WPD Virtual Statcom WP5 Report

For: Western Power Distribution

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Executive Summary

Political and social forces in the UK are driving the change towards the use of low carbon technologies (LCTs) such as renewable generation, electric vehicles (EVs) and the electrification of domestic heating. As LCTs are becoming integrated into existing electricity networks, technical constraints arise that can limit the total amount of generation or load a network can host. The Virtual Statcom project as an innovation project has investigated the technical feasibility of increasing network hosting capacity, for both generation and load, by optimising the reactive power dispatch of distributed generators (DGs).

To enable the investigation two algorithms were developed. The first is an algorithm to determine the generation or load hosting capacity of a network. The second is an algorithm to optimise the reactive power dispatch of existing generators with the aim of increasing hosting capacity. These two algorithms make up the Virtual Statcom algorithms.

Extensive analysis was undertaken using the Virtual Statcom algorithms with 3000 studies being undertaken covering extreme operating conditions and historic time series load / generation scenarios requiring circa 6 million power flow calculations. The following WPD networks, selected for different network characteristics, were used in the analysis; Barnstable 33 kV BSP, Pyworthy and North Tawton 33 kV BSP, Tiverton 33 kV BSP and Tiverton Moorhayes 11 kV Primary.

The key findings from the Virtual Statcom Project are:

- The Virtual Statcom algorithms released a small level of generation hosting capacity which depended on the network topology and assets. Therefore, the Virtual Statcom solution would need to be combined with other network interventions to increase the generation capacity benefits provided.
- The Virtual Statcom algorithms released load hosting capacity, with an average load hosting capacity increase of between 8-31 MW for each 33 kV BSP network assessed. This is equivalent to an extra 10,000 domestically connected EV's across the three BSP networks. The method to increase the load hosting capacity of a network also reduces overall electrical losses in a network.
- The Virtual Statcom optimisation algorithm demonstrated the ability to resolve or reduce constraints in networks through optimised reactive power dispatch, this has the potential to reduce the amount of active power curtailment required to manage network constraints.

The key findings have been used to develop high level specifications for a trial to demonstrate how the Virtual Statcom optimisation algorithm can be applied. This covers options for both a real time reactive power control system and a system planning tool to manage network constraints.

This project has shown that the Virtual Statcom can enable DNOs to increase the capacity of their networks to host more low carbon technologies, the next step of developing a demonstration project to build on the work delivered by Virtual Statcom project is underway.

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Table of Abbreviations

Abbreviation	Term
DG	Distributed Generator
FPL	Flexible Power link
LTDS	Long Term Development Statement (Nov 2018)
MW	Megawatts, unit for real power
Mvar	Mega volt-amperes reactive, unit for reactive power
NIA	Network Innovation Allowance
NOP	Normally open point
OPF	Optimal power flow
ORPD	Optimal reactive power dispatch
p.u.	Per unit
pf	Power Factor
PSC	Power Systems Consultants UK Ltd
PSS/E	Power System Simulator for Engineering
Python	A high-level, general-purpose programming language
RPF	Reverse power flow
SCADA	Supervisory Control and Data Acquisition
Statcom	Static Synchronous Compensator
UKPN	United Kingdom Power Networks
VBA	Visual Basic for Applications
WP	Work Package
WPD	Western Power Distribution

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1. Introduction

1.1. Introduction to Project

Western Power Distribution (WPD) engaged Power Systems Consultants UK Ltd. (PSC) to deliver an innovation project known as the Virtual Statcom project, the project was run by WPD and funded under the Ofgem, Network Innovation Allowance (NIA).

As an increasing number of low carbon technologies (LCTs) connect to distribution networks, technical constraints arise that can limit the total amount of generation or load a network can host. To overcome the technical constraints associated with LCTs and continue to operate a safe, secure and reliable network, WPD undertake traditional network reinforcements as well as initiating and leading innovation projects to develop new solutions. A key focus of innovation projects is to increase the utilisation of existing assets to defer network reinforcements, the Virtual Statcom project fits in this category of project.

The objective of the Virtual Statcom project was to determine the technical feasibility of increasing the network hosting capacity, for both generation and load, through implementing an algorithm to control and coordinate the reactive power output of existing generators in the distribution network.

The project was structured into the following 5 work packages (WP):

- WP1 - Virtual Statcom design, study zone selection and data validation.
- WP2 - Power flow simulations and Virtual Statcom algorithms implementation.
- WP3 - Graphical User Interface.
- WP4 - Time series comparison studies.
- WP5 - Virtual Statcom feasibility study reporting.

The work packages were delivered in order except WP3 and WP4 which were delivered in parallel.

1.2. Introduction to this Report

This report details the work completed in delivering WP4.

- Section 2 provides background to the project and explains the motivation and concept of the project.
- Section 3 provides a summary of the work undertaken Work Packages 1 to 4.
- Section 4 presents the conclusions from the Virtual Statcom project.
- Section 5 presents further work including specifications for a Virtual Statcom real time control system and a network planning tool and trial considerations.
- Section 6 presents the next steps required for a demonstration project

1.3. Western Power Distribution Networks Assessed

The Virtual Statcom project focused on WPD's Southwest region model. The network model has 42 Bulk Supply Points (BSPs) and eight Primary substations that have been modelled as part of WPD's Network Equilibrium project. The following list presents the three BSPs and one Primary selected as study networks for the Virtual Statcom project. Figure 1-1 shows the location of the study networks in WPD's southwest region. For more detail on the networks selected and network selection criteria refer to the Section 3.1.2.

- 33 kV Bulk Supply Point networks:
  - Barnstaple
  - Pyworthy and North Tawton
  - Tiverton
- 11 kV Primary Networks:
  - Tiverton Moorhayes Primary

Figure 1-1 - Location of study networks

2. Virtual Statcom Project Background

2.1. Passive Distribution Networks

The design of traditional distribution networks was based on a top down passive approach. In these traditional distribution systems, the primary function was to transfer power from the transmission system level Grid Supply Points (GSPs) to the Bulk Supply Points (BSPs) and onwards to primary substations and the end consumers of electricity. A key characteristic of passive distribution networks is that power flows were always considered in a single direction, notably from a higher voltage sources towards lower voltage loads.

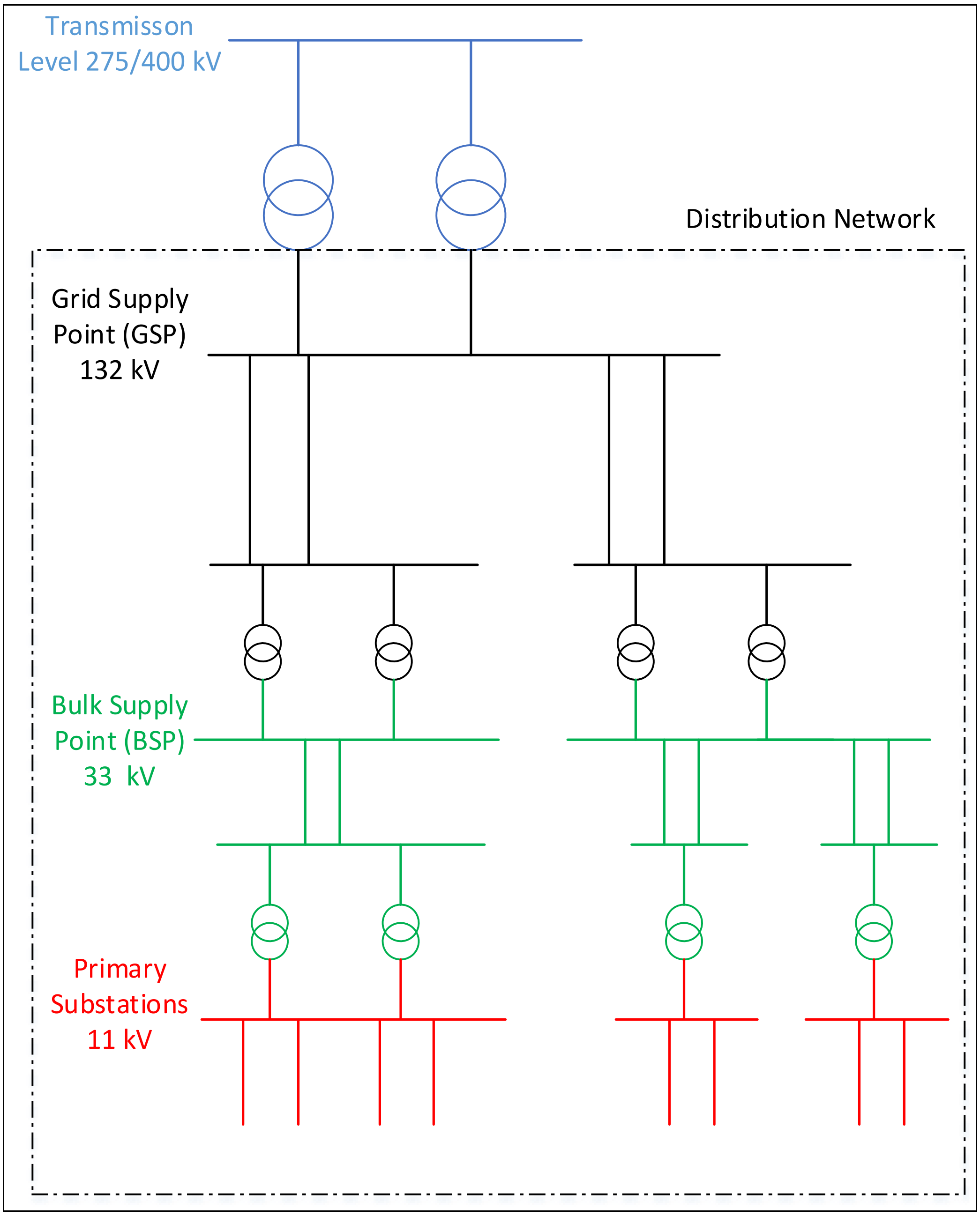

Figure 2-1 - Distribution Network layout

2.2. Accommodating Low Carbon Technologies

The past 10-20 years has seen an increase in LCTs connected to distribution networks such as renewable generation, battery storage systems, electric vehicle and heat pumps. In WPD's South West network LCTs predominantly consist of renewable generation (i.e. wind, solar) connected at 33 kV and 11 kV voltage levels. The increased adoption of LCTs changes the key characteristic of passive distribution networks. Power can now flow in either direction and is dictated by changing loads and generation which can be intermittent in nature.

The uptake of LCTs provides benefits of low carbon energy. They can also relieve network thermal constraints by supplying power closer to the load centres initially. This can therefore reduce loadings on upstream lines, cables and transformers. However, distribution networks cannot accommodate ever increasing connections of LCTs. Aside from the practical considerations such as land availability and favourable sites for renewable generation and battery storage, technical factors constrain the total amount of LCTs that can be connected.

A terminology used to quantify the level of LCTs a network can accommodate is "hosting capacity" [1] [2]. The Hosting Capacity of a network is defined as the total amount of LCTs that the network can accommodate without violating predefined operational, physical and statutory limits. Hosting Capacity can be broken down into generation hosting capacity and load hosting capacity.

The technical factors that can constrain the hosting capacity of a network include:

- Voltage regulation
- Voltage step constraints
- Thermal ratings
- Fault levels
- Power quality

The impact of these technical factors on hosting capacity is briefly explained in this section.

2.2.1. Voltage Regulation

The statutory voltage limits for distribution networks in the UK are set in the Electricity Safety, Quality and Continuity Regulations 2002 and are +/- 6% of the nominal voltage at 11 kV and 33 kV. These statutory voltage limits will be incorporated in to the Virtual Statcom project.

The traditional method of voltage regulation in passive distribution networks is to increase the bus voltage at BSPs and primary substations above the 33kV and 11 kV nominal ratings to account for the voltage drop along the distribution feeders and ensure that far end of feeders are within the statutory limits. However, the situation changes if distributed generators (DGs) are connected along the feeders or at the end of feeder. The connection of DGs can lead to voltage rise issues. This is due to the voltage at the point of connection of a DG being proportional to the real and reactive power of DG and load [3]. For combinations of load and generation, when load is less than generation a voltage rise takes places at the DGs point of connection. With traditional voltage regulation and DG, bus voltages along the feeder can exceed the +6% statutory voltage limit. It is for this reason that DGs are typically required to operate with a leading power factor (importing reactive power) to counter this voltage rise.

The voltage head room on a feeder limits the size of individual DGs and therefore the hosting capacity for the network. The voltage head room on a feeder is defined as the difference between the upper statutory voltage limit and the bus voltage at a given bus. To illustrate voltage head room, consider the following two bus example where:

- The bus voltage at the BSP is fixed at 1.0 p.u.
- The reactive power of the load and generator are ignored.
- 3 arbitrary scenarios are considered:
    - When the real power of the generator is less than the load. (Pg < Pd)
    - When the real power of the generator is equal to the load. (Pg =Pd)
    - When the real power of the generator is greater than the load. (Pg > Pd)

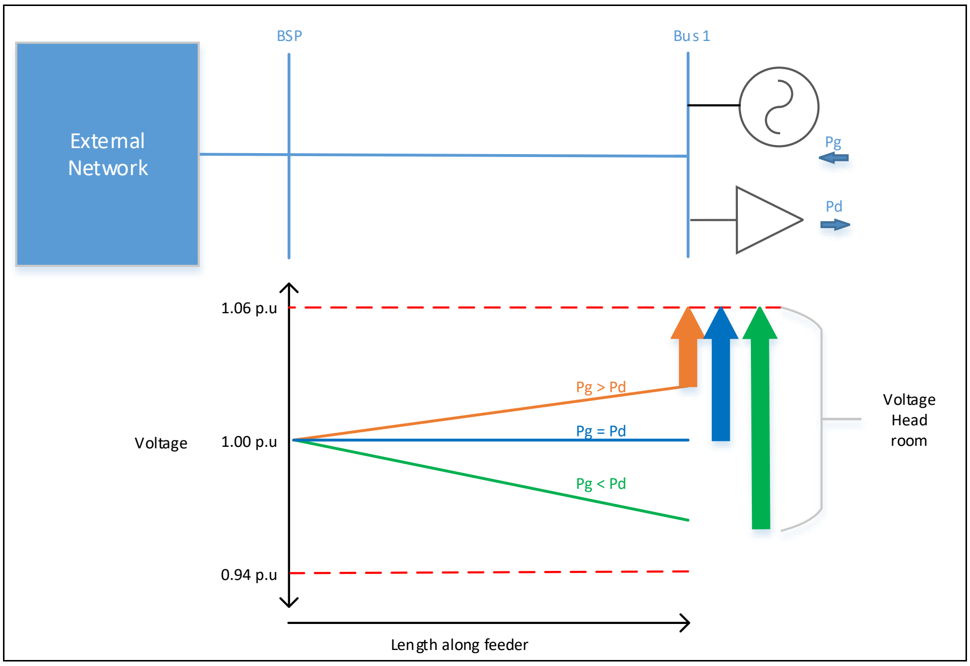

Figure 2-2 - Voltage head room

Figure 2-2 demonstrates that as the amount of real power from the generator (Pg) increases the voltage head room decreases.

2.2.2. Voltage Step Constraints

The hosting capacity may also be constrained by voltage step constraints. The voltage step constraints for distribution networks in the UK are set in the Distribution Planning and Connection Code and Engineering Recommendation P28. The voltage step constraints are +/- 3 % for frequently occurring events. The tripping of a DG can cause voltage steps in either direction depending on the size of the DG and system conditions, this can limit the size of a DG on a feeder, hence the hosting capacity. These voltage step constraints were incorporated in to the Virtual Statcom project.

2.2.3. Thermal Ratings

The installation of DGs in networks can be beneficial and can reduce the loading of lines, cables and transformers. However, as the total distributed generation installed increases, reverse power flows arise which can exceed the thermal ratings of connected equipment. Therefore, the hosting capacity can be limited by the thermal ratings of equipment. Further to this, some equipment such as transformer tap changers and circuit breakers have lower ratings under reverse power conditions limiting the hosting capacity even further.

2.2.4. Fault Levels

A distribution system is designed to safely handle a certain level of short circuit current. In passive distribution networks the short circuit current infeed was assumed to come from the upstream network. However, by adding distributed generation, this condition changes as the distributed generators will also contribute fault current. This can lead to the short circuit capacity of the distribution network being exceeded thus limiting the hosting capacity. Specific issues associated with fault levels are not part of the scope of this project and were not considered in the Virtual Statcom Project.

2.2.5. Power Quality

Increasing LCT connections has to potential affect voltage and current quality in the grid. The proliferation of power electronic based devices is expected to introduce impacts including; harmonic distortion (both characteristic and low order non-characteristic); rapid voltage changes; unbalance due to single phase connections; and long-term voltage variation and transients due to the connection and disconnection of various LCT sources. Specific issues associated with power quality were not part of the scope of this project and are not considered in the Virtual Statcom Project.

2.3. Techniques to Increase LCT Hosting Capacity

The traditional means to increase LCT hosting capacity is to undertake network reinforcements however, this can be costly and time consuming. Alternative means to increase hosting capacity include:

- Voltage control schemes to control transformer set points and switched capacitors.
- Reactive power or power factor regulation.

2.4. Virtual Statcom Concept

The existing DGs connected to WPD's BSPs and Primary networks operate with a fixed power factor between unity and 0.95 leading (import reactive power) and this may not be appropriate for all network conditions. This is the fundamental area that the Virtual Statcom project aims to investigate. The concept of the Virtual Statcom assumes that instead of operating with fixed power factor, the DGs can operate across a power factor range. By optimising the reactive power output of DGs in a network for different conditions through perhaps a new flexibility service, there is potential to increase the hosting capacity for both load and generation LCTs.

3. Summary of Virtual Statcom Project Work Packages

The objective of the Virtual Statcom project was to determine the technical feasibility of increasing a network's hosting capacity, for either generation and load, through implementing an algorithm to control and coordinate the reactive power output of existing generators in the distribution network. To achieve this objective the Virtual Statcom project was broken into the following Work Packages (WP):

- WP1 - Virtual Statcom design, study zone selection and data validation.
- WP2 - Virtual Statcom algorithms implementation and Power flow simulations.
- WP3 - Graphical User Interface.
- WP4 - Time series comparison studies.
- WP5 - Virtual Statcom feasibility study reporting.

A summary of work packages 1 to 4 are presented in this section. Further details on work packages 1 to 4 can be found in the individual work package reports [4, 5, 6, 7].

3.1. WP1 - Virtual Statcom Design, Study Zone Selection and Data Validation

Work Package 1 involved all the necessary preparation work required prior to commencing the implementation of algorithms and performing power system studies. This included the development of the initial design methodology for the Virtual Statcom algorithms as well as the selection and validation of the PSS/E network models that were to be used in the Virtual Statcom project.

3.1.1. Virtual Statcom Design Methodology

To guide the design methodology for the Virtual Statcom project and the specification of the Virtual Statcom algorithms a literature review was undertaken. The literature review captured the existing academic and industry knowledge from journal papers and other innovation projects.

The literature review identified the need for two distinct algorithms to be developed;

1. An algorithm to calculate the generation/load hosting capacity of a network - the hosting capacity algorithm.
2. An algorithm to optimise the reactive power dispatch of a network's generators - the optimisation algorithm.

These two algorithms together make up the Virtual Statcom algorithms.

To determine the whether the Virtual Statcom algorithms could increase network hosting capacity, it was necessary to be able to compare the existing network capacity before and after the optimisation algorithm optimises the reactive power output of generators. Figure 3-1 shows the high-level Virtual Statcom project design methodology developed in Work Package 1 and shows the interaction between the two Virtual Statcom algorithms.

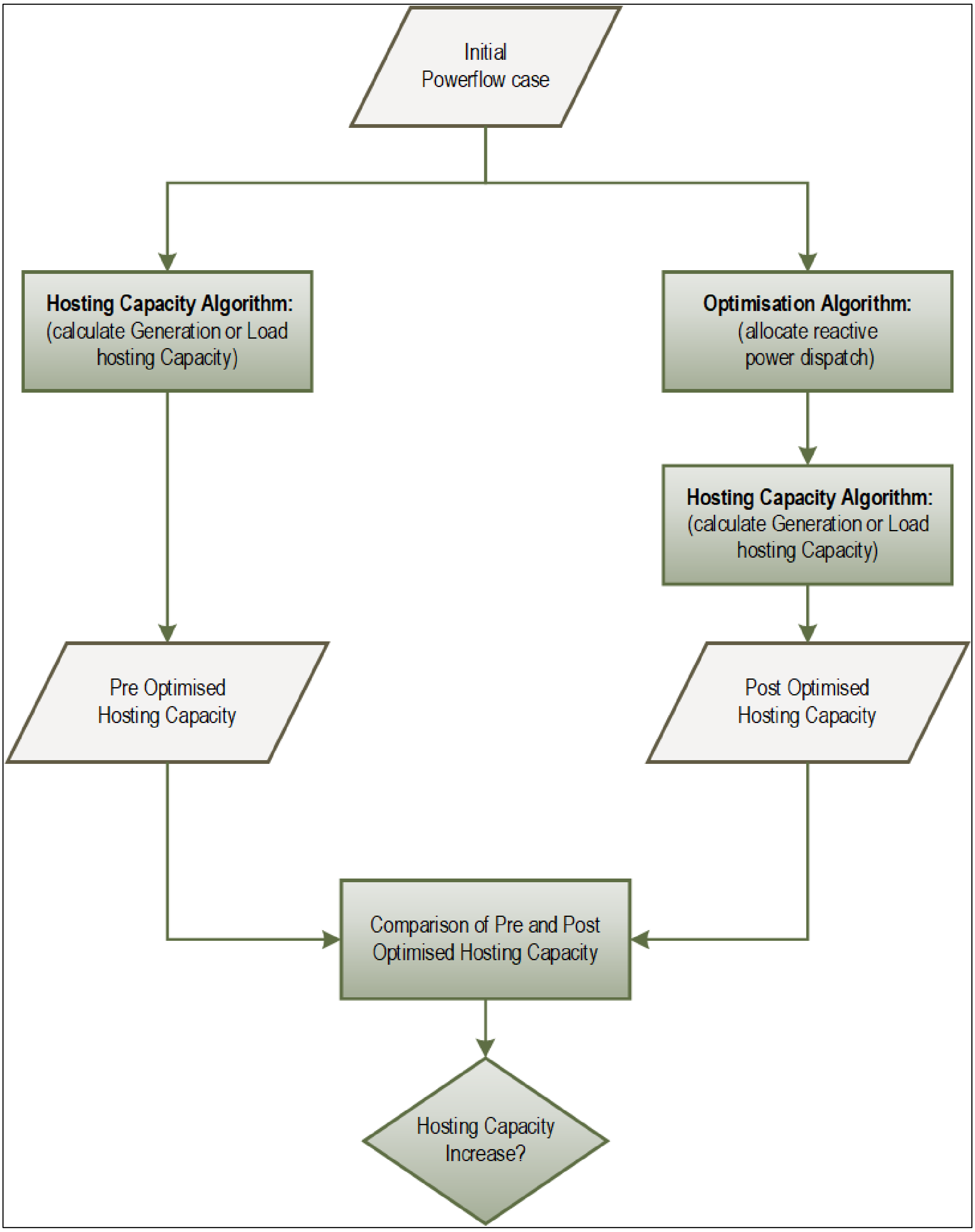

Figure 3-1 - Virtual Statcom design methodology

Hosting Capacity Algorithm Design

Two approaches to evaluate the hosting capacity of a network were identified; a per-node non-concurrent hosting capacity and concurrent hosting capacity. The concurrent hosting capacity approach was preferred for the Virtual Statcom project as it aligned with the objective of the Virtual Statcom project to calculate the maximum simultaneous generation or load that can be connected across a network compared to the maximum generation or load that can be connected to a single node (bus).

The Virtual Statcom project opted to use an iterative scaling method over an optimal power flow method identified, in the literature review, to calculate the concurrent hosting capacity for the method's computational simplicity, ability to incorporate contingency[1] configurations and was applicable to generation and load.

Table 3-1 provides the high-level methodology developed in Work Package 1 to determine the generation or load hosting capacity of a network.

Table 3-1 Generation and Load Hosting Capacity Methodology

Generation Hosting Capacity	Load Hosting Capacity
1. Place a 'dummy generator'[2] at the end of each feeder.	1. Identify existing network loads.
2. Scale the 'dummy generators' until there are network issues.	2. Scale the network loads until there are network issues.
3. Sum the 'dummy generators' and the existing generation. This is the network's generation hosting capacity.	3. Sum the new value of existing loads. This is the network's load hosting capacity.

Optimisation Algorithm Design

The literature review identified that optimising the reactive power output of existing DGs to increase network hosting capacity, was essentially an Optimal Reactive Power Dispatch (ORPD) problem [4]. The literature review also demonstrated that gradient-free solvers are best suited to solve ORPD problems.

Work Package 1 defined the optimisation of the existing network generators to increase network hosting capacity as an ORPD problem. The objective of the Virtual Statcom algorithm was to maximise generation or load hosting capacity by changing the reactive power output of existing network generators. Work Package 1 identified that it was possible to define an objective function that maximised the hosting capacity calculated from the hosting capacity algorithm directly, but this was discounted in favour of an objective function to maximise hosting capacity indirectly through maximising the available headroom for generation or load [4]. Defining the objective function to directly maximise hosting capacity was discounted as it places a high burden on computational resources, resulting in long solving times.

[1] A contingency is the terminology used to describe the removal of a power system asset(s) (e.g. a transmission line, a transformer) from a network in its normal operation configuration. The contingencies considered in the Virtual Statcom Project were a single circuit, a single transformer/voltage regulator and a single generator. Further details on contingency configurations is provided in the Work Package 2 report [5].

[2] A dummy generator is the term used in the Virtual Statcom project to describe new generators that are added to a PSS/E case.

A Particle Swarm Optimisation (PSO) solver was selected to be the solver for the optimisation algorithm. PSO was selected as it is a proven method often used to a benchmark ORPD problems and open source Python PSO packages were available. A high-level overview of the optimisation algorithm design developed in Work Package 1 is shown in Figure 3-2.

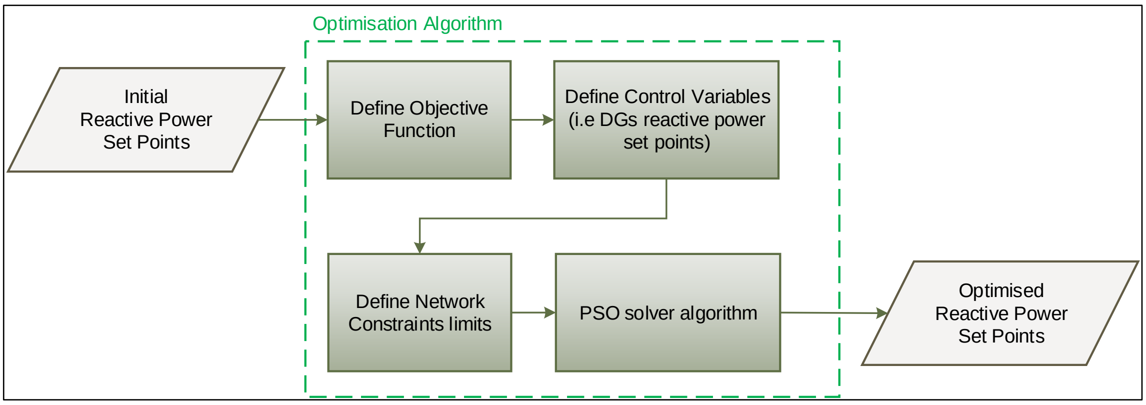

Figure 3-2 - Optimisation Algorithm High Level Design

3.1.2. Network Selection and Data Validation

The Virtual Statcom project focused on WPD's Southwest region. The network model for the South West Region has 42 BSPs and eight Primary substations had been modelled as part of WPD's Network Equilibrium project - a previous innovation project.

Three BSP networks and one Primary network were selected in Work Package 1 as study zones for the Virtual Statcom project. The aim when selecting networks was to select networks with different characteristics to test the applicability of the Virtual Statcom methodology. The selection criteria included; the amount of DGs installed, historical data granularity, networks with historical voltage regulation and thermal constraints, no existing reverse power limitations, and WPD's network owner experience. Table 3-2 presents the networks selected as study networks for the Virtual Statcom project and the reasons for selection. Historic supervisory control and data acquisition (SCADA) load and generation data obtained for each study network was validated to enable time series studies to be undertaken in Work Package 4.

Table 3-2 - Networks selected for the Virtual Statcom Project

Network Name	Voltage Level	Reason for Selection
Barnstaple BSP	33 kV	• Limited voltage headroom during a maximum generation and minimum load scenario. (i.e. a number of busses with voltages towards the top end of the allowable voltage range). • A branch with high thermal loading under a maximum generation and minimum load scenario.
Pyworthy and North Tawton BSPs	33 kV	• High number of existing generators in the network. • Several branches with high thermal loadings. • Network consists of two BSPs normally operated in parallel.

Tiverton BSP	33 kV	• Smaller and simpler network than Barnstaple and Pyworthy/ North Tawton BSP.
Tiverton Moorhayes Primary	11 kV	• Location of generators in the network are geographically dispersed compared to other 11 kV networks.

3.2. WP2 - Power System Analysis and Virtual Statcom Algorithms Implementation

Work Package 2 represented the most significant work package in the Virtual Statcom project. The work package included power system analysis of the selected networks, the implementation of the Virtual Statcom algorithms and simulation studies using Virtual Statcom algorithms to quantify the amount of additional hosting capacity that is released by the algorithms for edge case generation and load scenarios.

3.2.1. Study Networks Power System Analysis

As part of Work Package 2, power system analysis of each study zone network was undertaken using PSS/E[3]. The purpose of the analysis was to identify any network constraints present in the networks for given load / generation scenarios and network contingency configurations. The network constraints provided an indication of the study zone networks' ability to host increased levels of generation or load and enabled the validation of initial results when developing the Virtual Statcom algorithms.

The main findings of the power system analysis were that for the edge case generation and load scenario, where generation is at maximum output and load at a minimum, Barnstaple 33 kV BSP and Pyworthy and North Tawton 33 kV BSP networks had no capacity for additional generation in certain contingency configurations. Whereas, Tiverton 33 kV BSP had the capacity for additional generation in all contingency configurations. Further details of the power system analysis undertaken, and results are provided in the Work Package 2 report [5].

3.2.2. Virtual Statcom Algorithms Implementation

The Virtual Statcom algorithms designed in Work Package 1 were implemented and further developed in Work Package 2 to improve the accuracy and application of both the hosting and optimisation algorithms. This section presents the key developments of the Virtual Statcom algorithms in Work Package 2.

Hosting Capacity Algorithm

The hosting capacity algorithm implemented in Work Package 2 can be broken into 4 main parts:

- Placement of 'dummy generators' or identification of network loads

[3] Siemens PSS®E software version 34.2

- Scaling of generation or load
- Identifying and resolving power system violations
- Handling of contingency configurations

Three generator placement methods trialled in Work Package 2 identified that the method with highest network penetration of distributed generators provided the highest generation hosting capacity. This corresponded to when dummy generators were placed at both end buses[4] and existing generator buses. All generation hosting capacity studies in the Virtual Statcom project used this method for the placement of dummy generators, but the algorithm can be configured to place dummy generators at only end buses or existing buses. For load hosting studies the hosting capacity algorithm manipulated existing network loads rather than introducing new loads into the network.

The hosting capacity algorithm scales up the dummy generators or existing loads in scaling iterations until network constraints are exceeded. The constraints that are exceeded are resolved by reducing the generators or loads that have a significant impact on the constraints. The generators or loads used to resolve the constraints are then not scaled up in subsequent scaling iterations.

The hosting capacity algorithm delivered two approaches for including contingency configurations.

1) Traditional Planning approach
2) Per contingency configuration approach

At a high level, the traditional planning approach scales generation or load and then assesses the intact system and all contingency configurations for violations. This is compared to the per contingency configuration approach which sets a specific network configuration and scales generation or load and then assesses for violations in the current configuration only. The traditional planning approach was developed initially and then the per contingency approach was developed to enable further testing of the optimisation algorithm in specific network configurations.

Optimisation Algorithm

The power system analysis undertaken in Work Package 2 identified that some networks can be initially constrained in load / generation edge cases. This led to the development of prioritised objectives being included in optimisation algorithm. The optimisation algorithm prioritises resolving network constraints; the primary objective, before applying a secondary objective to increase the hosting capacity, the order of operation is shown in Figure 3-3.

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[4] End buses are the buses in a feeder that are electrically far away from the BSP or Primary bus bar. See [5] for further details on end buses.

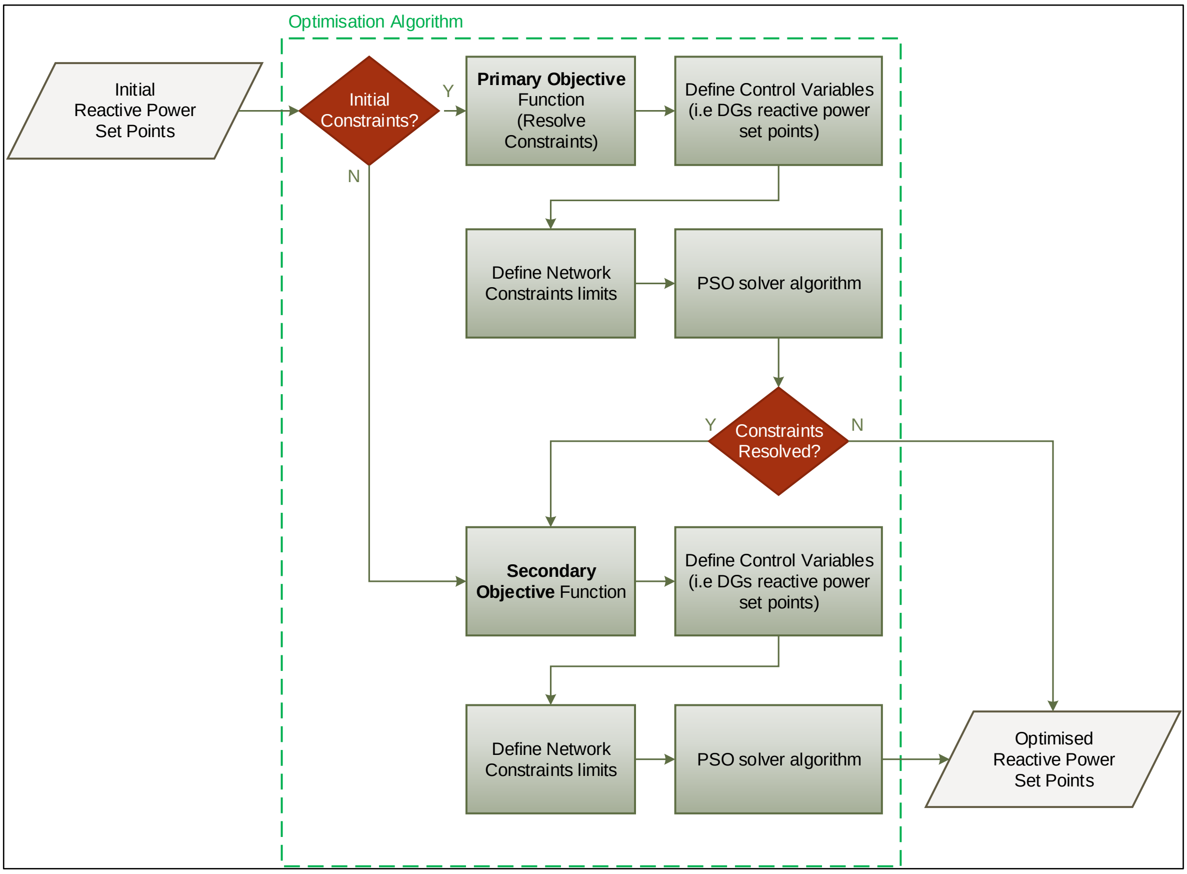

Figure 3-3 - Optimisation Algorithm

Reactive Power Assumption

A future Virtual Statcom flexibility service would require that connected generation and other reactive power devices in WPD's networks have the operational capability to export or import reactive power rather than operate with fixed power factor or reactive power output. In the development of the optimisation algorithm, it was initially assumed that the existing generators in the PSS/E models could operate across a reactive power range shown in Figure 3-4 a) as the blued shaded region. This resulted in limited reactive power being available to the optimisation algorithm in the maximum load minimum generation edge case. To ascertain the impact of reactive power in low generation scenarios the reactive power range assumption was updated to the blue shaded region in Figure 3-4 b). This reactive power range assumption does not reflect existing generators reactive power capabilities, or the modifications required to existing generators to provide a reactive power range, which is outside the scope of the project. Reactive power from other reactive devices such as capacitors, reactors, SVCs, STATCOM and MVDC links was not included as a control variable in the optimisation algorithm.

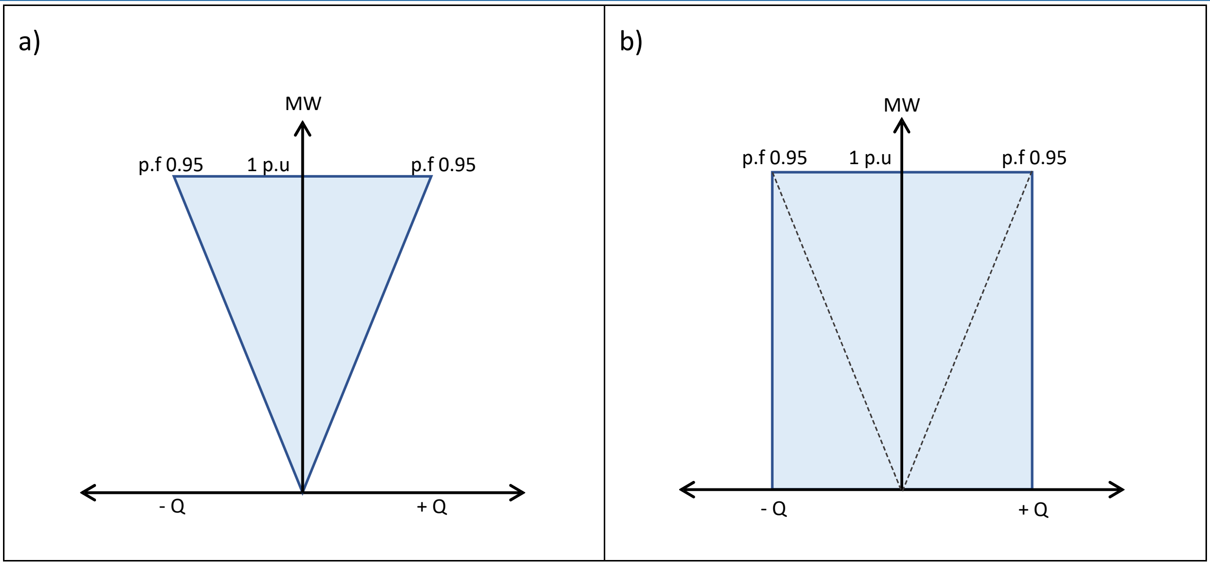

Figure 3-4 - Generator PQ capability assumption

Secondary Objective Function

The secondary objective function aim is to create headroom for generation or load by determining the optimum reactive power setpoints for existing network generators. The structure of the optimisation algorithm presented in Figure 3-3 allowed for multiple objective functions to be evaluated as part of the project.

Initially during the development of the optimisation algorithm two network level objective functions were trialled. The first aimed to increase the thermal headroom by reducing thermal loading (and therefore losses) on circuits and the second aimed increase the voltage headroom by reducing network voltages. For generation hosting these two objective functions are conflicting, in that increasing voltage headroom for generation reduces thermal headroom for generation and vice versa. Neither objective function alone resulted in increases in generation hosting capacity for all network configurations. For load hosting it was identified that the objective function to reduce thermal loading on circuits provides the greatest thermal and voltage headroom for load.

As a result of neither of the initial objective functions providing an increase in generation hosting a third objective function was trialled. The third objective function used a fixed weighting factor with the aim of obtaining a balance between increasing thermal vs voltage headroom to increase generation hosting capacity. The network's generation hosting capacity results using a fixed weighting factor objective function also did not provide capacity increases in all network configurations, showing that is it difficult to determine a fixed weighting factor for all network configurations in each network. This demonstrated a need to calculate a weighting factor that is dependent on the contingency configuration, generation and load scenario.

Power system analysis on certain network cases showed that feeder groups (i.e. feeders or feeders connected in parallel) are either thermally or voltage constrained when increasing generation. The analysis also identified that a manual reactive power dispatch could increase the generation hosting capacity of the network if the dispatch of reactive power in an individual feeder group was optimised separately to reduce its limiting constraint [5].

To fully assess a weighting factor objective function the optimisation algorithm was developed to be able to determine which feeder groups become thermally constrained and which feeder groups become voltage constrained and calculate a feeder group weighting factor. This aimed to optimise the reactive power of existing generator within a feeder group dependant on the voltage and thermal characteristics of the same feeder group – details on the implemented weighting factor objective function can be found in the Work Package 4 report [7].

3.2.3. Results and Key Findings

Virtual Statcom Studies Undertaken

The generation hosting and load hosting capacity studies were performed as part of Work Package 2. The generation hosting studies compared the following objective functions:

a) Reducing thermal loadings for each feeder group

b) Reducing voltage for each feeder group

c) Calculated weighting factor for each feeder group

The load hosting capacity studies assessed the reducing thermal loading objective function.

Virtual Statcom Optimisation Primary Objective

The results in Work Package 2 demonstrated the optimisation algorithm's primary objective can resolve or reduce constraints in networks with either a thermal loading or voltage constraint in separate feeder groups through optimised reactive power dispatch, thus reducing the amount of active power curtailment required [5]. The results identified a clear need to determine the constraints for a network at the feeder group level so that any optimisation can focus on the specific thermal loading or voltage constraint, and correctly handle situations where a feeder group has both thermal and voltage constraints.

Virtual Statcom Optimisation Secondary Objective

The results showed that no single, secondary objective function produced a generation hosting capacity increase under all system condition and configurations. The Virtual Statcom did release some generation capacity however the capacity benefit is small and depends on the specific network topology, existing generation levels and asset ratings. This identified that the Virtual Statcom solution needs to be combined with other interventions to maximise the potential for increasing the generation hosting capacity.

The results demonstrated that the reducing thermal loading objective function increases load hosting capacity. Minimising the thermal loading objective function provided a post optimisation increase in load hosting capacity for all network configurations, system generation and load profiles. The reducing thermal loading objective function also reduces network electrical losses. Reduced losses in power system networks leads to a reduction in the environmental impact of supplying electricity and lowers costs to the end customer.

Figure 3-5 quantifies the average load hosting capacity released by Virtual Statcom for each 33 kV BSP network in the maximum load minimum generation scenario, Tiverton Moorhayes 11 kV Primary load capacity released is included in Tiverton BSP. Figure 3-6 shows the load capacity released in terms of the extra domestically connected electric vehicles[5] that would be enabled to be connected in each network. It can be seen that the Virtual Statcom would enable the connection of 10,000 domestically connected EV's across the three BSP networks.

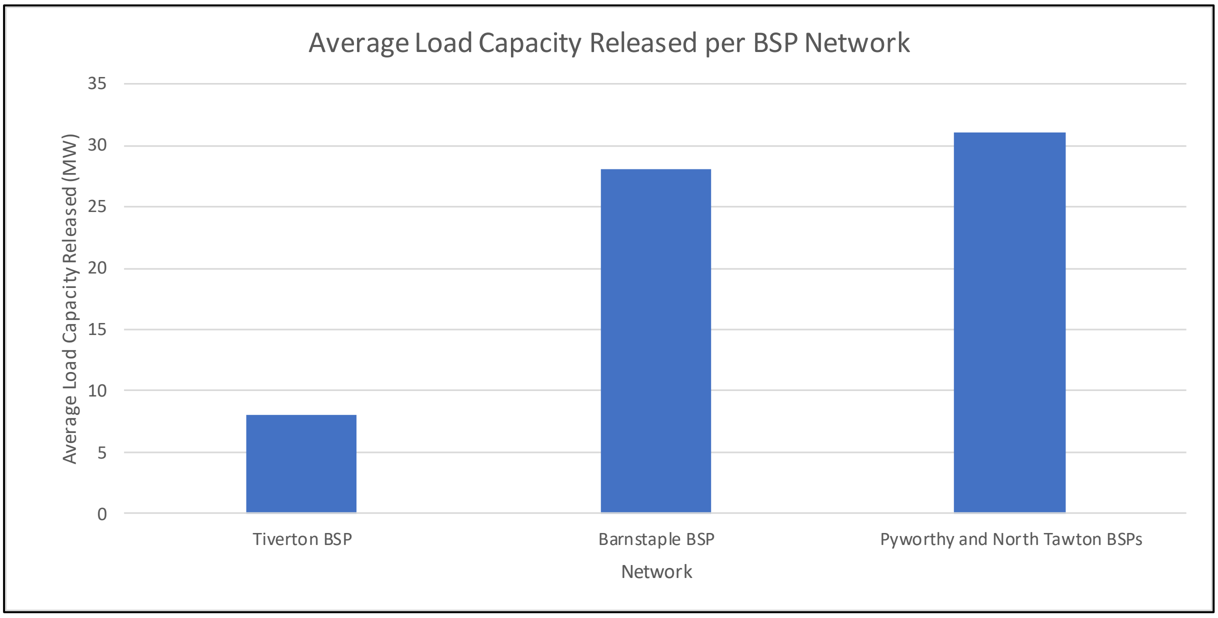

Figure 3-5- Average load capacity released by Virtual Statcom (MW)

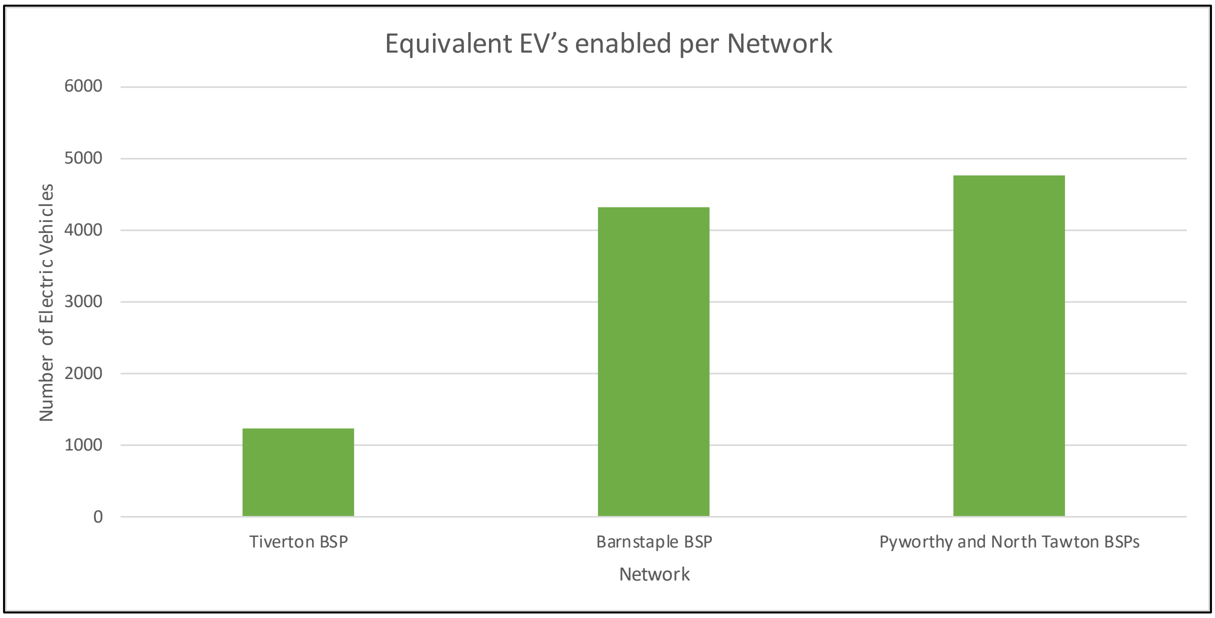

Figure 3-6 - Average load capacity released by Virtual Statcom as equivalent number of electric vehicles

[5] 7 kW domestic electric vehicle charging points have been used for the equivalent calculation.

3.3. WP3 - Graphical User Interface.

Work Package 3 developed a Graphical User Interface (GUI) to allow WPD to run the Virtual Statcom algorithms. The development of the GUI involved the integration of the Virtual Statcom hosting capacity and optimisation algorithms into a GUI so that the algorithms could be run from the GUI. Prior to this the algorithms were limited to being run from a Python software development environment.

The Virtual Statcom GUI was developed using agile development and user testing cycles and successfully delivered a GUI with the following functionality:

- Evaluation of the existing generation or load hosting capacity for a selected network zone, which is not necessarily one of the four study networks zones used in the Virtual Statcom project.
- Optimisation of existing generators reactive power using one of three objective functions developed and the evaluation of new network hosting capacity.
- The above two functions can be performed for snapshot load and generation scenarios or for time-series generation and load scenarios.
- Presents summary results and detailed results in an Excel spreadsheet output.

Details of the Virtual Statcom GUI developed are included in [6] and the IT specifications needed to run the GUI is included in Appendix A.

The development of the Virtual Statcom GUI provided several learnings that should be considered for future projects of a similar nature. The use of an agile development and testing approach when developing the GUI ensured an efficient process that met the functional and user requirements of the project. Additionally, future projects should consider prior to the onset of the GUI development; the configuration of end user systems where the GUI will be deployed, defining detailed functional requirements and defining user acceptance criteria.

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3.4. WP4 - Time Series Comparison Studies

Work Package 4 included adding time series functionality to the Virtual Statcom algorithms to allow the optimisation and per contingency hosting algorithms to be run for multiple load and generation scenarios. These scenarios being based on historic time series generation and load data with the purpose being to test the Virtual Statcom algorithms under a range of load and generation scenarios and analyse if any trends were apparent.

3.4.1. Virtual Statcom Time Series Studies Undertaken

The computational burden when performing time series studies using the Virtual Statcom is high and was considered when undertaking time series analysis. As a result, week-long periods were selected from 4 seasons for the time series studies covering all study networks with 3-hour time steps. Additionally, a more detailed time series study was performed for Tiverton 33 kV BSP covering 1 day in 1-hour time steps [7].

3.4.2. Results and Key Findings

The time series generation hosting capacity studies that compared objective functions over a single day showed that no one method of optimisation produces a benefit under all system conditions and configurations, the results were in line with the findings from Work Package 2.

The seasonal studies for the weighting factor objective function showed that there are cases where the automatic feeder group weighting factor provided benefit in some configurations but in others resulted in a reduced hosting capacity. This shows that minimisation of the weighting factor objective function does not guarantee the same or increased hosting capacity across all network configurations, generation and load scenarios. Additionally, the time series studies identified a limitation in the weighting factor calculation due to voltages not increasing linearly, it is therefore necessary to continuously reassess the network constraints as the network operation changes.

The time series load hosting capacity results showed that by optimising reactive power set points to reducing thermal loadings in a network produces a benefit under all system demand conditions and configurations. The results were in line with the findings from Work Package 2.

4. Virtual Statcom Project Conclusions

Section 3 of this report sets out the work undertaken, results and findings for the Virtual Statcom Project. The Virtual Statcom project delivered:

- **The Virtual Statcom hosting capacity algorithm** - to determine the available generation or load hosting capacity for a given network.
- **The Virtual Statcom optimisation algorithm** – to resolve or reduce network constraints and optimise the reactive dispatch for existing generators.
- **The Virtual Statcom GUI** - to run the Virtual Statcom Algorithms

The Virtual Statcom algorithms were used to investigate increasing generation and load hosting capacity for three of WPD's 33 kV BSP networks and one 11 kV Primary network:

- Barnstable 33 kV BSP
- Pyworthy and North Tawton 33 kV BSP
- Tiverton 33 kV BSP
- Tiverton Moorhayes 11 kV Primary

4.1. Virtual Statcom Hosting Capacity Algorithm

The Virtual Statcom hosting capacity algorithm can be used to determine the available generation or load hosting capacity for a given network in each contingency configuration. The algorithm is also able to be used to determine the contingency configuration with the lowest hosting capacity, termed the traditional planning hosting capacity.

4.2. Virtual Statcom Optimisation Algorithm

The Virtual Statcom optimisation algorithm has demonstrated the ability to resolve or reduce constraints in networks through optimised reactive power dispatch, this can reduce the amount of active power curtailment required to manage network constraints. There is the potential for a real time tool to use the Virtual Statcom optimisation algorithm to dispatch reactive power to resolve network constraints.

In networks with no network constraints the optimisation algorithm is able to minimise an objective function based on network power flows and bus voltages. The structure of the optimisation algorithm also allows different objective functions to be easily incorporated.

4.3. Optimisation to Increase Generation Hosting

The Virtual Statcom algorithm has shown that little generation capacity can be released by optimising the reactive power output of existing generators. A trade-off exists when optimising to increase thermal headroom and optimising to increase voltage headroom for generation. Due to this trade-off, network complexities and interactions between different feeder groups, minimising the objective function does not always provide an increase in generation hosting capacity for all network configurations, system generation and load profiles.

4.4. Optimisation to Increase Load Hosting

The Virtual Statcom has shown that load hosting capacity can be released by controlling the reactive power output of existing generators, the average hosting capacity released by the Virtual Statcom across the three BSP networks is equivalent to the domestic connection of 10,000 EV chargers[6]. The trade-off that exists when increasing generation in a network is not present when increasing load. More specifically, optimising to increase thermal headroom and optimising to increase voltage headroom for load have the same outcome of higher system voltages and lower network losses.

There is the potential for a real time Virtual Statcom tool to use optimised reactive power dispatch to reduce losses and improve the load hosting capacity of a network to serve the expected increases in load from LCTs. Reduced losses in power system networks also reduces the environmental impact of supplying electricity and lowers costs to the end customer.

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[6] This approximation is based on the installation of relatively standard, domestic 7 kW fast chargers.

5. Further Work

Throughout the development of the Virtual Statcom algorithms and analysis areas have been identified where the tool could be further developed and utilised. This section provides some further details and sets out high-level specifications for how the algorithms would need to be further developed to be trialled.

5.1. Specification for Virtual Statcom Real Time Control System

5.1.1. Distribution Network Operation Objectives

The objectives for distribution network operation can be broadly categorised into the following objectives:

- **Fundamental Operating Objective** - to supply electricity to customers with minimal disruptions, while ensuring network assets are operated safely and within allowable limits.
- **Enabling Low Carbon Technology (LCT) Objective** - to ensure that distribution networks can be operated to facilitate LCTs connections such as renewable generation; renewable generation, Electric Vehicles (EV) and Heat Pumps (HP).
- **Losses Minimisation Objective** - to operate distribution networks with losses minimised, a DNO license obligation.

5.1.2. Virtual Statcom Real Time Control System Overview

To support the distribution network operation objectives presented in Section 5.1.1, a real time control system is proposed that:

1. Uses reactive power management to reduce the amount of active power curtailment in networks when managing network constraints.
2. Uses reactive power management to reduce network losses.

The Virtual Statcom optimisation algorithms are suited to be incorporated into such a real time control system. The optimisation algorithm, presented in Section 3.2, has been developed with a primary objective of resolving constraints in a network through reactive power dispatch and then to apply a secondary objective function to the network.

A real time Virtual Statcom control system would be configured with the following two operating modes to manage reactive power.

1. Constraint Mitigation mode
2. Minimisation mode

The Constraint Mitigation Mode would be based on the Virtual Statcom optimisation algorithm's primary objective and use the reactive power available in the network to resolve or reduce network constraint(s). The ability of the real time system to resolve constraints would be dependent on the amount of reactive power available in the network at the time and the type(s) of constraints. If reactive power management is not able to resolve the constraint other network interventions would then be required.

The Minimisation Mode would be based on Virtual Statcom optimisation algorithm secondary objective and use the reactive power available in the network to minimise a selected objective function. It is expected the most appropriate would be to minimise network losses. Minimisation Mode would also run forecast analysis for a certain period ahead of time, to assess likely constraints and determine if there is sufficient reactive power available to resolve them.

The mode of operation would be determined in real time by continuously assessing the changing network conditions to identify constraints. If network constraints are identified in real time the Virtual Statcom system would run in Constraint Mitigation mode otherwise the Minimisation mode would continue.

5.1.3. Functional Requirements

Table 3-2 presents a proposed high-level design for a Virtual Statcom real time control system, it consists of 7 functional requirements, the functional requirements are described in Table 5-1.

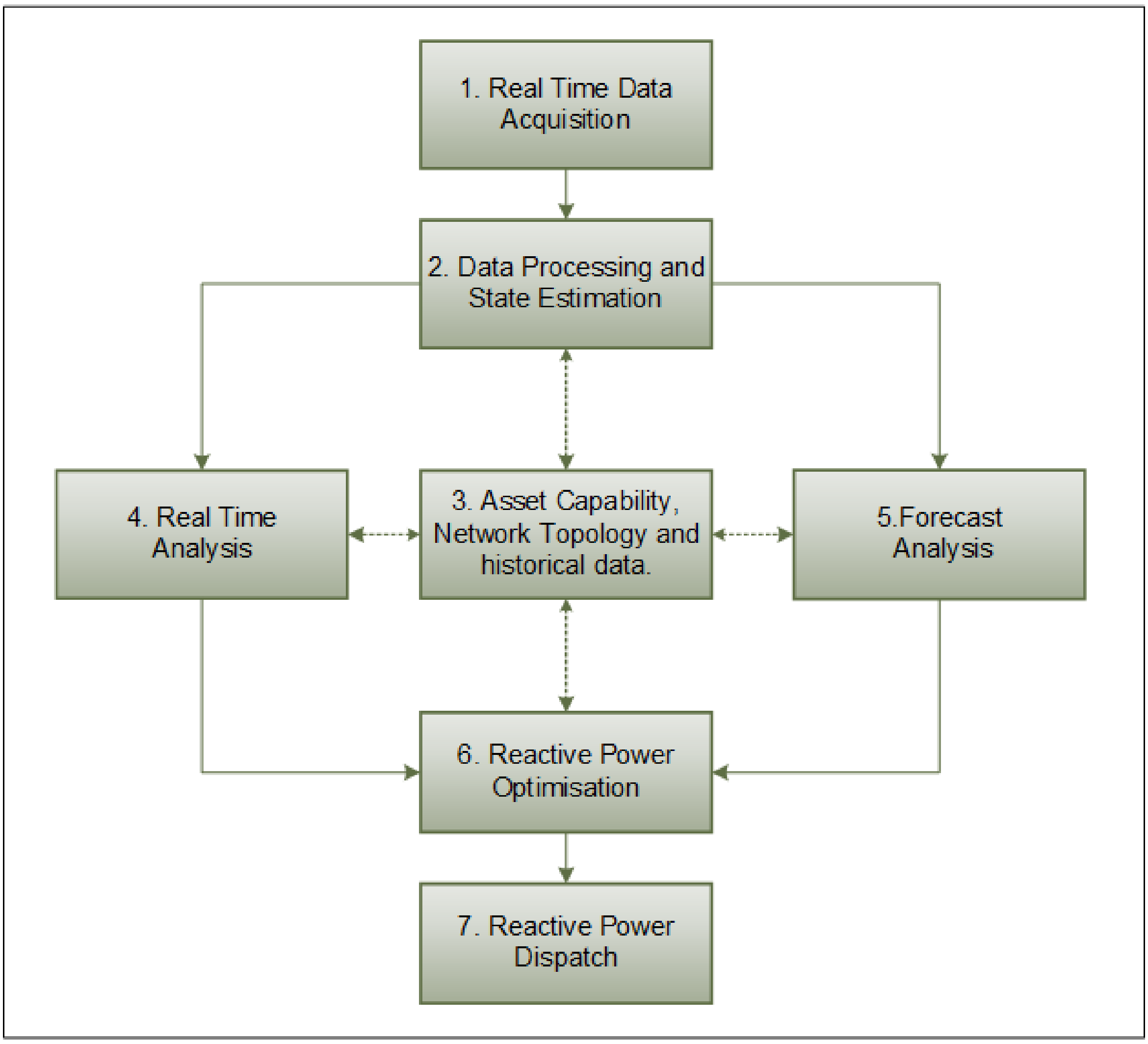

Figure 5-1 - Virtual Statcom Real Time Control System Functional Requirements Interaction

Table 5-1 - Virtual Statcom Real Time Control System Functional Requirements

Functional Requirement	Description
1. Real Time Data Acquisition	To enable meaningful real time analysis and control actions the system shall be able to retrieve real time measurement and topology data from field devices or existing SCADA systems, such as: • Network bus voltages • Network branches current flow • Generator real and reactive power • Reactive devices reactive power output • Circuit breakers position
2. Data Processing and State Estimation	The system shall be able to process retrieved data and perform state estimation[7] to create a network snapshot model suitable for power flow analysis.
3. Asset Capability, Topology and Historical Data	Store asset capability and historical data, such as: • Asset reactive power capability • Branch and transformer ratings • Network Voltage limits • Normal network operating configuration
4. Real Time Analysis	Perform power flow calculations and contingency analysis on the state estimator network model to identify network constraints.
5. Forecast analysis	Create a credible forecast network case to perform power flow calculation and contingency analysis to identify future network constraints.
6. Reactive power optimisation	Constraint Mitigation Mode – the system shall be able to optimise the available reactive power in a network model to mitigate network constraints. Minimisation Mode – the system shall be able optimise the available reactive power in a network model to minimise a pre-selected objective function (i.e. network losses).
7. Reactive power dispatch	The system shall be able to issue reactive set points to dynamic reactive power devices and switch static reactive power devices.

[7] State estimation uses statistical methods to overcome the imperfect nature of data inherent in power system networks.

5.2. Specification for Virtual Statcom Network Planning Tool

5.2.1. Distribution Network Planning Objectives

The objective of distribution network planning is to ensure that the distribution network operation objectives in Section 5.1.1 can be met for defined future planning scenarios. Future planning scenarios include forecasted generation and load edge cases[8], credible contingency configurations and the connection of new assets to the network.

5.2.2. Virtual Statcom Network Planning Tool Overview

A network planning tool that incorporates the Virtual Statcom optimisation algorithm is proposed to support distribution network planning by determining if reactive power dispatch can resolve constraints with sufficient confidence to avoid traditional network reinforcement.

A Virtual Statcom network planning tool would perform contingency analysis on a planning scenario and determine reactive power dispatch options to resolve constraints that arise. The tool would be able to assess new generation connections reactive power requirements and identify and assess network locations where reactive support could resolve constraints.

5.2.3. Functional Requirements

Figure 5-2 presents the proposed high-level design of a Virtual Statcom network planning tool, it consists of 3 function groups for which further detail is provided in Table 5-2:

1. Planning Base Case Network Configuration
2. Power System Analysis
3. Reactive Power Optimisation

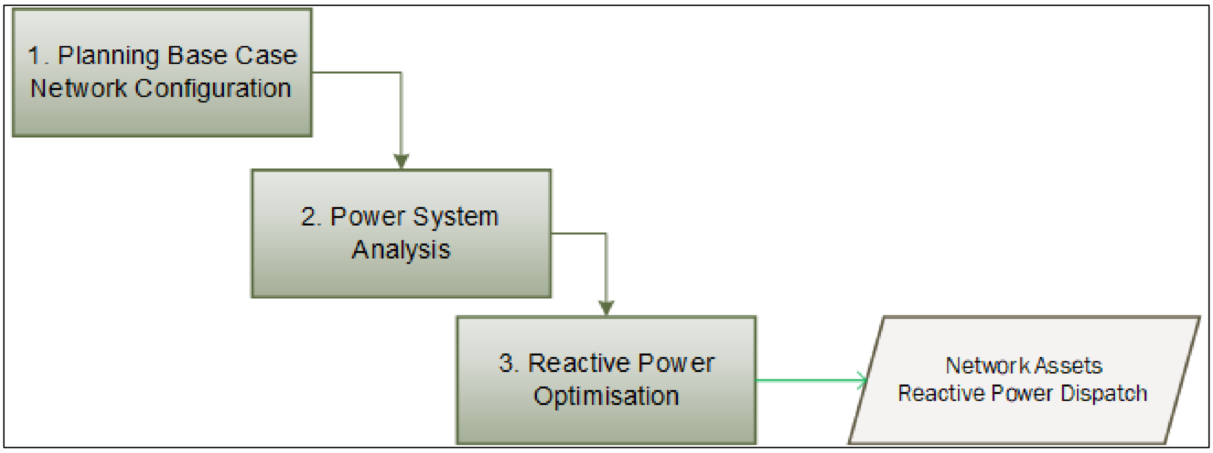

Figure 5-2 - Virtual Statcom Network Planning Tool Functional Requirements Interaction

[8] With the development and integration of the distribution future energy scenarios during RIIO-ED2 the number and variability of these edge cases are likely to increase.

Table 5-2 - Virtual Statcom Network Planning Tool Functional Requirements

Functional Requirement	Description
1. Planning Base Case Network Configuration	The tool shall be able to import planning scenarios cases and add new generation and/or configure existing reactive power devices to the network such as: • Generators • Statcom • MVDC links
2. Power System Analysis	The system shall be able to perform power flow calculations and contingency analysis on planning scenarios case to identify network constraints. This should have the ability to automatically vary the load and generation dispatch to cover identified operating edge cases.
3. Reactive Power Optimisation	The system shall be able to optimise the available reactive power in a network model to mitigate network constraints.

5.3. Trial Considerations

Sections 5.1 and 5.2 have presented specifications for proposed real time system control system and a network planning tool that are suitable for trial operation. This section presents the considerations needed when undertaking a trial of the specified real time system and the network planning tool.

5.3.1. Virtual Statcom Real Time System

Criteria for Suitable Trial Networks

The following criteria must be assessed when determining the suitability of networks to be included in a Virtual Statcom real time control system trial, the criteria are listed in order of precedence:

1. The availability and controllability of reactive power sources in the network.
2. The availability of real time network data
3. The historical losses of the network

The availability and controllability of reactive power sources in a network is vital to conduct a trial of the Virtual Statcom real time system as dispatch of reactive power is the output of the real time system. Where possible networks should be selected for a trial that have a high number of controllable reactive power sources.

The ability of a real time control system to undertake meaningful analysis and control action is underpinned by the availability and accuracy of real time data provided to the tool. Efforts should be made to selected networks for a trial that have high availability of real time measurement and topology data.

When no constraints are present in a network the Virtual Statcom real time control system will be configured to reduce the network losses. Networks with historically high losses would be suitable to determine the effectiveness of the control system to reduce losses. Additionally, theoretical constraints may be needed to demonstrate the effectiveness of the control system during a trial.

The following is an example network evaluation matrix, based on the above network selection criteria, that could be used to determine networks that are suitable for a trial. Example networks have been included to demonstrate networks that are an ideal candidate, realistic candidate or not suitable to be a trial network.

Table 5-3 - Trial Network Evaluation Matrix

Criteria	Network 1	Network 2	Network 3	Network 4	Network 5
Reactive power devices	✓	✓	✓	✓	✗
Controllable reactive power	✓	✓	✗	✓	-
Reactive power dispatchable from DNO control centre	✓	✗	✗	✗	-
High availability of real time network data	✓	✓	✓	✗	✓
High historical losses	✓	✓	✓	✓	✓
	Ideal Candidate	Realistic Candidate	Realistic Candidate	Realistic Candidate	Not Suitable

Network Upgrades to Facilitate Trial

A fully ready ideal candidate network is unlikely to exist, but existing innovation project trial networks could be utilised to minimise the requirements for additional network upgrades, such as network with active network management (ANM) or system voltage optimisation (SVO) control systems.

If network upgrades are required, they would need to focus on ensuring that reactive power devices in a trial network have the capability to operate over a reactive power range and that the reactive power can be dispatched from a DNOs control centre.

Ensuring that reactive power devices have the capability to operate over a reactive power range could require the following:

- Upgrading or enabling settings in existing control systems.
- Retro fitting reactive power control systems to existing reactive power devices.
- Installation of new reactive power devices.

To ensure that reactive power can be dispatched from DNO control centres two-way communication systems would be required to be upgraded or installed to allow:

- Data retrieval and signal exchange with network reactive devices.
- Dispatch instruction to be issued to network reactive devices.

Engagement with Distributed Reactive Power Device Operators

Customers would need to be engaged to determine the willingness to upgrade their assets and make them dispatchable from a DNO control centre. Customers would also need to be engaged to test reactive power capability and dispatchability of assets.

Interaction with Existing Control Systems

The Virtual Statcom real time control system will affect network voltages and power flows, so the interactions between the Virtual Statcom control system and existing control systems must be considered in the design of Virtual Statcom control system. A network control philosophy or hierarchy of network control actions also needs to be considered to avoid unintended control actions.

5.3.2. Virtual Statcom Network Planning Tool

Criteria for Suitable Trial System

All networks with reactive power devices would be suitable to be for a trial of the Virtual Statcom network planning tool. However, the greatest effectiveness will likely be demonstrated in networks that have high levels of existing DG and are experiencing capacity issues. The tool will then have the greatest option to demonstrate how alternative reactive power dispatch options can be used as an alternative to traditional network reinforcement.

Engagement with Reactive Power Connection Providers

The trial project would need to engage with customers to determine the willingness and costs associated with providing reactive power capability. This would also establish the real capability that can be obtained and optimum operational approaches. During the network planning processes and demonstration this could be both existing customers who may wish to participate in a reactive power market as well as new customers who are granted new connections with reactive power operating requirements during particular contingencies, the latter being a similar approach to existing ANM schemes.

6. Next Steps

This project has shown that the Virtual Statcom can enable DNOs to increase the capacity of networks to be able to host more low carbon technologies as well as reducing the overall network losses. To realise the benefits of this project and the potential for value to UK consumers a demonstration project is being considered. The key next steps for the demonstration project are the planning of:

1. A development/design phase
2. An implementation phase
3. A network trial phase

Taking this project forward as a demonstration project offers a great opportunity to further develop the learnings from this project. The project would aim to take these concepts, learning and tools developed to investigate and demonstrate the potential value to consumers of operating as a DSO and facilitating increased levels of low carbon technologies. The project team are currently working on the development of the demonstration project.

7. References

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Appendix A IT specification

The Virtual Statcom algorithms are designed to be run on a standard windows machine but, due to the number of power flow calculations being run for a study, can be quite computationally intensive. Additionally, when running multiple time series studies with a range of contingencies this can further increase. Algorithm optimisation is possible through the use of parallel processing / cloud-based computation but would require a dedicated system to be developed with algorithms to control the dispatching and processing of results between machines.

The main limitations on the performance of the Virtual Statcom algorithms come down to the CPU processing speed with the secondary factor being the system memory for storage of results. The size of the network model (number of buses) has an increase in the study time due to the duration for a load flow study to be completed and reach a convergent solution. The secondary factor is the amount of system memory required for the processing of the studies and results but since PSS/E is a relatively space efficient power system processing tool this is unlikely to take the requirements above those typically available on a modern high-performance machine.

The following tables sets out some details of the high-performance machine used by PSC during this Virtual Statcom project and the requirements of a standard windows machine

High-Performance Machine Specification:

Operating system	Windows 64bit
Storage space used	600 MB
Python Version	2.7
Processors	32 (AMD Ryzen Threadripper)
Cores Per Processor	1 (3.0 GHz)
System memory (RAM)	32 GB DDR4

Standard Machine Specification:

Operating system	Windows 64bit	
Free storage space	600 MB	
Python Version	2.7	
	Minimum	Recommended
Processors	Intel i5 or AMD Ryzen 5	Intel i7 or AMD Ryzen 7
System memory (RAM)	4GB	16 GB