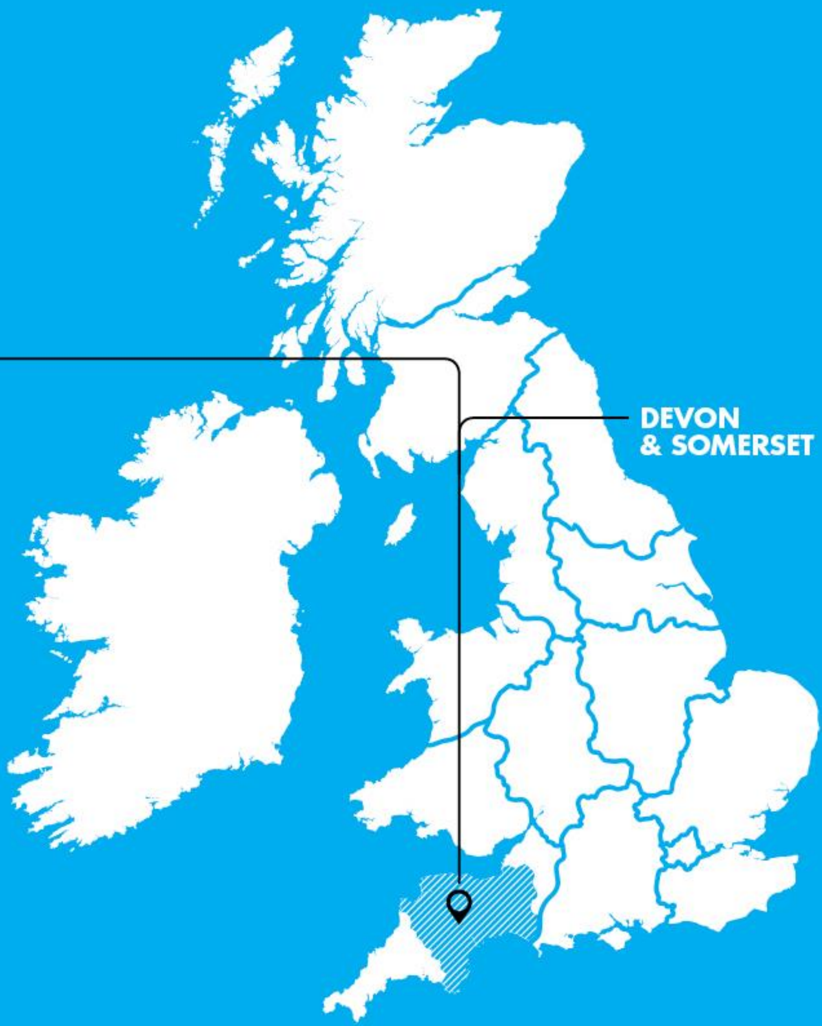
WESTERN POWER DISTRIBUTION

NETWORK EQUILIBRIUM

BALANCING GENERATION AND DEMAND



SDRC-4

Trialling and demonstrating the EVA method

LCN Fund
Low Carbon Networks

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Contents

Glossary

Term	Definition
ANM	Active Network Management
APT	Advanced Planning Tool
AVC	Automatic Voltage Control
BSP	Bulk Supply Point
CT	Current Transformer
DNO	Distribution Network Operator
EVA	Enhanced Voltage Assessment
FPL	Flexible Power Link
GIS	Geographical Information System
FTP	File Transfer Protocol
HV	High Voltage
kV	Kilo Volt
LCNF	Low Carbon Networks Fund
LCT	Low Carbon Technology
NMS	Network Management System
NOP	Normal Open Point
PSS/E	Power System Simulator for Engineering
SDRC	Successful Delivery Reward Criteria
SVO	System Voltage Optimisation
VLA	Voltage Limits Assessment
WPD	Western Power Distribution

1 Introduction

1.1 Network Equilibrium

Network Equilibrium is a Tier 2 Low Carbon Networks Fund (LCNF) project which aims to demonstrate how novel voltage and power flow management can release network capacity. This release in capacity shall allow the connection of new customers including embedded generation and Low Carbon Technologies (LCTs), to the distribution network during both normal and abnormal conditions.

The trial location for Network Equilibrium encompasses the 33kV and 11kV distribution networks in Western Power Distribution's (WPD) South West area across the counties of Somerset and Devon.

1.2 Methods

Network Equilibrium uses the latest advances in power, communication and computing systems to release network capacity. The project has been split into three technical methods as follows:

- The Enhanced Voltage Assessment (EVA) Method;
- The System Voltage Optimisation (SVO) Method; and
- The Flexible Power Link (FPL) Method.

This report focuses on the EVA method and will form the Ofgem Deliverable for Successful Delivery Reward Criteria (SDRC) 4: "Trialling and demonstrating the EVA method".

1.3 EVA Method

Enhanced Voltage Assessment (EVA) consists of two parts. Part 1 is the Advanced Planning Tool (APT) and part 2 is the Voltage Limits Assessment (VLA) work package.

The APT involves the creation of a planning tool which aims to enable better network and outage planning of distribution networks with increasing penetration of variable generation and demands. This is achieved through the tool's advanced functionalities, which include the production of forecasted power flows using weather forecasts and the network analysis using typical demand and generation profiles.

The VLA design involved stakeholder engagement, equipment specification investigations, literature reviews and system studies. This part of EVA aimed to explore the rationale behind the UK statutory voltage limits and step change limits and the possibility of their amendment.

1.4 Summary

This report forms one of the eight deliverables as part of Network Equilibrium. SDRC-4 entitled, "Trialling and demonstrating the EVA Method", presents the benefits of a potential adjustment of statutory voltage limits, quantifies the expected capacity to be released from each of the Equilibrium methods and provides recommendations for the modelling of SVO and FPL in advanced planning tools.

The report starts with an overview of the main outputs from the VLA work package, explaining the potential capacity release benefits from the amendment of the voltage limits and proposing the ranges for revised statutory voltage limits at 11kV and 33kV. Using the outputs from the VLA work, the document continues to discuss the results from the power system studies that quantified the expected capacity release from the proposed voltage limit amendments. The functionalities of the APT are presented in Section 3, focusing on how the various users of the tool can take advantage of its unique capabilities. Section 4 demonstrates how the FPL and SVO technologies have been simulated in the tool and provides recommendations for their modelling, while Sections 5 and 6 analyse the outputs from the studies completed to estimate the capacity release using SVO and FPL in the Equilibrium trial area. In Section 7, the SDRC-4 quantified benefits in the capacity release using each of the EVA, SVO and FPL technologies individually and combined are compared to the estimates produced at the bid stage. Finally, Section 8 summarises the outputs and learning gained from SDRC-4 and explains the important role this knowledge will play in the following stages of the project.

2 Potential benefits of adjusting the statutory limits

2.1 Voltage Limits Assessment – Main outputs

The main motivation behind the VLA part of Network Equilibrium's EVA Work Package, is the fact that the statutory voltage limits constrain the amount of generation that can be connected to the network. Furthermore, the rationale behind the existing voltage and step change limits is unknown within the industry, creating the requirement to explore whether they could be amended to release unused network capacity.

To further explain how the statutory voltage limits can constrain the available network capacity, consider Figure 2-1, which shows the voltage rise caused by the connection of a new generator. If this voltage rise in any operational scenario exceeds the statutory voltage limit of 1.06 p.u in 11kV and 33kV networks, then the generator would not be able to connect.

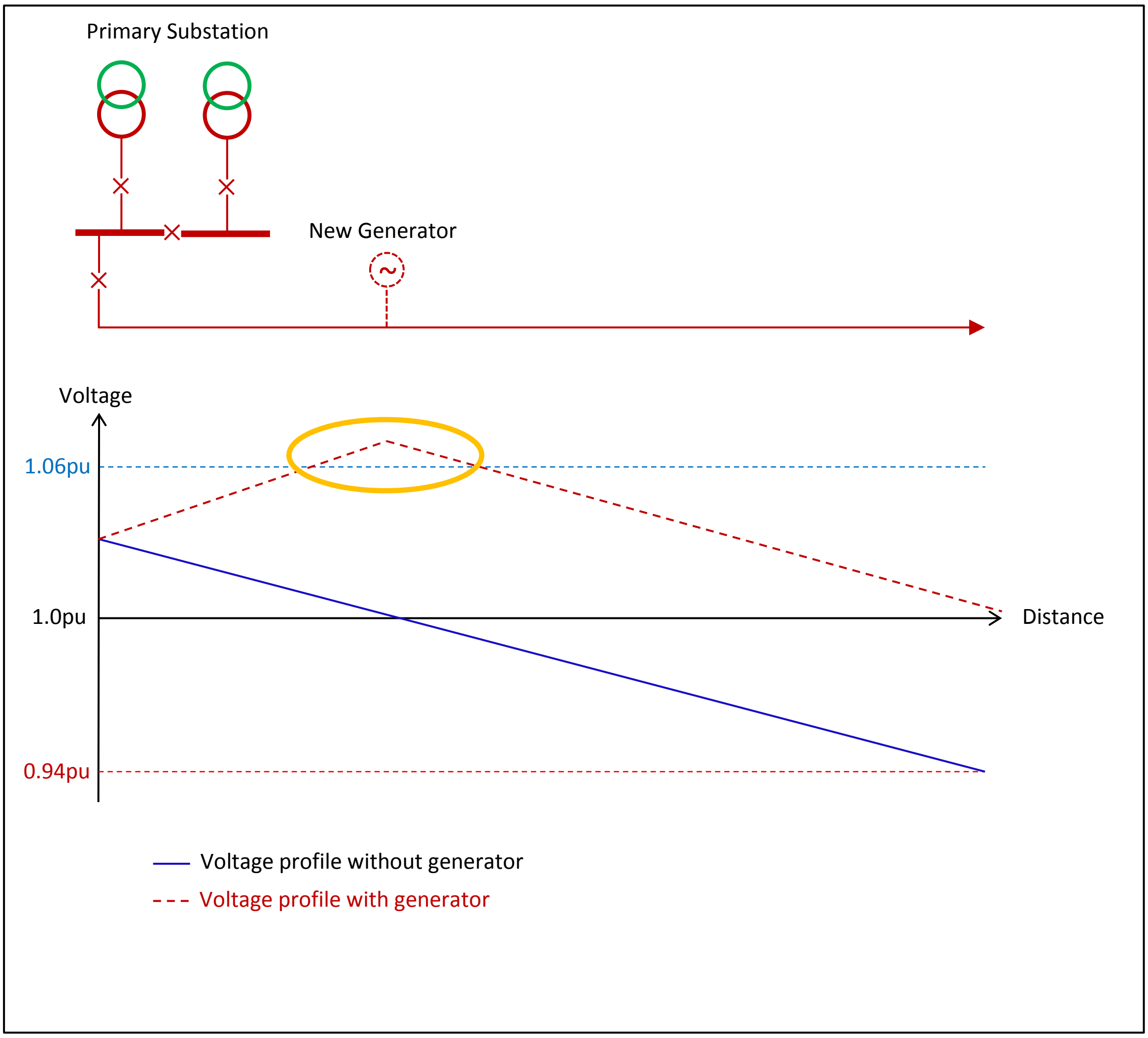

Figure 2-1 - Impact on voltage from new generation connection

If it was possible, however, to extend the high statutory voltage limit to 1.10 p.u, then the generation connection would be allowed without the need for network reinforcement.

Therefore, VLA explored the potential amendment of the statutory limits to release network capacity. This involved among others a number of power system studies, equipment investigations and consultation with the industry, with the full outputs of the study being presented in SDRC-1[1].

As part of the study, a questionnaire was sent out to industry stakeholders across the UK and Europe with the aim to collect information on how the voltage limits are currently implemented, identify the constraints they impose to network operators and understand what the industry thinks about their potential amendment. The responses have shown that the scope of the study was understood by the stakeholders and indicated a number of technical considerations to consider further.

The outputs of the VLA questionnaires were presented and discussed at the VLA Workshop which was held in Birmingham in October 2015. All DNO attendees generally recognised that the voltage limits impose constraints on the amount of new DG connections the network can support. It was also recognised that the relaxation of voltage limits could reduce the timescales and costs of new connections. A number of interesting technical considerations were also raised. The need for an active voltage control system was highlighted and the possibility of losing regulation at certain parts of the network and requiring transformer changes was discussed. It was also noted that a potential widening of statutory limits may need to be accompanied by a review of G59 protection settings[2]. Regarding step change limit amendments, these were associated with the operation of sensitive and protective equipment, resulting in commercial implications for DNOs. All of these aspects were further investigated in the following parts of the study.

From the equipment specification investigations it was concluded that even though existing 33kV and 11kV connected equipment would not need replacement, the new range of voltage variation should not be greater than ±10%. This should applied in a probabilistic manner so that operation in the extreme ends of that range would only be allowed for short periods of time.

The system studies showed that for the 33kV network a maximum limit of ±10% should be considered while for the 11kV a tighter range would be suitable due to voltage regulation and equipment sensitivity. Regarding the voltage step change limits, the 3% limit for infrequent planned events and the 10% limit for infrequent unplanned events are proposed to be maintained.

As the VLA work package has shown that the voltage limits should be amended to±10% at 33kV and a tighter range at 11kV should be investigated further, as part of SDRC-4 the

[1] Published 26/01/2016, https://www.westernpowerinnovation.co.uk/Document-library/2016/SDRC-1-Detailed-Design-of-the-enhanced-Voltage-Ass.aspx

[2] Recommended protection settings for generators connected to the Distribution network as stated in Energy Networks Association's (ENA) Engineering Recommendation G59: Recommendations for the Connection of Generating Plant to the Distribution Systems of Licensed Distribution Network Operators (Energy Network Association, Issue 3, Amendment 2, September 2015.

capacity release benefits of the amended voltage limits (±10% for 33kV, ±8% for 11kV) were quantified. Amending the statutory voltage limits to ±10% at 33kV, means that the lower voltage limit is 0.9 per unit (10% below unity, with unity defined as the 33kV nominal voltage) and the upper statutory limit is 1.1 per unit (10% above unity). Similarly, the ±8% voltage limits at 11kV mean that the lower voltage limit is 0.92 per unit (8% below unity, with unity defined as the 11kV nominal voltage), while the upper voltage limit is 1.08 (8% above unity) per unit.

2.2 Estimated capacity release – Amendment of statutory limits

The network capacity that could be released from the amendment of the statutory voltage limits was evaluated through a number of power system studies, utilising the APT.

As part of these studies, the generation and demand capacity of a number of 11kV and 33kV networks within the Equilibrium trial area was evaluated in different scenarios. Then, using the results of the studies, the total demand and generation capacity that could be released in the entire Equilibrium trial area was estimated.

2.2.1 Capacity released at 11kV

The demand and generation capacity at 11kV was evaluated by running two sets of power flow studies, each representing a different scenario:

1. Scenario i: Voltage limits set at 0.94 p.u. and 1.06 p.u.
2. Scenario ii: Voltage limits set at 0.92 p.u. and 1.08 p.u.

Scenario ii, considers the amendment of the statutory voltage limits to 0.92 p.u and 0.98 p.u as recommended by the VLA work package of Equilibrium. This amendment means that every point in the network is allowed to have a minimum voltage of 0.92 p.u. and a maximum voltage of 1.08 p.u. while in Scenario i the allowable voltages are between 0.94 p.u. and 1.06 p.u. If a generator for example, causes the network voltage at the point of connection to rise to 1.07 p.u., then in Scenario i the generator would not be allowed to connect as the voltage would go outside the allowable range. In Scenario ii, however, the voltage rise would be acceptable as the voltage is within the allowable voltage range, enabling the generator to connect.

The following substations within the Equilibrium trial area were analysed:

1. Staplegrove
2. Tiverton Moorhayes
3. Nether Stowey
4. Waterlake
5. Dunkeswell
6. Heddon Cross

The studies simulated the 12-month network operation, using the typical profiles of the Advanced Planning Tool developed as part of the project and quantified the range of demand and generation capacity in each network for each scenario. The range in the generation capacity is shown as an example in Figure 2-2.

Annual range of demand and generation capacity

The amount of demand and generation a network can support depends on the network operating conditions. As the operating conditions change with time, the amount of demand and generation that can be supported also changes with the varying network voltages and power flows. At periods of high demand as an example, the generation capacity of the network is higher than at times of low demands and vice versa. Therefore, within a year a network has a minimum and a maximum demand and generation capacity.

As shown in Figure 2-2, Staplegrove Primary substation for example, has a generation capacity which varies between 0 MW (periods of low demand) and 14 MW (periods of high demand) during a year in Scenario i. When assessing new generation connections for a standard connection, the worst case scenario of minimum demand and maximum generation is considered, to ensure that the new generator would be supported by the network at all times. This means, that Staplegrove Primary, with the existing statutory voltage limits cannot support any more generation connections since its minimum generation capacity is 0MW. This shows that the existing generation capacity of Staplegrove Primary is 0MW.

In Scenario ii, however, the range of generation capacity of Staplegrove Primary becomes 5MW-20MW, increasing the minimum capacity by 5MW and the maximum capacity by 6MW. This means that the network would be able to support 5MW more generation at all times within a year and up to 6MW more in certain periods through the adjustment of the statutory voltage limits. This increase in the range of generation capacity not only allows more generation to connect to the network (5MW) but also provides additional flexibility (6MW) in the usage of the available headroom for non-standard connections. WPD offers a number of non-standard connections which offer maximum utilisation of the network capacity by constraining the export of generators only when it is required in real-time. These include Active Network Management (ANM), timed and soft-intertrip connections. Therefore, the additional flexibility in the usage of the available headroom offered by the amendment of the voltage limits would be beneficial for non-standard connections.

From Figure 2-2, it can be seen that the annual range of generation capacity of all substations except Heddon Cross increases in Scenario ii, where the voltage limits are widened to 0.92 p.u. and 1.08 p.u. Heddon Cross Primary was the only substation that showed zero generation capacity indicating that it is constrained due to thermal issues and demonstrating how different substations can have different limitations in their available capacity.

Since the majority of Primaries had an increase in their minimum capacity, the analysis also shows that the generation capacity of 11kV networks is mostly limited by voltage constraints and not thermal.

Similar results were produced for the range in demand capacity, with all Primary substations showing an increase in the minimum and maximum annual demand capacities. These are shown in Figure 2-3.

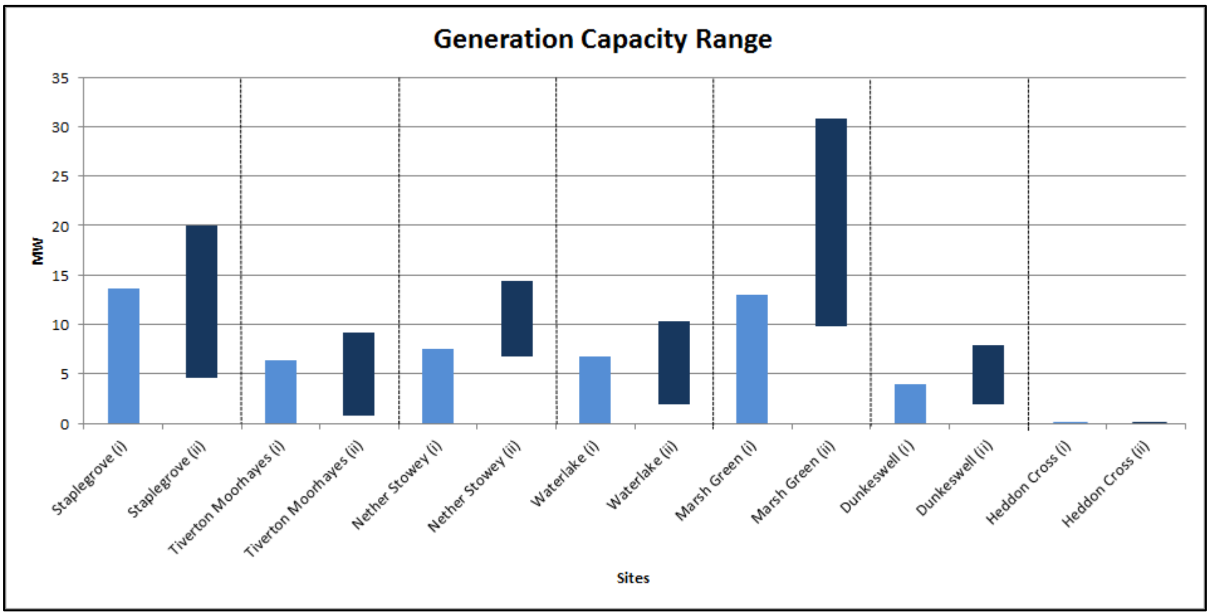

Figure 2-2 Generation Capacity Range in 11kV networks

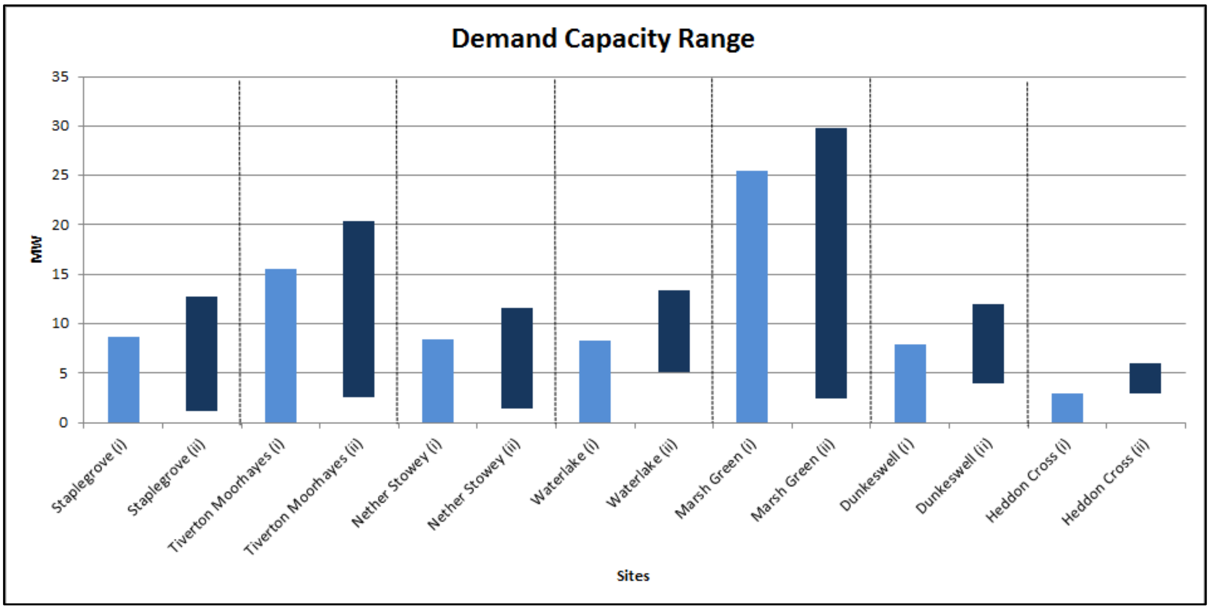

Figure 2-3 Demand Capacity Range in 11kV networks

Using the results from the studies, the increase in the minimum capacity due to the amendment of the voltage limits was calculated and is shown in Figure 2-4.

It was observed that only Heddon Cross substation didn't show an increase in both the demand and generation capacities, while the majority of substations had an increase larger than 24% in demand capacity and 12% in generation capacity.

As the increase in the minimum capacities available during the period analysed indicates the additional demand and generation that could be connected to the network following conventional planning practices, the above results show that across the 11kV networks analysed, 19MW of demand capacity and 25MW of generation capacity could be released.

The results have also shown that the maximum demand and generation capacities during the period analysed have also increased by 9MW and 15MW respectively due to the adjustment of the statutory voltage limits. This increase in the maximum demand and generation capacities indicates the amount of flexibility introduced by the amendment of the limits.

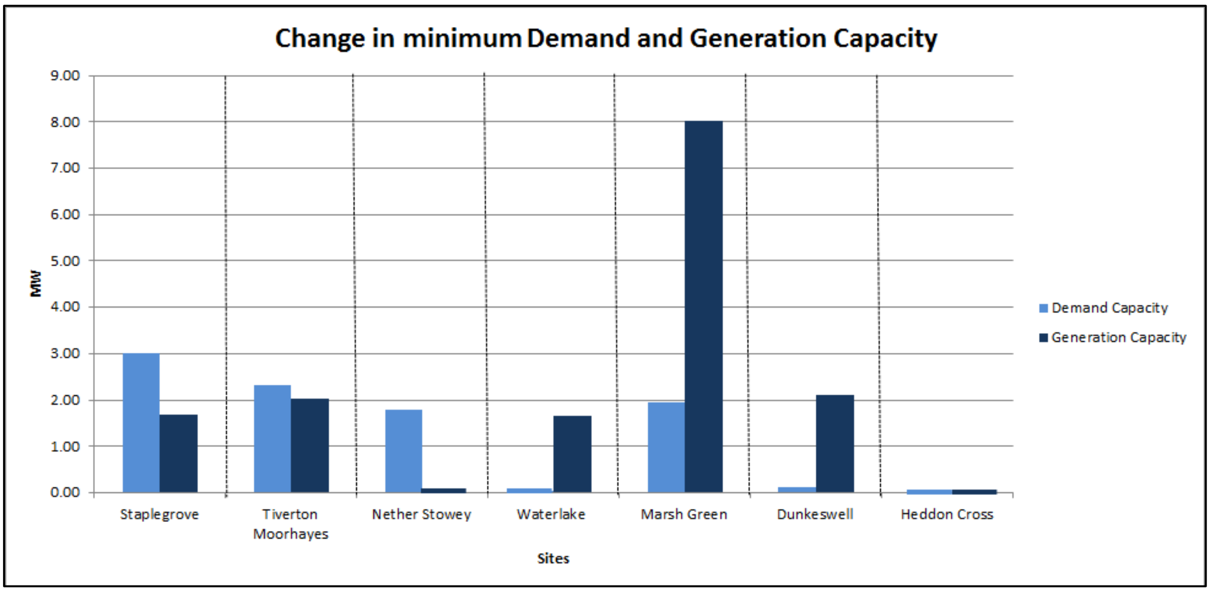

Figure 2-4 Change in minimum Demand and Generation Capacity

Estimated Total Capacity Released in Entire Trial Area

The results have been analysed to estimate the total capacity that could be released in the entire Equilibrium area from the amendment of the 11kV statutory voltage limits to 0.92 and 1.08 per unit. This was performed by finding the average increase per substation, which was 3.57 MW of generation capacity and 2.71 MW of demand per Primary. The results were then extrapolated to obtain the total capacity release for the 93 Primaries in the trial area, indicating that 259MW of demand and 341MW of generation could be released in total.

2.2.2 Capacity released at 33kV

The demand and generation capacity at 33kV was evaluated by running two sets of power flow studies, each representing a different scenario:

1. Scenario i: Voltage limits set at 0.94 p.u. and 1.06 p.u.
2. Scenario ii: Voltage limits set at 0.9 p.u. and 1.1 p.u.

Scenario ii, represents the ±10% amendment of the statutory voltage limits as recommended from the VLA work package.

The following BSP substations were analysed:

1. Bowhays Cross
2. Taunton Main
3. Bridgwater
4. Street

5. Exeter Main
6. Sowton
7. Tiverton
8. Barnstaple
9. Paignton
10. Totnes

Similarly to the 11kV analysis, the studies were run for a 12-month period and quantified the range of demand and generation capacity in each network for each scenario.

Using the results from the studies, the increase in capacity from the amendment of the voltage limits was calculated and is shown in Figure 2-5.

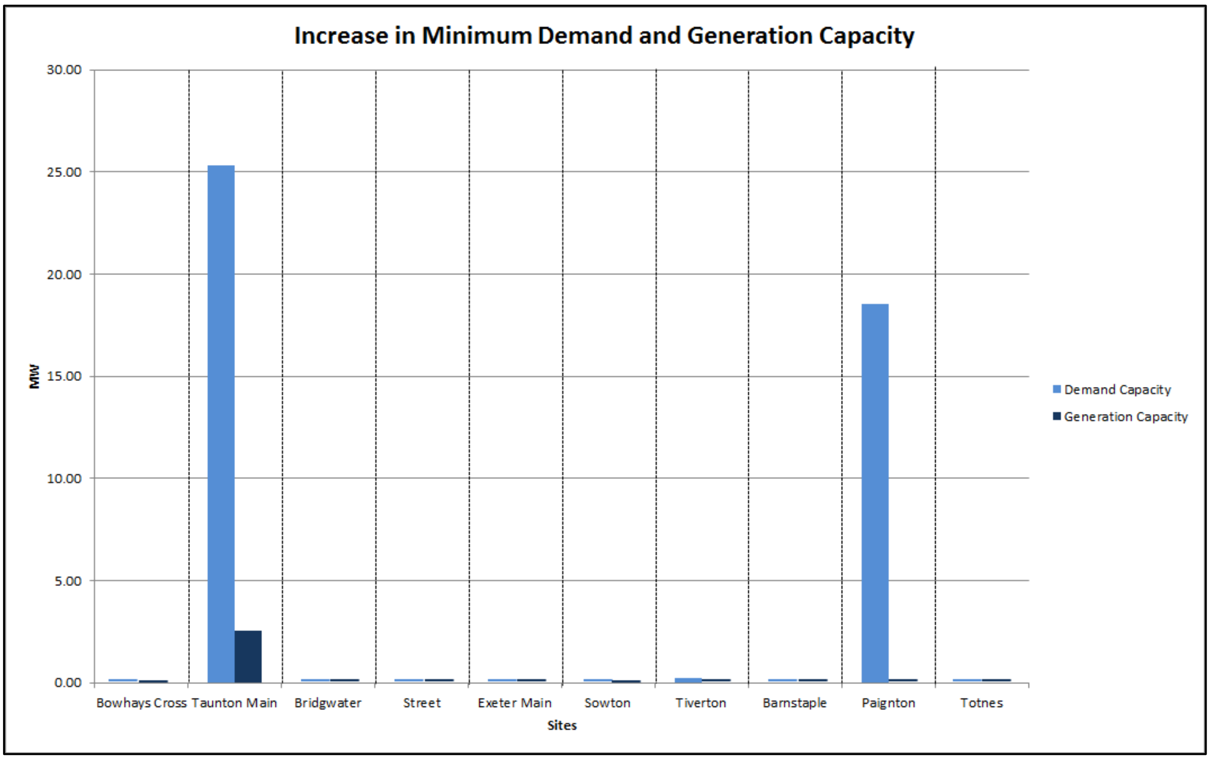

Figure 2-5 Increase in capacity with amendment of voltage limits (BSPs)

The results produced for the 33kV networks have shown differences with the behaviour observed in the 11kV networks. As can be seen from Figure 2-5, only one substation out of this sample showed an increase in its generation capacity with the amendment of the statutory voltage limits and three substations showed an increase in their demand capacity. The detailed investigation of the results has shown that the main reason only a limited number of substations have shown a change in their capacity is due to the way the APT calculates the network capacity. The learning gained from this investigation was used to revise the network evaluation methodology which is demonstrated in 2.2.3.

2.2.3 Calculation of the network capacity

To demonstrate the limitations in the capacity evaluation methodology followed by the tool that prevents it from producing representative results on certain substations, consider

Figure 2-6 where the logic of the methodology is shown. It starts by scaling all existing generation until it finds a voltage or a thermal constraint. Once it finds a constraint it stops and captures the generation added up until the previous round, which represents the network capacity estimate. However, if a thermal constraint is found on at least one of the substation's feeders for example as shown in Figure 2-6, then the scaling will stop and the evaluated capacity will still be limited to the value captured in the previous round, even if other feeders have only voltage constraints. This means that the benefits the VLA can have on the capacity of the feeders that are constrained by voltage cannot be visualised within this analysis and the estimates produced for the release of capacity are very conservative.

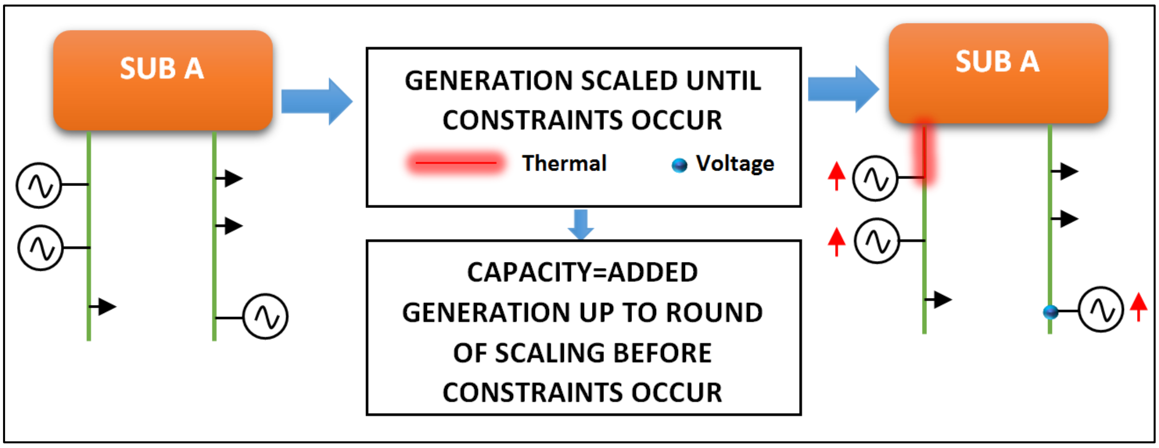

Figure 2-6 Capacity Evaluation Methodology Operation

The learning from the results, however, has been used to revise the logic that evaluates the network capacity which will then be used in the assessment of the benefits from the trials. The revised network capacity evaluation methodology has been simulated in the Power System Simulator for Engineering (PSS/E) power system analysis software and consists of the following steps:

1. Scale all existing generation until a voltage constraint or thermal constraint is found in the network analysed.
2. Check if there are any feeders with no constraints.
3. Continue scaling the feeders with no constraints.
4. Stop scaling once all feeders have constraints.

As the development of the tool is a continuous process, this methodology will replace the existing capacity evaluation methodology within the tool by the end of April 2017 and will provide a better understanding of the constraints in 33kV networks and the available capacity. The findings from the simulation of the revised methodology will be published by the end of April 2017.

At this stage, the conservative estimates will be used for the purposes of this document as they will provide a fair comparison with the conservative estimates produced at the bid stage. As the increase in the minimum capacities in the period analysed indicates the additional demand and generation that could be connected to the network following existing planning practices, the above results show that across the 33kV networks studied, 44MW of demand capacity and 2.76MW additional generation capacity could be released.

Estimated Total Capacity Released in Entire Trial Area

The results have been analysed to estimate the total capacity that could be released in the entire Equilibrium area from the amendment of the 33kV statutory voltage limits to 0.9 and 1.1 per unit.

This was performed by extrapolating the results to obtain the analogous figures for the 14 BSPs in the trial area. This has shown that 61MW of demand could be released in total and 4MW of generation.

2.2.4 Total Capacity Released from EVA Method

Combining all the above results, the studies have shown that in the Equilibrium area a total of 320MW of demand capacity and 341MW of generation capacity could be released from the EVA method. This is summarised in Table 2-1.

At the bid stage, it was estimated that 81MW of generation capacity would be released which is significantly lower than the 341MW estimated as part of the SDRC-4 analysis. This is because in the bid stage analysis, the voltage limits were amended to ±7% while the SDRC-4 analysis considered wider amendments to the voltage limits, as suggested from the work completed in SDRC-1, of ±10% for the 33kV network and the tighter range of ±8% for the 11kV network. As wider voltage limits were considered in this analysis, it was expected that the evaluated capacity benefits would be larger than the bid estimates. Additionally, the bid estimate was produced considering the capacity released at only 10 substations within the trial area. Since the amendment of the voltage limits would affect all of the 14 BSPs and 93 Primaries within the trial area, the SDRC-4 study results provide a more representative estimate.

Table 2-1 Total capacity release from EVA method

Demand Capacity Increase	Generation Capacity Increase
Minimum: 320MW	Minimum: 341MW

3 Demonstration of the Advanced Planning Tool

3.1 Overview of functionalities

The APT is the first part of EVA and involves the creation of a planning tool which aims to enable better network and outage planning of distribution networks with an increasing penetration of variable generation and demand. This will be achieved through the tool's advanced functionalities, which include the production of estimated power flows using weather forecasts and the network analysis using typical demand and generation profiles. The APT is built in the IPSA [3] power system analysis software.

3.2 The User Interface

All the studies (jobs) are created, run and the results stored on the tool specific server. Therefore, to use the APT, the user needs to firstly log onto the server using the APT client. Each user has a username and password which provide access to the tool.

The window for the creation of a new job is shown in Figure 3-1. When creating a study, the user needs to select the area they wish to analyse, with each area being defined as the network fed by the BSP or the Primary selected. The split of the network model into areas ensures that the speed of the tool is not compromised by the large size of the model. Furthermore, the user can choose the period they want to analyse using the typical or forecast profiles and specify whether they want to evaluate the network capacity by selecting the constraint analysis option.

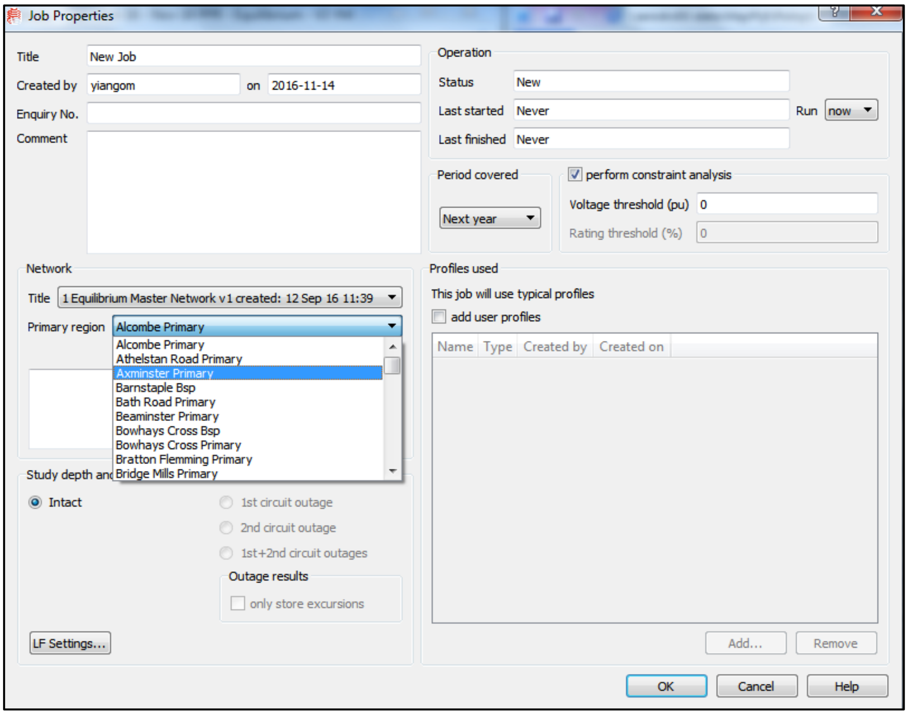

Figure 3-1 APT New Job User Interface

[3] http://www.ipsa-power.com/

Once a job is created, it is then left to run on the server until it is completed.

3.3 Network Model

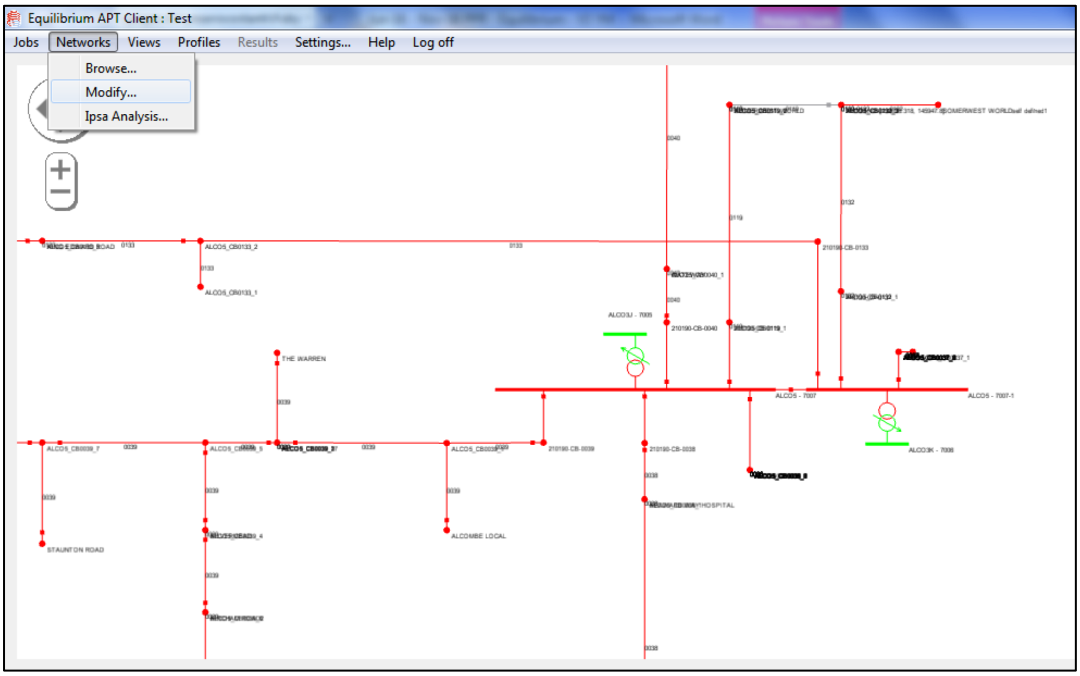

Figure 3-2 - Network Model View

The APT includes the network model of the 11kV and 33kV networks within the Equilibrium Trial area which consists of 14 BSPs and 93 Primaries. The network model has been created using information from WPD's Geographical Information System (GIS).

The user can explore the network model through the APT interface or in IPSA. When pressing the "Modify" button within the APT as shown in Figure 3-2, IPSA gets initiated and the user can modify the network model by adding or removing components (when planners need to model new generators for example). Then, the user can return to the APT to perform typical profile or capacity evaluation analysis on the modified network.

3.4 Results Display

The display of the results was designed in such a way to enable the planner to easily identify constrained parts of the network. For example, as shown in Figure 3-3, the results of the typical profile studies indicate the network locations that are constrained either due to thermal or voltage issues, with a red square, making it easier to visually detect any issues. These constrained locations, have been called "exceptions". Figure 3-3 also shows that all network issues are summarised in the exceptions window. The user can click on any of the exceptions, to be transferred to its location on the diagram.

Understanding the operation of the network during the analysis period without the need to manually process the results was another of the considerations taken. To fulfil this requirement, the range of the power flow of each branch within the period analysed is shown on the diagram, while for the busbars the voltage range is displayed. This is demonstrated in Figure 3-4. It is also possible to obtain graphs showing the power flow through a specific branch and the voltage variation at a busbar during the period analysed.

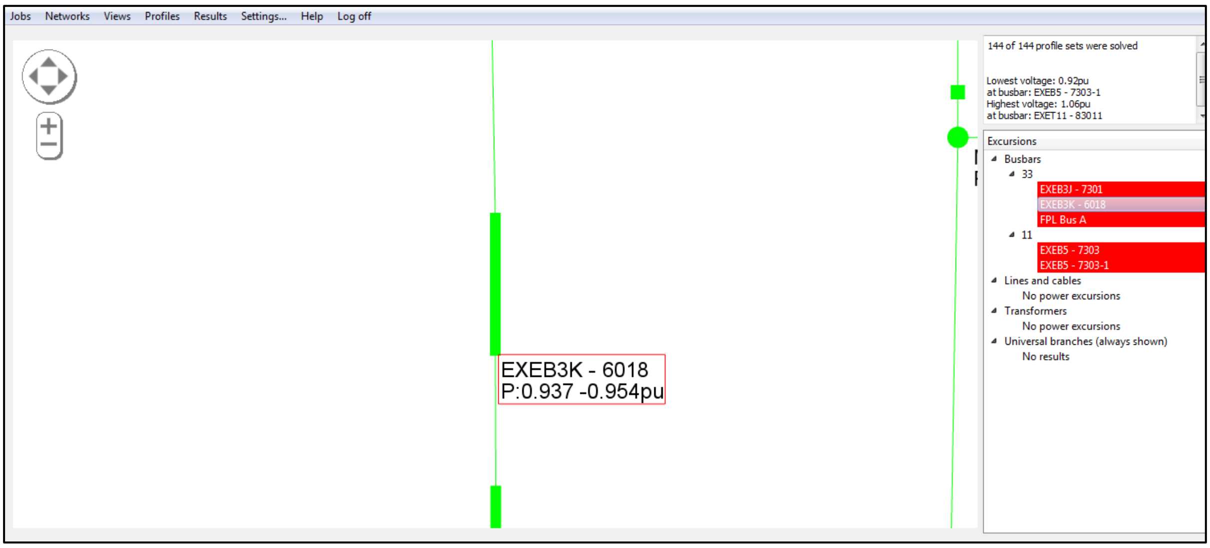

Figure 3-3 Results display - typical profile studies

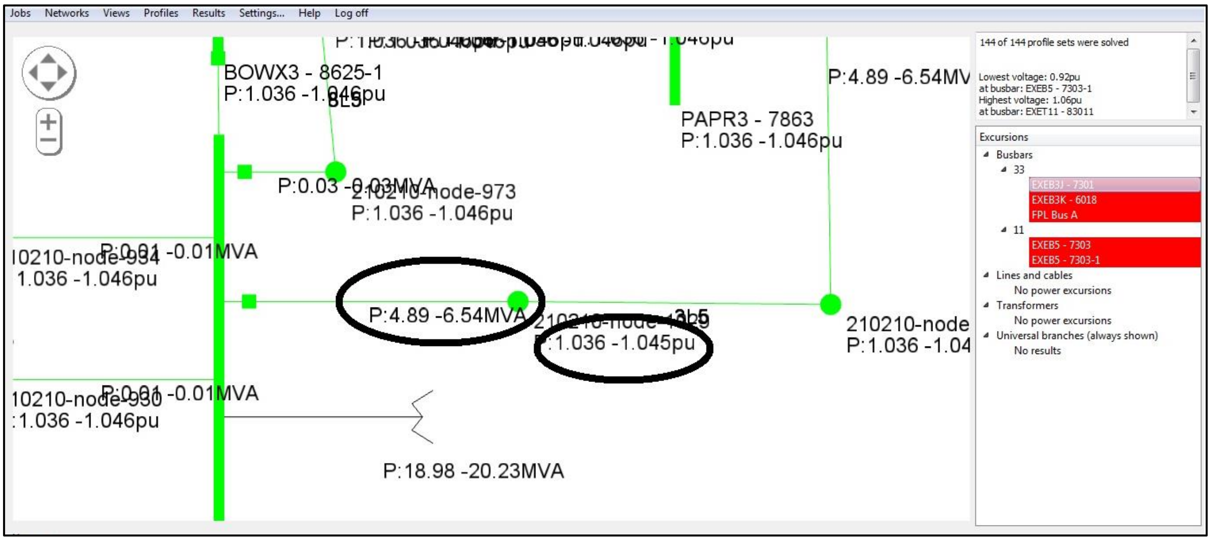

Figure 3-4 Results Range - typical profile studies

The display of the results for the capacity evaluation studies aimed to enable the user to easily see the demand and generation headroom in the network. A summary of the minimum and maximum headroom during the period analysed is provided at the results window, as shown in Figure 3-5.

48 of 48 profile sets were solved

Across the target region:
Added demand from 1.3263 MW to 8.0070 MW
Added generation from 1.2988 MW to 6.3376 MW

Figure 3-5 Summary of capacity headroom during period analysed

Additionally, the demand or generation headroom at a busbar can be plotted against time to see how the headroom varied during the analysis period. Figure 3-6 shows the demand capacity at the Blackmoor Vodaphone 11kV busbar as a function of time for the typical weekday during the two week period analysed.

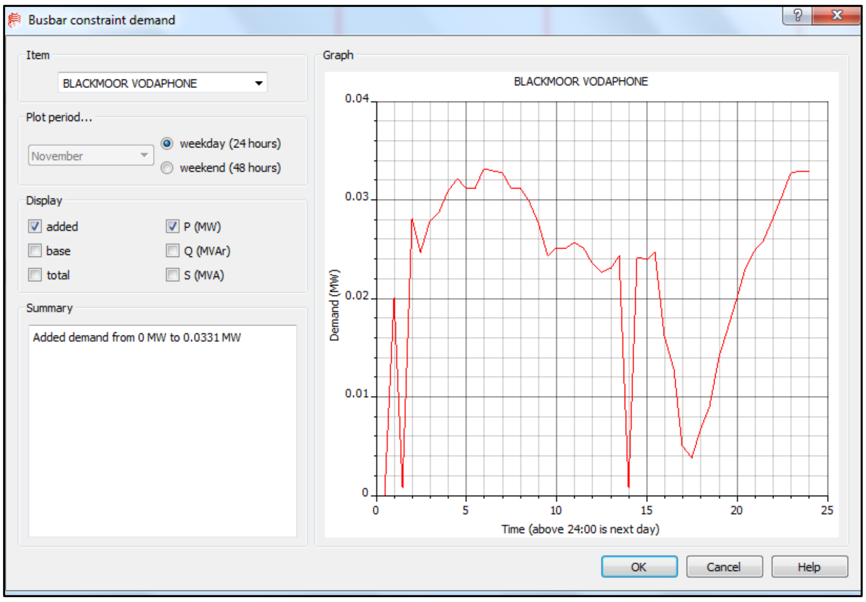

Figure 3-6 - Demand capacity evaluation results example

3.5 48-hour ahead forecasting

The APT receives 48-hour weather forecasts from the Met Office on a daily basis using the established File Transfer Protocol (FTP) link between our organisations. These weather forecasts are automatically used to forecast the demand and generation profiles for the following two days, which are then used in the forecast studies that produce the estimated power flows and voltages in the network.

Automatically producing the forecasted network operation results on a daily basis means that the outage planners can instantaneously see the expected network operation for the following two days, without the need to create, run studies and wait for their completion.

3.6 Using the SVO and FPL plugins

3.6.1 SVO

System Voltage Optimisation (SVO) is the Equilibrium technology that aims to release network capacity by optimising the network voltages in real time. The SVO implementation consists of a centralised system that will be assessing the state of the network in real-time to calculate and send optimised voltage control settings to Bulk Supply Points and Primary substations. Siemens' Spectrum Power 5 is SVO's centralised system and will be communicating with WPD's Network Management System (NMS) to receive information about the real-time operation of the network in order to assess its state. The algorithms within Spectrum Power 5 will perform the required relevant calculations to determine the optimised voltage control settings, which will then be sent to the AVC relays at the selected BSPs and Primary substations through the existing communications infrastructure. Its architecture is shown in Figure 3-7.

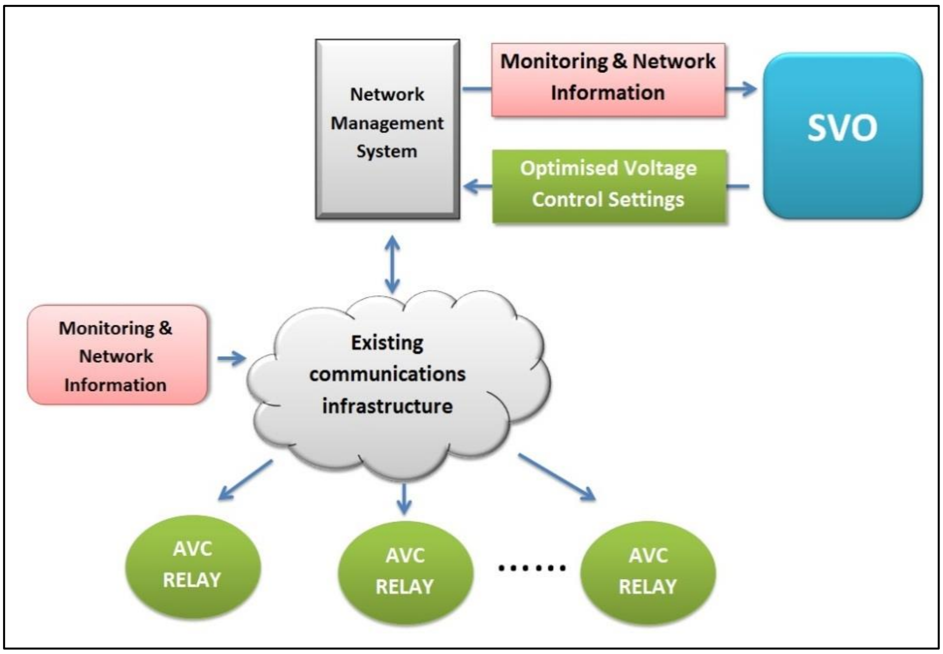

Figure 3-7 - SVO Architecture

The APT provides the capability of simulating SVO at any substation in the Equilibrium Trial area, showing the expected operation of the technology, evaluating its capacity release benefits and enabling its future planning.

To simulate SVO at a specific substation, the user needs to select and configure the SVO controller within IPSA as shown in Figure 3-8.

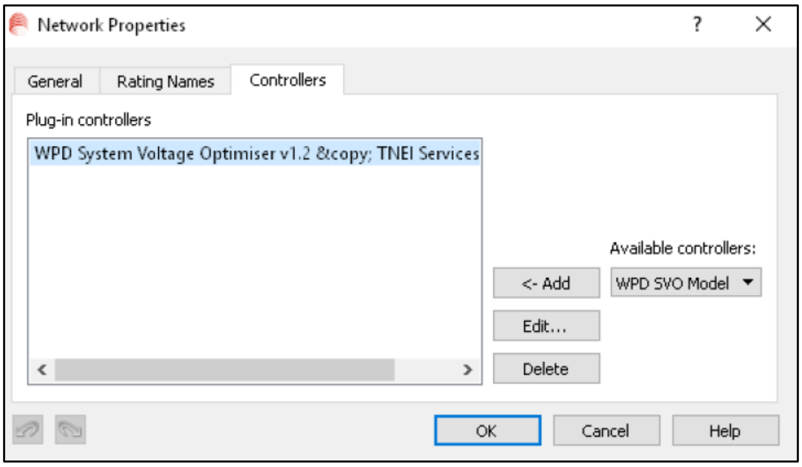

Figure 3-8 SVO configuration

Among other parameters, the voltage limits SVO is regulating to and its operational mode needs to be set from the following:

- Mode 1 – SVO makes the minimum target voltage adjustment required to ensure that the network voltages are within limits.
- Mode 2 - SVO tries to keep the network voltages as low as possible.
- Mode 3 – SVO tries to keep the network voltages as high as possible.

- Mode 4 – SVO tries to keep the network voltages close to the average of the upper and lower network limits.

3.6.2 FPL

The Flexible Power Link (FPL) Method aims to overcome voltage and thermal issues associated with paralleling different network groups by coupling them together using back-to-back AC-DC converters. Implementation of the FPL Method will increase the level of flexibility in the network by transferring excess power from one network group to another, as shown in Figure 3-9.

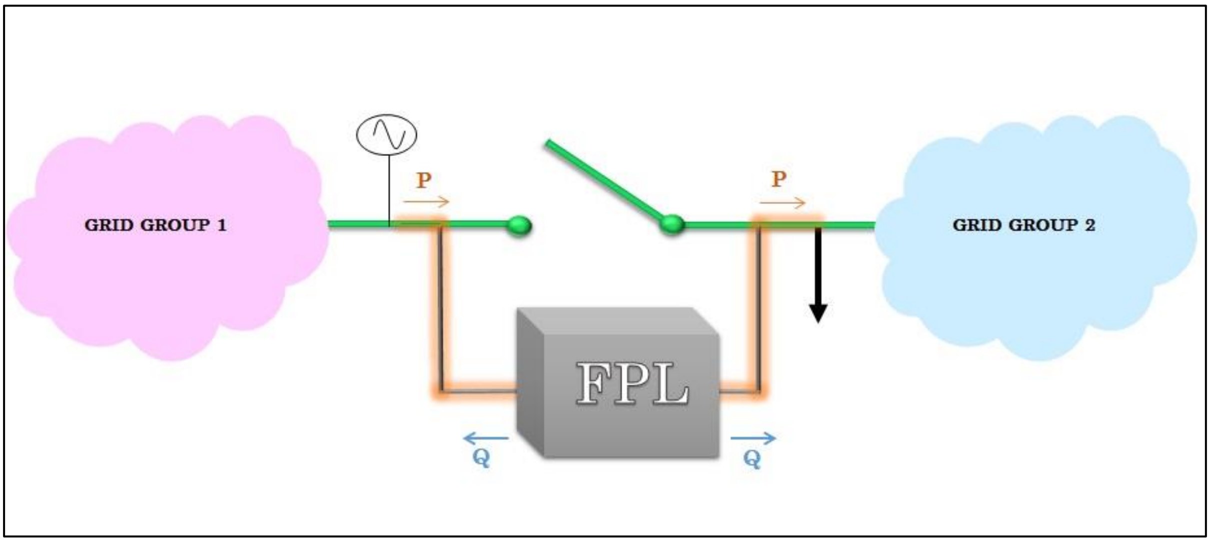

Figure 3-9 FPL Basic Operation

To simulate the FPL at a network location, the FPL needs to be configured within IPSA. The FPL is represented as a universal branch, therefore, it needs to be connected to the required location. This is demonstrated in Figure 3-10.

The APT provides the capability of simulating SVO at any substation in the Equilibrium Trial area, showing the expected operation of the technology, evaluating its capacity release benefits and enabling its future planning.

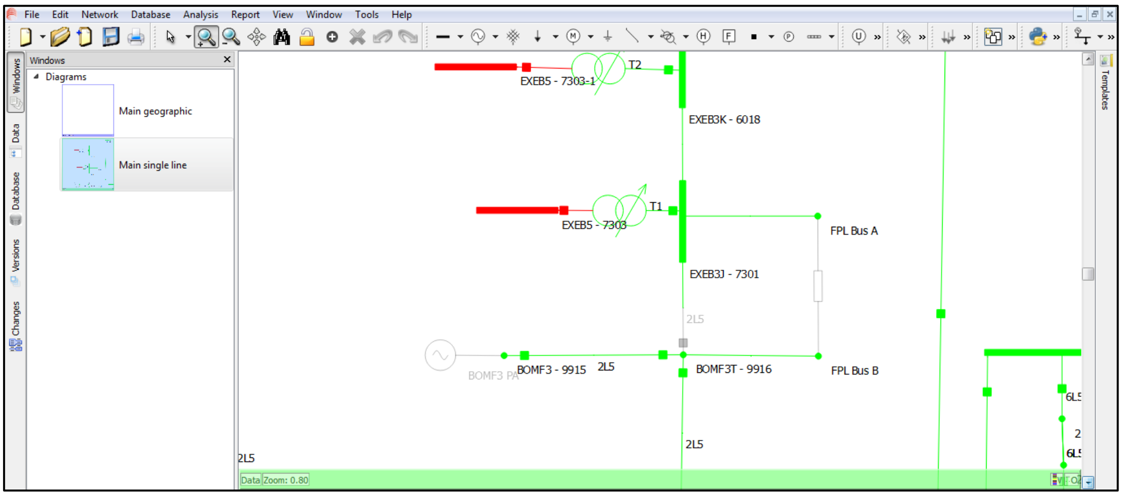

Figure 3-10 FPL Plugin connected across Normal Open Point

The available operational modes of the FPL are:

- Mode 1 – MW control only
- Mode 2 – Voltage/MVAr control only
- Mode 3 – MW then voltage control
- Mode 4 – Voltage then MW control

3.7 Evidence of EVA Demonstration at Equilibrium Workshop 3

The tool was demonstrated to other Distribution Network Operators (DNOs) at Workshop 3 on the 23rd of November. The attendees, representing their network planning and innovation teams, provided valuable feedback on the design and functionalities of the tool.

From the discussions, it was clear that the majority of DNOs face the same challenges with their existing planning tools. The fact that the 11kV networks are modelled separately than the 33kV and 132kV networks, limits the planner's ability to understand the interaction between the various network areas, therefore the fact that the APT provides a complete network view was appreciated. Interest was also shown in the functionality that evaluates the available capacity headroom as it could indicate areas of the network that require reinforcement and could be used for longer term planning than just to assess new connections. Some very good points were raised on the forecasting, recommending that longer term forecasting could be used in such a tool to see how the network will change in the future and represent scenarios. Furthermore, it was generally recognised that the 48-hour ahead forecast studies specifically could play an important role in the changing way that electricity distribution networks are operated. Being able to predict the network operation in the short-term is necessary for DNOs to act as Distribution System Operators as it will inform our requirements for non-network flexibility services like Demand Side Response.

Figure 3-11 APT Workshop Attendees

4 Recommendations for modelling SVO control components

From the design, development and testing of SVO within the APT, valuable knowledge has been gained on the functionalities the plugin should support and the way the user should interact with it for configuration purposes. To model SVO, it is recommended to incorporate the following characteristics to its functionalities:

1. Simulating at any BSP and Primary substation.
2. Calculating the maximum and minimum target voltage that can be applied to the substation without:
    a. Causing any voltage limit violations on any part of the network fed by the substation.
    b. Causing any substations fed by the SVO substation to either run out of taps or approach their maximum/minimum taps within a specified number of tap positions.

The steps followed by the SVO model to find the new target voltage settings are presented in Table 4-1.

Table 4-1 SVO Logic Sequence

SVO LOGIC STEPS
1. Create lookup table to link each SVO controlled transformer with all controlled or downstream busbars. Each busbar may be controlled by more than one transformer
2.For each SVO model, identify any busbar voltages (V_{ERR}) which are outside limits. For each SVO model identify busbars with the highest and lowest voltages (V_{MAX}, V_{MIN}).
3.If any busbar is outside the user defined limits ($V_{USERMAX}$, $V_{USERMIN}$) calculate the minimum changes in transformer target voltage ($\Delta V_{TARGET1}$, $\Delta V_{TARGET21}$) from: $\Delta V_{TARGET1} = V_{USERMAX} - V_{ERR}$ $\Delta V_{TARGET2} = V_{USERMIN} - V_{ERR}$
4.The new transformer target voltage is then given by: $If\ \Delta V_{TARGET1} > 0\ and\ \Delta V_{TARGET2} < 0$: All voltages OK, do not change target voltage $Else\ If\ \Delta V_{TARGET1} < 0\ amd\ \Delta V_{TARGET2} < 0$: Voltages high, reduce target voltage $V_{NEWTARGET} = \Delta V_{TARGET1} + V_{OLDTARGET}$ $Else\ If\ \Delta V_{TARGET1} > 0\ amd\ \Delta V_{TARGET2} > 0$:

Voltages low, increase target voltage $V_{NEWTARGET} = \Delta V_{TARGET2} + V_{OLDTARGET}$ $Else\ If\ \Delta V_{TARGET1} > 0\ amd\ \Delta V_{TARGET2} > 0$: Voltages both high and low, reduce target voltage $V_{NEWTARGET} = \Delta V_{TARGET1} + V_{OLDTARGET}$ *The change in target voltage will also be affected by the operating mode.*
Check that the change in target voltage is compatible with the transformer tap changers.
Check the transformers fed by the SVO controlled substations to ensure that they are not approaching their tap limits.

5 Recommendations for modelling FPLs

From the design, development and testing of the FPL plugin within the APT, valuable knowledge has been gained on the functionalities it should support and the way the user should interact with it for configuration purposes. To model FPL, it is recommended to incorporate the following characteristics to the plugin:

1. It can be connected to any 33kV or 11kV network.
2. It can make the P/Q set point decisions completely autonomous without any user intervention.
3. It must be able to perform thermal loading and voltage checks at every point on the two feeders and two substations the FPL interconnects.
4. It must be able to detect thermal and voltage threshold violations by monitoring the required points. The minimum points to be monitored as per the example of Figure 5-1 are:
    a. BSP1 thermal loading.
    b. BSP2 thermal loading.
    c. Thermal loading at all points between A and B on the interconnection line.
    d. Voltage at all points between A and B on the interconnection line.
5. The threshold limits should be configurable by the user for the detection of thermal and voltage violations.
6. It initiates the P/Q set point calculation once one or more thermal/voltage violations are detected.
7. The calculated P/Q set points successfully remove the identified threshold violations and do not cause any thermal or voltage constraints at the two BSPs and two feeders the FPL interconnects.
8. The calculated P/Q set points satisfy the restrictions imposed by the FPL operating window.
9. The operation of the FPL results in increase of network capacity.

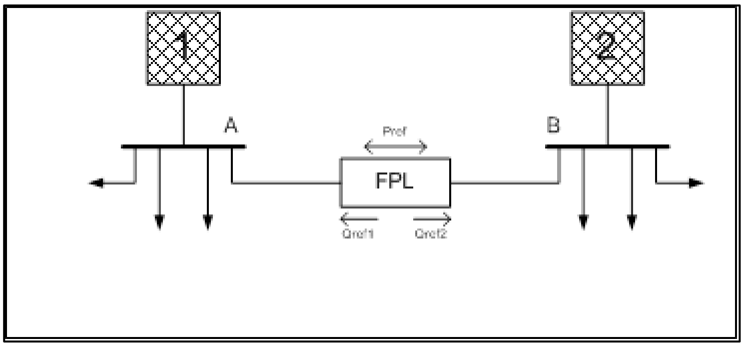

Figure 5-1 FPL Demonstration

One of the most important considerations taken when designing the FPL model was the need to have a logic that is flexible in the degree of optimisation it performs, to be able to understand how the capacity and flexibility benefits change with the different amounts of optimisation the FPL could perform. This was achieved by defining a number of parameters that need to be configured by the user when simulating an FPL. The FPL for example, starts to calculate the power transfers it needs to make (P setpoint) or the reactive power it needs to supply/absorb (Q set point) once one of the two BSPs has a thermal violation or any point along the two feeders has a voltage violation. A violation occurs when the pre-defined thresholds are exceeded. For BSP overloads, the thermal threshold is the percentage loading of the substation with respect to its firm capacity which when exceeded indicates a violation. This threshold is user defined. For example if the thermal threshold for Substation 1 was set by the user to 60%, it would mean that FPL would try to calculate the P/Q setpoints once the percentage loading of the substation reaches or exceeds 60%. Similarly, if the upper voltage threshold is set to 1.05 per unit, the FPL would start calculating the set points once the voltage of any busbar reaches or exceeds 1.05 per unit.

The usage of these thresholds that indicate violations, also means that the degree of optimisation the FPL is performing is fully adjustable, providing flexibility in the implementation of the logic. To try and balance the two networks for example, the thermal thresholds can be set to 50% at each substation, or to perform the minimum amount of power transfers required to remove constraints, the thresholds can be set very high to the actual limits. It is highly recommended to follow this approach when modelling FPLs in power system analysis software.

A summary of the logic is demonstrated in Figure 5-2.

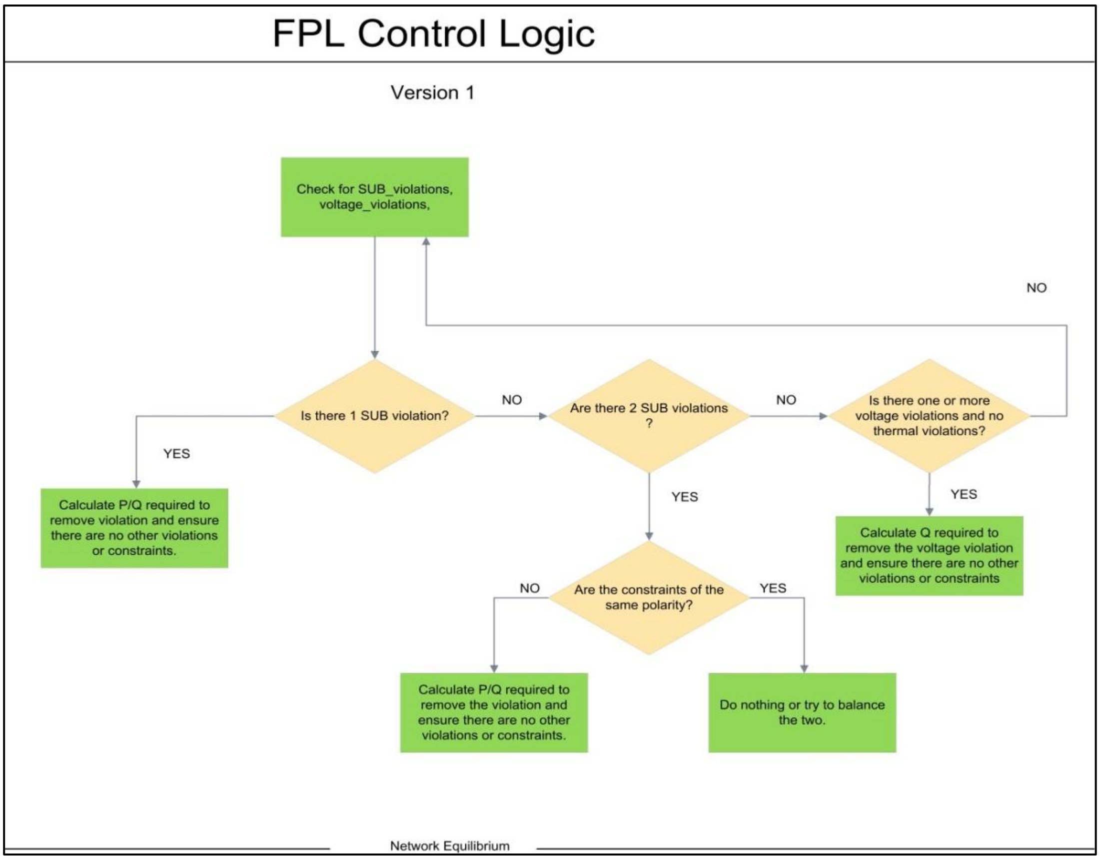

Figure 5-2 FPL Plugin Logic Summary

6 Estimated capacity release- Equilibrium Methods

6.1 System Voltage Optimisation

The network capacity that could be released from the usage of SVO in 11kV and 33kV networks was evaluated through a number of power system studies.

As part of these studies, the generation capacity at a number of 11kV and 33kV locations within the Equilibrium Trial area was evaluated in different scenarios. Then, using the results of the studies, the total generation capacity that could be released in the entire Equilibrium trial area was estimated.

Evaluating the capacity in SVO studies

As explained in Section 2.2.3, the methodology followed to calculate the network capacity, estimates the generation headroom by scaling all existing generation in the network chosen until a thermal or a voltage constraint is generated. The estimated capacity is the added generation up to the scaling round before the constraints were generated. However, the scaling of all generation can provide very conservative estimates when simulating technologies that can provide an improvement in the generation capacity of only certain feeders in the network being analysed. To explain this further, consider Figure 6-1 where the substation has one feeder being constrained due to thermal issues and one feeder due to voltage issues. The capacity evaluation methodology in this case will stop scaling all of the generators since there are thermal and voltage constraints in the network it analyses. However, it does not give a true indication on the capacity that could be added to the network with the usage of SVO, since SVO would be able to remove the constraint on the feeder with the voltage issues and enable more generation to connect. From this learning, a revised methodology has been defined, which is explained below.

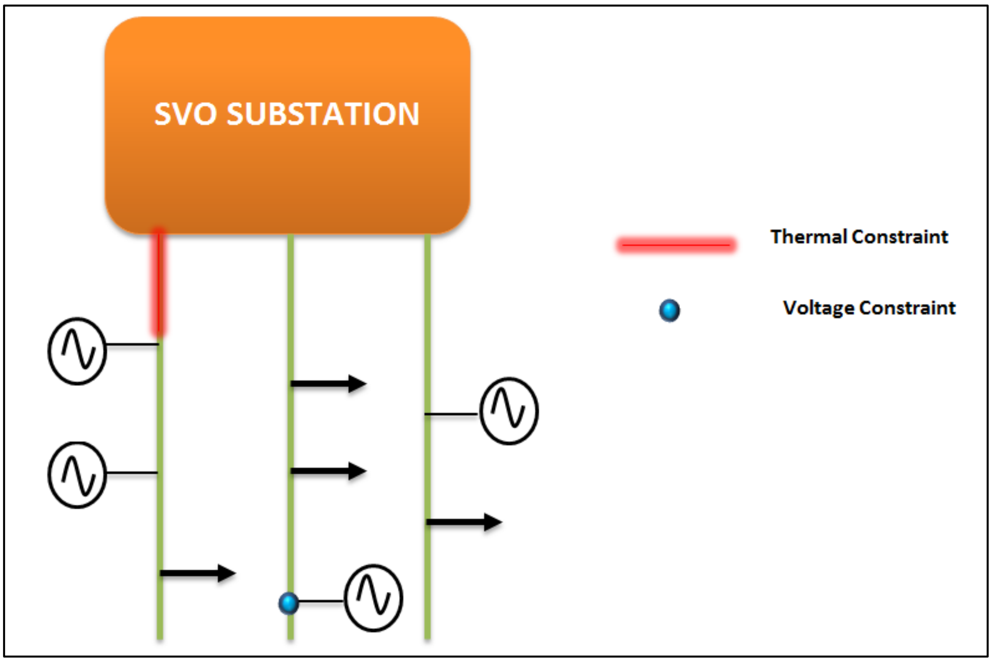

Figure 6-1 - Substation with feeders having different constraints

It was concluded that the methodology should be modified to follow the following rules:

1. Identify the generators in the selected network that cannot be further scaled due to voltage constraints.
2. Simulate SVO to modify the target voltage accordingly.
3. Continue scaling the identified generators until a voltage or thermal constraint is generated.

This revised methodology will form part of the SVO simulations in the APT. To overcome the challenges with the SVO plugin in the existing tool and validate the proposed methodology, the Power System Simulator for Engineering (PSS/E) power system analysis software was used to simulate the proposed methodology and quantify the capacity release benefits of SVO at BSPs, while the capacity release benefits of SVO at Primaries were investigated using this methodology in IPSA.

6.1.1 Capacity released using SVO in 33kV networks

Power system analysis was performed to find the range in the capacity release using SVO at the eight BSPs selected to take part in the Equilibrium Trials. The BSPs were selected based on a number of criteria including the capability of amending the target voltage at each substation and the condition of the existing voltage control equipment. This ensures that a representative sample of substations will take part in the trials, including both substations where the target voltage can be easily amended and substations which require a finer voltage control, maximising the learning potential form the trials.

Using the capacity evaluation methodology described above, the expected capacity release from the amendment of the BSP target voltage that SVO will perform was evaluated.

It was found that a reduction of 0.024 per unit in the target voltage at the BSP analysed could release 18MW of generation capacity, providing a capacity release of 4MW per 0.01 per unit reduction in target voltage. This was calculated using:

$$Capacity\ release\ with\ 0.01\ Target\ V\ reduction = \frac{Total\ capacity\ released}{Total\ Target\ V\ reduction} \times 0.01$$

$$= \frac{20}{0.05} \times 0.01$$

=3.6MW

To quantify the capacity release benefits of each BSP it was necessary to know the capability SVO will have to amend the target voltage at each substation. When the network operates at maximum demand and minimum generation, the voltages in the network will be low, meaning that SVO will be able to perform the minimum target voltage reduction out of all operating conditions in that scenario. When the network operates at minimum demand and maximum generation, the network voltages will be high, meaning that SVO will be able to perform the maximum target voltage reduction out of all operating conditions. Therefore, by running two sets of power system studies representing those scenarios, the minimum and maximum possible target voltage reductions at each BSP were produced. These are demonstrated in Table 6-1.

Table 6-1 SVO Target voltage reduction ranges for each BSP

BSP	MIN TARGET VOLTAGE REDUCTION	MAX TARGET VOLTAGE REDUCTION
BRIDGWATER	0	0.067
EXETER CITY	0	0.070
PAIGNTON	0.005	0.032
EXETER MAIN	0.005	0.058
TAUNTON	0.021	0.074
TIVERTON	0.024	0.032
RADSTOCK	0.024	0.072
BOWHAYS CROSS	0.054	0.087

Using the target voltage reduction ranges of Table 6-1 and the calculated capacity release per 0.01 per unit reduction in target voltage, the minimum and maximum expected capacity releases per BSP were produced, as shown in Figure 6-2 and Figure 6-3. From these, the average generation capacity release for each was calculated and is shown in Figure 6-4.

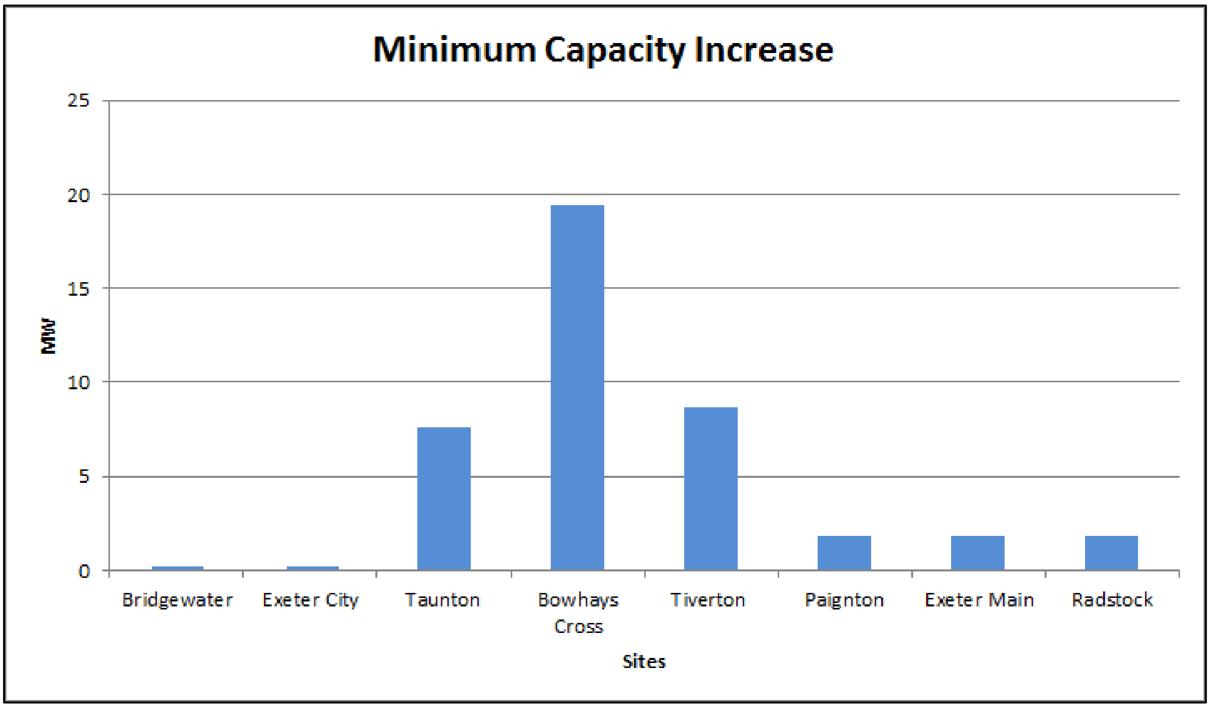

Figure 6-2 Minimum BSP Generation Capacity Increase

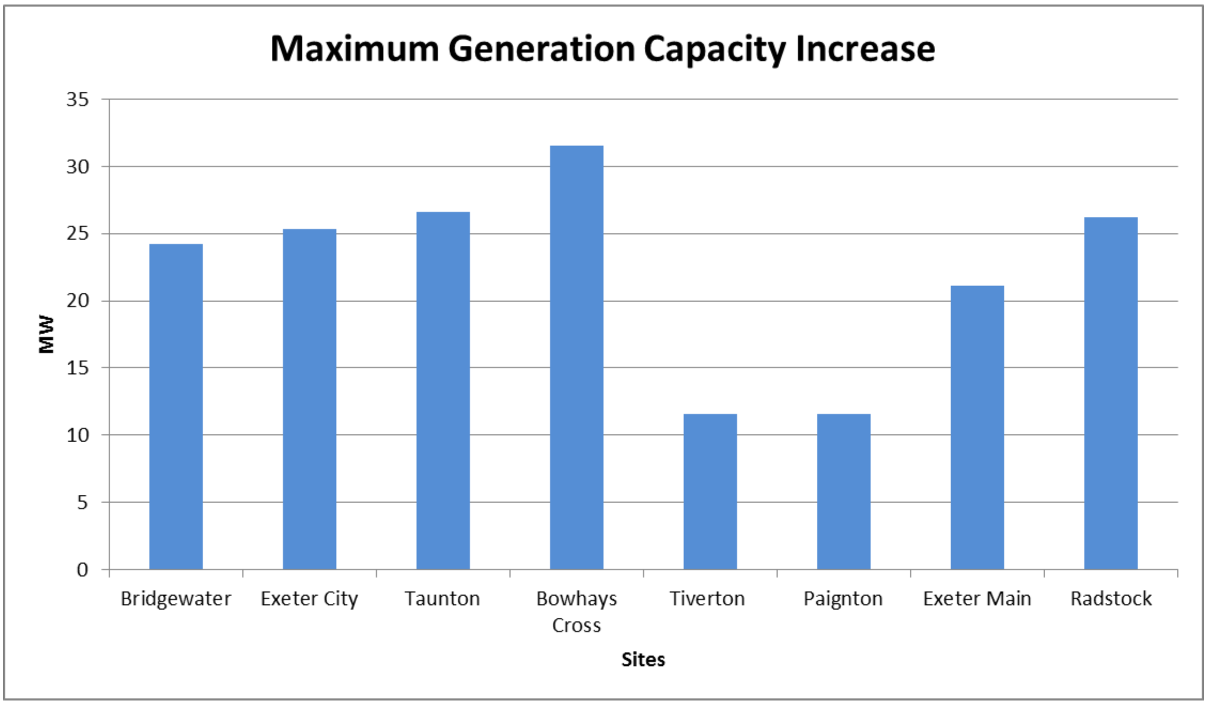

Figure 6-3 Maximum BSP Generation Capacity Increase

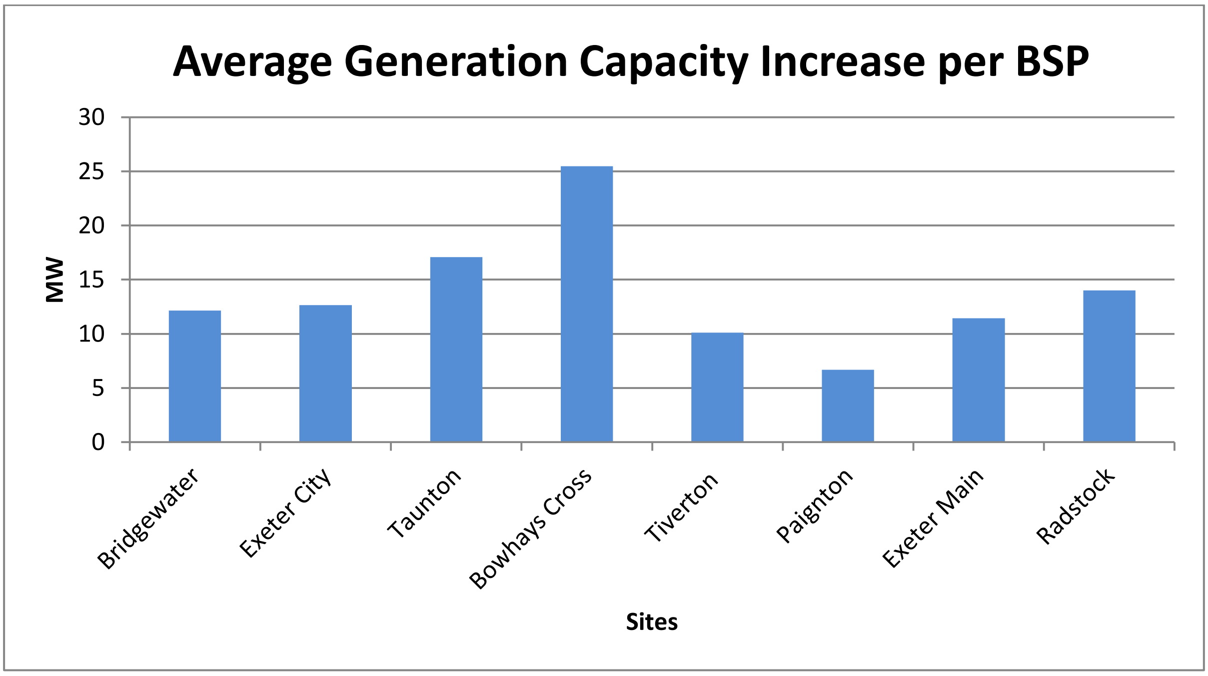

Figure 6-4 Average Generation Capacity Increase per BSP using SVO

The analysis has shown that across all eight BSPs, the estimated generation capacity release is 109MW.

Considering the potential roll-out of the SVO technology in the entire Equilibrium Trial area, by extrapolating the results to the 14 BSPs of the area it is calculated that a capacity release of 190MW could be achieved.

6.1.2 Capacity released using SVO in 11kV networks

Power system analysis was performed to find the capacity release using SVO in the 11kV network.
As part of this analysis, four Primaries within the trial area were analysed for the scenario of maximum generation and minimum demand. These Primaries were chosen based on the capability of amending the target voltage at each substation, ensuring that SVO would be able to perform target voltage adjustments and therefore producing representative simulation results. The amount of generation capacity that can be released in the most constrained (due to voltage) feeders of each Primary using SVO was evaluated and is shown in Figure 6-5.

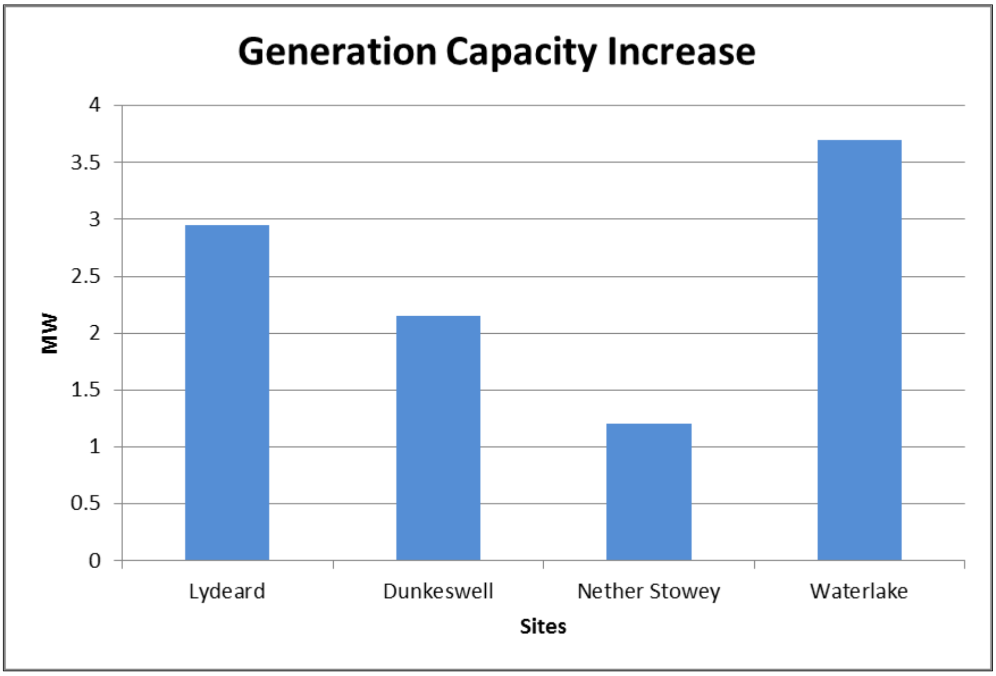

Figure 6-5 Generation capacity Increase per Primary using SVO

The analysis has shown that the average generation capacity release at the Primaries using SVO is 2.5MW. By extrapolating the average generation capacity release to the eight Primary substations that will take part in the SVO trials, the total generation capacity release using SVO in the 11kV network is 20MW.

Considering the potential roll-out of the SVO technology in the entire Equilibrium Trial area, by extrapolating the results to the 93 Primaries of the area it is calculated that a capacity release of 232MW could be achieved.

Estimated Total Capacity Released using SVO

From the above results, the total capacity release using SVO at the eight selected BSPs and eight Primaries is 129MW.

At the bid stage, the expected capacity release from SVO was evaluated at 195MW while the SDRC-4 estimate is 129MW. The SDRC-4 SVO simulations produced valuable knowledge on the target voltage reductions SVO would be able to apply at each of the selected sites, therefore producing a capacity release estimate that is analogous to the SVO window of operation, information that was not available at the bid stage.

Furthermore, the potential roll-out of SVO in the entire Equilibrium area, could provide a generation capacity release of 422MW.

6.2 Flexible Power Link

The network capacity that could be released from the usage of the FPL was evaluated through a number of power system studies.

As part of these studies, the generation and demand capacity at a number of 33kV locations within the Equilibrium Trial area was evaluated in different scenarios. Then, using the results of the studies, the generation capacity that could be released in the entire Equilibrium trial area was estimated.

6.2.1 Capacity released using FPL

The generation capacity of various 33kV networks was evaluated by running two sets of power flow studies, each representing a different scenario:

1. Scenario A: FPL is switched off.
2. Scenario B: FPL provides MW transfers and MVAr support.

The FPL was simulated at the following NOP locations:

1. NOP between Barnstaple and Taunton BSPs, at Quartley Switching Station
2. NOP between Barnstaple and Taunton BSPs, at bus-section of Exebridge Primary Substation
3. NOP between Tiverton and Taunton BSPs, at Tiverton Moorhayes Primary Substation
4. NOP between Exeter City and North Tawton BSPs, at Winslake Foot Switching Station.

The main benefit the FPL technology offers, is the flexibility in the usage of the available network capacity. For this reason, the studies performed, quantified the minimum amount of flexibility that the FPL can introduce in the networks it interconnects.

To further explain the impact the FPL can have on the capacity of the two networks it interconnects, consider the example of Figure 6-6, where feeders A and B are shown. Feeder A has a capacity of 5MW while Feeder B has no capacity, meaning that 5MW more generation can be connected to Feeder A while zero generation can be connected to Feeder B. Feeder B has no generation capacity due to high voltage issues.

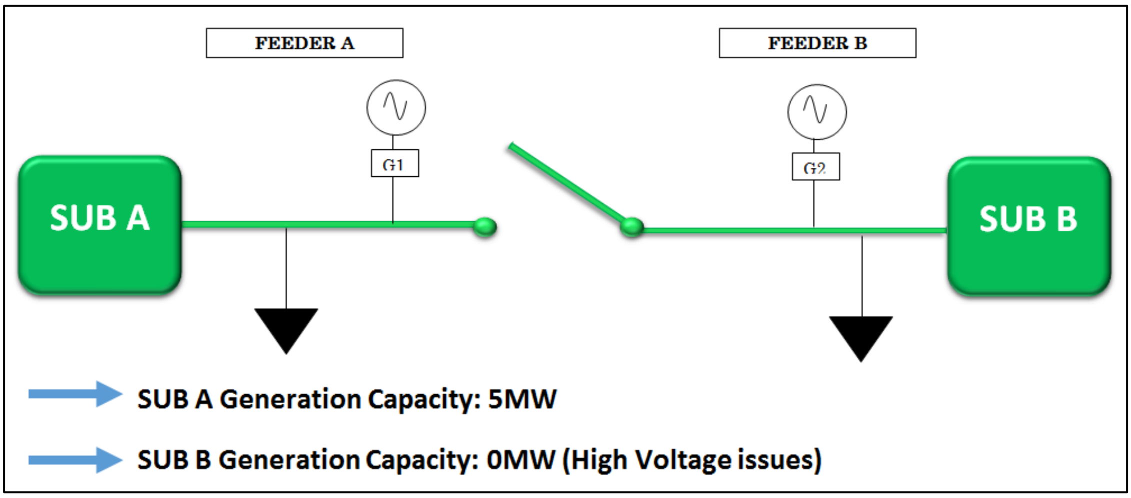

Figure 6-6 FPL demonstration network before interconnection

The reactive power support of the FPL can remove the high voltage constraints in Feeder B by absorbing reactive power, which in this case increases the generation capacity of Feeder B to 7MW, as shown in Figure 6-7.

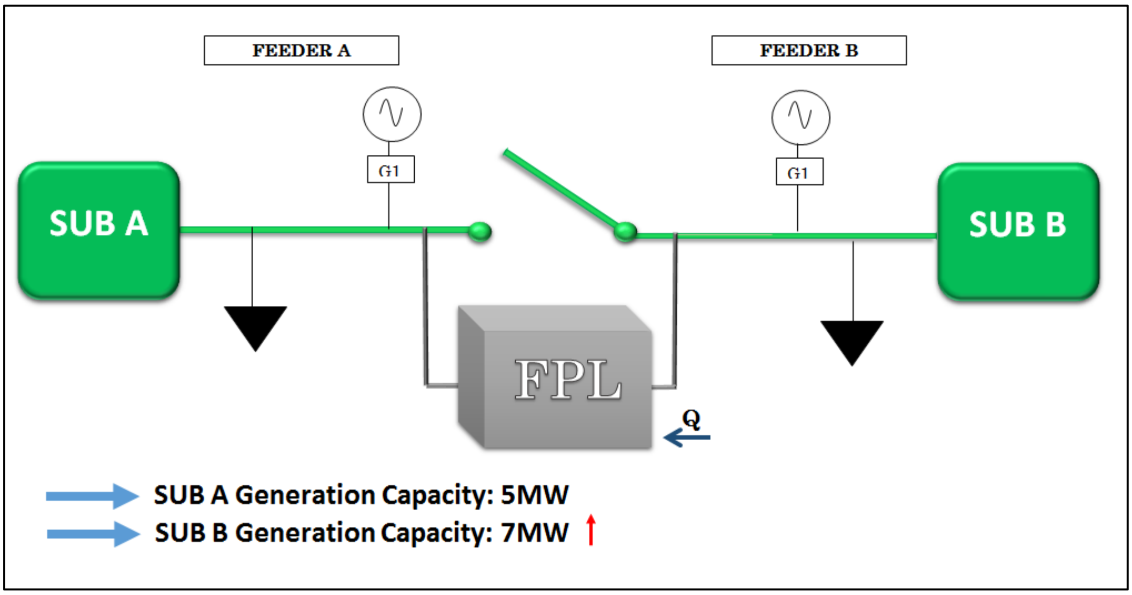

Figure 6-7 FPL demonstration network with FPL providing reactive power support

Additionally, with the active power transfer capability of the FPL, the flexibility in the generation capacity of each feeder can increase significantly. This is demonstrated in Figure 6-8 where the FPL is transferring 7MW of active power from Feeder A to Feeder B (since Feeder B now can support 7MW), increasing the generation capacity of Feeder A to 12MW. In a similar way, by transferring 5MW of power from Feeder B to Feeder A (since Feeder A can support 5MW), the generation capacity of Feeder B increases to 12MW. Therefore, in this particular example, the FPL provides the flexibility of shifting 12MW of generation capacity between the two networks it interconnects. This is particularly beneficial for non-standard connections. WPD offers a number of non-standard connections which enable maximum utilisation of the network capacity by constraining the export of generators only when it is required in real-time. These include Active Network Management (ANM), timed and soft-intertrip connections. Therefore, by shifting the generation capacity to the network that needs it in real-time, the FPL could enable the generators to export at times they could not export before. Hence, releasing network capacity through the flexibility it introduces.

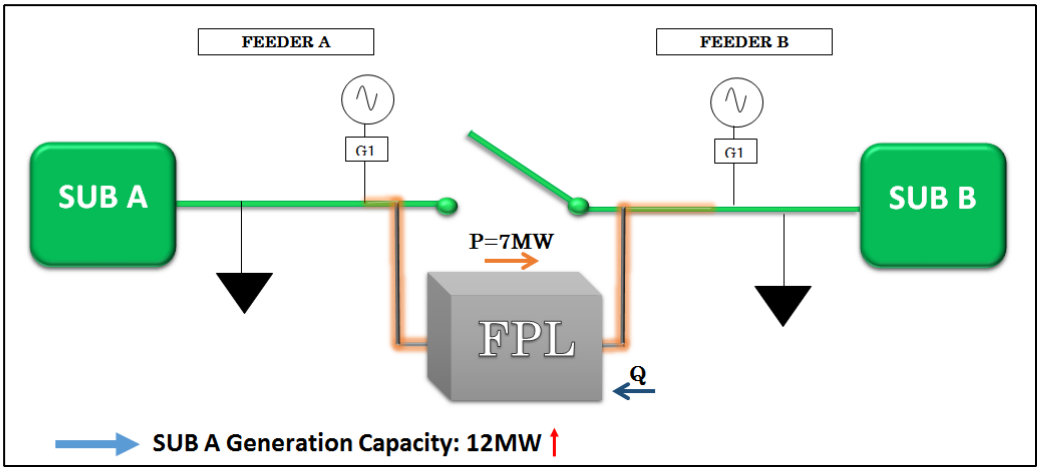

Figure 6-8 FPL demonstration network with FPL providing active power transfers and reactive power support

To demonstrate the impact the FPL can have on the flexibility of the network connections, the change in the minimum generation capacity of each feeder that took part in the FPL simulations is shown in Figure 6-9. In the case of the FPL interconnecting Barnstaple and Taunton BSPs, it can be seen that 8MW of generation flexibility can be introduced in the Barnstaple side and 17MW of generation flexibility in the Taunton side. This means that up to 8MW of capacity can be shifted from Taunton to Barnstaple and up to 17MW of capacity from Barnstaple to Taunton, increasing the network flexibility across the two substations by a minimum of 25MW.

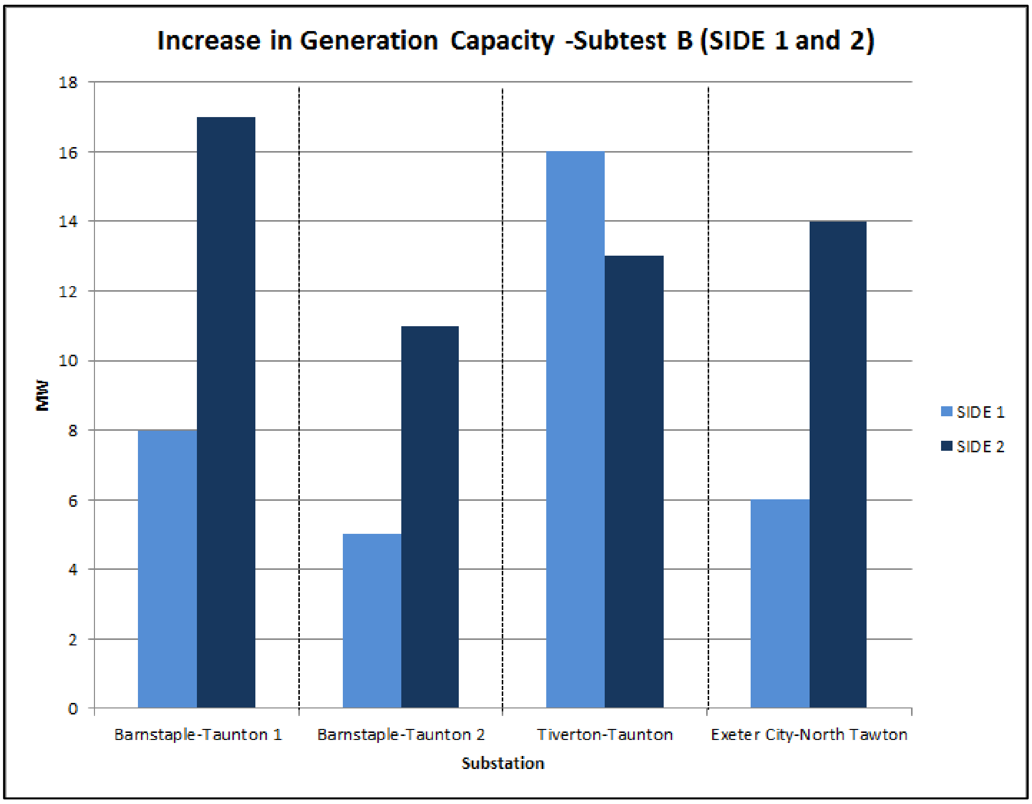

Figure 6-9 Increase in generation capacity flexibility using FPL

Estimated Total Capacity Released in Entire Trial Area using FPL

The results have been analysed to estimate the total capacity that could be released in the entire Equilibrium area from the installation of the FPL. This has shown that 22.5MW of generation capacity can be generated with the usage of the FPL.

In the bid stage, the capacity release using the FPL was estimated to be 36MW, however, only one specific location was considered in the selected area for the technology, producing a different capacity release estimate.

In the Equilibrium Trial area, there are 9 potential 33kV NOP locations for the FPL, therefore by extrapolating the results it is calculated that with the roll-out of the FPL technology across all the available locations, a generation capacity release of 202MW could be achieved.

7 Capacity Released from EVA, SVO and FPL

The sets of studies completed as part of SDRC-4 provided valuable information on the operation of each of the Equilibrium techniques, giving a more detailed insight into the effect they can have on the available network capacity.

The results of the studies are summarised in Table 7-1 which also shows the estimates produced at the bid stage.

Table 7-1 – Estimated Capacity Released from EVA, SVO and FPL

Technique	Estimated Capacity to be released – SDRC-4 Studies	Estimates produced at the bid stage	Estimated Capacity to be released with method rollout in entire Equilibrium area
EVA	341MW	81MW	341MW
SVO	129MW	195MW	422MW
FPL	22.5MW	36MW	202MW
All combined	492.5MW	344MW	965MW

At the bid stage, it was estimated that 81MW of capacity would be released for DG connections using EVA, which is significantly lower than the 341MW indicated by the SDRC-4 studies. This is because in the bid stage analysis, the 33kV voltage limits were amended to ±7% while the SDRC-4 analysis considered wider amendments to the voltage limits, as suggested from the work completed in SDRC-1, of ±10% for the 33kV network and the tighter range of ±8% for the 11kV network. As wider voltage limits were considered in this analysis, it was expected that the evaluated capacity benefits would be larger than the bid estimates. Additionally, the bid estimate was produced considering the capacity release only at 10 substations within the trial area. Since the amendment of the voltage limits would affect all of the 14 BSPs and 93 Primaries within the trial area, the SDRC-4 study results provide a more representative estimate.

As Table 7-1 shows, at the bid stage, the expected capacity release from SVO was evaluated at 195MW while the SDRC-4 estimate is 129MW. The SDRC-4 SVO simulations produced valuable knowledge on the target voltage reductions SVO would be able to apply at each of the selected sites, therefore producing a capacity release estimate that is analogous to the SVO window of operation, information that was not available at the bid stage. Additionally, by extrapolating the results of the simulations to the entire Equilibrium area of 14BSPs and 93 Primaries, the potential capacity release form the rollout of the technology was found to be 422MW.

The detailed SDRC-4 studies showed that the FPL is transferring capacity from one side to the other, providing flexibility in the usage of the existing capacity in the two networks it interconnects. This increase in flexibility is the main capacity benefit from the FPL device, which across the four locations investigated was found to be an average of 22.5MW. In the bid stage, however, one specific location was considered in the selected area for the technology, producing a different capacity release estimate. Additionally, by extrapolating the results of the simulations to the entire Equilibrium area where there are 9 candidate locations for the FPL technology, the potential capacity release form the rollout of the FPL was found to be 202MW.

The combined evaluated capacity release of the SDRC-4 studies is 68MW higher than the bid estimate which is mainly due to the difference in the capacity release estimated for the EVA technology. It is important to note, however, that at the bid stage the capacity released using all of the technologies combined was estimated to be larger than their arithmetic sum due to the benefits introduced by the usage of the APT, providing better estimates of the worst case conditions. The produced results for the VLA studies completed in the APT were generated using the APT's typical generation and demand models, instead of the traditional worst case scenarios. Therefore, the benefits of the improved modelling are included in the produced results for the biggest part of the evaluated benefits. For this reason, the combined capacity release benefits of all the technologies is estimated to be the sum of the capacity released from each until further information is collected from the trials of SVO and FPL.

The capacity release benefits of the Equilibrium technologies will be further quantified in the trials of the SVO and FPL technologies, enabling comparisons to be made between the theoretical benefits and the actual and providing the most valuable learning generated from this project. Additionally, the revised network capacity evaluation methodology will be implemented within the APT, to update the simulated benefits of VLA in 33kV networks and provide further information on the type of the expected constraints. This will be published by the end of April 2017.

8 Summary and Next Steps

This report, explored the potential benefits from the amendment of the statutory limits, quantified the capacity released from each of the EVA, SVO and FPL technologies and demonstrated the functionalities of the APT. From this work, valuable learning was gained on the most suitable methodology to follow when assessing the benefits of the various technologies, which will be used in the quantification of the benefits in the Equilibrium trials. A revised network capacity evaluation methodology has been created which will be incorporated within the APT and used to provide a better understanding of the constraints in 33kV networks and the available capacity with the amendment of the voltage limits. The findings from the simulation of the revised methodology will be published by the end of April 2017.

In the months to follow, the installation and testing of the SVO and FPL technologies will take place in preparation of the commencement of the technology trials. The data collected from the trials will provide knowledge on their actual operation in the network, enabling comparisons to be made between real network behaviour and the modelling done in the APT. The quantification of the actual benefits of the SVO and FPL technologies will be an important part of the remaining project deliverables, which will be completed using the learning obtained from SDRC-4. The trialling and demonstrating of the SVO and FPL methods will be described in SDRC-5 (April 2018) and SDRC-6 (October 2018) respectively.