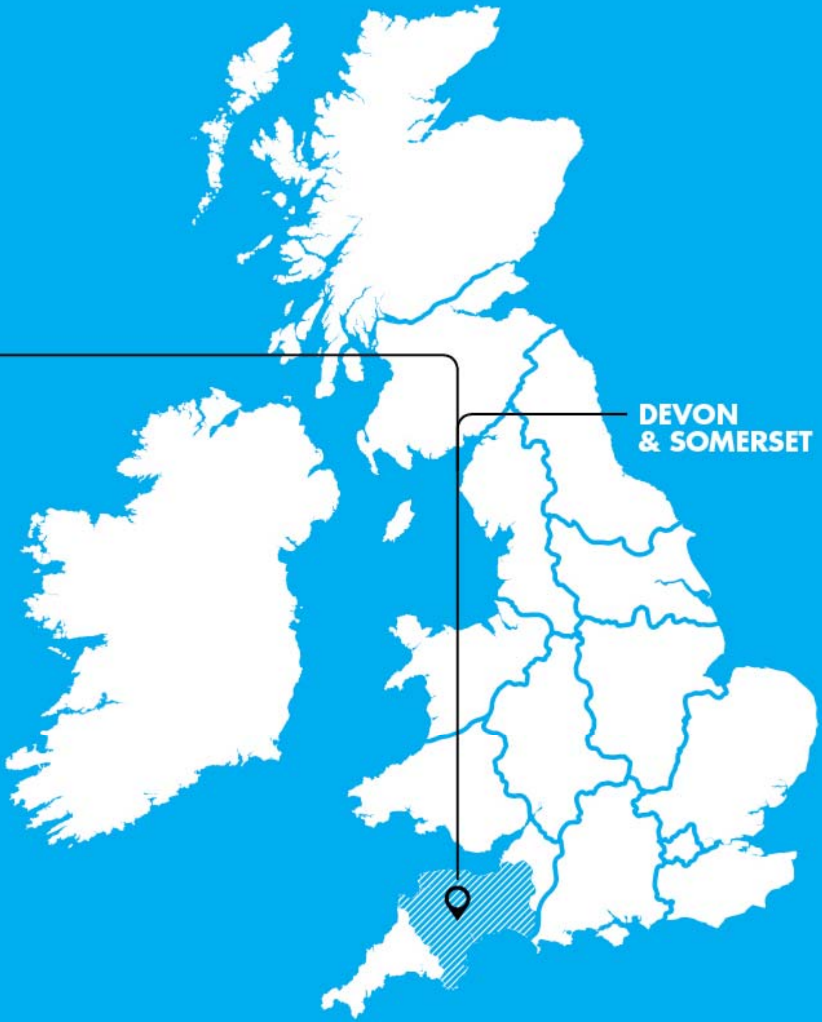
WESTERN POWER DISTRIBUTION

NETWORK EQUILIBRIUM

BALANCING GENERATION AND DEMAND

Closedown Report



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Contents

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1.0 PROJECT TITLE

Network Equilibrium

2.0 PROJECT BACKGROUND

Summary

The focus of Network Equilibrium was to balance voltages and power flows across the distribution system, using three Methods to integrate Distributed Generation (DG) within electricity networks more efficiently and deliver major benefits to distribution customers.

The Problem that Network Equilibrium addresses is that electricity infrastructure in the UK was originally designed and developed for passive power distribution requirements. Managing the integration of significant levels of DG and on the present distribution network has highlighted that the original network design can cause voltage management and thermal constraint issues. To address these issues we require the development of solutions, which take a strategic engineering approach, considering the whole system and not solving constraints on an ad-hoc basis.

The Problem was addressed by developing and trialling three innovative Methods across the South West licence area:

1. Enhanced Voltage Assessment (EVA);
2. System Voltage Optimisation (SVO); and
3. Flexible Power Link (FPL).

The project assessed the capacity, financial and carbon benefits that the Methods would bring to the 33kV and 11kV distribution network through the technology trials.

At the time of project initiation, the Network Equilibrium project was estimated to release 11.3 GW of capacity for DG across Great Britain (GB) by 2050, at a cost saving of £1.5bn when compared with the most efficient traditional solutions presently in use, such as network reinforcement. The Solution has enabled Distribution Network Operators (DNOs) to: (i) plan complex networks more effectively for DG; (ii) optimise voltages and power flows to fully utilise the existing electricity network; and (iii) balance generation and demand more efficiently, increasing the resilience of networks and securing electricity supplies for more distribution customers during outages (maintenance, new connections and fault restoration).

Aim

Network Equilibrium aimed to demonstrate how novel voltage and power flow management approaches can improve the utilisation of DNOs’ electricity networks. The Methods would unlock capacity for increased levels of DG, during normal operation and outage conditions (maintenance, new connections and fault restoration), which disrupt the electricity network.

Problem to be solved

The electricity infrastructure in GB was originally designed for passive power distribution. Historically, this was the most economical way of developing electricity networks. Network demands were relatively predictable; demand growth was incremental; there were low penetrations of DG; and there was little or no reliance on IT/communications systems. However, passive operation of electricity network is not compatible with accommodating high levels of intermittent DG, electric vehicles or heat pumps.

DNOs are frequently dealing with high volumes of customer connection applications. At the time of project initiation the WPD South West licence area was typically receiving 145 High Voltage (HV) and Extra High Voltage (EHV) DG connection applications per month and this trend was continually increasing. The HV or EHV DG connection applications were from a mixture of DG sources, however, the majority were solar photovoltaic (PV) installations. WPD now has approximately 4GW of connected, accepted and offered DG within the South West licence area.

Integrating significant levels of DG has caused voltage management and thermal constraint issues within electricity distribution networks, as evidenced by the Institution of Engineering and Technology (IET) Power

Networks Joint Vision report, “Electricity Networks – Handling a shock to the system” and supported by an external study that was carried out for WPD (focusing on the South West licence area in particular). The severity of these issues are compounded during network outages and also as the numbers of connected DG increases.

Continuing to use conventional solutions to address these issues will result in customers facing higher connection costs, attributed with conventional network reinforcement schemes across larger areas, and longer connection times. The level of DG already connected to existing passive network in the Network Equilibrium trial area has saturated the available capacity to accommodate new connections. Therefore, the ultimate cost for distribution customers will be higher than if innovative solutions are used. In addition, continuing to adopt conventional methods is likely to slow the uptake of renewable DG, which is contrary to GB’s Carbon Plan.

3.0 SCOPE AND OBJECTIVES

Network Equilibrium set out to address the Problem in a more cost effective manner than the traditional approach. The new approach involved developing new design and operating processes to transform passive distribution networks into active distribution systems through the use of new technologies, including monitoring and control systems. The project originally identified five main objectives as detailed in the Full Submission Pro-forma (FSP) and replicated in Table 3-1 below.

Table 3-1 – The five main objectives of Network Equilibrium

Number	Objective
1	Increase the granularity of voltage and power flow assessments, exploring potential amendments to ENA Engineering Recommendations and statutory voltage limits, in 33kV and 11kV networks, to unlock capacity for increased levels of low carbon technologies, such as DG;
2	Demonstrate how better planning for outage conditions can keep more customers (generation and demand) connected to the network when, for example, faults occur. This is particularly important as networks become more complex, with intermittent generation and less predictable demand profiles, and there is an increased dependence on communication and control systems.
3	Develop policies, guidelines and tools, which will be ready for adoption by other GB DNOs, to optimise voltage profiles across multiple circuits and wide areas of the network.
4	Improve the resilience of electricity networks through FPL technologies, which can control 33kV voltage profiles and allow power to be transferred between two, previously distinct, distribution systems.
5	Increase the firm capacity of substations, which means that the security of supply to distribution customers can be improved during outage conditions, leading to a reduction in customer interruptions (CIs) and customer minutes lost (CMLs).

4.0 SUCCESS CRITERIA

Table 4-1 – Success criteria and evidence of completion

FSP	Project Direction	Description	Evidence	Status
9.1	SDRC-1	Detailed design of the Enhanced Voltage Assessment (EVA) Method	1. Conduct a questionnaire and workshop with GB DNOs (and other relevant stakeholders) to discuss and explore amendments to existing statutory voltage limits and Engineering Recommendations; 2. Share a report with the industry detailing evidence for the limiting factors for 11kV and 33kV statutory voltage limits including new and existing transformers, tap changers, cables, overhead lines, switchgear, CTs, VTs customer equipment, stating the limiting factors and safety margins will be detailed for future evaluations; 3. Issue a discussion paper suggesting where the statutory limits for 11kV and 33kV networks could be amended; and 4. A DNO relevant specification and guide to implementation of an EVA power system analysis tool.	✓
9.2	SDRC-2	Detailed design of the System Voltage Optimisation (SVO) Method	1. Create a technical specification (including performance metrics) with input from UK DNOs; 2. Sharing of the SVO algorithm design and considerations to facilitate SVO; and 3. Make detailed designs available explaining how SVO will be installed for DNOs and interested parties.	✓
9.3	SDRC-3	Detailed design of the Flexible Power Link (FPL) Method	1. Share FPL specification used in the tender; 2. Detail the performance metrics of how FPL will be measured; 3. System incorporation design, physical and protection; 4. Sharing detailed designs of how the FPL will be installed by request of other DNOs; 5. Define the key considerations when incorporating a FPL within 33kV networks; and 6. Record of knowledge and learning throughout the design process that would be relevant to the incorporation of FPLs into the 11kV network.	✓
9.4	SDRC-4	Trialling and demonstrating the EVA Method	1. A report demonstrating the potential benefits of adjusting the statutory limits; 2. Demonstration of EVA power system analysis software for planning and operational uses; 3. Recommendations to GB DNOs on how to model the SVO control components; 4. Recommendations to GB DNOs on how to model the FPL; and	✓

FSP	Project Direction	Description	Evidence	Status
			5. Use the EVA power system analysis models to quantify the capacity released for each of the Methods, individually and when combined together. These will be compared to the estimates included in Section 4.1.4 of the FSP.	
9.5	SDRC-5	Trialling and demonstrating the SVO Method	1. Installation of SVO across 8 BSPs and 8 primary substations; 2. Report on the installation of SVO equipment at BSPs and primary substations; 3. Report on the implementation of the SVO solution; 4. Report on the performance and capacity released by the SVO Method; and 5. Sharing of policies with other DNOs.	✓
9.6	SDRC-6	Trialling and demonstrating the FPL Method	1. Installation and commissioning of the 33kV FPL; 2. A guide to implementation and use of FPL, detailed evaluation of the performance, capacity increased through the technique in the report; 3. Sharing of policies with other DNOs; and 4. An assessment of what has been learnt through the trial that would be relevant to the deployment of FPLs across the 11kV networks.	✓
9.7	SDRC-7	Trialling and demonstrating the integration of the EVA, SVO and FPL Methods	Publication of a report detailing: 1. Quantification of how all three techniques can be incorporated together and the impacts; 2. Analysis of the passive and active generation and demand capacity that can be released across the eight different BSPs; and 3. Cost-benefit analysis of the Methods, deployed separately and integrated, including the capital expenditure and projected operations and maintenance costs.	✓
9.8	SDRC-8	Knowledge capture and dissemination	1. Knowledge and learning dissemination reports and presentations; 2. Network data being made available for each of Equilibrium's Methods; 3. Six-monthly progress reports submitted to Ofgem throughout the project; 4. Equilibrium project presentations delivered at eight industry conferences during the course of the project from March 2015 to June 2019; and 5. Equilibrium project presentations delivered at each of the LCNI conferences during the course of the project.	✓

5.0 EXECUTIVE SUMMARY

The Network Equilibrium project was awarded funding through Ofgem's Low Carbon Networks Fund Second Tier funding mechanism and commenced in March 2015. The project aimed to develop and trial new technologies that were able to actively control voltage and power flows on the South West distribution network, leading to the release of network capacity and providing a solution that allows DG to connect in a more cost-effective and timely manner compared to traditional solutions.

Distribution networks have historically been developed to be passive in nature because they were traditionally demand dominated. The typical network was characterised by power flowing from high to low voltages with predictable customer load profiles and very limited DG capacity. In recent years, however, there has been a sustained increase in DG uptake on the distribution network. The trend is set to continue as renewable generation costs continue to fall and the UK implements its Carbon Plan.

The shift in the way distribution networks operate due to increasing levels of DG uptake has caused voltage and thermal issues to appear more frequently on the network. The capacity of the network in its passive form has been used up, meaning that in certain areas, generation customers are prohibited to connect unless they are curtailed with an Active Network Management (ANM) scheme at times when the network is experiencing these issues.

Network Equilibrium was developed to address this problem by utilising active techniques to release capacity that is otherwise hidden due to the passive nature of the network. Three Methods were developed, trialled and evaluated in our South West licence area. These Methods are:

1. Enhanced Voltage Assessment (EVA)
2. System Voltage Optimisation (SVO)
3. Flexible Power Link (FPL)

The EVA Method has investigated whether the UK statutory voltage limits on the 33kV and 11kV distribution network could be relaxed with the aim of increasing generation capacity. The studies found that it was possible to permit 33kV networks to operate within a ±10% voltage range and 11kV networks within a ±8% voltage range without affecting customer supplies. The Method also developed an Advanced Planning Tool (APT), which has allowed network changes to be modelled using time-series data forecasts load / generation profiles to better inform system planning decisions. Software models of the SVO and FPL Methods were also developed as part of the APT to give planning engineers the ability to assess the merits of installing these technologies in comparison to traditional reinforcement and ANM solutions.

Through the SVO Method, the project has developed a centralised control system that is able to control the voltage on the 33kV and 11kV networks in real-time on the South West distribution network based on measurements that it receives from the network. The SVO technology is able to reduce network voltages to allow increased generation capacity whilst still ensuring the network complies with statutory voltage limits. The voltage on the distribution network is set by Automatic Voltage Control (AVC) systems at BSP and primary substations and the target voltage for these systems has traditionally been set at a high level to cater for maximum demand conditions i.e. the passive network as previously described. The high limits are limiting the number of generator connections as voltages under maximum generation conditions are now exceeding the statutory limits. The SVO system acts to reduce the voltage set-points dependent on the prevailing network conditions to release voltage headroom for new DG to connect. SVO has shown that it can release 210MW of generation capacity over the scale of the Method trial area.

The FPL Method has successfully developed and trialled a 33kV AC-DC-AC back-to-back Voltage Source Converter (VSC) that is able to connect two separate 33kV networks on the South West distribution network which could otherwise not have been connected together. The FPL has demonstrated that it can provide active and reactive power flow control between the two 33kV networks to facilitate the release of generation capacity, provide active power balancing between the networks and voltage regulation on either of the two networks independently. The trial of the FPL has shown that it has released 20MW of generation capacity and has enabled power to be balanced more effectively across the 33kV distribution network. The FPL Method has also demonstrated the device can contribute significant additional substation firm capacity.

The development and demonstration of the Methods has contributed a substantial body of learning on the feasibility and potential benefits of widening statutory voltage limits on the 33kV and 11kV distribution networks. In a similar fashion, the Methods have increased the TRL of active distribution network technology to the point where the SVO and FPL technologies can be replicated on the wider GB distribution network where they will provide additional tools for DNOs to connect customers at lower costs to the counterfactual approach. In addition, the release of network capacity that the Methods provide enables the deferment and avoidance of traditional reinforcement capital investment that provides associated socialised benefits to network customers through reduced electricity costs.

6.0 DETAILS OF THE WORK CARRIED OUT

6.1 Overview

This section provides a summary of the work carried out for each of the Methods that were implemented for Network Equilibrium. Each sub-section provides an overview of that Method and a description of the work that was carried out including studies, investigations, design, testing and installation.

6.2 EVA Method

Overview

The EVA Method explored existing engineering practices and standards, which are used to manage and plan voltages on the distribution network and investigated how these could be improved to help release additional network capacity. The Method focussed on improvements that could be implemented on 11kV and 33kV networks as these typically experience higher volumes of connection applications that require additional capacity to be created.

The Method was delivered in two distinct parts. The first part of the Method involved Voltage Limit Assessment (VLA), which investigated the rationale behind the statutory UK voltage limits and whether these could be amended without impacting safety and service delivered to customers. The second part of the Method sought to create an Advanced Planning Tool (APT) to improve network planning on distribution networks in order to understand where latent capacity may exist.

Voltage Limit Assessment

The statutory voltage limits which apply to public electricity networks in the UK have remained unchanged since 1934 and are currently legislated for within the Electricity, Safety, Quality and Continuity Regulations (ESQCR) 2002. The upper voltage limit for each voltage level on the distribution system can often be the limiting factor when attempting to connect DG to the network. Figure 6-1 below shows how the voltage profile on a typical 11kV feeder can change and exceed voltage limits if DG were to be connected.

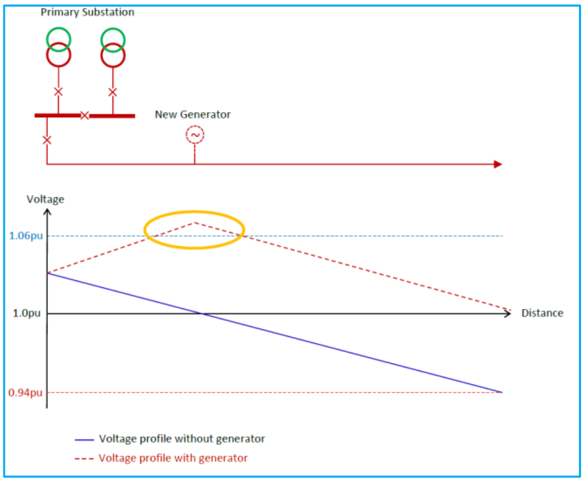

Figure 6-1 – Voltage limitation for a connecting generator

DNOs often encounter voltages which fall outside statutory limits when studying a new DG connection. The requirement for reinforcement of the distribution network to mitigate voltage issues can result in long delays and significant expenditure for both the DNO and the DG customer wishing to connect.

VLA aimed to establish the type and scale of amendments that could be made to the current statutory limits and studied the benefits that could be derived if these amendments were to be implemented.

The VLA was delivered in three distinct parts:

- Engagement with stakeholders;
- Investigation of the voltage limits and possible impact on equipment; and
- Study of the proposed amendments to voltage limits.

Stakeholder engagement played a key role in capturing views on the impact of potential amendments to voltage limits. The first part of the engagement involved the production of questionnaires, which were circulated to a diverse range of stakeholders across the UK and Europe including: DNOs, iDNOs, TSOs, manufacturers, suppliers, generators, trade bodies, regulatory bodies, consultants and academics. There was an excellent response to the questionnaires and the general consensus amongst the stakeholders was that amendments could have positive impacts. However, they were mindful of the potential implications of changing the voltage limits including the effect on equipment insulation levels and increases in reactive power and fault level. The results from the questionnaires were then debated and discussed with DNOs at a Network Equilibrium VLA Workshop held in Birmingham in October 2015.

A thorough investigation of voltage limits and system requirements was carried out by the project team and captured within Successful Delivery Reward Criteria (SDRC)-1, “Detailed Design of the Enhanced Voltage Assessment Method”. This work built upon the responses received from the stakeholder questionnaires and the work carried out by Electricity North West Limited (ENWL) through the Innovation Funding Incentive (IFI) project, “Changing Standards”. The investigation compared the statutory voltage requirements in the UK and the harmonised standards applied across Europe. In addition, an assessment of network components was carried out to establish the implications of amending voltage limits on plant specifications. The results from the investigation showed that other countries in Europe typically have slightly wider limits compared with the UK and that current equipment specifications would not hinder an incremental increase of UK limits. Power system studies were also performed to establish the technical implications of running 11kV and 33kV networks with increased voltage limits. The results from these studies showed that operating 33kV networks could be permitted within a ±10% range, however, this should only be applied in a probabilistic manner so that operation in the extreme ends of that range would only be expected for short periods of time. The studies also showed that voltage regulation on 11kV networks would be more difficult to manage and an increase in voltage limits would need to be capped at around ±8%.

Using these proposed new voltage limit changes a methodology was developed to calculate the additional network capacity that could be released. Figure 6-2 shows one particular instance of how the increase in generation capacity was calculated using amended voltage limits.

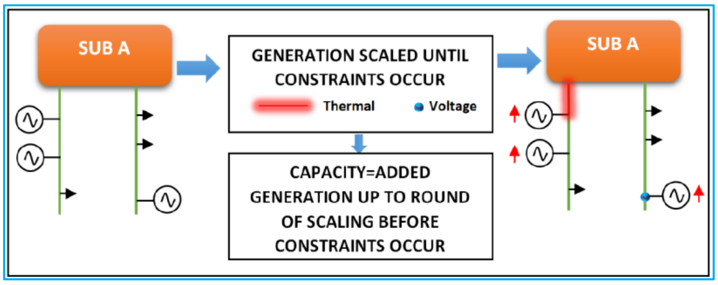

Figure 6-2 – Calculation of capacity released through VLA

The methodology was applied and capacity release was calculated at BSPs and primary substations within the Network Equilibrium trial area. The overall result showed that increasing the voltage limits could result in substantial capacity benefits.

Following the publication of the original capacity release figures in SDRC-4 “Trialling and Demonstrating the EVA Method” further improvements were made to the methodology and power system plug-ins were developed to calculate maximum and average capacity release figures, which were published in SDRC-7 “Trialling and Demonstrating the Integration of the EVA, SVO and FPL Methods”.

Advanced Planning Tool

The APT was developed in order to produce a tool that would improve system planning across the distribution network. The APT provides more granularity compared with existing methods through the ability to carry out time-based studies on the network. This additional granularity would be extremely beneficial when trying to assess the impact of variable power flows over time on the network. The APT development also investigated the possibility of including forecasted operational load flows using weather forecast and network demand/generation information.

The creation of the tool followed a well-established process previously used for other software tools. The first step of the process was to capture the objectives of the APT into a list of user requirements and then develop this into a specification.

Following review and approval of the specification, the APT was developed using PSS/E V32 power system analysis software package[1].

The APT includes three separate plug-ins which are used for time-based power system studies: EVA (VLA), SVO and FPL Methods. These plug-ins allowed network planning engineers to assess if capacity could be released on a particular BSP or primary substation following implementation of the VLA, SVO and/or FPL Method(s). The operation of the plug-ins was verified using the BSPs and primaries located within the trial area for Network Equilibrium. A user guide was produced as part of the development of the APT which provides a step-by-step guide for operating the tool and extracting data.

Figure 6-3 shows the output from the time-based VLA plug-in.

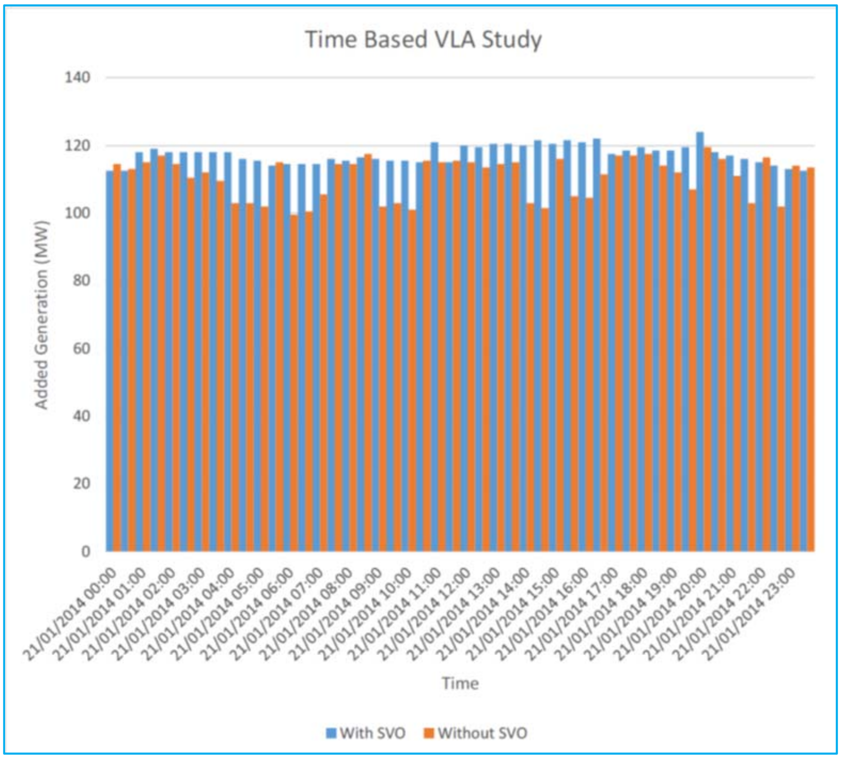

Figure 6-3 – Results of APT VLA

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[1] Power System Simulator for Engineering (PSS/E) is a software tool developed by Siemens. It can perform a range of power system analysis functions such as load flow, short circuit and transient stability studies.

6.3 SVO Method

Overview

The traditional design of distribution networks was based on the assumption that power would flow from transmission level down through the various voltage levels to consumers. Target voltages were set to ensure that the voltages across the network were maintained within the limits defined in the ESQCRs during periods of maximum demand when the highest voltage was expected. However, power flow on the distribution network is now bi-directional due to increasing penetration DG, especially in rural areas. This can mean that worst case voltage conditions may occur during periods of maximum generation as opposed to maximum demand. The SVO Method sought to dynamically control voltage on the distribution network in order to maximise the level of DG that can be connected to network while maintaining voltage within statutory limits. The SVO system replaced the traditional Automatic Voltage Control (AVC) schemes at Bulk Supply Points (BSPs) and primary substations that operated on fixed target voltages. The system calculated optimum target set-point voltages for each particular substation in real-time based on network measurements. These dynamic target set-point voltages were then sent to the respective substation over the existing communication infrastructure.

Substation selection process

The first stage of the SVO Method involved selecting 16 suitable trial sites that would be used to demonstrate the capability of the system. During the bid stage, 22 substations had been shortlisted from the 228 sites available in the South West licence area. The selection process was detailed within SDRC-2, “Detailed Design of SVO Method”, and considered a number of aspects to derive the maximum amount of learning during the trials:

- **Capability to change target voltage** – Power system studies were conducted for each substation to understand the capability to modify target voltage without exceeding voltage limits downstream. The results showed that a number of substations could change their target voltage within a large range and still maintain voltages within limits. Whereas other substations had limited scope to change the target voltage. Substations with varying levels of target voltage modification capability were chosen to achieve the maximum learning during the trials.
- **Substation equipment and site** – An assessment was made for each of the substations to understand the capability of existing equipment and whether any works were planned, which could have an impact on the implementation of SVO. Early design work identified that cost savings could be made by integrating SVO at substations equipped with more modern AVC relays. In addition, coordinating with existing reinforcement or refurbishment schemes could drive synergy savings during delivery.
- **Customer impact** – Although implementation of SVO would maintain voltages within statutory limits, voltage profiles were likely to vary much more compared with the current static AVC set-points. Using knowledge of the network, customers that could be sensitive to voltage variation were considered when deciding which sites to select for SVO.

After considering the aspects above for each substation, the most suitable sites were chosen. There were 16 sites selected in total (eight BSPs and eight primary substations). These are shown geographically in Appendix 3.

SVO procurement

A functional specification was developed for the SVO system which was used as part of the open tendering process followed to procure the technology. The specification was incorporated into the Invitation to Tender (ITT) which allowed prospective manufacturers to accurately tender for the contract to supply the SVO system. Through the detailed assessment of the tenders that were submitted, Siemens was selected to supply SVO using their Spectrum Power 5 (SP5) control system.

SVO control system

Siemens’ SP5 was the tool that was used to implement the centralised voltage control system of SVO. SP5 is a software based control system that is used to control and optimise electricity distribution networks. The SP5 system was hosted on a separate platform with a communication interface with the Network Management System (NMS)[2] as shown in Figure 6-4.

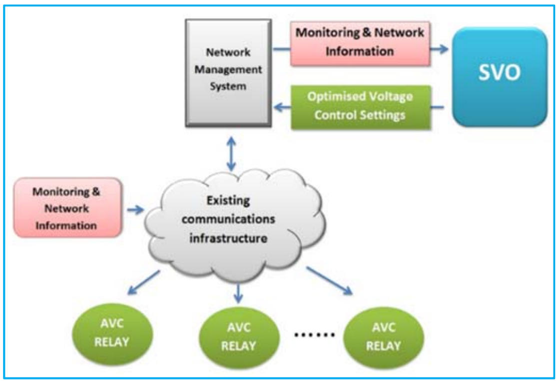

Figure 6-4 – SVO architecture diagram

Development of the SVO control system included the production of detailed 11kV and 33kV network models in order to calculate the optimised voltage. The work that was undertaken during the EVA Method was used to create the topology for each of the models. Following creation of the network models, all switching components (such as circuit breakers and isolators) were manually added to the models to replicate the real-time topology of the network. The next step to finalise the models involved mapping of the Supervisory Control And Data Acquisition (SCADA) data points (active and reactive power measurements, switch statuses, tap position indicators) to the model. This allowed the SVO control system to accurately replicate the current system conditions for each of the substations in the trial area.

Full validation of the models was performed with Siemens before performing the Factory Acceptance Testing (FAT) on all the software modules.

After successful completion of the FAT, the necessary hardware was installed to allow the SVO system to communicate with the NMS and its performance was verified under various System Integration Tests (SIT).

SVO hardware design and installation

A detailed design had to be produced for each of the substations identified for SVO implementation. The design included the new hardware to be installed along with modifications to wiring and telecommunication infrastructure. Two distinct design options were identified for implementing SVO:

- **MicroTAPP Design** – this was implemented where existing MicroTAPP relays were installed. This AVC relay has the capability to select from up to eight pre-defined settings. Modifications to existing wiring was required in order to choose one of the eight settings on the MicroTAPP relay. This design was implemented at two of the substations in the trial area (Lydeard St Lawrence 33/11kV and Waterlake 33/11kV).
- **SuperTAPP SG Design** – the remaining 14 sites were equipped with new SuperTAPP SG AVC relays that could accept dynamic set-points over SCADA. A new standard AVC panel was developed and approved to accommodate the new SuperTAPP SG relays which simplified the integration design, installation work and testing.

It was decided to trial two relay installations so that the performance of the SVO system could be compared between operation with pre-defined group settings (MicroTAPP) and with dynamic set-points (SuperTAPP). In most cases the existing AVC relays had to be replaced however, in the instances where MicroTAPP AVC relays were available, these could be used to provide SVO functionality. Figure 6-5 and Figure 6-6 below show images of the two types of relay installations that were provided as part of the SVO Method.

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[2] The Network Management system (NMS) is a software platform that WPD control engineers use to visualise, manage and control distribution networks assets in real-time to ensure supplies are safe and secure.

Figure 6-5 – SuperTAPP SG relay installation

Figure 6-6 – MicroTAPP relay installation

An installation plan was developed for all the sites to ensure that network outages and resources were coordinated. Installation work began on the first site, Colley Lane 33/11kV, in February 2017 and with all sites energised with SVO enabled by February 2018. A number of lessons were captured during the commissioning of the first SVO sites. This included updates to relay software and tapchanger lock-out signals which were able to be implemented in the subsequent SVO installations through updates to the designs.

6.4 FPL Method

Overview

The FPL Method aimed to develop a 33kV back-to-back AC-DC converter to allow two 33kV distribution network groups to be connected in parallel through the device. This parallel configuration would not have been able to be safely achieved without the FPL due to circulating currents, protection grading and fault level issues. The FPL was designed to control the active and reactive power flow at its terminals to release network capacity and provide voltage support to the network in both normal and abnormal network running conditions. In addition, the FPL is able to increase the firm capacity of the interconnected networks as it is able to reduce peak demand through the 132/33kV BSP transformers by balancing power flows locally at 33kV. A schematic diagram is provided in Figure 6-7 which shows the principle of the FPL operation.

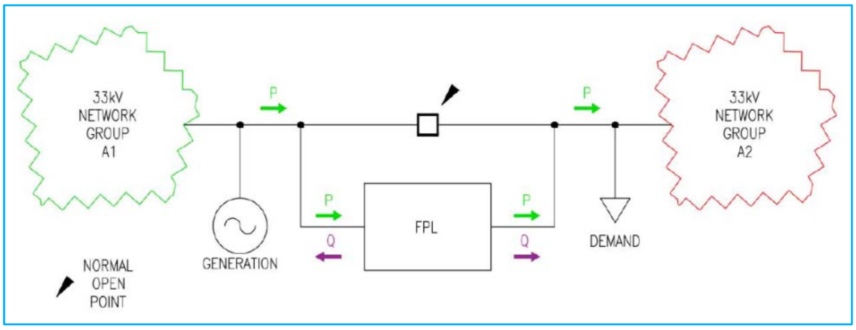

Figure 6-7 – Schematic of FPL operation

Site selection process

The first stage of the Method involved selecting a suitable trial location which would be used to demonstrate the capability of the FPL. During the initial stages of the project, 11 available sites were identified that had a 33kV interconnection between BSPs and were located in the South West licence area. A shortlist process narrowed the selection to four sites that had good power transfer capability and available space. The final selection process was detailed within SDRC-3, "Detailed Design of the FPL Method", and considered a number of aspects to derive the maximum amount of learning during the trials:

- **Availability of space** – Each site was assessed on the availability of existing free space for locating the FPL and its ancillary equipment as well as space that could be made available through reconfiguring the existing equipment.
- **Network connection** – An assessment was made for each of the sites to understand if the FPL could be connected to the existing equipment, whether any modifications to the site would be required to facilitate the connection, and if so, understanding the extent of the changes that were required.
- **Substation access** – The sites were analysed to understand if there was sufficient access for the delivery and offloading of the largest FPL components and whether there was any obstructions on potential delivery routes.
- **Customer impact** – Network outages would be required for the safe connection and subsequent testing of the FPL on the 33kV network. The customers that could be affected by these outages were considered when deciding which sites to select for the FPL.

After considering the aspects above for each shortlisted substation, the most suitable site was found to be 33/11kV Exebridge primary substation which interconnects the 132/33kV Barnstaple and Taunton BSPs. These BSPs are also supplied from different Grid Supply Points (GSPs), namely Alverdiscott and Tainton GSPs, which provides an additional level of complexity.

FPL procurement

The FPL was procured through an open and competitive tendering process that sought to engage manufacturers of medium voltage power electronic converters across the globe. A detailed technical specification was developed for the FPL and incorporated into the ITT which allowed prospective manufacturers to accurately tender for the contract to supply the FPL. A thorough technical and commercial analysis of the tenders that were submitted led to the selection of ABB to supply the FPL device.

FPL design

The design of the FPL began by defining a set of standard network configurations to allow the integration of the FPL onto the 33kV distribution network as well as a cost benefit analysis of each option. The most appropriate FPL network configuration for the Exebridge site was selected from these options on the basis that it satisfied the technical requirements of both the FPL and the local network whilst also allowing suitable operational flexibility. The original electrical diagram of the site is shown in Figure 6-8 and the FPL connection configuration is shown in Figure 6-9.

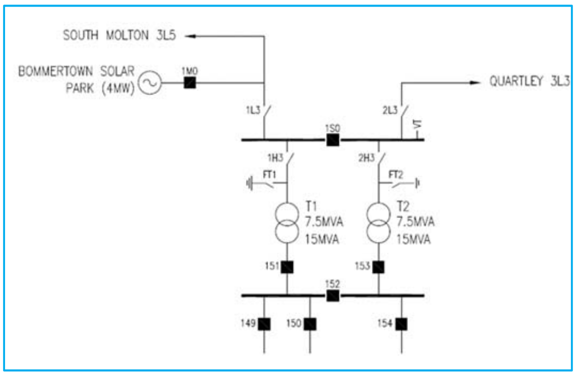

Figure 6-8 – Original Exebridge single line diagram

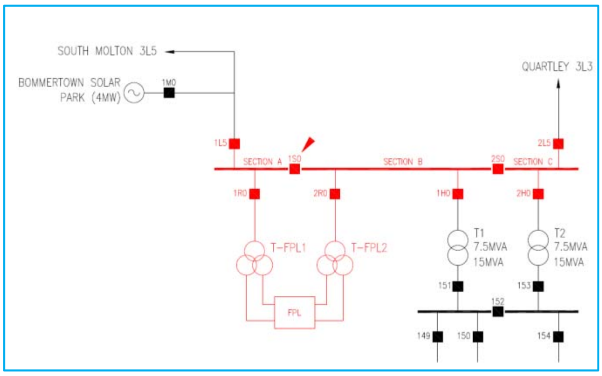

Figure 6-9 – Integration of FPL at Exebridge

The design from this point forward was divided into two main aspects: the detailed design of the FPL device by ABB and the design of the equipment and modifications required at Exebridge to allow the safe connection of the device to the 33kV network.

A detailed design review process was carried out on the ABB design submissions to ensure the FPL met the requirements of the technical specifications in the contract and informed the design requirements for the site works. The design of the site works was carried out in parallel with the design review and included the specification of new 33kV switchgear, protection systems, telecontrol systems, LV supplies, earthing and civil works. The original layout of the site is shown in Figure 6-10 and the final site layout design is shown in Figure 6-11.

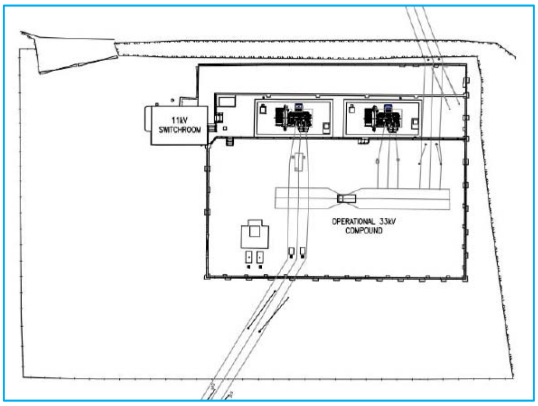

Figure 6-10 – Original Exebridge site layout

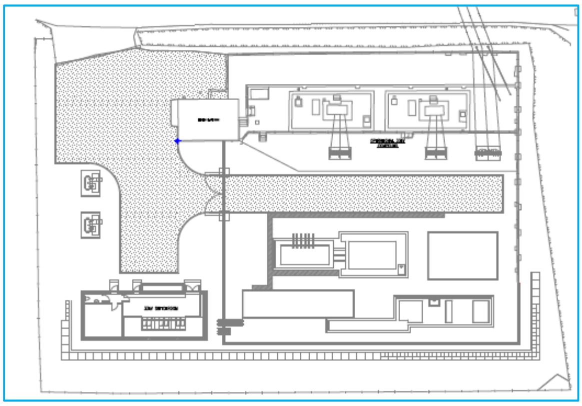

Figure 6-11 – Final site layout with integrated FPL

FPL testing

Particular emphasis was placed on the thorough testing of the FPL and its auxiliary systems due to the relative immaturity of power electronic equipment when compared to traditional distribution equipment such as transformers and switchgear. The FPL underwent a FAT at the manufacturer's facilities and Site Acceptance Testing (SAT) conducted in-situ at the Exebridge site. A rigorous testing specification was produced at each stage of the equipment testing that outlined the test pass criteria, methodology and sequence of tests.

FPL control system

The FPL Control Module (CM) is a bespoke piece of software designed to calculate the active and reactive power set-points for the FPL based on real-time measurements from the network. The FPL CM was developed by Nortech Ltd in parallel with the design and development of the ABB FPL. The FPL CM software was hosted on a number of servers with a communication interface to NMS as shown in Figure 6-12 to enable it to communicate with equipment on the external distribution network.

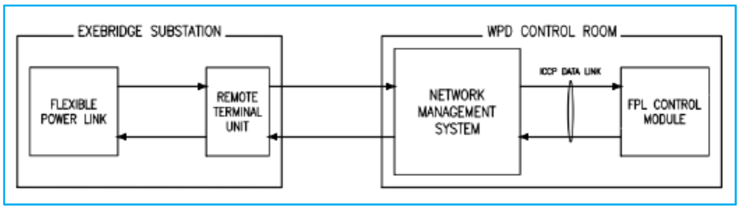

Figure 6-12 – FPL control module architecture diagram

A detailed power system model was produced of the two 33kV network groups up to the 132kV busbar at each GSP interconnected by the FPL. This enabled the CM to accurately replicate the current system conditions in the trial area and allow its in-built logic to calculate valid set-points for the FPL. All cable and overhead line impedances as well as switching components (such as circuit breakers and isolators) were manually added to the models and allowed the system to replicate the real-time topology of the network. The final step was to map the SCADA data points (active and reactive power measurements, switch statuses, tap position indicators etc.) to the model.

Full validation of the model was performed in collaboration with Nortech Ltd before performing the FAT of the CM. After successful completion of the FAT, the CM was connected to the NMS and SIT was carried out to test its performance using real-time network data in a safe testing environment .The tests also checked that modifications to the NMS operated correctly.

Trialling methodology

The FPL was successfully energised and operated in open-loop control initially. In this mode the FPL CM was generating set-points but they were inhibited from reaching the FPL. The FPL was instead manually assigned both P and Q set-points. The gradual transition to full closed-loop control was carried out to enable monitoring of the systems and to avoid unnecessary outages. Once confidence was gained in the stability of the systems, the CM was allowed to control the FPL in closed-loop mode. In closed-loop mode the CM was initially instructed to issue P set-points only. After a period of time the CM was operated in its full operation mode i.e. to send both P and Q set-points to the FPL.

7.0 OUTCOMES OF THE PROJECT

7.1 Outcomes of the EVA Method

Overview

The outcomes of the EVA Method have shown that implementing changes to voltage limits in the UK could help to release network capacity across 11kV and 33kV distribution networks. Power system studies performed for the Network Equilibrium trial area show average capacity releases of 30MW at BSPs and 2MW at primary substations. In addition, the development of the APT has provided an efficient method for engineers to carry out time-based power system studies.

Voltage Limit Assessment

The work which was carried out as part of the VLA has generated the following outcomes:

- **33kV Voltage Limit Amendments** – investigation and studies of the trial area have shown that increasing the existing voltage limits of ±6% at 33kV to ±10% would be technically feasible. However, sustained operation at the extremities of these limits would not be advisable due to the additional stresses that would be experienced.
- **11kV Voltage Limit Amendments** – similarly to the 33kV network, investigation and studies of the trial area at 11kV have shown that increasing the existing voltage limits is technically feasible. However, the voltage limits can only be extended from ±6% to around ±8% due to limitations on voltage regulation on the 11kV network.
- **Expert Opinions** – stakeholder engagement has highlighted additional areas that would need to be assessed more thoroughly if a permanent change were to be made to the voltage limits in the UK. These areas include:
    - Detailed assessment of the impact on the LV network from changes to upstream voltage limits;
    - Detailed analysis of system faults and reactive power across different voltage levels; and
    - Further engagement with manufacturers and customers to explore potential impacts.

The VLA was applied across the 16 substations that were included with in the Network Equilibrium Trial area. A summary of the outcome of implementing the amendments is shown in Table 7-1 and Table 7-2.

Table 7-1 – Average 33kV capacity released through EVA

Bulk Supply Point	Average capacity released (MW)
Bowhays Cross	33.80
Bridgwater	124.53
Exeter City	0.00
Exeter Main	17.51
Paignton	0.00
Radstock	0.00
Taunton	66.49
Tiverton	0.00

Table 7-2 – Average 11kV capacity released through EVA

Primary substation	Average capacity released (MW)
Colley Lane	0.00
Dunkeswell	0.34
Lydeard St Lawrence	0.32
Marsh Green	2.65
Millfield	5.57
Nether Stowey	0.44
Tiverton Moorhayes	4.06
Waterlake	2.66

Advanced Planning Tool

The development and implementation of the APT has generated a number of outcomes that are beneficial for planning networks in WPD’s area and also provide valuable learning for other UK DNOs.

- **Network Models** – The development of the APT involved a significant power system modelling exercise carried out to capture the 132kV, 33kV and 11kV networks within and around the Network Equilibrium trial area. Whilst a model of the 132kV and 33kV network was already available, albeit in a different format, production of the 11kV models and integration of all the models was complex. Using network information from our Geographical Information System (GIS), “EMU”, the models were imported into IPSA and a detailed exercise was performed to verify the data and correct inaccuracies. Following this exercise, full network models for the trial area have now been produced and are being used as a part of live SVO system.
- **SVO Plug-in** – The development of the APT also included the provision of a plug-in which could be used to simulate the deployment and operation of SVO at other substations across the network (not just limited to the trial area). The plug-in for SVO has been successfully implemented for use in PSS/E alongside the VLA functionality. A GUI was developed for use in PSS/E as shown in Figure 17-1 in Appendix 3.
- **FPL Plug-in** – In addition to the SVO plug-in, an FPL plug-in was developed which allowed engineers to evaluate the performance of an FPL when implemented at other sites on the network. The development of the FPL plug-in calculated the capacity that could be released across two connected BSPs when using the FPL power transfer capability. The plug-in was scripted in Python and a GUI was developed for use in PSS/E as shown in Figure 17-2 in Appendix 3.

- **Documentation** – The development of the APT and associated plug-ins also included the production of documentation in the form of user manuals. These documents are critical for ensuring transfer of the Methods to BAU.
  - **SVO PSS/E Simulation Tools Overview and Operation Guide** – provides a guide on how to interpret and operate the SVO plug-in.
  - **FPL PSS/E Simulation Tools Overview and Operation Guide** – provides a guide on how to interpret and operate the FPL plug-in.

7.2 Outcomes of the SVO Method

Overview

The outcomes for the SVO Method have shown that it is possible to enable dynamic control of system voltage to release load and generation capacity on both 11kV and 33kV networks. The architecture for implementing an SVO control system has been developed and implemented along with detailed network models. Standard designs have been produced for deploying SVO using both MicroTAPP and SuperTAPP SG AVC relays.

Increased network operation visibility

The state estimation functionality of SVO provided additional visibility on the operation of the network as it produced estimates of the power flows and voltages at the points in the network where no measurements are available.

On 33kV networks, active power and reactive power are usually measured at the 132/33kV transformers supplying the network, at the 33/11kV transformers and at all distributed generation connections or other 33kV connected loads. Voltage measurements are normally obtained on the 11kV side of the primary transformers fed by that 33kV network and current measurements are available for each 33kV feeder at the BSP and at all primary transformers. An example of these measurements are shown in Figure 7-1 with all measured analogues in blue text. The orange text in Figure 7-1 shows the points in the network where certain network parameters are not measured. With its state estimation functionality, SVO is using the electrical models of the network and the available measurements in order to calculate active, reactive power and voltage across each particular network area, so that the entire network operation is understood before proceeding to perform any voltage optimisation tasks.

On the majority of 11kV networks active and reactive power, along with current, are measured at the substations. Therefore, SVO provided visibility of the voltages and power flows across the feeders as also shown in Figure 7-1.

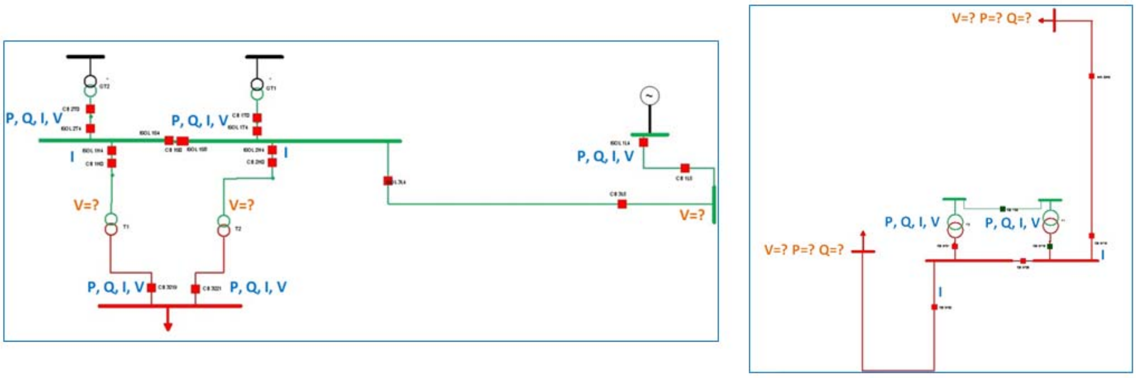

Figure 7-1 – Analogue measurements (blue colour) and estimated values (orange colour) in a BSP network (left) and a Primary network (right)

Detailed network operation data

Through the operation of SVO, detailed network operation data has been collected and provided learning on the transient nature of the network operation. The data that was collected was stored, creating a database of historic values which included among others tap position indicators and all instantaneous changes of voltages and power flow measurements.

In BAU operation, tap positions are not archived at all and analogues are only stored as half-hourly averages. Therefore, capturing all analogue changes by SVO provided detailed network data that were previously unavailable and enabled greater understanding of the dynamic changes in network operation. An example of the historic tap positions of GT1 at Tiverton BSP, for a week is shown in Figure 7-2.

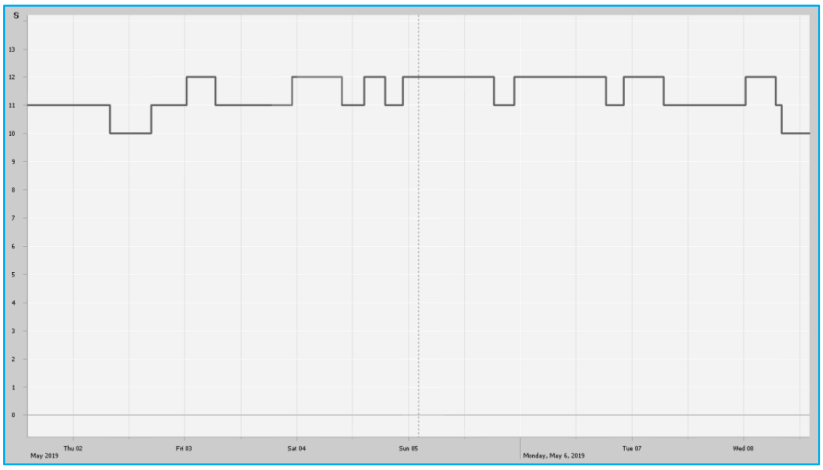

Figure 7-2 – Historic Tap Positions of GT1 at Tiverton BSP during a week in May 2019

Voltage optimisation

Voltage optimisation performed at the various SVO sites has successfully changed the target voltage settings at both BSPs and primary substations in real-time, responding to the actual network operating conditions. This has proved that the actual headroom available to change the target voltage in 33kV and 11kV networks is much larger than what can be estimated through traditional power system studies.

SVO operation at Tiverton BSP for a week is shown as an example in Figure 7-3, which presents all SVO target voltage set-points (maroon line) compared with the default static setting (yellow line).

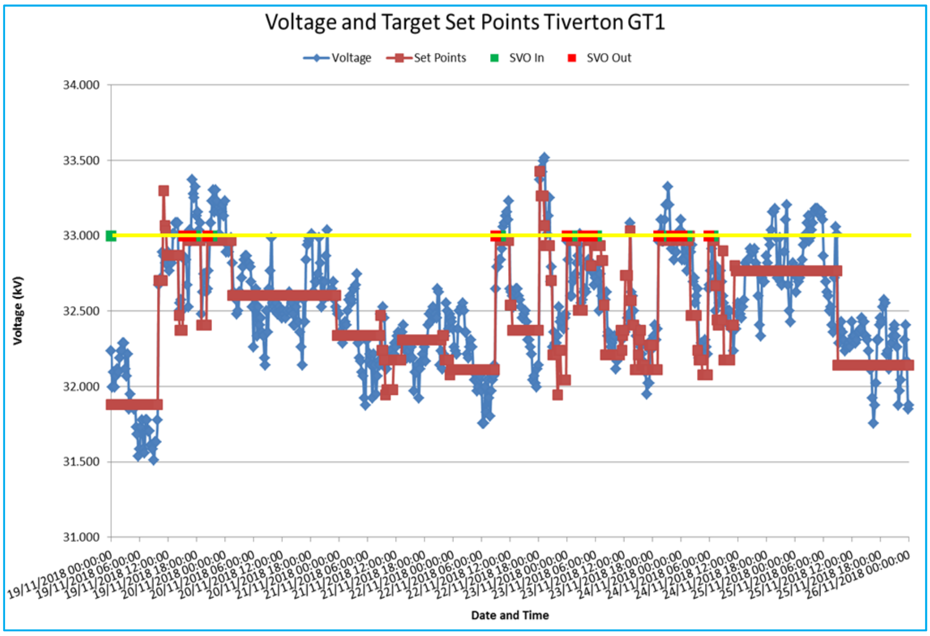

Figure 7-3 – SVO Operation at Tiverton GT1 for a week

SVO policies and procedures

Developing new policies and procedures is a critical part of connecting new technologies to the distribution network. They ensure the new technology is integrated effectively into the main business and allow other DNOs to replicate the Method without duplication of effort. The primary policy document is the Standard Technique (ST) which covers aspects including the integration of equipment and systems onto the network and how to safely operate, control, inspect and maintain equipment and systems.

For Network Equilibrium a suite of new policies was developed to assist engineers with the connection and on-going operation of SVO. These are described below:

- **Operation and Control of System Voltage Optimisation** – Created with close cooperation with control engineers and includes all information required to operate SVO from the NMS. The document explains the basic operation of the system, how to enable and disable SVO at each site and what actions need to be taken for each SP5 alarm that is received in the NMS.
- **System Voltage Optimisation Technology for use on the 33kV and 11kV Network – Engineering Equipment Specification** – As part of the project, significant knowledge has been gained on the various elements of the SVO technology and their required performance. This knowledge has been captured in this policy document which provides the detailed specification of the SVO technology.
- **Application and Connection of the System Voltage Optimisation technology for the Network Equilibrium project** – Includes the requirements for the application and connection of SVO in 33kV and 11kV networks. It demonstrates all considerations that need to be taken into account when implementing SVO and the required works that need to be completed.

7.3 Outcomes of the FPL Method

Overview

The outcomes of the FPL Method have shown that it is possible to develop a fully operational back-to-back power electronic converter on the GB 33kV distribution network and successfully use it to manage power flows between two distribution systems that could not otherwise be permanently connected in parallel. The Method has shown that the FPL can release significant capacity on the 33kV network by enabling active power transfer between distribution systems and independent reactive power control at each side of the FPL to regulate network voltage.

The architecture and full operational system required for implementing an FPL control system has also been developed and implemented along with the associated power system network models that are used to calculate the FPL set-points.

A detailed description of the testing, installation and connection works for the FPL Method can be found in SDRC 6, “Trialling and Demonstrating the FPL Method”.

FPL installation, connection and energisation

The FPL converter and its associated ancillary equipment located in the converter container passed their respective factory tests by the end of August 2017. The FPL software that is installed in the FPL container and controls the converter, cooling systems, protection systems etc. was successfully tested in the factory in October 2017. The FPL transformer manufactured by KONČAR was tested successfully at their facilities in October 2017. The various components of the FPL were delivered to the Exebridge site as per the project schedule and were delivered in their entirety by the end of November 2017. A picture of the software factory testing and the site installation is given in Figure 7-4 and Figure 7-5 respectively. The FPL was successfully energised during the hot commissioning activities in late March 2018. After energisation, the FPL underwent the site acceptance testing process and successfully passed all respective tests. Most notably, the FPL was successfully operated at the full rated power of 20MW for four hours during the temperature rise test.

Figure 7-4 – FPL software testing in the ABB factory

Figure 7-5 – delivery of the FPL container

FPL CM integration

The FPL CM successfully passed its factory tests by 17 November 2017 and subsequently passed its integration testing at the end of December 2017. A process was then started to migrate the CM from the test environment to the operational environment to enable the system to communicate with the FPL at site. This was done in parallel with the commissioning of the FPL at Exebridge. Figure 7-6 shows a screenshot of the NMS showing the integration of the CM.

The FPL CM was built with a graphical user interface to improve the integration and interactivity of the module with its users. The interface allowed selected authorised users to visualise the network conditions and FPL CM calculations in real-time as well as change CM operational settings. A graphic showing the interface is given in Figure 7-7.

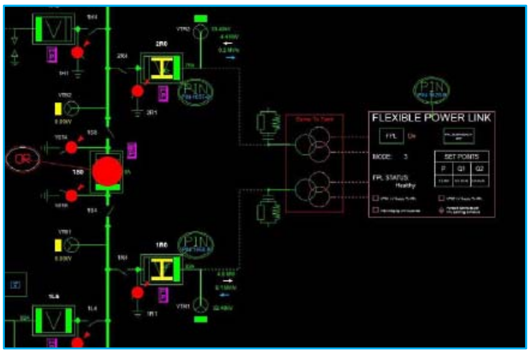

Figure 7-6 – FPL and CM integrated with NMS

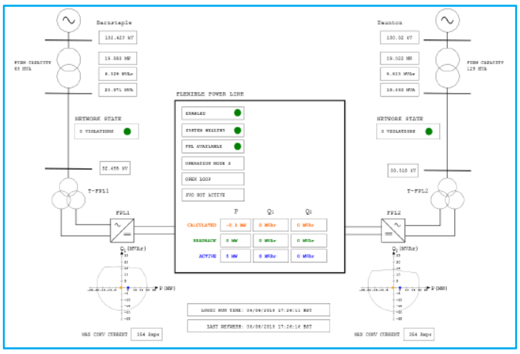

Figure 7-7 – FPL CM graphical user interface

FPL policies and procedures

Two ST documents have been produced as part of the FPL Method and they are described as follows:

- **ST:OC1AC – "Operation and Control of ABB 33kV Flexible Power Link installed at Exebridge Primary Substation for use on the Network Equilibrium project"** – describes how to operate and control the ABB FPL on the 33kV network. It is imperative that this type of policy is produced to ensure that operators are able to safely operate and control the equipment. The document was reviewed by the relevant parties in the main business prior to approval and release. The document gives a succinct explanation of the technology and its constituent parts. It goes on to describe how to safely energise and de-energise the FPL as well as the conditions required to ensure the safe operation of the device. The document also instructs operators on the action to take should an alarm or fault occur related to the device. This policy is a live document on our intranet and has been circulated to other DNOs at various dissemination events.
- **ST:SP2CAD – "Inspection and Maintenance of ABB 33kV Flexible Power Link installed at Exebridge Primary Substation for use on the Network Equilibrium project"** – covers WPD's requirements for the inspection and maintenance of the ABB 33kV FPL. This document was produced in collaboration with the manufacturer to describe the routine inspection and maintenance activities that WPD must undertake to ensure the device operates reliably and safely in service. In these documents particular

emphasis is placed on the safety of operators as they include procedures for visual inspection and intrusive maintenance activities. The maintenance intervals that were agreed have been included in our maintenance logging system, CROWN. This system generates work items automatically based on the maintenance intervals and the ST is referenced as a guide to implementing these work items.

An additional procedure document titled **"FPL Control Module Update Guide"** was produced as part of the development of the FPL CM. This document describes the process to be followed to ensure that the electrical models within the FPL CM are kept up to date, accurate and manageable. The document provides a clear methodology for updating the model which can then be used to train main business staff in the update procedure or act as a reference to ensure that a consistent approach is adopted. Having an up to date and accurate model is critical to ensuring the FPL behaves safely and predictably in service.

7.4 Improvement in Network Performance

EVA Method

The EVA Method does not directly improve network performance as the VLA, SVO and FPL plug-ins were developed to improve system planning capability. However, it can be inferred that the Method indirectly improves network performance by allowing engineers to effectively assess the suitability of deploying the Methods at other locations and therefore facilitating further project replication.

SVO Method

SVO has successfully managed to control the voltages on both 33kV and 11kV networks in real-time, responding to the dynamic operation of the network and releasing network capacity. Through the operation of SVO, it was demonstrated that the optimised target voltage settings at both BSP and primary substations vary with time and are lower than the traditional static setting for the majority of the time. An example of the operation of SVO at Tiverton Moorhayes primary substation for a week is shown in Figure 7-8.

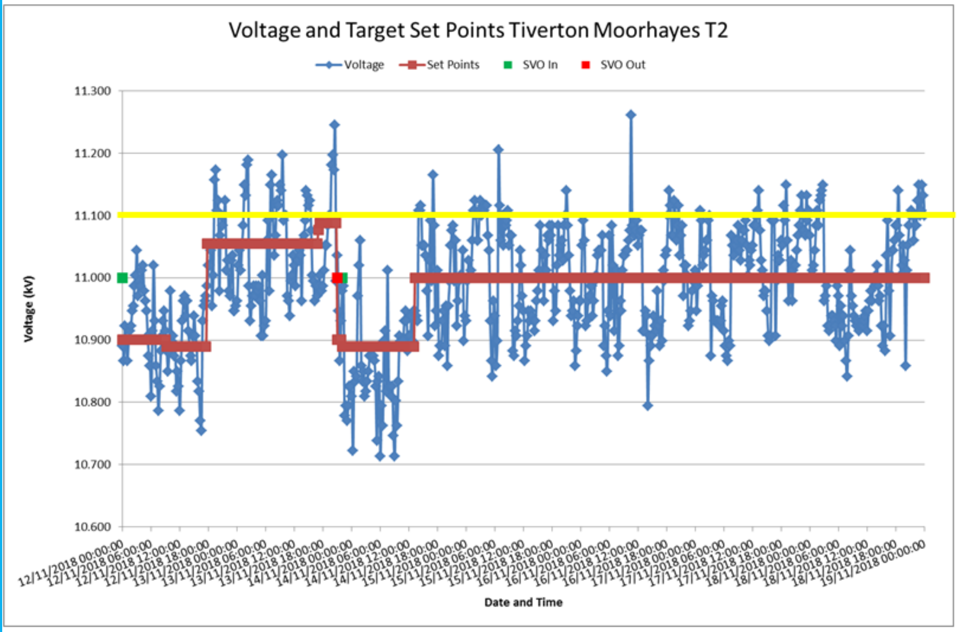

Figure 7-8 – Operation of SVO at a primary substation for a week

FPL Method

The FPL has successfully demonstrated that it is able to release existing network capacity by being able to transfer active power across network groups and by regulating the reactive power, and hence the voltage, at its terminals. In addition, the ability of the FPL to independently control reactive power on both sides enables the device to provide voltage support on both networks. Figure 7-9 shows the FPL providing voltage regulation over a two week period by absorbing reactive power on the Barnstaple BSP side of the device. There is a high level of DG connected to this BSP and it is therefore susceptible to voltage rise violations. The FPL can be seen to manage the voltage thus avoiding the network exceeding statutory voltage limits. Voltage regulation on the 33kV network would normally be performed by tap changer operation on the BSP 132/33kV transformers. A secondary benefit, therefore, is that the FPL acts to reduce tap changer operations.

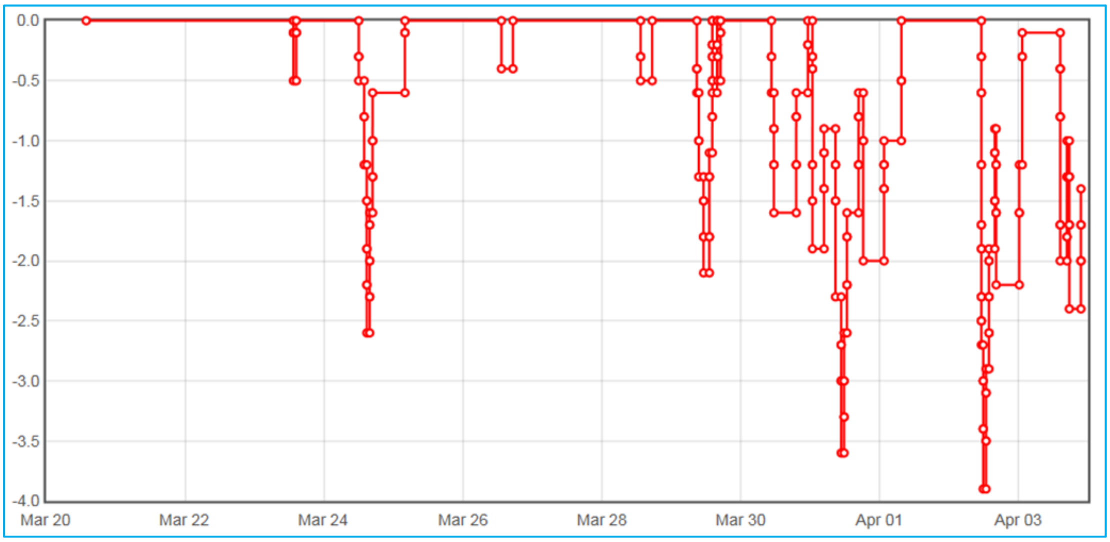

Figure 7-9 – Reactive power (MVar) absorption by the FPL over two week period

The FPL Method is able to reduce the loading of the BSP transformers during periods of peak demand. The FPL does this by transferring active power across the grid groups to reduce the power flowing from the 132kV network through the heavily loaded BSP transformers. Figure 7-10 demonstrates the flow of active power through the FPL to reduce peak transformer loading at Taunton BSP. It can be seen that the peak power occurs as expected during the peak morning and evening hours.

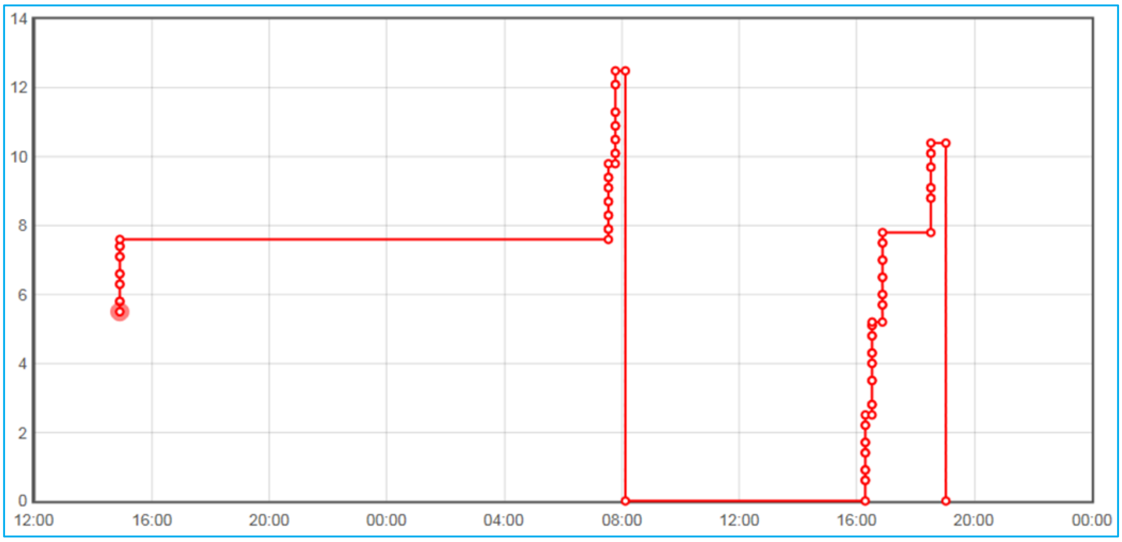

Figure 7-10 – Active power (MW) flow through the FPL (Barnstaple to Taunton)

7.5 Changes to TRL

EVA Method

The TRL of the EVA Method was estimated to be at Level 5 in the original Equilibrium bid and was anticipated to increase to Level 8 as a result of the Method implementation. The project has successfully achieved this level as it satisfies the definition: “Full scale demonstration in a working environment to test and improve technologies so they are ready for commercial deployment”. The VLA has demonstrated that there is scope to widen the statutory 33kV and 11kV voltage limits, whilst the APT is fully functioning set of tools that improves system planning capability.

SVO Method

The TRL of the SVO system was initially estimated at Level 6 when the original bid documentation was created. This was based on the fact that such a voltage control system has not been used or demonstrated in the same way as SVO before. Additionally, innovation projects that had explored intelligent voltage control when the bid was created, had focused on lower voltage networks and were not really for a business as usual roll-out on a larger scale. Through the Network Equilibrium project, the TRL of the SVO method has increased from Level 6 to Level 8 as it has demonstrated the operation of the technology at a large scale and increased its readiness for business rollout.

The SVO system is a full-scale demonstration that has been successfully designed, tested, installed and trialled on the 33kV and 11kV distribution networks. SVO is now being operated as part of main business and a host of documentation including policies, designs and specifications exist to enable replication of the Method at other locations on the distribution network.

FPL Method

The TRL of FPL technology was estimated to be at Level 6 in the original Equilibrium bid. This assessment was on the basis that across the globe there had been very few demonstrations of similar technology on the distribution network. Examples of back-to-back converters for power flow management were found to be used for niche industrial or transmission network applications. The Method implemented in this project has increased the TRL from Level 6 to Level 8 as it satisfies the definition: “Full scale demonstration in a working environment to test and improve technologies so they are ready for commercial deployment” that is given in the Ofgem guidance.

The FPL is a full-scale demonstration that has been successfully designed, tested, installed and trialled on the 33kV distribution network. The FPL is now being operated as part of the main business and a host of documentation including policies, designs and specifications exists to enable replication of the Method at other locations on the distribution network.

8.0 PERFORMANCE COMPARED TO THE ORIGINAL PROJECT AIMS, OBJECTIVES AND SUCCESS CRITERIA

8.1 EVA Method

Table 8-1 provides a list of Project Aims that the EVA Method has successfully contributed towards during the delivery of Network Equilibrium.

Table 8-1 – EVA contribution towards Project Aims

Project Aim	Contribution	Status
Increase the granularity of voltage and power flow assessments, in 33kV and 11kV networks, to unlock capacity for increased levels of low carbon technologies, such as distributed generation (DG)	The development of the APT has provided the ability to conduct studies with much greater granularity and accuracy. The results of the studies have shown that significant capacity can be released for the connection of both generation and load.	Complete
Demonstrate how better planning for outage conditions can keep more customers (generation and demand) connected to the network when, for example, faults occur	The APT allows for daily load flow curves to be used in time-based power system studies. This provides outage planning engineers with accurate network constraint information which can assist in determining which customers can remain connected during outages.	Complete
Develop policies, guidelines and tools, which will be ready for adoption by other GB DNOs, to optimise voltage profiles across multiple circuits and wide areas of the network	The plug-ins and supporting documentation that have been produced as part of the EVA Method have been shared with all GB DNOs and are available to wider stakeholders through our website (https://www.westernpower.co.uk/innovation/projects/network-equilibrium).	Complete

8.2 SVO Method

Table 8-2 provides a list of Project Aims that the SVO Method has successfully contributed towards during the delivery of Network Equilibrium.

Table 8-2 – SVO contribution towards project aims

Project Aim	Contribution	Status
Increase the granularity of voltage and power flow assessments, in 33kV and 11kV networks, to unlock capacity for increased levels of low carbon technologies, such as distributed generation (DG)	SVO has successfully managed to optimise the voltage profiles in 33kV and 11kV networks. This resulted in lower voltage profiles than in normal operation for the majority of the time and has released significant capacity for DG and load connections.	Complete
Develop policies, guidelines and tools, which will be ready for adoption by other GB DNOs, to optimise voltage profiles across multiple circuits and wide areas of the network	A number of policies have been developed as part of SVO to assist engineers with the connection and ongoing operation of the technology. These include the Operation and Control of System Voltage Optimisation Standard Technique, the Engineering Equipment Specification for SVO and the Application and	Complete

Project Aim	Contribution	Status
	Connection of the System Voltage Optimisation technology for the Network Equilibrium project.	

8.3 FPL Method

Table 8-3 provides a list of Project Aims that the FPL Method has successfully contributed towards during the delivery of Network Equilibrium.

Table 8-3 – FPL contribution towards Project Aims

Project Aim	Contribution	Status
Increase the granularity of voltage and power flow assessments, in 33kV and 11kV networks, to unlock capacity for increased levels of low carbon technologies, such as distributed generation (DG)	The Method has successfully demonstrated the development of a 33kV FPL and associated control system. The system is able to transfer active power between two 33kV distribution networks previously unable to be connected together. In addition, the FPL has demonstrated that it can control reactive power at its terminals, thus enabling the FPL to perform voltage regulation on the 33kV network. The FPL has released up to 20MVA of generation capacity on the 33kV network in the trial area.	Complete
Develop policies, guidelines and tools, which will be ready for adoption by other GB DNOs, to optimise voltage profiles across multiple circuits and wide areas of the network	The policies and supporting documentation that have been produced as part of the FPL Method have been shared with all GB DNOs and are available to wider stakeholders through our website.	Complete
Improve the resilience of electricity networks through flexible power link (FPL) technologies, which can control 33kV voltage profiles and allow power to be transferred between two, previously distinct, distribution systems	The Method has demonstrated active power transfer from a generation dominated network to load dominated network through the FPL. It has been shown that this transfer reduces peak BSP transformer loading in the load dominated network and assist with voltage regulation on the generation dominated network. The voltage regulation is further improved by the independent modulation of reactive power on each side of the FPL. This capability reduces voltage violations which otherwise would be increasingly likely due to greater volumes of intermittent renewable DG being connected to the network.	Complete
Increase the firm capacity of substations, which means that the security of supply to distribution customers can be improved during outage conditions, leading to a reduction in customer interruptions (CIs) and customer minutes lost (CMLs)	The FPL Method is able to provide active and reactive power support to either of the interconnected BSPs when under an N-1 scenario i.e. a transformer is taken out of service for maintenance or due to a transformer fault. The FPL reduces the loading on the remaining transformers in service and provides voltage support on the 33kV network.	Complete

9.0 REQUIRED MODIFICATION TO THE PLANNED APPROACH DURING THE COURSE OF THE PROJECT

9.1 Overview

Regular reviews of the planned approach were carried out over the course of the project to ensure that the committed learning would be produced within the original budget and the timelines. As is good practice in all innovation projects, specific methodologies and processes identified at the outset of the project were modified and developed to enhance learning and achieve time and cost savings where possible. The following sections detail the modifications to the planned approach to the project.

9.2 EVA Method

The EVA Method successfully delivered against the requirements set-out in the Project Aims and SDRCs detailed in Section 3.0 and Section 4.0 of this report, respectively. However, some modifications to the APT had to be implemented to ensure the EVA Method was successful, as follows:

- **Forecasting constraints** – The initial plan was to include a forecasting element within the APT which used weather forecast and historical load profile information to determine 48 hour constraint forecasts. Several issues regarding the accuracy of the forecast information were observed during the development and testing phase. The learning from the development has been shared internally with the EFFS Network Innovation Competition (NIC) project to resolve the issues and develop the forecasting element of the APT.
- **Software** – The APT development was originally planned for implementation using the IPSA power system analysis software package. However, during the design phase it was discovered that the APT functionality could be replicated much faster using Python scripts within PSS/E. As such, the decision was taken to develop the APT functionality and SVO / FPL plug-ins within PSS/E.

9.3 SVO Method

During the design and trials phase of the SVO method certain changes were made to the planned approach for the technology, applying the learning that was gained in the process in order to ensure its successful operation.

- **Network model design and creation** – Initially, the network models representing each of the 16 SVO networks would include the SVO controlled substation and its feeders up to the second Normal Open Point (NOP). This would ensure that even in the situation where the first NOP would close, SVO would be able to perform its state estimation and optimisation functions. However, it was found that by modelling the networks to the second NOP, the size of the network model increased significantly making the network display unnecessarily large. Since the occasions where the first NOP closes are not frequent, it would not provide any significant benefit extending the network models for the purposes of the trials. It was therefore decided to set the first NOP as the modelling boundary. Additionally, the IPSA network models for SVO were intended to be extracted from the APT, but since the planning tool was developed in PSS/E, alternative procedures were put in place for the creation of the SVO network models. These involved creating PSS/E models of the networks after extracting the necessary information from the NMS, and then converting the models into IPSA before importing into SP5.
- **Autonomous operation of SVO** – With the stable operation of the system being proven in the trials, certain operational procedures have been automated in the later trial stages, making the day-to-day operation of the technology more efficient and independent of manual intervention from Control Engineers. Initially, whenever an SVO site had a red alarm, the SVO operation would be disabled automatically but would require a Control Engineer to manually re-enable the site through the NMS after the alarm cleared. The numerous investigations that were done following this procedure have shown that in most cases the reason the site’s status turned red was transient due to issues with communications. On all the occasions, the site could be safely re-enabled straight after the event

with no operational implications as the various safety checks that were added to SP5 ensured that no action was taken that could compromise the network. Therefore, additional logic was then added in the NMS in order to re-enable the site automatically an hour after it was disabled due to a red optimisation alarm. This increased the on-time of the technology, reduced the amount of time spent by Control Engineers to manually re-enable sites and also provided additional learning by making it easier to see how long each site would maintain green optimisation status.

9.4 FPL Method

The FPL Method successfully delivered against the requirements set-out in the SDRCs and Project Aims detailed in Section 3.0 and Section 4.0 of this report, respectively. However, some modifications were required during the delivery of the FPL Method to ensure that the Method was successful.

- **FPL LV supply reliability** – The FPL has two incoming LV supplies for its ancillary equipment. During the design phase it was determined that two new supplies should be installed as part of the enabling works. These supplies would be derived from the 11kV feeders that supplied the surrounding area around Exebridge. During the trial phase the 11kV circuit that supplied the ancillary equipment experienced a number of transient faults. The impact of the loss of supply was reduced due to the FPL having UPS capability so did not have to shutdown immediately. A decision was made to swap the ancillary supplies on to the adjacent distribution substation (which was supplied from a different 11kV feeder). This solution has resolved the issue and was relatively simple to implement.
- **FPL CM server configuration** – The FPL CM software is operated on two dual redundant servers: the primary server runs the main instance of the FPL CM and a standby server operates in hot standby to take over operation of the FPL CM if the primary server fails or needs to be maintained. A third server was specified as a test server which was used to test updates/patches to the FPL CM in a safe offline environment. During the implementation of the project it was decided to add a fourth server which operated as a second test server. This was achieved at minimal additional cost to the project and allowed a full replication of the operational system. This was beneficial for testing modifications to the FPL CM software as full replication of the operational environment is more likely to identify software bugs.
- **FPL CM optimisation** – The FPL CM design that was implemented for the initial energisation of the FPL involved calculating and applying an FPL set-point when a network violation was detected. If the violation remained unchanged, the FPL would continue to operate at this set-point. Developing an optimisation element within the CM had been identified during the design phase, however, it was decided to postpone this development so that the FPL energisation date was not delayed. The optimisation has since been implemented and involves the CM continually evaluating the set-point. If a violation is now no longer present, or has reduced in severity, the CM will adjust the set-point to ensure that the FPL is not transferring more real or reactive power than necessary. This significantly improved the FPL efficiency.

10.0 SIGNIFICANT VARIANCE IN EXPECTED COSTS AND BENEFITS

	Total Budget	Expected Spend June 19	Actual Spend June 19	Variance £	Variance %
Labour	**1262**	**889**	**887**	**-2**	**0%**
WPD Project Management & Programme office	510	420	428	8	2%
Project Kick Off & Partner / Supplier Selection	33	33	33	0	0%
Detailed design & modelling	101	101	92	-9	-8%[1]
Installation of Equipment - 11kV & 33kV	290	56	55	-1	-1%
FPL Technologies - Substation Installation 33kV	241	220	221	1	0%
Capture, analyse & verify data for EVA, SVO & FPL	58	35	33	-2	-6%
Dissemination of lessons learnt	29	24	25	1	4%
Equipment	**6691**	**6691**	**6489**	**-202**	**-3%**
Project Kick Off & Partner / Supplier Selection	2	2	2	0	0%
Procurement of SVO Equipment	1540	1540	1375	-165	-11%[2]
Procurement of FPL Technologies 33kV	4550	4550	4496	-54	-1%
FPL Technologies - Substation equipment 33kV	599	599	616	17	3%
Contractors	**3339**	**2695**	**2680**	**-15**	**-1%**
Detailed design & modelling	804	804	804	0	0%
Delivery of SVO Technique - 11kV & 33kV	392	325	321	-4	-1%
Installation of Equipment - 11kV & 33kV	650	125	121	-4	-4%
Implementation of Solution	46	46	46	0	1%
Implementation of Solution	139	110	105	-5	-4%
FPL Technologies - Substation Installation 33kV	740	740	750	10	1%
Capture, analyse & verify data for EVA, SVO & FPL	445	445	436	-9	-2%
Dissemination of lessons learnt	123	100	97	-3	-3%
IT	**396**	**330**	**320**	**-15**	**-3%**
1. WPD - Advanced Network Modelling and Data Recovery	130	125	114	-11	-9%[3]

1. WPD - Procurement of SVO Equipment	60	50	51	-4	-5%
Installation of Equipment - 11kV & 33kV	60	9	9	0	-5%
6. WPD - Implementation of Solution	46	46	46	0	1%
FPL Technologies - Substation Installation 33kV	100	100	100	0	0%
Travel & Expenses	**159**	**159**	**132**	**-27**	**-17%**[4]
Contingency	**1190**	**0**	**0**	**0**	**0%**
Other	**53**	**33**	**33**	**0**	**1%**
TOTAL	**13090**	**10797**	**10542**	**-261**	**-2%**

Notes on line item changes and variations

1 – Efficiencies in detailed design and the production of standard designs enabled savings.

2 – Cost savings through the utilisation of existing systems to interface with the SVO system rather than replication of data provision etc.

3 – Cost savings were enabled through the use of an existing advanced network modelling methodology created as part of the previous FlexDGrid project.

4 – Cost savings through remote working and co-location of project personnel.

The project has been delivered for a total value of £10.54M, representing a cost saving of over £2.5M that will be returned to customers.

11.0 LESSONS LEARNT ON THE METHODS

11.1 EVA Method

Business case and benefits

The original business case for the EVA Method calculated that the post-trial Method cost would be £300k for a post-trial project scale replication. This cost was based on replacement relays and additional network monitoring equipment that would be required to implement the new ±8% voltage levels on the 11kV network and ±10% on the 33kV network on the scale of the project trial area. The analysis presented in SDRC-7 "Trialling and Demonstrating the Integration of the EVA, SVO and FPL Methods" has shown that this post-trial Method cost is still applicable and, therefore, the business case remains unchanged. The expectation that there would be no on-going additional operational costs associated with EVA that would affect the business case for the Method is confirmed.

Lessons learnt

Table 11-1 summarises the main learning points that have been captured throughout the development of the Method.

Table 11-1 – Lessons learnt on the EVA Method

Item	Learning
Potential requirement for additional reactive power absorption equipment	The investigation work for the EVA Method considered the impact that changing voltage limits would have on networks. One particular aspect that had not previously been considered was the need for additional reactive power consumption. The UK grid has been experiencing much lower levels of demand during the summer due to the increasing penetration of renewable energy. Lower levels of active power generally result in lower requirements for reactive power which has to be absorbed elsewhere in the system. Increasing voltage limits could compound this issue and increase the requirement for reactive power absorption.
Impact on fault levels	Engagement with various stakeholders highlighted the importance of monitoring the effect that changes to voltage limits could have on fault levels. Increasing the voltage at the connection point of DG would increase the fault level contribution from that particular generator. Therefore, changing system voltages on a wider scale will instigate the need to investigate system fault levels.

11.2 SVO Method

Business case and benefits

The original business case for the SVO Method was based on the cost of traditional network reinforcement compared against the cost of SVO. In the initial bid it was estimated that the capacity released by SVO was 195MW and this corresponded to an equivalent traditional reinforcement cost (i.e. base case cost) of £28.9m.

The Method trials concluded that the average capacity release of the SVO is 210MW which is higher than the initial calculation in the bid at 195MW.

The projected post-trial Method cost of SVO, at the bid stage, was £3.0m. This was based on savings from the project cost budget of SVO, which is £4.09m. The project has delivered the SVO to the original planned budget, however, learning from the delivery of the SVO's central control system and the on-site activities at the 16 sites has enabled a re-baselined estimation of the post-trial Method cost to be £1.718m. This saving of over £1.2m has been calculated on the basis that less additional development would be required for the future implementation, where the system that has been developed as part of the project is suitable for roll-out; this is largely due to additional developments carried out as part of the project that were originally out of scope. Another significant saving is the level of monitoring required on the system to ensure that voltage stays within statutory limits at all times throughout the entirety of the network. Trialling of the complete SVO system has shown that if the data within the central system is live and accurate then minimal monitoring is required. A slight increase in the post-trial cost has been identified, which is the person days effort to ensure that the central system is live and up to date to ensure that the background model, enabling the real-time voltage calculations, to remain accurate.

Lessons learnt

Item	Learning
Available network headroom for target voltage amendment	SVO has demonstrated that in practice, the capability to amend the target voltage set-point at both BSP and primary substations is much larger than can be estimated from traditional power system studies. For example, the actual target voltage amendment window at a primary for a week was 57% wider in reality compared with the estimated value through power flow studies, and 88% wider for a BSP.
Optimal target voltage set-point variation	The optimal target voltage set-point at BSP and primary substations varies significantly in real-time, responding to the dynamic and complex nature of modern electricity networks. This reinforces the need for a control system that has full network visibility and the capability to perform state estimation in order to provide knowledge on the detailed network operation, in the same way as the SVO system has done. This is fundamental for any type of intelligent network control.

11.3 FPL Method

Business case and benefits

The original business case for the FPL Method was based on the cost of traditional network reinforcement compared against the cost of installing the FPL equipment. In the initial bid it was estimated that the capacity released by the FPL would be 36.2MW and this corresponded to an equivalent traditional reinforcement cost (i.e. base case cost) of £15m.

The Method trials concluded that the average capacity release of 20MW per FPL is lower than the initial calculation in the bid. However, the average cost of the traditional reinforcement is not affected by the revised FPL capacity because the same equipment would still need to be installed in both base case scenarios.

The cost to deliver the FPL was in line with the project budget of £6.95m as documented in Section 10.0. In the original bid, the post-trial Method cost was projected to be £5.6m. The actual cost of the FPL is higher than the post-trial Method cost because it includes some costs that are borne from this being the first ever installation of its kind on the GB distribution network. If another FPL were to be built on the network again (i.e. post-trial) significant savings would be achieved in the design engineering of the FPL and its associated centralised control system due to the existence of standard designs, procedures and a large body of project learning. Detailed analysis performed in SDRC-7 “Trialling and Demonstrating the Integration of the EVA, SVO and FPL Methods” showed that the projected savings align well with the £1.35m difference between the project cost and the post-trial Method cost. Therefore, the post-trial Method cost remains valid and in turn it can be seen that the original business case for the project is unchanged on the basis of the trial. The FPL could still achieve substantial savings to GB if deployed across UK DNOs.

Learning learnt

Table 11-2 summarises the main learning points that have been captured throughout the development of the Method.

Table 11-2 – Lessons learnt on the FPL Method

Item	Learning
Site selection	Selecting the appropriate site to install the FPL was a critical part of the successful implementation and trialling of the FPL Method. Allowing sufficient time to analyse the different sites helped to inform the early stages of the design and helped contribute to the overall success of the trial. Despite Exebridge substation having a large footprint, the existing equipment arrangement was not an efficient use of this space and modifications had to be carried out so that the FPL could be installed. Allowance was made in the Method budget costs for these modifications, however, if these could be avoided for future installations there could be significant financial savings. The layout of the FPL device components was optimised as far as possible during the design stage. For the same power rating it is expected that the footprint would remain the same. This should be allowed for in future designs. Locating the FPL at an existing substation meant that LV supplies were readily available. This is a key factor as the FPL required two separate supplies: a 120kVA rated supplied for the pre-charger unit for the DC link; and an 80kVA supply for the auxiliary equipment. Preferably the LV supplies should come from two separate sources to provide redundancy. The existing substation LV supplies were replaced at Exebridge as they were not large enough for the FPL demand.
Network models	Important learning was generated throughout the project on the optimum way to approach the production, quality assurance, verification and update of power system models for innovation technologies. The initial FPL CM model was produced as part of the project, however, a significant amount of effort was required in subsequent revisions to make it more user friendly, easier to update find faults and complete verification. The main learning point from the project implementation is that a clear and concise design standard or guide is required to be produced at an early stage of the development of the network model. This document should specify and standardise the design of the model. The standard should include how to connect new loads, generators, circuit breakers, lines and transformers etc. and also ensure a rigorous naming convention is employed for all components. An additional benefit of the standard or guide is that it can include a methodology for updating the model. This information can then be used to train main business staff on the process. Having an up to date and accurate model is critical to ensuring the FPL behaves safely and predictably in service. During the course of the project delivery, these principles were captured in an update procedure document which was used as a reference for the staff tasked with updating the model in BAU. This document will form the basis of a specific design standard in future innovation projects utilising power system models.
CM testing	The demarcation of responsibilities for CM testing in the contract between customer and the manufacturer was not explicitly clear leading to issues of interpretation of the requirements. Therefore, the contract must clearly and concisely demarcate these responsibilities. It must also specify the parties responsible for producing the testing specification and any temporary works required to facilitate the testing. The testing of a software based control system is complex and requires significant integration testing with existing DNO systems, namely the NMS. The key to successful integration testing is therefore thorough offline point-to-point and end-

	to-end tests between subsystems. This may require simulation of hardware components. The benefits of this approach are: the early identification of issues relating to: data interpretation; communication protocols; and control logic. This greatly de-risks the commissioning activities performed at site. It is important to ensure that the contract captures all of the anticipated SIT requirements to reduce contract variations. The contract should also specify that the operational manual for the control system is to be made available in draft form a minimum of two months prior to the FAT. This was not explicitly specified in the FPL CM contract and led to the manual being unavailable during the development of the FAT test specification. This can lead to the omission of items from the specification. An operational scenarios document was produced during the detailed design phase of the FPL CM. It was valuable for the overall testing approach of the FPL CM and helped define both the FAT and SIT test specifications. This document captured all of the operational requirements of the CM along with the corresponding logic response from both the CM and the SCADA systems. This repository was also valuable as it could be referenced by the project and stakeholder teams as an aide memoir during the build phase of the project. It is highly recommended that this document is produced for future control systems of this nature.

12.0 LESSONS LEARNT FOR FUTURE INNOVATION PROJECTS

12.1 Overview

This section captures the learning that was generated throughout the implementation of Network Equilibrium and which could be applied to future innovation projects to ensure that the outputs and benefits of these projects are realised in a timely and efficient manner. The initial part of this section focusses on general project learning which is captured in Table 12-1 and then goes on to present the learning specific to each Method.

Table 12-1 – General project learning

Item	Learning
Engagement with internal stakeholders	The delivery of an innovation project often requires the design and installation of novel systems, equipment and processes that are new to the business and may require staff members to adapt their existing work practices or learn to carry out new or additional tasks. In addition, the internal stakeholders will take ownership of the innovation technology as it transitions into BAU. For future innovation projects it is recommended to develop a change management plan and engagement strategy to outline the project team's approach early in the project. The strategy should identify the stakeholders that will have an impact on the requirements for the design, installation and operation of the project Methods. The engagement activities can then be built into the project management tools (i.e. project schedule and action log) to ensure a thorough and consistent approach. The stakeholders should be made aware of the overall aims and objectives of the project as well as the specific aims and objectives of each project method. Through these initial interactions, the roles and responsibilities of each party can be formalised and reporting lines were set up to ensure clear communication between the parties. It is key to involve relevant stakeholders at each Method stage gate review. Regular meetings are beneficial for two way transfer of knowledge and ideas, as well as progress monitoring and issue resolution
Cross-method communication and coordination	Cross-method communication and coordination is a key element of the project learning. The implementation of the SVO and FPL Methods was undertaken in parallel due to the requirements of the project schedule. Both Methods were reliant on common internal stakeholder teams for the delivery of certain work packages. It became apparent that greater levels of communication were required between the SVO and FPL Method work package managers to avoid the scheduling of resources for one Method affecting the schedule for the other. After this initial learning experience a greater emphasis was put on cross-method communication and coordination and there were a number of benefits acquired through adopting this learning. The scheduling of tasks that utilised common resources was improved. Since SVO testing and integration with SCADA had the priority in the schedule there was a lot of learning that was shared with the FPL CM work package team which avoided large amounts of unnecessary duplication of effort. An example was the configuration of the ICCP communication link that facilitated the signal communication between the SCADA system and the SVO/FPL CM systems. Through improved coordination, the SVO configuration was successfully utilised for the FPL CM with minimal modifications.

12.2 EVA Method

Table 12-2 – Lessons learnt from the EVA method

Item	Learning
Engagement with external stakeholders	Ensuring early communication with industry stakeholders produced valuable information for the EVA Method. In particular, DNOs, manufacturers and consultants were able to provide additional insights into some of the challenges that could be faced if voltage limits were to be changed. Having this information at an early stage helped to avoid duplication of activities which had previously been carried out by others.
Define clear system performance requirements at contract stage	Clear and concise accuracy requirements were produced for the APT during the very early stages of project development before detailed design had been carried out. As with most new technologies it was important to set a threshold limit which must be passed and include this within the contract documentation. During the testing of the APT issues were observed with the accuracy of the forecasts. Following this WPD were able to apply this defined set of criteria and enter into negotiations with the APT supplier about the next steps to resolve the matter. Having clear system performance criteria included at an early stage prevented the design of a sub-optimal system.

12.3 SVO Method

Table 12-3 – Lessons learnt from the SVO method

Item	Learning
Clearly define and capture the responsibilities of each system that the technology interacts with	During the design stage of the SVO Method, the responsibilities of each system (SP5, NMS, AVC relay) under various operating conditions were captured in a document, defining the actions that each system should take. This document was used in the FAT, SIT and SAT, and also during the trials of the technology. It was also very helpful when troubleshooting issues as it accelerated the identification of issues.
The right Design approach can increase how efficiently the technology is built	When developing the SVO models it was critical that a simple and robust naming convention was developed. Developing and fixing this naming convention made the model building process more efficient and ensured that the analogue measurements were accurately mapped from the NMS to SP5. In addition, the convention avoided days of manual work.

12.4 FPL Method

Table 12-4 – Lessons learnt from the FPL method

Item	Learning
Switchgear integration	The FPL is designed to integrate with the existing network through 2 nos. 33kV circuit breakers connected across the device. These circuit breakers are required to provide protection of the FPL from both network and internal faults; to connect and disconnect the FPL as part of the control sequence; and to accommodate measurement devices used to monitor current, voltage and frequency. ABB did not provide these circuit breakers as standard and, therefore, they had to be included as part of the site design. This introduced a layer of complexity and an additional interface point between WPD and ABB. For future FPL installations,

	however, if the FPL manufacturer were to include the HV switchgear as an integral part of the FPL then this could significantly simplify the design and installation work. The FPL had automatic control over the circuit breakers, which was a significant departure from standard WPD practice as normally only the NMS or operational engineers on site can control HV switchgear. However, the changes were successfully implemented and captured in updated policy and procedure documentation.
FPL transformers	The FPL requires transformers on either side of the converter to step-down the grid voltage for correct operation of the power electronics. The standard design involves two separate transformers for each side of the FPL. Instead, the two transformers were combined into one tank which reduced the use of materials, saved time and costs associated with testing, delivery and installation; reduced civil costs; and consolidated interfacing for the control systems. A failure of a single transformer, when supplied as two separate units, would still result in the FPL being out of service, therefore, combining the transformers did not increase the impact of a failure. The only additional risk with this configuration is that a catastrophic failure may cost more to repair should this occur. It is recommended that future installations adopt the same approach as used for Network Equilibrium.
FPL Testing	The FPL for Network Equilibrium could not be tested as one complete unit in controlled laboratory conditions due to the physical size of the assembled device and the capability of the test equipment in the manufacturer’s laboratory. For future projects it is recommended that the manufacturer submits a clear test procedure for the device. The information submitted in the initial contractual documentation did not state clearly that the FPL components would be tested individually rather than as a complete device. This would reduce the impact of potential failures during testing and limit the time on-site for commissioning. Witnessing the manufacturer tests also proved to be extremely valuable as a number of errors were noted during the software FAT. As the project team were in attendance at this FAT, all of the information was available to make a clear, informed decision. In this particular instance, the decision was made to cancel the software FAT and re-test again after a series of fixes were applied. For the FPL and transformer FATs, the timescales were extremely tight for setting up, conducting and witnessing the tests. This meant that the witnessing engineers were under pressure to ensure that the tests were conducted safely and in alignment with the test procedures. In future contracts it would be prudent for manufacturers to allow additional testing time for devices being designed and built for innovation projects (especially where deviations are being made to standard designs). It would also be beneficial for the manufacturer to submit a testing programme which has milestones for them to complete a pre-FAT before witness testing occurs. This would help to prevent a similar situation to what happened during the initial software FAT.

13.0 PROJECT REPLICATION

13.1 EVA Method

Overview

The production of the APT involved the development of complex network models. A process for developing these models was prepared during the design stage so that it would be possible to replicate the procedures for future implementation.

The process that was developed includes details of the input data required to generate the models, step-by-step guide for production of the model and how to test and verify the accuracy of the model produced. Having written the process and updated it throughout the trials, replication of new network models can now be undertaken in a much shorter timescale compared with the process prior to Network Equilibrium (which would have been an entirely manual process).

A key part of the APT deployment is the ability to perform VLA on the modelled network and establish the capacity benefits across a range of voltages. After completing the verification of the network a user can specify the existing voltage limits and proposed amendments to establish the change in capacity that could be released.

The SVO and FPL plug-ins that were developed as part of the APT are important tools which can be used when assessing the potential replication of the SVO and FPL Methods. The plug-ins were developed in PSS/E using Python scripts. This allows replication across different software packages.

Business-as-usual cost

There are no upfront BAU costs for the replication of the Method as the EVA tools have already been developed and tested. They can now be applied at sites outside the Network Equilibrium project trial area and provide indication of the associated capacity release benefits at these locations.

The EVA tools will be made available to other DNOs to allow them to replicate the assessments that were made as part of Network Equilibrium on their networks. There is no direct cost associated with the EVA tools, however, each DNO would need to apportion engineering time for implementation. For example, time would be required for engineers to familiarise themselves with the tools, perform checks on system models, rectify any issues with those models and perform a series of tests to confirm correct operation. We estimate that around two to three person weeks (for a Senior Engineer) would be required for implementation of the EVA tools for another DNO.

13.2 SVO Method

Overview

The design of the SVO technology ensured the scalability of the solution so that it can be applied to other network areas.

The IT architecture of the solution is shown in Figure 13-1, which demonstrates the two virtual servers that host the various SVO software modules. Two virtual servers need to be used to ensure redundancy and high availability, such that if the main server fails the stand-by server can automatically pick the entire load and ensure the system operation remains uninterrupted. These virtual servers can be sized depending on the requirements of the particular system and the volume of information that will be processed and stored. If SVO is expanded to further areas for example, then the capacity of the servers might require an increase depending on the additional data points that will be exchanged over ICCP link and the increase in the total number of nodes in the network models.

A full electrical model of each network that will be controlled by SVO is required, as it is fundamental to the operation of the state estimation and optimisation modules. The network model needs to include as a minimum the infeed to the SVO controlled substation, the transformers and all switching components at the substation and the feeders fed by the substation to the first NOPs including all connected loads and generation and any switching equipment.

In order to be able to transfer monitoring information from the NMS to the SVO, and control signals between the two systems, an ICCP link needs to be configured to establish this interconnection. The ICCP link provides the capability of exchanging this information in real-time.

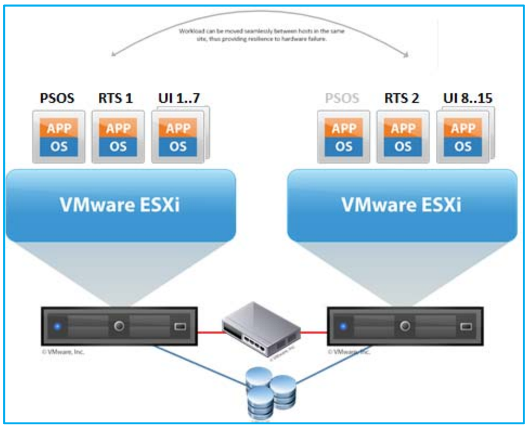

Figure 13-1 – SVO IT architecture

The substations that will be controlled by SVO need to have appropriate AVC relays installed on site, which can accept analogue set-points or perform group setting control. The SuperTAPP SG relay was used in the Network Equilibrium project as it can receive analogue set-points and implement fine voltage control and the MicroTAPP relay was used for the group control. It is recommended to implement fine voltage control in order to ensure that the SVO system can implement all of the optimised set-points that it calculates to maximise the benefits from its operation.

Business-as-usual cost

The design and implementation of the SVO system involved a significant amount of development work which ensured that the final system was successfully integrated with our existing systems and is ready for future roll-outs. Applying the SVO technology to further network areas will be less costly and will require less time than the original implementation due to the completion of development activities including the ones below:

- The IT architecture of the solution has been standardised according to WPD's IT practices;
- The exchange of measurements, controls and alarms between SVO and the NMS has been implemented;
- The procedures for the creation of the SVO network models have been developed and documented;
- The testing specifications for the SVO system have been developed and implemented; and
- The policy for the operation of SVO through the NMS has been developed and implemented.

Replicating SVO at another site in one of our licence areas, following the Network Equilibrium trial, would involve updating the SP5 model, installation of equipment at the respective substations and carrying out testing. The cost of the replication would likely be in the region of around £107k per site. This compares cost is around 43% lower than the post-trial costs that were included in the original FSP due to the efficiencies, standards and learning that have been developed throughout the trials.

Other DNOs wishing to replicate SVO would benefit from the learning and documentation produced as part of Network Equilibrium, helping to reduce the time required for design, integration and testing. It is expected that application of this learning for future projects would achieve around a 40% reduction in cost per site for a project of an equivalent scale of Network Equilibrium (based on the Method cost). This equates to a cost of around £157k per site including the apportioned cost of the SVO control system, updates to designs for DNO specific requirements, purchase of relays, installation and testing. A list of the physical components required for replication are listed in Appendix 5.

13.3 FPL Method

Overview

The FPL constitutes the FPL converter located at site and its associated centralised control system (FPL CM). The FPL converter was supplied by ABB and has been successfully installed and integrated onto the 33kV distribution network. The two technical policies that were produced as part of the Method (Inspection & Maintenance and Operation & Control) have allowed the device to be connected, managed and operated safely and correctly on the network. These policies have subsequently been made available to the other UK DNOs.

The FPL CM software was developed by Nortech Ltd and has been successfully integrated with the NMS. The software is installed on a set of servers located in the main server room. The server architecture that has been implemented involves two operational servers (primary and stand-by) and two test servers. The FPL CM requires the installation of additional third party software applications to enable it to carry out its functions. These are as follows:

- **iHost[3] Platform** – A central host platform also developed by Nortech Ltd. The FPL CM software application is integrated within Nortech's iHost platform to enable it to interface with the NMS via the ICCP communications protocol.
- **IPSA** – A power systems analysis tool that is used by the FPL CM to calculate and validate set-points for the FPL.

The FPL CM also requires a power systems model of the electrical networks that the FPL is connecting together. This is downloaded onto the servers and is made available for loading into the FPL CM. The specific requirements for the electrical model are captured in an update and maintenance guide developed as part of the Method.

Business-as-usual costs

The FPL is the first installation of its kind on the GB distribution network and therefore a significant amount of upfront work was carried out by the project team to ensure the device was able to be safely connected and operated on the network. There will be significant business-as-usual cost savings attributable to the standardisation of designs and the body of project learning that has been captured throughout the trial. Some examples are given as follows:

- The 33kV switchgear technical specifications which include protection relay and interlocking requirements have been developed and standardised for the connection of the FPL;
- The information exchange between the FPL and NMS i.e. measurement, control, alarm and trip signals has been standardised;
- The testing specifications for the FPL and its associated control system have been developed and implemented; and
- The policies that document how to operate and control the FPL on the distribution network as well as to inspect and maintain the device in the field have been approved and are operational in main business.

The aforementioned areas will make subsequent installations more cost and time efficient. Overall, for further installations of the FPL and FPL CM in both WPD and other DNO licence areas, we would expect the replication cost to match the post-trial cost of £5.6m. A list of the physical components required for replication are listed in Appendix 5.

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[3] The iHost platform is proprietary software developed by Nortech Ltd. It is a central host platform that is able to receive and store data from any number of remote sites using a variety of communication channels and protocols.

14.0 PLANNED IMPLEMENTATION

14.1 EVA Method

The development of APT has been successfully completed and reported earlier in this document with further details of the design and implementation covered in SDRC-1 and SDRC-4 respectively. The development of the tool has allowed VLA to be carried out across a number of substations which has indicated the capacity benefits that could be realised. The production of detailed network models along with the APT algorithms has highlighted that the additional granularity provided can significantly improve the accuracy and speed of capacity calculations.

The results from VLA show that relaxation of voltage limits could have positive effects in the connection of higher levels of embedded generation, reducing the timescales and costs of new connections. The outputs from the VLA have been forwarded to the industry for further investigation and consultation. The work carried out also recommended further coordination with other working groups (WG) such as ER P28 WG and the LV harmonisation group.

The successful development of the SVO and FPL plug-ins now provides planning engineers the ability to assess the viability of deploying SVO or an FPL to resolve a network constraint. For example, when performing system studies for a new customer connection enquiry, the results from running the plug-in complements the traditional reinforcement and ANM solutions. Currently, the application of the plug-ins is limited to the areas that have already been modelled as part of the trials. However, as discussed above, additional modelling can be carried out where necessary to assess the suitability of SVO and FPL installations as an alternative solution.

14.2 SVO Method

SVO has been successfully implemented, demonstrating the optimisation of voltages in 33kV and 11kV networks. The trials of the technology have provided valuable additional network visibility and detailed network operation information that is not available through the traditional control systems that DNOs have.

The complex, dynamic nature of electricity distribution networks was shown in the optimisation decisions taken by SVO. It is clear that in order to be able to implement any type of intelligent network control as part of the responsibilities of a Distribution System Operator (DSO), it is necessary to have full network visibility and the capability of performing state estimation through the control system.

The network capacity benefits of SVO have been evaluated through power system studies performed using the developed SVO plug-in. Even though the studies were more conservative compared to the real SVO operation, they have shown significant capacity benefits from the optimisation of voltages in both 33kV and 11kV networks.

SVO is remaining operational on the networks that took part in the trials and will continue to optimise the voltages but also provide valuable network information that will be used in further analysis.

Recognising the benefits of the SVO technology both in terms of the additional network capacity it releases and the visibility it provides on the real-time network operation, further work will be undertaken in order to identify the network areas that the technology should be expanded to and whether that will be done using the existing SVO system or by integrating the functionalities within the NMS.

14.3 FPL Method

The FPL has been successfully developed, connected and trialled on the distribution network as part of Network Equilibrium. The Method has shown that using the FPL to interconnect two distribution networks provides significant capacity benefits that can be used for the connection of additional generation and/or demand. The FPL has also demonstrated secondary benefits such as the ability to regulate voltage on the 33kV network and also to reduce BSP transformer loading at times of peak demand, both of which increase system security. A range of connection options, policies and guides have been produced and capture the learning encountered during the trial. This body of documentation has reduced the perceived risk associated with the utilisation of this type of converter technology on the HV network and will enable the device to be implemented at other sites with less upfront engineering work. The learning from the FPL trial coupled with the FPL plug-in developed as part of the EVA Method allows network planning engineers to treat the FPL as a viable and complementary solution to traditional reinforcement.

In its current form, the FPL Method is suitable to be replicated on the 33kV distribution network on the basis of the demonstrated benefits and the scale of deployment as originally presented in the business case is valid. There are, however, some additional considerations that could further optimise the benefit of the FPL in the future. The FPL is a highly versatile and flexible technology that can support the network in a number of different ways depending on how the FPL is controlled. For the purpose of this project, the FPL was controlled from a centralised controller that used the FPL to remove network violations i.e. to maximise capacity. This was the basis of the project business case. However, the ABB FPL has a number of operational modes that can be implemented locally and perform different network support functions. They were not investigated as they fell outside the scope of this project. In addition, there is scope to build on the logic already developed for the CM so that it could optimise the use of the FPL for different functions. A further investigation could be warranted to understand the benefits of applying these different control philosophies and more importantly how they could be managed by the central controller to unlock further benefits of the FPL.

15.0 LEARNING DISSEMINATION

Dissemination of learning during Network Equilibrium has taken place through active stakeholder engagement throughout the course of the project. The feedback and opinions received from this engagement has been extremely valuable in shaping the outcome of the project and will be taken forward into future projects also. The presentations and documentation produced as part of the project has also provided key learning with respect to the benefits of balancing power flow and voltages across distribution networks.

Learning dissemination has taken place in various forms during the project including:

- Workshops with UK DNOs and other stakeholders
- Presentations (individually led and also at events / conferences)
- Site visit with UK DNOs
- Publication of technical papers
- CIRED Conferences
- LCNI Conferences
- IET ACDC Power Transmission Conference
- Website

The initial engagement undertaken on Network Equilibrium focussed on obtaining the opinions of DNOs, industry bodies and manufacturers to inform the direction of the project. This engagement was conducted first of all through the use of targeted questionnaires and was followed by a specific workshop to discuss the outcomes. The feedback gained from this engagement was extremely beneficial for WPD and those involved.

Throughout the course of the project regular updates on the progress of the project were provided through presentations at WPD organised events and industry conferences. This was supplemented by the publication of project progress documentation and regular updates on WPD's Innovation website. Figure 15-1 and Figure 15-2 below show other DNO staff members attending the project closedown technical dissemination event and FPL site visit on 15 May 2019.

Figure 15-1 – DNO technical dissemination

Figure 15-2 – DNO technical dissemination FPL site visit

There has been significant interest from the power industry across the world during the course of the project. As such the learning generated from the project was captured in technical documentation which has been circulated to relevant stakeholders including all UK DNOs. The technical documentation consists of papers that have been produced and published for international conferences such as CIRED and the ACDC Power Transmission Conference.

The learning generated from technical documentation is complemented with that which has been published in the most recent SDRC documents. The SDRC documentation describes learning that has been generated throughout each of the Methods from design through to implementation. In addition to the SDRC documentation, a specific learning document has also been produced for the FPL Method which describes development in back-to-back DC converter technology and what improvements could be made for new FPL applications.

We are very grateful to ENWL who have carried out a thorough peer review of the information provided in the Closedown Report and the supporting documentation included herein. A letter confirming the peer review of the Closedown Report which documents the project's findings, outputs and learning is attached in Appendix 4.

16.0 KEY PROJECT LEARNING DOCUMENTS

16.1 Project progress reports

Progress report 1 – December 2014 to May 2015
Progress report 2 – June 2015 to November 2015
Progress report 3 – December 2015 to May 2016
Progress report 4 – June 2016 to November 2016
Progress report 5 – December 2016 to May 2017
Progress report 6 – June 2017 to November 2017
Progress report 7 – December 2017 to May 2018
Progress report 8 – June 2018 – November 2018
Progress report 9 – December 2018 – May 2019

16.2 Presentations

VLA Workshop October 2015: https://www.westernpower.co.uk/downloads/2539
Balancing Act September 2016: https://www.westernpower.co.uk/downloads/1901
Balancing Act June 2019: https://www.westernpower.co.uk/downloads/41767

16.3 SDRC reports

SDRC 1 – Detailed Design of the Enhanced Voltage Assessment Method
SDRC 2 – Detailed Design of SVO Method
SDRC 2 – Appendix
SDRC 3 – Detailed Design of FPL Method
SDRC 4 – Trialling and demonstrating the EVA method
SDRC 5 – Trialling and demonstrating the SVO Method
SDRC 6 – Trialling and demonstrating the FPL Method
SDRC 7 – Trialling and Demonstrating the Integration of the EVA, SVO and FPL Methods
SDRC 8 – Knowledge Capture and Dissemination

16.4 Additional Reports and Data

SVO Data Hub - https://www.westernpower.co.uk/downloads/32227

FPL Data Hub - https://www.westernpower.co.uk/downloads/32236

FPL Development and Improvement – https://www.westernpower.co.uk/downloads/51712

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Appendix 1 – Glossary of terms

Term	Definition
AC	Alternating Current
ANM	Active Network Management
APT	Advanced Planning Tool
AVC	Automatic Voltage Control
BAU	Business as Usual
BSP	Bulk Supply Point
CIRED	International Conference and Exhibition on Electricity Distribution
CM	Control Module
DC	Direct Current
DG	Distributed Generation
DNO	Distribution Network Operator
DSO	Distribution System Operator
EFFS	Electricity Flexibility and Forecasting System
EHV	Extra High Voltage
ENA	Energy Networks Association
ENWL	Electricity North West Limited
ER	Engineering Recommendation
ESQCR	Electricity Safety, Quality and Continuity Regulations
EVA	Enhanced Voltage Assessment
FAT	Factory Acceptance Test
FPL	Flexible Power Link
FSP	Full Submission Pro-forma
GB	Great Britain
GIS	Geographic Information System
GUI	Graphical User Interface
GW	Gigawatt
HV	High Voltage
ICCP	Inter-Control Centre Protocol
IET	Institution of Engineering and Technology
IFI	Innovation Funding Incentive
IPSA	Interactive Power System Analysis

ITT	Invitation to Tender
LCNI	Low Carbon Networks & Innovation
LV	Low Voltage
MW	Megawatt
NIC	Network Innovation Competition
NMS	Network Management System
NOP	Normal Open Point
P	Active Power
PSOS	Power System Observer Server
PSS/E	Power System Simulator for Engineering
PV	Photovoltaic
Q	Reactive Power
RTS	Real-Time Server
RTU	Remote Terminal Unit
SAT	Site Acceptance Test
SCADA	Supervisory Control and Data Acquisition
SDRC	Successful Delivery Reward Criteria
SIT	System Integration Test
ST	Standard Technique
SVO	System Voltage Optimisation
TRL	Technology Readiness Level
UPS	Universal Power Supply
VLA	Voltage Limit Assessment
VSC	Voltage Source Converter
WG	Working Group
WPD	Western Power Distribution

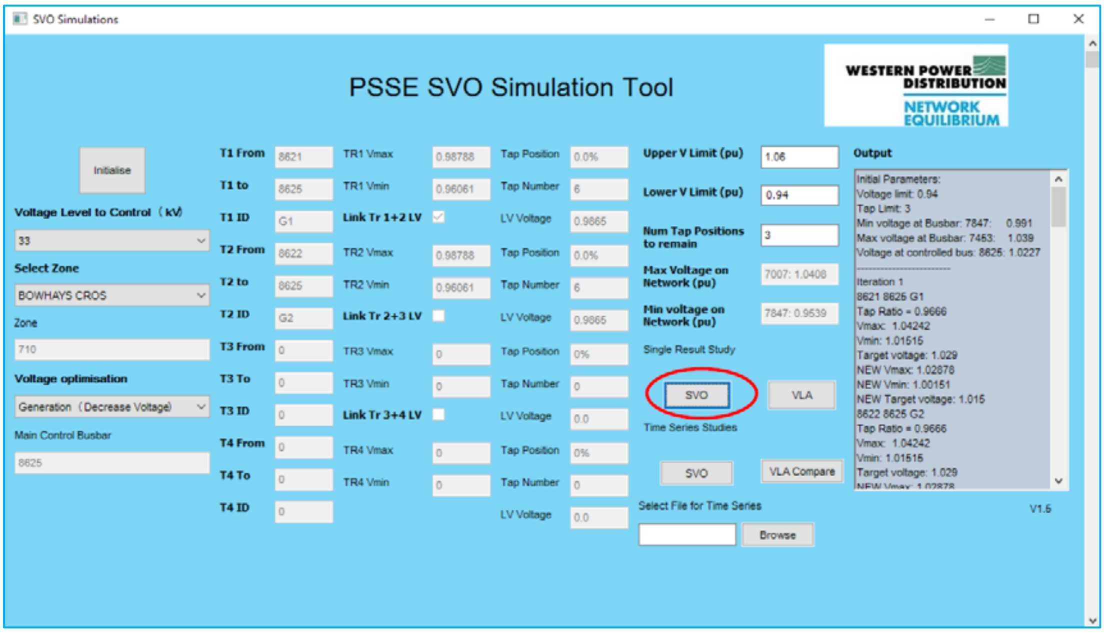
Appendix 2 – SVO and FPL installation sites

SVO BSP substation installation locations

SVO primary substation installation locations

FPL installation location

Appendix 3 – APT Plug-in GUI



Voltage Level to Control（kV) 33

Select Zone BOWHAYS CROS

Zone 710

Voltage optimisation Generation（Decrease Voltage)

Main Control Busbar 8625

T1 From	8621	TR1 Vmax	0.98788	Tap Position	0.0%
T1 to	8625	TR1 Vmin	0.96061	Tap Number	6
T1 ID	G1	**Link Tr 1+2 LV**	☑	LV Voltage	0.9865
T2 From	8622	TR2 Vmax	0.98788	Tap Position	0.0%
T2 to	8625	TR2 Vmin	0.96061	Tap Number	6
T2 ID	G2	**Link Tr 2+3 LV**	☐	LV Voltage	0.9865
T3 From	0	TR3 Vmax	0	Tap Position	0%
T3 To	0	TR3 Vmin	0	Tap Number	0
T3 ID	0	**Link Tr 3+4 LV**	☐	LV Voltage	0.0
T4 From	0	TR4 Vmax	0	Tap Position	0%
T4 To	0	TR4 Vmin	0	Tap Number	0
T4 ID	0			LV Voltage	0.0

Upper V Limit (pu) 1.06

Lower V Limit (pu) 0.94

Num Tap Positions to remain 3

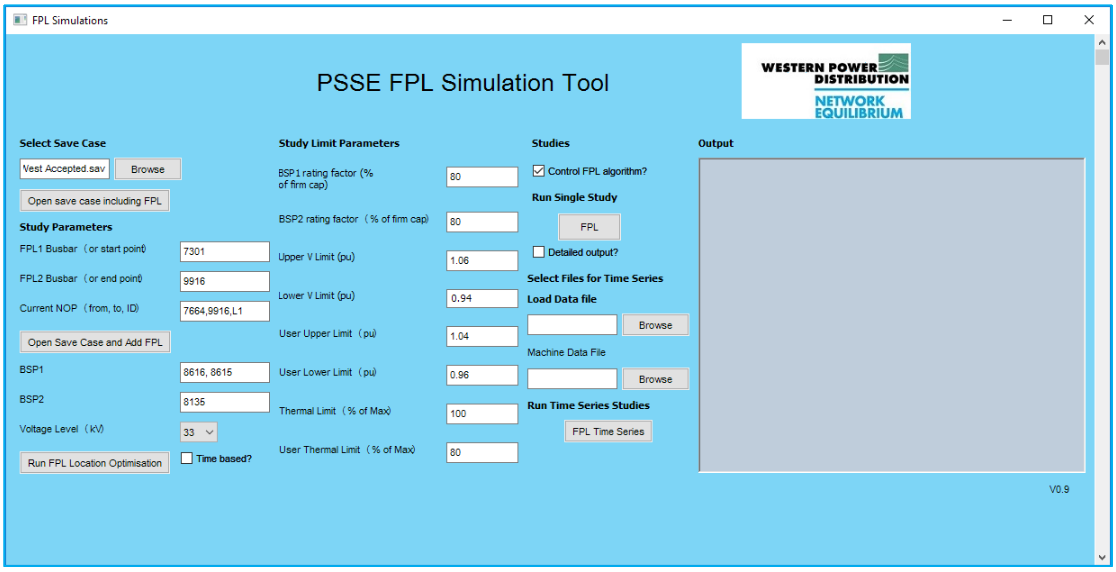
Max Voltage on Network (pu) 7007: 1.0408

Min voltage on Network (pu) 7847: 0.9539

Output

```
Initial Parameters:
Voltage limit: 0.94
Tap Limit: 3
Min voltage at Busbar: 7847:    0.991
Max voltage at Busbar: 7453:    1.039
Voltage at controlled bus: 8625: 1.0227
-----------------------------
Iteration 1
8621 8625 G1
Tap Ratio = 0.9666
Vmax:  1.04242
Vmin: 1.01515
Target voltage: 1.029
NEW Vmax: 1.02878
NEW Vmin: 1.00151
NEW Target voltage: 1.015
8622 8625 G2
Tap Ratio = 0.9666
Vmax:  1.04242
Vmin: 1.01515
Target voltage: 1.029
NEW Vmax: 1.02878
```

Figure 17-1 – SVO plug-in for PSS/E



Select Save Case

Vest Accepted.sav

Study Parameters

FPL1 Busbar（or start point) 7301

FPL2 Busbar（or end point) 9916

Current NOP（from, to, ID) 7664,9916,L1

BSP1 8616, 8615

BSP2 8135

Voltage Level（kV) 33

☐ Time based?

Study Limit Parameters

BSP1 rating factor (% of firm cap) 80

BSP2 rating factor（% of firm cap) 80

Upper V Limit (pu) 1.06

Lower V Limit (pu) 0.94

User Upper Limit（pu) 1.04

User Lower Limit（pu) 0.96

Thermal Limit（% of Max) 100

User Thermal Limit（% of Max) 80

Studies

☑ Control FPL algorithm?

Run Single Study

☐ Detailed output?

Select Files for Time Series

Load Data file

Machine Data File

Run Time Series Studies

Output

Figure 17-2 – FPL plug-in for PSS/E

Appendix 4 – Peer review letter

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Bringing energy to your door

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Jonathan Berry
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3 June 2019

Dear Jonathan

Network Equilibrium Closedown Report

Thank you for the opportunity to review your closedown report for the Network Equilibrium project which I read with great interest.

The closedown report clearly demonstrates the benefits of optimising the voltage settings, within wider statutory limits, in real time to create capacity for generation on the 33kV and 11kV networks. These findings are complementary to our findings in the Smart Street project which applied similar optimisation to the low voltage network.

We can see the benefits of using an advanced planning tool to better inform decisions regarding the investment required to connect generators. We intend to review this tool in more detail to assess its applicability to our design processes.

The use of a flexible power link to provide active power balancing is interesting but we do not believe that this solution suits our network currently. I do understand that the levels of generation applications received in the South West were unprecedented and warranted this type of solution but to date we have not seen the same scale of applications. We will, however, store this learning as a solution if the situation arises.

The report is clear and understandable and now holds the relevant information to allow us to assess the methods applicability to our network, particularly now that the section on “Facilitating Replication” has been modified following our previous comments.

We believe that real time co-ordinated management of voltages across the entire distribution network is vital to allow GB to meet the demanding targets for decarbonisation and the learning from this project can help to facilitate this.

Yours sincerely

Geraldine Paterson

Digitally signed by Geraldine Paterson
DN: c=GB - UNITED KINGDOM,
email=geraldine.paterson@enwl.co.uk
, o=Electricity North West,
ou=Innovation, cn=Geraldine
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Date: 2019.06.12 12:34:43 +01'00'

Geraldine Paterson
Innovation Strategy & Transition Engineer

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Appendix 5 – List of physical components for replication

EVA Method

There are no physical components required to replicate the EVA Method. However, software tools, have been developed to calculate the benefits of adopting VLA, SVO Method and FPL Method.

SVO Method

Table 17-1 describes the physical components required to replicate SVO. Further details of the components can be found in SDRC-5.

Table 17-1 - SVO replication equipment

Item	Description of item used for Network Equilibrium
SVO Control System	The SVO control system comprises of both software and hardware elements. Spectrum Power 5 (Siemens) is the software system which runs the various modules for calculating and managing the voltage set points for SVO. The software is hosted on two main servers: the Power System Observer Server (PSOS) and the Real-Time Server (RTS). There is also a back-up RTS which runs in hot-standby mode.
AVC Relays	SuperTAPP SG relays were used for installations where a new relay was required. If the substation has MicroTAPP relays installed already it is possible to use these for SVO purposes. The number of relays required corresponds directly to the number of transformers at the particular substation where SVO is applied.
Auxiliary Equipment	Integration of SVO into an existing substation also requires new auxiliary wiring and relays to be installed. In particular, sites with MicroTAPP installations require auxiliary relays to be installed as part of the logic scheme which interfaces with SCADA.

FPL Method

Table 17-2 describes the physical components required to replicate the FPL. Further details of the components can be found in SDRC-6.

Table 17-2 - FPL replication equipment

Item	Description of item used for Network Equilibrium
FPL Control System	Similar to SVO, the FPL control system comprises of both software and hardware elements. Nortech Management developed the software system to calculate the FPL set-point using violation based limits. This software system operates in the iHost environment – a central host platform also developed by Nortech. The software is hosted on two main servers: the primary operational server and a backup server that runs in hot-standby. The FPL CM also has two non-operational servers that act as a mirror of the operational system. These servers are used to test and debug modifications to the FPL CM in a safe offline environment.
FPL Converter	3.25kV back-to-back AC-DC converter. The converter is housed in a bespoke container manufactured by ABB incorporating the power electronic components, control infrastructure and HMI.
FPL Transformer	Two 33/3.25kV transformers housed in one tank to connect the high voltage network to the ABB converter. The transformer was designed and manufactured by Končar and installed within a noise enclosure.

FPL Filter	Two 33kV high pass filters are connected on either side of the converter to mitigate the higher order harmonics generated by the device. The filters comprise of resistors, capacitors and air-cored reactors mounted on steel supports.
FPL Cooling System	The power electronics are water cooled using a bespoke system designed and manufactured by VDL Delmas. The main pumps and control system are mounted in the FPL container connected to an external heat exchanger.
33kV Switchgear	The interface between the FPL and the network was provided by two 33kV circuit breakers. The circuit breakers were equipped with interlocking, VTs and CTs to interface directly with ABB equipment.
Protection	A dedicated 33kV protection panel was required to marshall the various protection alarm and trip signals from the FPL. In addition, an intertripping scheme was installed to prevent the FPL from inadvertently islanding in the event of a fault.