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Virtual Statcom:
Work Package 2 Report

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Client Reference	**NIA_WPD_37**
PSC Reference	**JK7261-TR-03 Rev 03**
Date	**15/11/2019**

List of Revisions

Revision	Date	Description of changes
0A	06/09/19	Draft plan/skeleton sent to WPD for comment
01	07/10/2019	Draft version sent to WPD for comment
02	12/11/2019	Revision 2 issued to WPD for approval
03	15/11/2019	Final revision (page numbers corrected)

Revision	Date	Signatures		
		Author	Peer Review	Approved
01	07/10/2019	Grant McCormick	David Mills	David Mills
02	12/11/2019	Grant McCormick	David Mills	David Mills
03	15/11/2019	Grant McCormick	David Mills	David Mills

Executive Summary

Political and social forces in the UK are driving the change towards clean low carbon technologies such as renewable generation. As renewable distributed generators (DGs) 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 is an innovation project that seeks to investigate the technical feasibility of increasing the network hosting capacity, for both generation and load, by the optimising the reactive power dispatch of DGs.

As part of this investigation two main algorithms have been developed. The first is an algorithm to determine the generation and load hosting capacity of a network and the second is an algorithm to optimise the reactive power dispatch of existing generators. The optimisation is undertaken at a network level and based on either reducing thermal loadings, reducing bus voltages deviation from the nominal voltage or a combination of both by using a weighting factor. The algorithms developed allow for comparisons of the network's load and generation hosting capacity to be made between the original reactive power dispatch and new optimised reactive power dispatches.

Hosting comparison simulations have been undertaken for the following WPD networks, selected for different characteristics:

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

The comparison studies identified the following key findings:

- A limitation exists in in the hosting capacity algorithms approach that can cause post optimisation increases to be overstated.
- Using optimised reactive power dispatch determined on a network level for losses and/or voltage deviation affects a network's hosting capacity but does not guarantee an increase in all network configurations.
- The optimisation weighting factor is very sensitive to different load and generation scenarios and network configurations.
- In some networks, limited reactive power exists from the existing generation and greater benefit may be achieved through reactive power control of future generation.

To address the key findings and fully investigate the potential of the Virtual Statcom concept it is proposed to:

- Revise the hosting algorithms approach when network limits are initially breached for a given load and generation scenario.
- Implement a feeder-group based Virtual Statcom optimisation as opposed to the current network-based optimisation and an algorithm to calculate the voltage vs thermal loading weighting factor for each network configurations.
- Implement an option to optimise the reactive power from newly connected generation introduced by the hosting algorithms.

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1 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
Statcom	Static Synchronous Compensator
UKPN	United Kingdom Power Networks
VBA	Visual Basic for Applications
WP	Work Package
WPD	Western Power Distribution

2 Introduction

2.1 Introduction to the project

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

As an increasing number of distributed generators (DGs) connect to distribution networks, technical constraints arise that can limit the total amount of generation a network can host. To overcome the technical constraints associated with distributed generators 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 is 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.

If the project demonstrates benefit it will enable more generation and load to be connected to the distribution network without the need for network reinforcement.

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

- WP1 - Data gathering/validation and study zone selection.
- WP2 - Power flow simulations & Virtual Statcom algorithms.
- WP3 - Graphical User Interface.
- WP4 - Time series comparison studies.
- WP5 - Virtual Statcom feasibility study reporting.

The work packages are being delivered in order.

2.2 Structure of this report

This report details the work completed in delivering Work Package 2 - Power flow simulations & Virtual Statcom algorithms.

- Section 3 provides background to the project and explains the motivation and concept of the project.
- Section 4 presents the networks selected for this project and assessments of each network for different load and generation scenarios. The selected study networks are:
  - Barnstable 33 kV Bulk Supply Point
  - Pyworthy and North Tawton 33 kV Bulk Supply Point
  - Tiverton 33 kV Bulk Supply Point
  - Tiverton Moorhayes 11 kV Primary
- Section 5 details the hosting capacity algorithms developed and presents the hosting capacities for the selected study networks.

- Section 6 presents the optimisation algorithm developed using a particle swarm optimisation engine to calculate reactive power set-points for existing generators in the selected network.
- Section 7 analyses the results from the Virtual Statcom and determines if hosting capacity is increased after optimisation of the reactive power dispatch in the selected study networks.
- Section 8 presents the conclusions and recommendations from Work Package 2.

3 Virtual Statcom project background

3.1 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 was that power flows were always considered in a single direction, notably from a higher voltage sources towards lower voltage loads.

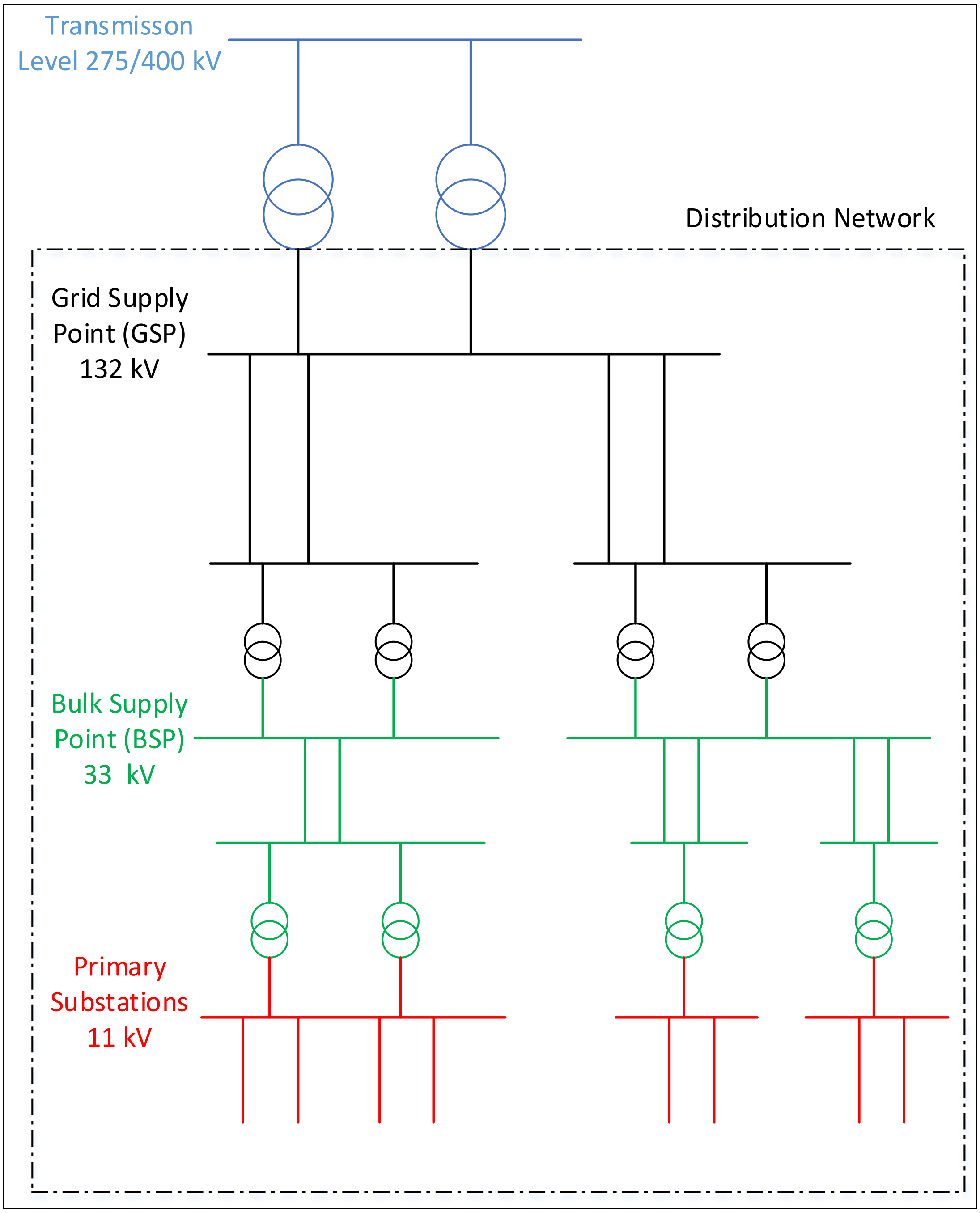


Figure 3-1 - Distribution Network layout

3.2 Accommodating Distribution Connected Generation

The past 10-20 years has seen an increase in generators connected to distribution networks, known as Distributed Generators (DGs). In WPD's South West network DGs predominantly consist of renewable generation (i.e. wind, solar) connected at 33 kV and 11 kV voltage levels. The increase of DGs changes the key characteristic of passive distribution networks. Power will now flow in either direction and is dictated by changing loads and generation which can be intermittent in nature.

The uptake of DGs provides benefits of low carbon energy. Initially, it can also help relieve network thermal constraints by supplying power closer to the load centres. This can therefore reduce loadings on upstream lines, cables and transformers. However, distribution networks cannot accommodate ever increasing connections of DGs. Aside from the practical considerations such as land availability and favourable sites for wind or solar irradiance, technical factors will constrain the total amount of DGs that can be connected.

A terminology used to quantify how much generation a network can accommodate is "hosting capacity" [1] [2]. The **Hosting Capacity** of a network is defined as the total amount of distributed generation that the network can accommodate without violating predefined operational, physical and statutory limits.

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.

3.2.1 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 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. ($P_g < P_d$)
  - When the real power of the generator is equal to the load. ($P_g = P_d$)
  - When the real power of the generator is greater than the load. ($P_g > P_d$)

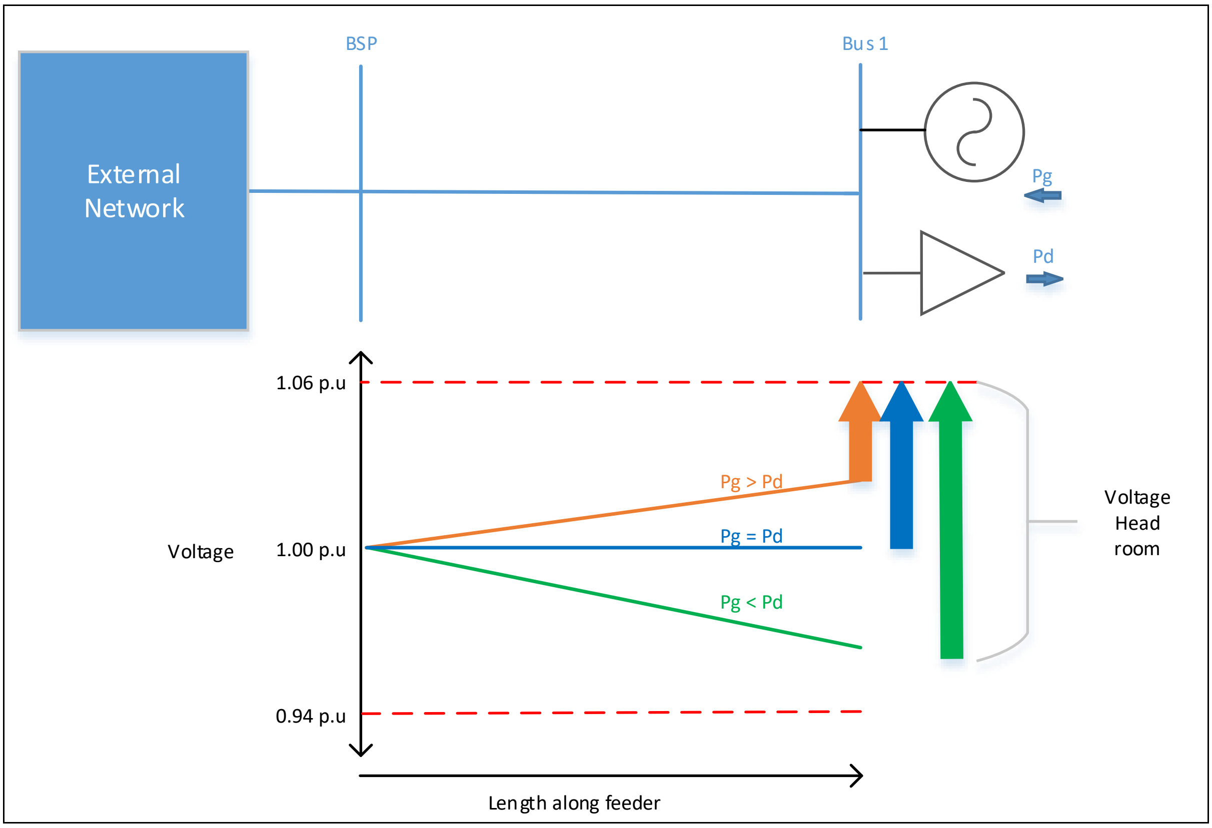


Figure 3-2 - Voltage head room

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

3.2.2 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 also limit the size of DG on a feeder and hence hosting capacity. These voltage step constraints will be incorporated in to the Virtual Statcom project.

3.2.3 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.

3.2.4 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 therefore will not be considered any further in the Virtual Statcom Project.

3.2.5 Power Quality

By increasing DG connections, there is the potential to 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 DG sources. Specific issues associated with power quality are not part of the scope of this project and therefore will not be considered any further in the Virtual Statcom Project.

3.3 Techniques to Increase Hosting Capacity

The traditional means to increase hosting capacity is to undertake network reinforcements - 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.

It is worth nothing that non-firm connections that require active power curtailment under certain system conditions which are becoming more prevalent in distribution networks, increase the total installed generation however, do not increase a network's hosting capacity.

3.4 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). While this is appropriate for the extreme case of maximum generation and minimum load this fixed power factor may not be appropriate for all network conditions. This is the fundamental concern that the Virtual Statcom project aims to investigate. The concept of the Virtual Statcom is to assume 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, the hosting capacity can be increased.

4 Assessment of Selected Networks

4.1 Selected study networks

The Virtual Statcom project focuses on WPD's Southwest region model. The network model has 42 BSPs and eight Primary substations that have been modelled as part of the WPD's Network Equilibrium project. Three BSPs and one Primary were selected as study zones for the Virtual Statcom project. The aim in selecting networks was to select networks with different characteristics to test the applicability of the Virtual Statcom methodology across a range of network scenarios, 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, for more detail on the networks selected networks refer to the WP1 report [4]. Table 4-1 presents the networks selected as study networks for the Virtual Statcom project and the reasons for selection.

Table 4-1 - 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 BSP 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.

4.2 Context of Analysis for Virtual Statcom Project

Power system analysis of each study network was undertaken. The purpose of the analysis was to identify if any power system network violations or constraints are present in the networks for given load and generation scenarios. Violations and constraints that are identified provide an indication of the study networks' ability to host increased levels of load and generation before proceeding with the simulation of hosting capacity and Virtual Statcom algorithms. Only violations in each study network are considered, for clarity this includes the grid connection transformer branch and all connected branches and busses downstream.

4.2.1 Assessment Methodology

Four intact system cases were developed with different combinations of minimum/maximum load and generation. The four cases used for the power system analysis were:

- Maximum load – Minimum generation
- Minimum load – Maximum generation
- Minimum load – Minimum generation
- Maximum load – Maximum generation

The cases developed represent operational edge cases scenarios and are used to identify network constraints/violations. The cases are based on the loads provided in the original WPD PSS/E model, the generators installed capacity and minimum load scaling factors from the Long Term Development Statement - Nov 2018 (LTDS). Details of the how each case was developed and the load and generation details for each case is included in Appendix A.

Analysis of each study network under multiple network configurations was also performed. The first network configuration considered is the intact configuration with equipment in the normal operating configuration (connected as per SLDs in LTDS) and subsequent configurations consider the intact network configuration with one power system component (or group of components) removed. The power system component (or group of components) removed is known as a contingency. The contingencies considered in the analysis are a single circuit, a single transformer/voltage regulator and a single generator (for voltage step limits). Appendix B provides a detailed list of the contingencies considered for each study network, note that bus sections are not considered as a contingency for the Virtual Statcom project as the loss of a bus section results in the loss of multiple circuits.

The analysis was performed using Siemens Power System Simulator for Engineering (PSS/E) software. The software was used to provide a full steady state alternating current (AC) power flow solution of the intact network and contingency configurations for each operational scenario. The power flow solution calculates the bus voltages and power flows on branches (lines and transformers) for the network which were assessed against thermal, voltage and voltage step limits. The limits used in the studies (see Appendix C) are based on equipment ratings and statutory requirements set out in the Electricity Safety, Quality and Continuity Regulations 2002.

4.2.2 Power System Analysis Assumptions

The most significant assumption that affects the results that are presented in this section is that post contingent actions have not been modelled or simulated to resolve network violations identified. However, PSC notes that in the operation of their networks WPD have operational processes, policies and procedures available such as inter-trips, network reconfiguration, special protection schemes and generator runback schemes to manage network violations both pre and post contingency, should they arise. For the full list of assumptions for the power system analysis see Appendix C.

4.3 Barnstaple 33 kV BSP Network Assessment Summary

4.3.1 Network Overview

Barnstaple 33 kV BSP supplies five feeder groups as shown in Figure 4-1, the BSP is fed from two 132/33 kV transformers. The network model has eight generators at 33 kV with a total installed capacity of 48 MW, embedded generation in the 11 kV primary networks is modelled across the 11 kV primary buses with a total installed capacity of 12 MW. The network experiences a load range from a minimum load of 15 MW to a maximum load of 46 MW and has a firm capacity of 68.6 MVA. Details of the individual loads and generation for the 33 kV and 11 kV sites in Barnstaple BSPs are provided in Appendix A.

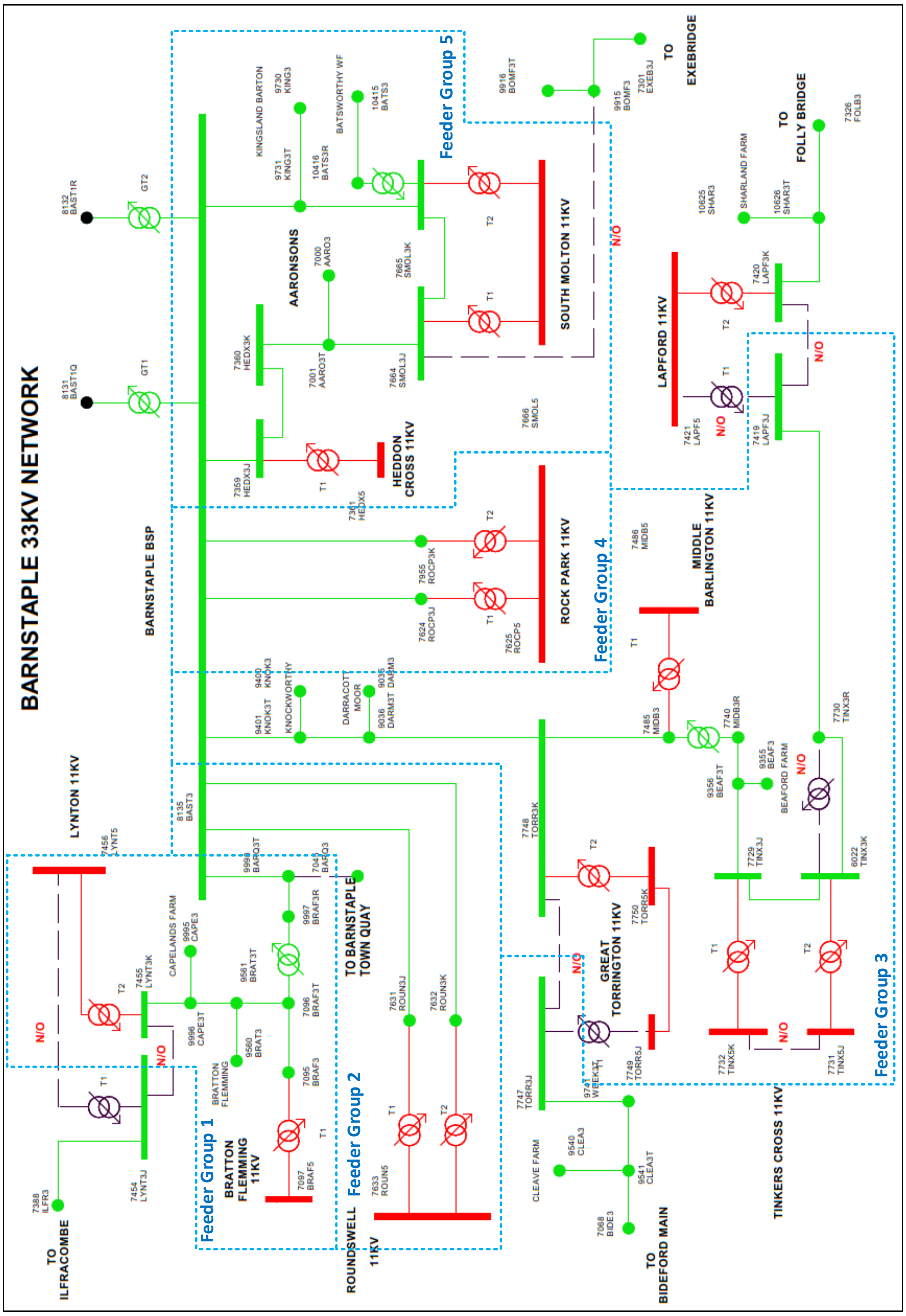


Figure 4-1 - Barnstaple 33 kV BSP feeder groups (normal operation)

4.3.2 Intact Configuration Assessment Summary

The power system analysis identified one thermal violation that was present in the two cases with maximum generation for Barnstaple 33 kV BSP network in the intact configuration. No violations were identified in the intact configuration for the two cases with minimum generation.

Initial power system analysis during work package 2 (WP2) identified voltage violations in the intact system. Further analysis, with the study network transformers taps initially set to their nominal tap position (then allowed to auto tap during the power flow calculation), resolved the earlier voltage violations identified. All network analysis has been undertaken with the study networks' transformers initially set to their nominal tap position, for further details on this see Appendix C.

The violation identified in the intact configuration shows that, cases with maximum generation with Barnstaple 33 kV BSP network in the intact configuration, there is no additional generation capacity available downstream of the Batsworthy voltage regulator. The detailed analysis of the Barnstaple 33 kV BSP network is provided in Appendix D.

4.3.3 Contingency Configurations Assessment Summary

The power system analysis identified multiple thermal violations for contingency configurations of Barnstaple 33 kV BSP network in the minimum load maximum generation case and one thermal violation was identified in the maximum load maximum generation case. No contingency configurations violations were identified in the two cases with minimum generation.

The contingency configurations violations identified further introduce restrictions for feeder group 5. The detailed analysis of the Barnstaple 33 kV BSP network is provided in Appendix D.

4.3.4 Barnstaple 33kV BSP Power System Analysis and Hosting Capacity Impact

The intact and contingency violations identified in the power system analysis indicates that for scenarios where there is high generation and low load, the generation hosting capacity is restricted on Barnstaple feeder groups 5 and may require operational measures to manage. No restrictions on generation hosting capacity were identified for the Barnstaple feeder groups 1 to 4 for the cases analysed.

4.4 Pyworthy and North Tawton 33 kV BSPs Network Assessment Summary

4.4.1 Network Overview

Pyworthy and North Tawton 33kV BSPs are normally operated in a meshed configuration and supply five feeder groups as shown in Figure 4-2, the meshed BSPs are fed from three 132/33 kV transformers at Pyworthy and one 132/33 kV transformer at North Tawton. The network model has 16 generators at 33 kV with a total installed capacity of 98 MW, embedded generation in the 11 kV primary networks is modelled across the 11 kV primary buses with a total installed capacity of 49 MW. The network experiences a load range from a minimum load of 21 MW to a maximum load of 70 MW. The firm capacity of Pyworthy and North Tawton BSPs are 100.6 MVA and 71.5 MVA respectively. Details of the individual loads and generation for the 33 kV and 11 kV sites in Pyworthy and North Tawton BSPs are provided in Appendix A.

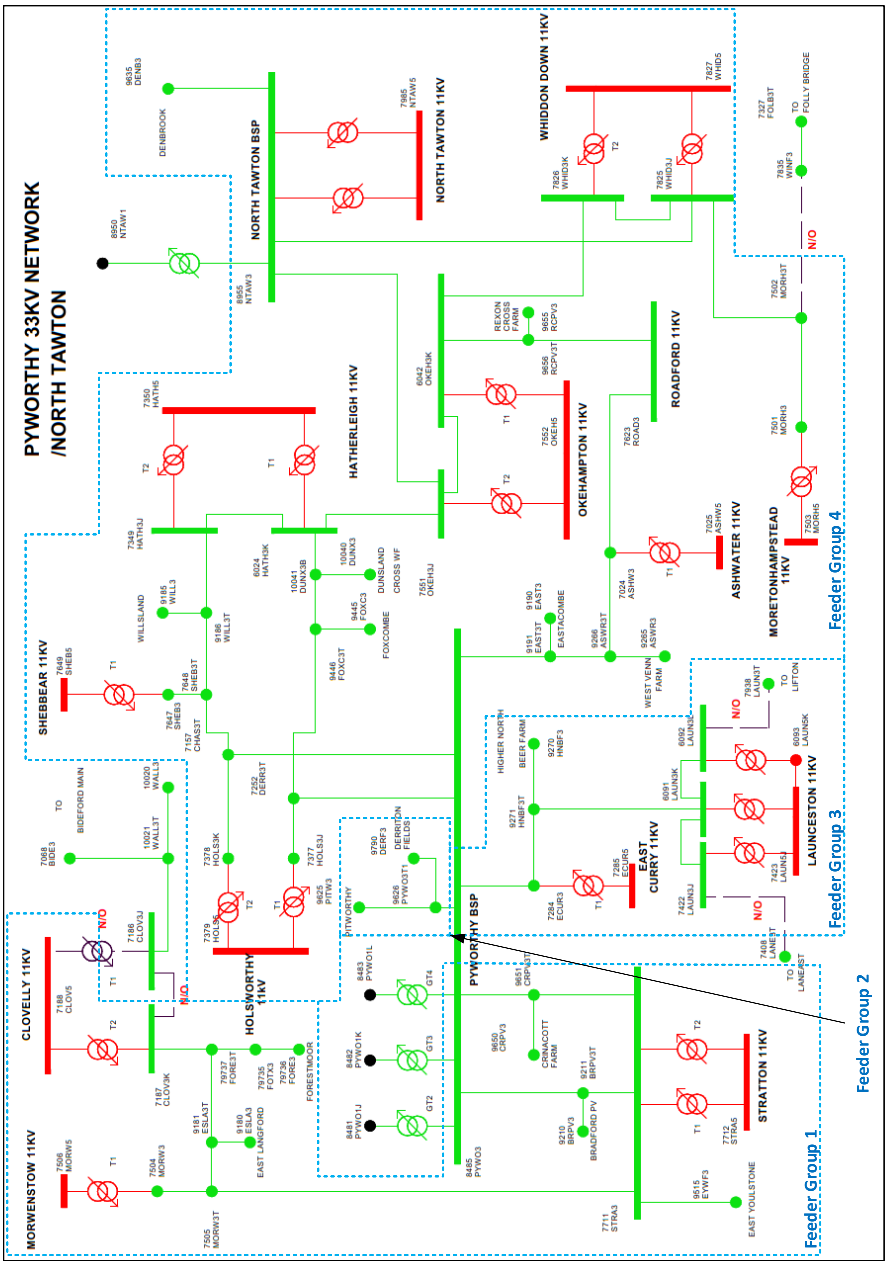


Figure 4-2 – Pyworthy and North Tawton 33 kV BSP feeder groups (normal operation)

4.4.2 Intact Configuration Assessment Summary

The power system analysis identified two reverse power flow violations on 33/11 kV primary supply transformers in both the minimum load maximum generation case and maximum load maximum generation case for Pyworthy and North Tawton 33 kV BSP network the intact configuration. No intact configuration violations were identified in the two cases with minimum generation.

The intact configuration violations identified show that traditional reinforcement methods or primary network reconfigurations may be required for embedded generation at the 11 kV levels in the minimum load maximum generation case. These reverse power flow violations do not affect the generation hosting capacity for 33 kV generation in the feeder groups. The detailed analysis of the Pyworthy and North Tawton BSPs network is provided in Appendix E.

4.4.3 Contingency Configuration Assessment Summary

The power system analysis identified multiple thermal and voltage violations for contingency configurations of Pyworthy and North Tawton 33 kV BSPs network in the minimum load maximum generation case. No contingency violations were identified in the two cases with minimum generation.

The contingency violations identified restrict the generation hosting capacity of feeder group 1 and introduce restrictions for feeder group 4. The detailed analysis of the Pyworthy and North Tawton BSPs network analysis is provided in Appendix E.

4.4.4 Pyworthy and North Tawton 33kV BSP Power System Analysis and Hosting Capacity Impact

The contingency violations identified in the power system analysis indicates that for scenarios where there is high generation, that the generation hosting capacity is restricted on feeder group 4 and may require operational measures to manage. No restrictions on generation hosting capacity was identified for the Pyworthy and North Tawton feeder groups 1, 2 and 3 for the cases analysed.

4.5 Tiverton 33 kV BSP Network Assessment Summary

4.5.1 Network Overview

Tiverton 33 kV BSP supplies three feeder groups as shown in Figure 4-3, the BSP is fed from two 132/33 kV transformers 132/33 kV. The network model has four generators at 33 kV with a total installed capacity of 19 MW, embedded generation in the 11 kV primary networks is modelled across the 11 kV primary buses a with a total installed capacity of 25 MW. The network experiences a load range from a minimum load of 15 MW to a maximum load of 50 MW. The firm capacity of Tiverton BSPs is 67.5 MVA. Details of the individual loads and generation for the 33 kV and 11 kV sites in Tiverton 33 kV BSP are provided in Appendix A.

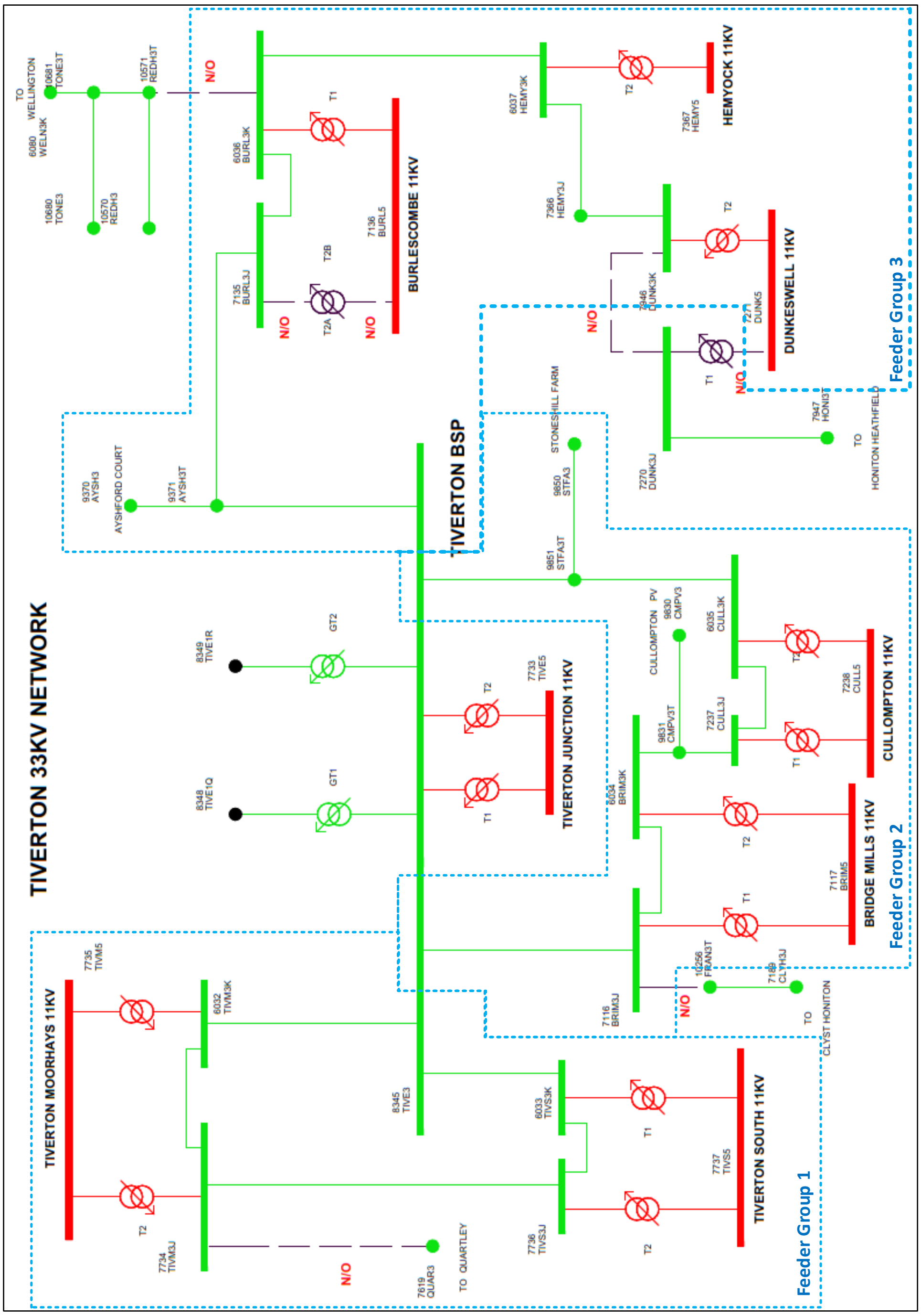


Figure 4-3 - Tiverton 33 kV BSP feeder groups (normal operation)

4.5.2 Intact Configuration Assessment Summary

The power system analysis identified no violations for the Tiverton 33 kV BSP network in ‘the intact system configuration in the four cases analysed.

4.5.3 Contingency Configuration Assessment Summary

The power system analysis identified no violations for the Tiverton 33 kV BSP network in contingency configurations in the four cases analysed.

4.5.4 Tiverton 33kV BSP Power System Analysis and Hosting Capacity Impact

No intact or contingency violations were identified for the Tiverton 33 kV BSP network in the four cases analysed. This indicates that there is voltage and/or thermal headroom available for increased generation hosting on each of the three feeder groups for the combinations of load and generation analysed.

4.6 Tiverton Moorhayes 11 kV Network Assessment Summary

4.6.1 Network Overview

Tiverton Moorhayes 11 kV Primary network consists of a main 11 kV bus with six radial feeders in normal operation, the primary network is supplied by two 33/11 kV Transformers. Tiverton Moorhayes primary has a firm capacity of 14 MVA. The Tiverton Moorhayes primary SLD has not been included here as it is does not scale well to fit but is included in Tiverton Moorhayes 11 KV Network (PSS/E SLD). The network model has 2 generators at 11 kV with a total installed capacity of 1.95 MW. The network experiences a load range from a minimum load of 1.9 MW to a maximum load of 6.4 MW. Further details of the loads and generation are provided in Appendix A.

4.6.2 Intact Configuration Assessment Summary

The power system analysis across the four cases identified only one thermal violation for the Tiverton Moorhayes 11 kV network in the intact system configuration for the maximum load minimum generation case. The violation identified shows there is a load hosting constraint on one of the feeders. The detailed analysis of the Tiverton Moorhayes 11 kV Network Analysis is provide in Appendix F.

4.6.3 Contingency Configuration Assessment Analysis Summary

For the power system analysis of the Tiverton Moorhayes 11 kV Primary network each feeder and 33/11 kV supply transformer is treated as contingency. No contingency violations for Tiverton Moorhayes 11 kV Primary network where identified, but each contingency results in the loss of load and generation connected to the contingency feeder.

4.6.4 Tiverton 11 kV Primary Power System Analysis and Hosting Capacity Impact

The intact system violation identified for the Tiverton Moorhayes 11 kV Primary indicates there is a load hosting constraint on one of the feeders. However, no violations were identified that show the generation hosting capacity of any of the radial feeders has been exceeded in the four cases analysed. This indicates that there is voltage and/or thermal headroom available for increased generation hosting on each of the 6 radial feeders for the combinations of load and generation analysed.

4.7 Load and Generation Scenario Violations Assessment Summary

Table 4-2 provides a summary of violations identified in the selected networks in the assessments under the four load and generation scenarios presented in Section 4.2. Note that table only provides a summary of the load and generation scenarios where violations were identified. No thermal or voltage violations for the intact system or contingency configurations were identified for Tiverton 33 kV BSP network in the four load and generation scenarios assessed.

Table 4-2 - Selected network violations summary

Network	Load/Generation Scenario	Constraints in intact system?	Constraints in contingency configurations?
Barnstaple 33 kV BSP	Min Load Max Gen	YES (I)	YES (I)
	Max Load Max Gen	YES (I)	YES (I)
Pyworthy and North Tawton 33 kV BSP	Min Load Max Gen	NO	YES (I, V)
Tiverton Moorhayes 11 kV Primary	Max Load Min Gen	YES (I)	YES (I)

(I) =Thermal violation
(V) =Voltage violation

5 Network Capacity Hosting Algorithms

To determine the benefit of the Virtual Statcom, it is necessary to be able to compare the existing network hosting capacity before and after the Virtual Statcom algorithm optimises the reactive power output of existing generators. This section presents the algorithms developed in the Virtual Statcom project to calculate a networks' hosting capacity and the hosting capacity for each study network.

The algorithms are based on concurrent iterative scaling methodology and algorithm design set out in the Virtual Statcom Work package 1 report [4] but have been further developed throughout Work Package 2. The algorithms calculate the generation and load hosting capacity for the following scenarios; traditional network planning, intact system and per contingency configurations.

5.1 Hosting Capacity Scenarios

The generation and load hosting capacity algorithms developed consider 3 scenarios namely; the traditional planning hosting capacity, the intact system configuration and per contingency configurations hosting capacity.

Traditional Planning Hosting Capacity

The traditional planning hosting capacity is the maximum amount of concurrent generation or load that a network can accommodate such that there are no thermal, voltage or voltage step violations in the intact system configuration or any possible network contingency. This provides a very conservative estimate of the capacity that could be released in every possible running arrangement. The contingencies considered in the algorithms are an outage on a single circuit, transformer/voltage regulator or generator (for voltage step limits). Appendix B provides a detailed list of the contingencies considered for each study network, note that bus sections are not considered as a contingency for the Virtual Statcom project as the loss of a bus section results in the loss of multiple circuits.

The developed hosting capacity algorithm provides the network's traditional hosting capacity for comparison before and after optimisation to assess the benefit of the Virtual Statcom.

In order to provide more meaningful evaluation of the benefits of the Virtual Statcom and to enable better understanding of the capacity that could be released in various running arrangements, the hosting capacity is also calculated for the following network configurations; the intact system configuration and each individual contingency configurations.

Intact System Hosting Capacity

The intact system hosting capacity is the maximum amount of concurrent hosting capacity that can be accommodated in the normal operating configuration (according the LTDS SLDs) such that no thermal, voltage or voltage step violations in occur this configuration.

Contingency Configuration Hosting Capacity

The per contingency configuration hosting capacity is the amount of concurrent hosting capacity that can be accommodated in the current contingency operating configuration such that no thermal, voltage or voltage step violations occur.

5.2 Hosting Capacity Algorithms Model Checks

The hosting capacity algorithms have been developed as a generic algorithm that can be applied to any of WPD's BSPs or Primary networks. To ensure that the network selected is suitable for subsequent hosting capacity algorithms, initial model checks are performed.

The model checks algorithm shown in Figure 5-1, sets all transformer taps in the selected network to their nominal tap positions and runs an initial load flow to assesses if the PSS/E model converges. The algorithm then checks if any reverse power flow (RPF) violations exist on supply transformers in BSP networks (i.e. 33/11 kV transformers) at the existing load and generation levels and modifies the reverse power flow rating. This is done to remove the reverse power flow violations which do not have any impact on the 33 kV generation hosting capacity.

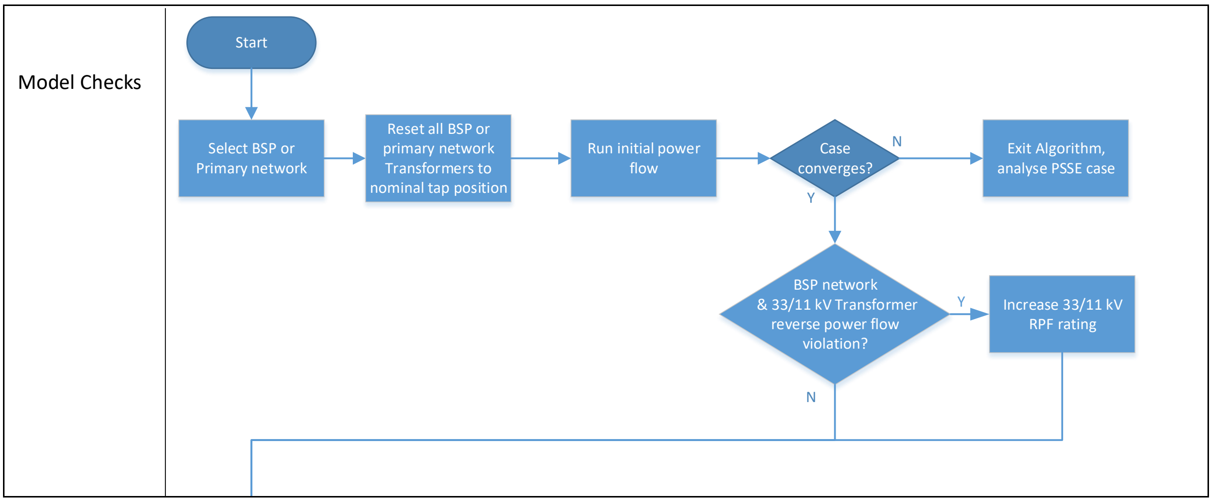


Figure 5-1 – Model checks algorithm details

5.3 Hosting Capacity Algorithms Scaling

5.3.1 Generation scaling

Three generation scaling approaches were trialled in WP2, all approaches involved the placement of 'dummy' generators within the selected network. The three approaches trialled were:

1) Placing 'dummy generators at exiting generator busses.
2) Placing 'dummy' generators at end busses.
3) Placing dummy generation at existing generator busses and end busses.

Placing dummy generators is preferred over scaling of existing network generation for the Virtual Statcom project as the optimisation algorithm uses the existing generators output to set reactive power limits for optimisation.

After trailing the 3 approaches, the 'scale existing and dummy' generators option was selected as the default option for the generation hosting capacity algorithms as it gives the highest generation hosting capacity and better represents the network generation hosting capacity across the various feeders of each network, details of the scaling approach assessment is provided in Appendix H.

Figure 5-2 presents the placement of 'dummy' generator stage in the generation hosting capacity algorithms, the default option of placing dummy generators at end busses and existing generator busses is highlighted in Figure 5-2 by the bold boxes and solid connectors. The algorithm identifies end busses in the selected network and places dummy generators at the end busses and existing generator busses in the selected BSP or Primary network.

Two methods to identified end busses were developed, a power flow approach to identify sink busses and a network analysis path finding approach. The default option used for the generation hosting capacity algorithms is the sink bus approach for further details the identify end busses algorithm see Appendix J.

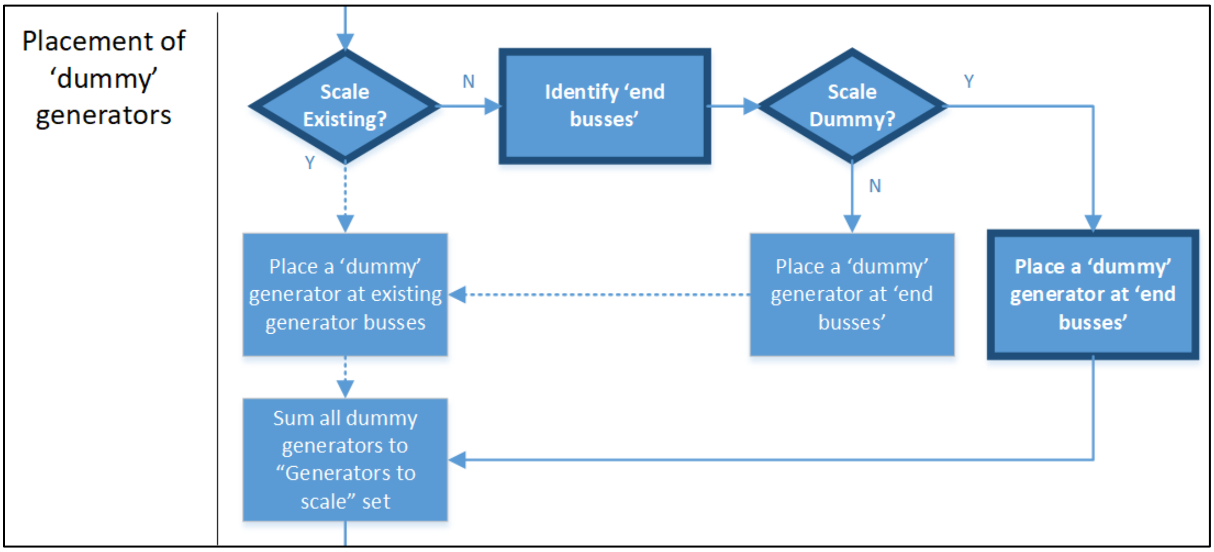


Figure 5-2 - 'Placement of dummy generators' stage

When a dummy generator is placed the algorithm assigns it a generation output of zero. It should be noted that generation will be placed at the main voltage level of the network being assessed. i.e. for BSPs networks only 33 kV connected generators will be scaled and for Primary networks only 11 kV connected generation will be scaled. The algorithms implement hardcoded MW scaling increments of 2 MW for 33 kV networks and 0.02 MW for 11 kV networks. These increments have been chosen for speed of calculation and to provide comparable results.

5.3.2 Load Scaling

The load hosting capacity algorithms identify and scale existing loads. The algorithm implements hardcoded scaling percentages increase of 10 % for 33 kV networks and 100 % MW for 11kV networks. These increments have been chosen for speed of calculation and to provide comparable results.

5.4 Generation Hosting Capacity Algorithms

Two algorithms have been developed to determine the hosting capacity in the 3 hosting capacity scenarios, traditional planning, intact system and per contingency. One algorithm calculates the traditional hosting capacity and the other calculates the intact system and per contingency hosting capacity.

The algorithms have been developed to utilise the same functions, but with different logic structures to produce the desired output. At a high level the traditional planning hosting capacity algorithm scales generation then assesses the intact system and all contingency configurations for violations compared to the intact system and per contingency algorithm which sets a network configuration and scales generation then assesses for violations in the current configuration only. The following two algorithms are described in more detail in the following two sections.

5.4.1 Traditional planning

Figure 5-3 shows the traditional planning hosting algorithm. On the first run, the selected network is assessed for thermal, voltage, voltage step and reverse power flow violations before any generation is scaled up. If any intact system or contingency violations are identified it will store these and exit the algorithm. If the first run assessment did not identify any intact system or contingency violations the algorithm will proceed to scale up the dummy generators in the network.

After the power flow is run, if thermal, voltage, voltage step or reverse power violations are identified the algorithm will perform sensitivity analysis to determine the generators to scale back to resolve the voltage violation, generation scaled back will not be scaled up in further iterations of the algorithm. The key functions used to identify and resolve network violations are in presented in Appendix I.

Once the algorithm has stopped scaling all ‘dummy’ generators in the ‘dummy’ generator set, the traditional hosting generation hosting capacity is calculated as the sum of the real power output of the ‘dummy’ generators and the real power output of existing generation for iteration with the maximum generation.

Post optimisation algorithm (see Section 6) the hosting capacity algorithms are run again using the ‘Optimised option’. This option enables the algorithm to load the configuration specific optimised reactive power set points into the existing generators while scaling dummy generation.

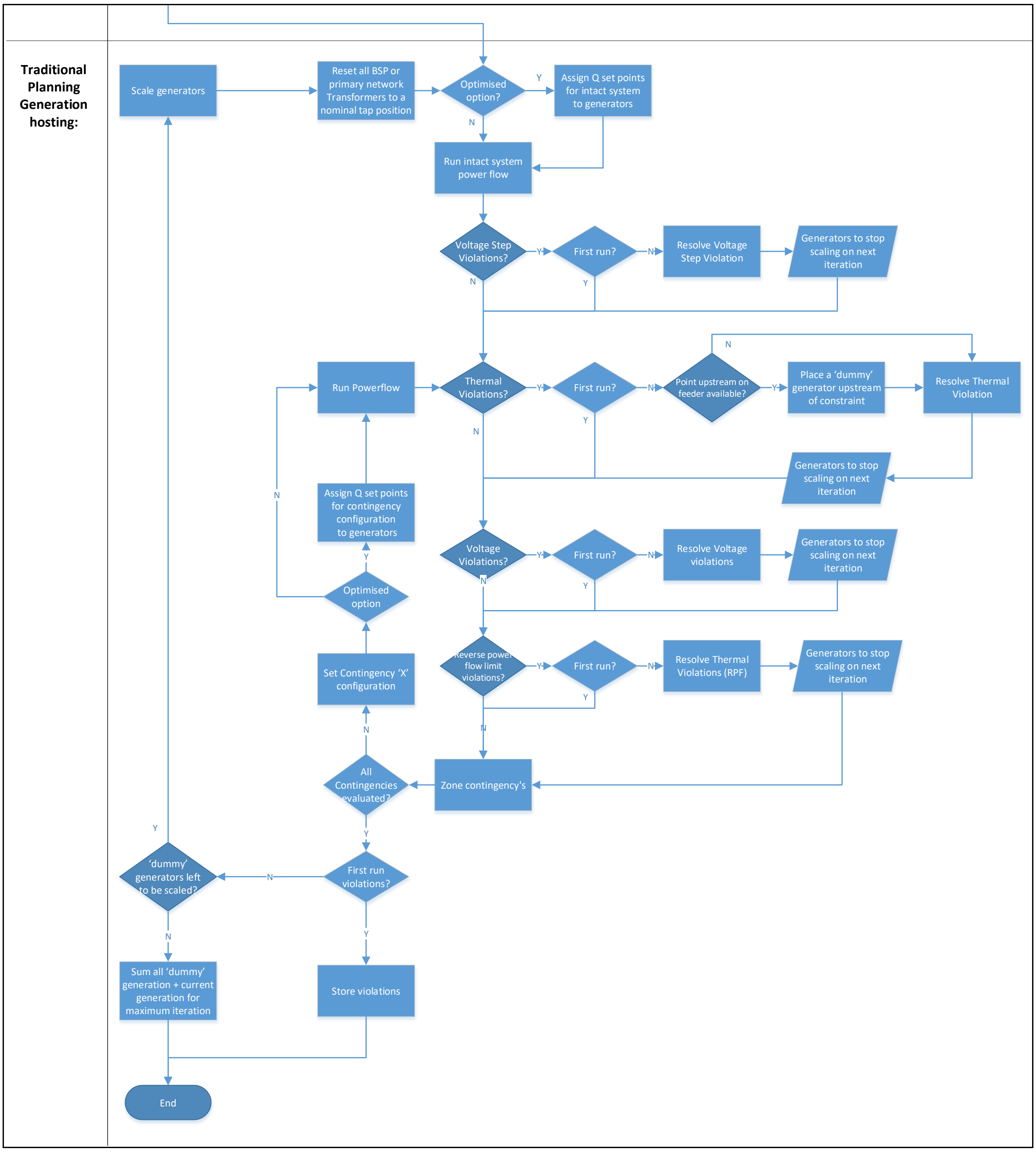


Figure 5-3 – Traditional planning generation hosting capacity algorithm

5.4.2 Intact/per Contingency Approach

Figure 5-4 shows the intact/per contingency hosting algorithm. On the first run, the selected network is assessed for thermal, voltage, voltage step and reverse power flow violations before any generation is scaled up. If any violations are in the current configuration (intact or contingency) it will store these and move on to the next configuration until all configurations have been assessed. If the first run assessment did not identify any violations the algorithm will proceed to scale up the dummy generators in the network for the current configuration.

After the power flow is run, if thermal, voltage, voltage step or reverse power violations are identified the algorithm will perform sensitivity analysis to determine the generators to scale back to resolve the voltage violation, generation scaled back will not be scaled up in further iterations of the algorithm. The key functions used to identify and resolve network violations are in presented in Appendix I.

Once the algorithm has stopped scaling all ‘dummy’ generators in the ‘dummy’ generator set, the generation hosting capacity for the current configuration is calculated as the sum of the real power output of the ‘dummy’ generators and the real power output of existing generation for iteration with the maximum generation. The algorithm stores the hosting capacity then proceeds with the next configuration assessment.

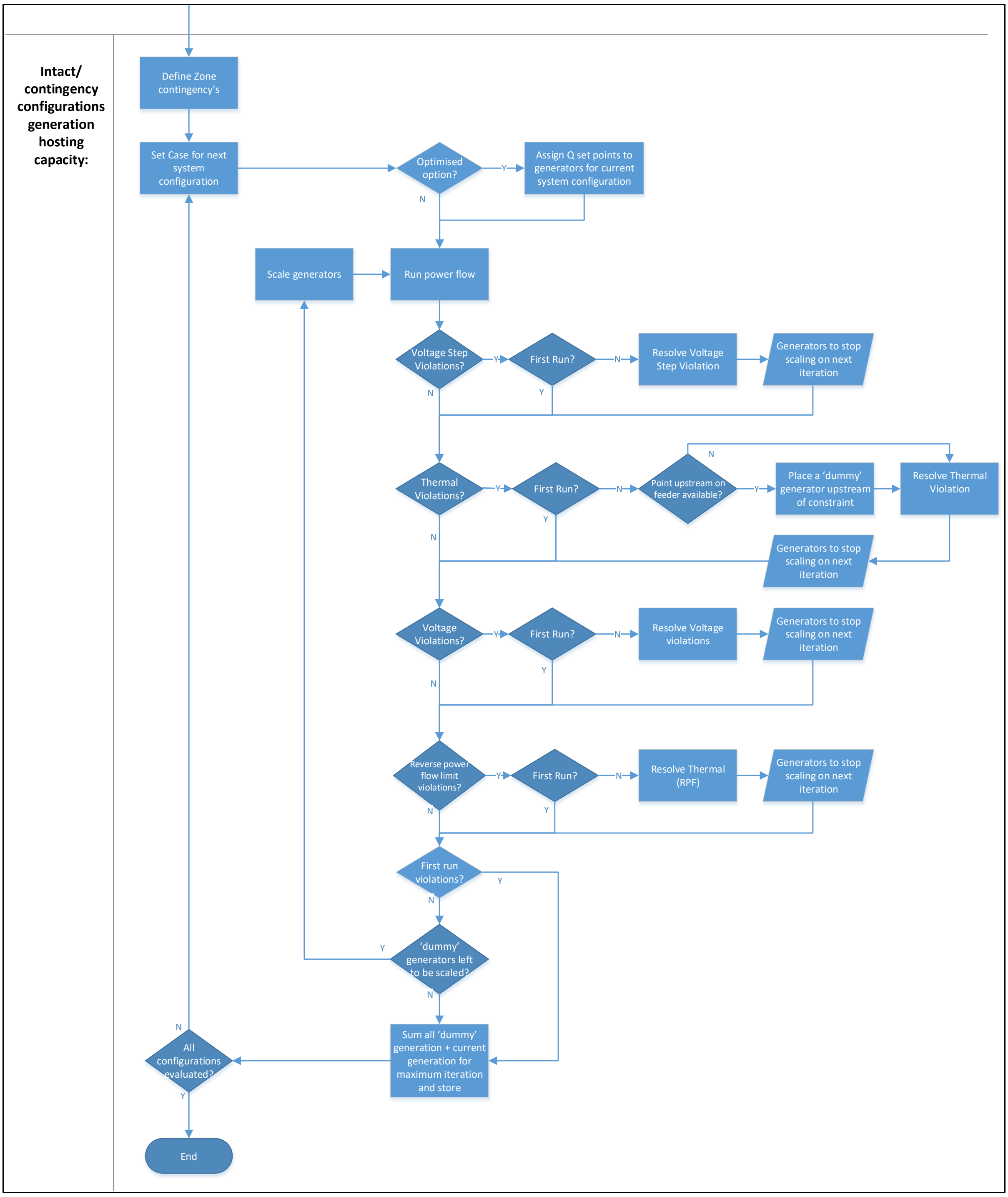


Figure 5-4 - Intact/per contingency generation hosting capacity algorithm

5.5 Load Hosting Capacity Algorithms

The algorithm used to determine the load hosting capacity is similar to the generation hosting except the existing network loads are scaled up rather than generation and only thermal and voltage violations are assessed after each power flow is run. The traditional planning load hosting algorithm is showing in Figure 5-5 and the intact system/per contingency load hosting algorithm is shown in Figure 5-6.

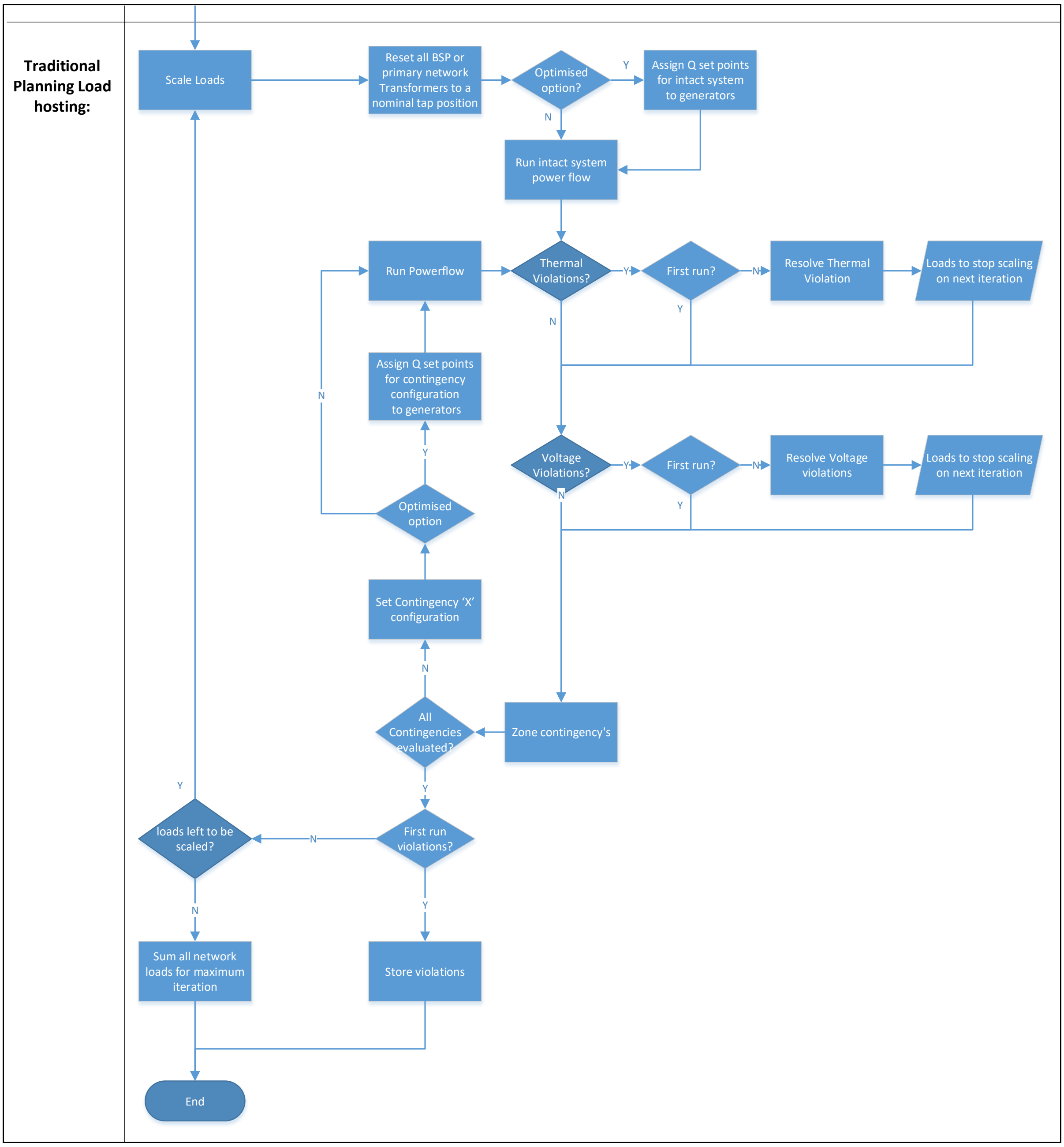


Figure 5-5 – Traditional Planning load hosting capacity algorithm

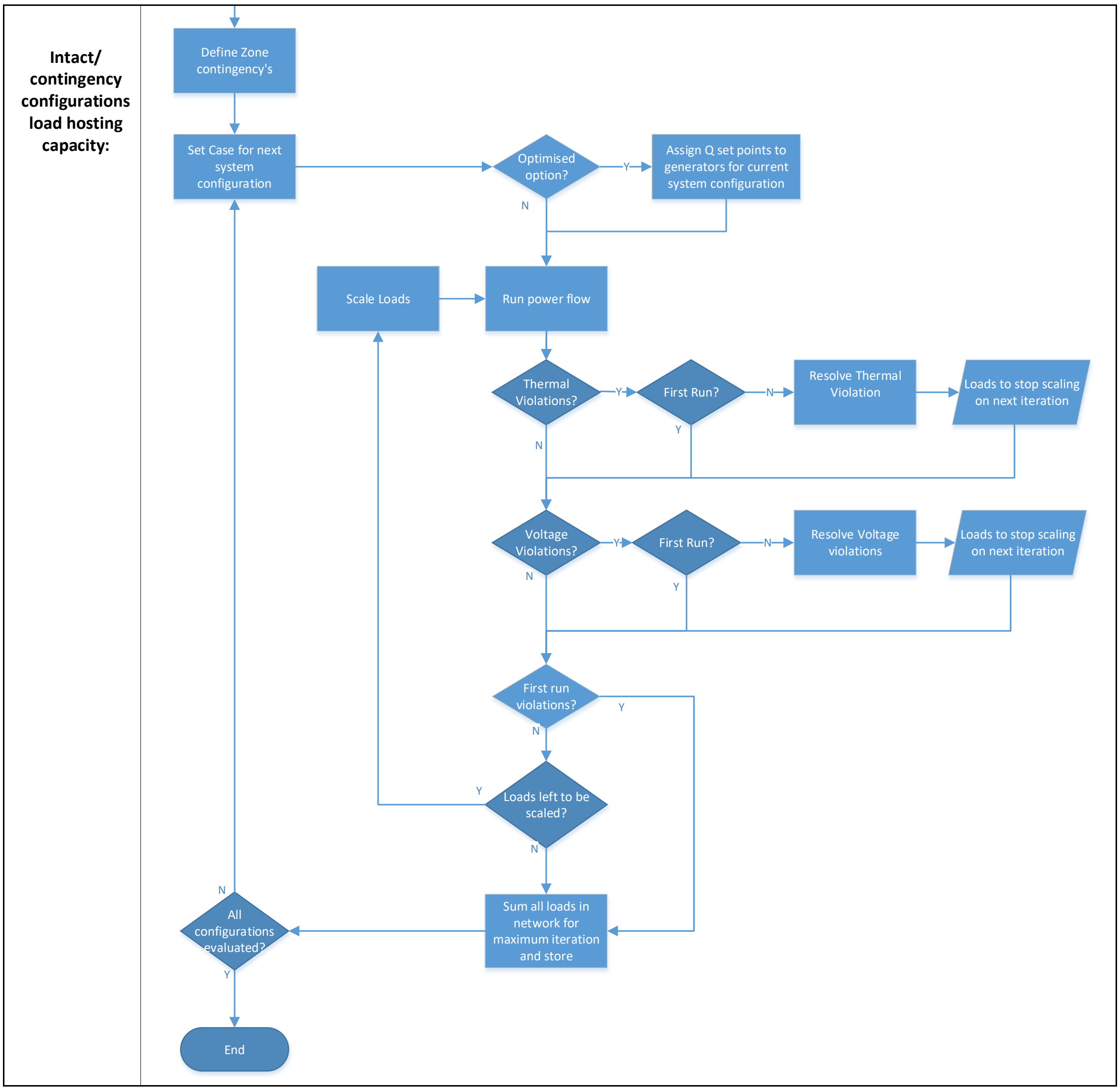


Figure 5-6 - Intact/per contingency generation load hosting capacity algorithm

5.6 Generation and Load Hosting Capacity Results

This section provides a summary of the results from the hosting capacity algorithm for the selected study zones in the Virtual Statcom project. Results in this section and subsequent report sections are presented for two load and generation scenarios, a Minimum load, Maximum generation and a Maximum load 10% Generation. The Minimum load, Maximum generation scenario is used to test the networks generation hosting capacity. Whereas, the Maximum load 10% Generation scenario is used to test the networks load hosting capacity. 10% generation in included in the scenario as the Virtual Statcom optimisation algorithm, presented in Section 6, calculates reactive power base on a power factor so requires existing generators to have generation greater than 0 MW.

In study networks where there are existing contingency configuration violations the worst contingency is defined as the contingency that causes the highest network violation(s) as this restricts the traditional planning hosting capacity. Otherwise, the worst contingency is the contingency in the per contingency analysis that has the lowest hosting capacity. Red numbers in the tables in this section indicate that no generation/load was scaled due to a violation or violations being identified in the first run assessments of the hosting capacity algorithms.

5.6.1 Barnstaple 33 kV BSP

Table 5-1 presents the generation and load hosting capacity results for Barnstaple 33 kV BSP. The limited results for the minimum load maximum generation scenario are as expected based on the violations identified in the network analysis in Section 4.3.

Table 5-1 - Barnstaple 33 kV Generation and load hosting capacity results

Network	Load/Generation Scenario	Generation Hosting Capacity (MW)	Load Hosting Capacity (MW)
Barnstaple 33 kV BSP	Min load Max Gen traditional planning	60.42	12.77
	Min load Max Gen intact system	60.42	12.77
	Min load Max Gen worst contingency	60.42	12.77
	Max Load 10% Gen traditional planning	106.21	61.08
	Max Load 10% Gen intact system	164.50	111.91
	Max Load 10% Gen worst contingency	104.34	61.35

5.6.2 Pyworthy and North Tawton 33 kV BSP

Table 5-2 presents the generation and load hosting capacity results for Pyworthy and North Tawton 33 kV BSP. The limited results for the minimum load maximum generation scenario are as expected based on the violations identified in the network analysis in Section 4.4.

Table 5-2 – Pyworthy and North Tawton 33 kV Generation and load hosting capacity results

Network	Load/Generation Scenario	Generation Hosting Capacity (MW)	Load Hosting Capacity (MW)
Pyworthy and North Tawton 33 kV BSP	Min load Max Gen traditional planning	146.91	21.00
	Min load Max Gen intact system	245.22	190.23
	Min load Max Gen worst contingency	146.91	21.00
	Max Load 10% Gen traditional planning	217.11	96.75
	Max Load 10% Gen intact system	291.65	183.08
	Max Load 10% Gen worst contingency	238.64	118.07

5.6.3 Tiverton 33 kV BSP

Table 5-3 presents the generation and load hosting capacity results for Tiverton 33 kV BSP.

Table 5-3 – Tiverton 33 kV Generation and load hosting capacity results

Network	Load/Generation Scenario	Generation Hosting Capacity (MW)	Load Hosting Capacity (MW)
Tiverton 33 kV BSP	Min load Max Gen traditional planning	59.78	90.56
	Min load Max Gen intact system	103.82	139.62
	Min load Max Gen worst contingency	59.95	104.07
	Max Load 10% Gen traditional planning	91.05	64.16
	Max Load 10% Gen intact system	123.4	110.94
	Max Load 10% Gen worst contingency	92.89	68.79

5.6.4 Tiverton Moorhayes 11 kV Primary

Table 5-4 presents the generation and load hosting capacity results for Tiverton Moorhayes 11 kV Primary. The limited results for the maximum load 10% generation scenario are as expected based on the violations identified in the network analysis in Section 4.6.

Table 5-4 – Tiverton Moorhayes 11 kV Generation and load hosting capacity results

Network	Load/Generation Scenario	Generation Hosting Capacity (MW)	Load Hosting Capacity (MW)
Tiverton Moorhayes 11 kV Primary	Min load Max Gen traditional planning	12.56	14.61
	Min load Max Gen intact system	23.13	26.42
	Min load Max Gen worst contingency	12.49	14.30
	Max Load 10% Gen traditional planning	0.2	6.38
	Max Load 10% Gen intact system	0.2	6.38
	Max Load 10% Gen worst contingency	0.2	6.38

6 Optimisation Algorithm

6.1 Initial Conditions and Generator Constraints

The Virtual STATCOM optimisation algorithm is applied for each contingency configuration individually to identify a target set-point for each generator to optimise the system in terms of either voltage or thermal loadings. The flow chart in Figure 6-2 details the overall Virtual STATCOM process making use of particle swarm optimisation. Further details regarding each of the objective functions are included in the following sections.

Prior to determining the optimum set-point for each generator it is important to determine the reactive power limits for each generator. As a starting point, it is assumed that each existing generator in the system is capable of operating between the limits of 0.95 leading and 0.95 lagging. This is based on the generator's dispatched MW export rather than machine rating (MBASE).

After setting up the PSS/E model for each contingency the generator is tested at the extremes of reactive power dispatch to determine if a trip would result in a voltage step change of greater than 3%. The allowable reactive power limits are reduced until this is no longer an issue (Figure 6-1) and depending on the specific network constraints could result in an entirely leading or lagging power factor. The summary for each network details the total import / export reactive power available from the existing generators for each contingency.

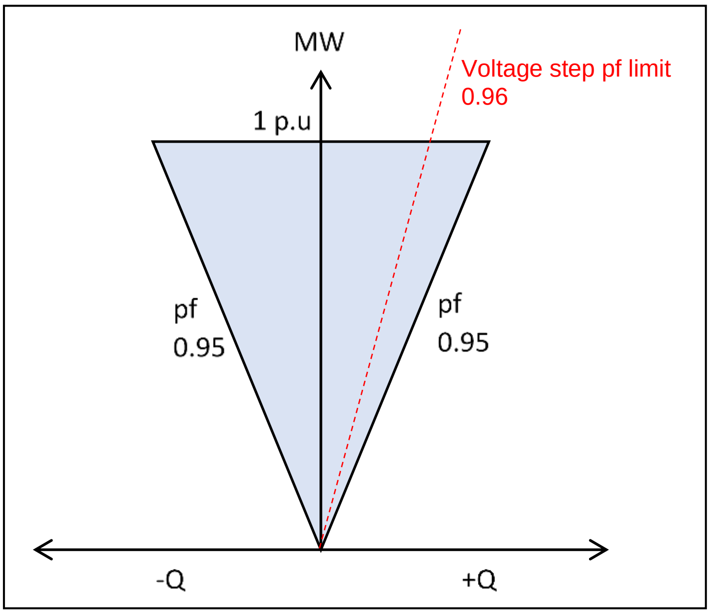


Figure 6-1 - PQ capability of existing distributed generation

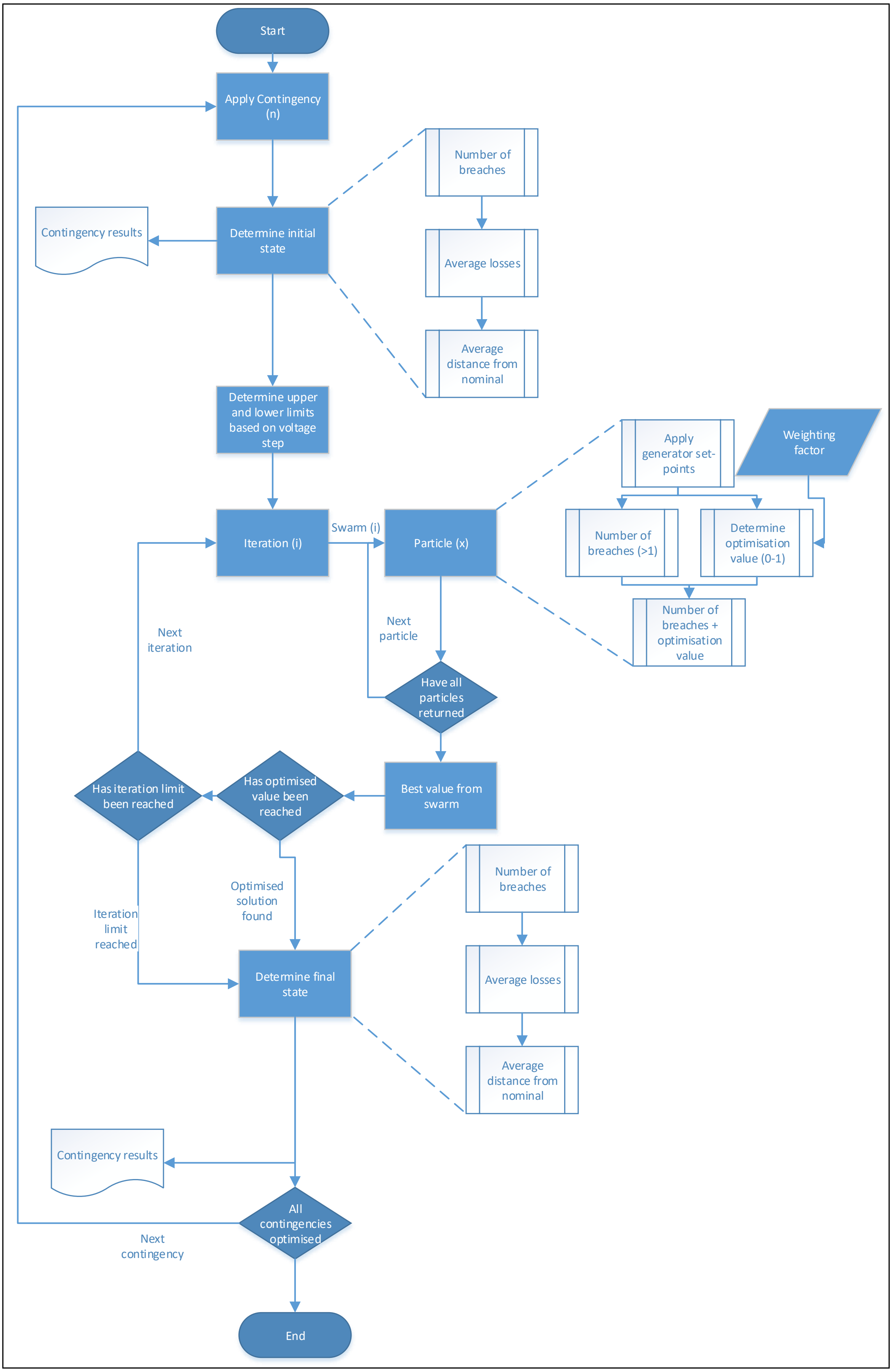


Figure 6-2 – Virtual STATCOM optimisation process

6.2 Development of Objective Functions

Several objective functions were developed to target different areas where headroom for the connection of new embedded generation may be facilitated. The two objective functions focussed on either reducing the deviation of the system voltages from a target or reducing the loading on branches through changes in the reactive power set-point of the existing embedded generation. The preference towards each of these objective functions was controlled through a weighting factor (w) to allow for optimisation between these points.

In some networks or/and contingencies the system already showed breaches in the operational limits detailed in Appendix C. In these cases, initially the objective function works to resolve these issues prior to considering any further optimisation. The particle swarm optimisation (PSO) algorithm implemented makes use of the Python module pyswarm [5]. Each particle must return a single value and the PSO algorithm aims to reduce the returned values to 0.0.

6.2.1 Objective Function to Resolve Breaches

In some contingencies there is an initial breach in the voltage or thermal limits for the WPD network. In these cases, there is no benefit in optimising the voltages or losses unless these breaches can be resolved. To ensure that preferential treatment is given to resolving the breaches before considering further optimisation the number of voltage and thermal breaches are determined as follows.

Equation 1:

$$N_{breaches} = \left(N_{hi-volts} + N_{low-volts} + N_{overloaded\_branches} + N_{transformer\_rpf}\right)$$

Where:

$N_{hi-volts}$ is the number of busbars with voltages greater than 1.06 p.u.
$N_{low-volts}$ is the number of busbars with voltages lower than 0.94 p.u.
$N_{overloadded\_branches}$ is the number of transformers or circuits loaded greater than 100%
$N_{transformer\_rpf}$ is the number of transformers where the reverse power flow limit has been exceeded

6.2.2 Objective Function to Optimise System

The objective function to optimise the entire case is based on either reducing the busbar deviation from a target voltage or reducing the loading on each branch. The overall aim is to minimise both values with a weighting factor (w) applied to determine the priority that is given to each function. The equations considered in the objective function are shown in the following equations:

Equation 2:

$$minF = wD_v + (1-w)L_{br}$$

Equation 3:

$$D_v = \sum_{i=1}^{no.\ bus}\left(\frac{V_i - V_{target}}{V_{limit} - V_{target}}\right)^2 \begin{cases} V_{limit} = 1.06\ where\ V > V_{target} \\ V_{limit} = 0.94\ where\ V < V_{target} \end{cases}$$

Equation 4:

$$L_{br} = \sum_{i=1}^{no.\ branches} {\frac{I_i}{I_{rating}}}^2 + \sum_{i=1}^{no.\ transformers} {\frac{S_i}{S_{rating}}}^2$$

Where:

V_i =Voltage at busbar i
I_i =Current in branch i
S_i =Apparent power in transformer i

The weighting factor (λ_1) alters how much the objective function prioritises for voltage or thermal rating improvements. The optimum weighting factor is going to be dependent on the specific network configuration / dispatch arrangement and further optimisation will be necessary. As an initial comparison of the impact, three weighting factors have been considered in this report:

- w=0 - The objective function minimises branch thermal loading only.
- w=1 - The objective function minimises deviation from target voltage[1], set to 1.p.u.
- w=0.5 – The objective function optimises between reducing voltage and reducing branch loading. The benefit of this specific weighting factor will depend on whether voltages or branch loading is the limited factor.

6.2.3 Overall Optimisation

The overall objective function ($ObjF$) optimisation algorithm takes the sum of the number of breaches ($N_{breaches}$) and the minimising function ($minF$).

Equation 5:

$$ObjF = minF + N_{breaches}$$

The overall optimisation aims to find generator power factor setpoints which find the overall minimum of these values. As a result, any result which has no voltage or thermal limit excursions ($N_{breaches} = 0$) has a significant preference even if no further optimisation is possible.

6.3 Development of Particle Swarm

The Virtual Statcom optimisation routine is delivered using a particle swarm optimisation methodology. At a high level the approach of this is to iteratively attempt to improve the overall solution by testing potential solutions known as particles. The particles are moved around in the search space and the movement of each particle is influenced by its local best-known position as well as the best-known position from all the other particles (the swarm). The overall outcome should therefore be to move the swarm of particles towards the best solution in the search space.

The particle swarm optimisation (PSO) was implemented as part of this project using the existing Python module pyswarm [5]. This module was selected as it is well developed, documented and works with Python version 2.7. There are multiple python packages available

[1] In this study this is set to 1.0 p.u. but will be an input available via the graphical user interface.

that implement PSO but the majority of these are developed for Python 3+ which is not compatible with the PSS/E version 34 that is used by WPD.

In addition to the objective function and the upper / lower bounds for the generators the following inputs are available to the PSO algorithm. At a high level these have the following impact on the overall outcome:

- *swarmsize* – This is the number of particles in the swarm, a larger number of particles increasing the likelihood of finding an overall global minimum but at significantly increasing computational times. Several different inputs were tested as detailed below (section 6.3.1).
- *maxiter* – This is the maximum number of iterations for the overall swarm before the optimisation terminates. A default value of 30 was selected but will be controllable through the user interface.
- *omega* – This is the velocity scaling factor for an individual particle and a default value of 0.5 was used.
- *phip* – This is the scaling factor which determines how much a particle searches away from its best known position. The default value of 0.5 was used.
- *phig* – This is the scaling factor for searching away from the swarm's best known position. The default value of 0.5 was used.
- *minstep* – This is the minimum stepsize of a swarm's best position before the search terminates. A value of 0.001 was used based on some initial sensitivity tests and will be controllable through the user interface.
- *minfunc* – This is the minimum change of a swarm's best objective value before the search terminates. A value of 0.005 was used based on some initial sensitivity tests and will be controllable through the user interface.

6.3.1 Swarm Size and Computational Challenges

The most significant impact of the PSO algorithm in terms of optimisation output and computational time is the size of the swarm. The following table presents a comparison of the difference swarm size has on the outcome compared with computational time. The comparison has been carried out for the Pyworthy and North Tawton 33 kV networks during the maximum load and minimum generation dispatch. These results are presented for an intact system optimising to either reduce thermal loading (w=0) or deviation from nominal (w=1).

Table 6-1 – Comparison of swarm size on computational time

	w=0				w=1			
Swarm Size	Change in Losses (%)	Change in Voltage (%)	Duration (seconds)	Total Particles	Change in Losses (%)	Change in Voltage (%)	Duration (seconds)	Total Particles
10	-1.1%	22.9%	4	28	0.7%	-6.1%	11	59
50	-1.0%	23.8%	6	73	0.9%	-15.4%	40	352
100	-0.9%	22.9%	13	149	1.0%	-13.7%	65	798

As expected, the results show that increasing the swarm size can significantly increase the overall duration taken to find an optimum solution.

- Where w=0 the change in losses between a swarm size of 10 and 100 is not significant.
- Where w=1, the change in deviation from nominal voltage as a result of the swarm size is significant but as is the computational time.

The results presented above are for a single network configuration, in this case the intact system. In the complete Virtual STATCOM optimisation an optimum set-point is found for every contingency. For this zone of the WPD network there are 48 contingencies and therefore the difference in computational time can become significant. Based on the data above the difference between running for a swarm size of 10 vs 100 would be approximately 45 minutes.

At this stage the studies are aiming to demonstrate a proof of concept and allow testing of the various objective functions, weighting factors, dispatch arrangements and potential for hosting capacity improvement. Therefore, the studies detailed in the remainder of this report were carried out on a swarm size of 10. Once fine tuning of the optimisation algorithms has been completed further analysis and recommendations on the swarm size will be established.

6.4 Summary of Virtual Statcom Operation to Resolve Existing Constraints

The following sections present a summary of the Virtual Statcom operation in trying to resolve existing constraints on the system. Results are presented for each study network being considered in this study during minimum load, maximum generation and maximum load, 10 % generation scenarios.

Regarding the results presented in this section it should be noted again that, as first presented in Section 4.2.2, post contingent actions have not been modelled in the Virtual Statcom project. This allows analysis of whether the Virtual Statcom can resolve the need for such post contingency actions.

6.4.1 Barnstaple 33 kV BSP Virtual Statcom Operation Summary

Table 6-2 shows the summary of the Virtual Statcom operation on Barnstaple 33 kV BSP. For the minimum load, maximum generation scenario the Virtual Statcom was able to resolve the thermal overloading in the intact system but was not able to resolve the thermal constraints caused by the worst contingency. Therefore, the traditional planning generation hosting algorithms was unable to increase the dummy generation. There are no existing constraints to resolve in the maximum load, 10 % generation scenario.

Table 6-2 - Barnstaple Virtual Statcom operation summary

Load/Generation scenario	Existing constraints	No. set points issued by Virtual Statcom (Per weighting case)	All Existing Constraints Removed?		
			(w=0)	(w=0.5)	(w=1)
Min load, max gen traditional planning	6 x Thermal	247	No	No	No
Min load, max gen intact system	1 x Thermal	8	Yes	Yes	Yes
Min load, max gen worst contingency	3 x Thermal	8	No	No	No

Barnstaple 33 kV BSP Virtual Statcom Operation Intact system analysis

The thermal violation in the intact system, as identified in the network assessment studies, is the Batsworthy voltage regulator and is caused by generation connected downstream of the voltage regulator at Batsworthy windfarm (BATS3 and BATA3).

Table 6-3 sets out the optimised reactive power setpoints calculated by the Virtual Statcom for the different weighting factors. It demonstrates that the thermal overload of the Batsworthy voltage regulator can be resolved by optimising the reactive power set points for the downstream generation without the need to curtail active power.

Table 6-3 - Barnstaple 33kV min load max gen – intact system analysis, generation at Batsworthy windfarm

Existing generator (PSS/E model bus)	Generation real power (MW)	Initial reactive power (Mvar)	Optimised reactive power (Mvar)		
			(w=0)	(w=0.5)	(w=1)
BATS3	17.1	-5.62	-2.21	-4.47	-5.16
BATA3	1.2	-0.394	-0.323	-0.38	0.338
Thermal Violation					
SMOL3K_BATS3R_R1		102 %	98 %	99 %	100%

Barnstaple 33 kV BSP Virtual Statcom Operation worst contingency analysis

Table 6-4 shows the violating constraints for the worst contingency (‘‘Aaronson T’) pre- and post-optimisation and demonstrates that even though the Virtual Statcom was not able to resolve all constraints, it was able to able to reduce the thermal overload constraints. Post contingency measures are needed to manage this contingency for the minimum load maximum generation scenario, but under less onerous load and generation scenarios a Virtual Statcom could remove the need for post contingency measures.

Table 6-4 - Barnstaple 33 kV min load, max gen - worst contingency analysis

Contingency	Constraints	Pre optimisation %	Objective function weighting: w=0	w=0.5	w=1
AARO3_AARO3T_L1+AARO3T_HEDX3K_L1+AARO3T_SMOL3J_L1	SMOL3K_KING3T_L1	117.9	111.55	116.08	115.68
	SMOL3K_BATS3R_R1	101.6	Resolved	100.89	100.42
	BAST3_KING3T_L1	118.4	110.36	115.48	116.52

6.4.2 Pyworthy and North Tawton 33 kV BSP Virtual Statcom Operation Summary

Table 6-5 shows the summary of the Virtual Statcom operation for Pyworthy and North Tawton 33 kV BSP. For the minimum load, maximum generation scenario the Virtual Statcom was not able to resolve the thermal constraints caused by the worst contingency therefore the traditional planning load and generation hosting algorithms ability to scale dummy generation is restricted. There are no existing constraints to resolve in the maximum load, 10 % generation scenario.

Table 6-5 – Pyworthy and North Tawton Virtual Statcom operation summary

Load/Generation scenario	Existing constraints	No. set points issued by Virtual Statcom (Per weighting case)	All existing constraints removed?		
			(w=0)	(w=0.5)	(w=1)
Min load, max gen traditional planning	17 voltage 1 Thermal	752	No	No	No
Min load, max gen intact system	No	16	n/a	n/a	n/a
Min load, max gen worst contingency	17 voltage 1 Thermal	16	No	No	No

Pyworthy and North Tawton 33 kV BSP Virtual Statcom Operation worst contingency analysis

Table 6-6 and Table 6-7 show the violating voltage and thermal constraints for the worst contingency (North Tawton GT1 transformer) pre- and post-optimisation. Post contingency measures are needed to manage this contingency for the minimum load maximum generation scenario .

The analysis demonstrates that a trade-off exists between optimising to reduce circuit loadings (w=0) vs reducing voltages (w=1). When the objective function weighting factor is 1, the reactive power set points calculated reduce voltage constraints but increase the loading on the thermal constraint. The opposite can also be seen when the objective function weighting factor is w=0, the loading on the thermal constraint is reduced but the bus voltages increase.

This contingency configuration identifies an expected limitation of the Virtual Statcom. For an initial load and generation scenario, if a network configuration causes both voltage and thermal violations in the same feeder group the Virtual Statcom, as currently configured will, not be able to resolve both violation types.

Table 6-6 – Pyworthy and North Tawton, min load, max gen - worst contingency analysis (thermal)

			Objective function weighting function		
Contingency	**Constraint**	**Pre optimised loading %**	**w=0**	**w=0.5**	**w=1**
NTAW1_NTAW3_G1	DERR3T_PYWO3_L1	102.8	102.4	103.0	104.5

Table 6-7 – Pyworthy and North Tawton, min load, max gen - worst contingency analysis (voltage)

			Pre Optimised Voltage	Objective function weighting function		
Contingency	**Bus Number**	**Name**	**voltage_pu**	**w=0**	**w=0.5**	**w=1**
NTAW1_NTAW3_G1	6024	HATH3K	1.068	1.077	1.067	Resolved
	6042	OKEH3K	1.092	1.102	1.089	1.080
	7349	HATH3J	1.068	1.077	1.067	Resolved
	7501	MORH3	1.097	1.109	1.094	1.086
	7502	MORH3T	1.099	1.110	1.095	1.087
	7551	OKEH3J	1.092	1.102	1.089	1.080
	7623	ROAD3	1.073	1.077	1.067	1.062
	7825	WHID3J	1.099	1.110	1.096	1.087
	7826	WHID3K	1.099	1.110	1.096	1.089
	7985	NTAW5	1.077	1.089	1.074	1.066
	8955	NTAW3	1.106	1.118	1.103	1.094
	9185	WILL3	1.065	1.073	1.064	Resolved
	9186	WILL3T	1.065	1.073	1.064	Resolved
	9635	DENB3	1.112	1.125	1.109	1.101
	9655	RCPV3	1.074	1.077	1.068	1.062
	9656	RCPV3T	1.074	1.077	1.068	1.062
	20790	DNBW3	1.112	1.125	1.109	1.101

● Increasing voltage from pre optimised voltage ● Decreasing voltage from pre optimised voltage

6.4.3 Tiverton 33 kV BSP Virtual Statcom Operation Summary

For Tiverton 33 kV BSP there are no existing constraints to be resolved in either the minimum load, maximum generation scenario or maximum load, 10 % generation scenario.

6.4.4 Tiverton Moorhayes 11 kV Primary Virtual Statcom Operation Summary

Table 6-8 shows the summary of the Virtual Statcom operation for Tiverton 11 kV Primary network. For the minimum load, maximum generation scenario there are no existing constraints to be resolved, for the maximum load, 10 % generation scenario one Thermal constraint exists.

Table 6-8 – Tiverton 33 kV BSP Virtual Statcom operation summary

Load/Generation scenario	**Existing constraints**	**No. set points issued by Virtual Statcom** (Per weighting case)	**All existing Constraints removed?**		
			(w=0)	(w=0.5)	(w=1)
Max load, 10 % gen traditional planning	1 Thermal	16	No	No	No
Max load, 10 % gen intact system	1 Thermal	2	No	No	No
Max load, 10 % gen worst contingency	1 Thermal	2	No	No	No

Tiverton Moorhayes 11 kV BSP Virtual Statcom Operation Intact system analysis

The Virtual Statcom is not able to resolve the violation in the maximum load, 10 % generation scenario due to the real power flow on the thermal constraint exceeding the MVA rating of the circuit.

7 Virtual Statcom Capacity Benefits

7.1 Tiverton 33 kV BSP Virtual Statcom Detailed Demonstration

Tiverton 33 kV BSP has been chosen for a detailed demonstration of the Virtual Statcom as there are no intact or contingency configurations violations in both the minimum load, maximum generation and maximum load, 10 % generation scenarios. The demonstration focuses on the minimum load, maximum generation scenario for generation hosting and the maximum load, 10 % generation scenarios for load hosting.

7.1.1 Analysis of Objective Function Performance

Table 7-1 shows that the objective function performance is as expected and reduces losses when a weighting factor of w=0 is selected and shows the network average nominal voltage is reduced when a weighting factor of w=1 is selected. Table 7-1 also shows the losses versus voltage trade-off, in that when losses are the lowest, voltages are the highest and vice versa.

Table 7-1 – Objective function performance for Tiverton 33 kV BSP Virtual Statcom operation summary

	Losses (initial) MW	Losses (w=0) MW	Losses (w=0.5) MW	Losses (w=1) MW	D_v (initial)	D_v (w=0)	D_v (w=0.5)	D_v (w=1)
Min load Max Gen intact system	0.373	0.359	0.391	0.393	0.0164	0.024	0.0083	0.0074
Min load Max Gen worst contingency	0.373	0.353	0.390	0.398	0.0187	0.066	0.0078	0.0043
Max load 10% Gen intact system	0.641	0.639	0.641	0.643	0.0110	0.0115	0.0110	0.0107
Max load 10% Gen worst contingency	0.634	0.628	0.635	0.636	0.0266	0.0307	0.0258	0.0254

D_v is a unit less ratio described by Equation 3: in Section 6.2.2

To visualise the performance of the objective function. Figure 7-1, Figure 7-2 and Figure 7-3 provide the voltage profile and branch loadings for the different setpoints calculated for the Tiverton 33 kV BSP intact system in the minimum load maximum generation scenario. The figures show that bus voltages increase when optimising for losses and vice versa. They also show that the weighting factor is not evenly distributed between w=0 and w=1, in the intact system configuration shown in the figures the results show that a weighting factor of w=0.5 is closer to optimising solely for nominal voltages (w=1) than optimising for losses (w=0).

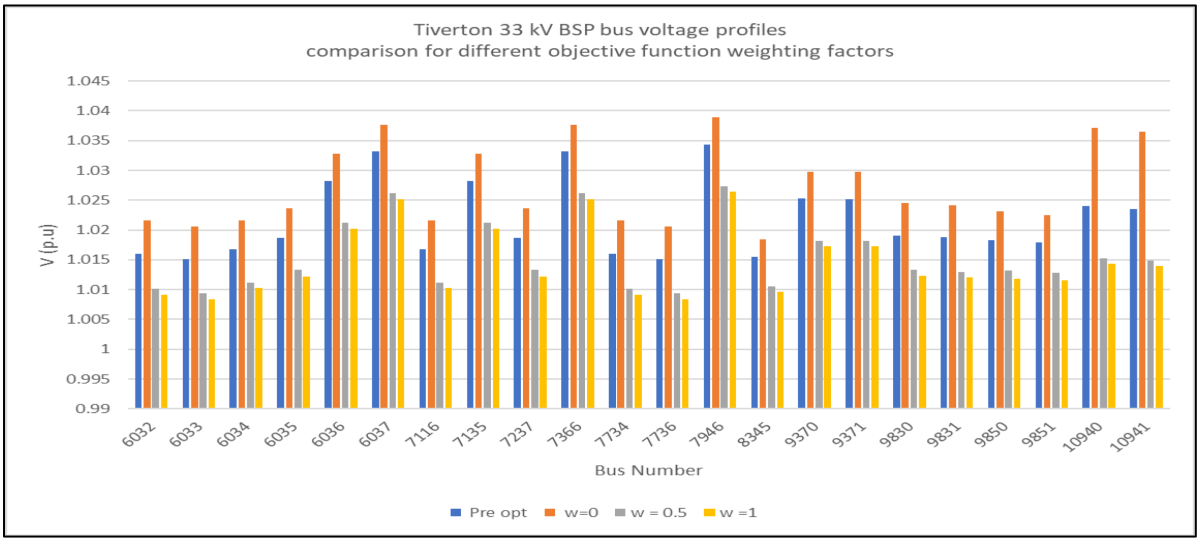


Figure 7-1 - Initial Tiverton BSP 33 kV bus voltages for different weighting factors

Note: the network 11 kV busses have not been plotted as they are the control bus of the 33/11 kV supply transformer(s) tap changer.

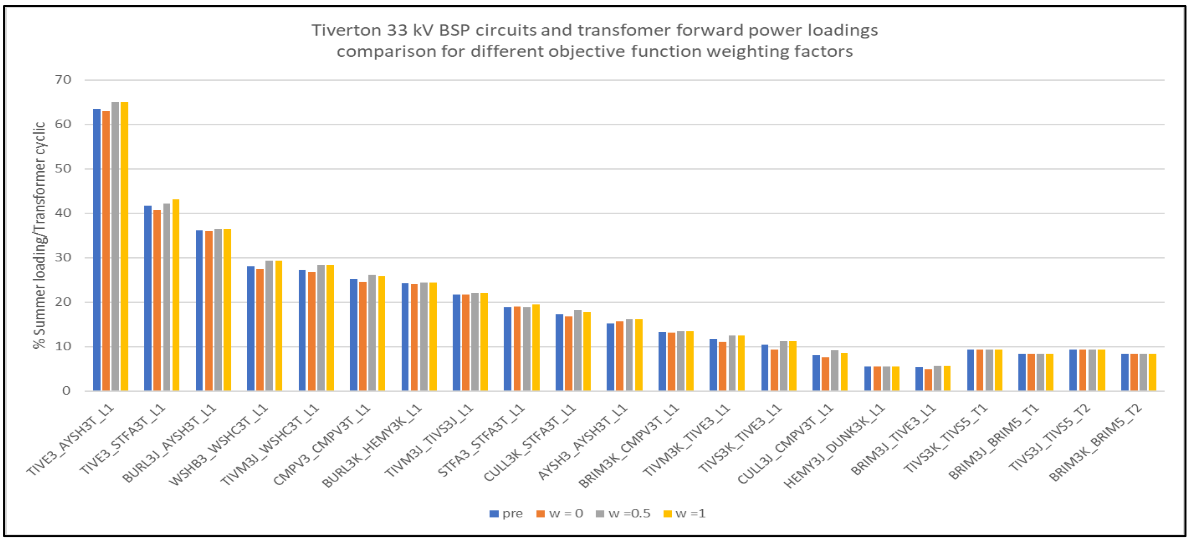


Figure 7-2 - Initial Tiverton BSP circuit and transformer loadings for different weighting factors (intact configuration)

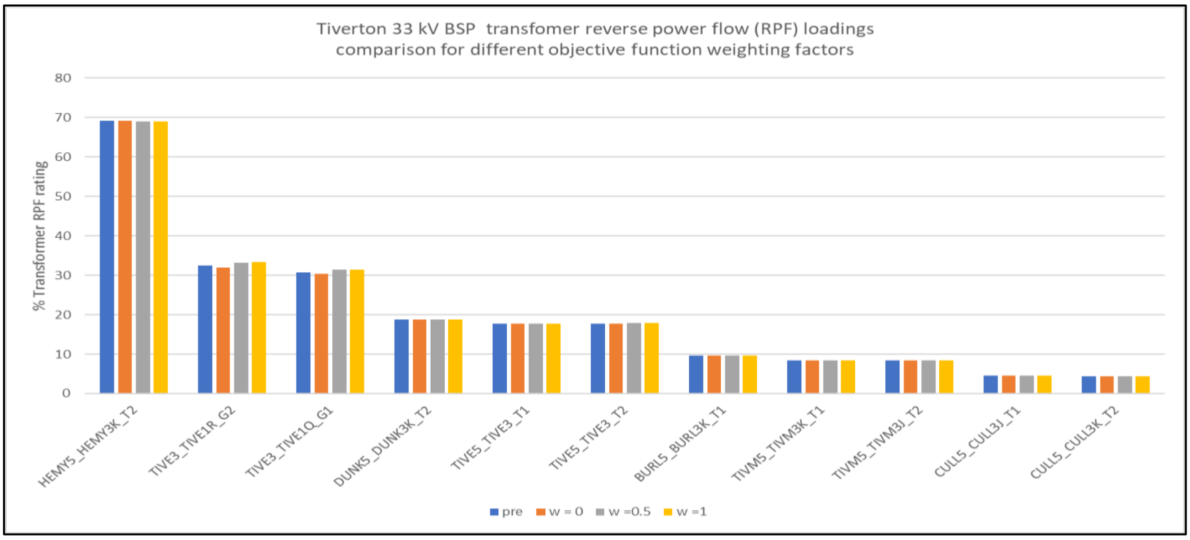


Figure 7-3 - Initial Tiverton BSP RPF loadings for different weighting factors (intact configuration)

7.1.2 Generation Hosting Capacity - Intact System/Per Contingency

Table 7-2 provides an overview of the benefit (an increase in generation hosting capacity) realised by using optimised reactive power dispatch setpoints for existing network generators covering the different objective function weighting factors for Tiverton 33 kV BSP network. The generation hosting capacity has been determined based on the minimum load, maximum generation scenario and reactive power capability is based on the MW dispatch of each generator.

A benefit is shown by a green tick if the post optimised hosting capacity is greater than the pre-optimised hosting capacity, no benefit is shown by a yellow equals sign and a reduction in capacity is shown by a red cross.

Cases highlighted in yellow in the table below provided counterintuitive results. These showed the post optimisation capacity was equal to or worse than the pre-optimised hosting capacity. Further analysis has been performed on these situations and is presented in Section 7.1.3.

Table 7-2 –Tiverton 33 kV BSP comparison of pre and post-optimisation generation headroom capacity

Tiverton 33 kV Network configuration	Limiting violation(s) type(s) from hosting capacity algorithm[2]	w=0	w=0.5	w=1	Max benefit (MW)	Mvar available (Min/Max)
Intact system	RPF, I	✓	×	×	0.9	-6.1/6.1
BSP infeed transformers contingencies						
TIVE3_TIVE1Q_G1	RPF	=	×	×	n/a	-6.1/5.9
TIVE3_TIVE1R_G2	RPF	=	×	×	n/a	-6.1/5.9
Circuit contingencies						
TIVM3K_TIVE3_L1	I	✓	×	×	0.45	-6.1/5.2
TIVS3K_TIVE3_L1	I	✓	×	×	0.54	-6.1/5.7
BURL3K_HEMY3K_L1	RPF, I, V	✓	✓	×	1.70	-6.1/6.1
BRIM3J_TIVE3_L1	I, V	×	×	×	n/a	-6.1/6.1
HEMY3J_DUNK3K_L1	RPF, I, V	✓	✓	×	0.81	-6.1/6.1
TIVM3J_TIVS3J_L1	RPF	×	×	×	n/a	-6.1/5.8
CULL3K_STFA3T_L1+ TIVE3_STFA3T_L1+ STFA3_STFA3T_L1	V	×	✓	✓	1.24	-4.8/4.8
BRIM3K_CMPV3T_L1+ CULL3J_CMPV3T_L1+ CMPV3_CMPV3T_L1	RPF, V	✓	×	×	0.29	4.8/4.8
BURL3J_AYSH3T_L1+ TIVE3_AYSH3T_L1+ AYSH3_AYSH3T_L1	V	×	✓	✓	1.80	-4.6/4.6
TIVM3J_WSHC3T_L1+ WSHB3_WSHC3T_L1	RPF, I	✓	×	×	0.06	-4.1/4.1
33/11kV Primary Supply Transformers contingencies						
All 33/11 kV supply transformers.	RPF, I	✓	×	×	1.02	-6.1/6.1

[2] It is possible to have more than type of violation in the last iteration due to the capacity hosting algorithm logic/order for checking and resolving violations.

In general, the results in Table 7-2 above show that for the Tiverton 33 kV BSP network:

- If a thermal violation (RPF or I) was the limiting violation a weighting factor of w=0 provides benefit.
- If a voltage violation was the limiting violation a weighting factor of provides benefit.

7.1.3 Tiverton 33 kV Generation Hosting Further Analysis

This section provides further analysis on the counterintuitive results, i.e. where the post-optimised capacity was equal to or worse than the hosting capacity with non-optimised reactive power dispatch.

Contingency of BSP infeed Transformer (GT1 or GT2)

The initial results show that there is no benefit from implementing the Virtual Statcom during these contingencies to increase the generation hosting capacity. The limiting constraint is a result of reverse power flow on the remaining transformer (GT1 or GT2) and as such only a reduction in the reactive power flow through these would allow for an increase in hosting capacity.

Table 7-3 – Pre- and post-optimisation for GT1 and GT2 contingencies

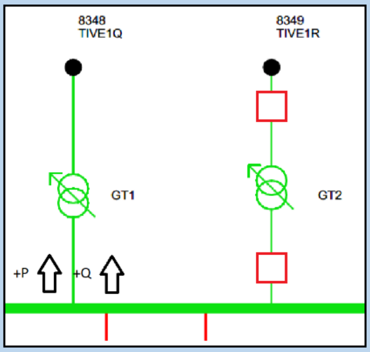
Tiverton 33 kV Network configuration	Limiting violation(s) type(s) on from hosting capacity algorithm*	w=0	w=0.5	w=1
BSP infeed transformers contingencies				
TIVE3_TIVE1Q_G1	RPF	=	✗	✗
TIVE3_TIVE1R_G2	RPF	=	✗	✗

The initial system model for Tiverton has approximately 5 Mvar import to the Barnstaple network during an outage on one of the BSP infeed transformers (G1 or G2). Therefore, an improvement in the generation hosting capacity is expected if this can be reduced without increasing system voltages above limits. To reduce this Mvar import, the Mvar will need to be supplied from the embedded generation through the reduction of losses (w=0). Alternatively, any optimisation to reduce voltages (w=0.5 or 1) would increase the Mvar import and therefore reduce the headroom available.

Table 7-3 above shows this affect for w=0.5 and w=1 but does not demonstrate the anticipated benefit for w=0. More detailed analysis into w=0 showed that during either the TIVE3_TIVE1Q_G1 or TIVE3_TIVE1R_G2 contingency configurations there is a minor benefit but due to the step size when scaling back generation the hosting capacity appears the same. The scaling algorithm scales back generation using a fixed step size to reduce the RPF violation to less than RPF rating.

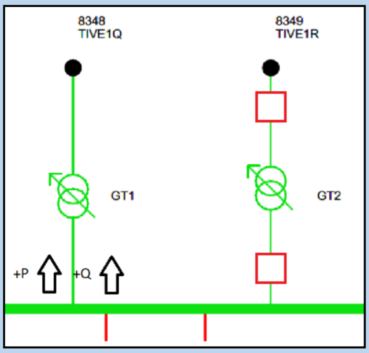
Table 7-4 shows the MW and Mvar flows before dummy generation was scaled for the TIVE3_TIVE1R_G2 contingency configuration with different reactive power setpoints. It shows that when a weighting factor of w=0 was used the Mvar flow is close to zero and the transformer MVA headroom increases by 0.44 MVA.

Table 7-4 - Pre generation scaling for different reactive power dispatch

TIVE3_TIVE1R_G1 flows	pre	w=0	w=0.5	w=1	MW/Mvar flow directions
MW	28.00	28.01	27.98	27.98	
Mvar	-5.09	0.02	-7.16	-8.38	
MVA flow	28.45	28.01	28.89	29.21	
MVA headroom	16.55	16.99	16.11	15.79	
Headroom increase	0	0.44	-0.44	-0.76	

The step size used to resolve violations in the Tiverton 33 kV BSP network is 0.8 MW (0.1 MW for each of the 8 dummy generators). Table 7-5 shows the transformer loading after scaling up the dummy generation. When w=0 the transformer loading is less than the original loading for the same level of dummy generation added. However, if another 0.8 MW dummy generation was added it would exceed 100%. This highlights that the 100% rating of the transformer falls between a step and that the step size used to resolve violations in the hosting capacity algorithms can hide minor benefits.

Table 7-5 - Post generation scaling for different reactive power dispatch

TIVE3_TIVE1R_G1 flows	pre	w=0	w=0.5	w=1	MW/Mvar flow directions
MW	44.36	44.39	43.57	43.57	
Mvar	-5.83	-0.70	-7.86	-9.05	
MVA flow	44.74	44.39	44.28	44.50	
MVA headroom	0.26	0.61	0.72	0.50	
TX Loading (%)	99.42%	98.65%	98.39%	98.90%	
Dummy generation added (MW)	16.8	16.8	16	16	

Contingency of TIVM3J_TIVS3J_L1 Circuit

The results suggest that there is no benefit from implementing the Virtual Statcom for the TIVM3J_TIVS3J_L1 contingency configuration. Further analysis of these results detailed below suggests that a network level optimisation may not realise as much capacity benefit as a per feeder optimisation approach. A per feeder optimisation approach would allow the feeders which are thermally constrained to be treated differently to those which are voltage constrained.

Table 7-6 – Pre and post-optimisation for TIVM3J_TIVS3J_L1 contingency

Tiverton 33 kV Network configuration	Limiting violation(s) type(s) on from hosting capacity algorithm*	w=0.0	w=0.5	w=1
Circuit contingencies				
TIVM3J_TIVS3J_L1	RPF	×	×	×

Table 7-7 below details the headroom created per feeder group for each of the weighting factors. The results show that:

- Three of the feeder groups are thermally constrained and an increase in headroom is achieved with a weighting factor of 0
- One feeder group is voltage constrained and an increase in headroom is possible with a weighting factor of 1.0

This implies that if generators related to the first three feeder groups were optimised to resolve thermal constraints and the last feeder group was optimised for voltage constraints an overall increase in headroom would be possible.

Table 7-7 – Contingency TIVM3J_TIVS3J_L1 per feeder group post-optimisation benefit

bus number	bus name	Gen ID	pre	w=0	w=0.5	.0	Maximum
6034	BRIM3K	ZZ	17.10	18.00	17.55	17.10	
9830	CMPV3	ZE	0.00	0.00	0.00	0.00	
9850	STFA3	ZE	0.00	0.00	0.00	0.00	
	Feeder Group dummy Generation total		**17.10**	**18.00**	**17.55**	**17.10**	18.00
7736	TIVS3J	ZZ	22.30	22.80	19.50	21.80	
	Feeder Group dummy Generation total		**22.30**	**22.80**	**19.50**	**21.80**	22.80
7946	DUNK3K	ZZ	6.00	6.12	6.00	6.00	
9370	AYSH3	ZE	0.00	0.00	0.00	0.00	
	Feeder Group dummy Generation total		**6.00**	**6.12**	**6.00**	**6.00**	6.12
10940	WSHB3	ZZ	9.60	4.27	10.20	10.20	
10941	WSHC3T	ZE	6.50	7.50	6.00	6.00	
	Feeder Group dummy Generation total		**16.10**	**11.78**	**16.20**	**16.20**	16.20
	Total dummy Capacity (MW)		61.50	58.69	59.25	61.10	63.12
	Difference (MW)			-2.81	-2.25	-0.40	1.62

Table 7-8 demonstrated this with a manual example where the generators highlighted blue have been optimised to reduce losses and those highlighted green to reduce voltages. For this contingency these reactive power set-points would have resulted in a 0.5 MW increase in generation hosting capacity. Note, these results have been calculated manually rather than using the network optimised results, a new optimisation algorithm design is needed to fully maximise a per-feeder optimisation approach.

Table 7-8 – Contingency TIVM3J_TIVS3J_L1 feeder based optimisation example

Generators			Pre-optimisation		Feeder-based	
Bus	**Name**	**ID**	**P (MW)**	**Q (Mvar)**	**P (MW)**	**Q (Mvar)**
6034	BRIM3K	ZZ	17.1	0	18	0
7734	TIVM3J	ZP	0	0	0	0
7736	TIVS3J	ZZ	22.3	0	22.8	0
7946	DUNK3K	ZZ	6	0	5.5	0
9370	AYSH3	P1	4.55	0	4.55	1.4955
9370	AYSH3	ZE	0	0	0	0
9830	CMPV3	P1	4	-0.812	4	1.3147
9830	CMPV3	ZE	0	0	0	0
9850	STFA3	P1	4	-0.81	4	1.3147
9850	STFA3	ZE	0	0	0.1	0
10940	WSHB3	PA	6	-1.218	6	-1.4
10940	WSHB3	ZE	9.6	0	6.4	0
10941	WSHC3T	ZZ	6.5	0	9.2	0
Total			80.05	-2.84	80.55	2.72
Total Dummy			61.50	0.00	62.00	0.00
Total Existing			18.55	-2.84	18.55	2.72
Difference			-	-	**0.50**	**5.56**

Contingency of BRIM3J_TIVE3_L1 Circuit

For the BRIM3J_TIVE3_L1 contingency the results suggest that there is no benefit from implementing the Virtual Statcom. Further analysis of these results also support that a network level optimisation may not realise as much capacity benefit as a per feeder optimisation approach. A per feeder optimisation approach would allow the feeders which are thermally constrained to be treated differently to those which are voltage constrained.

Table 7-9 - Pre and post-optimisation for BRIM3J_TIVE3_L1 contingency

Tiverton 33 kV Network configuration	Limiting violation(s) type(s) on from hosting capacity algorithm*	w=0.0	w=0.5	w=1
Circuit contingencies				
BRIM3J_TIVE3_L1	I, V	×	×	×

Table 7-10 below details the headroom created per feeder group for each of the weighting factors. The results show that:

- One of the feeder groups is thermally constrained and an increase in headroom is achieved with a weighting factor of w=0
- The other two feeder groups are not clearly voltage or thermally constrained as the weighting factor does not show a significant benefit for the other weighting factors.

However, this may be that the weighting factors tested are too extreme and an optimum weighting factor somewhere between 0 and 0.5 may have shown a benefit.

This implies that the first feeder group should be optimised to resolve thermal constraints whilst the last two need to focus on a mixture of thermal and voltage constraints.

Table 7-10 - Contingency BRIM3J_TIVE3_L1 per feeder group post-optimisation benefit

Bus number	Bus name	Gen id	pre	w=0	w=0.5	w=1	Maximum
7946	DUNK3K	ZZ	6.00	6.14	6.00	6.00	
9370	AYSH3	ZE	0.00	0.00	0.00	0.00	
	Feeder Group dummy Generation total		**6.00**	**6.14**	**6.00**	**6.00**	6.14
6034	BRIM3K	ZZ	2.70	5.60	0.00	0.00	
9830	CMPV3	ZE	6.00	3.00	8.50	8.50	
9850	STFA3	ZE	0.00	0.00	0.00	0.00	
	Feeder Group dummy Generation total		**8.70**	**8.60**	**8.50**	**8.50**	8.60
7734	TIVM3J	ZP	16.20	0.00	14.00	14.00	
7736	TIVS3J	ZZ	8.95	28.50	9.36	9.36	
10940	WSHB3	ZE	5.86	3.27	9.50	9.50	
10941	WSHC3T	ZZ	9.00	6.32	7.00	7.00	
	Feeder Group dummy Generation total		**40.02**	**38.09**	**39.86**	**39.86**	39.86
	Total dummy Capacity (MW)		54.72	52.82	54.36	54.36	54.60
	Difference (MW)			-1.90	-0.35	-0.35	-0.12

A manual investigation was carried out and is presented in Table 7-11 where the generator highlighted blue has been optimised for thermal constraints, green for voltages and orange focussing only slightly on thermal. The results show that this approach would increase the available headroom by 0.55 MW.

Table 7-11 - Contingency BRIM3J_TIVE3_L1 feeder based optimisation example

Generators			Pre-optimisation		Feeder-based	
Bus	**Name**	**ID**	**P (MW)**	**Q (Mvar)**	**P (MW)**	**Q (Mvar)**
6034	BRIM3K	ZZ	2.70	0.00	2.70	0.00
7734	TIVM3J	ZP	16.00	0.00	16.00	0.00
7736	TIVS3J	ZZ	8.95	0.00	8.95	0.00
7946	DUNK3K	ZZ	6.00	0.00	6.00	0.00
9370	AYSH3	P1	4.55	0.00	4.55	1.00
9370	AYSH3	ZE	0.00	0.00	0.35	0.00
9830	CMPV3	P1	4.00	-0.81	4.00	0.10
9830	CMPV3	ZE	6.00	0.00	6.00	0.00
9850	STFA3	P1	4.00	-0.81	4.00	0.23
9850	STFA3	ZE	0.00	0.00	0.20	0.00
10940	WSHB3	PA	6.00	-1.22	6.00	-1.97
10940	WSHB3	ZE	6.17	0.00	6.17	0.00
10941	WSHC3T	ZZ	9.00	0.00	9.00	0.00
Total			73.38	-2.84	73.93	-0.65
Total Dummy			54.83	0.00	55.38	0.00
Total Existing			18.55	-2.84	18.55	-0.65
Difference			-	-	**0.55**	**2.19**

This analysis demonstrates that not only is a per-feeder optimisation algorithm necessary but also that the weighting factor for the concentration between thermal and voltage issues cannot be an input. Instead the weighting factor will need to be determined as part of the optimisation algorithm based on the particular sensitivities of each of the feeder groups. A high-level approach to this is presented in Section 8.4.3.

7.1.4 Load Hosting Capacity - Intact System/Per Contingency

Table 7-13 provides an overview of the benefit (an increase in load hosting capacity) realised by using optimised reactive power dispatch setpoints for existing network generators for the different objective function weighting factors for Tiverton 33 kV BSP network. The load hosting capacity has been determined based on the maximum load, 10 % generation scenario and reactive power capability is based on the MW dispatch of each generator.

A benefit is shown by a green tick if the post optimised hosting capacity is greater than the pre-optimised hosting capacity, no benefit is shown by a yellow equals sign and a reduction in capacity is shown by a red cross.

The results shown in Table 7-13 are inconclusive due to limited reactive power to the Virtual Statcom algorithm. During the maximum load and 10% generation scenario, the maximum reactive power available in a network configuration is +/- 0.61 Mvar across the network (4 generators).

Table 7-12 –Tiverton 33 kV BSP comparison of pre and post-optimisation load capacity

Tiverton 33 kV Network configuration	Limiting violation(s) type(s) from hosting capacity algorithm	w=0	w=0.5	w=1	Mvar available (Min/ Max)
Intact system	I	✗	✓	✓	-0.61/0.61
BSP infeed transformers contingencies					
TIVE3_TIVE1Q_G1	I	✓	✗	✗	-0.61/0.61
TIVE3_TIVE1R_G2	I	✓	✗	✗	-0.61/0.61
Circuit contingencies					
TIVM3K_TIVE3_L1	I	✗	✗	✗	-0.61/0.61
TIVS3K_TIVE3_L1	I	✗	✗	✗	-0.61/0.61
BURL3K_HEMY3K_L1	I	✗	✗	✗	-0.61/0.61
BRIM3J_TIVE3_L1	I	✓	✗	✗	-0.61/0.61
HEMY3J_DUNK3K_L1	I	✓	✗	✗	-0.61/0.61
TIVM3J_TIVS3J_L1	I	✗	✗	✗	-0.61/0.61
CULL3K_STFA3T_L1+ TIVE3_STFA3T_L1+ STFA3_STFA3T_L1	I	✓	✓	✓	-0.48/0.48
BRIM3K_CMPV3T_L1+ CULL3J_CMPV3T_L1+ CMPV3_CMPV3T_L1	I	✗	✓	✓	-0.48/0.48
BURL3J_AYSH3T_L1+ TIVE3_AYSH3T_L1+ AYSH3_AYSH3T_L1	I	✗	✗	✗	-0.46/0.46
TIVM3J_WSHC3T_L1+ WSHB3_WSHC3T_L1	I	✗	✗	✗	-0.41/0.41
33/11kV Primary Supply Transformers contingencies					
All 33/11 kV supply transformers	I	✓	✗	✗	-6.1/6.1

7.2 Barnstaple 33 kV BSP Virtual Statcom summary

7.2.1 Generation Hosting Capacity - Intact System/Per Contingency

Table 7-13 provides an overview of the benefit (an increase in generation hosting capacity) realised by using optimised reactive power dispatch setpoints for existing network generators for the different objective function weighting factors for Barnstaple 33 kV BSP network.

Table 7-13 - Barnstaple 33 kV BSP comparison of pre and post-optimisation generation headroom capacity

Barnstaple 33 kV Network configuration	Limiting violation(s) type(s) from hosting capacity algorithm	w=0	w=0.5	w=1	Max benefit (MW)
Intact system	I*	✓	✓	✓	73.06
BSP infeed transformers contingencies					
BAST1Q_BAST3_G1	I*	✓	✓	✓	9.8
BAST1R_BAST3_G2	I*	✓	✓	✓	9.8
Circuit contingencies					
HEDX3J_BAST3_L1	I*	=	=	=	n/a
SMOL3K_KING3T_L1+ BAST3_KING3T_L1+ KING3_KING3T_L1	I*	=	=	=	n/a
AARO3_AARO3T_L1+ AARO3T_HEDX3K_L1+ AARO3T_SMOL3J_L1	I*	=	=	=	n/a
BATS3_BATS3R_L1	RPF	×	×	×	n/a
SMOL3K_BATS3R_R1	RPF	×	×	×	n/a
All other circuit contingencies	I*	✓	✓	✓	86.04
33/11kV Primary Supply Transformers contingencies					
All 33/11 kV supply transformers.	I*	✓	✓	✓	74.72

I* there is an intact system violation in Barnstaple 33kV BSP for the min load max gen scenario.

The detailed demonstration for Tiverton BSP in Section 7.1 has shown limitations using a network optimisation approach and this also applies to Barnstaple for the contingencies where the contingency configuration removes the intact system violating component. (i.e. BATS3_BATS3R_L1 and SMOL3K_BATS3R_R1 contingencies). The contingencies in Table 7-13 where the weighting factor has no impact shows that the Virtual Statcom is unable to resolve the violations for these contingencies.

The key finding from the Barnstaple 33 kV results are from the contingencies where there has been a post optimised hosting capacity benefit for all weighting factors (with large benefit). In these cases, the Virtual Statcom has resolved the violations present in the contingency configuration which allows the generation hosting capacity algorithm to scale generation. This highlights the benefit of the Virtual Statcom optimisation to resolve violations but due to the generation hosting capacity approach, of not scaling generation if there is a violation in the network before generation scaling, the post optimised generation increase is overstated.

7.2.2 Load Hosting Capacity - Intact System/Per Contingency

A comparison of pre and post-optimisation load capacity for Barnstaple 33 kV network is presented in Appendix L. The results show benefits in most configurations with a weighting factor of w=0, but these are minor compared to total load increase. The benefits are minor due to limited reactive power to the Virtual Statcom algorithm. During the maximum load and 10% generation scenario, the maximum reactive power available in a network configuration is +/- 1.6 Mvar across the network (8 generators).

7.3 Pyworthy and North Tawton 33 kV BSP summary

7.3.1 Generation Hosting Capacity - Intact System/Per Contingency

Pyworthy and North Tawton 33 kV BSP generation hosting capacity results are presented in Appendix L. A key finding from the results is there are contingency configurations where the post optimised hosting capacity shows benefit for all objective function weighting factors but, unlike the similar cases in Barnstaple 33 kV BSP network (Section 7.3) there are no initial violations in the contingency configuration for Pyworthy and North Tawton 33 kV BSP. See Appendix L for the full table of Pyworthy and North Tawton pre and post optimisation generation benefit.

Table 7-14 – Example contingency showing benefit for all weighting factors analysis

Pyworthy and North Tawton 33 kV Network configuration	Limiting violation(s) type(s) from hosting capacity algorithm*	w=0	w=0.5	w=1	Max benefit (MW)
OKEH3K_WHID3K_L1	V	✓	✓	✓	3.98

The contingency shown in Table 7-14 has been analysed to determine if results where all weighting factors show benefit are credible. The findings show that the results are credible and is based on Pyworthy and North Tawton 33 kV BSP network having a large number of dummy generators (28 before upstream placed generators) in the hosting capacity algorithm. As the reactive power dispatch changes for each weighting factor, the dummy generators dispatch changes but for all cases the total dummy generation is greater than for the non-optimised reactive power dispatch case. Figure 7-4 shows how the dummy generation dispatch changes for the different objective function weighting factors.

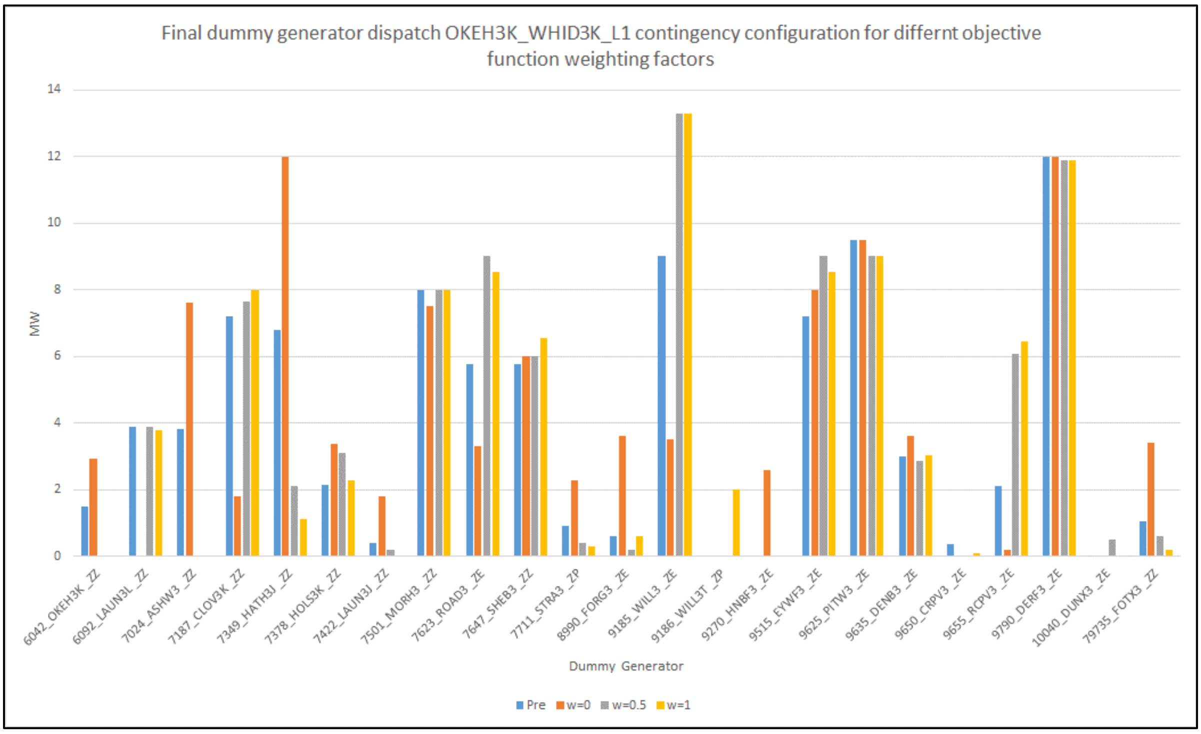


Figure 7-4 - Dummy generator dispatch for OKEH3K_WHID_L1

7.3.2 Load Hosting Capacity - Intact System/Per Contingency

A comparison of pre- and post-optimisation load capacity for Pyworthy and North Tawton 33 kV network is presented in Appendix L. The results show benefits in most configurations with a weighting factor of w=0, but these are minor compared to total load increase. The benefits are minor due to limited reactive power to the Virtual Statcom algorithm, during the maximum load and 10% generation scenario the maximum reactive power available in a network configuration is +/- 3.2 Mvar across the network (16 generators).

7.4 Tiverton Moorhayes 11kV Primary Summary

7.4.1 Generation Hosting Capacity - Intact System/Per Contingency

A comparison of pre- and post-optimisation generations capacity for Tiverton Moorhayes 11 kV Primary network is presented in Appendix L. The results show benefits in some configurations, but these are minor compared to the total dummy generation added. This is due to the limited reactive power available from the two existing generators in the primary network +/- 0.64 Mvar.

7.4.2 Load Hosting Capacity - Intact System/Per Contingency

A comparison of pre- and post-optimisation load capacity for Tiverton Moorhayes 11 kV network is presented in Appendix L. The results show no benefit in most configurations due to a thermal violation in the maximum load, 10% generation scenario that the Virtual Statcom cannot resolve. The one contingency configuration (that removes the violating component) shows a benefit but is minor due to limited reactive power to the Virtual Statcom algorithm. During the maximum load and 10% generation scenario the maximum reactive power available in a network configuration is +/- 0.064 Mvar across the network (2 generators).

7.5 Summary of Capacity Benefits Results

This section presents a summary of the 33 kV BSP and 11 kV Primary results considered in this study and presents the generation or load capacity increase created as a result of the Virtual Statcom. This capacity increase is presented for each weighting factor (w=0, 0.5, 1). Analysis has been carried out for the minimum load, maximum generation scenario for generation hosting and the maximum load, 10 % generation scenario for load.

Results are presented for the traditional system planning approach which determines the additional capacity that can be achieved for any system contingency. The available headroom is also presented for the intact system and most limiting contingency.

7.5.1 Barnstaple 33 kV BSP – Generation

Table 7-15 shows the additional generation hosting capacity available in the Barnstable 33 kV BSP network. Under the traditional planning approach, it is not possible to accommodate any additional generation as the Virtual Statcom cannot resolve all violations caused in contingency configurations for the minimum load, maximum generation scenario.

In the intact system after optimising the generator set-points the Virtual Statcom can resolve the violation and accommodate generation into this region of the network. As described in Section 7.2 the capacity is overstated due to the hosting capacity algorithms approach when violation exist in the intact system for the initial load and generation scenario.

Table 7-15: Generation hosting capacity increase in Barnstable 33 kV BSP created by Virtual Statcom

Load/ Generation scenario	Pre-optimisation generation hosting capacity (MW)	Capacity Increase (MW)			Capacity Increase (%)		
		(w=0)	(w=0.5)	(w=1)	(w=0)	(w=0.5)	(w=1)
Min load Max Gen traditional planning	60.42	0	0	0	0	0	0
Min load Max Gen intact system	60.42	73.06	72.5	68.93	121%	120%	114%
Min load Max Gen worst contingency	60.42	0	0	0	0	0	0

7.5.2 Barnstaple 33 kV BSP – Load

Table 7-16 shows the additional load hosting capacity available in the Barnstable 33 kV BSP. During maximum load, 10 % generation scenario there is a benefit in the hosting capacity possible when the weighting factor =0.0, but as mentioned in Section 7.2 these benefits are minor due to limited reactive power available to the Virtual Statcom.

Table 7-16: Load hosting capacity increase in Barnstable 33 kV BSP created by Virtual Statcom

Load/ Generation scenario	Pre-optimisation Load hosting capacity (MW)	Capacity Increase (MW)			Capacity Increase (%)		
		(w=0)	(w=0.5)	(w=1)	(w=0)	(w=0.5)	(w=1)
Max load 10% Gen Traditional planning	61.08	0.73	-0.28	-0.12	1.2%	-0.5%	-0.2%
Max load 10% Gen intact system	111.91	0.6	0.06	-0.04	0.5%	0.1%	0.0%
Max load 10% Gen worst contingency	61.35	0.7	-0.25	-0.25	1.1%	-0.4%	-0.4%

7.5.3 Pyworthy and North Tawton 33 kV BSP – Generation

Table 7-17 shows the additional generation hosting capacity available in the Pyworthy and North Tawton 33 kV BSP network. Under the traditional planning approach, it is not possible to accommodate any additional generation since there are violations in contingency configurations that the Virtual Statcom is not able to resolve in the minimum load maximum generation scenario.

Investigating the intact system alone, after optimising existing generators reactive power setpoints, there is a slight increase in the available hosting capacity of the network with a weighting factor of 1.0 (optimising for voltages). However, the impact of the weighting factor is important and a value of 0.0 (optimising for thermal loading) would result in a reduced hosting capacity as more voltage limits are breached.

Table 7-17: Generation hosting increase in Pyworthy and North Tawton 33 kV BSP created by Virtual Statcom

Load/ Generation scenario	Pre-optimisation generation hosting capacity (MW)	Capacity Increase (MW)			Capacity Increase (%)		
		(w=0)	(w=0.5)	(w=1)	(w=0)	(w=0.5)	(w=1)
Min load Max Gen traditional planning	146.914	0	0	0	0	0	0
Min load Max Gen intact system	245.9	-10.3	1.6	2.13	-4.2%	0.7%	0.9%
Min load Max Gen worst contingency	146.914	0	0	0	0	0	0

7.5.4 Pyworthy and North Tawton 33 kV BSP – Load

Table 7-18 shows the additional load hosting capacity available in the Pyworthy and North Tawton 33 kV BSP network. During maximum load, 10 % generation scenario there is a benefit in the hosting capacity possible when the weighting factor =0.0, but as mentioned in

Section 7.3 these benefits are minor due to limited reactive power available to the Virtual Statcom.

Table 7-18: Load hosting capacity increase in Pyworthy and North Tawton 33 kV BSP created by Virtual Statcom

Load/ Generation scenario	Pre-optimisation Load hosting capacity (MW)	Capacity Increase (MW)			Capacity Increase (%)		
		(w=0)	(w=0.5)	(w=1)	(w=0)	(w=0.5)	(w=1)
Max load 10% Gen traditional planning	96.7	1.1	-0.7	-0.5	1.1%	-0.7%	-0.5%
Max load 10% Gen intact system	183.1	1.0	-0.2	0.2	0.6%	-0.1%	0.1%
Max load 10% Gen worst contingency	118.1	0.6	0.0	-1.8	0.5%	0.0%	-1.5%

7.5.5 Tiverton 33 kV BSP – Generation

Table 7-19 shows the additional generation hosting capacity available in the Tiverton 33 kV BSP network. The Virtual Statcom has relatively limited benefit in this network region due to the relatively small levels of reactive power available and the reverse power flow limits of the BSP infeed transformers. In the cases presented in able 7-20, the slight improvements possible (<1.0 %) are as a result of reducing thermal loading on the circuits (w=0).

Table 7-19: Generation hosting capacity increase in Tiverton 33 kV BSP created by Virtual Statcom

Load/ Generation scenario	Pre-optimisation generation hosting capacity (MW)	Capacity Increase (MW)			Capacity Increase (%)		
		(w=0)	(w=0.5)	(w=1)	(w=0)	(w=0.5)	(w=1)
Min load Max Gen Traditional planning	59.8	0.5	0.0	-0.5	0.9%	-0.1%	-0.9%
Min load Max Gen intact system	103.8	0.9	-0.5	-0.4	0.9%	-0.5%	-0.4%
Min load Max Gen worst contingency	59.9	0.0	-0.8	-0.8	0.0%	-1.3%	-1.3%

7.5.6 Tiverton 33 kV BSP – Load

Table 7-20 shows the additional load hosting capacity available in the Tiverton 33 kV BSP network. In maximum load, 10 % generation scenario there is negligible benefit due to the very small level of reactive power available from the distributed generation (+/-0.61 Mvar).

Table 7-20: Load hosting capacity increase in Tiverton 33 kV BSP created by Virtual Statcom

Load/ Generation scenario	Pre-optimisation Load hosting capacity (MW)	Capacity Increase (MW)			Capacity Increase (%)		
		(w=0)	(w=0.5)	(w=1)	(w=0)	(w=0.5)	(w=1)
Max load 10% Gen traditional planning	64.17	0.35	0.35	0.35	0.6%	0.5%	0.5%
Max load 10% Gen intact system	110.94	0.00	0.00	0.0%	0.0%	0.0%	0.0
Max load 10% Gen worst contingency	68.79	0.21	0.00	0.0%	0.3%	0.0%	0.0

7.5.7 Tiverton Moorhayes 11 kV Primary – Generation

Table 7-21 shows the additional generation hosting capacity available in the Tiverton Moorhayes 11 kV Primary network. The Virtual Statcom has relatively limited benefit in this network region due to the small levels of reactive power available.

Table 7-21: Generation hosting capacity increase in Tiverton Moorhayes 11 kV BSP created by Virtual Statcom

Load/ Generation scenario	Pre-optimisation generation hosting capacity (MW)	Capacity Increase (MW)			Capacity Increase (%)		
		(w=0)	(w=0.5)	(w=1)	(w=0)	(w=0.5)	(w=1)
Min load Max Gen Traditional planning	1.95	-0.01	-0.02	-0.02	-0.1%	-0.18%	-0.18%
Min load Max Gen intact system	1.95	-0.04	0	0	0.1%	0%	0
Min load Max Gen worst contingency	1.95	0.12	0.06	0.06	0.93%	0.5%	0.5%

7.5.8 Tiverton Moorhayes 11 kV Primary – Load

Virtual Statcom is not able to resolve the thermal violation in the intact configuration for the maximum load, 10 % generation scenario. Therefore, due to the hosting capacity algorithm approach, no load scaling takes place in traditional planning approach, intact system and worst contingency configurations.

8 Virtual Statcom Project WP2 Conclusions

This report sets out the results and findings for Work Package 2 of the Virtual Statcom project which has developed algorithms to determine the available generation and load hosting capacity before and after optimising the reactive dispatch of existing generators for three of the WPD 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

Results have been presented in detail for the minimum load, max generation and maximum load, 10 % generation scenarios. These have been selected to investigate the extremes of the operating positions on the WPD network and in the case of the maximum load, 10% generation scenario to ensure that some reactive power was available to demonstrate the capability of the Virtual Statcom.

8.1 Generation and Load Hosting Algorithms

The generation and load hosting algorithms have been developed to present the available hosting capacity for each contingency. These contingencies have consisted a single circuit outage (circuit, transformer or generator) and highlighted those contingencies which are the most restrictive to accommodating additional generation or load. Additionally, the traditional planning approach has been presented which is the maximum additional generation or load that can be accommodated such that the system will remain within voltage and thermal constraints for all the contingencies.

Analysis of multiple options for determining the available generation hosting capacity has shown that the preferred method for generation hosting is to scale dummy generators placed at both end buses and existing generator buses. The method for assessing load hosting capacity scales existing loads only. In the case where voltage or thermal violations are reached, during load/generation scaling, these are resolved using a voltage or thermal sensitivity factor before increasing generation/load levels at the remaining scaling locations. Once no dummy generators/scalable loads exist the available hosting capacity has been determined and testing on multiple networks and dispatch levels has shown this to be a robust approach.

For some load and generation scenarios in the study networks analysed thermal and/or voltage violations are present in either the intact system configuration or contingency configurations. In these cases, no load or generation is scaled. The results presented in this report demonstrate a limitation in this approach in that it causes the post optimisation hosting results to be overstated if the Virtual Statcom can resolve the violations.

8.2 Virtual Statcom Approach

The Virtual Statcom algorithm has been developed to initially test different generator set-points that resolve all breaches in either voltage or thermal constraints. Once these have been resolved (if any existed) further optimisation aims to either reduce the deviation from a nominal voltage or reduce the thermal loading on a circuit. The preference towards each of these approaches is dependent on the weighting factor assigned as an input to the objective function.

Analysis of the weighting factor has shown that the impact on system voltage or thermal loading is heavily dependent on the dispatch arrangement and network configuration. Initial results suggest that the optimum weighting factor is dependent on the specific contingency and limiting conditions. Further analysis is necessary to identify the optimum weighting factor during or prior to running the Virtual Statcom optimisation.

8.3 Virtual Statcom Optimisation

The load and generation hosting algorithms were run on the initial study network model and then again once optimum reactive power set-points for existing generators had been identified by the Virtual Statcom optimisation engine. The results showed that the potential benefit of increasing hosting capacity was significantly dependant on:

- The available reactive power within the network
- The weighting factor selected for the objective function

In cases where there is limited reactive power available in the system the potential for the Virtual Statcom during extremes of dispatch arrangements is clearly very limited. However, there are still some very slight benefits shown and the selection of the weighting factor has a more significant impact.

In cases where the system is already breaching thermal or voltage limits for a specific contingency the Virtual Statcom offers a significant improvement. In some cases, the Virtual Statcom optimisation can fully resolve the breaches and therefore makes it possible to significantly increase the generation or load hosting capacity during the contingency. In other cases, the breaches cannot be fully resolved but they can be reduced meaning the level of circuit overload is reduced.

8.4 Further Analysis

This report has presented some interesting findings and areas for further analysis to fully explore the potential of the Virtual Statcom concept. These can be categorised into the following areas and further details as to how these can be implemented are included in the following sections:

- Generator hosting capacity when network limits breached
- Feeder-group based Virtual Statcom optimisation
- Virtual Statcom thermal vs voltage optimisation weighting factor
- Reactive power available to Virtual Statcom in low generation cases
- Utilising dummy generation reactive power

The modifications proposed in this section are to be implemented in the as part of the next work package.

8.4.1 Generator Hosting Capacity

The algorithm to determine the generation/load hosting capacity stops if there is a thermal or voltage violation in the initial system model since this cannot be resolved without adjusting the existing generation or load. As a result, if the Virtual Statcom is able to resolve this initial violation it appears that it is able to offer a significant increase in the generation/load hosting capacity.

This is clearly demonstrated in the analysis on the Barnstaple 33 kV network (section 7.2) where a thermal violation in 1 feeder group is breached in the initial system model. Therefore, once the Virtual Statcom has resolved this breach it is possible to add dummy generators elsewhere on the system without re-introducing this thermal breach. However, this shows some unrealistically high levels of increase in the generation hosting capacity (>70 MW).

To address this the generation/load hosting algorithms should be modified to allow generation to still be added to the network even if there is an initial system breach. This will be achieved by allowing generation to be added so long as the initial system breach does not get worse. As a result, the generation would be added to different feeder groups and follow the approach detailed in the following flowchart (Figure 8-1). The load hosting algorithm should be modified in a similar way.

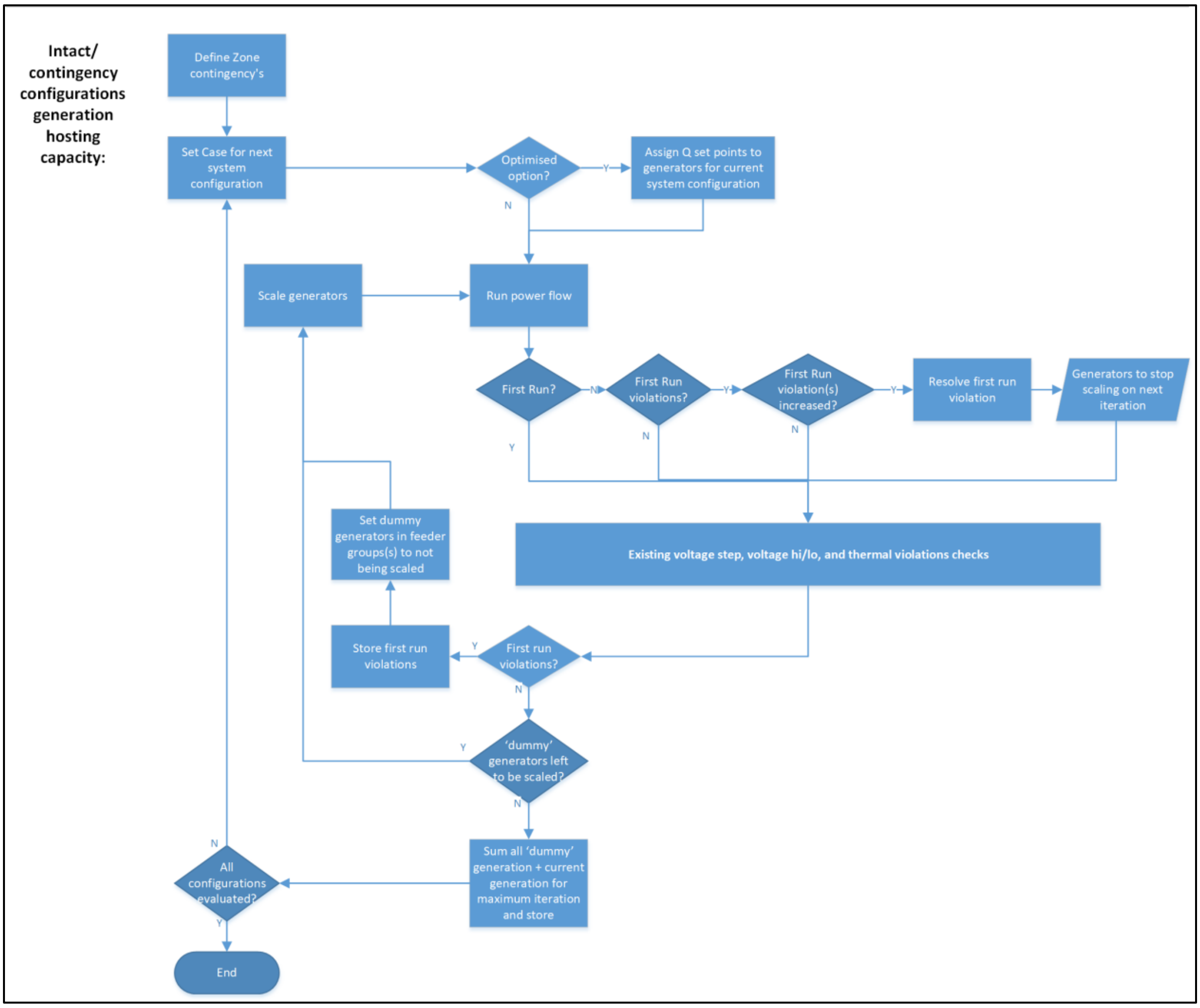


Figure 8-1 – Proposed Generator Hosting Algorithm

8.4.2 Feeder-group Based Virtual Statcom Optimisation

The analysis detailed in Section 7 has shown that in some networks it is not possible to optimise the entire network based on either targeting voltage or thermal related issues. It is possible that some feeder groups within a network are thermally constrained whereas other feeder groups are voltage constrained. To address this the Virtual Statcom would be better placed to optimise reactive power dispatch for the thermal constraints in some feeder groups and voltage constraints in other feeder groups.

A manual example to test this approach on the Tiverton 33 kV network for two contingencies (TIVM3J_TIVS3J_L1 and BRIM3J_TIVE3_L1) has been presented (Section 7.1.3). In both contingencies if the thermally constrained feeder groups had been optimised separately to the voltage constrained feeder groups then post-optimisation there would have been an increase in the generation hosting capacity.

To address this the Virtual Statcom algorithms will need to be modified to target each feeder group independently and a proposed approach to this is detailed in the flowchart below (Figure 8-2).

8.4.3 Virtual Statcom Thermal vs Voltage Optimisation Weighting Factor

The Virtual Statcom algorithm needs to determine whether the system should be optimised for voltages or thermal constraints. It was originally intended that this would be controlled via a user selectable weighting factor (w) and values of 0.0, 0.5 and 1.0 have been analysed. In carrying out this analysis it has become apparent that the potential for increasing the generation hosting capacity is very sensitive to this weighting factor. Therefore, it is necessary to determine this weighting as part of the Virtual Statcom optimisation algorithm.

The proposed approach to achieve this is to determine the sensitivity of a feeder group for increases in generation. This sensitivity will investigate the changes in voltage and thermal loading to determine which is most significantly impacted. From this a weighting factor will be determined for the specific feeder group and this will be used for optimisation. The proposed implementation of this for the Virtual Statcom is shown in the flowchart below (Figure 8-2).

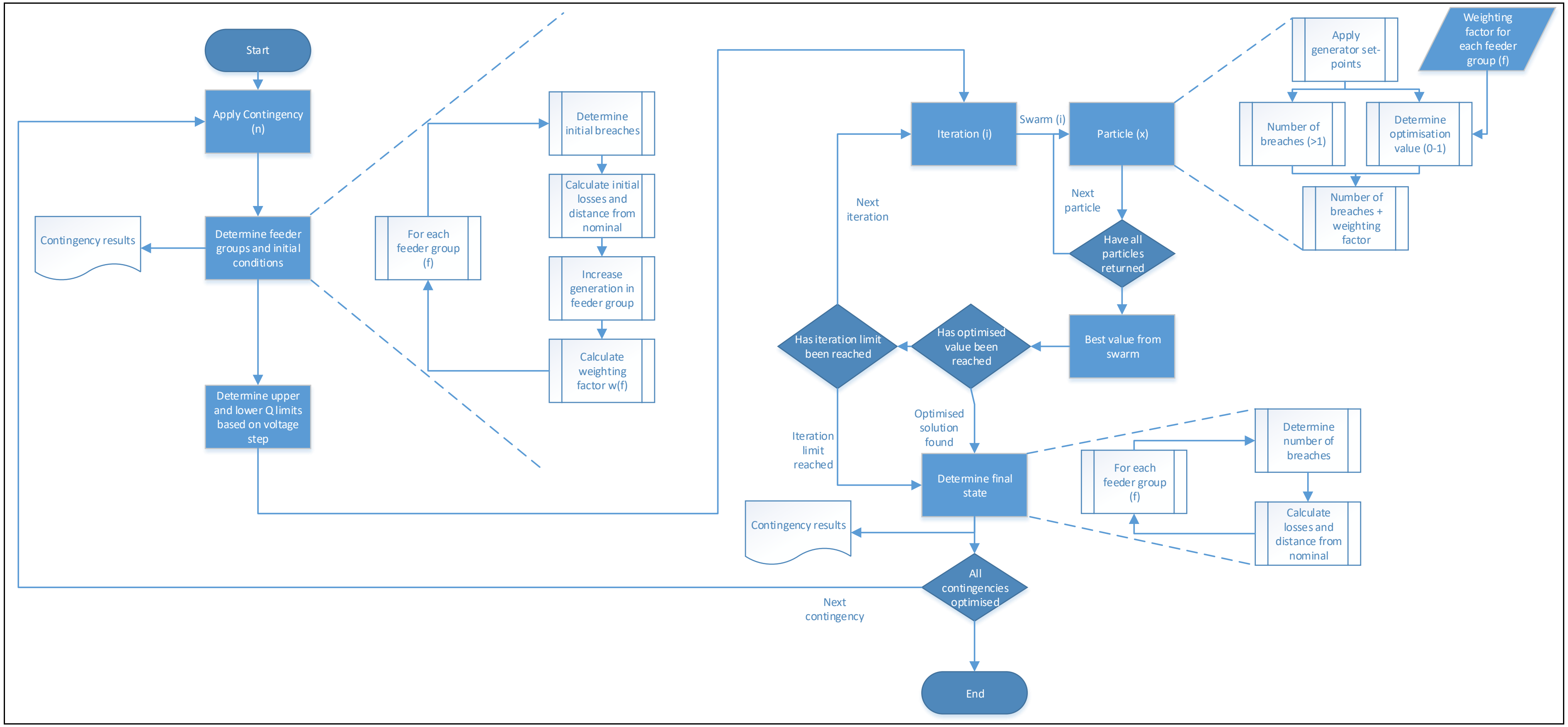


Figure 8-2 – Proposed Virtual Statcom Algorithm

8.4.4 Reactive Power Available in Low Generation Cases

The results presented in this report focus on the minimum load, maximum load scenario for generation hosting and the maximum load, 10% and generation scenario for load hosting. The assumption used to determine the reactive power range available to the Virtual Statcom, is based on the real power output of the generator with fixed power factor of 0.95 leading and 0.95 lagging as shown in Figure 8-3a). A consequence of this assumption is that in the maximum load 10% generation very little reactive power is available to the Virtual Statcom and this results in either inconclusive or very minor benefits when determining the load hosting capacity.

To ascertain if there are any benefits for scenarios with low generation the reactive power allocation assumption will be modified. The modified assumption will assume that the reactive power available at maximum real power with power factor of +/- 0.95 is available when a generator is at 10% of maximum real power and above as shown in Figure 8-3b).

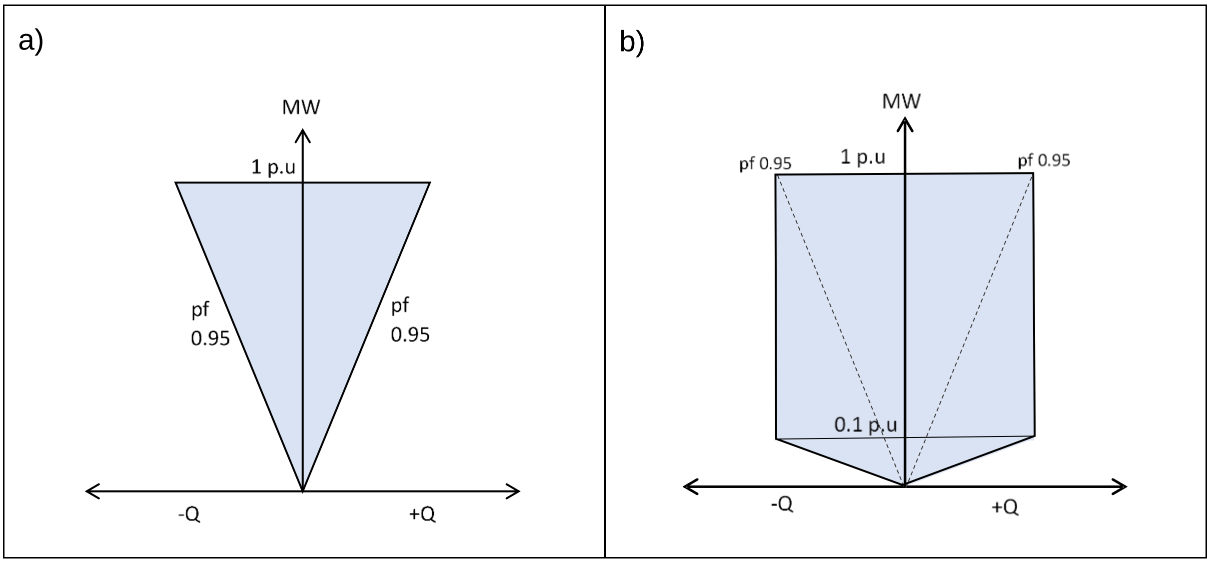


Figure 8-3 - Reactive power allocation assumption

8.4.5 Utilising Dummy Generators Reactive Power Capability

The algorithms developed for the Virtual Statcom currently scale the real power of dummy generators to obtain the generation hosting capacity and optimise the reactive power of existing generators. In some of the contingency configurations, limited reactive power is available to resolve either thermal or voltage violations. A proposed approach to provide more reactive power to the Virtual statcom is to include an option that also incorporates reactive power control for the dummy (new) generators. The following provides a high level of the approach to be developed:

- Run the generation hosting capacity algorithm to place and scale dummy generators.
- At the end of the scaling iteration re-classify dummy generators as “new” generators.
- Run the optimisation algorithm using the “new” and existing generators.
- Run the generation hosting capacity algorithm with optimised reactive power set points for the “new” and existing generators.

The approach of using “new” generators has the potential to provide the requirements for new connections in the network in order to release generation hosting capacity.

9 References

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Appendix A Intact System Case Creation, Load and Generation Details

A1 Initial Intact system case set up

A1.1 33 kV networks:

The initial case provided for the WPD South West region was a maximum load minimum generation case, this was used as the starting case from which 3 other cases were derived where only loads and generation in the study zones are scaled with all other loads and generation remaining as per original case.

<u>Minimum load Maximum generation case set up:</u>
Starting with the maximum load minimum generation case:

- Loads in Barnstaple 33 kV BSP, Tiverton 33 kV BSP, Pyworthy 33 kV BSP and North Tawton 33 kV BSP were scaled to 30% of the maximum load.
- Battery loads in Barnstaple 33 kV BSP, Tiverton 33 kV BSP, Pyworthy 33 kV BSP and North Tawton 33 kV BSP were removed.
- All generation (including batteries) put in service in Barnstaple 33 kV BSP, Tiverton 33 kV BSP, Pyworthy 33 kV BSP and North Tawton 33 kV BSP

<u>Maximum load Maximum generation case setup:</u>
Starting with the maximum load minimum generation case:

- All generators put into service in Barnstaple 33 kV BSP, Tiverton 33 kV BSP, Pyworthy 33 kV BSP and North Tawton 33 kV BSP.

<u>Minimum load minimum generation case setup:</u>
Starting with the maximum load minimum generation case:

- Loads in Barnstaple 33 kV BSP, Tiverton 33 kV BSP, Pyworthy 33 kV BSP and North Tawton 33 kV BSP were scaled to 30% of the maximum load.
- Battery loads in Barnstaple 33 kV BSP, Tiverton 33 kV BSP, Pyworthy 33 kV BSP and North Tawton 33 kV BSP were removed.

This resulted in the following 4 cases being used in the power system studies.

1. Maximum load minimum generation.
2. Minimum load maximum generation.
3. Maximum load maximum generation.
4. Minimum load minimum generation.

A1.2 11 kV network

The initial case that WPD provided for the Tiverton Moorhayes 11 kV Primary networks was maximum load minimum generation case, this was used as the starting case from which 3 other cases were derived.

<u>Minimum load Maximum generation case set up:</u>
Starting with the maximum load minimum generation case:

- Loads in Tiverton Moorhayes 11 kV Primary were scaled to 30% of the maximum load.
- All generation put into service in Tiverton Moorhayes 11 kV Primary.

<u>Maximum load Maximum generation case setup:</u>
Starting with the maximum load minimum generation case:

- All generators put into service in Tiverton Moorhayes 11 kV Primary.

<u>Minimum load minimum generation case setup:</u>
Starting with the maximum load minimum generation case:

- Loads in Tiverton Moorhayes 11 kV Primary were scaled to 30% of the maximum load.

This resulted in the following 4 cases being used in the power system studies.

1. Maximum load minimum generation.
2. Minimum load maximum generation.
3. Maximum load maximum generation.
4. Minimum load minimum generation.

A2 Maximum Load - 10% Generation Intact System Case Set-up

A2.1 33 kV networks

Starting with the 33kV maximum load maximum generation case:

- Scale generation to 10% of maximum generation

A2.2 11 kV network

Starting with the 11kV maximum load maximum generation case:

- Scale generation to 10% of maximum generation

A3 Barnstaple Base Case Load and Generation

A3.1 Load

Table A9-1and Table A1-2 set out the minimum and maximum load used in the Barnstaple 33 kV BSP power system analysis.

Table A9-1 – Barnstaple BSP 33 kV loads

33 kV Load	Min Load		Max Load	
Site	MW	Mvar	MW	Mvar
Aaronsons	1.3	0.4	4.4	1.3
Total:	1.3	0.4	4.4	1.3

Table A1-2 – Barnstaple BSP 11 kV loads

11 kV Load	Min Load		Max Load	
Site	MW	Mvar	MW	Mvar
Bratton Flemming	0.62	0.18	2.1	0.6
Heddon Cross	1.36	0.39	4.5	1.3
Great Torrington	0.54	0.15	1.8	0.5
Lynton	0.79	0.23	2.6	0.8
Middle Barlington	0.53	0.15	1.8	0.5
Rock Park	2.69	0.77	9.0	2.6
Roundswell	1.97	0.56	6.6	1.9
Roundswell (battery)	0	0	3.75	0
South Molton	1.59	0.45	5.3	1.5
Tinkers Cross J	0.54	0.15	1.8	0.5
Tinkers Cross k	0.83	0.24	2.8	0.8
Total:	14.5	3.3	41.9	10.9

Table A1-3 – Barnstaple BSP load total

	Min Load		Max Load	
	MW	Mvar	MW	Mvar
Barnstaple 33kV BSP Load Total:	15.8	3.7	46.3	12.2

A3.2 Generation

Table A1-4 and Table A1-5 set out the minimum and maximum generation used in the Barnstaple 33 kV BSP power system studies.

Table A1-4 – Barnstaple BSP 33kV Generation

33 kV Generation	Min Generation		Max Generation	
Site	MW	Mvar	MW	Mvar
Batsworthy A Windfarm	0	0	1.2	-0.4
Batsworthy Windfarm	0	0	17.1	-5.6
Beaford Farm	0	0	5.0	0.0
Bratton Flemming	0	0	5.0	0.0
Capelands Farm	0	0	7.5	0.0
Darracott Moor	0	0	2.4	-0.8
Kingsland Barton	0	0	5.0	-1.6
Knockworthy	0	0	5.0	0.0
Total:	0	0	48.2	-8.5

Table A1-5 – Barnstaple BSP 11kV Generation

11 kV Generation	Min Generation		Max Generation	
Site	MW	Mvar	MW	Mvar
Great Torrington 11kV	0	0	2.7	0
Lynton 11kV	0	0	0.3	0
Rock Park 11kV	0	0	0.4	0
Roundswell 11kV	0	0	6.2	-1.2
South Molton 11kV	0	0	1.1	0
Tinkers Cross J 11kV	0	0	1.3	0
Total:	0	0	12.2	-1.2

Table A1-6 – Barnstaple BSP generation total

	Min Generation		Max Generation	
	MW	Mvar	MW	Mvar
Barnstaple 33kV BSP Generation Total:	0	0	60.4	-9.7

A4 Pyworthy and North Tawton base case load and generation

A4.1 Load

Table A1-7 and Table A1-8 set out the minimum and maximum load for Pyworthy and North Tawton 33 kV BSP.

Table A1-7 – Pyworthy and North Tawton BSPs 33 kV loads

33 kV Load	Min Load		Max Load	
Site	MW	Mvar	MW	Mvar
Roadford 33 kV	0.29	0.06	0.95	0.20
Total:	0.29	0.06	0.95	0.20

Table A1-8 – Pyworthy and North Tawton BSPs 11 kV loads

11 kV Load	Min Load		Max Load	
Site	MW	Mvar	MW	Mvar
Ashwater 11kV	0.3	0.1	1.2	0.2
Clovelly 11kV	1.4	0.3	4.7	1.0
East Curry 11 kV	0.9	0.2	2.9	0.6
Hatherleigh 11kV	1.7	0.3	5.6	1.1
Holsworthy 11kV	2.1	0.4	7.1	1.5
Launceston 11kV	0.0	0.0	0.0	0.0
Launceston 11kV	3.2	0.7	10.8	2.2
Moretonhampstead 11kV	0.8	0.2	2.7	0.6
Morwenstow 11kV	1.5	0.3	5.1	1.1
North Tawton 11 kV	1.2	0.2	3.9	0.8
Okehampton 11kV	2.4	0.5	8.1	1.7
Shebbear 11 kV	0.9	0.2	3.1	0.6
Stratton 11 kV	3.2	0.7	10.6	2.2
Whiddon Down 11 kV	1.0	0.2	3.2	0.7
Total:	20.7	4.2	69.1	14.1

Table A1-9 – Pyworthy and North Tawton BSPs load total

	Min Load		Max Load	
	MW	Mvar	MW	Mvar
Pyworthy and North Tawton BSPs Load Total:	21.0	4.3	70.0	14.3

A4.2 Generation

Table A1-10 and Table A1-11 set out the minimum and maximum generation for Pyworthy and North Tawton 33 kV BSP.

Table A1-10 – Pyworthy and North Tawton BSPs 33kV Generation

33 kV Generation	Min Generation		Max Generation	
Site	MW	Mvar	MW	Mvar
Ashwater (West Venn farm) 33 kV	0	0	7	0
Bradford 33 kV	0	0	5	0
Crinacott Farm	0	0	5	0
Denbrook 33 kV	0	0	18	-5.902
Derriton Fields	0	0	9.5	0
Dunsland Cross	0	0	6.2	-2.268
East Langford 33 kV	0	0	5	0
East Langford 33 kV	0	0	3.2	0
East Youlstone 33 kV	0	0	4	0
Forestmoor 33 kV	0	0	3	0
Foxcombe 33 kV	0	0	5	0
Higher North Beer farm 33 kV	0	0	7.0	0
Pitworthy 33 kV	0	0	12.3	0
Rexon Cross Farm	0	0	3.5	0
Roadford 33 kV	0	0	1.2	0
Willsland 33kV	0	0	3.3	0
Total:	0	0	98.2	-8.2

Table A1-11 – Pyworthy and North Tawton BSPs 11kV Generation

11 kV Generation	Min Generation		Max Generation	
Site	MW	Mvar	MW	Mvar
Ashwater 11kV	0	0	2.0	0.0
East Curry 11 kV	0	0	8.0	0.0
Hatherleigh 11kV	0	0	3.6	0.0
Holsworthy 11kV	0	0	13.5	0.0
Launceston 11kV	0	0	5.6	0.0
Moretonhampstead 11kV	0	0	0.2	0.0
Morwenstow 11kV	0	0	9.4	0.0
Okehampton 11kV	0	0	0.5	0.0

Shebbear 11 kV	0	0	2.2	0.0
Stratton 11 kV	0	0	3.7	0.0
Total:	0	0	**48.7**	**0.0**

Table A1-12 – Pyworthy and North Tawton BSPs Generation total

	Min Generation		Max Generation	
	MW	Mvar	MW	Mvar
Pyworthy and North Tawton BSP(s) Generation Total:	0	0	146.9	-8.2

A5 Tiverton base case load and generation

A5.1 Load

Table A1-13 and Table A1-14 set out the minimum and maximum load for Tiverton 33 kV BSP.

Table A1-13 – Tiverton BSP 33 kV loads

33 kV Load	Min Load		Max Load	
Site	MW	Mvar	MW	Mvar
Stoneshill Farm (battery)	0	0	0.7	0.7
Total:	0	0	0.7	0.7

Table A1-14 – Tiverton BSP 11 kV loads

11 kV Load	Min Load		Max Load	
Site	MW	Mvar	MW	Mvar
Bridge Mills	1.7	0.3	5.8	0.9
Burlescombe	0.9	0.1	3.1	0.5
Cullompton	2.2	0.3	7.3	1.2
Dunkeswell	0.8	0.1	2.8	0.4
Hemyock	1.2	0.2	4.0	0.6
Tiverton Junction	2.9	0.5	9.6	1.5
Tiverton Moorhayes	1.8	0.3	5.9	0.9
Tiverton South	3.3	0.5	11.0	1.7
Total:	14.8	2.4	49.3	7.8

Table A1-15 – Tiverton BSP load total

	Min Load		Max Load	
	MW	Mvar	MW	Mvar
Tiverton BSP Load Total:				

A5.2 Generation

Table A1-16 and Table A1-17 set out the minimum and maximum generation for Tiverton 33 kV BSP.

Table A1-16 – Tiverton BSP 33 kV generation

33 kV Generation	Min Generation		Max Generation	
Site	MW	Mvar	MW	Mvar
Ayshford Court PV	0	0	4.6	0.0
Cullompton PV	0	0	4.0	-0.8
Stoneshill Farm	0	0	4.0	-0.8
WSHB3	0	0	6.0	-1.2
Total:	0	0	18.6	-2.8

Table A1-17 – Tiverton BSP 11 kV generation

11 kV Generation	Min Generation		Max Generation	
Site	MW	Mvar	MW	Mvar
Burlescombe 11 kV	0	0	1.5	0
Cullompton 11 kV	0	0	3.7	0
Dunkeswell 11 kV	0	0	2.0	0
Hemyock 11 kV	0	0	5.5	0
Tiverton Junction 11 kV	0	0	8.3	0
Tiverton Moorhayes 11 kV	0	0	3.5	0
Tiverton South 11 kV	0	0	0.1	0
Total	0	0	24.6	0

Table A1-18 – Tiverton BSP 33 kV generation total

	Min Generation		Max Generation	
	MW	Mvar	MW	Mvar
Tiverton BSP Generation Total:	0	0	43.2	-2.8

A6 Tiverton Moorhayes 11 kV base case load and generation

A6.1 Load

The Tiverton Moorhayes 11 kV primary model contains 432 individual loads. Table A1-19 presents the total Tiverton Moorhayes primary load.

Table A1-19 – Tiverton Moorhayes Primary load totals

	Min Load		Max Load	
	MW	Mvar	MW	Mvar
Tiverton Moorhayes 11 kV Primary:	1.91	0.39	6.37	1.30

A6.2 Generation

The Tiverton Moorhayes 11 kV primary model contains 2 generators, shown inTable A1-20.

Table A1-20 – Tiverton Moorhayes Primary generation totals

11 kV Generation	Min Generation		Max Generation	
Site	MW	Mvar	MW	Mvar
318054 11 kV	0	0	0.79	-0.26
317212 11 kV	0	0	1.16	-0.38
Total:	0	0	1.95	-0.64

Appendix B Study Zone Contingencies

B1 Barnstaple 33 kV BSP Contingencies

Contingency Type		Contingency
Line/cable:		BATS3_BATS3R_L1
		HEDX3J_BAST3_L1
		LAPF3J_TINX3R_L1
		MIDB3_TORR3K_L1
		ROCP3J_BAST3_L1
		ROCP3K_BAST3_L2
		ROUN3J_BAST3_L1
		ROUN3K_BAST3_L2
Transformers:		BRAF3_BRAF5_T1
		BRAF3T_BRAF3R_R1
		HEDX3J_HEDX5_T1
		LYNT3K_LYNT5_T2
		MIDB3_MIDB3R_R1
		MIDB3_MIDB5_T1
		ROCP3J_ROCP5_T1
		ROCP5_ROCP3K_T2
		ROUN3J_ROUN5_T1
		ROUN3K_ROUN5_T2
		SMOL3J_SMOL5_T1
		SMOL3K_BATS3R_R1
		SMOL3K_SMOL5_T2
		TINX3J_TINX5K_T1
		TINX3K_TINX5J_T2
		TORR3K_TORR5K_T2
BSP Tie Transformers		BAST1Q_BAST3_G1
		BAST1R_BAST3_G2
'T' connection contingencies	Kingsland Barton 'T'	SMOL3K_KING3T_L1
		BAST3_KING3T_L1
		KING3_KING3T_L1
	Aaronsons 'T'	AARO3_AARO3T_L1
		AARO3T_HEDX3K_L1
		AARO3T_SMOL3J_L1
	Barnstaple town 'T'	BAST3_BARQ3T_L1
		BRAF3R_BARQ3T_L1
	Beaford farm 'T"	TINX3J_BEAF3T_L1

		MIDB3R_BEAF3T_L1
		BEAF3_BEAF3T_L1
	Knockworthy – Darracott Moor 'T'	TORR3K_DARM3T_L1
		DARM3_DARM3T_L1
		DARM3T_KNOK3T_L1
		BAST3_KNOK3T_L1
		KNOK3_KNOK3T_L1
	Capelands Farm – Bratton Flemming 'T'	LYNT3K_CAPE3T_L1
		BRAT3T_CAPE3T_L1
		CAPE3_CAPE3T_L1
		BRAF3_BRAF3T_L1
		BRAF3T_BRAT3T_L1

B2 Pyworthy and North Tawton 33 kV BSP Contingencies

Contingency Type	Contingency
Line/cable:	ASHW3_ROAD3_L1
	ECUR3_PYWO3_L1
	FOTX3_FORE3_L1
	HATH3K_DUNX3B_L1
	HATH3K_OKEH3J_L1
	NTAW3_DENB3_L1
	OKEH3J_NTAW3_L1
	OKEH3K_WHID3K_L1
	PITW3_PYWO3T1_L1
	PYWO3T1_DERF3_L1
	STRA3_EYWF3_L1
	WHID3J_NTAW3_L1
Transformers/ Voltage Regulators:	ASHW3_ASHW5_T1
	CLOV3K_CLOV5_T2
	ECUR3_ECUR5_T1
	HATH3J_HATH5_T2
	HATH3K_HATH5_T1
	HOLS3J_HOLS5_T1
	HOLS3K_HOLS5_T2
	LAUN3J_LAUN5J_T2
	LAUN3K_LAUN5J_T1
	LAUN3L_LAUN5K_T3
	MORH3_MORH5_T1
	MORW3_MORW5_T1
	NTAW5_NTAW3_T1
	NTAW5_NTAW3_T2
	OKEH3J_OKEH5_T2
	OKEH3K_OKEH5_T1
	SHEB3_SHEB5_T1
	STRA3_STRA5_T1
	STRA3_STRA5_T2
	WHID3J_WHID5_T1
	WHID3K_WHID5_T2
BSP Tie Transformers	NTAW1_NTAW3_G1
	PYWO1J_PYWO3_G2
	PYWO1K_PYWO3_G3
	PYWO1L_PYWO3_G4

‘T’ connection contingencies	Rexon Cross Farm ‘T’	OKEH3K_RCPV3T_L1
		ROAD3_RCPV3T_L1
		RCPV3_RCPV3T_L1
	Bradford ‘T’	STRA3_BRPV3T_L1
		PYWO3_BRPV3T_L1
		BRPV3_BRPV3T_L1
	Higher North Beer Farm ‘T’	LAUN3K_HNBF3T_L2
		ECUR3_HNBF3T_L2
		HNBF3_HNBF3T_L1
	Crinacott Farm ‘T’	STRA3_CRPV3T_L1
		PYWO3_CRPV3T_L1
		CRPV3_CRPV3T_L1
	Moretonhampstead ‘T”	MORH3_MORH3T_L1
		MORH3T_WHID3J_L1
	Laneast ‘T	LAUN3J2_LANE3T_L1
	Eastacombe -West Venn farm ‘T’	ASHW3_ASWR3T_L1
		EAST3T_ASWR3T_L1
		ASWR3_ASWR3T_L1
		PYWO3_EAST3T_L1
		EAST3_EAST3T_L1
	Forestmoor – East Langford – Morwenstow ‘T’	CLOV3K_FORE3T_L1
		ESLA3T_FORE3T_L2
		FORE3_FORE3T_L2
		MORW3_MORW3T_L1
		MORW3T_STRA3_L1
		MORW3T_ESLA3T_L1
		ESLA3_ESLA3T_L1
	Willsland – Shebbear – CHAS3T ‘T’	HATH3J_WILL3T_L1
		SHEB3T_WILL3T_L1
		WILL3_WILL3T_L1
		CHAS3T_HOLS3K_L1
		CHAS3T_SHEB3T_L1
		CHAS3T_PYWO3_L1
		SHEB3_SHEB3T_L1
	Foxcombe – DERR3T ‘T’	DERR3T_FOXC3T_L1

		FOXC3_FOXC3T_L1
		FOXC3T_DUNX3B_L1
		DERR3T_HOLS3J_L1
		DERR3T_PYWO3_L1

B3 Tiverton 33 kV BSP Contingencies

Contingency Type		Contingency
Line/cable:		BRIM3J_TIVE3_L1
		BURL3K_HEMY3K_L1
		HEMY3J_DUNK3K_L1
		TIVM3K_TIVE3_L1
		TIVM3J_TIVS3J_L1
		TIVS3K_TIVE3_L1
Transformers:		BRIM3J_BRIM5_T1
		BRIM3K_BRIM5_T2
		BURL3K_BURL5_T1
		CULL3J_CULL5_T1
		CULL3K_CULL5_T2
		DUNK5_DUNK3K_T2
		HEMY3K_HEMY5_T2
		TIVE5_TIVE3_T1
		TIVE5_TIVE3_T2
		TIVM3K_TIVM5_T1
		TIVM3J_TIVM5_T2
		TIVS3K_TIVS5_T1
		TIVS3J_TIVS5_T2
BSP Tie Transformers		TIVE3_TIVE1Q_G1
		TIVE3_TIVE1R_G2
‘T’ connection contingencies	Stoneshill ‘T’	CULL3K_STFA3T_L1
		TIVE3_STFA3T_L1
		STFA3_STFA3T_L1
	Ayshford Court ‘T’	BURL3J_AYSH3T_L1
		TIVE3_AYSH3T_L1
		AYSH3_AYSH3T_L1
	WSHC3T	TIVM3J_WSHC3T_L1
		WSHB3_WSHC3T_L1
	Cullompton ‘T’	BRIM3K_CMPV3T_L1
		CULL3J_CMPV3T_L1
		CMPV3_CMPV3T_L1

Appendix C Study Limits and Assumptions

C1 Thermal and statutory limits

The following limits are used in the power system studies.

C1.1 Thermal ratings:

Table C1-1 - Thermal ratings for studies

Asset Type	Rating/Limits
Lines/Cables	100% summer rating
Transformers (forward power)	Transformer cyclic rating
Transformers (reverse power)	Transformer reverse power rating

C1.2 Voltage limits:

Table C1-2 - Voltage limits for studies

Asset Type	Rating/Limits
Bus Voltages (11kV, 33 kV)	0.94 p.u. < Nominal Voltage < 1.06 p.u.

C1.3 Voltage step limits:

Table C1-3 - Voltage step limits for studies

Event	Rating/Limits
Tripping of single generator	Voltage deviation < +/-3%

C2 Assumptions

- Post contingent automatic schemes (inter-trips, generator runback) have not been modelled or simulated.
- During contingency studies if load and/or generation becomes islanded this results in lost load and generation.
- In order to achieve initial balanced bus voltages (according to transformers AVR setpoints) across the study zone and within the transformers tap setpoint tolerance the tap changers will be set back to nominal tap position prior any power system analysis.

Appendix D Barnstaple 33 kV BSP Network Analysis

D1 Intact network analysis

Table D1-1Table D shows a summary of the intact network violations for Barnstaple 33 kV BSP network. Note the table reports on cases where violations were identified.

Table D1-1 – Barnstaple 33 kV Network Violations Summary Table for Base Case

Case	Voltage Violations	Voltage Step Violations	Summer Branch Loading Violation	Transformer Nameplate rating violation	Transformer Reverse Power rating violation
Min Load Max Gen			1		
Max Load Max Gen			1		

D1.1 Minimum Load Maximum Generation – Intact system branch violations

For the minimum load maximum generation case the voltage regulator, connecting Batsworthy windfarm to South Molton 33 kV bus bar, exceeds its thermal rating, shown in Figure D1-1. The thermal loading on the voltage regulator is dependent on the generation output of Batsworthy Windfarm. This thermal violation indicates that, in the case modelled, the rating of the voltage regulator is a thermal constraint and restricts the downstream generation hosting capacity on the feeder to its thermal rating of 18.3 MVA.

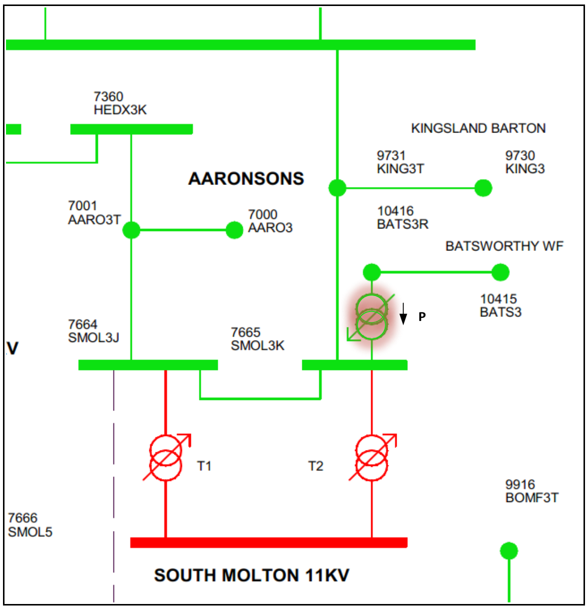


Figure D1-1 - SMOLK_BATSR_R1 branch overload

D1.2 Maximum Load Maximum Generation – Intact system branch violations

The SMOLK_BATSR_R1 branch violation that occurs in minimum load maximum generation also occurs in the maximum load maximum generation as it is caused by maximum generation. See Section D1.1above.

D2 Contingency configuration analysis

Table D1-2 shows a summary of the contingency violations for Barnstaple 33 kV BSP network. Appendix A contains the complete list of contingencies applied to the Barnstaple BSP 33 kV Network. Note the table reports on cases where violations were identified and excludes any base case violations already reported.

Table D1-2 – Barnstaple 33 kV Network Violations Summary Table for Contingencies

Case	Contingency	Voltage Violations	Voltage Step Violations	Summer Branch Loading Violation	Transformer Nameplate rating violation	Transformer Reverse Power rating violation
Min Load Max Gen	HEDX3J_BAST3_L1			2		
	SMOL3K_KING3T_L1+ BAST3_KING3T_L1+ KING3_KING3T_L1			2		
	AARO3_AARO3T_L1+ AARO3T_HEDX3K_L1+ AARO3T_SMOL3J_L1			3		
Max Load Max Gen	AARO3_AARO3T_L1+ AARO3T_HEDX3K_L1+ AARO3T_SMOL3J_L1			1		

D2.1 Minimum Load Maximum Generation – Contingency branch violations

Contingency Type	Contingency
Line/cable	HEDX3J_BAST3_L1

Barnstaple – Heddon Cross 33 kV circuit contingency

The loss of the HEDXJ_BAST3_L1 circuit in the minimum load maximum generation case results in the BAST3_KING3T_SMOL3K_L1 circuit exceeding its thermal rating, as shown in Figure D1-2. The direction of real power flow, shown on Figure D1-2, shows that, downstream of the violation, generation is greater than load and that real power is being provided back to Barnstaple 33 kV bus. This thermal violation indicates that, in the case modelled, the rating of the BAST3_KING3T_SMOL3K_L1 circuit is a thermal constraint and restricts the downstream generation hosting capacity on the feeder for the HEDXJ_BAST3_L1 contingency. This constraint restricts the generation hosting capacity of feeder group 5. However, the violations indicate there is potential for increased load hosting capacity on feeder group 5.

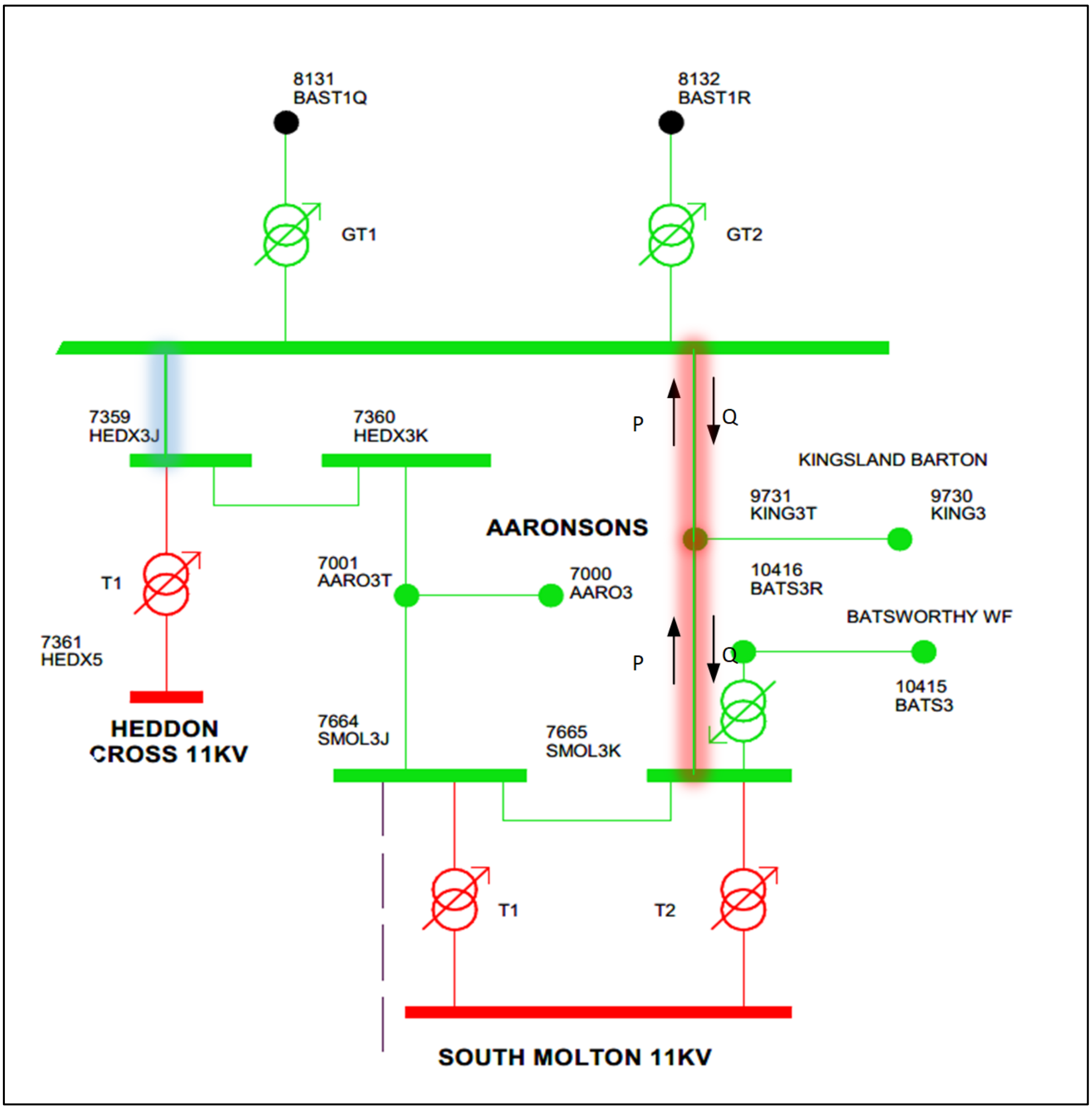


Figure D1-2 - SMOL3K_BAST3 via KINGT branch overloading

D2.2 Maximum Load Maximum Generation – Contingency Branch violations

Contingency Type		Contingency
'T' connection contingencies	Aaronson T	AARO3_AARO3T_L1
		AARO3T_HEDX3K_L1
		AARO3T_SMOL3J_L1

Aaronson T circuits contingency

The loss of the "Aaronson T" circuits on the maximum load maximum generation case can results in the BAST3_KING3T_L1 circuit exceeding its thermal rating, as shown in Figure D1-3. The direction of real power flow, shown in Figure D1-3, shows that, downstream of the violation, generation is greater than load and that real power is being provided back to Barnstaple 33 kV bus. This thermal violation indicates that, in the case modelled, the rating of the BAST3_KING3T_L1 circuit is a thermal constraint and restricts the downstream generation hosting capacity on the feeder for the "Aaronson T" circuits contingency. This constraint restricts the generation hosting capacity of feeder group 5. However, the violations indicate there is potential for increased load hosting capacity on feeder group 5.

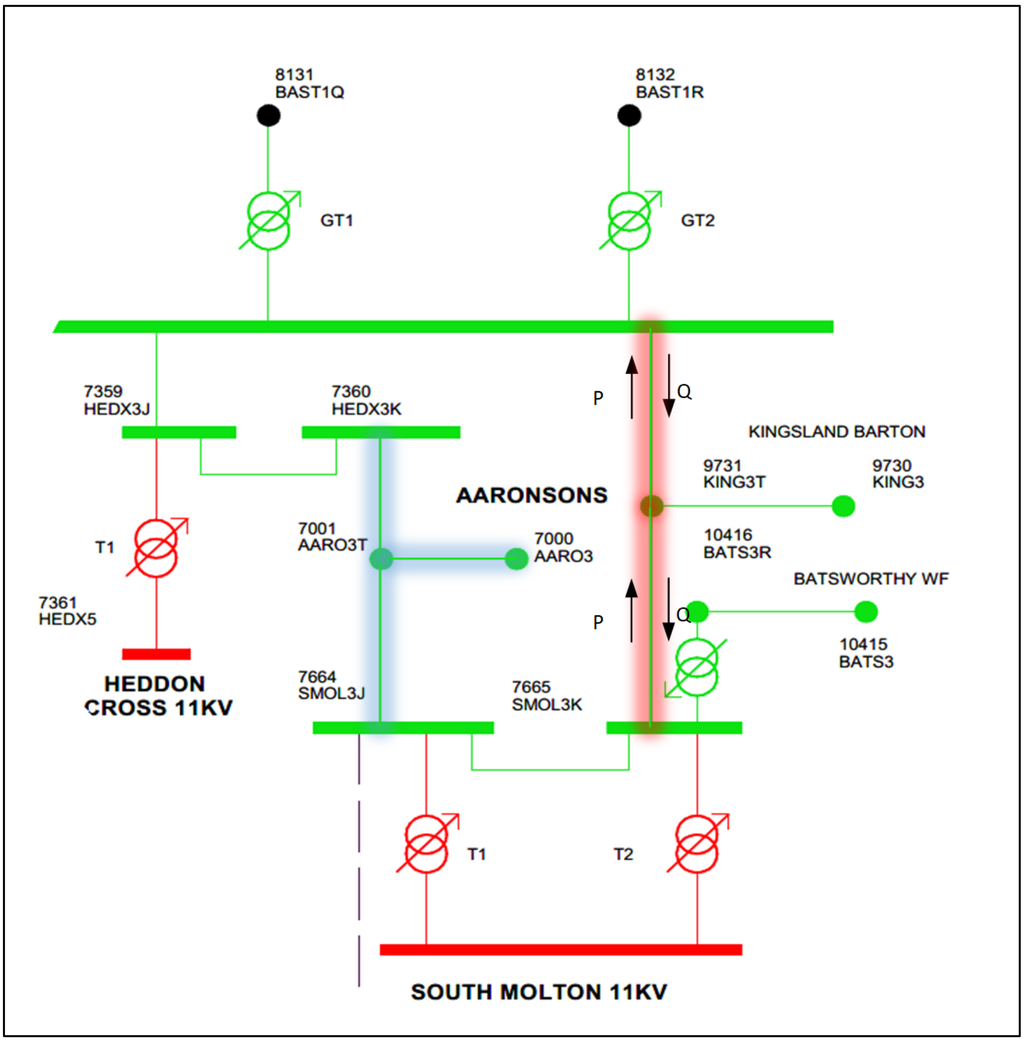


Figure D1-3 – BAST3_KING3T_L1 branch overloading

Kingsland Barton T circuits contingency

The loss of the “Kingsland Barton T” circuits on the maximum load maximum generation case can results in the BAST3_HEDXBJ_L1, HEDX3K_ AARO3T_L1 and AARO3T_SMOL3J_L1 circuits exceeding its thermal rating, as shown in Figure D1-4. The direction of real power flow, shown in Figure D1-4, shows that, downstream of the violation, generation is greater than load and that real power is being provided back to Barnstaple 33 kV bus. This constraint restricts the generation hosting capacity of feeder group 5. However, the violations indicate there is potential for increased load hosting capacity on feeder group 5.

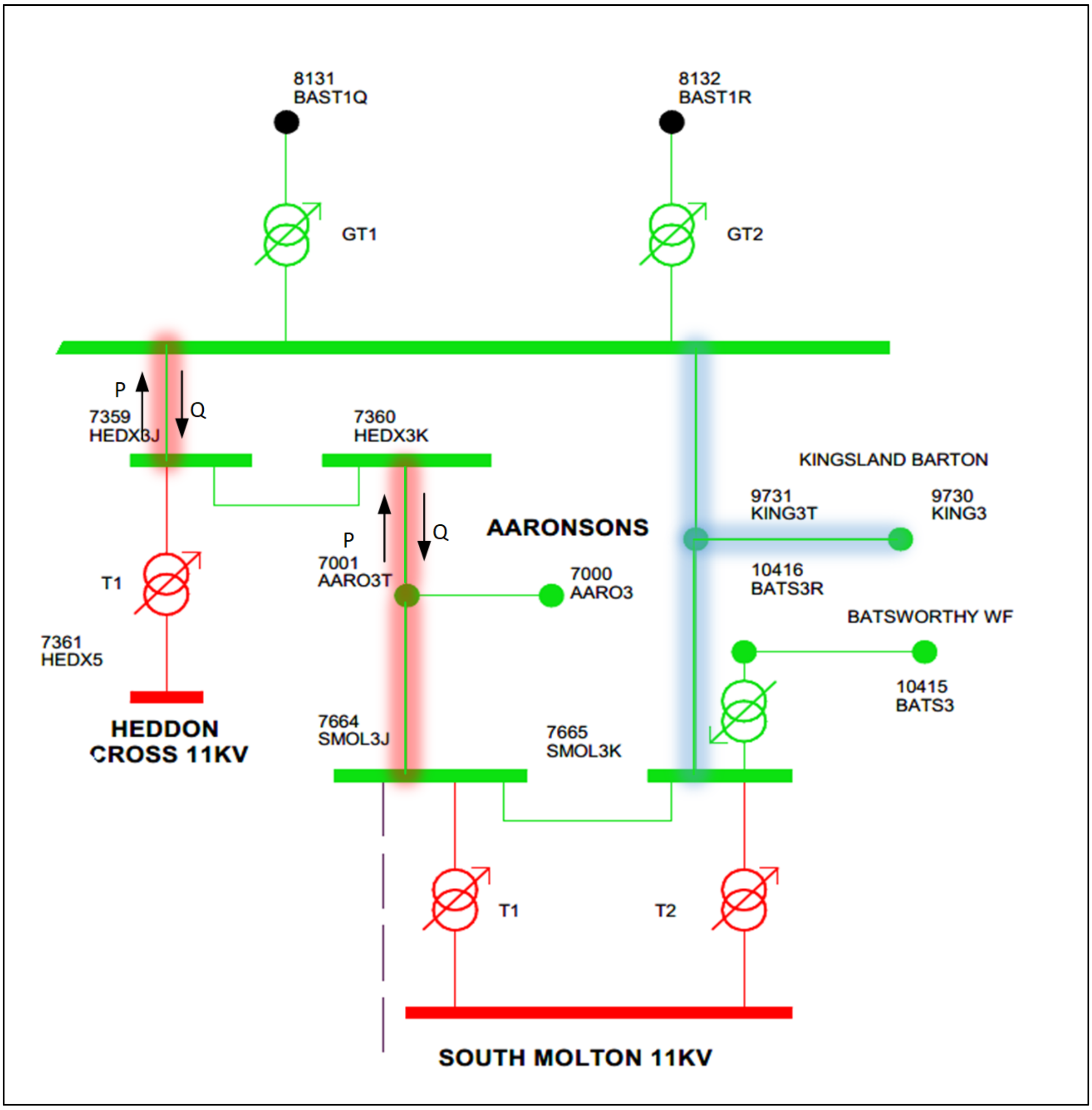


Figure D1-4 - Kingsland Barton T contingency thermal overloads

Appendix E Pyworthy and North Tawton 33 kV BSPs Network Analysis

E1 Intact network analysis

Table E1-1 shows a summary of the Intact system violations for Pyworthy and North Tawton 33 kV BSP network. Note the table reports on cases where violations were identified.

Table E1-1 - Pyworthy and North Tawton Violations for Intact system

Case	Voltage Violations	Voltage Step Violations	Summer Branch Loading Violation	Transformer Nameplate rating violation	Transformer Reverse Power rating violation
Min Load Max Gen					2
Max Load Max Gen					1

E1.1 Minimum Load Maximum Generation – 'N' Transformer reverse power flow violations

<u>ECUR3_ECUR5_T1 and MORW3_MORW5_T1</u>

In the minimum load maximum generation case the transformers connecting East Curry 11kV to East Curry 33kV (feeder group 3) and Morwenstow 11kV to Morwenstow 33kV (feeder group 1) overloads on reverse power flow, shown in Figure E1-5. The violations are due to high 11 kV generation in the case at East Curry and Morwenstow. The violations do not restrict the generation hosting capacity of the feeder groups 1 and 3.

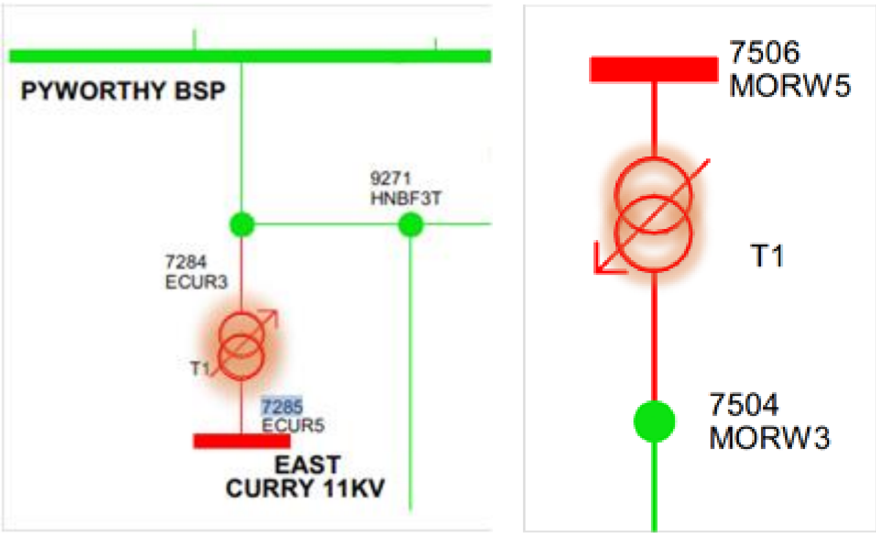


Figure E1-5 – ECUR3_ECUR5_T1 and MORW3_MORW5_T1 reverse power violation

E1.2 Maximum Load Maximum Generation – 'N' Transformer reverse power flow violations

<u>ECUR3_ECUR5_T1</u>

This is the same transformer reverse power violation as in minimum load maximum generation case see Section E1.1of this appendix.

E2 Contingency Configuration Analysis

Table E1-2 shows a summary of the contingency violations for Pyworthy and North Tawton 33 kV BSP network. Appendix A contains the complete list of contingencies applied to the Pyworthy and North Tawton BSP 33 kV Network. Note the table reports on cases where violations were identified and excludes any base case violations already reported.

Table E1-2 – Pyworthy and North Tawton 33 kV Network Violations Summary Table for Contingencies

Case	Contingency	Voltage Violations	Voltage Step Violations	Summer Branch Loading Violation	Transformer Nameplate rating violation	Transformer Reverse Power rating violation
Min Load Max Gen	NTAW1_NTAW3_G1	17 High Voltage Violations		1		

Minimum Load Maximum Generation – Intact system branch violations

Contingency Type	Contingency
BSP Tie Transformers	NTAW1_NTAW3_G1

The loss of NTAW1_NTAW3_G1 can result in the DERR3T_PYWO3_L1 branch overloading, shown in Figure E1-6. This thermal violation can constrain the generation hosting capacity of feeder group 5. For the level of load and generation in the case, operational measures or automatic schemes would be needed to manage the network post contingency.

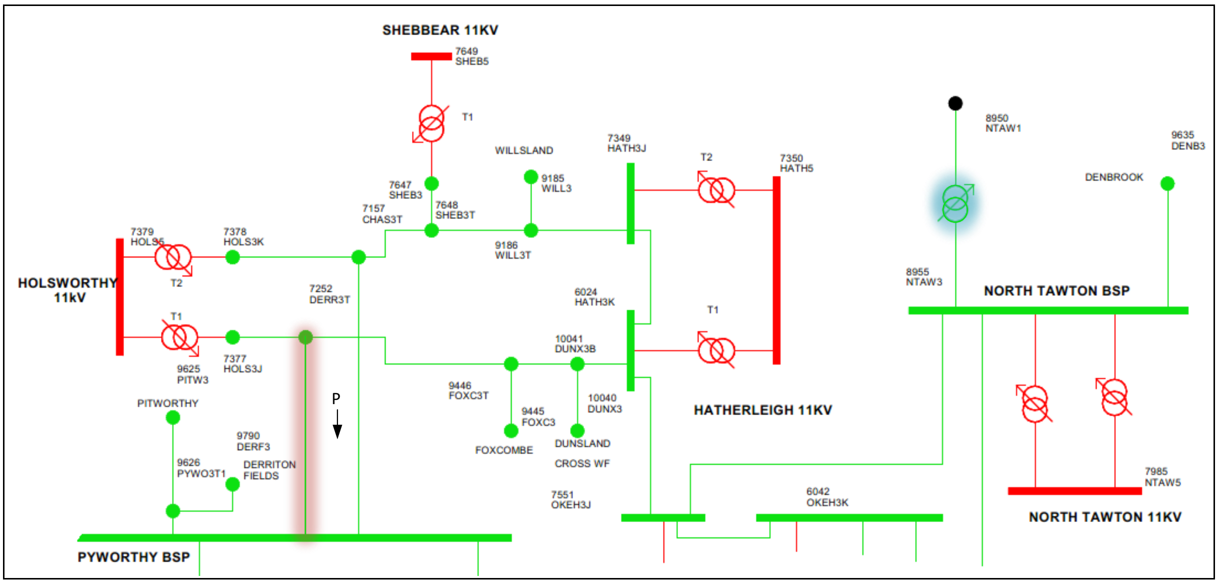


Figure E1-6 – DERR3T_PYWO3 _L1 branch overloading

E2.1 Minimum Load Maximum Generation – Contingency Voltage Violations

Contingency Type	Contingency
BSP Tie Transformers	NTAW1_NTAW3_G1

The loss of the NTAW1_NTAW3_G1 can result in high voltages in as many as 17 nodes shown in Figure E1-7. These voltage violations constrain the generation hosting capacity of feeder group 4. For the level of load and generation in the case, operational measures and/or automatic schemes are required to manage the network post contingency.

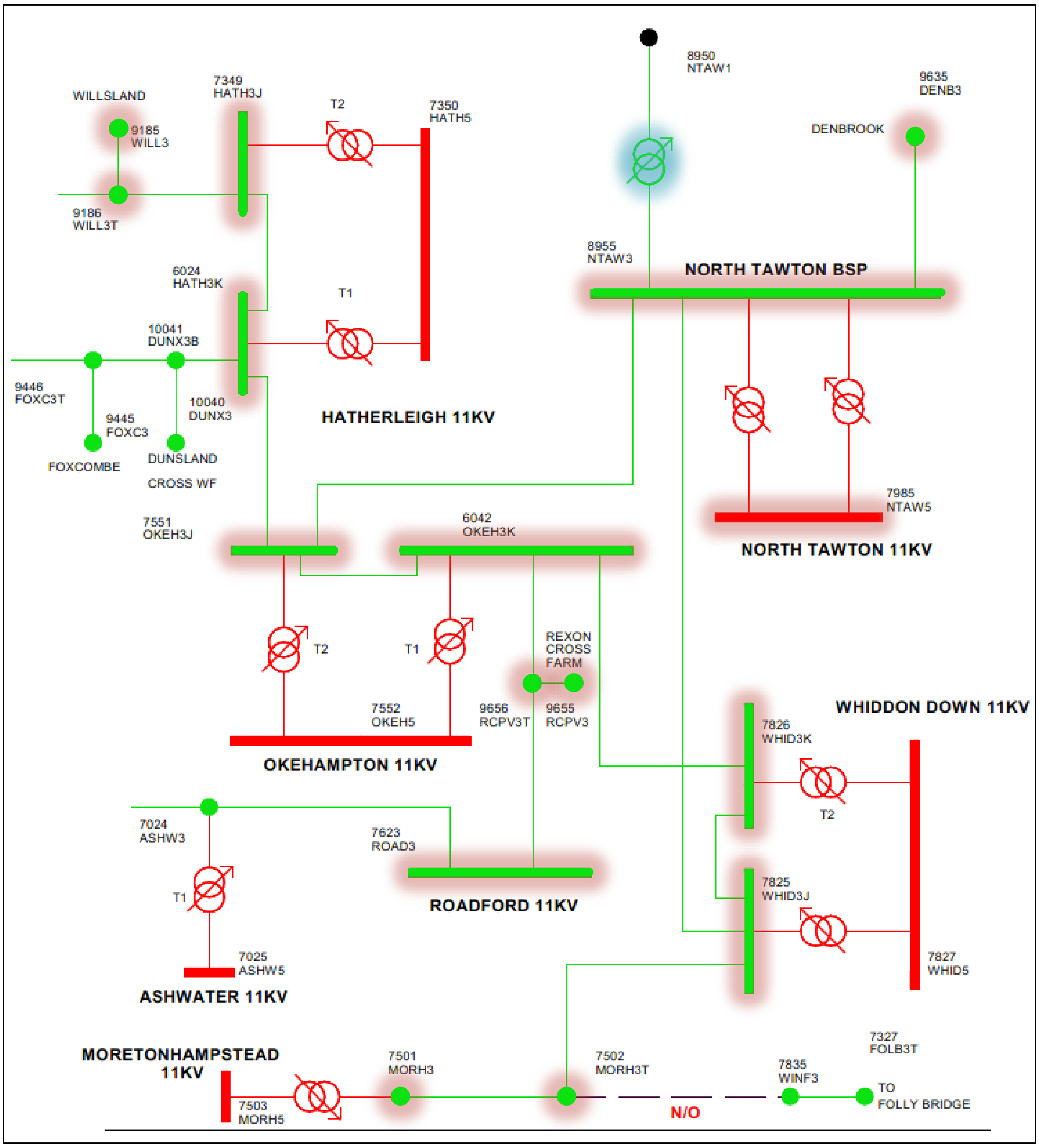


Figure E1-7 – High voltages following NTAW1_NTAW3_G1 contingency

Note: The capacitors connected at Okehampton North Tawton 11 kV in the model are in service for all cases studied. These have a direct impact on the magnitude of bus voltages shown in Figure E1-7.

Appendix F Tiverton Moorhayes 11 kV Network Analysis

F1 Intact system network analysis

Table F1-1 shows a summary of the 'N' violations for Tiverton Moorhayes 11 kV primary network. Note the table reports on cases where violations were identified.

Table F1-1 - Tiverton Moorhayes violations summary

Case	Voltage Violations	Voltage Step Violations	Summer Branch Loading Violation	Transformer Nameplate rating violation	Transformer Reverse Power rating violation
Max Load Min Gen			1		

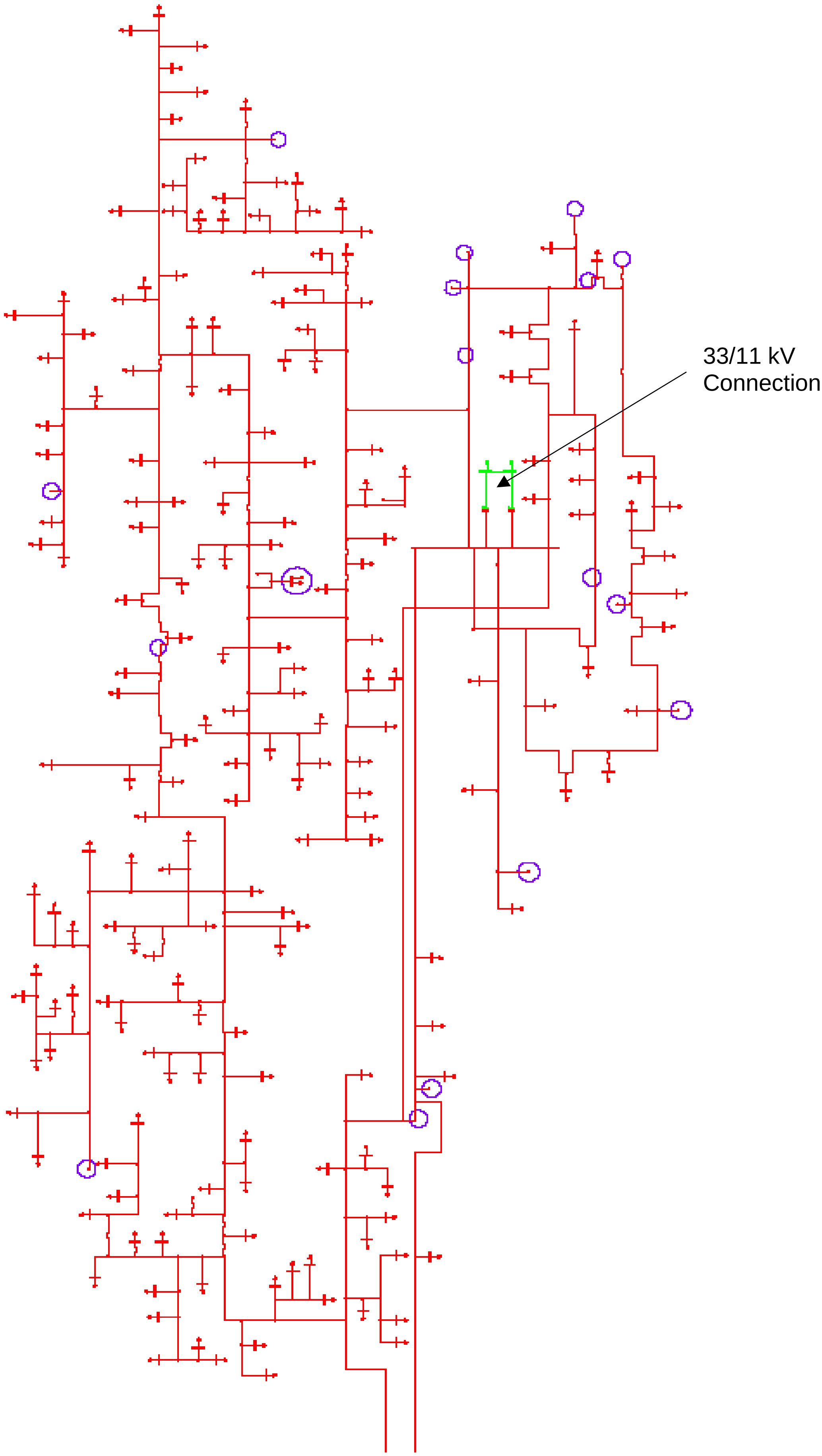
F1.1 Maximum Load Minimum Generation – 'N' Branch violations

The base case in the maximum load minimum has a branch violation for the circuit between busses 95447 and 95600. The branch violation is dependent on the load and generation mix downstream on the feeder.

F2 N-1 analysis

The Tiverton Moorhayes 11 kV Primary network consists of a main 11 kV bus with 6 radial feeders. Each feeder is treated as contingency. There are no contingency violations for Tiverton Moorhayes 11 kV Primary network, but each contingency results in the loss of load and generation connected to the contingency feeder.

Appendix G Tiverton Moorhayes 11 KV Network (PSS/E SLD)



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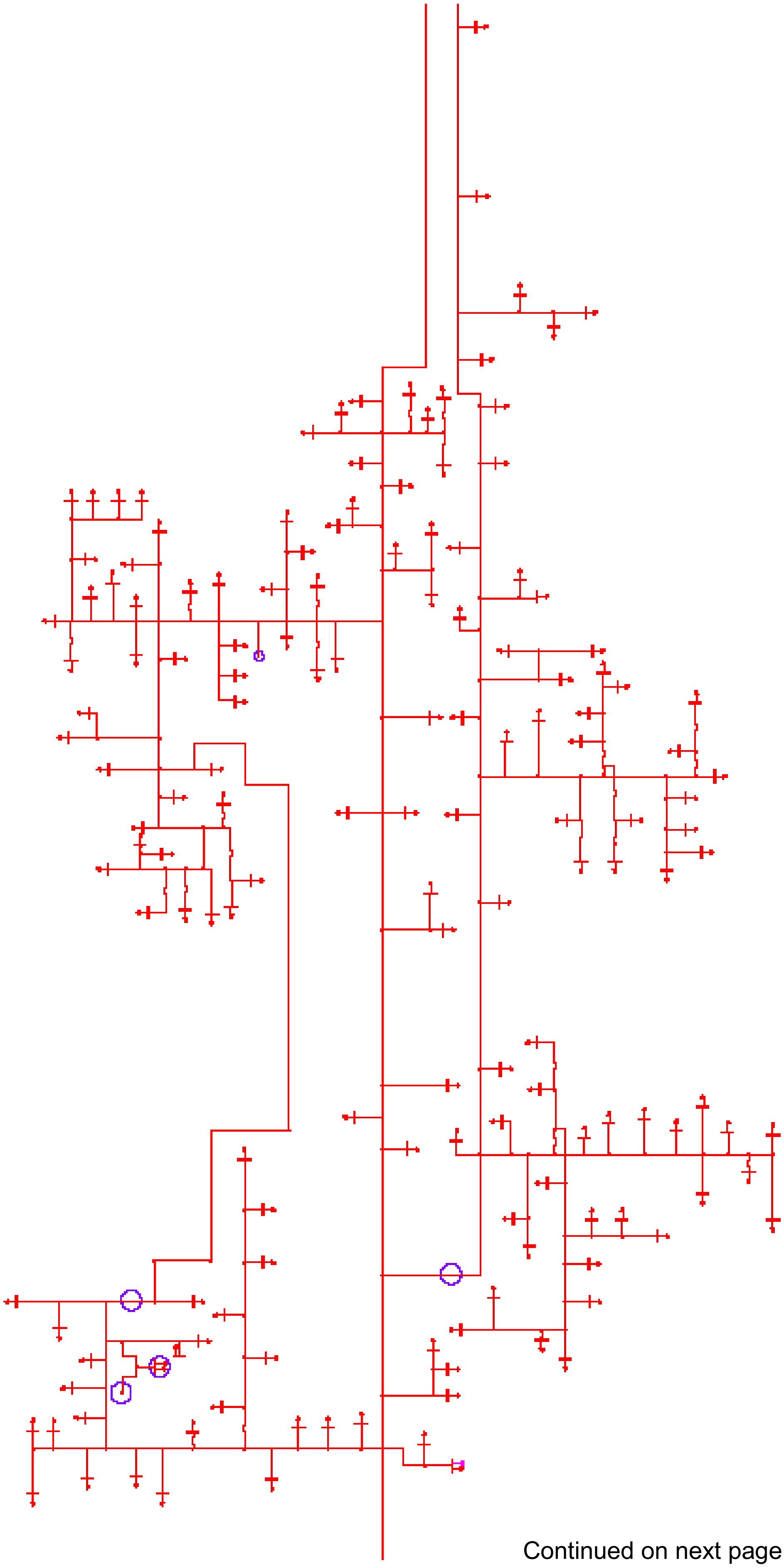

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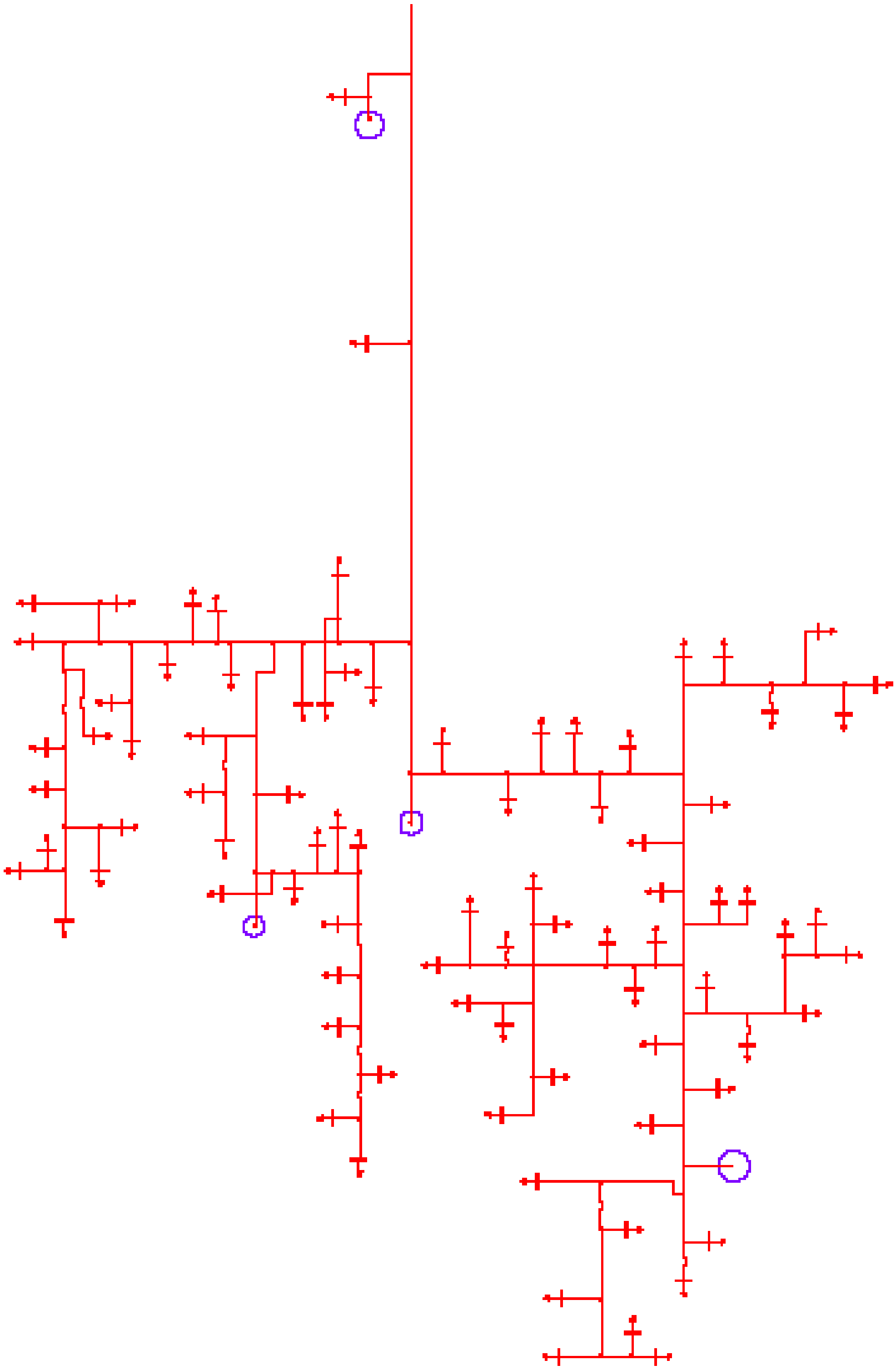


Appendix H Scaling Approach Assessment for Generation Hosting

The implemented generation hosting capacity algorithms includes options to test the effect of scaling different generators. The algorithm tested 3 scaling approaches:

1. Scaling existing generators.
2. Placing and scaling 'dummy' generators.
3. Placing and scaling 'dummy' generators and scaling existing generators.

The hosting capacity results for the different generator scaling approaches are presented in this Appendix.

H1 Barnstaple 33 kV BSP Generation Hosting Capacity Results Summary

The generation hosting capacity algorithm described in above was used to compare the three different scaling approaches for the generation hosting for Barnstaple 33kV BSP for the four base cases. The matrix shown in Table H9-1 provides a summary of the output of the algorithm for the different load and generation cases assessed.

Table H9-1 - Algorithm output for Barnstaple 33 kV BSP for load and generation cases

	Minimum load	Maximum Load
Minimum Generation	Hosting capacity determined for all scaling approaches.	Hosting capacity determined for all scaling approaches.
Maximum Generation	Intact system and/or contingency violation identified.	Intact system and/or contingency violation identified.

Where the algorithm identifies that a violation exists this indicates that operational measures are required to manage the network for this generation and load case.

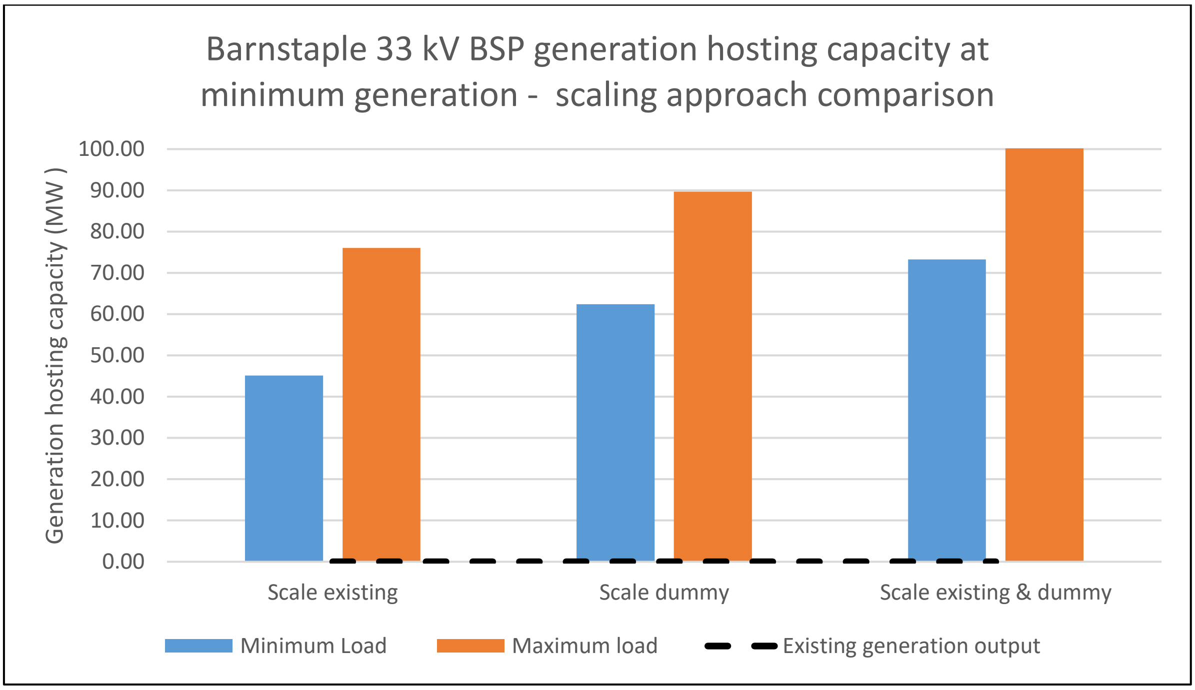


Figure H1-1 – Barnstaple 33kV BSP: Generation hosting capacity scaling method comparison (minimum generation cases)

Figure H1-1 presents the results from the algorithm for the 3 different scaling methods for the minimum load minimum generation and maximum load minimum generation cases. The results show in the ‘scale existing’ and ‘scale existing & dummy’ scaling options, as expected the generation hosting capacity is higher when higher load is present in the network.

H2 Pyworthy and North Tawton 33 kV BSP Generation Hosting Capacity Results Summary

The generation hosting capacity algorithm described in Section 0 was used to compare the three different scaling approaches for the generation hosting for Pyworthy and North Tawton 33kV BSPs for the four base cases. The matrix shown in Table H1-2 provides a summary of the output of the algorithm for the different load and generation cases assessed.

Table H1-2 - Algorithm output for Pyworthy and North Tawton 33 kV BSPs for load and generation cases

	Minimum load	Maximum Load
Minimum Generation	Hosting capacity determined for all scaling approaches	Hosting capacity determined for all scaling approaches.
Maximum Generation	Intact system and/or contingency violation identified.	Hosting capacity determined for all scaling approaches.

Where the algorithm identifies that a violation exist this indicates that operational measures are required to manage the network for the generation and load scenario.

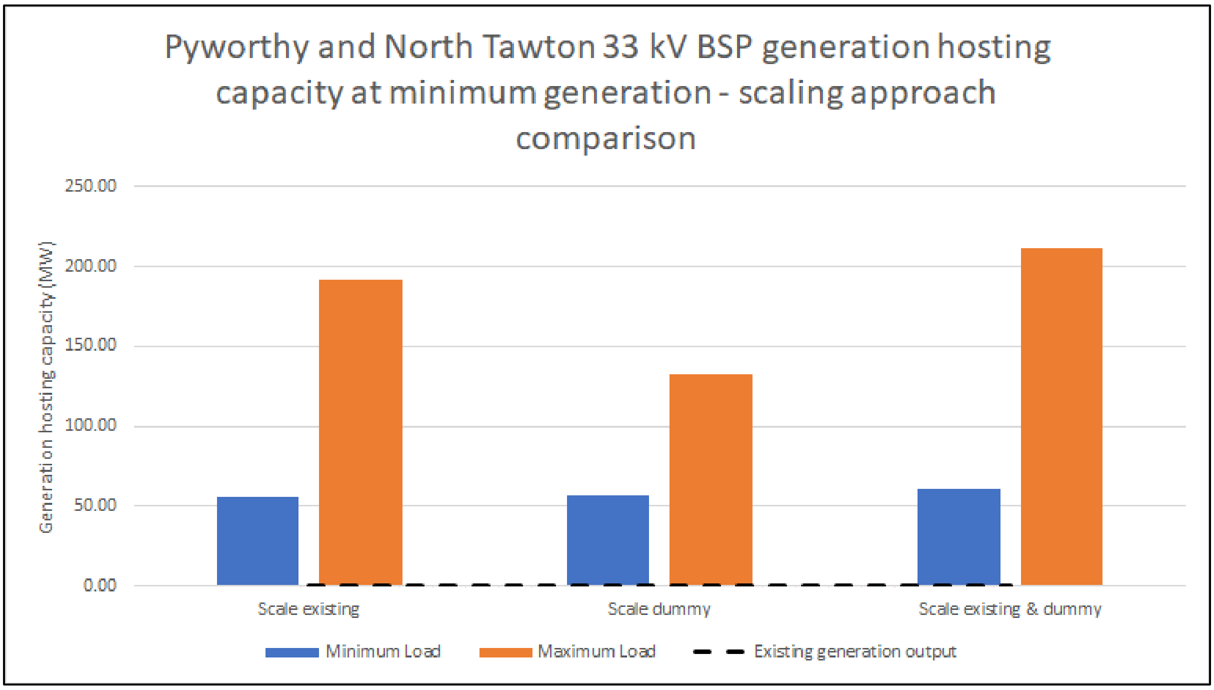


Figure H1-2 – Pyworthy and North Tawton 33kV BSP: Generation hosting capacity scaling method comparison (minimum generation cases)

Figure H1-2 presents the results from the algorithm for the three different scaling methods for the minimum load minimum generation and maximum load minimum generation cases. The results show as expected that the generation hosting capacity is higher when higher load is connected in the network. It can also be seen from the results that overall, the highest generation hosting capacity is achieved in the 'scale existing & dummy' this is due to the highest penetration of generators across the network. Figure H1-2 also shows that when only dummy generators are scaled that the hosting capacity can be less than scaling existing generators, this is due to network topology and the location of existing generators and where dummy generators are placed.

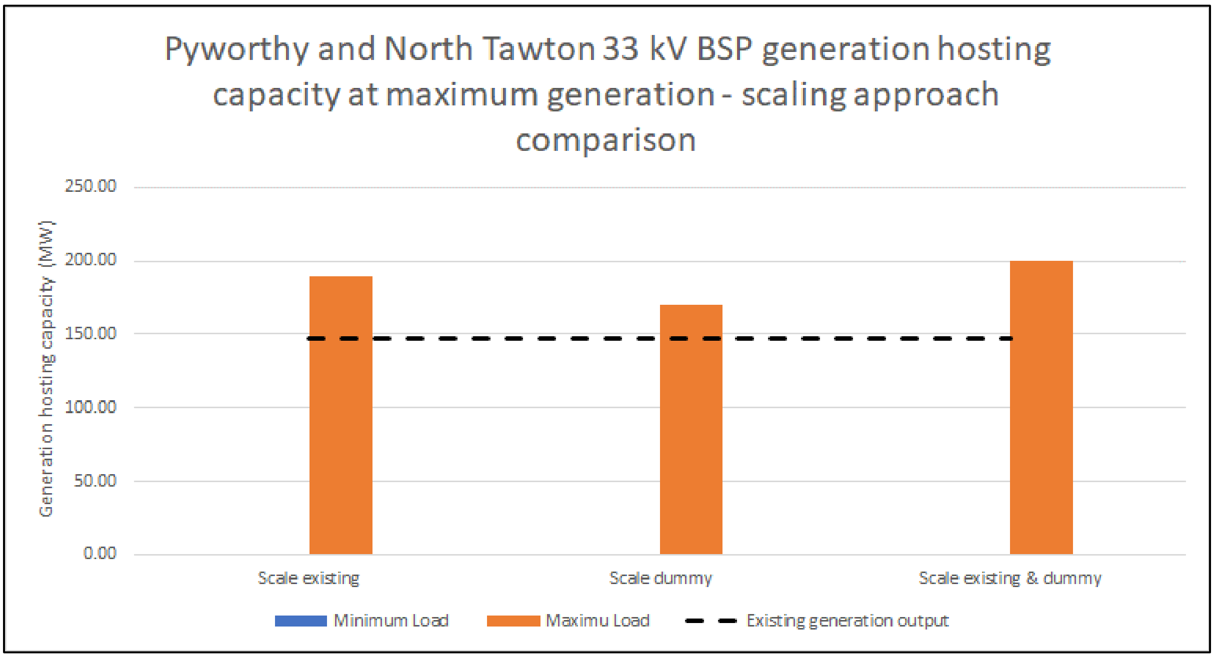


Figure H1-3 – Pyworthy and North Tawton 33kV BSP: Generation hosting capacity scaling method comparison (maximum generation cases)

H3 Tiverton 33 kV BSP generation hosting capacity results summary

The generation hosting capacity algorithm described in Section 0 was used to compare the three different scaling approaches for the generation hosting for Tiverton 33kV BSPs for the four base cases. The matrix shown in Table H1-3 provides a summary of the output of the algorithm for the different load and generation cases assessed.

Table H1-3 - Algorithm output for Pyworthy and North Tawton 33 kV BSPs for load and generation case

	Minimum load	Maximum Load
Minimum Generation	Hosting capacity determined for all scaling approaches.	Hosting capacity determined for all scaling approaches.
Maximum Generation	Hosting capacity determined for all scaling approaches.	Hosting capacity determined for all scaling approaches.

Figure H1-4 –Tiverton 33kV BSP: Generation hosting capacity scaling method comparison (minimum generation cases)

Figure H1-4 presents the results from the algorithm for the three different scaling methods for the minimum load minimum generation and maximum load minimum generation cases. The results show that as expected the generation hosting capacity is higher when higher load is connected in the network. It can also be seen from the results that overall, the highest generation hosting capacity is achieved in the 'scale existing & dummy' this is due to the highest penetration of generators across the network as can be seen in Appendix K.

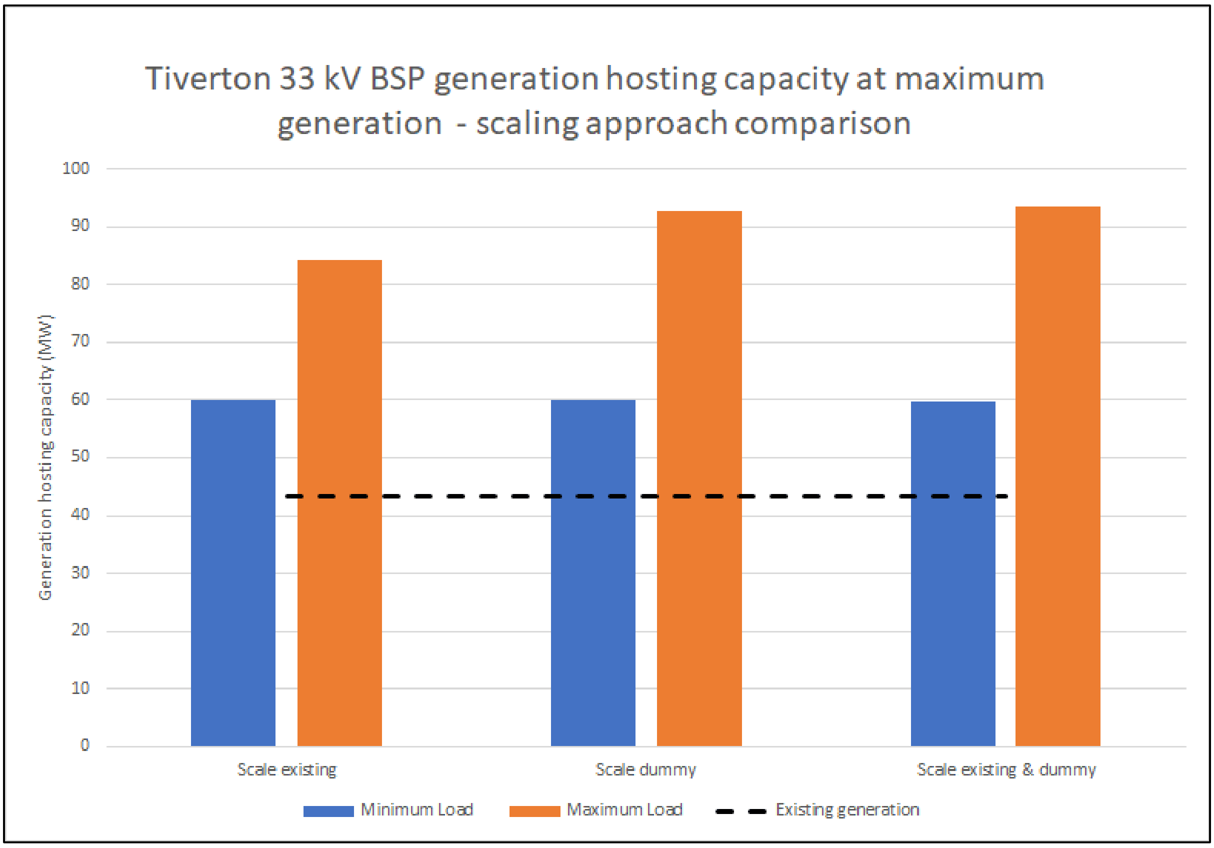


Figure H1-5 –Tiverton 33kV BSP: Generation hosting capacity scaling method comparison (maximum generation cases)

Figure H1-5 presents the results from the algorithm for the 3 different scaling methods for the minimum load maximum generation and maximum load maximum generation cases.

The results show as expected that the generation hosting capacity is higher when higher load is connected in the network. However, unlike the cases for minimum generation the hosting capacity for minimum load is similar for all the scaling methods and only a noticeable difference is identified between the 'scale existing' option and the 'scale dummy' or 'scale existing & dummy option' for maximum load cases. The results show that for all except the 'scale existing & dummy' option at minimum load that scaling from a non-zero generation profile provides higher network hosting capacity. This indicates that the initial output of existing generators influences the capacity hosting calculation.

H4 Tiverton Moorhayes 11 kV Primary generation hosting capacity results summary

The generation hosting capacity algorithm described in Section 0 was used to compare the three different scaling approaches for the generation hosting for Tiverton 33kV BSPs for the four base cases. The matrix shown in Table H1-4 provides a summary of the output of the algorithm for the different load and generation scenarios assessed.

Table H1-4 - Algorithm output for Pyworthy and North Tawton 33 kV BSPs for load and generation scenarios

	Minimum load	**Maximum Load**
Minimum Generation	Hosting capacity determined for all scaling approaches.	Intact system and/or contingency violation identified.
Maximum Generation	Hosting capacity determined for all scaling approaches.	Hosting capacity determined for all scaling approaches.

Where the algorithm determines that constraints exist this indicates that operational measures are required to manage the network for the generation and load scenario.

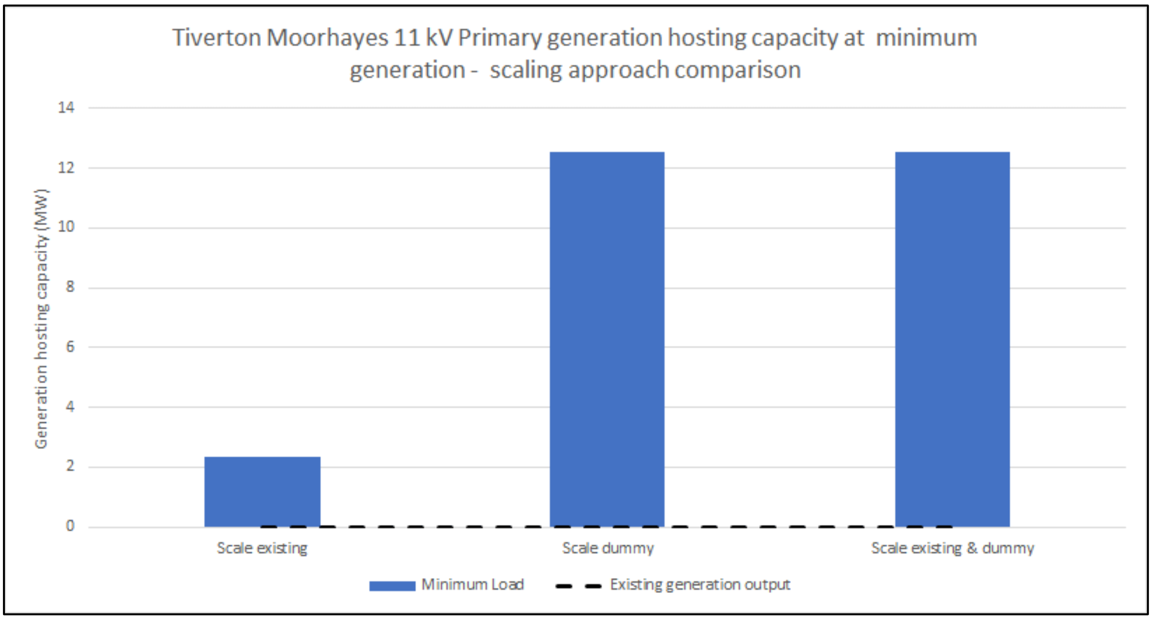


Figure H1-6 –Tiverton Moorhayes 11kV Primary: Generation hosting capacity scaling method comparison (minimum generation cases)

Figure H1-6 presents the results from the algorithm for the three different scaling methods for the minimum load, minimum generation case. The results show a significant increase in the generation hosting capacity for the 'Scale dummy' and 'Scale existing & dummy' options. This is expected as the existing generators are only located on two of the feeders, whereas placement of dummy generators occurs across all feeders.

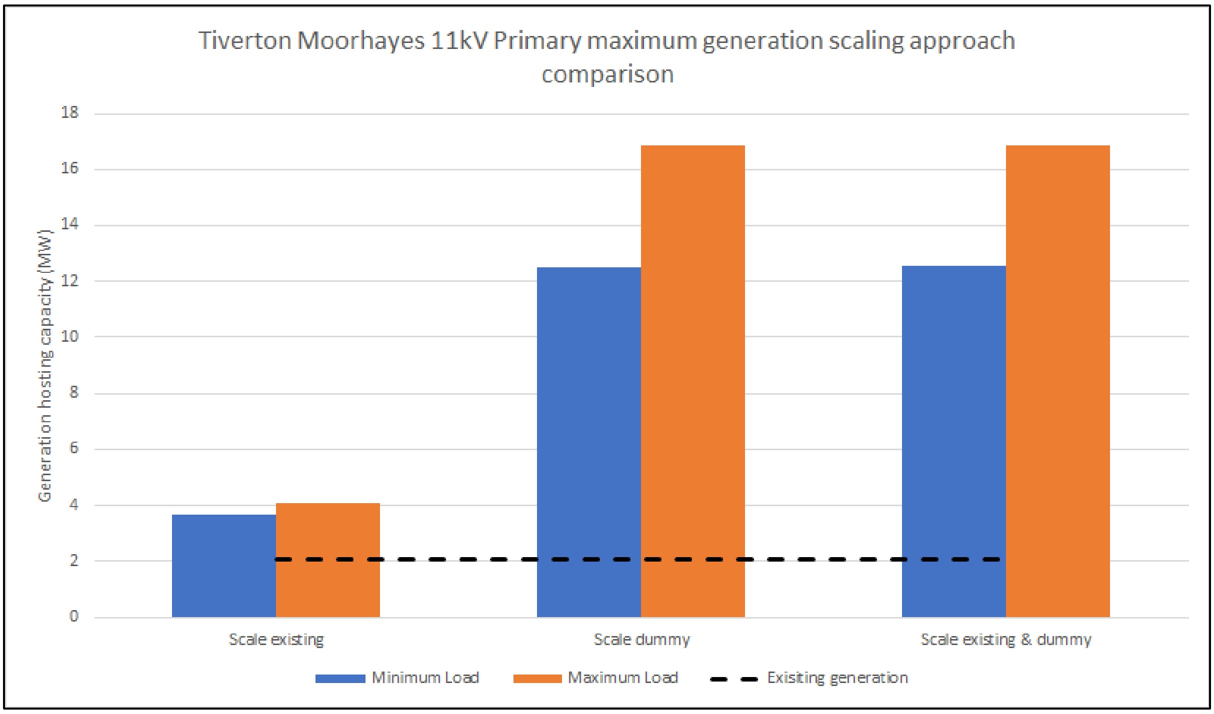


Figure H1-7 –Tiverton Moorhayes 11kV Primary: Generation hosting capacity scaling method comparison (maximum generation cases)

Figure H1-7 presents the results from the algorithm for the three different scaling methods for the minimum load-maximum generation and maximum load-maximum generation cases. The results show a significant increase in the generation hosting capacity for the ‘Scale dummy’ and ‘Scale existing & dummy’ options. This is expected as the existing generators are only located on two of the feeders, whereas placement of dummy generators occurs on all the feeders.

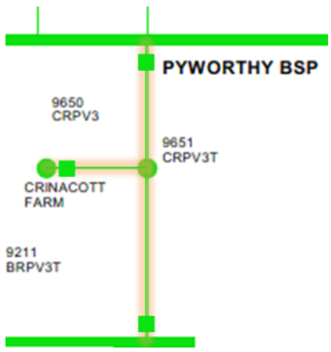
Appendix I Hosting Capacity Algorithms Key Functions

This appendix details the key functions developed and used in the hosting capacity algorithm.

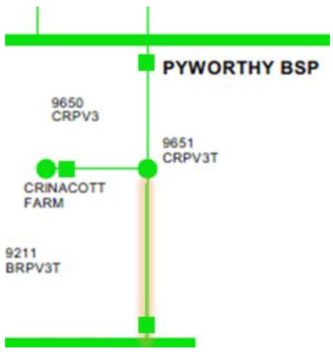
I1 Determine Zone Contingencies

The hosting capacity is required to be evaluated for N-1 network configurations. This requires contingencies for each case to be defined prior to the scaling of generation or load. The hosting capacity algorithm needs to be generic so that it can be applied to other networks. Therefore, the contingencies must be determined dynamically for a selected study zone. Note that the contingencies to be considered in the hosting capacity algorithm are the same as the contingencies considered in the network analysis presented in Section 4.

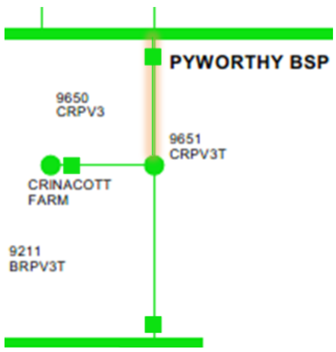
Most contingencies consist of a single branch element (line, cable or transformer) that is connected to a bus at either end of the element. However, where either generation or load has been 'tapped' or 'T'ed (shown in Figure I1-1) into an existing branch without circuit breakers, care must be taken to ensure the contingency removes all necessary branch elements to reflect a realistic outage or post fault situation. Figure shows an example of a simple 'T' connection and the normal location of circuit breakers and compares possible contingency combination.



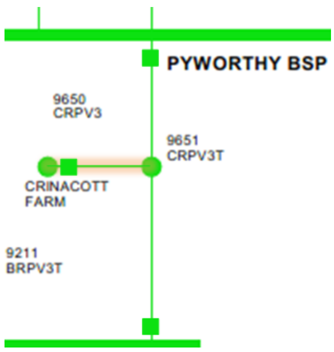
a) The removal of the highlighted branches results in a realistic contingency



b) The removal of the highlighted branch leaves Crinacott Farm incorrectly remaining connected to the upper bus bar



c) The removal of the highlighted branch leaves Crinacott Farm incorrectly remaining connected to the lower bus bar



d) The removal of the highlighted branch disconnects Crinacott Farm, but power can still flow on the upper to lower bus branch.

Figure I1-1 - Tee contingency example

Note that there can also be adjacent 'T' connections, as shown in the Figure I1-2 below, that must also be identified correctly, to ensure that potential voltage and thermal violations in N-1 analysis are realistic.

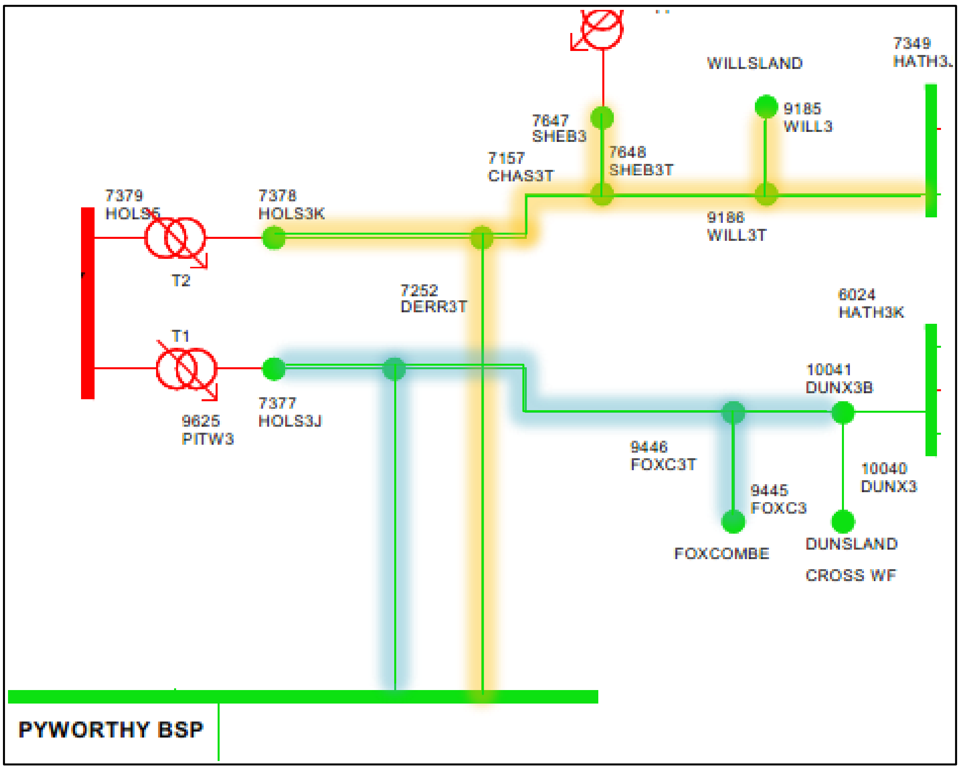


Figure I1-2 - Adjacent 'T'ed connections example

The PSS/E models being used to develop the hosting algorithms do not have circuit breaker modelled, so trip/switch PSS/E events cannot be used to identify the 'T' connection branches. Therefore, the function to determine the 'T' circuits relies on the WPD naming convention for 'T' circuits, which is to indicate these by the letter 'T' at the end of the bus name, for example 'CRPV3T', 'CHAS3T', 'SHEB3BT', 'WILL3T', 'DERR3T' and 'FOXCOMBE', in Figure and Figure I1-2.

The pseudo code for the function to determine zone contingencies is as follows:

Input(s): Zone Branches

- Identify branch elements that are not zero impedance branches and not connected to a 'T' bus and save these as single branch contingencies.
- Identify 'T' busses.
- For each 'T' bus, identify branches connected to a 'T' bus and save as a 'T' bus branch set.
- For each 'T' bus branch set test if connected to an adjacent 'T'
  - If connected to an adjacent 'T' merge unique branch elements and save as a 'T' contingency.
  - If not connected save as a 'T' contingency.

Output(s): Single Contingencies, 'T' Contingencies

I2 Scale generators

The pseudo code for the function to scale generation is as follows:

Input(s): Set of generators to scale, MW increment

- On the first run of function do not scale generation.
- After the first run update each generators MW output to the current generator output plus the MW increment. (If generator is normally modelled with reactive power, maintain power factor at new MW output)

Output(s): Updated set of generators to scale set

Note – in the scaling existing generation option, an existing generator will not be limited by its installed MVA capacity.

I3 Thermal functions

After the power flow is run, if thermal violations (i.e. thermal loading greater than 100%) are present the algorithm performs sensitivity analysis to determine the generators to scale back to resolve the thermal violation, generation scaled back will not be scaled up in further iterations of the algorithm.

The algorithm also determines if there is a location upstream of the violating branch where a new 'dummy' generator can be placed.

The following example based on the network shown in Figure I1-3 demonstrates how the algorithm places a generator upstream of a thermal violation.

- A 'dummy' generator called 'Feeder 1' is placed at Bus 2.
- The algorithm scales generator 'Feeder 1' until the branch between Bus 1 and Bus 2 overloads.
- The algorithm scales back generator 'Feeder 1' to reduce the thermal violation.
- The algorithm then determines the power flow direction to identify the bus upstream of the constraint, in this example Bus 1.
- If Bus 1 is not the main BSP bus the algorithm places a new 'dummy' generator 'Feeder 1-1' at Bus 1.
- The algorithm then stops scaling generator 'Feeder 1' and starts scaling 'Feeder 1-1' until the branch between Bus 1 and the BSP bus overloads.

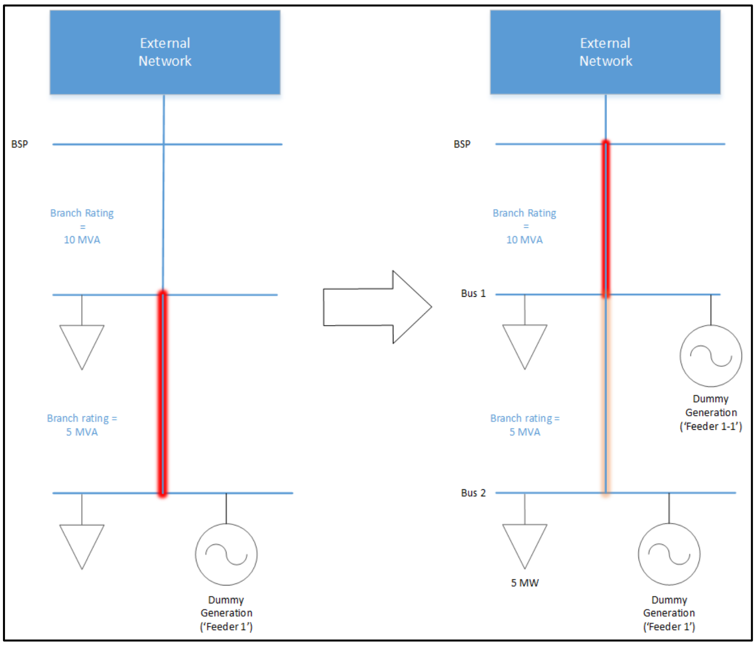


Figure I1-3 - Thermal constraint example

<u>Reverse Power flow (RPF) violations:</u>

After the power flow simulation is run, if a reverse power flow on a transformer exceeds its reverse power flow rating the algorithm will perform sensitivity analysis to determine the generators to scale back to resolve the RPF violation, generation scaled back will not be scaled up in further iterations of the algorithm.

The algorithm also will check which of the below options is being run for network infeed transformers (132/33kV for BSP networks or 33/11kV for primary networks):

- Option 1 (default) - will perform sensitivity analysis to determine the generators to scale back to resolve the RPF violation.
- Option 2 - will ignore the reverse power flow violations on connection transformers and continue to scale the 'dummy' generators.

Option 2 is included to test the hosting capacity of the network excluding the upstream transformer constraints. This provides comparison between results and demonstrates what the hosting capacity could be if the reverse power flow ratings of the transformers are increased.

I3.1 Identify thermal violations

The pseudo code for the function to identify zone thermal violations is as follows:

Input(s): Power flow solution, Zone branches.

- ➢ Identify lines/cable voltage regulators with branch MVA flows greater than 100% of the summer MVA rating.

Output(s): thermal constraints

I3.2 Identify reverse power flow violations

The pseudo code for the function to identify zone thermal violations is as follows:
Input(s): Power flow solution, Zone transformers.

- For each transformer determine if the power is flowing from HV to LV (forward power) or LV to HV (reverse power).
- For transformers with forward power, identify transformers with branch MVA flows greater than 100% of the cyclic plate rating.
- For transformers with reverse power, identify transformers with branch MVA flows greater than 100% of the reverse power rating.

Output(s): thermal violations, reverse power violations

I3.3 Resolve thermal violations

If a thermal violation is identified during the scaling of generation, the resolve thermal violations function:

- Determines the generators that have an adverse effect on the thermal violation.
- Scales back the causation generators sequentially until the violation has been reduced to less than 95% of the summer branch rating or transformer reverse power flow ratings (a 5% safety margin has been used to ensure conservative results).
- Sets a flag to stop scaling the causation generators.

To determine the generator(s) that are causing the thermal violation(s), sensitivity analysis is used. For each generator being scaled, the thermal sensitivity factor (*t.s.f*) of the thermal violation to the generator MVA output is calculated. To calculate the *t.s.f* a comparison of the violating branch loading with the generator in service and the generator out of service is calculated. This is then normalised to a %/MVA rating based on the MVA output of the generator. In equation form:

$$t.s.f = \frac{Violating\ Branch\ Flow\ \%\ MVA_{Pre} - Violating\ Branch\ Flow\ \%\ MVA_{Post}}{MVA\ output\ of\ generator}$$

Where:
$Violating\ Branch\ Flow\ \%\ MVA_{Pre}$ =the branch loading with the generator in service
$Violating\ Branch\ Flow\ \%\ MVA_{Post}$ =the branch loading with the generator out of service.

Note that the $MVA\ output\ of\ generator$ of the generator is the MVA output of generator the in the current scaling iteration not the MVA rating of the generator.

Using the above definition of sensitivity, if:

- *t.s.f* > 0 %/MVA, this means that branch loading is higher when this generator is in service (i.e. an increase in generator output will cause an increase in branch loading)
- *t.s.f* < 0 %/MVA, this shows that branch loading is lower when this generator is in service. (i.e. an increase in generator output will cause a decrease in branch loading)
-

Figure I1-4 shows a flow chart of the implemented resolve thermal violations function.

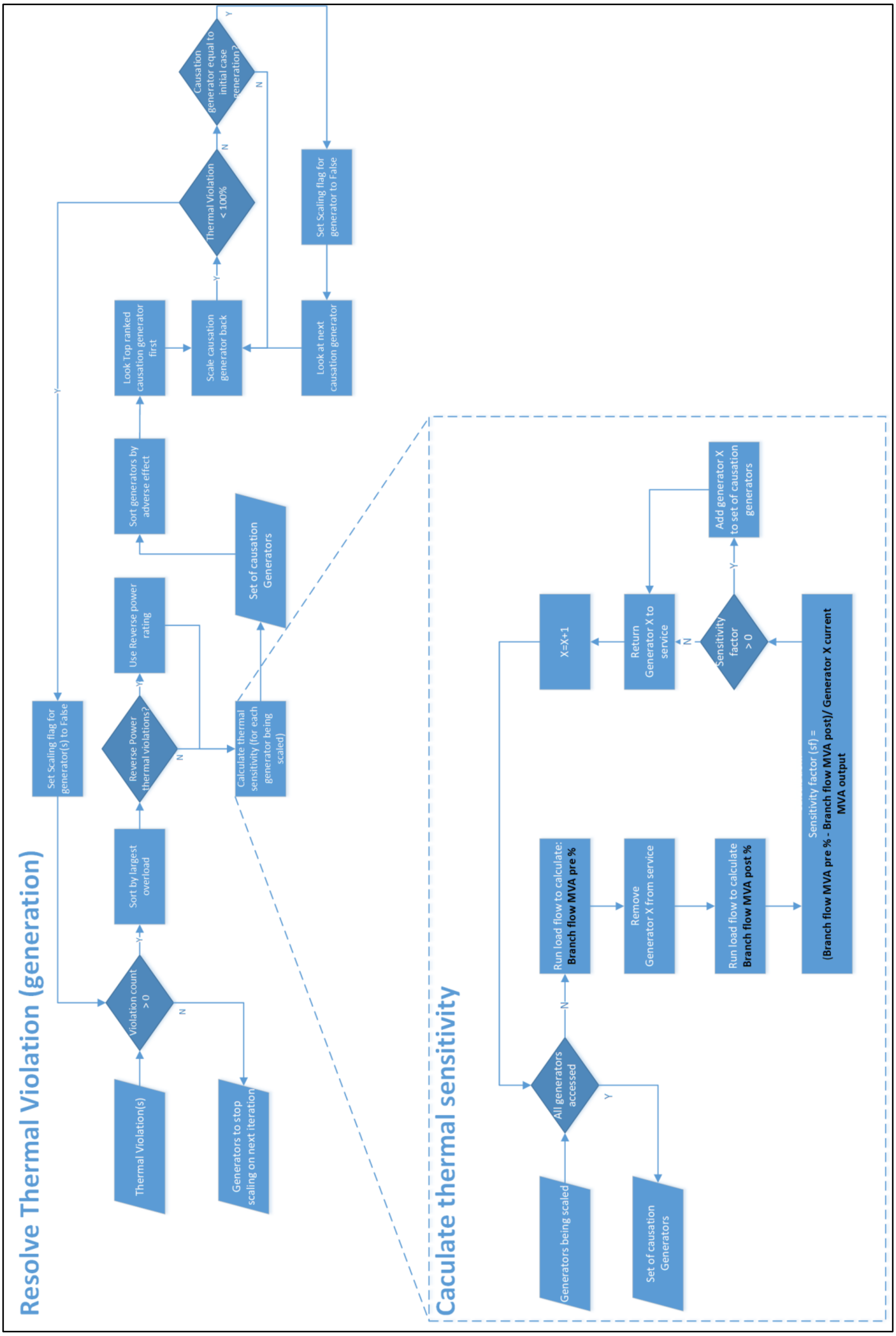


Figure I1-4 - Resolve thermal violation function

I4 Voltage functions:

After a power flow is run, the algorithm will determine if any voltage steps greater than +/-3% exist by tripping each 'dummy' generator in turn and running a power flow. If the voltage step limit of +/- 3% is exceeded the 'dummy' generator that causes the voltage step will be scaled back to a value that does not cause a voltage step, generation scaled back will not be scaled up on further iterating of the algorithm. The key functions for voltage step constraints are presented here.

I4.1 Identify voltage violations

The pseudo code for the function to identify zone voltage violations is as follows:

Input(s): Power flow solution, Zone busses.

- Identify busses with bus voltages higher than 1.06 p.u.
- Identify busses with bus voltages lower than 0.94 p.u.

Output(s): High bus voltage violations, Low bus voltage violations.

I4.2 Resolve voltage violations

If a voltage violation is identified during the scaling of generation, the resolve voltage violations function:

- Determines the generators that have a negative effect on the voltage violation.
- Ranks the generators by the magnitude of negative effect it has on the voltage violation.
- Scales back the causation generators one by one, in order of the magnitude of the generators negative effect, until the violation has been reduced to less than 95% of the voltage limits. (a 5% safety margin has been used to ensure conservative results).
- Sets a flag to stop scaling any causation generator that have been scaled back.

To determine the generator(s) that are causing the voltage violation sensitivity analysis is used with transformer taps locked. For each generator being scaled, the voltage sensitivity factor (*v.s.f*) of the voltage violation to the generator MVA output is calculated. To calculate the *v.s.f* a comparison of the bus voltage with the generator in service and the generator out of service is calculated, this is then normalised to a p.u./MVA rating based on the MVA output of the generation.

In equation form:

$$v.s.f = \frac{Violating\ Bus\ Voltage\ p.u_{Pre} - Violating\ Bus\ Voltage\ p.u_{Post}}{MVA\ output\ of\ generator}$$

Where:

$Violating\ Bus\ Voltage\ p.u_{Pre}$ =the bus voltage with the generator in service
$Violating\ Bus\ Voltage\ p.u_{Post}$ =the bus voltage with the generator out of service.

Note that the $MVA\ output\ of\ generator$ of the generator is the MVA output of generator the in the current scaling iteration not the MVA rating of the generator.

Using the above definition of sensitivity:

- For high voltage violations:
  - *v.s.f* > 0 p.u/MVA, this shows that the bus voltage is higher when this generator is in service (i.e. a causing generator)
  - *v.s.f* < 0 p.u/MVA, this shows that the bus voltage is lower when this generator is in service.
- For low voltage violations:
  - *v.s.f* > 0 p.u/MVA, this shows that the bus voltage is higher when this generator is in service
  - *v.s.f* < 0 p.u/MVA, this shows that the bus voltage is lower when this generator is in service. (i.e. a causing generator)

Figure I1-5 shows a flow chart of the implemented resolve voltage violations function.

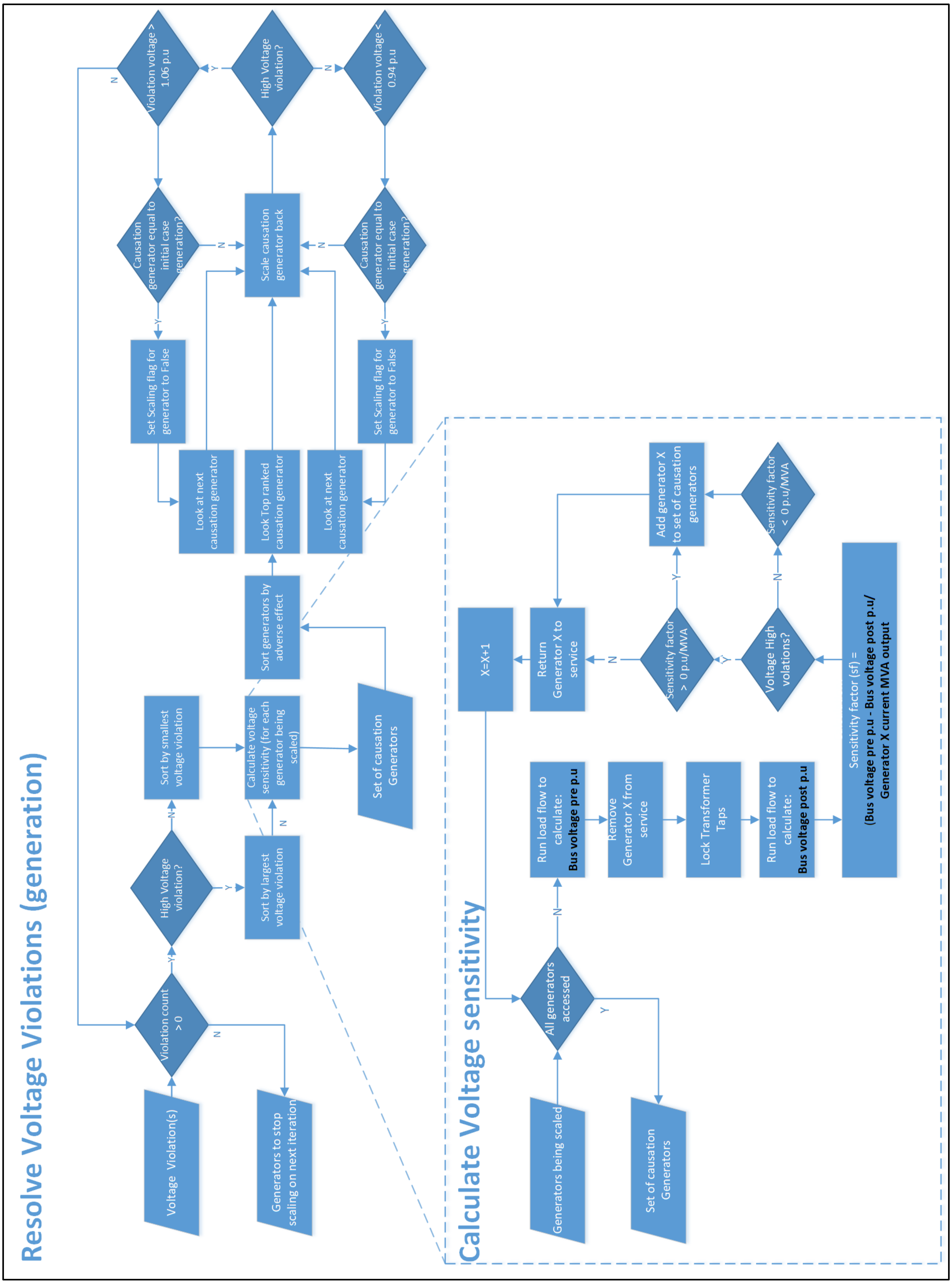


Figure I1-5 - Implemented resolve voltage violations function

I5 Identify voltage step violations

After a power flow is run, the algorithm will determine if any voltage steps greater than +/-3% exist by tripping each 'dummy' generator in turn and running a power flow. If the voltage step limit of +/- 3% is exceeded the 'dummy' generator that causes the voltage step will be scaled back to a value that does not cause a voltage step, generation scaled back will not be scaled up on further iterating of the algorithm.

The pseudo code for the function to identify zone voltage step violations is as follows:

Input(s): Power flow solution, Zone busses, generator set.

- Store zone bus voltages from the initial power flow solution.
- Lock transformer taps.
  - The transformer taps are locked during the calculation, as voltage step change will occur before transformer tap changer action.
- Remove each generator from the generator set in turn and compare the zone bus voltages with the zone bus voltages when the generator was in service.
  - If the voltage deviation is above +/- 3% store the bus and causing generator

Output(s): Voltage step violations including causing generator

I5.1 Resolve voltage step violations

If a voltage step violation is identified during the scaling of generation, the resolve voltage step violations function:

- Scales back the causing generator one by one, until the voltage step change is less than +/- 2.85%. (a 5% safety margin has been used to ensure conservative results).
- Sets a flag to stop scaling any causation generator that have been scaled back.

Figure I1-6 shows a flow chart of the implemented resolve voltage violations function.

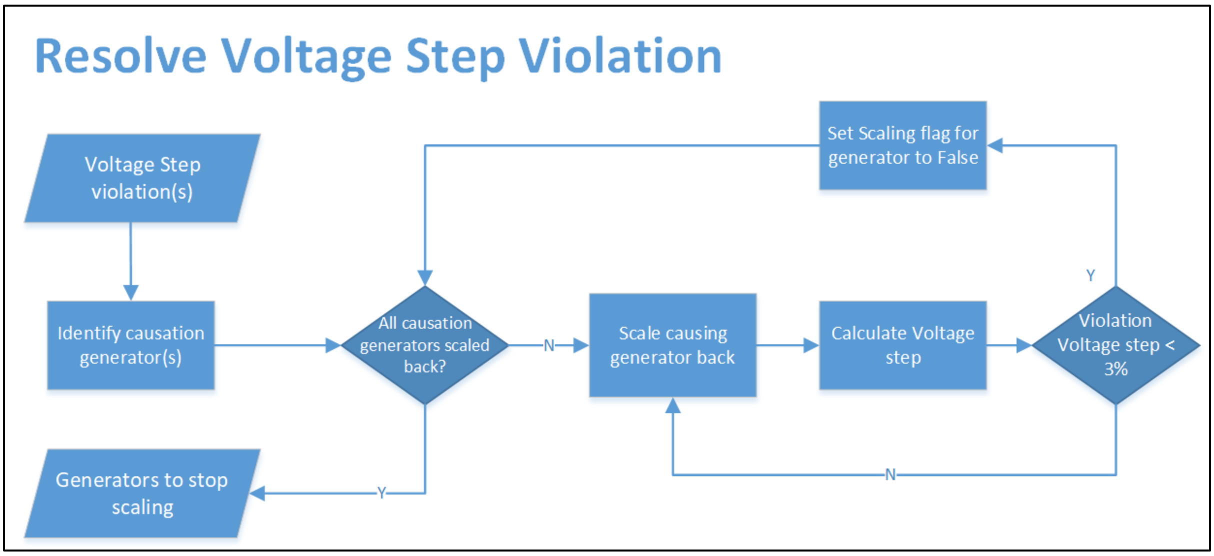


Figure I1-6 - Implemented resolve voltage step violation function

Appendix J Identify End Bus Algorithm

J1 Identify 'end busses'

The pseudo code for the function to identify the zone 'end busses' is as follows.

Input(s): Zone Branches, Zone busses, power flow solution, method selection

- Ignore any busses that have existing generation or have a lower nominal voltage than the nominal voltage of the zone of interest.
- Determine the bus or busses connected to the GSP or the BSP based on connected nominal voltages. These become the "central busses".
- Determine the busses at the extent of the zone of interest using one of the two described methods below:

  Method 1: Sink-bus

  - For each bus in the zone of interest that isn't a BSP or GSP connection bus, evaluate if power is flowing into it. If power is flowing out, it is not a sink bus.
  - If there is only power flowing into a bus, it is considered a 'sink' and the bus must be at the extent of the zone. Sink busses are considered "end-busses"

  Method 2: Path Finding

  - Identify all paths from the BSP or GSP connection bus to each other bus in the zone of interest
    - Path finding is done using existing python package NetworkNX
  - Identify all unique branch paths from the BSP or GSP connection bus to each other bus that is not a subset of any other paths in the zone of interest
  - The last bus in each unique path must be at the extent of the zone and these are considered "end-busses"
- Remove busses that are next to the 'central busses' and have negligible impedance

Output(s): List of end busses

Note - The Sink bus and Path finding methods of identifying end busses were tested to determine the most efficient and reliable results to maximize hosting capacity. For complex meshed networks with parallel paths it was determined that the path-finding method may not return the optimum location to place generation for calculating maximum hosting capacity. It was also determined that that Sink Bus method has a faster execution time for large networks and is relatively similar to the path finding method for smaller networks. See Section 0of the appendix. Both methods have been left as an option for completeness however, the default is the sink-bus method.

Figure J1-1, Figure J1-2 and Figure J1-3 show the detailed flow of the associated functions.

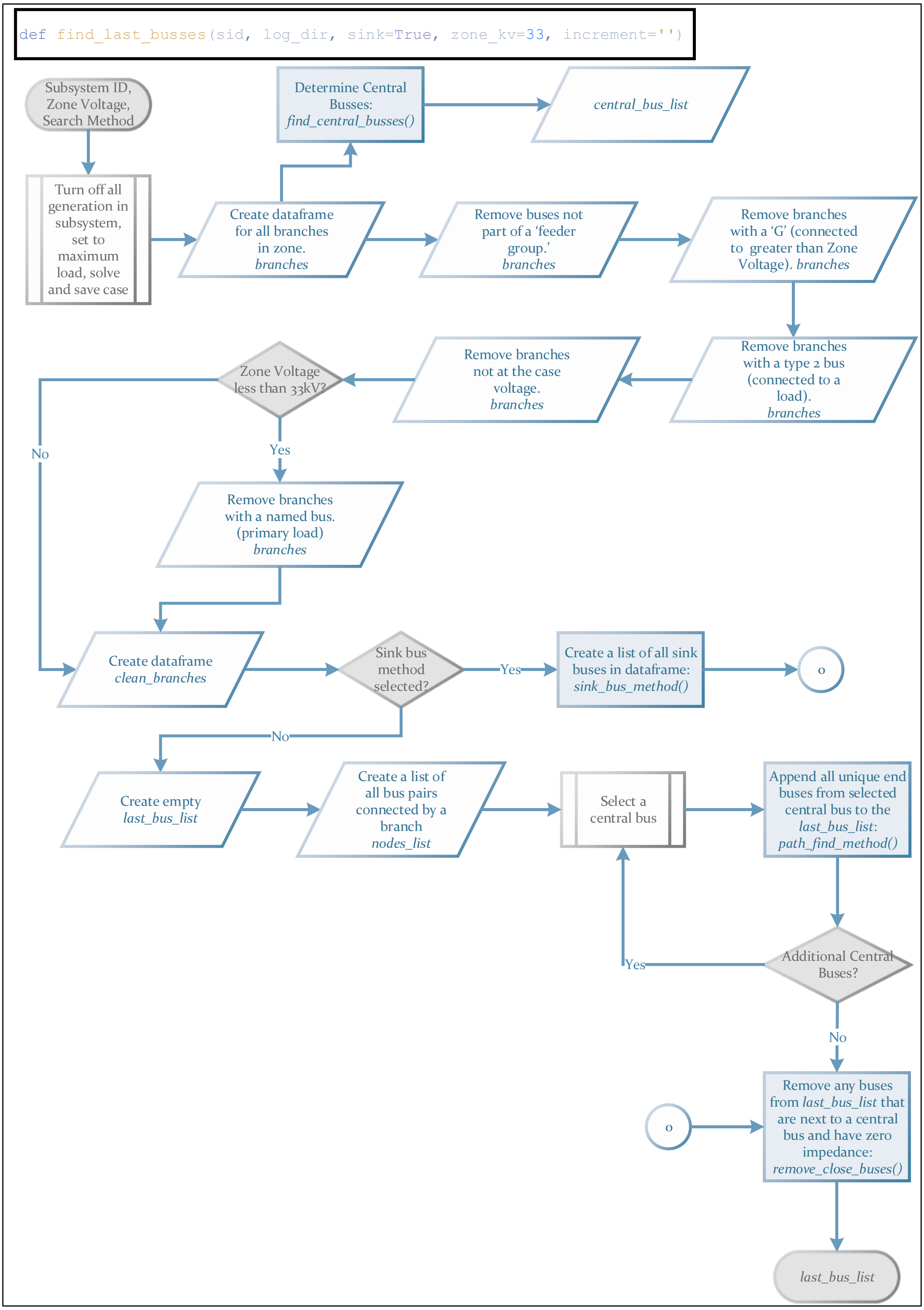


Figure J1-1 - Find last buses function flow

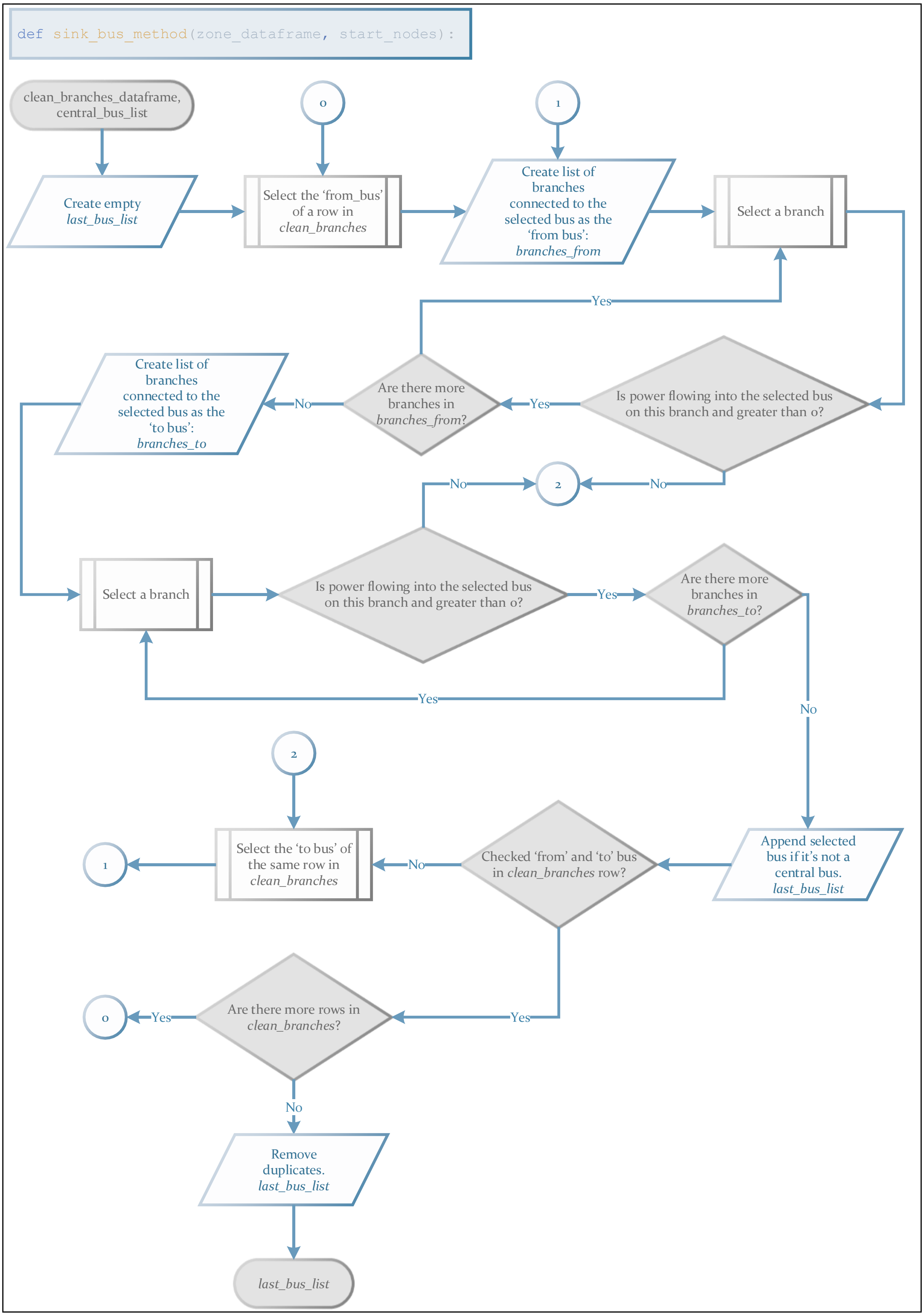


Figure J1-2 - Sink bus method

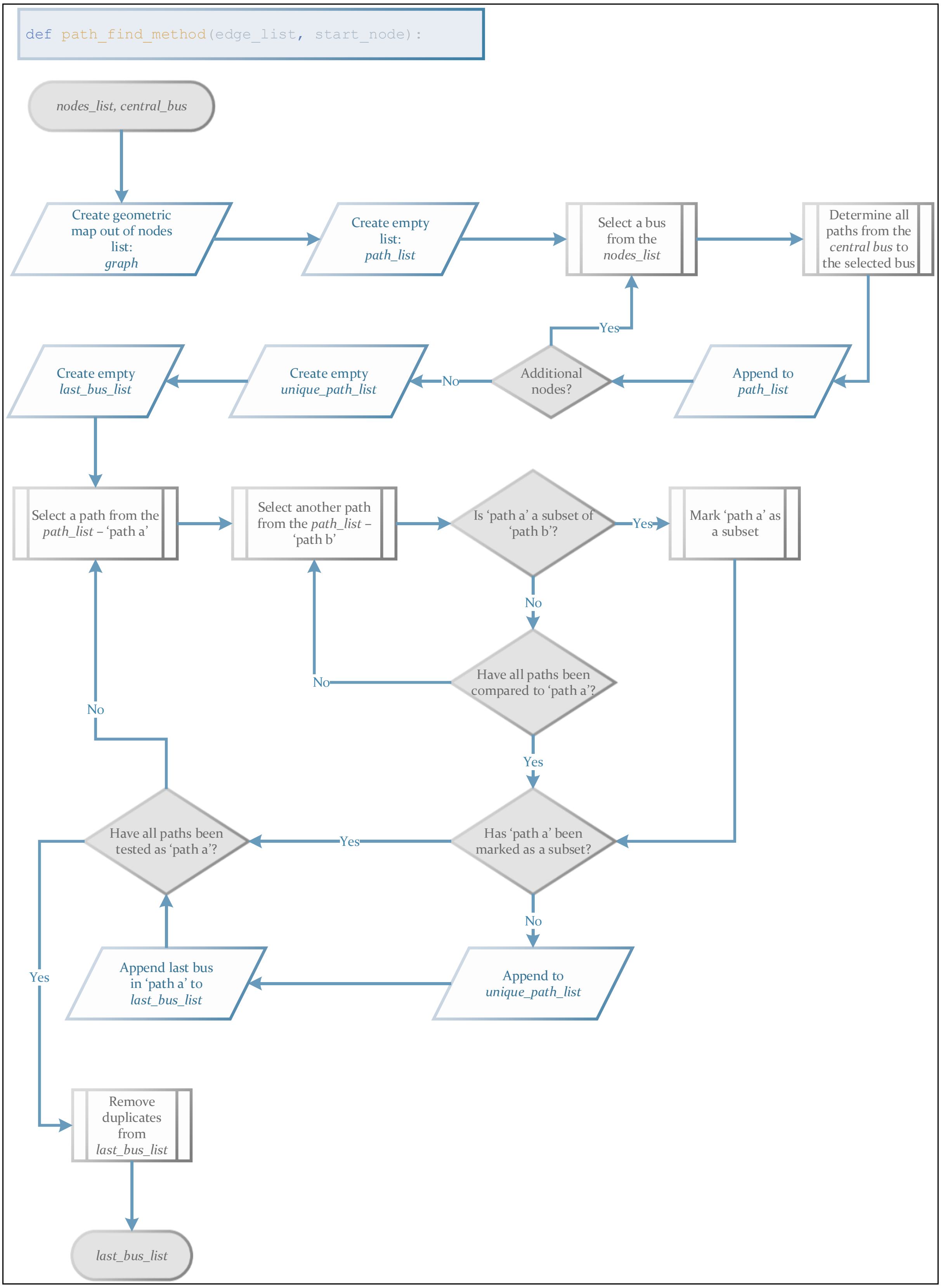


Figure J1-3 - Path finding method

J2 Performance comparison of end bus methods

The following provides a comparison of the performance for the path finding method vs the sink bus method to determine end bus locations.

Path Finding method
Initializing PSSE...

*++++++++++++++++++++++++++++++++
+++++++++++++*
Loading 33 kV Case: [200]
Finding end busses to place generators...
Solving case...
...Case Solved.
Finding all paths from bus 8135...
Finding all unique paths from bus 8135...
Removing zero impedance busses next to [8135]...

Case run took 0 minutes and 1.34 seconds

*++++++++++++++++++++++++++++++++
+++++++++++++*
Loading 33 kV Case: [220, 880]
Finding end busses to place generators...
Solving case...
...Case Solved.
Finding all paths from bus 8955...
Finding all unique paths from bus 8955...
Finding all paths from bus 8485...
Finding all unique paths from bus 8485...
Removing zero impedance busses next to [8955, 8485]...

Case run took 0 minutes and 1.54 seconds

*++++++++++++++++++++++++++++++++
+++++++++++++*
Loading 33 kV Case: [540]
Finding end busses to place generators...
Solving case...
...Case Solved.
Finding all paths from bus 8345...
Finding all unique paths from bus 8345...
Removing zero impedance busses next to [8345]...

Case run took 0 minutes and 0.72 seconds

*++++++++++++++++++++++++++++++++
+++++++++++++*
Loading Case:
C:\Users\Perry\Desktop\testing\WorkingPSSEModels\11kV\310023_TivertonMoorhayes_Final.sav
Finding end busses to place generators...

Sink bus method
Initializing PSSE...

*++++++++++++++++++++++++++++++++
+++++++++++++*
Loading 33 kV Case: [200]
Finding end busses to place generators...
Solving case...
...Case Solved.
Looking for sink busses...
Removing zero impedance busses next to [8135]...

Case run took 0 minutes and 1.54 seconds

*++++++++++++++++++++++++++++++++
+++++++++++++*
Loading 33 kV Case: [220, 880]
Finding end busses to place generators...
Solving case...
...Case Solved.
Looking for sink busses...
Removing zero impedance busses next to [8955, 8485]...

Case run took 0 minutes and 0.89 seconds

*++++++++++++++++++++++++++++++++
+++++++++++++*
Loading 33 kV Case: [540]
Finding end busses to place generators...
Solving case...
...Case Solved.
Looking for sink busses...
Removing zero impedance busses next to [8345]...

Case run took 0 minutes and 0.64 seconds

*++++++++++++++++++++++++++++++++
+++++++++++++*
Loading Case:
C:\Users\Perry\Desktop\testing\WorkingPSSEModels\11kV\310023_TivertonMoorhayes_Final.sav
Finding end busses to place generators...

Solving case...
...Case Solved.
Finding all paths from bus 7735...
Finding all unique paths from bus 7735...
Removing zero impedance busses next to [7735]...

Case run took 0 minutes and 8.05 seconds

Script run took 0 minutes and 46.53 seconds

Solving case...
...Case Solved.
Looking for sink busses...
Removing zero impedance busses next to [7735]...

Case run took 0 minutes and 2.44 seconds

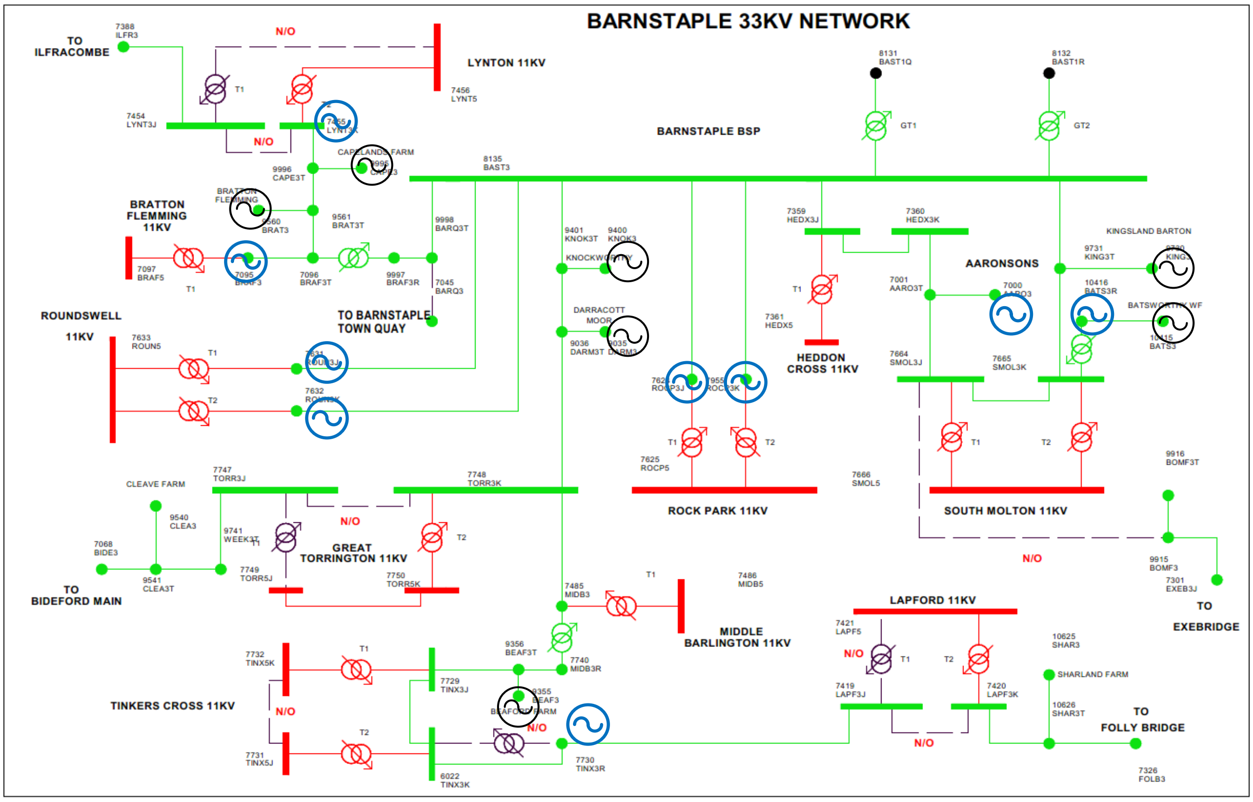
Script run took 0 minutes and 41.25 seconds

Appendix K Network End Bus Locations

K1 Barnstaple 33 kV BSP network end busses

The following table and SLD shows where the end bus function places dummy generators in Barnstaple 33 kV BSP network.

Dummy Gen	Bus Number	Bus Name
1	7000	AARO3
2	7095	BRAF3
3	7455	LYNT3K
4	7624	ROCP3J
5	7631	ROUND3K
6	7632	ROUND3J
7	7730	TINX3R
8	7955	ROCP3K
9	10416	BATS3R



Key:

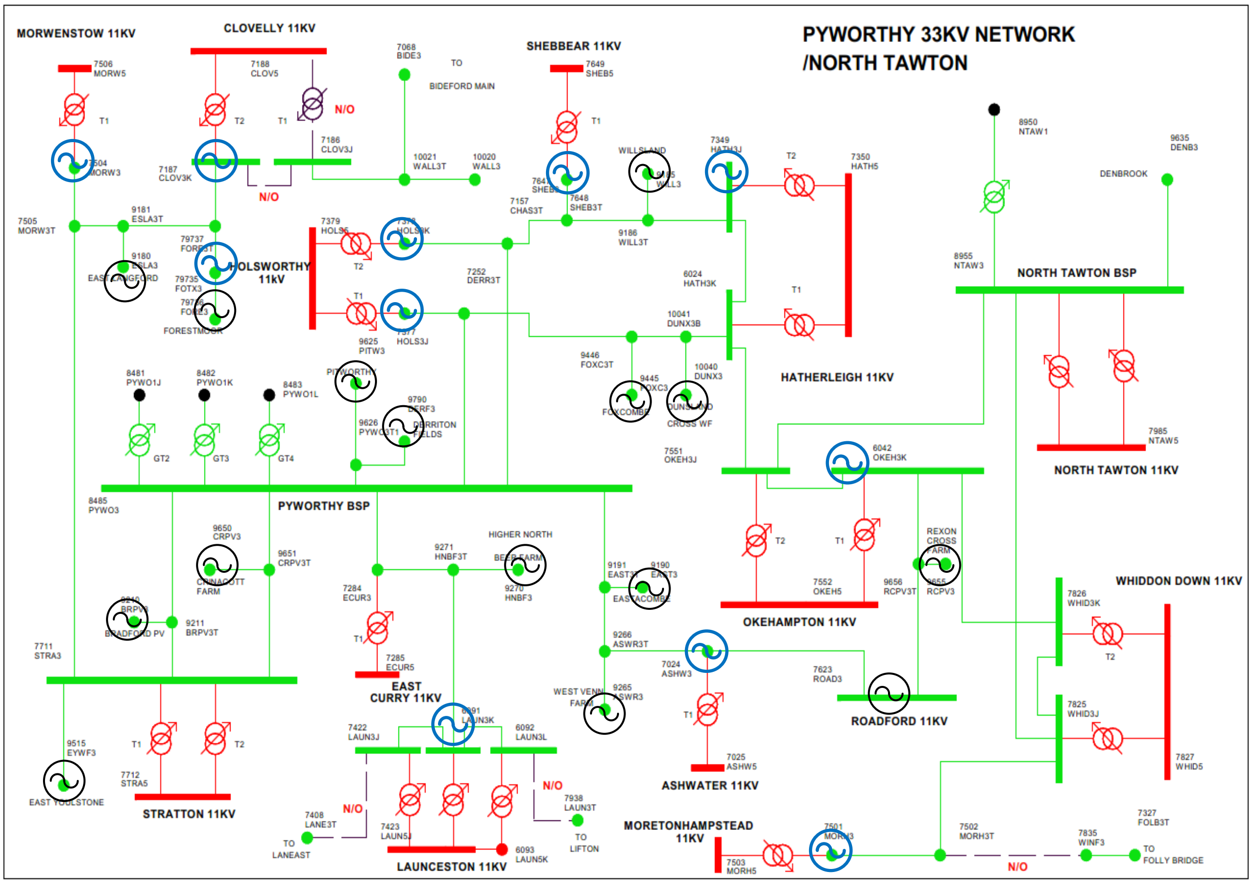

Existing Generator


Dummy Generator

K2 Pyworthy and North Tawton 33 kV BSP network end busses

The following table and SLD shows where the end bus function places dummy generators in Pyworthy and North Tawton 33 kV BSPs network.

Dummy Gen	Bus Number	Bus Name	Dummy Gen	Bus Number	Bus Name
1	6042	OKEH3K	10	7501	MORH3
2	6092	LAUN3L	11	7504	MORW3
3	7024	ASHW3	12	7647	SHEB3
4	7187	CLOV3K	13	7711	STRA3
5	7349	HATH3J	14	9651	CRPV3T
6	7377	HOLS3J	15	79735	FOTX3
7	7378	HOLS3K	16	79737	FORE3T
8	7406	LAUN3J2	17	79738	FORE31
9	7422	LAUN3J	18	79739	FORE32



Key:

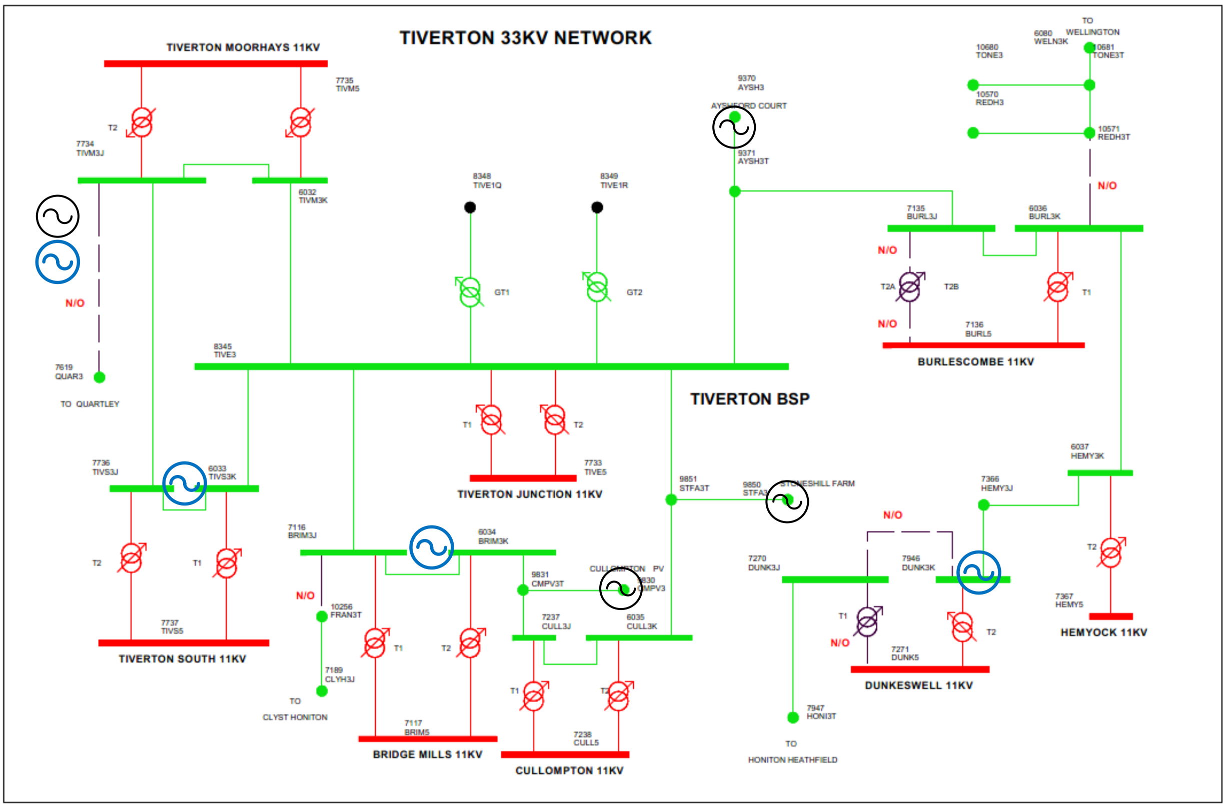
Existing Generator

Dummy Generator

K3 Tiverton 33 kV BSP network end busses

The following table and SLD shows where the end bus function places dummy generators in Tiverton 33 kV BSPs network.

Dummy Gen	Bus Number	Bus Name
1	6034	BRIM3K
2	7946	DUNK3K
3	7736	TIVS3J
4	10941	WSHC3T



Key:


Existing Generator


Dummy Generator

K4 Tiverton Moorhayes 11 kV Primary network end busses

The following table and shows where the end bus function places dummy generators in Tiverton Moorhayes 11 kV BSPs network.

Dummy Gen	Bus Number	Dummy Gen	Bus Number	Dummy Gen	Bus Number
1	95002	32	95253	63	95489
2	95006	33	95259	64	95495
3	95013	34	95279	65	95497
4	95019	35	95294	66	95500
5	95027	36	95302	67	95506
6	95030	37	95304	68	95508
7	95032	38	95310	69	95512
8	95039	39	95322	70	95521
9	95057	40	95324	71	95523
10	95069	41	95327	72	95532
11	95071	42	95333	73	95563
12	95073	43	95349	74	95570
13	95077	44	95355	75	95575
14	95084	45	95357	76	95587
15	95097	46	95359	77	95604
16	95107	47	95377	78	95613
17	95125	48	95379	79	95625
18	95159	49	95383	80	95636
19	95171	50	95389	81	95640
20	95183	51	95402	82	95650
21	95188	52	95406	83	95683
22	95192	53	95417	84	95686
23	95208	54	95429	85	95694
24	95210	55	95434	86	95696
25	95218	56	95445	87	95714
26	95233	57	95451	88	95762
27	95241	58	95453	89	95764
28	95243	59	95463	90	95775
29	95245	60	95465	91	95781
30	95247	61	95469	92	95812
31	95251	62	95481		

Appendix L Optimised Hosting Capacity Results

L1 Barnstaple 33 kV BSP network

L1.1 Load hosting capacity - intact system/per contingency

Barnstaple 33 kV Network configuration	w=0	w=0.5	w=1	Max benefit (MW)
Intact system	✓	✓	×	0.6
BSP infeed transformers contingencies				
BAST1Q_BAST3_G1	✓	×	×	0.69
BAST1R_BAST3_G2	✓	×	×	0.68
Circuit contingencies				
HEDX3J_BAST3_L1	✓	×	×	0.34
LAPF3J_TINX3R_L1	✓	×	×	0.61
MIDB3_TORR3K_L1	✓	×	×	0.31
ROCP3J_BAST3_L1	×	×	×	n/a
ROUN3J_BAST3_L1	✓	×	×	0.47
ROUN3K_BAST3_L2	✓	×	×	0.44
ROCP3K_BAST3_L2	×	×	×	n/a
BATS3_BATS3R_L1	✓	×	×	0.23
BRAF3T_BRAF3R_R1	×	×	×	n/a
MIDB3_MIDB3R_R1	✓	✓	✓	1.06
SMOL3K_BATS3R_R1	✓	×	×	0.23
SMOL3K_KING3T_L1+ BAST3_KING3T_L1+ KING3_KING3T_L1	✓	×	×	1.28
BAST3_BARQ3T_L1+ BRAF3R_BARQ3T_L1	✓	×	×	0.11
AARO3_AARO3T_L1+ AARO3T_HEDX3K_L1+ AARO3T_SMOL3J_L1	✓	×	×	0.80
TINX3J_BEAF3T_L1+ MIDB3R_BEAF3T_L1+ BEAF3_BEAF3T_L1	✓	✓	×	0.76
TORR3K_DARM3T_L1+ DARM3_DARM3T_L1+ DARM3T_KNOK3T_L1+ BAST3_KNOK3T_L1+ KNOK3_KNOK3T_L1	×	×	×	0.00
LYNT3K_CAPE3T_L1+ BRAT3T_CAPE3T_L1+ CAPE3_CAPE3T_L1+ BRAF3_BRAF3T_L1+ BRAF3T_BRAT3T_L1+ BRAT3_BRAT3T_L1	✓	×	×	0.40
33/11kV Primary Supply Transformers contingencies				
TINX3K_TINX5J_T2	✓	×	×	0.53

BRAF3_BRAF5_T1	✓	✗	✗	0.30
HEDX3J_HEDX5_T1	✓	✓	✗	1.01
LYNT3K_LYNT5_T2	✓	✗	✗	0.15
MIDB3_MIDB5_T1	✓	✓	✓	0.53
ROCP3J_ROCP5_T1	✗	✗	✗	n/a
ROCP5_ROCP3K_T2	✗	✗	✗	n/a
ROUN3J_ROUN5_T1	✓	✗	✗	0.47
ROUN3K_ROUN5_T2	✓	✗	✗	0.82
SMOL3J_SMOL5_T1	✓	✗	✗	0.05
SMOL3K_SMOL5_T2	✓	✓	✓	0.67
TINX3J_TINX5K_T1	✓	✓	✗	0.31
TORR3K_TORR5K_T2	✓	✗	✗	0.21

L2 Pyworthy and North Tawton 33 kV BSP network

L2.1 Generation hosting capacity - intact system/per contingency

Pyworthy and North Tawton 33 kV Network configuration	w=0	w=0.5	w=1	Max benefit (MW)
Intact system	×	×	✓	0.24
BSP infeed transformers contingencies				
PYWO1J_PYWO3_G2	✓	✓	✓	14.86
PYWO1K_PYWO3_G3	✓	✓	✓	13.20
PYWO1L_PYWO3_G4	✓	✓	✓	12.51
NTAW1_NTAW3_G1	=	=	=	0.00
Circuit contingencies				
HATH3K_OKEH3J_L1	✓	✓	×	1.62
HATH3K_DUNX3B_L1	×	×	✓	3.38
OKEH3K_WHID3K_L1	✓	✓	✓	3.98
ASHW3_ROAD3_L1	✓	×	×	3.90
ECUR3_PYWO3_L1	×	×	×	n/a
OKEH3J_NTAW3_L1	×	×	×	n/a
STRA3_EYWF3_L1	✓	✓	×	0.41
WHID3J_NTAW3_L1	×	×	×	n/a
NTAW3_DENB3_L1	✓	×	×	0.29
PITW3_PYWO3T1_L1	✓	✓	✓	3.77
PYWO3T1_DERF3_L1	✓	×	✓	3.04
FOTX3_FORE3_L1	✓	✓	✓	1.12
OKEH3K_RCPV3T_L1+ ROAD3_RCPV3T_L1+ RCPV3_RCPV3T_L1	✓	✓	×	1.81
STRA3_BRPV3T_L1+ PYWO3_BRPV3T_L1+ BRPV3_BRPV3T_L1	✓	×	×	4.43
LAUN3K_HNBF3T_L2+ ECUR3_HNBF3T_L2+ HNBF3_HNBF3T_L1	✓	✓	✓	2.02
STRA3_CRPV3T_L1+ PYWO3_CRPV3T_L1+ CRPV3_CRPV3T_L1	✓	×	×	0.88
MORH3_MORH3T_L1+ MORH3T_WHID3J_L1	✓	×	×	0.47
ASHW3_ASWR3T_L1+ EAST3T_ASWR3T_L1+ ASWR3_ASWR3T_L1+ PYWO3_EAST3T_L1+ EAST3_EAST3T_L1	×	×	×	n/a
CLOV3K_FORE3T_L1+ ESLA3T_FORE3T_L2+ FORE3_FORE3T_L2+ MORW3_MORW3T_L1+ MORW3T_STRA3_L1+ MORW3T_ESLA3T_L1+ ESLA3_ESLA3T_L1	✓	×	×	0.63
HATH3J_WILL3T_L1+ SHEB3T_WILL3T_L1+	✓	×	✓	2.05

WILL3_WILL3T_L1+ CHAS3T_HOLS3K_L1+ CHAS3T_SHEB3T_L1+ CHAS3T_PYWO3_L1+ SHEB3_SHEB3T_L1				
DERR3T_FOXC3T_L1+ FOXC3_FOXC3T_L1+ FOXC3T_DUNX3B_L1+ DERR3T_HOLS3J_L1+ DERR3T_PYWO3_L1	×	×	×	n/a
33/11kV Primary Supply Transformers contingencies				
HATH3K_HATH5_T1	✓	×	✓	3.00
OKEH3K_OKEH5_T1	✓	✓	×	1.54
LAUN3K_LAUN5J_T1	✓	✓	✓	3.21
LAUN3L_LAUN5K_T3	✓	✓	×	1.97
ASHW3_ASHW5_T1	×	×	×	n/a
CLOV3K_CLOV5_T2	✓	✓	×	0.42
ECUR3_ECUR5_T1	×	×	✓	0.04
HATH3J_HATH5_T2	×	×	×	n/a
HOLS3J_HOLS5_T1	✓	✓	✓	1.67
HOLS3K_HOLS5_T2	×	×	×	n/a
LAUN3J_LAUN5J_T2	✓	✓	×	2.81
MORH3_MORH5_T1	×	×	×	n/a
MORW3_MORW5_T1	×	✓	×	1.18
OKEH3J_OKEH5_T2	✓	✓	×	1.99
SHEB3_SHEB5_T1	✓	✓	×	0.41
STRA3_STRA5_T1	×	×	✓	1.87
STRA3_STRA5_T2	✓	×	✓	3.26
WHID3J_WHID5_T1	×	✓	✓	2.35
WHID3K_WHID5_T2	✓	✓	×	0.20
NTAW5_NTAW3_T1	×	✓	×	1.83
NTAW5_NTAW3_T2	✓	✓	✓	3.23

L2.2 Load hosting capacity - intact system/per contingency

Pyworthy and North Tawton 33 kV Network configuration	w=0	w=0.5	w=1	Max benefit (MW)
Intact system	✓	×	✓	1.03
BSP infeed transformers contingencies				
PYWO1J_PYWO3_G2	✓	✓	✓	1.86
PYWO1K_PYWO3_G3	✓	✓	✓	2.34
PYWO1L_PYWO3_G4	✓	×	×	2.46
NTAW1_NTAW3_G1	✓	✓	×	0.64
Circuit contingencies				
HATH3K_OKEH3J_L1	✓	×	×	0.53
HATH3K_DUNX3B_L1	✓	✓	×	0.26
OKEH3K_WHID3K_L1	✓	×	×	0.88
ASHW3_ROAD3_L1	✓	×	✓	0.69
ECUR3_PYWO3_L1	✓	✓	✓	0.91

OKEH3J_NTAW3_L1	✗	✗	✓	0.01
STRA3_EYWF3_L1	✓	✗	✗	0.70
WHID3J_NTAW3_L1	✓	✗	✗	0.70
NTAW3_DENB3_L1	✓	✗	✗	1.27
PITW3_PYWO3T1_L1	✓	✗	✗	0.60
PYWO3T1_DERF3_L1	✓	✗	✗	0.13
FOTX3_FORE3_L1	✓	✗	✗	0.41
OKEH3K_RCPV3T_L1+ ROAD3_RCPV3T_L1+ RCPV3_RCPV3T_L1	✗	✗	✗	n/a
STRA3_BRPV3T_L1+ PYWO3_BRPV3T_L1+ BRPV3_BRPV3T_L1	✓	✓	✗	1.05
LAUN3K_HNBF3T_L2+ ECUR3_HNBF3T_L2+ HNBF3_HNBF3T_L1	✗	✗	✗	n/a
STRA3_CRPV3T_L1+ PYWO3_CRPV3T_L1+ CRPV3_CRPV3T_L1	✓	✗	✓	1.51
MORH3_MORH3T_L1+ MORH3T_WHID3J_L1	✓	✗	✗	1.29
ASHW3_ASWR3T_L1+ EAST3T_ASWR3T_L1+ ASWR3_ASWR3T_L1+ PYWO3_EAST3T_L1+ EAST3_EAST3T_L1	✓	✗	✓	0.97
CLOV3K_FORE3T_L1+ ESLA3T_FORE3T_L2+ FORE3_FORE3T_L2+ MORW3_MORW3T_L1+ MORW3T_STRA3_L1+ MORW3T_ESLA3T_L1+ ESLA3_ESLA3T_L1	✓	✗	✗	1.00
HATH3J_WILL3T_L1+ SHEB3T_WILL3T_L1+ WILL3_WILL3T_L1+ CHAS3T_HOLS3K_L1+ CHAS3T_SHEB3T_L1+ CHAS3T_PYWO3_L1+ SHEB3_SHEB3T_L1	✓	✓	✗	1.22
DERR3T_FOXC3T_L1+ FOXC3_FOXC3T_L1+ FOXC3T_DUNX3B_L1+ DERR3T_HOLS3J_L1+ DERR3T_PYWO3_L1	✓	✓	✓	3.45
33/11kV Primary Supply Transformers contingencies				
HATH3K_HATH5_T1	✓	✓	✗	0.85
OKEH3K_OKEH5_T1	✓	✗	✗	0.56
LAUN3K_LAUN5J_T1	✓	✓	✓	2.99
LAUN3L_LAUN5K_T3	✓	✓	✗	2.40
ASHW3_ASHW5_T1	✓	✗	✗	0.74
CLOV3K_CLOV5_T2	✓	✗	✗	1.15
ECUR3_ECUR5_T1	✓	✓	✗	1.12

HATH3J_HATH5_T2	✓	×	✓	1.12
HOLS3J_HOLS5_T1	✓	✓	✓	0.94
HOLS3K_HOLS5_T2	✓	✓	×	1.23
LAUN3J_LAUN5J_T2	✓	✓	✓	3.88
MORH3_MORH5_T1	✓	×	×	0.45
MORW3_MORW5_T1	✓	✓	✓	3.18
OKEH3J_OKEH5_T2	✓	×	×	0.48
SHEB3_SHEB5_T1	✓	×	×	0.67
STRA3_STRA5_T1	✓	✓	✓	1.53
STRA3_STRA5_T2	✓	✓	✓	1.41
WHID3J_WHID5_T1	✓	×	×	0.10
WHID3K_WHID5_T2	✓	×	×	0.34
NTAW5_NTAW3_T1	✓	✓	✓	2.00
NTAW5_NTAW3_T2	✓	✓	✓	1.81

L3 Tiverton Moorhayes 11 kV Primary network

L3.1 Generation hosting capacity - intact system/per contingency

Tiverton 11 kV Network configuration	w=0	w=0.5	w=1	Max benefit (MW)	Mvar available (Min/ Max)
Intact system	✗	✗	✗	n/a	-0.64/0.64
Primary infeed transformers contingencies					
TIVM3J__T1	✓	✓	✓	0.03	-0.64/0.64
TIVM3J__T2	✓	✓	✓	0.03	-0.64/0.64
Circuit contingencies					
7735_95000_1	✗	✗	✗	n/a	-0.4/0.4
7735_95167_1	✗	✓	✓	0.01	-0.64/0.64
7735_95755_1	✗	✗	✗	n/a	-0.64/0.64
7735_95785_1	✗	✓	✓	0.01	-0.64/0.64
7735_95813_1	✗	✓	✓	0.01	-0.64/0.64
7735_95911_1	✗	✗	✗	n/a	-0.64/0.64
7735_95000_1	✗	✗	✗	n/a	-0.26/0.26

L3.2 Load hosting capacity - intact system/per contingency

Tiverton 11 kV Network configuration	w=0	w=0.5	w=1	Max benefit (MW)	Mvar available (Min/ Max)
Intact system	=	=	=	n/a	-0.064/0.064
Primary infeed transformers contingencies					
TIVM3J__T1	=	=	=	n/a	-0.064/0.064
TIVM3J__T2	=	=	=	0.03	-0.064/0.064
Circuit contingencies					
7735_95000_1	=	=	=	n/a	-0.04/0.04
7735_95167_1	=	=	=	n/a	-0.064/0.064
7735_95755_1	=	=	=	n/a	-0.064/0.064
7735_95785_1	=	=	=	n/a	-0.064/0.064
7735_95813_1	=	=	=	n/a	-0.064/0.064
7735_95911_1	=	=	=	n/a	-0.064/0.064
7735_95000_1	✗	✓	✓	0.6	-0.026/0.026