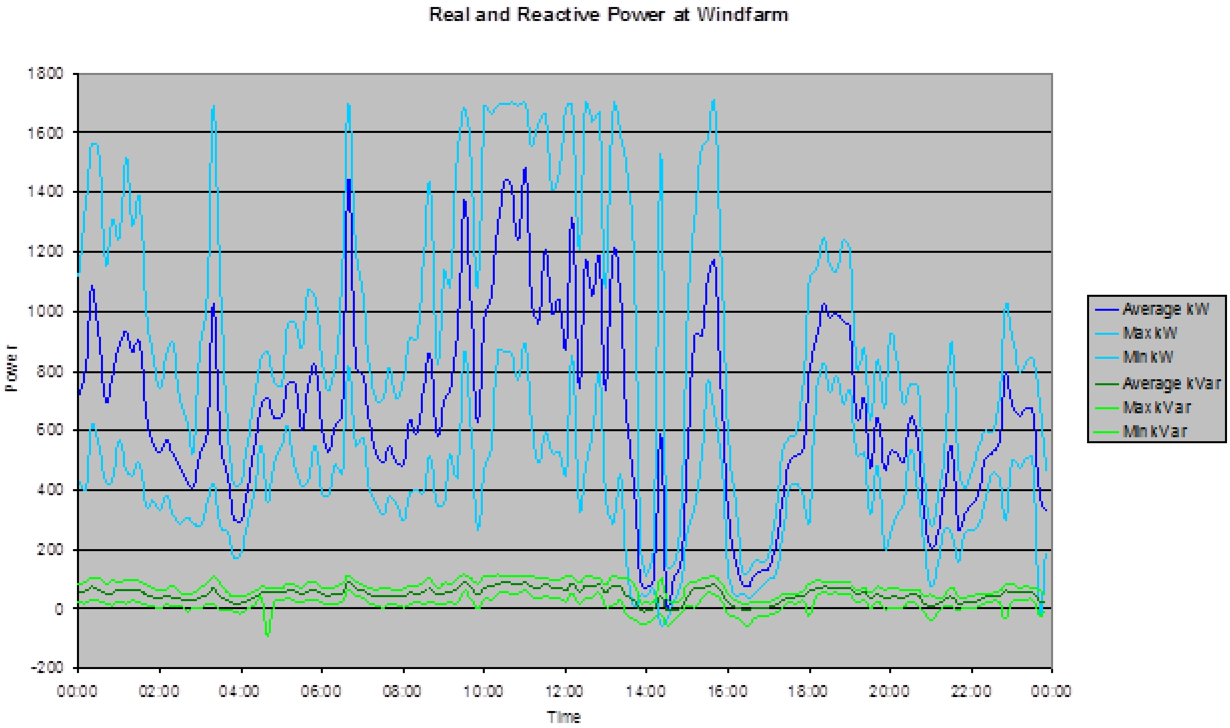


Figure 16: Power output of the windfarm

Figure 17 shows the reactive power output of the D-SVC during the same period, it can be seen to swing from exporting to importing (leading to lagging power factor) to either help reduce the voltage or increase it.

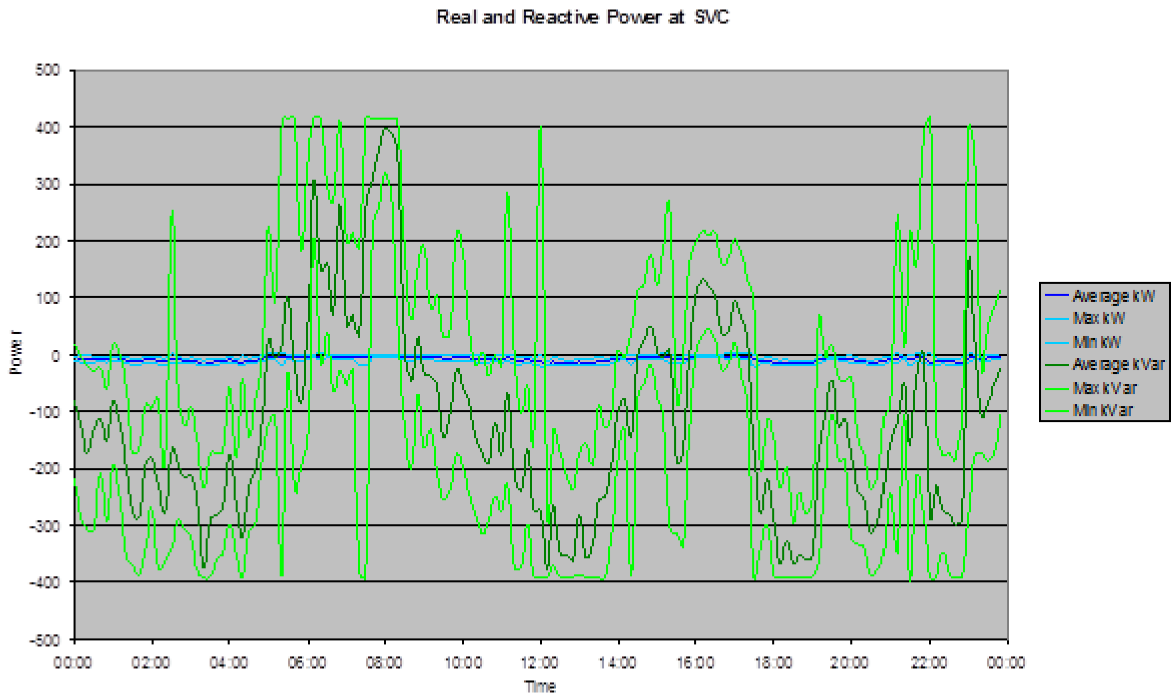


Figure 17: Power output of the D-SVC

Figure 18 shows the voltage at the LV side of the transformer at the D-SVC, the profile closely matches the reactive power output of the D-SVC.

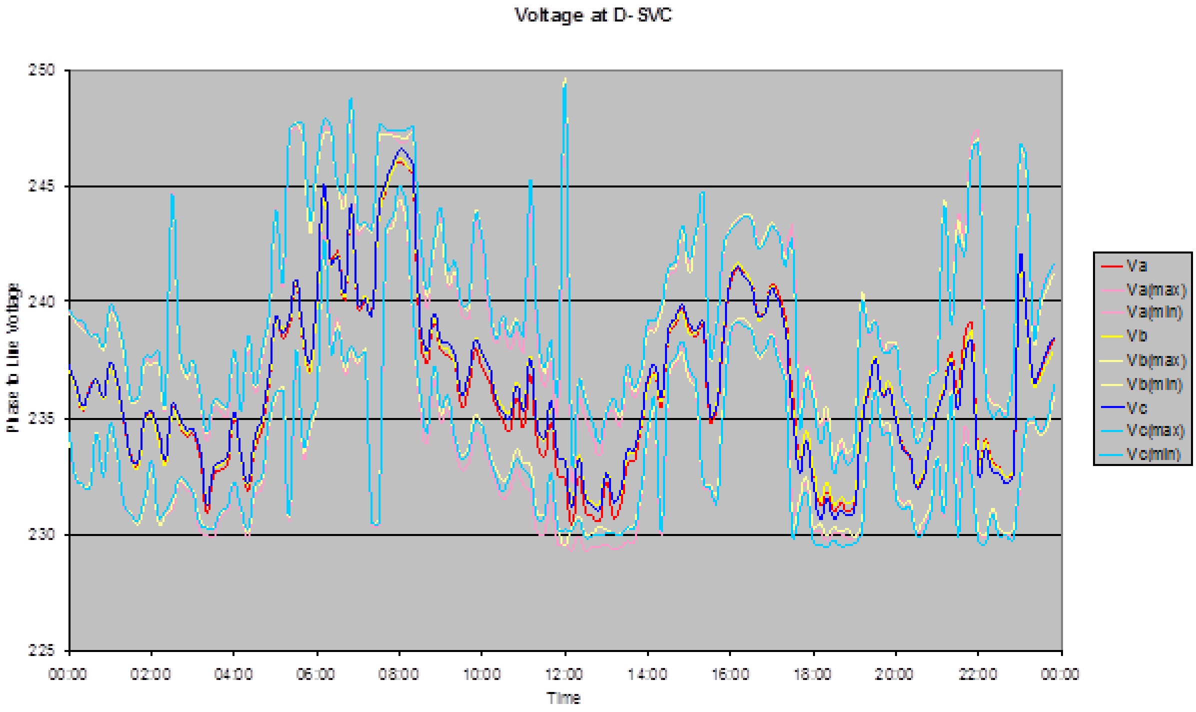


Figure 18: Voltage at the LV side of the D-SVC

Figure 19 shows the voltage at the windfarm, equivalent to the HV side of the D-SVC. The profile does not follow LV voltage at the D-SVC or the windfarm's power output closely.

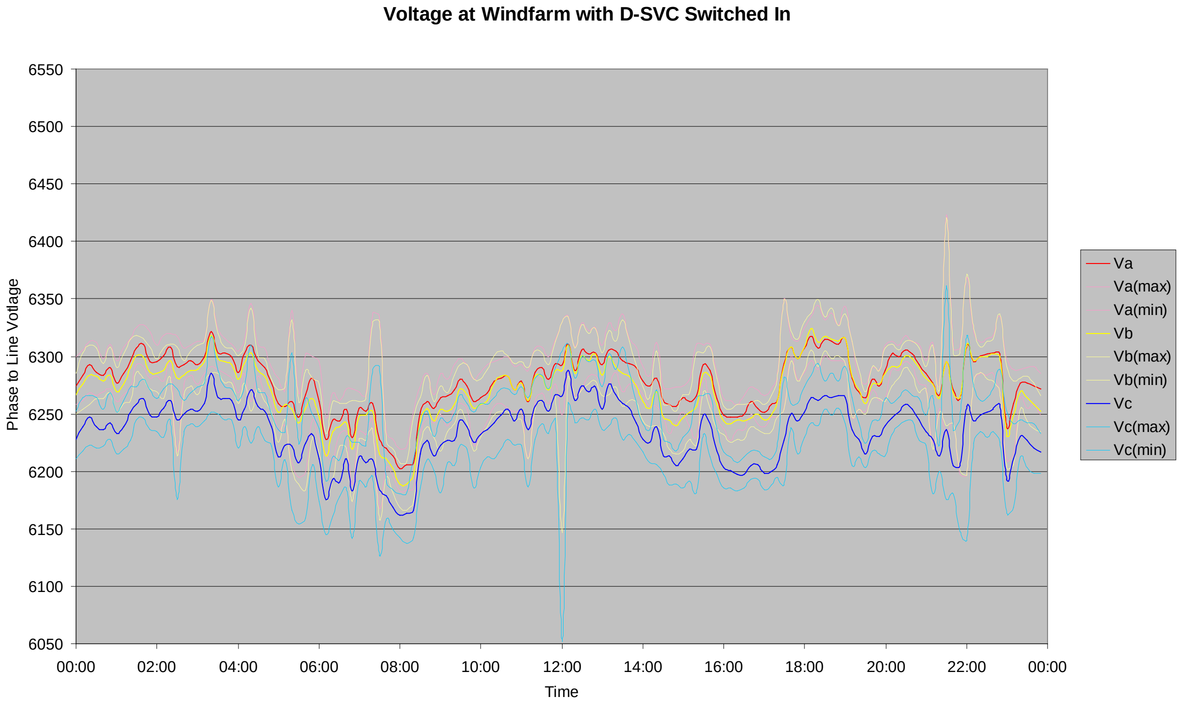


Figure 19: Typical HV voltage profile with the D-SVC running

Figure 20 shows the voltage at the Primary Substation, it is clear that the voltage profile at the generator is heavily influenced from this profile.

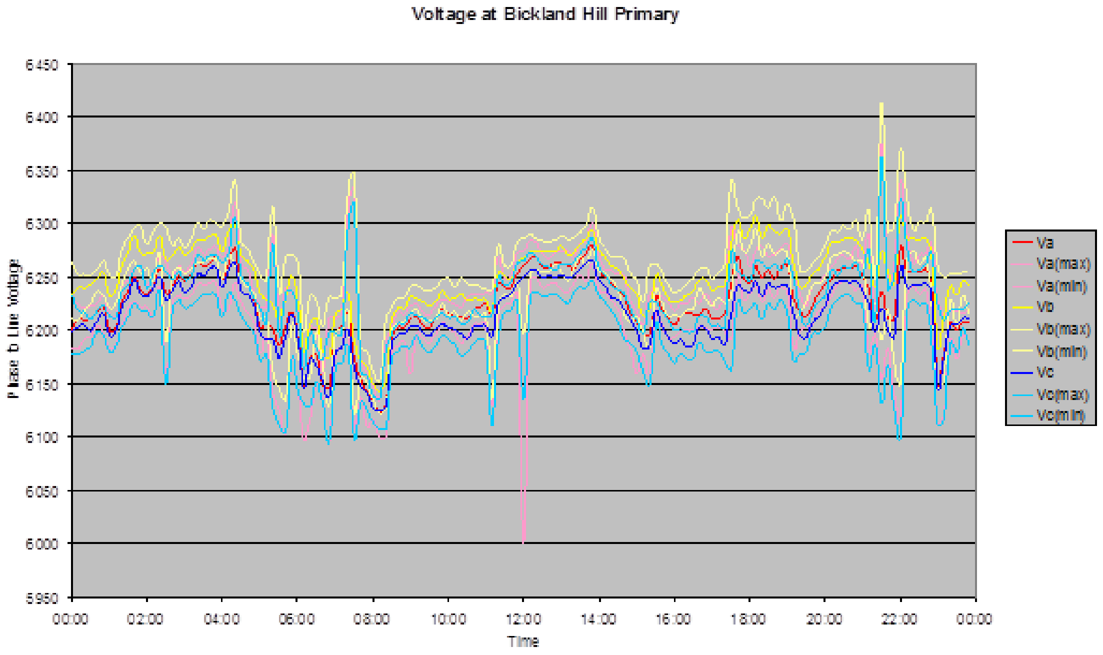


Figure 20: Voltage at Bickland Hill Primary substation

To get a better demonstration of the D-SVC, the voltage profile at the windfarm was taken from a comparably windy day with a comparable voltage profile shown in Figure 21. The voltage deviations are smaller with the D-SVC switched in, mostly staying within a 6150-6350V range compared to 6150-6400V range. This roughly translates to reduction of 50V line voltage or 86.6V phase voltage at peak, which is a modest reduction at 11kV. Additionally the short term spikes are smaller with the D-SVC helping to smooth the voltage.

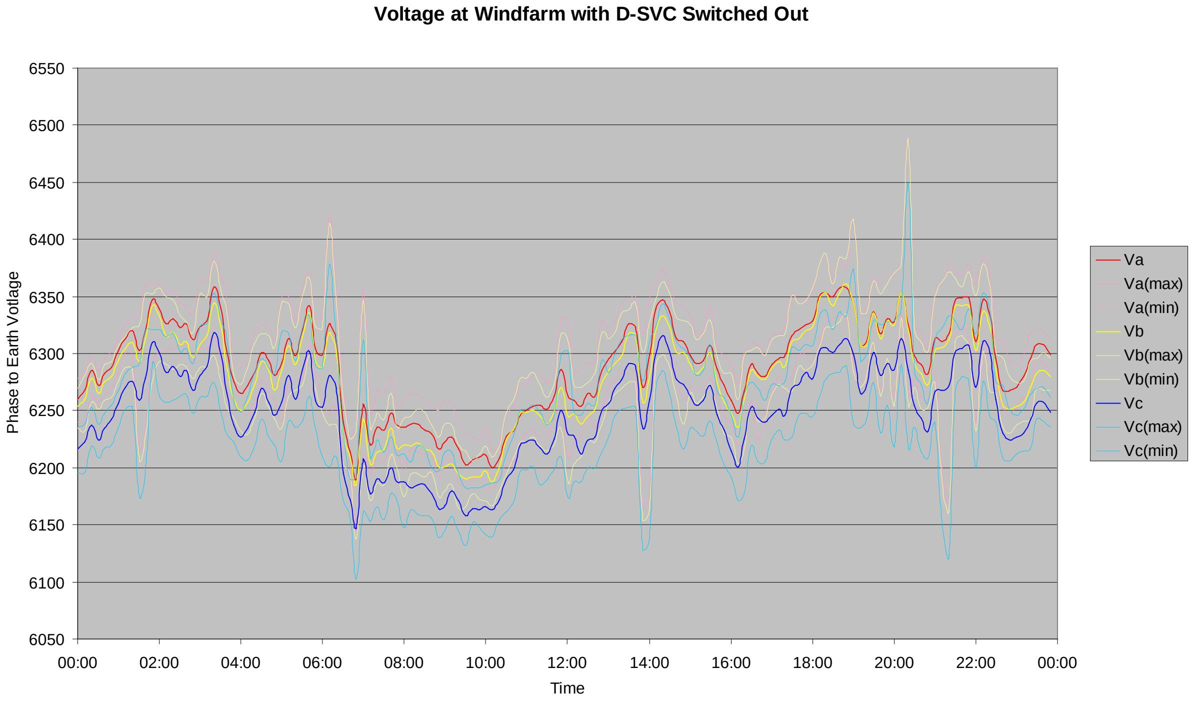


Figure 21: A comparable day without the D-SVC switched in

5.2.2 High resolution data from additional testing

Additional work was carried out to verify that the D-SVC was behaving as expected and to establish why the system was tripping on undervoltage. The work demonstrated the D-SVCs capabilities in all three modes. A detailed set of the results and analysis from the tests are in Appendix A. The report was written shortly after tests were carried out and analyses the voltage and power profiles in detail for all three modes. The Hitachi report produced from the same information is also included in Appendix B.

Figure 22 shows the different control modes which were tested over the first day. The effects are easily distinguishable from the voltage profile on the LV side of the transformer. This is not as easily seen on the HV voltage profile in Figure 23 due to the impact on the voltage profile from the tap changer and the windfarm.

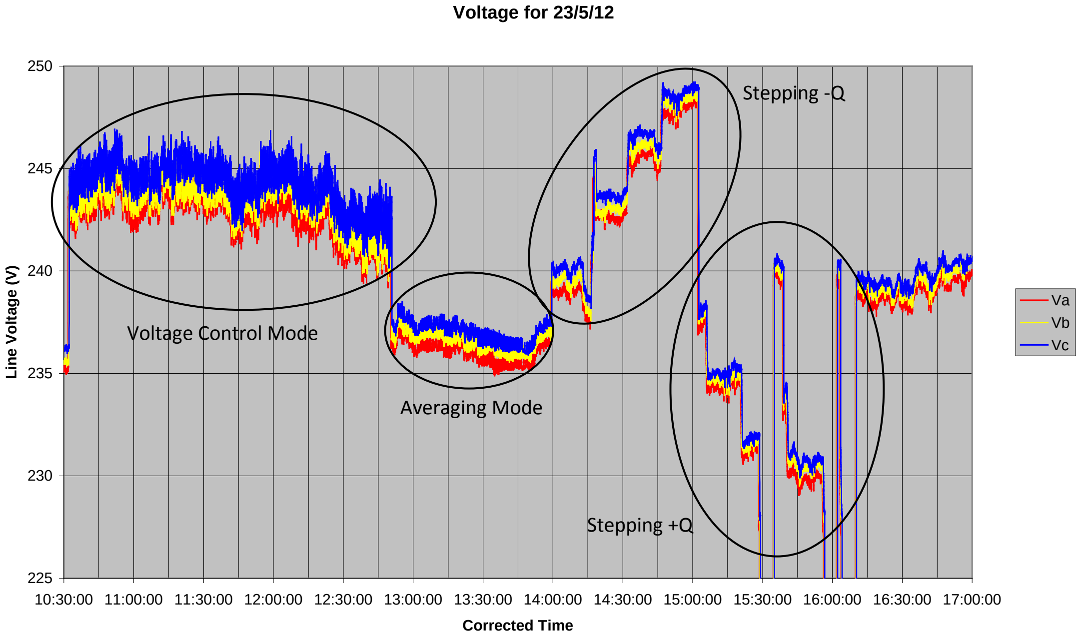


Figure 22: Voltage profile on the LV side of the D-SVC for the various tests varied out

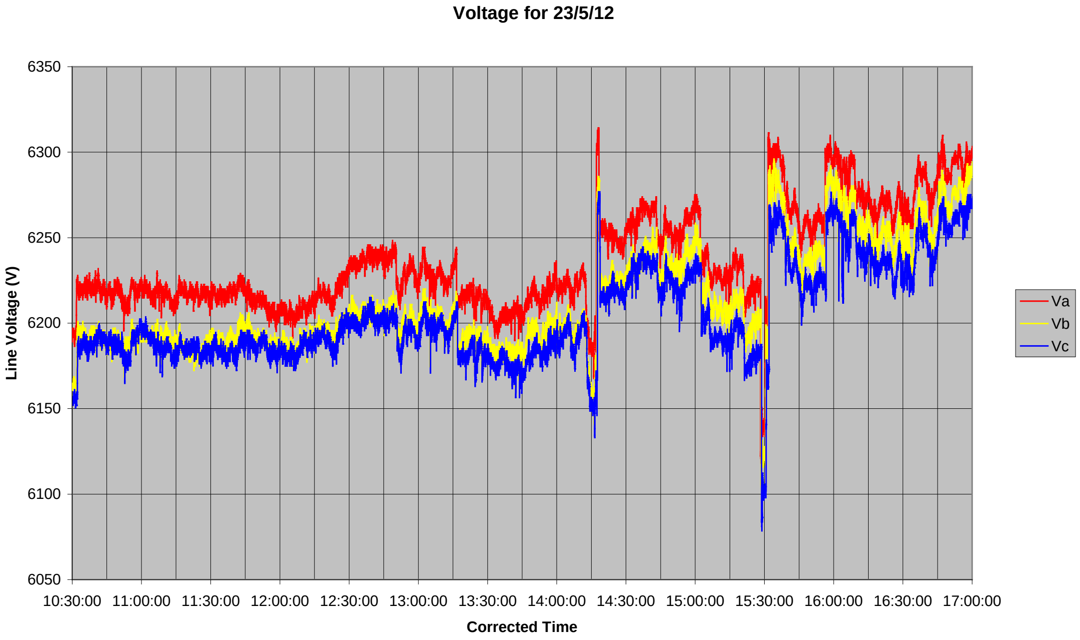


Figure 23: Voltage profile on the HV side of the D-SVC for the various tests varied out

Graphs and analysis of these results are in Appendix A.

Hitachi did additional modelling to assess the D-SVC’s performance, comparing measured output with modelled performance. Figure 24 shows the HV voltage from the tests and compares it to the calculated voltage profile without the D-SVC. It shows the D-SVC boosting the voltage when the voltage is below the set point and a reduction when it is above the set point compared to when it is off. This supports the hypothesis that the D-SVC helps reduce the HV voltage.

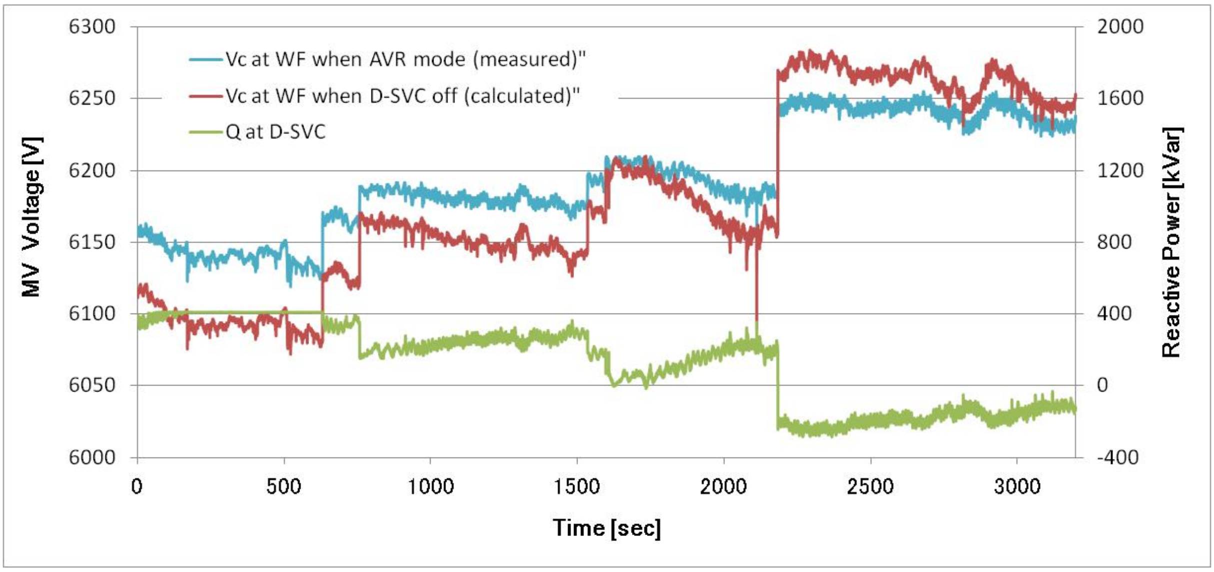


Figure 24: Calculated Vc at WF when D-SVC off

Hitachi conducted analysis on the range of voltage between the maximum and minimum at each point along the feeder. The voltage range was assessed from the recorded data which demonstrates that the variation of voltage increases, the further away from the D-SVC the measurement is taken. This shows the D-SVC's voltage smoothing capabilities. Figure 25 shows how the average range of voltage is reduced closer down the feeder towards the D-SVC while it is running compared to when it is switched off.

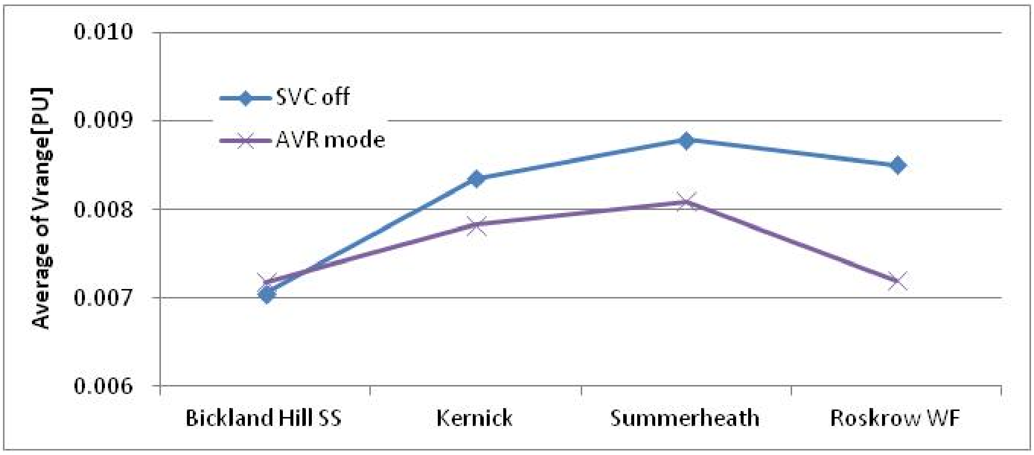


Figure 25: Average of Vrange

Analysis and data for Hitachi's graphs and modelling are in Appendix B.

5.2.3 Impact on peak voltage

One of the key performance characteristics of the D-SVC was its ability to reduce the voltage of the line in real terms while the generator was exporting power. The ability of the D-SVC to do this would allow more generation to be connected to rural 11kV networks where voltage rise from the generator is usually the limiting factor. The D-SVC, with its ability in import reactive power, would be able to reduce the voltage during these conditions.

The D-SVC does have an impact on the voltage. The reactive power absorbed by the D-SVC, as it is stepped down in 100kVAr steps, is shown in Figure 26. The visible effect on the HV voltage, is shown in Figure 27. As the voltage reduces the D-SVC trips, then the breaker is reclosed and the D-SVC continues to absorb reactive power.

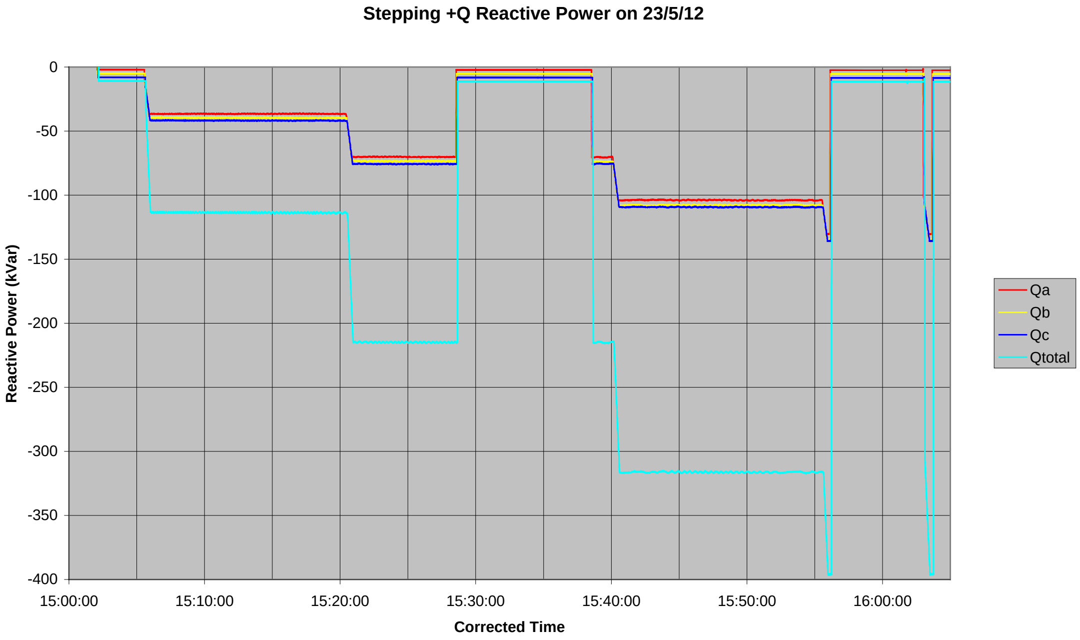


Figure 26: Reactive power output of the D-SVC

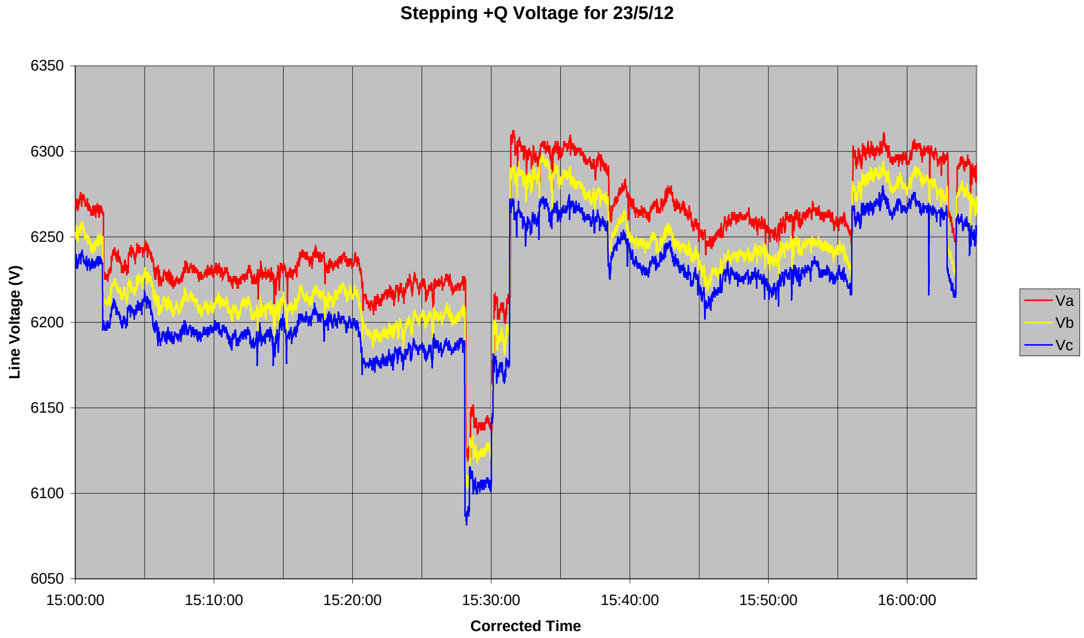


Figure 27: HV voltage while the D-SVC is absorbing reactive power

The graphs above in section 6.2.1 and 6.2.2 help quantify the relationship between the D-SVC's reactive power output and the HV voltage. In the graphs, Figure 19 and Figure 21, a direct comparison of the voltage profile can be made between two days of variable wind speed, one day with the D-SVC and one day without. Both days shown in the graphs are weekdays in spring so the load profile on Falmouth Bickland Hill primary substation is similar, thus meaning that the primary voltage profile is also similar. Although the profile of the windfarm's output is quite different, they are similar in terms of the range of output from moderate export to no export over the course of the day. All these factors contribute to similar voltage profiles. The range of voltages from peak to trough are reduced and the peak voltage is 50V line voltage less when the D-SVC is running.

The direct effect of the D-SVC reducing voltage can be seen when the levels of reactive power being absorbed is increased in steps, as shown in Figure 27. Figure 28 shows data from the following day when the reactive power was only being stepped down to 200kVAr to avoid further tripping. At 13:46 the D-SVC is turned off, its output before this is 200kVAr dropping to 0kVAr. This step change can be seen on the HV voltage graph, taking the Vc, the voltage is 6,136V then jumps to 6,173V. This 37V line voltage (or 64V phase voltage) step change is in line with the 50V output observed from full output. This therefore supports the view that the D-SVC is reducing voltage.

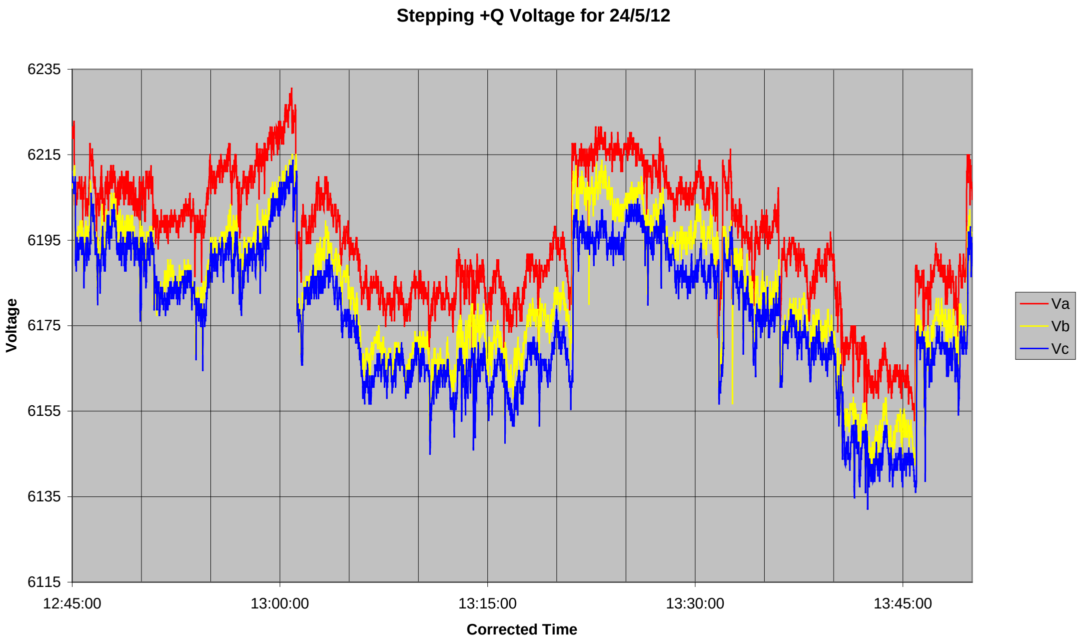


Figure 28: HV Voltage while reactive power is being absorbed

Hitachi carried out modelling work on the output of the D-SVC. The measured values were taken and the algorithms were used to calculate what the voltage profile would have been if the D-SVC was not operating as shown in Figure 24. From this work it can be seen that with the D-SVC absorbing around 300kVAr, the HV voltage is 6,245V compared to the calculated value of 6,275V. The modelling shows a 30V line voltage (52V phase voltage) improvement with the D-SVC operating.

There is an observable improvement on reducing the voltage at peak output. To explore this effect in more depth in the second phase the size of the adjacent generator will be reduced. In this phase if both the generator and D-SVC were outputting at their maximum levels, the equivalent power factor would be 0.976. For a smaller generator this would be a lower figure and have more of an impact on the voltage. Further improvements should be made from impedance matched transformers. The largest impact of the voltage along the entire feeder is from the primary substation voltage so incorporating the centralised control of the D-VQC to influence this will have a large impact on the overall voltage optimisation.

5.2.4 Impact on voltage smoothing

The D-SVC can respond quickly to changes in voltage and power as it is built from power electronics. This makes it ideal to respond quickly to any changes that occur faster than the tapchanger scheme at the primary. These quick variations in power and voltage are often seen from the output of intermittent generation such at windfarms and photovoltaic parks as the wind varies or as fast moving clouds shade the photovoltaic park. Each of the D-SVC modes has smoothing incorporated within their functionality. With AVR mode, which is most useful for keeping the system within statutory limits, the control algorithm reduces all fluctuations. In ARV mode, the algorithm targets longer term fluctuations in the region of minutes while in SFV focuses on short term fluctuations in the region of seconds.

Under AVR mode the D-SVC works hard, frequently hitting its upper and lower limit of output as shown in Figure 17 above. The disadvantage of the AVR mode is when the voltage is significantly above or below the set point the full output is being used to reduce or raise this set point thus leaving no further capacity to smooth any variations.

Figure 29 shows the windfarm abruptly starting to export. Figure 30 shows the HV voltage at the same time while the D-SVC is running in AVR mode. The impact on the voltage from the export can be seen as it increases however the voltage profile fluctuates less than the export profile and there is not a change in these fluctuations between the generator exporting and not.

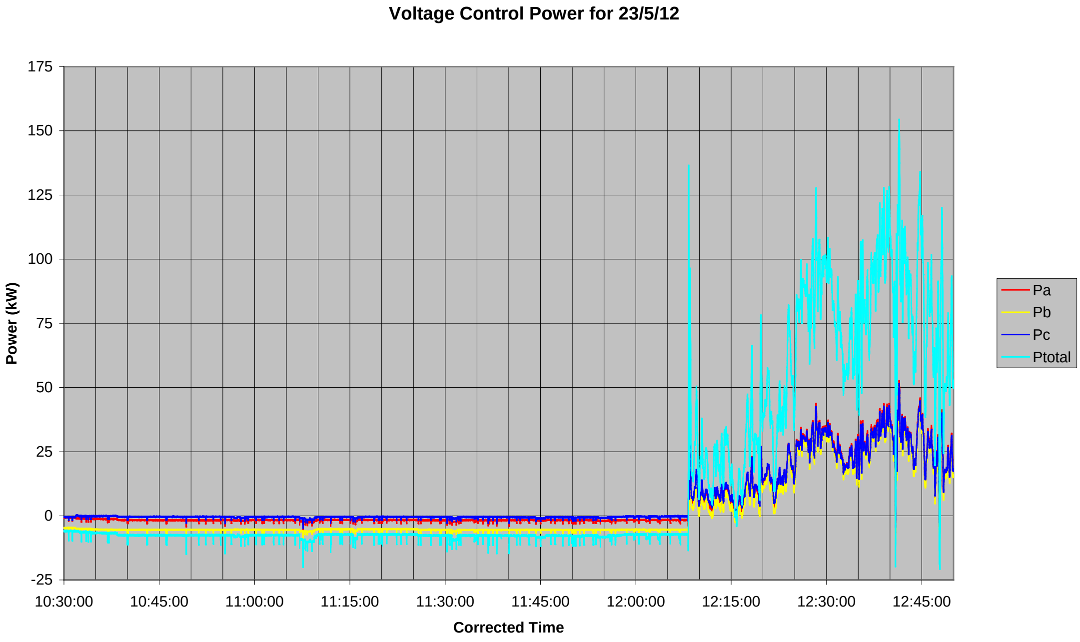


Figure 29: Real power output of the windfarm

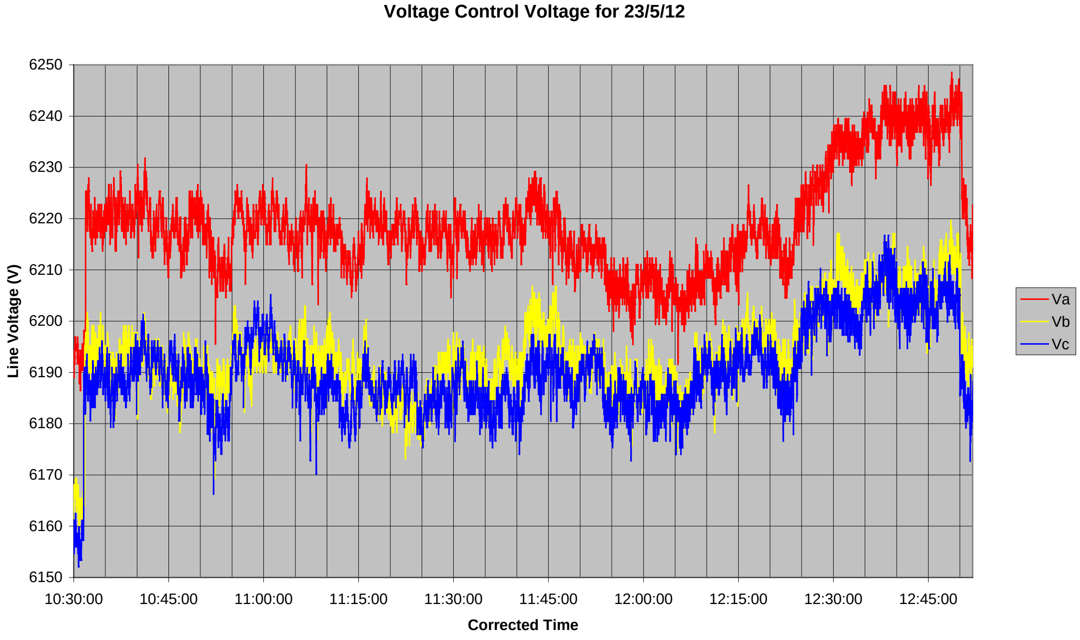


Figure 30: HV voltage with the D-SVC operating in AVR mode

In ARV mode the D-SVC operates less, in Figure 31 the D-SVC operates within a quarter of its maximum output.

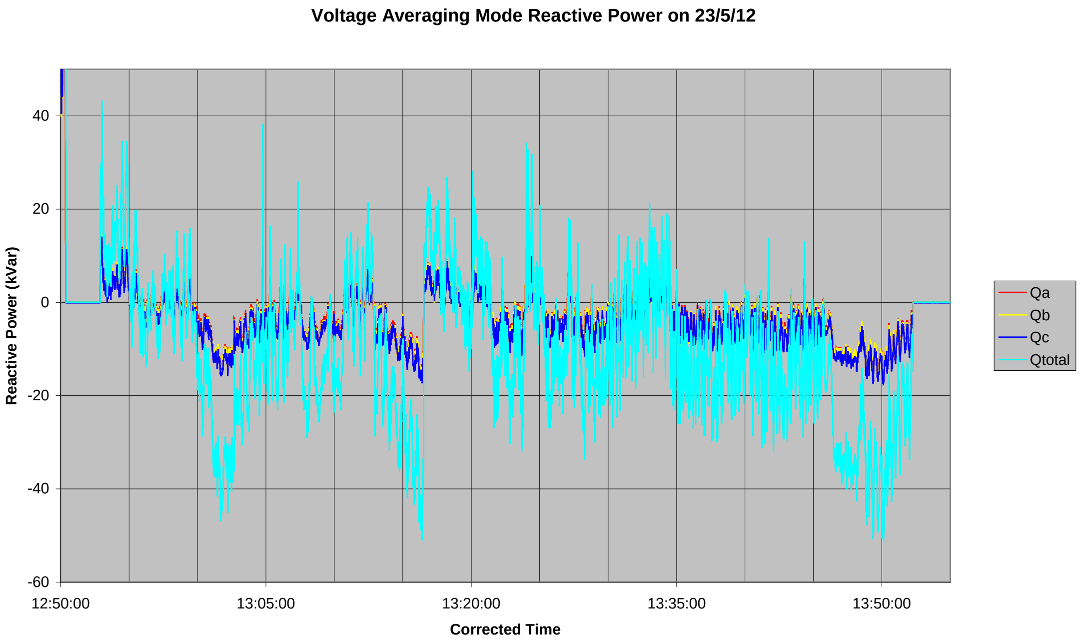


Figure 31: D-SVC reactive power output in ARV mode

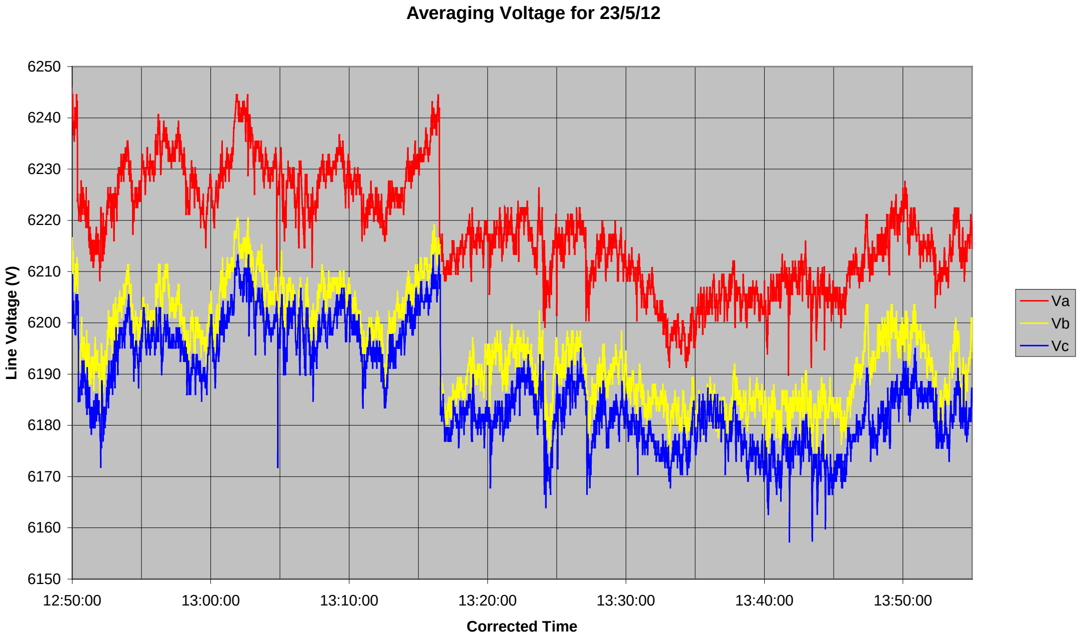


Figure 32: HV voltage while the D-SVC operates in ARV mode

In Figure 32 the D-SVC responds well to the voltage fluctuation at 13:16 but has limited impact as the magnitude of reactive power is low.

The D-SVC in SFV mode outputs even less reactive power limited its impact as shown in Figure 33.

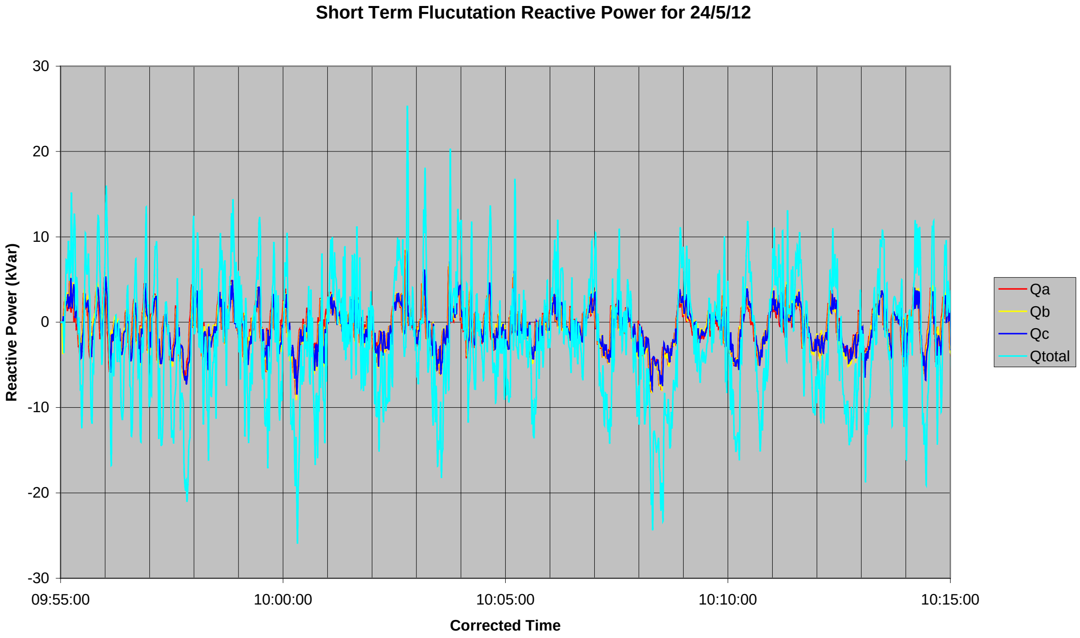


Figure 33: D-SVCs reactive power output in SFV mode

Both ARV and SFV modes demonstrate the D-SVC's ability to smooth voltage but the way the modes operate means they have limited impact on the system. Therefore they are less useful modes compared to AVR mode. The AVR mode combines the D-SVC's smoothing ability with ability to manage peak and trough voltages. This mode also uses far more of the D-SVC's output range thus increasing its utilisation.

5.2.5 Impact on the range of voltage variation

An area that the D-SVC helped improve the voltage was in the range of variation seen from the 10 minute average data. The data from the sub.nets record the average, minimum and maximum in ten minute periods. It is noticeable that the range between the maximum and minimum from these readings are improved while the D-SVC is operating. Moreover the impact from the D-SVC can be seen while looking at the average range of values along the feeder. This is demonstrated in Figure 25. This improvement is due to the D-SVC's ability to smooth out spikes as discussed in 6.2.3.

The key benefit of this is more predictable voltage profiles from intermittent distributed generation. As DNOs move towards time series modelling, capacity will be released from reducing the swings in voltage allowing a higher propagation of generation onto the network. The effectiveness of this reduction is improved the closer to the D-SVC in the network the reading is measured. Therefore the ideal D-SVC location is close to the feeder end as it was in this instance. The impact of intermittent generation is improved, particularly when it is connected close to the feeder end where the generation's impact is worse. This confirms that the ideal scenario to use D-SVCs is in rural networks where distributed generation is connected.

5.2.6 Impact of reactive power on voltage ratios

As described in 6.1.3 the reactive power produced from the D-SVC meant the ratio between the HV and LV voltage was not linear. As this was causing trips on undervoltage from the LV connected protection relays analysis was carried out on the measured values to confirm this. Figure 34 shows the HV voltage vs the LV voltage while the D-SVC is not operating. The relationship is directly proportional as expected.

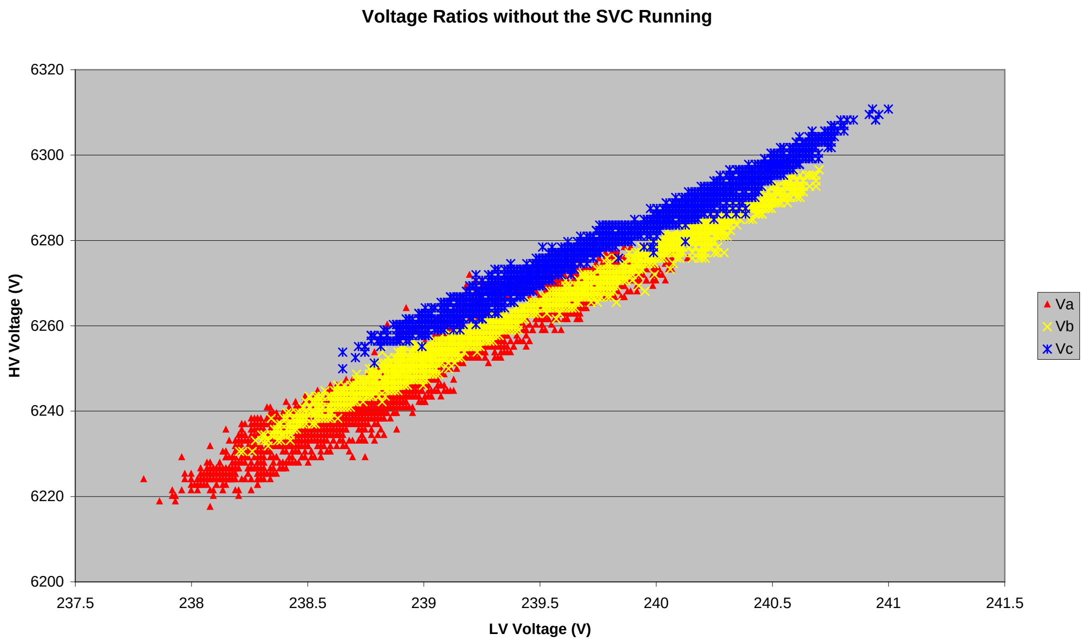


Figure 34: Voltage ratio without the D-SVC running

Figure 35 shows the same HV voltage vs LV voltage but while AVR mode is running. This mode is the most frequently used due to its performance as explained above. The linear relationship is now gone, this is due to the varied reactive power output in AVR mode.

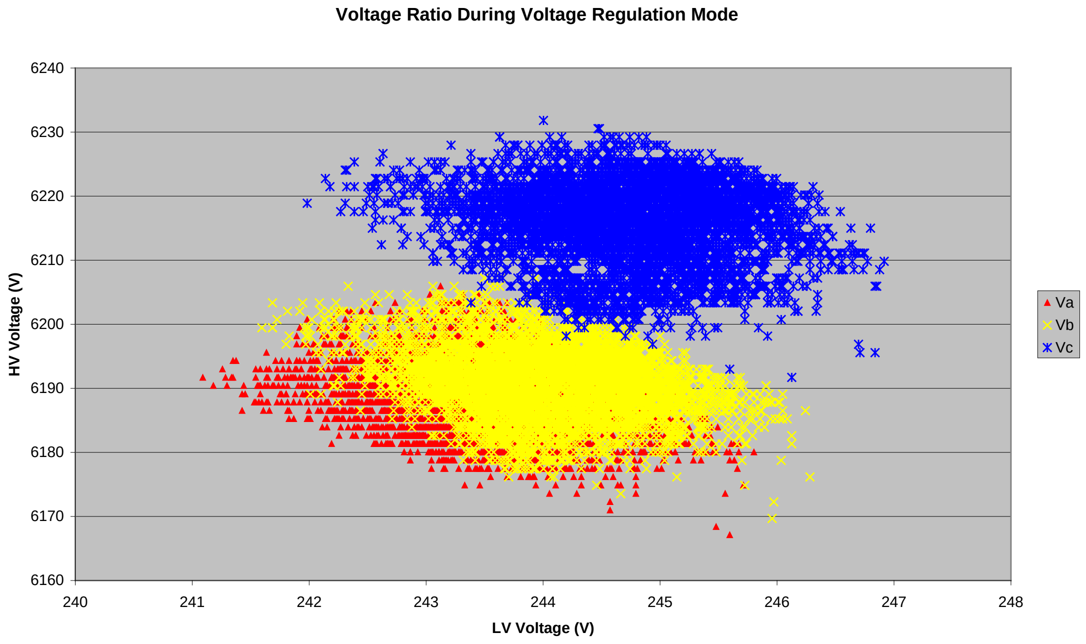


Figure 35: Voltage ration with the D-SVC operating in AVR mode

The lack of linearity does not have a significant impact on the network unless an LV connected device is trying to use LV voltage as a proxy for HV voltage and is assuming a linear relationship like the protection relay installed at the D-SVC. Most devices that require the HV voltage will measure it via a VT. If a LV voltage is required as a proxy it is important that the reactive power is also measured to calculate the correct HV voltage.

5.2.7 Discrepancy between LV performance and HV performance

Measuring the output on the LV side of the transformer as well as the HV side of the transformer did reveal that the voltage performance on the LV side closely matched the reactive power output of the D-SVC. Figure 36 shows the LV voltage following the increase in reactive power from the D-SVC.

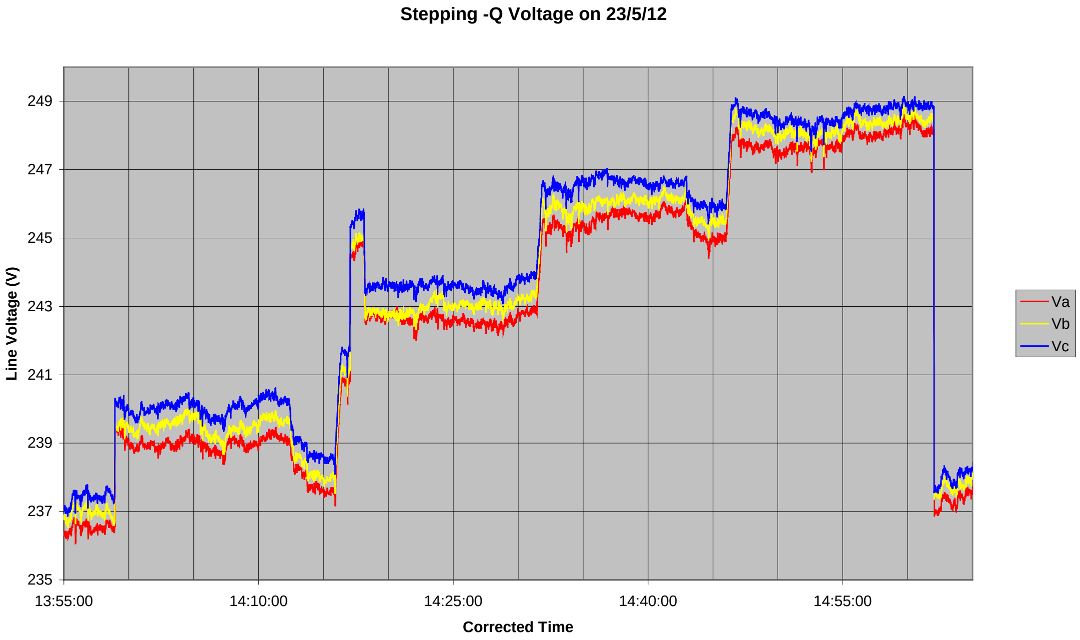


Figure 36: LV voltage as reactive power export is increased

The coincident HV graph is shown in Figure 37. Although the steps in reactive power are still identifiable they are less obvious. There are a few reasons for the discrepancy. The HV voltage is highly influenced by the voltage at the primary as shown in 6.1.1. The primary bar voltage will always have a large impact along the feeder. The generator will also influence the voltage on the HV, particularly if the generator is large in comparison to the D-SVC. Finally the performance of the transformer will have an impact on how well the LV connected D-SVC can control the HV voltage.

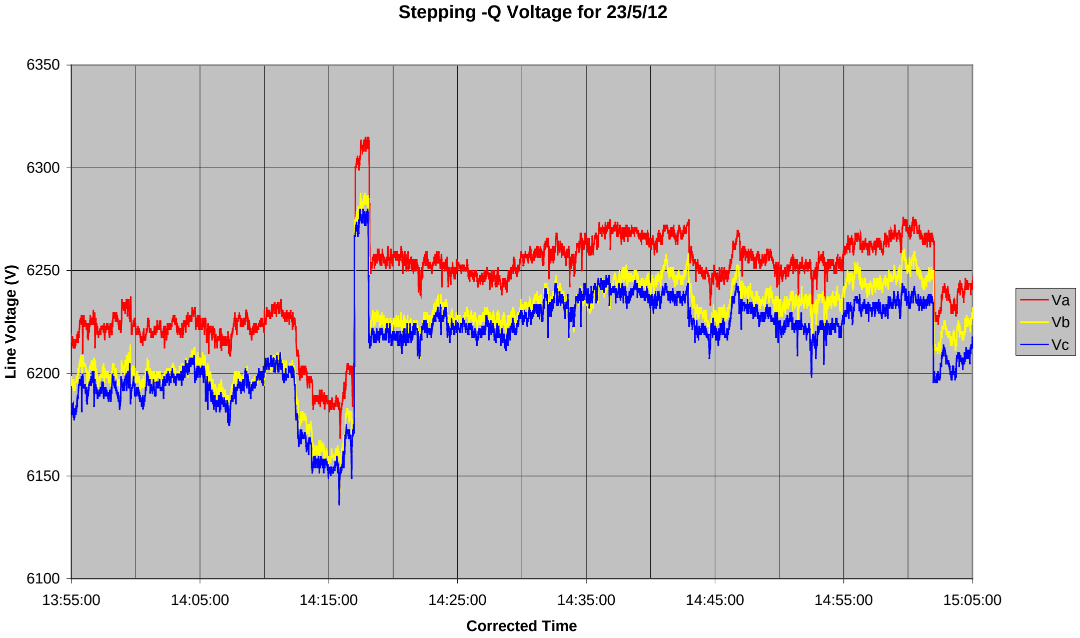


Figure 37: HV voltage as reactive power export is increased

The discrepancy in correlation of the HV performance raised concerns about the performance of the transformer. As detailed in Section 6.1.4 the specification of the transformer was investigated further and it has been decided to order bespoke impedance matched transformers for the second phase to improve the HV performance. The locations of the D-SVCs for the second phase will also be adjacent to smaller generators compared to the D-SVC's size.

5.2.8 Key Learning Points

- The output of the D-SVC follows the generation output well
- The HV voltage is predominately driven by the tap changers at the primary substation
- The material impact from D-SVC at peak is a reduction in voltage of around 50V line voltage
- Voltage smoothing is improved by the D-SVC

5.3 System Modelling

To predict the impact that installing a D-SVC on the distribution network will have, it is important to be able to model its impact. This allows the best location to be identified and to assess the benefits of installing such a device. Hitachi modelled the D-SVC's performance in this trial however WPD also did some internal modelling to understand the impact on the system.

5.3.1 Data extraction

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. Figure 38 shows the DINIS network that the D-SVC is connected to.

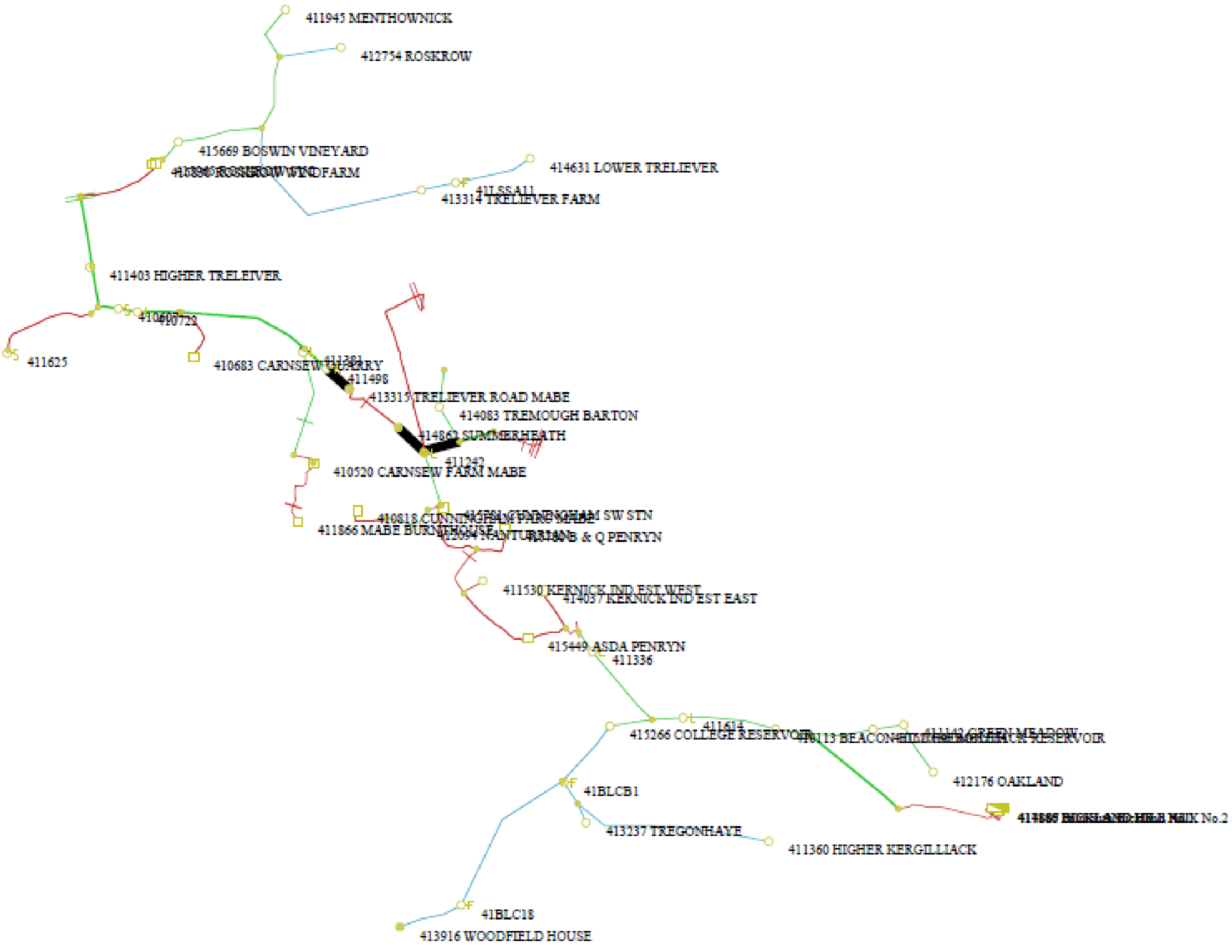


Figure 38: A screen shot from DINIS of the 11kV network

An initial extract was quite simple, 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 DINIS, this was much more time consuming and required specialist resources. One of the key aspects was to index link the lines to the nodes. This allowed the connectivity of the model to be established easily. 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.

5.3.2 Power flow modelling

The D-SVC was modelled in DINIS as this is where the native data for the 11kV network resided and is the standard tool for all WPD 11kV planners. As there is not a reactive power source as a default in DINIS, the D-SVC was set up as a generator in voltage control mode with zero real power to simulate the AVR mode. Initially this did not work well as the D-SVC was unstable swinging from its maximum output leading to lagging and only solving at either extreme. The modelling was revisited; as a result of this the primary source was altered to a fixed voltage source which rectified this stability issue.

Modelling the D-SVC fully in DINIS required time series analysis to get a full view of how the D-SVC will react under various network conditions. The worst cases can the modelled to ensure what the D-SVC would not adversely affect the network. To assess the real benefit of the D-SVC for a planner a more transient style analysis would be required.

5.4 System Integration

The interface of the D-SVC and the D-VQC with WPD systems is important. This allows the Hitachi systems to work within the WPD architecture seamlessly allowing remote access and control through traditional means. Trialling a system that can be integrated in this way lends itself to closer rollout and makes the system relevant to WPD's wider business needs.

5.4.1 Interface with PowerOn

The most critical integration of any operational piece of equipment is with PowerOn. This ensures safe operation of the equipment and allows Control to interact with the device effectively. If this is not the case, outages may take longer to restore effecting customer minutes lost.

Several basic controls and statuses must be communicated between the D-SVC and Control. The state of the D-SVC and the ability to turn it on and off are the most important. This allows the D-SVC to be turned off in an emergency and visibility of the D-SVC to the control engineer. This interface has been used extensively during the course of the project avoiding an engineer to be next to the D-SVC when it is being operated.

For the second phase this interface becomes more important as there will be multiple D-SVCs on the same network. The D-VQC will be influencing the tapchanger and this has potentially significant impacts on the wider network. The system will be automated to allow minimal interaction while the system is operating normally, but allowing quick intervention when required through the network diagram on PowerOn.

5.4.2 Communications

A single D-SVC requires limited access to communications only requiring status updates and tele-control which can be easily catered for with traditional SCADA. In the second phase a much higher bandwidth of communication is required. The system operates in a closed loop control taking data from multiple sensors on the network every few seconds to be analysed by the D-VQC to then send voltage set points to the D-SVCs. It is envisaged that at least 16 sensors will be spread across a primary substation's network, most of which we be at remote locations close to the feeder ends. A resilient and reliable communication network capable of a high band width is required. This performance is difficult to achieve through traditional DNO communication technology and so requires a different solution to do it effectively.

5.4.3 Proprietary protocols

Hitachi's equipment was designed to be stand alone with only Hitachi proprietary protocols to communicate to other devices. In Phase 2 the D-VQC is required to communicate to third party sensors, the tapchanger relay and with PowerOn to operate correctly. This means that Hitachi needs to develop another interface for the D-VQC to communicate. It was decided that DNP3 was a good choice due to its flexibility and the wide range of compatible devices used in substations. Also WPD has experience of using DNP3 already. As part of phase 2, Hitachi has committed to develop the D-VQC with a DNP3 interface.

5.4.4 Interface with the tapchangers

In Hitachi's original design the D-VQC was envisaged to control the tapchangers directly 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 function 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.

5.4.5 Sensors

The number of required pole top sensors was originally not specified by Hitachi but to get full coverage of a primary, in excess of 16 sensors would be required. These sensors are required to measure real power, reactive power, current and voltage. The pole top sensors need to be in locations where communications are accessible and they need to compact so as not to clutter the poles with extra equipment.

5.4.6 Key learning points

- Good interface with PowerOn is critical
- Communication needs to be fast and reliable
- The protocols used need to be well understood

6. Performance compared to the original Project aims, objectives and success criteria

This project's primary objectives were intended to meet three of Ofgem's LCNF specific requirements:

- A specific piece of new (i.e. unproven in GB) equipment (including control and communications systems and software) that has a Direct Impact on the Distribution System;
- A novel arrangement or application of existing Distribution System equipment (including control and communications systems and software); and
- A novel operational practice directly related to the operation of the Distribution System;

The focus of the project was looking at the effectiveness of the D-SVC to control the fluctuations of voltage on rural networks. The first phase of work had an additional element for informing the second phase of the project.

The aims and objectives for this project were to:

- Address fluctuations seen on long distribution lines due to DG
- Determine the effectiveness the D-SVC
- Test a single D-SVC
- From these tests inform the development of the D-VQC, and
- Inform the system optimisation of multiple D-SVCs

The project demonstrated that the D-SVC does reduce voltage fluctuations on long lines due to DG. As shown in Section 6.2 and in particular Section 6.2.3, the voltage profile is smoothed by the D-SVC improving the adverse effect of the connected wind farm. The effectiveness of the D-SVC is also discussed in Section 6.2, the D-SVC was shown to reduce the peak voltage by 50V and help smooth the voltage profile. The effectiveness of the D-SVC is also demonstrated in Figure 25, which shows the improvement in voltage smoothing between system normal and the D-SVC switched in.

The first phase was planned to test a single D-SVC, the focus was to gain learning on how best to install and commission a D-SVC which are detailed in section 6.1. This section highlights the importance of the enclosure, integration with PowerOn and appropriate voltage protection settings. This learning and the developed installation techniques will be implemented while installing the new D-SVCs. The learning from the first phase also informed the need for new impedance matched transformers and to use HV VTs for a better protection setup and monitoring. The testing of the D-SVC also helps increase the understanding of how it operates in various conditions which will inform the test plan for the second phase and allow for more accurate and detailed modelling of multiple devices.

The learning from this phase also allows the specification of the D-VQC to be modified to include a DNP3 interface and thus improve the project plan for the second phase. This has allowed the second phase to address integration and communication issues, detailed in Section 6.4, in a proactive way which will lead to more relevant project outcomes for the second phase.

There were two specific success criteria associated with Phase 1 as listed in the registration proforma:

- Identify optimum settings for the D-SVCs for a given load and to achieve optimum voltage
- Use changes in set points & low pass filter to increase our understanding of D-SVC performance for a given set of parameters and a given network load.

Both of these criteria were explored in depth by the project. The D-SVCs were trialled in all three available settings to investigate their effect. It was concluded from the trials that keeping absolute voltage in check, while getting most of the smoothing benefits, AVR mode was the best setting. Both ARV and SFV modes helped smooth the output but did not use the D-SVC to its full capacity and did not aid maintenance of the voltage within absolute limits.

The three different mode settings where trialled in a range of network conditions, the AVR setting helped reduce and control the voltage most effectively and therefore was the optimal way of running the D-SVC.

The set points were modelled at the beginning of the project and did not have an impact on the operation of the D-SVC. The low pass filter was investigated through the analysis of the harmonics caused by the D-SVC. After some misleading results from the sub.nets, the effects on power quality were verified and these results were not as concerning. The low pass filter reduced unwanted harmonics and controlled flicker.

In summary the effectiveness of a single D-SVC on rural networks is roughly 50V in terms of its absolute reduction in voltage and it smoothed the voltage profile of the feeder being affected by the distributed wind generator as mentioned above.

One of the success criteria was specifically geared towards the second phase:

- Utilise learning gained from the above items to ensure that a D-VQC can be developed to optimise multiple networked D-SVCs over a wide distribution network.

This learning has already been critical to modifying the scope to produce a more relevant and improved project plan for Phase Two. However as further work is yet to be done, this success criteria is due to be delivered as part of Phase 2.

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

7.1 Change to project structure

Phase 1 of the project highlighted some key learning points. The second phase of the project will be modified to take account of these.

There are several areas for the second phases which will be expanded to gain the best and most relevant learning from the project:

- The original project was focussed on the Hitachi devices and systems and how they impacted upon the electrical system. However, the integration of these devices was not considered in the first phase. On evaluation of the outcomes, it is apparent that closer integration is required for security and safety. Therefore we need to integrate Hitachi’s systems with PowerOn. Moreover, a new interface needs to be developed to allow this to happen. This ensures forward compatibly so that future control systems would be able to use this new interface.
- The intended location for the second phase was South Wales to give the project more breadth. The South West has a higher density of distributed generation, with a higher proportion of these at the end of feeders. There is also a wider variety of types and sizes making it more suitable for such a project. Connecting the three new D-SVCs and D-VQC on a network without sufficient generation to test the system as rigorously would mean limited learning would be gained.
- One of the key findings from the first phase was that the voltage control performance was not as expected. This was due to using a standard transformer which was not specifically

impedance matched to the device. This will be investigated further by using impedance matched transformers. The original Phase 2 plan did not have the time frames or the budget to do this.

- Another aspect of the project which needs to be explored further, is the communications infrastructure. After initial investigation, it was found that the traditional radio solution does not have the bandwidth or coverage for this application. Therefore, developing a new and appropriate communication infrastructure is key and was not originally planned for. This is also an opportunity to look for an innovative and transferable communication solution.

Scope	Original Project	New Project
Electrical impact of D-SVCs on the 11kV network	Included	Expanded further
Learn how to install a D-SVC	Included	Built on
Integration with PowerOn	N/A	Included
Development of DNP3 interface for the D-VQC	N/A	Included
Inclusion of tap changer relay and interface	N/A	Included
Ideal communication infrastructure developed	N/A	Included
Impedance matched transformers used to connection the D-SVCs	N/A	Included

This extra scope and consequent increase in cost significantly reframes the project, enough to warrant a new project being registered rather than trying to adjust the current project to the detriment of obtaining beneficial learning.

7.2 Increase of time testing the D-SVC

After the D-SVC tripping out from the voltage protection it was decided to keep the D-SVC on the system longer to assess its long term effect. Initially, it was not used effectively for several months as the protection settings were incorrect. The D-SVC therefore spent a significant amount of time disconnected between trips. The extended time also allowed for this time to be made up.

7.3 Removal of monitoring

The sub.net at Summerheath stopped working 18 months after installation, as this was the only pole top sub.net on the project it was less accessible. The monitoring did not give useful additional data compared to the other monitors and so the decision made to remove this monitor. This is covered in Section 6.1.5 in more depth.

8. 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 but equally any benefits which would have been realised from the second phase have not been realised.

Allocated budget and DNO contribution:

	Budget
Project LCNF Budget	£525,000.00
DNO Contribution	£90,000.00
Total Budget	£615,000.00

In terms of the first phase, expenditure is detailed below:

Description	Forecast	Actual	Variation (%)
WPD Labour	£20,000	£55,862.53	179%[1]
Contractors	£20,000	£18,139.81	-9%[2]
Equipment	£15,000	£99,461.28	563%[3]
Payments to Hitachi	£369,739	£369,739.01	0%[4]
Phase 1 Total	**£424,739**	**£543,202.63**	**28%**
Full Project Total	**£615,000**	**£543,202.63**	**-12%**

There was an overspend in the first phase, however this is due the problems around the level and difficulty of integration of the Hitachi systems into WPDs existing infrastructure. As detailed above, the D-SVC was originally envisaged as a standalone device. This is reflected in the amount of WPD labour required to work through various solutions for the protection issues, additional verification of the results and integration of PowerOn. Other costs for additional relays, RTUs and battery chargers all contributed to the increased equipment costs.

Each of the cost variances above are explained in more detail:

- The variance in the WPD labour was due to the increased complexity of the installation and commissioning. There was more time required setting up the D-SVC than originally envisaged. This was compounded by the additional troubleshooting required when the protection was not operating correctly.
- Some of the contractor's costs were incorporated into the Equipment costs as the contract for the equipment included installation.
- There was an increase in the amount of equipment needed from that that was originally planned. The D-SVC was envisaged to be standalone however it became clear that closer integration was needed so radio equipment, an RTU, protection panels and a battery plus charger to power the equipment were installed. It was also decided to increase the level of monitoring which also added to this cost.
- Hitachi's payments are exactly as was planned at this stage, there is an outstanding payment due once the D-VQC is delivered and there is an increased cost of developing the extra functionality of using DNP3 protocols of £50k which will be part of the new phase 2 project.

The key reason for extra expenditure was to ensure that the Hitachi systems were aligned and operating with our systems rather than the systems working independently. This was key to understanding the D-SVC well enough to allow multiple devices along with an overarching control scheme on to our system for the second phase. This benefit has allowed us to better inform the scope for a new second phase project ensuring that an integration focused scope delivers as expected. This allowed us to take the most appropriate learning from the first phase and implement it. If this had not been done, the original scope of work, time scales and cost would be prohibitive. Therefore to get the most learning out of the project, it was important to order ideally matched transformers and design a fully compatible system.

In terms of planned costs for the second phase, they were roughly three times of planned costs for the first phase. This took into account a small reduction in cost per D-SVC install and the cost of installation of the D-VQC. It was clear that the level of equipment and time needed for each install is more than originally budgeted and a much higher integration cost for the all three D-SVCS and the D-VQC needs to be budgeted for in the new second phase project.

The new project for the second phase: Voltage Control System Integration will require a larger budget than the one originally specified in the original project to cover the wider and deeper scope. The additional of costs will include:

- More representative costs of installing the D-SVCs from the experience gained from this phase
- For Hitachi to develop a D-VQC with DNP3 protocols
- Deeper and more detailed integration with WPD’s existing systems
- An integrated tap change scheme
- Better and more widespread monitoring
- Implementation of a more capable communications solution, better suited to this task
- Detailed testing of the D-SVC at the PNDC

These modifications to scope improve the project’s relevance and scalability by taking account of the learning that we have gained from this phase this making this investment better value for money.

9. Lessons learnt for future Projects

This project had a number of learning outcomes that will be able to inform the next phase but also other projects.

- A comprehensive design phase analysing all the technical implications can save time and ensure all equipment is correctly programmed
- More stage gates are programed into the schedule to ensure the project is running to time and all dependences are taken account of
- Allow more risk mitigation for supplies to ensure all equipment operates as expected
- Only use monitoring equipment that has a proven track record

There are several specific areas of technical learning from this project which listed below which will directly inform the new Tier 1/NIA project.

- The level voltage control realised was below the expected levels. This was partially due to the power difference between the D-SVC and the wind turbine. The performance would have benefited from an impedance tuned transformer.
- The transformer that is selected needs to have a HV VT metering unit to ensure that appropriate protection can be fitted and get visibility for the HV voltages and power from the D-SVC.
- The D-SVC needs to integrate with PowerOn as control engineers do not want a separate system. The system requires to be automated but have enough feedback to the control engineer so they know what it is doing and most importantly a way to disable the system is required.

- There are limitations in the current options available for WPD for high bandwidth, low latency communication to relatively remotes areas of network.

10. Planned implementation

The learning set out in this report will be directly used to plan the new Tier 1/NIA project and improve the scope over the original second phase. It will also help inform what to consider when connecting a device which produces reactive power and what control, protection and infrastructure is required.

For this reason, the project was terminated at the end of Phase 1 and the new scope for Phase 2 will be included in a new Tier 1/NIA project. This new project will also incorporate the following additional learning objectives:

- Extended timescales to allow for the specification and procurement of bespoke matched transformers
- A reliable, scalable and high performance communication system that can be used in remote rural areas
- Develop high accuracy, specifically designed, pole top sensors which are less obtrusive
- Close integration of the D-SVC, D-VQC, the remote and the customised tap changer relay into WPD's existing systems using DNP3 interfaces compatible for future devices
- Develop a process to correctly model reactive power devices on the 11kV network

If we abandoned Phase 2 at this point, the wide spread voltage control scheme that could be implemented across generation dominated rural networks would not be trialled. This is still an innovative and novel project using multiple reactive power devices controlled by a central controller. It incorporates traditional voltage control of the AVC scheme with the new devices to increase the voltage optimisation. This sophisticated scheme has the ability to be implemented in business as usual either in part or full. Across large parts of the network voltage limitations are the predominant constraint for generation. A voltage control scheme like this could be a viable alternative to conventional reinforcement. It also aligns well with alternative connections as additional functionally or rolled out as a scheme in its own right.

Power electronics based equipment, and specifically STATCOMs, are widely regarded as the next significant piece of new technology to be used on the DNO's network by international academics. They have been investigated by other international Network Operators with promising results. The UK's Transform model in WS3 consistently selects STATCOMs as the solution to voltage infringements. Without completing this next logical step of the project it would severely hamper the future roll out of power electronic based reactive power devices on the UK DNO's networks.

11. Facilitate Replication

11.1 Knowledge Required

The knowledge required to better understand the impact of a D-SVC on the 11kV rural network includes:

- Gain a better understanding of power flow analysis
- Understand how reactive power affects voltage the 11kV network

- Connection of electrical equipment on the 11kV network
- Integration of third party equipment into DNO control systems
- Optimal Wireless communication
- Power quality
- Protection settings

It is intended that this learning will be directly used in the second phase of the project and disseminated internally and externally to all relevant stakeholders. . This project was reported on during both the 2012 and 2013 Low Carbon Network Fund Conferences.

Design documents and specifications for the equipment developed for this project are available on request.

11.2 Products/Services Required

The key external products and services required to reproduce this project are:

- A 11kV connected STATCOM, in this case Hitachi's D-SVC
- The manufacturer's support in integrating said device into the DNO's systems

11.3 Project IPR

The D-SVC and its control systems are based on background IPR and therefore no development work on either of these have has happened as part of the project. The knowledge learnt from how into incorporate this equipment into the DNO's systems is listed in the key learning outcomes in Sections six and seven.

The relays and monitoring equipment we used were not modified and were used in their core functions so that did not generate any IPR.

12. 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,

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Derbyshire,

DE74 2TU

Email: wpdinnovation@westernpower.co.uk

Appendices

Appendix A – WPD report on the high resolution test data

Appendix A – WPD
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Appendix B – Hitachi report on the high resolution test data

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report on the high re

Appendix C – Calculation for deriving new under and over voltage protection settings

Appendix C –
Calculation for derivi

Appendix D – Transformer Guidance

Appendix D –
Transformer Guidanc