SP ENERGY NETWORKS

Flexible Networks for a Low Carbon Future

St Andrews Series Voltage Regulator Location Study

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Executive Summary

As part of the LCNF Tier 2 Flexible Networks project, SPEN is installing and testing an automatic voltage regulator (AVR) in the 11kV St Andrews secondary distribution network. It is planned that this will be located on one of the two St Andrews to Anstruther circuits in the vicinity of the St Andrews Bay Hotel where there are known voltage issues during backfeeding conditions.

Whilst SPEN already have a number of AVRs installed on their network, the deployment of the AVR for this purpose represents the use of the technology for a novel application: voltage support to enable load transfer during conditions of high demand. This AVR application should deliver improved network performance and increased network capacity, one of the key aims of the Flexible Networks project. It will also facilitate future flexible network control by enabling automated load transfer between St Andrews and Anstruther HV networks.

A modelling study has been undertaken by TNEI, to determine the optimum location of the AVR between St Andrews and Anstruther under combined peak loading conditions. This concludes that the AVR should be located on St Andrews feeder 25 downstream (i.e. on the Anstruther side) of Cambo Lodge, between pole 125 and pole 87 to permit St Andrews feeder 25[1] to be backfed from Anstruther, via Crail Soule, as far as a new NOP at Grange NOJA. To increase the extent of the backfeed of St Andrews feeder 25 as far as Harbour Pumping Station GMS, the AVR must be located immediately adjacent to the existing Crail Soule (pole 87) on the St Andrews side.

These studies indicate that with deployment of the AVR, it is possible to transfer load to Anstruther to achieve up to 20% capacity headroom at St Andrews primary substation under n-1 conditions, in comparison to the existing P2/6 demand capacity headroom of 7%, a 13% increase.

However, taking account of the peak loading characteristics and firm capacity of the Anstruther network, to which part of the St Andrews load is being transferred, it may, under certain conditions, be necessary to utilise the short term transformer thermal rating to permit full load transfer from feeder 25. Alternatively, consideration could be given to moving the NOP on feeder 25 towards Anstruther to reduce the magnitude of the load transfer, for a very small percentage of time. This would be required for a limited duration, when the total load at the Anstruther primary substation and the total load to be backfed on St Andrews feeder 25 (including losses) exceeded the firm capacity of the Anstruther network. Such an approach would, however, require the installation of additional network controllable points.

[1] See note under Section 1.1 for an explanation of the terminology used in this report.

Glossary

ABSW	Air break switch
AVR	Series (Automatic) voltage regulator
C/B	Circuit breaker
FNC	Flexible Network Control
GMS	Ground mounted substation
Gridkey	Low Voltage (LV) substation monitoring system
GVR	Automatic circuit recloser (GVR is brand name)
LDC	Line Drop Compensation
MDI	Maximum Demand Indicator
NOJA	Automatic circuit recloser (NOJA is brand name)
NOP	Normally open point (a normal point of isolation part way along a feeder)
PI	Process Instrumentation – SPEN's Network Monitoring Data Historian System
PNDC	Power Networks Demonstration Centre
Soule	Network controllable point (Soule is brand name)
SPEN	Scottish Power Energy Networks
Subnet	Low Voltage (LV) substation monitoring system

1 Existing Network

1.1 Circuit Configuration & Report Terminology

The current circuit configuration for St Andrews feeder 25, feeder 13 and Anstruther feeder 12 is shown in Figure 1-1, indicating key switching and network control points.

With reference to Figure 1-1, in this report the term "feeder 25" is used to describe the part of the 11kV circuit between St Andrews and Anstruther primary substations that is, under current normal running conditions, supplied by C/B 25 at St Andrews. A parallel path, between C/B 13 at St Andrews and Priestden Road GMS (which is part way along "feeder 25"), means that, with network reconfiguration, the part of feeder 25 beyond Priestden Road GMS could be supplied by St Andrews "feeder 13". This running configuration, which reduces the load that would need to be picked up from Anstruther under backfeed conditions, is considered further in the study.

Similarly, by relocation of one of the existing normally open points (NOP) on feeder 25 (currently at Crail Soule) some demand on St Andrews "feeder 25" could instead be supplied from Anstruther "feeder 12", as postulated by this study.

For clarity and simplicity, in this report:-

- where the term "feeder 25" is used it shall be taken to mean the section of interconnecting circuit between St Andrews and Anstruther currently supplied by C/B 25 at St Andrews (i.e. up to the current NOP at Crail Soule and including the two parallel branches up to Boarhills Soule NOP and Pinkerton Road GMS NOP);
- where the term "feeder 13" is used it shall be taken to mean the circuit between St Andrews and the NOP adjacent to Priestden Road GMS, currently supplied by C/B 13 at St Andrews; and
- where the term "feeder 12" is used it shall be taken to mean the section of interconnecting circuit between St Andrews and Anstruther currently supplied by C/B 12 at Anstruther (i.e. up to the current NOP at Crail Soule, and including the two parallel branches up to their NOPs at Boarhills Soule and Pinkerton Road GMS).

Currently, the capacity for load sharing between Anstruther feeder 12 and St Andrews feeder 25, which might be required during fault conditions or maintenance conditions, is limited by voltage constraints. Under high loading conditions, the customer voltage at the St Andrews Bay Hotel (now known as Fairmont St Andrews Resort) and along feeder 25 towards St Andrews primary is, at times of high loading, below statutory limits whilst backfeeding from Anstruther feeder 12 (where the NOP is located at Grange NOJA or St Andrews primary substation).

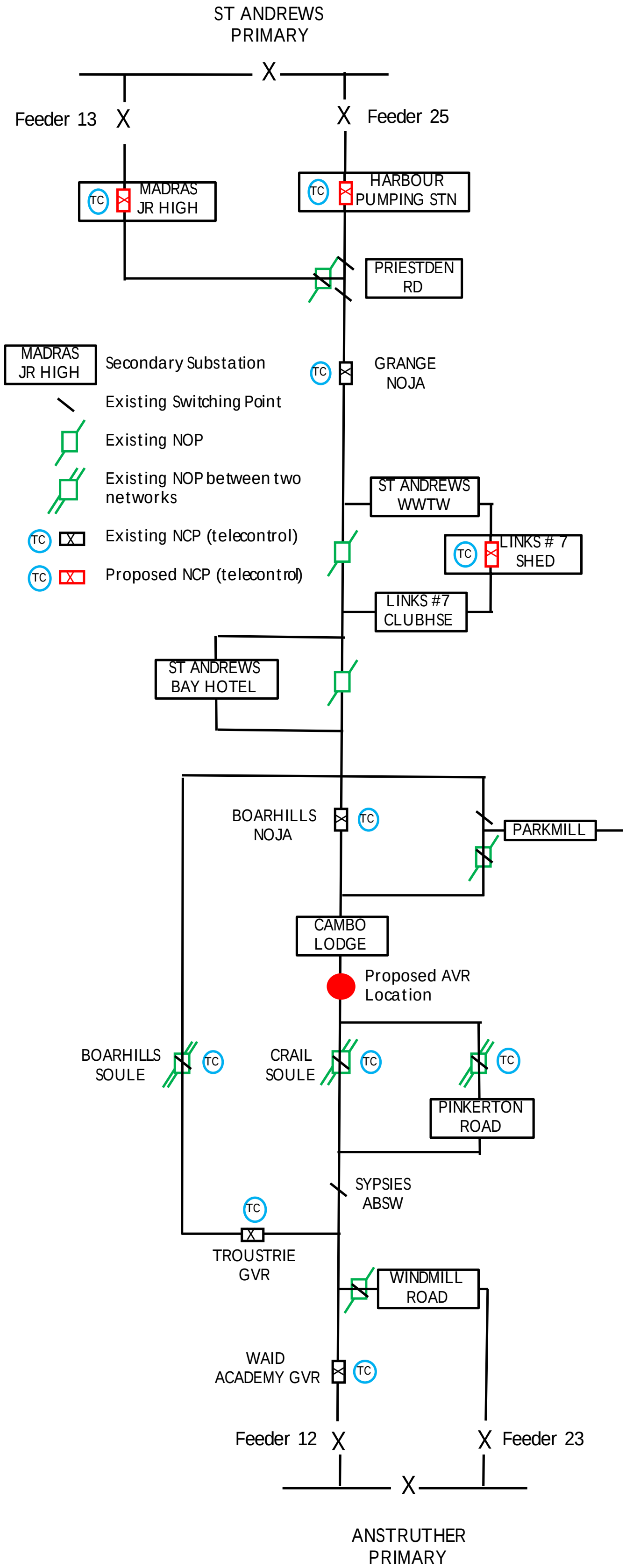


Figure 1-1 St Andrews F25 and Anstruther F12 Circuit Configuration

It is understood from discussion with SPEN that feeder 25 backfeed is to be achieved by closing Crail Soule NOP but it is noted that there are two further possible backfeed connection arrangements (via Boarhills Soule and via Pinkerton Road GMS). These alternative backfeeds should not be used because their lower circuit ratings may lead to thermal capacity constraints. It is understood that suitable operational controls have been introduced by SPEN to ensure that, in future, only the circuit through Crail Soule will be used for backfeeding.

1.2 Load Transfer Opportunities

Network capacity headroom is defined as the difference between the maximum load on the HV network group and the network group firm capacity under an n-1 contingency condition (for the P2/6 group types assessed). For SP Distribution, HV network groups are defined as a single HV network supplied from the 33kV network through two primary transformers. In order to comply with P2/6, the maximum load should therefore not exceed the network group firm capacity. Permanent or dynamic load reduction, e.g. through load transfer to other adjacent parts of the network, can therefore provide a means of effectively increasing the headroom of networks approaching firm capacity.

As part of the Flexible Networks project detailed analysis is being undertaken by TNEI and University of Strathclyde to quantify the increase in effective headroom capacity that may be created through load switching/transfer from the St Andrews HV network group to adjacent HV networks groups. Optimisation algorithms to automatically carry out dynamic switching actions are also being investigated.

This will be facilitated through existing network controllable points (NCPs), supplemented by a number of new NCPs at locations to be identified. Temporary (and potentially automatic) transfer of load from St Andrews network to Anstruther network by moving the normally open point on the circuit (currently at Crail Soule), is one mechanism whereby this transfer can be delivered.

In order to facilitate this load transfer, however, any voltage constraints must first be removed. High loading on St Andrews feeder 25, particularly the significant load from the St Andrews Bay Hotel, reduces voltage to below statutory limits when backfeeding from Anstruther feeder 12. This interconnection was thus identified at an early stage by SPEN as an opportunity to install an AVR to enable backfeeding and thus, flexible network control.

Figure 1-2 shows the daily load cycle on both St Andrews feeder 25 and Anstruther feeder 12 on a typical winter loading day (6th March 2013). It can be seen that there is approximately 700kVA difference in tea time peak load. In passing, it should also be noted that the early morning loading pattern for St Andrews feeder 25 during winter is somewhat higher than that of typical HV feeder load profiles. This load pattern is consistent across all three phases and may, for example, be due to economy 7 heating. The other St Andrews HV feeders display more typical daily load profiles. This difference in load pattern between feeders underlines the importance of assessing feeder load profiles on a case-by-case basis.

A load transfer to Anstruther feeder 12 during contingency conditions will release some capacity on the St Andrews network. The magnitude of load transfer possible will depend on the loading and available thermal capacities of Anstruther feeder 12 circuit and Anstruther primary transformer, as well as voltage limits.

It is important to appreciate that the capacity for creation of headroom through load transfer will be at a maximum if the time of the peak loading for the feeder to be used for load transfer corresponds to the time of the peak loading of the primary substation from which load is to be transferred. If these peak loadings do not occur at the same time, then the headroom created will be correspondingly less than the theoretical maximum. In the case of the St Andrews to Anstruther feeder, analysis of 2013 loading data indicates that the feeder 25 load at the time of the peak loading at St Andrews primary is within 2% of the absolute peak load on feeder 25. Thus, the theoretical headroom gains predicted by the following analysis are therefore felt to be representative of the headroom that could be released in practise.

In the event that the feeder peak loading occurs at a different time to the primary substation from which load is to be transferred then an additional assessment, at aggregate feeder peak loading must also be undertaken to check for voltage (and thermal) constraints under these worst-case backfeeding conditions.

This study assesses **dynamic** load transfer as a means of creating capacity headroom. If a permanent load transfer was to be considered (which is outside the scope of this project), then it would also need to include an assessment of the impact on CI/CMLs and network losses resulting from such a transfer. An adverse change to CI/CML performance could occur if, for example, customers previously connected to a primary substation through an underground cable network were transferred to a long overhead network.

Also, the reduction of capacity headroom on the network that load is permanently transferred to should not result in that network approaching or exceeding its firm capacity under high loading conditions or the benefits may be diminished as the requirement for potentially significant network reinforcement at another location will be accelerated.

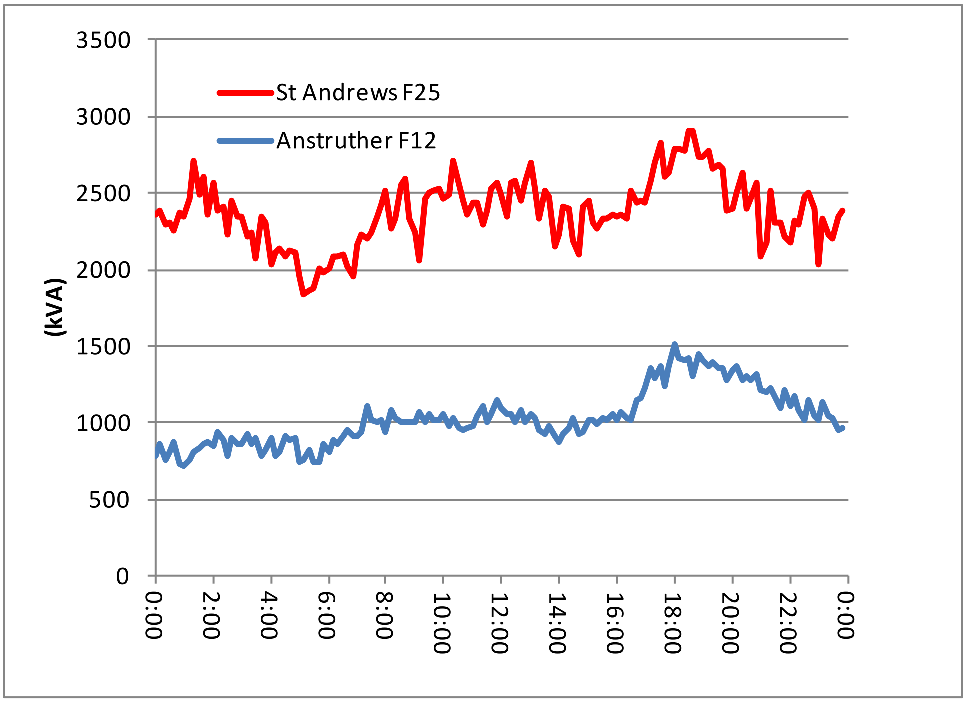


Figure 1-2 Daily Load Cycle on St Andrews feeder 25 and Anstruther feeder 12 (6th March 2014)

2 Methodology

The proposed solution to removing the voltage constraint and facilitating flexible network control on St Andrews feeder 25 is the installation of an automatic voltage regulator (AVR). A new Cooper Power System VR32 200A voltage regulator has been procured for this purpose. Network studies are required to determine where this AVR should be installed to achieve the desired effect. The selected location should take account of the fact that the AVR is subsequently to be incorporated into a Flexible Network Control (FNC) scheme. The methodology used for these network studies is described below.

2.1 Network Modelling

The IPSA model of the St Andrews 11kV network prepared as part of the Flexible Networks project was used as a basis for the modelling process. This model was constructed as follows:

- Extract circuit data (connectivity, length, conductor type) from SPEN GIS and determine conductor ratings from SPEN cable database information (a cable database for WinDEBUT was provided)
- Extract secondary transformer data (location, rating) from SPEN GIS, and impedance data from SPEN SAP database where available (generally only for ground-mounted substations)
- Apply impedance assumptions for pole mounted substations (5% of rating)
- Convert GIS data to IPSA model using bespoke script, include transformer impedance and check that load flow results are broadly as would be expected based on expected loading behaviour and voltage drop.

The network model was reduced to comprise only St Andrews feeders 13 and 25, and Anstruther feeder 12.

2.1.1 Secondary Substation Loading Methodology

The loading at each secondary substation was determined based on common SPEN practice for 11kV network modelling (ground mounted substation load based on MDI loading, pole mounted substation load based on percentage of transformer rating). Loads were then scaled to match the corresponding total HV feeder currents at Anstruther and St Andrews as recorded by PI.

Secondary substation loads were then compared to measured data from Gridkey and Subnet iHost monitors installed as part of the Flexible Networks project, where available. Some loads were then adjusted to better represent the actual measured load for the timestamp under consideration, followed by minimal rescaling of other secondary substation loads to match the HV feeder currents.

The methodology used can be summarised as follows:

- Extract MDI data for ground mounted substations from SPEN SAP database
- Determine secondary substation loads based on common SPEN practice

- Refine loads to match the corresponding HV feeder currents (assuming a primary substation voltage of 1.01pu as used in SPD licence area)
- Use measured data from network monitoring implemented as part of Flexible Networks to refine substation loads
- Validate loading assumptions by comparison of calculated and measured circuit voltage profiles

2.1.2 Load Flow Analysis Methodology

Modelling to determine the optimum location of the AVR was carried out as follows:

- Run load flow studies with the network under intact conditions and backfed conditions for peak loading to determine extent of any voltage excursions and thermal loading.
- Model the AVR at different locations along the feeder and determine the optimum location which enables the maximum extent of backfeed, whilst keeping network voltages and thermal loadings within limits.

2.2 Input Data

2.2.1 Circuit Data

Conductor connectivity, length, type and sizes were exported from SPEN's UMV GIS. This export was performed in mid 2012 and the model therefore reflects the network's current state in 2012, which, for the purposes of these studies, is understood to be suitably reflective of the current network. The appropriate ratings were then determined from conductor data exported from the SPEN WinDEBUT cable database, given in Appendix A. Where rating information for a particular cable type was missing, this was supplemented with appropriate rating assumptions and in-house data. Table 2-1 gives critical circuit ratings along feeder 25 and 13 from St Andrews and feeder 12 from Anstruther in Poweron. These are replicated in the IPSA network model.

Table 2-1 Key circuit ratings

	Rating (A) St Andrews side	Rating (A) Anstruther side
Boarhills Soule	421	123
Crail Soule	421	421
Pinkerton Road GMS	130	130
St Andrews Primary Feeders	276 - 325	
Anstruther Primary Feeders		315 - 421

2.2.2 Transformer Data

Secondary transformer data including ratings was exported from SPEN GIS, and impedance data provided from SPEN SAP database where available (generally only for ground-mounted substations) was included.

Based on TNEI experience, pole mounted substations were assumed to have an impedance of 5% of the transformer rating.

2.2.3 Secondary Substation Loading

The loading of ground mounted and pole mounted secondary substations was estimated using a similar approach to current SPEN practise as follows:-

The initial load value for each secondary substation was arrived at as follows:

- For ground mounted substations, MDI data was used where available,
- For pole mounted substations, the initial load value was set to 35% of the transformer rating.

An initial value of 20% was originally proposed for pole mounted substations, as this is the approach that is widely used by SPEN in 11kV modelling, however when the load model was compared to measured data, 35% was shown to better match the measured voltage profile along the feeder. The load modelling validation and refinement approach is described further in Section 2.3.

The load at each secondary substation is then linearly scaled down until the overall modelled HV feeder loading matches the measured feeder loading for the particular timestamp being considered.

Measured load data (provided in 10 minute intervals and taken from the additional monitoring deployed as part of the Flexible Networks project) was used to verify modelled secondary substation loading. Monitors at secondary substations are located on all LV feeder phases. The total secondary substation LV load was calculated from the aggregated feeder loading.

<u>Note on Generation</u>

It was initially understood that no generation was connected to this circuit based on LTDS data but, in the course of the study, it has come to light that there is an embedded 500kW CHP generator at St Andrews Bay Hotel. Further details about the characteristics of the generator are provided in Appendix B. It has been assumed for modelling purposes that this generator would not export onto the network, as it is not permitted to do so under the terms of the connection agreement.

It should be noted, however, that further investigation of 12 months' worth of Settlement metering data for the St Andrews Bay Hotel has revealed that there were a total of 6 occasions over that year where there may have been some level of export from the Hotel. Although likely to be minimal, the exact level of export could not be quantified as there is no export meter fitted. These instances typically occurred during the early hours of the morning in winter and may coincide with periods of low hotel occupancy.

It is judged unlikely that this could lead to a situation where reverse power flow through the regulator due to generation export occurs as the periods of generation export over the year are very small (and, for a chance of reverse power flow through the AVR to occur, they would need to be concurrent with running in the backfeed arrangement). It is nevertheless recommended that discussions be held with the hotel to ensure that generation export does not take place in the future.

Based on this judgement, it is considered appropriate to operate the new regulator in the Bi-Directional Reverse Power Sensing mode (as opposed to the Cogeneration mode). Bi-directional must also be used in order to deliver the required outcomes of the Flexible Networks project.

2.2.4 HV Feeder Loading

The HV feeder loading for St Andrews and Anstruther for a particular timestamp was extracted from the iHost current data. This provides data in 10 min intervals. Voltage measured on the primary transformer busbars was available from iHost however, the recorded values were found to be erroneous and the source of the error is currently under investigation. In lieu of this, we have therefore used a HV voltage of 1.01pu or 11.1kV, which is typical of the voltage set point for primary transformers in the SPD licence area.

To determine both St Andrews and Anstruther feeder peak loading, iHost data and PI data for 2013-2014 was reviewed. iHost data has significantly more granularity than PI data, and so this was used once a comparison established good general correlation between PI data and iHost data at St Andrews.

From iHost data, the maximum cumulative loading for St Andrews feeder 25 and Anstruther feeder 12 and maximum loading on each feeder was extracted, along with timestamps (assuming a power factor of 0.98) and this is shown in Table 2-2 below.

Table 2-2 Maximum peak and cumulative feeder loading in 2013

St Andrews Feeder 25 Maximum	Anstruther Feeder 12 Maximum	Cumulative Feeder Maximum
5th Dec 2013 @ 16.30	25th Nov 2013 @ 17.30	5th Dec 2013 @ 16.30
3.27MW, 0.66MVar	1.55MW, 0.31MVar	3.27MW, 0.66MVar 1.24MW, 0.25MVar

It was inferred from review of the feeder current duration curves from PI data that the network was operating in intact conditions during each of the above time stamps.

The 5th December 16.30 timestamp was therefore selected for modelling as the peak combined loading of St Andrews feeder 25 and Anstruther feeder 12.

2.3 Load modelling validation

Validation of the load modelling assumptions was undertaken using iHost Data from measurement devices installed on secondary substations as part of the Flexible Networks project. Two timestamps were selected: 6th March & 9th March 18.30, both with good iHost data availability, and a tea time peak demand that is generally representative of high loading conditions.

A load flow was undertaken on the network model and the voltage profile down the feeder on both the 11kV and the LV side of each secondary transformer was recorded. This was then compared to the measured voltages on the LV side of each transformer at the same timestamp.

As the voltage on the LV side of the secondary substation is recorded for all three LV phases, the average measured LV voltage was calculated for comparison with the IPSA model. The measured LV phase voltage was found to vary between phases by up to 3% for the timestamps assessed so this assumption is deemed to be reasonable. Secondary substation voltage was not measured at 11kV.

Figure 2-1 shows the comparison between the modelled IPSA voltage profile at LV and 11kV and the measured LV voltages. There is some variation along the feeder, but in general the profile shape shows reasonable agreement and this provides confidence that the model loading assumptions are valid.

The secondary substation loading assumptions were refined by using measured load for monitored substations at the same timestamp. Voltage profile results are shown for comparison in Figure 2-1 and agree well with load modelling assumptions.

Possible reasons for deviation from measured voltage profile values were explored in detail. This provides wider learning about the usefulness of extensive secondary substation monitoring and how it can be used to improve network modelling. Prospective sources of divergence include:

- Primary substation voltage may not be at 11.1kV. As mentioned above, because the primary transformer voltage monitors are not providing sensible values, it is not possible to confirm this. However, a review of the PI data suggests that primary transformer voltage may vary between at least 10.5kV to 11.5kV (depending on the primary transformer tap setting) although the voltage set point is 11.1kV. The modelled voltage profile is shown for the case in which the primary substation voltage is 11.0kV in Figure 2-2. This indicates that a lower modelled primary voltage would improve agreement with measured voltage profiles trends.
- Many secondary substations (pole-mounted and ground-mounted) are not monitored with Gridkey or Subnet iHost monitors installed as part of the Flexible Networks project. Assumptions are therefore made for these

loads however actual experienced loads are likely to vary from assumed loads at any measurement timestamp. This is confirmed by comparison of modelled loads, based on the assumptions described in Section 2.2.3, to measured loads from secondary substations monitored as part of the Flexible Networks project (although loads are broadly comparable). Also, any intermittent point loads (such as large pumps at waste water treatment works) that are not monitored, or which are monitored but operate intermittently at a frequency greater than the measurement resolution, may also introduce discrepancies. These will produce corresponding deviations when comparing modelled LV voltages to measured voltages.

- Secondary transformer (11/0.415kV) tap settings may not be set to nominal.
- Calibration of monitors may be incorrect.
- The voltage recorded by the GridKey device at Harbour Pumping Station is higher than that at the primary substation; this is likely to be indicative of an error in the monitoring equipment due to the proximity of Harbour Pumping Station to the primary.

Aside from the CHP generator at the St Andrews Bay Hotel, there is no other generation thought to be connected to feeder 25 so this should not be a cause of the observed voltage discrepancies (although, of course, this might not always be the case generically).

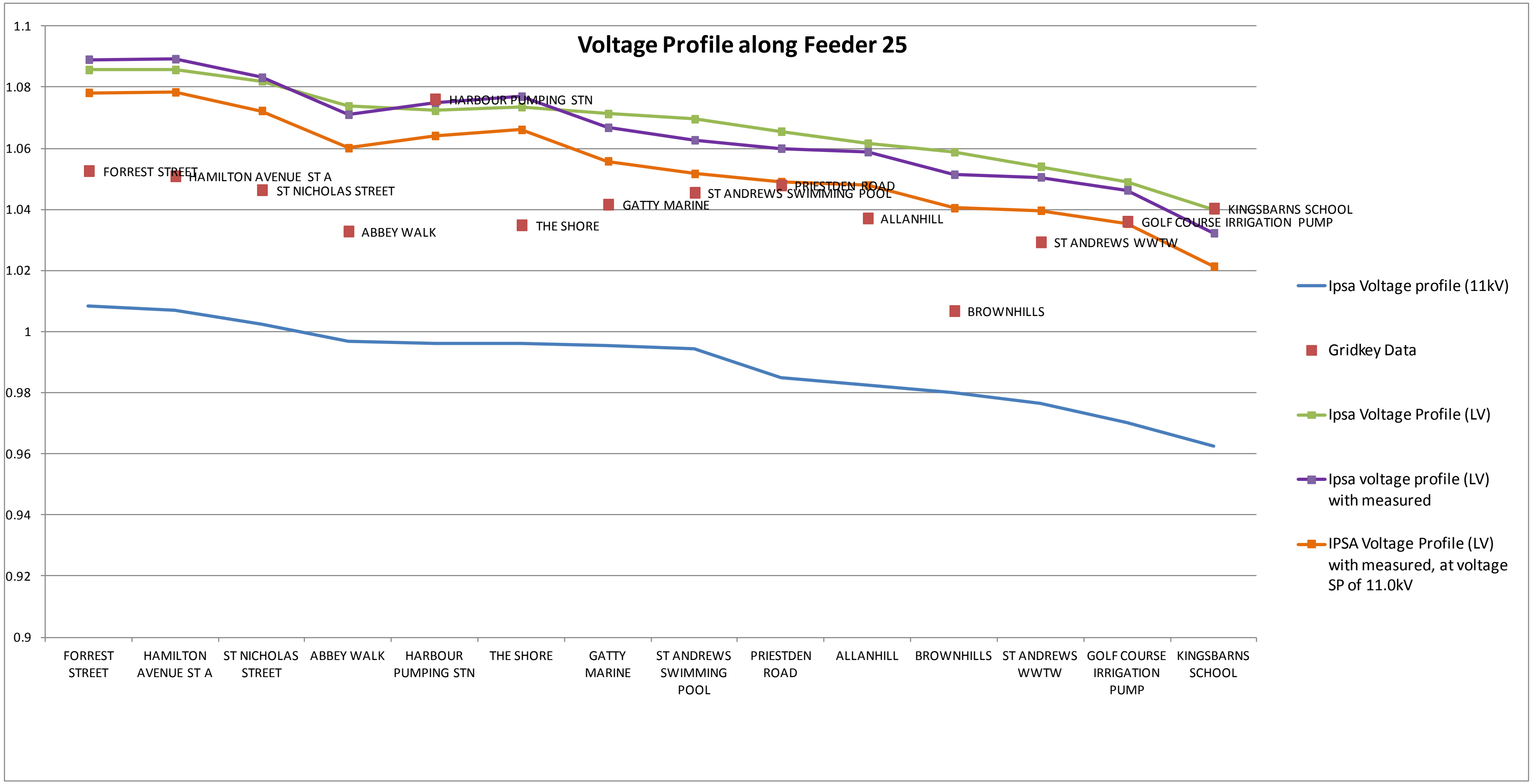


Figure 2-1 Voltage Profile along St Andrews Feeder 25 on 6th March 18.30 - comparison between modelled results and network monitoring

2.3.1 Load at St Andrews Bay Hotel

The St Andrews Bay Hotel is connected directly to the 11kV network. There is an onsite HV/LV transformer. There are no other 11kV loads on St Andrews Feeder 25 and Anstruther Feeder 12.

There were some problems with obtaining data from the installed Gridkey monitoring equipment at St Andrews Bay Hotel. In lieu of this, SPEN has provided access to half hourly Settlement Metering data for the Bay Hotel, which shows that the maximum winter (November to February) loading of the Bay Hotel is 791kW, 232kVAr (import). This occurs around 1pm on the 12th of February 2013.

The maximum teatime winter loading is 737kW, 192kVAr (import) around 6pm on the 26th of February 2013. This was modelled with the AVR to confirm voltage compliance and that the AVR rating was not exceeded for loading conditions at this timestamp.

For network loading validation studies, a load of 452kW, 96.9kVar was used as this is representative of typical March load around the timestamps considered (settlement metering data for March 2014 was not available at the time of analysis). At the time of peak loading for feeder 25, the settlement metering data indicates a hotel load of approximately 160kW, 14kVar.

It is important to understand the peak loading of St Andrews Bay hotel for optimal AVR siting as this is the most significant load along Feeder 25 and where undervoltage issues have been experienced and reported during backfeeding from Anstruther.

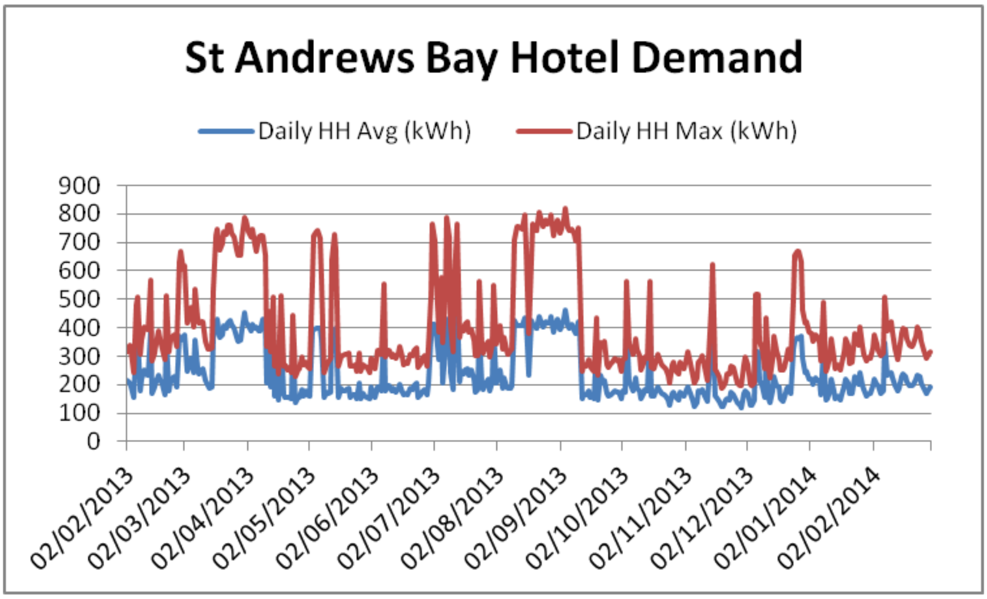


Figure 2-2 Annual demand profile for St Andrews Bay Hotel Feb 2013 – Feb 2014

2.4 AVR Data and Modelling Approach

2.4.1 AVR Specifications

The AVR purchased by SPEN for installation in the St Andrews HV network is a Cooper Power System VR32 200A 3-phase (3 tank) automatic voltage regulator (AVR). The AVR is of IEEE Standard C57.15 : 2009 Type B, which is the most common AVR type used for pole mounting.

2.4.2 AVR Model

In these studies the voltage regulator has been modelled as a simple transformer with impedance properties as given in Table 2-3. This data, further details of which may be found in Appendix C, was provided by SPEN. The AVR load bushing target voltage was set to a maximum of 1.05pu in order to keep all HV busbars within statutory voltage limits. The tap setting was not constrained to match the discrete percentage steps provided by the physical AVR device. No regulator Line Drop Compensation (LDC) settings were applied.

It has been assumed that the AVR is connected with the source (S) bushing towards Anstruther and the load (L) bushing towards St Andrews and that it will be configured to operate in the Bi-Directional Reverse Power Sensing mode in accordance with current SPEN policy as defined in ESDD-02-008 Issue 2.

The impedance of the AVR varies across the tapping range (see plot in Appendix C for a Type B AVR) but, for modelling purposes, we have conservatively assumed a constant impedance equivalent to the maximum impedance, which occurs at the greatest extent of the tapping range (+/-16 steps). AVR losses will be assessed in more detail as part of a PNDC testing programme for Flexible Networks.

AVR losses would reduce if the impedance of the AVR was modelled to vary across the tapping range (see Appendix B, Figure B-1) and thus the AVR would demonstrate slightly improved performance in terms voltage uplift along the feeder. This applies to both Type A and Type B AVRs. The AVR type would need to be considered if this dependency was to be modelled in detail as Type A and B AVRs have slightly different impedance characteristics across the tapping range.

Each single phase voltage regulator tank provides approximately 10% automatic adjustment of the phase voltage which, for a three-tank, closed-delta configuration, as is to be used for St Andrews, is equivalent to 15% regulation range on the line to line voltage on the unregulated supply on the source bushing of the voltage regulator. For a 3 tank device, this is equivalent to individual tap steps of almost 1%, with sixteen steps above and sixteen steps below rated voltage (from IEEE Standard Requirements, Terminology, and Test Code for Step-Voltage Regulators) IEEE Std C57.15™-2009.

As part of the wider Flexible Networks project, monitoring data obtained from AVR deployment and testing will be used to validate a customised AVR power systems model in IPSA as well as to refine the modelling approach, as part of the Flexible Networks project.

Table 2-3 AVR Technical Specifications

Parameter	*Value*
Rated Voltage (V)	11,000
Rated Load Current (A)	200
% Z1	0.6
% X1	0.58
% R1	0.18
% Z0	0.62
% X0	0.59
% R0	0.19
Base MVA	3.8

Table 2-4 AVR Tapping Specifications

Parameter	*Value*
Minimum	-10% (Phase Voltage) -15% (Line Voltage)
Maximum	10% (Phase Voltage) 15% (Line Voltage)
Tap step	0.9375%

2.5 Load Flow Test Cases

2.5.1 Base Case Load Flows

Two "Base Case" scenarios were considered to evaluate the existing performance of the network:

- Base Case Intact. Feeder 25 is supplied by St Andrews, Feeder 12 is supplied by Anstruther. Main feeder NOP at Crail Soule, other NOPs in parallel feeds at Boarhills Soule and Pinkerton Road GMS.

- Base Case backfeed. Feeder 25 is backfed from Anstruther to a revised normally open point at Grange NOJA.

The voltage profile was calculated along St Andrews feeder 25 and Anstruther feeder 12 to the circuit NOPs to check that the feeder voltage remained within statutory limits. Thermal limits of circuits were checked to ensure that they are not exceeded at any point.

2.5.2 'Test Cases' with an AVR

Under the backfed scenario, the voltage along feeder 25 is known to drop below statutory limits under high loading conditions and so a voltage regulator (AVR) is proposed to mitigate this problem.

Three further test scenarios were derived to determine where the AVR should be located and how far back towards St Andrews primary substation load can be supported, via the AVR, without voltages falling below statutory limits (or exceeding them on the network immediately adjacent to the regulator). Each test case represents a possible flexible backfeed configuration, using existing network controllable points, supplemented with two additional network controllable points at Harbour Pumping Station and Links No. 7 Sheds GMS:

1. Test Case 1 – Feeder 25 backfed from Anstruther to St Andrews primary substation
2. Test Case 2 – Feeder 25 backfed from Anstruther to Links No. 7 Sheds GMS
3. Test Case 3 – Feeder 25 backfed from Anstruther to Harbour Pumping Station GMS

As a minimum consistent with the original project objectives, these studies should demonstrate that the addition of the AVR will allow load up to at least Grange NOJA to be supported from Anstruther feeder 12.

2.5.3 Note on Voltage Dependency of Network Loads

Within this study, as per typical SPEN network assessment and in accordance with normal DNO modelling practice, all loads have been modelled as having constant power consumption, independent of their terminal voltage (as opposed to fixed impedance loads, which have a linear load-voltage dependency)[2]. Whilst this does not fall directly within the scope of this assessment, it is noted that in studying the impact of AVR technology, the assumption that all loads are constant power (P, Q) is, to a degree, optimistic as the model does not predict the actual increased current on the source side of the AVR resulting from the increased load terminal voltage delivered by the AVR, which would be seen using fixed impedance load modelling.

[2] The impact of different load types connected to the network is currently being investigated by several distribution network innovation projects, such as the LCNF Tier 2 CLASS and Smart Street projects, by Electricity North West

Network modellers should therefore be alert to this and make an appropriate allowance of sufficient thermal headroom on the AVR to ensure that some voltage dependency of loads would not cause the rating of the AVR to be exceeded.

3 Results

The following cases were considered for assessment of the optimal positioning of an AVR along feeder 25.

Table 3-1 Base Case and Test Case Definitions

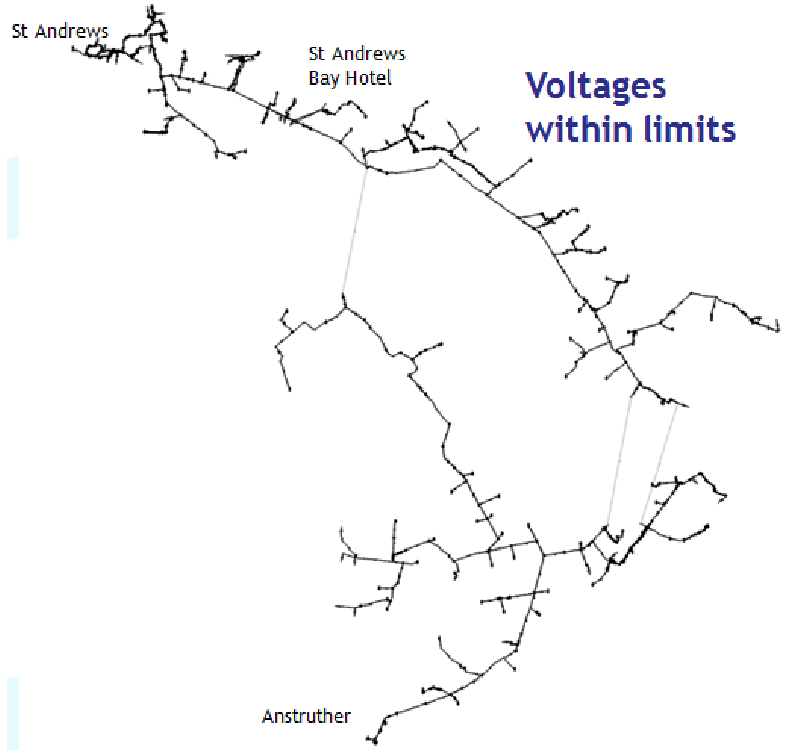
Case	Configuration	Comments
Base Case 1 – Intact	Feeder 25 supplied by St Andrews, feeder 12 supplied by Anstruther	
Base Case 1 – Backfeed	Feeder 25 backfed from Anstruther to Grange NOJA	
Base Case 2 – Intact	Feeder 13 and part of feeder 25 supplied by St Andrews, feeder 12 supplied by Anstruther	Alternative Configuration
Base Case 2 – Backfeed	Feeder 25 backfed from Anstruther to Grange NOJA	Same as Base Case 1
Test Cases Without an AVR		
Test Case 1 – Backfeed ALL feeder 25	All feeder 25 backfed from Anstruther	
Test Case 2 – Backfeed feeder 25 to Links No. 7 Sheds GMS	Feeder 25 backfed from Anstruther to Links No. 7 Sheds GMS	
Test Case 3 – Backfeed feeder 25 to Harbour Pumping Station GMS	Feeder 25 backfed from Anstruther to Harbour Pumping Station GMS	
Test Cases With an AVR		
Test Case 1 – Backfeed to Grange NOJA from Anstruther with AVR	Feeder 25 backfed from Anstruther to Grange NOJA	AVR at Cambo Lodge
Test Case 2 – Backfeed ALL feeder 25 with AVR	Feeder 25 backfed from Anstruther to St Andrews primary	AVR on main line near Troustrie ABSW
Test Case 3 – Backfeed ALL feeder 25 with AVR	Feeder 25 backfed from Anstruther to St Andrews primary	Alternative Configuration AVR at Sypsies ABSW
Test Case 4 - Backfeed feeder 25 to Harbour Pumping Station GMS with AVR	Feeder 25 backfed from Anstruther to Harbour Pumping Station GMS	AVR at Crail Soule

Base Cases

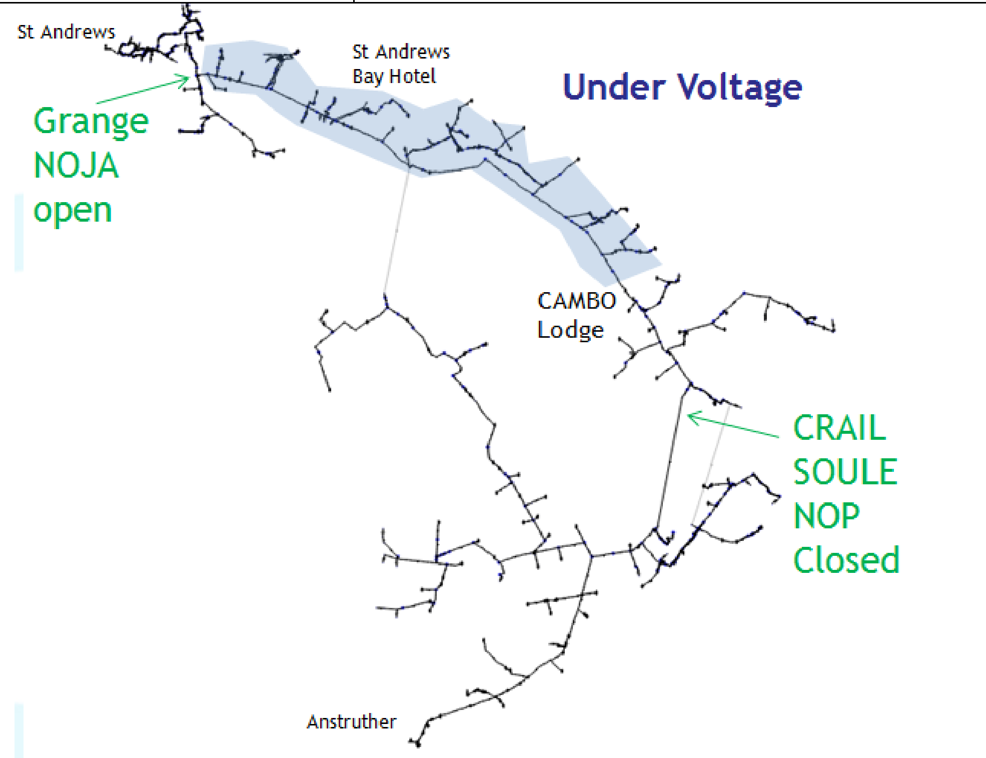
Table 3-2 shows the two base cases considered, under intact and back fed conditions. For each case, a load flow study was undertaken and the active power and reactive power at each primary substation have been recorded. For Base Case 1 Intact, the loads at St Andrews and Anstruther match the iHost data for the corresponding timestamp of 05/12/2013 16.30. Results are based on the validated load models and a load of 500kW, 150kVar at St Andrews Bay Hotel to capture more onerous high loading conditions towards the end of feeder 25. This compares well with results using monitored secondary substation loads and the St Andrews Bay Hotel load from this timestamp.

Table 3-2 Base Case Results

1. Base Case 1 - Intact	
Description:	Feeder 25 supplied by St Andrews, feeder 12 supplied by Anstruther
NOPs:	Crail Soule Boarhills Soule Pinkerton Road GMS
Load at St Andrews (feeder 25):	3.27MW, 0.66MVAr, 3.336MVA
Load at Anstruther (feeder 12):	1.24MW, 0.25MVAr, 1.265MVA
Max Current (A) at St Andrews Feeder 25 C/B	170A
Max Current (A) at Anstruther Feeder 12 C/B	67A



2. Base Case 1 - Backfeed	
Description:	Feeder 25 backfed from Anstruther to Grange NOJA
NOPs:	Grange NOJA Boarhills Soule Pinkerton Road GMS
Load at St Andrews:	1.03MW, 0.16MVar, 1.042MVA
Load at Anstruther:	3.53MW, 0.94 MVAr, 3.653MVA
Max Current (A) at St Andrews Feeder 25 C/B	54A
Max Current (A) at Anstruther Feeder 12 C/B	192A (including backfeed load)



The shaded area of the diagram indicates where an out-of-statutory limits voltage condition exists.

The results show, as expected, that under the base case backfeed arrangement, the voltage along feeder 25 falls below statutory voltage limits. A voltage regulator is therefore required somewhere in the region of Cambo Lodge to resolve these undervoltages. Section 3.2 presents the results of three backfeed scenarios and the optimum AVR location for each of these cases.

3.1.1 Alternative Circuit Configuration

The intact base case results above demonstrate that there are some substantial voltage constraints when backfeeding from Anstruther along feeder 25 to St Andrews primary.

At the request of SPEN, an alternative circuit configuration at the St Andrews end of feeder 25 has been considered to reduce magnitude and extent of the voltage constraints. By moving the normally open point at Priestden Road, it is possible to disconnect the St Andrews end of feeder 25 and instead connect the more lightly-loaded feeder 13. This change in configuration is show in Figure 3-1.

TNEI was requested to model this option as part of the AVR test cases.

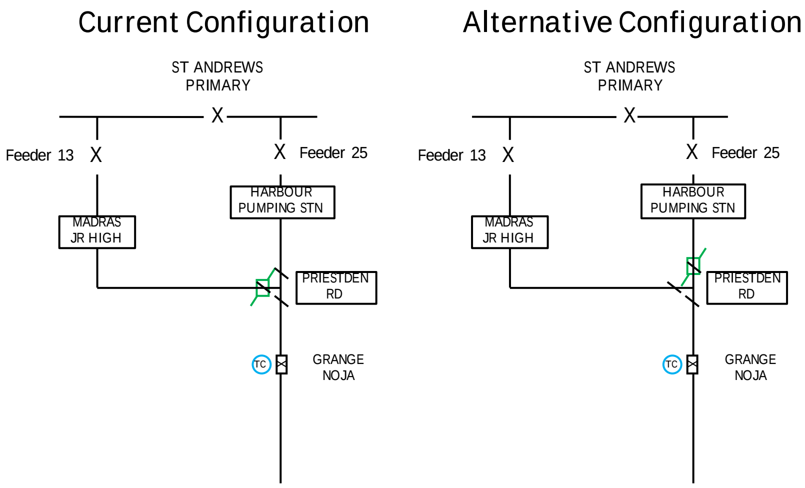


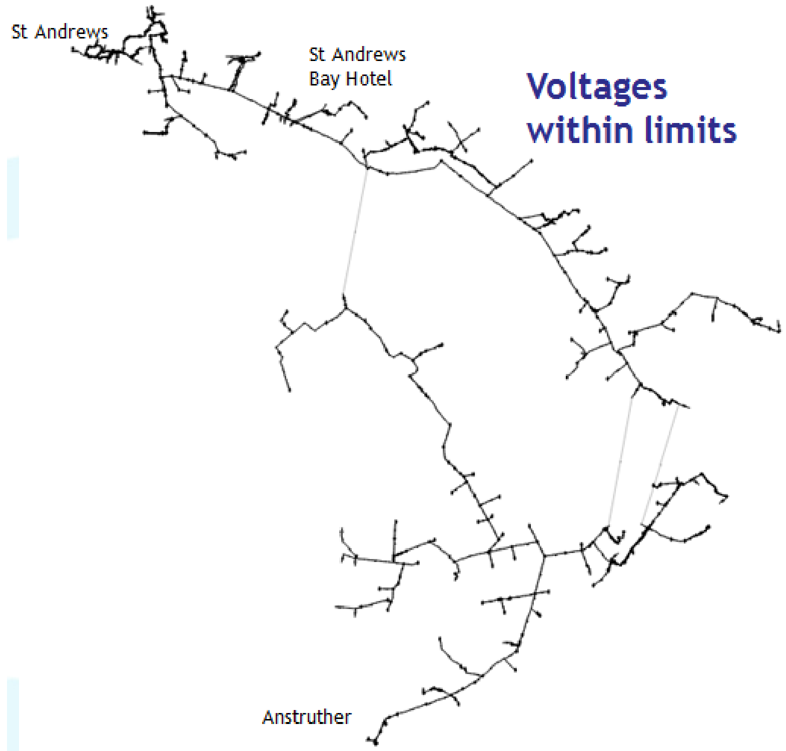
Figure 3-1 Alternative Feeder 13 Circuit Configuration at St Andrews

Table 3-3 shows the intact and backfeed base cases considered, with the alternative feeder 13 circuit configuration at St Andrews. The interconnecting circuit load (maximum current at C/B 13) at St Andrews primary is significantly reduced under intact conditions. It should be noted that, from an Anstruther loading perspective, the Base Case 1 and Base Case 2 backfeed running arrangements are, by definition, the same (i.e. the same amount of additional backfeed load is picked up in both cases).

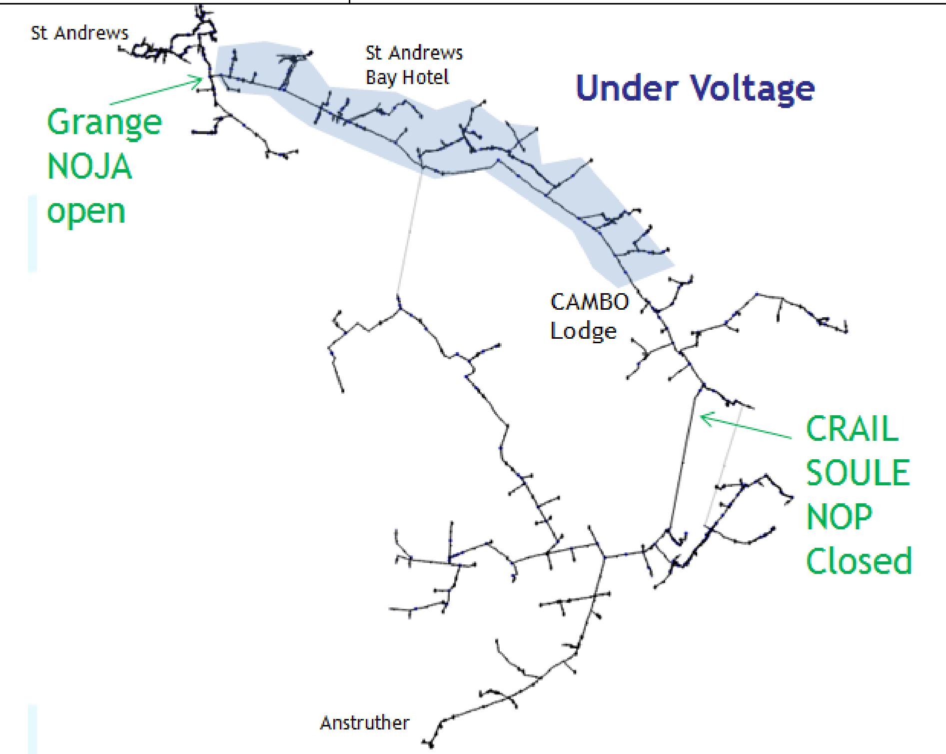
By reducing the load on the St Andrews end of the feeder by such a reconfiguration, in backfeed conditions where the feeder load is picked up as far as St Andrews Primary, the undervoltages should not extend as far towards Anstruther as they do for the current running arrangement.

Table 3-3 Base Case Results – Alternative Circuit Configuration

3. Base Case 2 – Intact	
Description:	Feeder 13 and part feeder 25 supplied by St Andrews, feeder 12 supplied by Anstruther
NOPs:	Crail Soule Boarhills Soule Pinkerton Road GMS
Load at St Andrews (feeder 13 and part feeder 25):	2.79MW, 0.68MVar, 2.872MVA
Load at Anstruther (feeder 12):	1.24MW, 0.25MVar, 1.265MVA
Max Current (A) at St Andrews Feeder 13 C/B	149A
Max Current (A) at Anstruther Feeder 12 C/B	67A



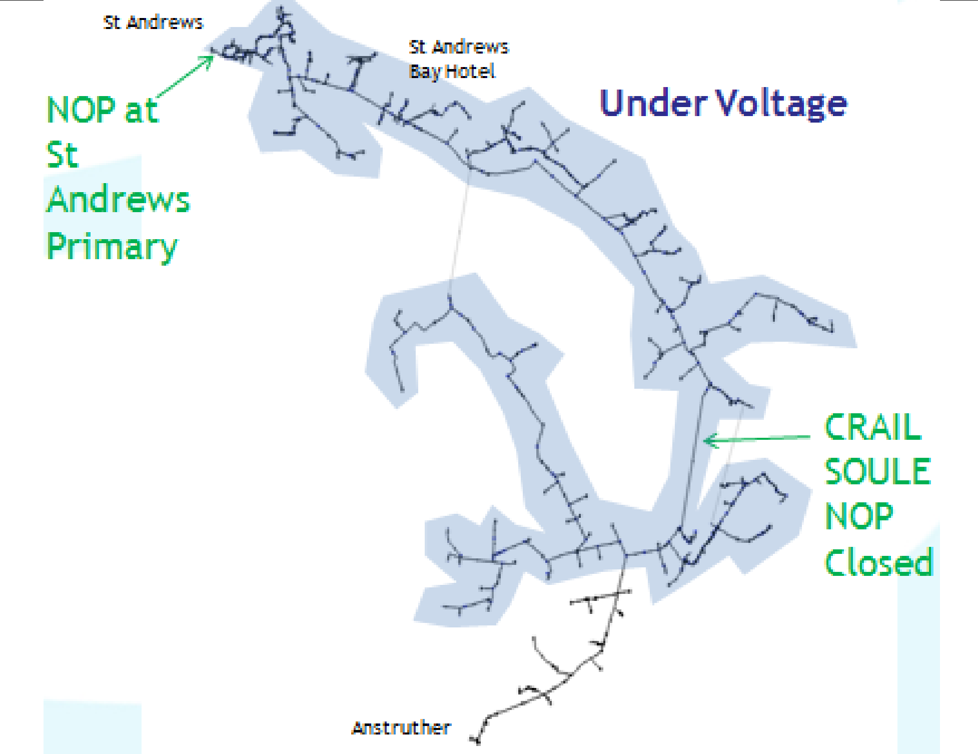
4. Base Case 2 – Backfeed	
Description:	Feeder 25 backfed from Anstruther to Grange NOJA
NOPs:	Grange NOJA Boarhills Soule Pinkerton Road GMS
Load at St Andrews:	0.903MW, 0.138MVar, 0.913MVA
Load at Anstruther:	3.53MW, 0.94MW, 3.653MVA
Max Current (A) at St Andrews Feeder 13 C/B	33A
Max Current (A) at Anstruther Feeder 12 C/B	192A (including backfeed load)



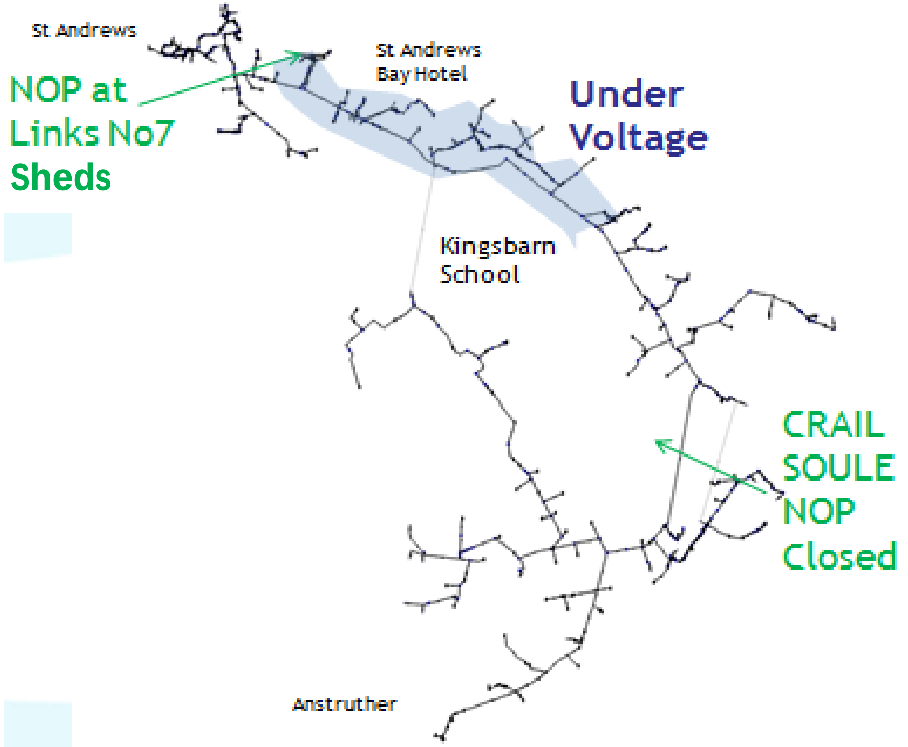
3.2 Test Cases without an AVR

The figures below show the extent of undervoltage in each of the backfeed test cases considered, without an AVR.

1. Test Case 1 - Backfeed ALL feeder 25	
Description:	All feeder 25 backfed from Anstruther
NOPs:	St Andrews primary (feeder 25) Boarhills Soule Pinkerton Road GMS
Voltage excursions:	St Andrews primary to near Troustrie ABSW, on main line (Anstruther feeder 12)
Voltage at NOP:	**V = 0.824pu (also undervoltages occur on spur sections)**



2. Test Case 2 - Backfeed feeder 25 to Links No. 7 Sheds GMS	
Description:	Feeder 25 backfed from Anstruther to Links No. 7 Sheds GMS
NOPs:	Links No. 7 Sheds GMS Boarhills Soule Pinkerton Road GMS
Voltage excursions:	Links No. 7 Sheds – Kingsbarns School
Voltage at NOP:	**V = 0.940pu (also undervoltages occur on spur sections)**



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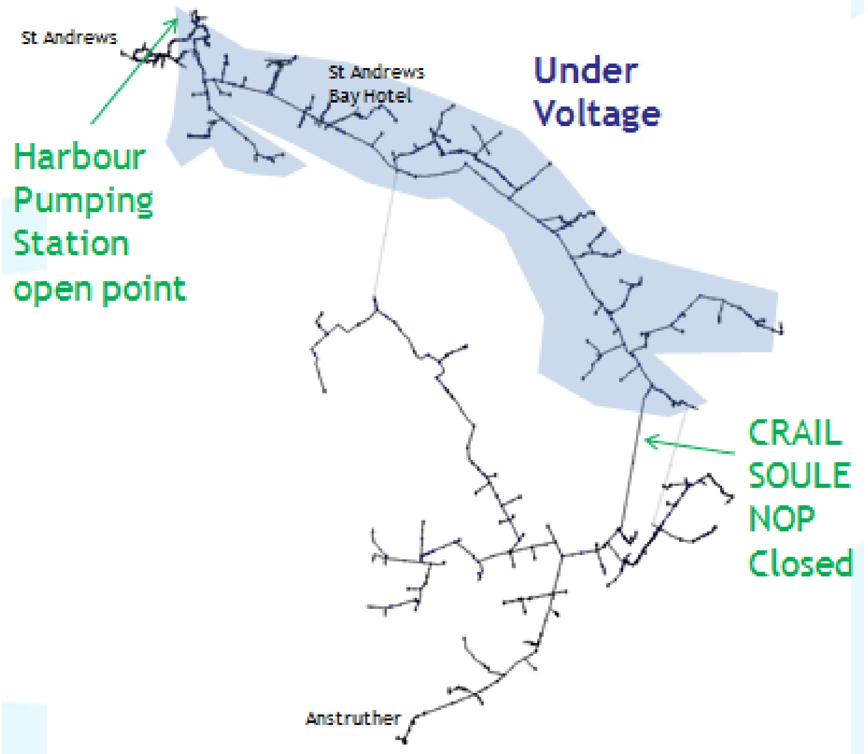
3. Test Case 3 - Backfeed feeder 25 to Harbour Pumping Station GMS	
Description:	Feeder 25 backfed from Anstruther to Harbour Pumping Station GMS
NOPs:	Harbour Pumping Station GMS Boarhills Soule Pinkerton Road GMS
Voltage excursions:	Harbour Pumping Station – Crail Soule
Voltage at NOP:	**V = 0.881 pu**



3.3 Test Cases with AVR

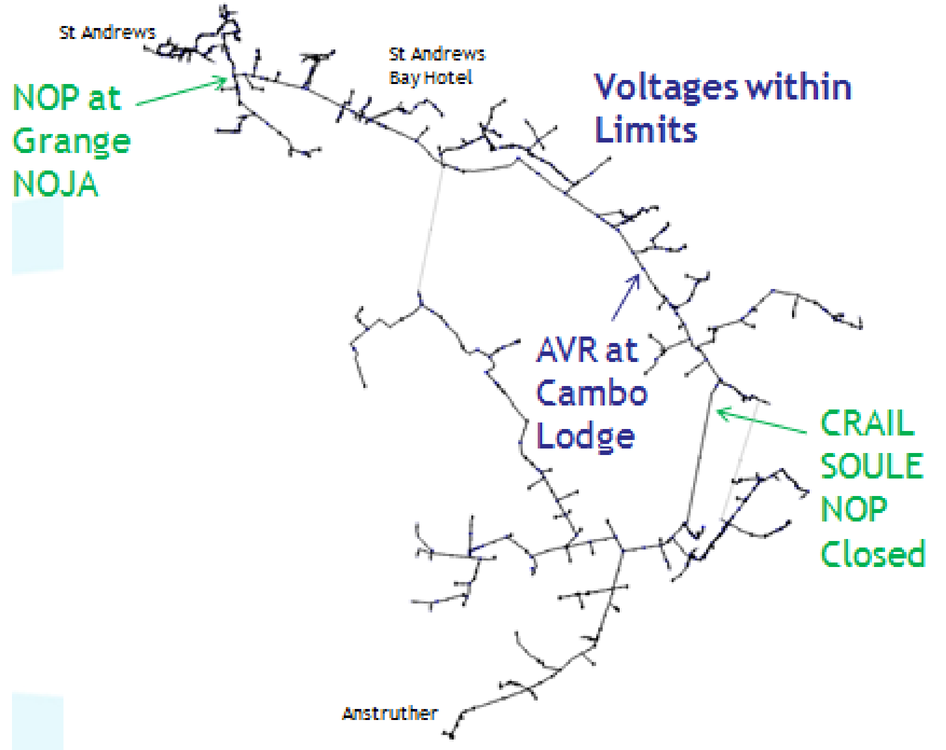
3.3.1 Summary of Potential AVR Locations

1. Cambo Lodge (feeder 25, in range from pole 88 – 127)
2. On main line near Troustrie ABSW (Anstruther feeder 12, in vicinity of pole 68, on the Anstruther side of the Troustrie spur)
3. Sypsies ABSW (Anstruther Feeder 12 pole 78 -81)
4. Crail Soule (St Andrews feeder 25 Pole 88 – 90)

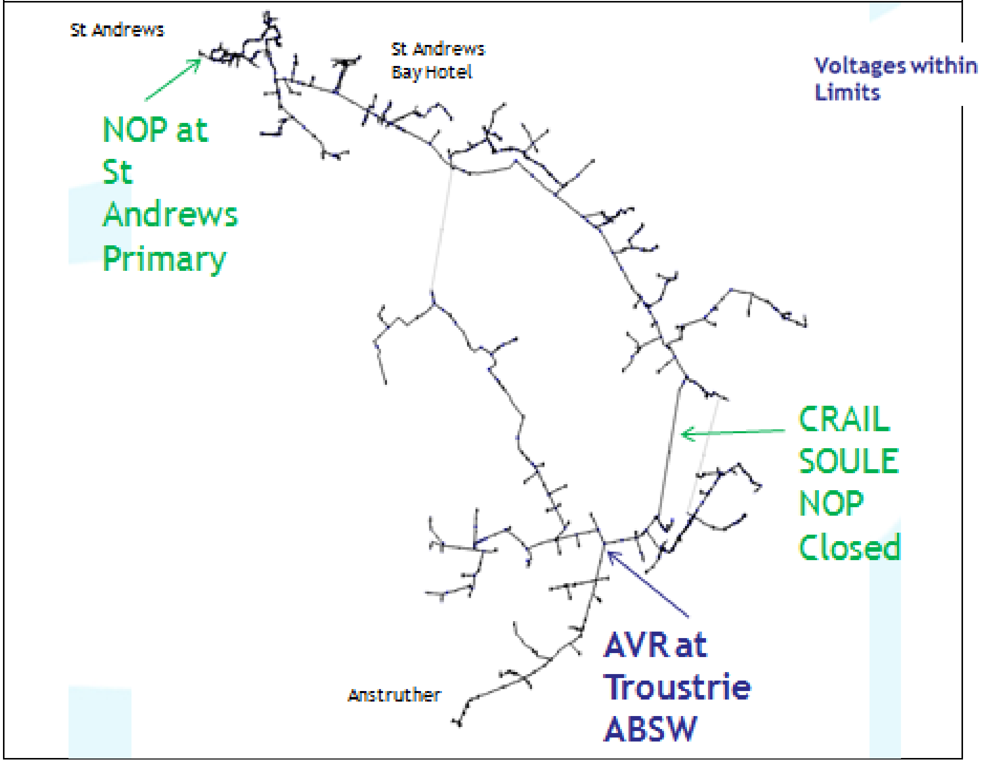
The results from the analysis of these configurations are shown below and summarised in table 3-4.

3.3.2 Results

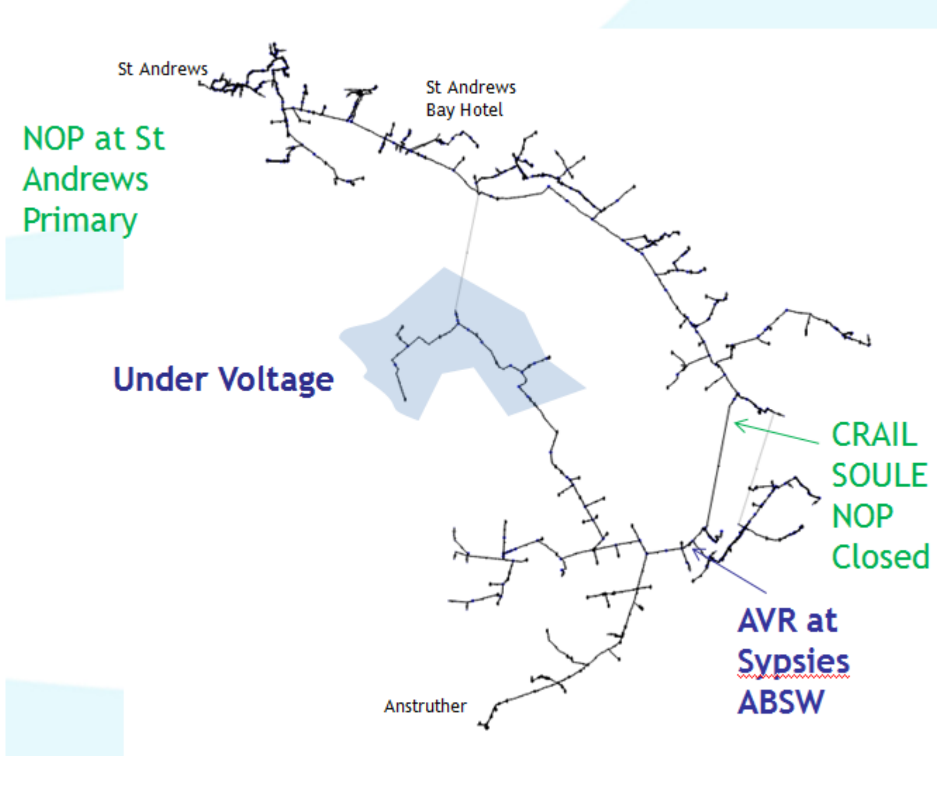
1. Test Case 1 - Backfeed to Grange from Anstruther with AVR	
Description:	Feeder 25 backfed from Anstruther to Grange NOJA
NOPs:	Grange NOJA Boarhills Soule Pinkerton Road GMS
AVR Location	Cambo Lodge
AVR Tap Ratio	4.05%
AVR Loading	102 Amps
Possible operating scenario	



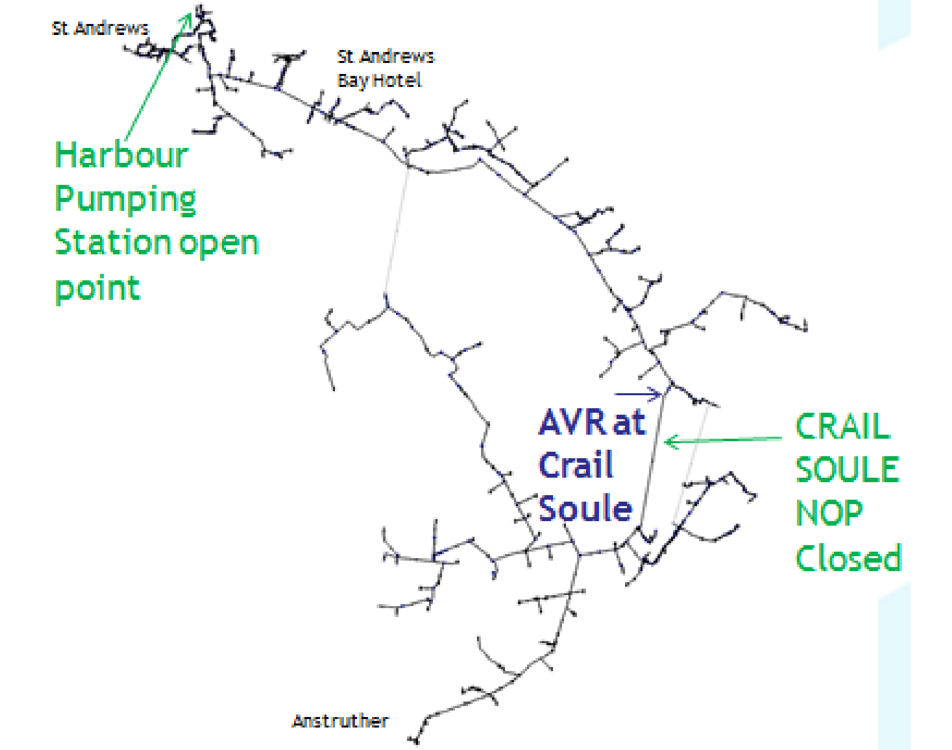
2. Test Case 2 - Backfeed ALL feeder 25 with AVR	
Description:	All Feeder 25 backfed from Anstruther
NOPs:	St Andrews primary (feeder 25) Boarhills Soule Pinkerton Road GMS
AVR Location	On main line near Troustrie ABSW (feeder 12, in vicinity of pole 68, on the Anstruther side of the Troustrie spur)
AVR Tap Ratio	11.25%
AVR Loading	**240 Amps - AVR overloaded**
AVR Overloaded (no benefit taken of "ADD-AMP" feature). Not a viable operating scenario	



3. Test Case 3 – Backfeed ALL feeder 25 *with alternative Feeder 13 Circuit Configuration at St Andrews* with AVR	
Description:	Feeder 25 backfed from Anstruther to St Andrews Primary
NOPs:	St Andrews Primary Boarhills Soule Pinkerton Road GMS
AVR Location	Sypsies ABSW
AVR Tap Ratio	11.25%
AVR Loading	188 Amps
A few branches on Anstruther feeder 12 have voltage excursions slightly below statutory limits	



4. Test Case 4 - Backfeed feeder 25 to Harbour Pumping Station GMS with AVR	
Description:	Feeder 25 backfed from Anstruther to Harbour Pumping Station
NOPs:	Harbour Pumping Station Boarhills Soule Pinkerton Road GMS
AVR Location	Crail Soule
AVR Tap Ratio	7.4%
AVR Loading	144 Amps
Possible operating scenario	



3.4 Assessment of Results

Table 3-4 shows how much of feeder 25 can be backfed from Anstruther whilst maintaining the feeder within statutory voltage limits. Two scenarios are considered; the current circuit configuration along feeder 25 and the alternative feeder 13 circuit configuration. The voltage immediately next to the load bushing of the AVR remains within statutory limits for the test cases analysed.

To facilitate the assessment of the demand reduction and capacity headroom increase from the proposed load transfer and AVR deployment, Table 3-5 gives the calculated feeder loading adjacent to primary substation circuit breakers for St Andrews feeder 25 and Anstruther feeder 12 for the current configuration whilst Table 3-6 provides the feeder loadings for the alternative (St Andrews feeder 13) running arrangement.

Table 3-4 Comparison of AVR Locations

Approximate AVR Location	**Limit of Backfeed from Anstruther feeder 12**	
	Along Feeder 25	With alternative Feeder 13 Circuit Configuration
1. Cambo Lodge (Pole 125)	Grange NOJA	Grange NOJA
2. On main line near Troustrie ABSW	Grange NOJA	St Andrews Primary
3. Sypsies ABSW	Grange NOJA	St Andrews Primary
4. Crail Soule	Harbour Pumping St.	Madras Junior High

Table 3-5 Load results for AVR Locations in Current Feeder 25 Circuit Configuration

Approximate AVR Location	NOP	St Andrews feeder 25 load (MVA)	Anstruther feeder 12 load (MVA)
1. Cambo Lodge (Pole 125)	Grange NOJA	1.039	3.666
2. On main line near Troustrie ABSW	Grange NOJA	1.039	3.663
3. Sypsies ABSW	Grange NOJA	1.039	3.652
4. Crail Soule	Harbour Pumping St.	0.569	4.269

Table 3-6 Load results for AVR Locations in Alternative Feeder 13 Circuit Configuration

Approximate AVR Location	NOP	St Andrews feeder 13 load (MVA)	Anstruther feeder 12 load (MVA)
1. Cambo Lodge (Pole 125)	Grange NOJA	0.642	3.667
2. On main line near Troustrie ABSW	St Andrews Primary	0	4.491
3. Sypsies ABSW	St Andrews Primary	0	4.479
4. Crail Soule	Madras Junior High	0.295	4.114

3.4.1 Current Feeder 25 Circuit Configuration

From a voltage compliance perspective, it can be seen that along feeder 25, under the current configuration, the furthest backfeed that can be achieved is to Harbour Pumping station. This is achieved by locating the AVR adjacent to Crail Soule.

The recommendation of this study is therefore that, if the configuration of feeder 25 remains unchanged, the AVR should be located as close to Crail Soule as possible (between pole 88 – 90) to allow the maximum load transfer from St Andrews to Anstruther.

3.4.2 Alternative Feeder 13 Circuit Configuration at St Andrews

As seen from Table 3-4, an AVR at Sypsies ABSW would allow the entire feeder to be supplied from Anstruther if the alternative feeder 13 circuit configuration at St Andrews is adopted. For this configuration, the AVR should be located adjacent to Sypsies ABSW, between pole 78 and pole 81 on Anstruther feeder 12.

This has obvious operational advantages as, in the event of a first circuit outage at St Andrews, it would allow the full load along feeder 13 and part of feeder 25 to be supplied. However, it locates the AVR outside the St Andrews trial flexible network control scheme and therefore does not allow SPEN to fully achieve the FNC trial objectives.

3.4.3 Implications of Subsequent Network Change

It is important to recognise that the foregoing analysis relates to the St Andrews and Anstruther circuits as they are currently configured. If additional load or generation is connected to these specific feeders or networks then as part of normal network development activity, the operational characteristics of the AVR must be borne in mind when the network is being reassessed for the suitability of connection of new customers.

Specifically, there will be implications for AVR configuration and operation if generation is subsequently installed between Sypsies ABSW and Crail Soule (or indeed, at a point beyond Crail Soule under backfeed running conditions) if that generation leads to reverse power flow through the regulator. In that scenario, current SPEN policy requires that the AVR is operated only in Co-generation Reverse Power sensing mode, which might not be an appropriate setting for those customers on the Anstruther side of the AVR under normal running conditions. This issue could potentially be addressed through the remote (or automatic) change of the regulator reverse power sensing mode but this degree of complexity goes beyond the scope of the current project.

It does, however, underline the importance of undertaking a thorough reassessment of the network when conditions change, particularly those parts of the network where AVRs have been installed.

4 Conclusions

4.1 AVR Location

The results indicate that, for the present operating arrangement, where feeder 12 at Anstruther interconnects to feeder 25 at St Andrews, installation of the AVR on feeder 25 downstream (i.e. on the Anstruther side) of Cambo Lodge, between pole 125 and pole 87 (as shown below in figure 4.1) would permit feeder 25 to be backfed from Anstruther, via Crail Soule, as far as Grange NOJA.

In order to increase the extent of the backfeed of St Andrews feeder 25 as far as Harbour Pumping Station GMS then the AVR must be located immediately adjacent to the existing Crail Soule (pole 87) on the St Andrews side.

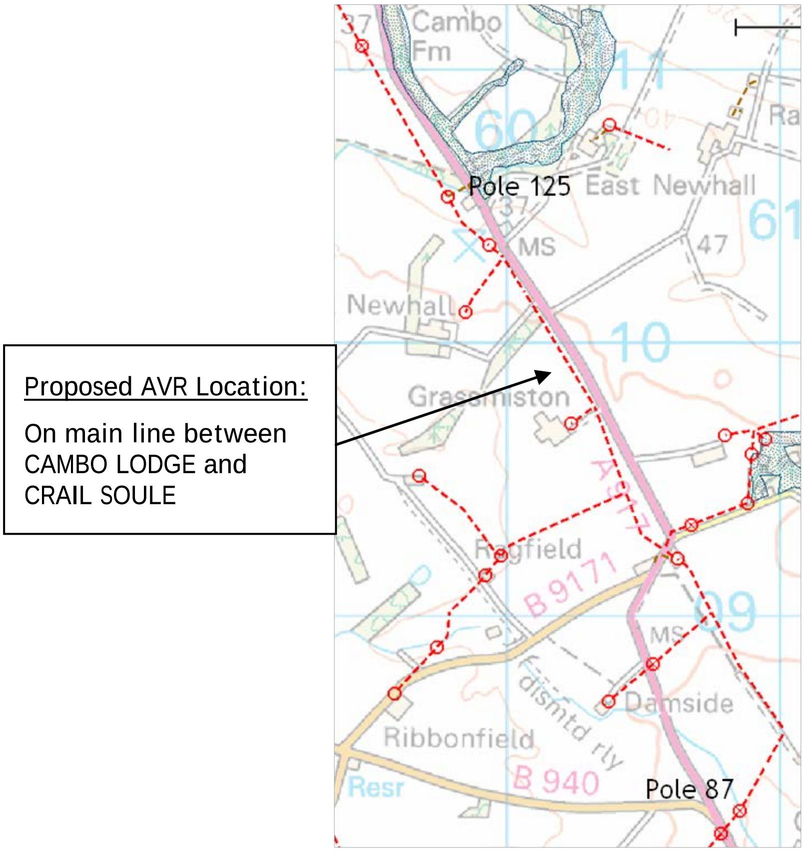


Figure 4-1 – Proposed AVR location

It is not possible to locate the AVR such that the whole of feeder 25 can be backfed from Anstruther, without overloading the AVR at times of peak loading.

4.1.1 Alternative Feeder 13 Circuit Configuration at St Andrews

If the alternative feeder 13 circuit configuration is adopted at St Andrews then the AVR could be located further along the main interconnecting circuit towards Anstruther at Sypsies ABSW, between pole 78 and pole 81 on feeder 12, as this will enable the whole of the circuit up to St Andrews primary substation via feeder 13 to be backfed from Anstruther. This would, however, result in a configuration where the AVR is not located within the St Andrews trial flexible network control scheme. As a consequence, although, it may be possible to release marginally more capacity headroom with the AVR in this location, the reconfiguration of the network resulting from a dynamic change of NOP would not result in a change in the direction of current flow through the regulator and, in consequence, would not provide a demonstration of the generic FNC arrangement which this project is seeking to assess (i.e. the requirement to include, as part of the FNC logic, the sequenced control of the AVR to take it out of auto control and tap it to neutral, prior to the reconfiguration of the network).

For the purposes of delivering the objectives of the Flexible Networks project, it is therefore recommended that the AVR is installed between poles 125 and 87, as close as is possible to the Crail Soule.

This does not preclude the running arrangement for the St Andrews to Anstruther circuit from being amended, such that feeder 13 at St Andrews, rather than feeder 25, is connected to Anstruther feeder 12. Neither does this preclude the AVR from being relocated at a later time should this be felt operationally beneficial.

4.2 Additional Capacity Headroom

The demand capacity headroom improvement from deployment of the AVR on feeder 25 is based on n-1 contingency conditions (first circuit outage), consistent with the application of P2/6. St Andrews HV network firm capacity is 21MVA based on a single transformer outage[3]. The firm capacity of Anstruther HV network based on a single transformer outage is 10MVA[3], (however in conversation with SPEN, it has been confirmed that a short term rating of 13MVA is acceptable for up to 3 hours). The maximum load on the St Andrews network and Anstruther network in 2013 was 19.5MVA and 9.2MVA respectively, from the 2013/14 LTDS.

The capacity headroom is the firm capacity less the maximum load, divided by the firm capacity expressed as a percentage. The present capacity headroom based on peak load at St Andrews and Anstruther is therefore 7.1% and 8% respectively.

Results are presented below in Table 4-1 for the demand reduction (in MVA) and effective headroom added (as a percentage of firm capacity) at St Andrews for each potential AVR location (in the existing feeder 25 configuration). Also shown is the corresponding increase in demand (in MVA) at Anstruther.

The demand reduction is the peak feeder load minus the total feeder load under the revised (backfeeding) running arrangement. The capacity headroom added (at St Andrews) is the demand reduction divided by the firm capacity, again expressed as a percentage. These are based on the load that could be transferred through deployment of the AVR from St Andrews to Anstruther, under peak

[3] SP Distribution Long Term Development Statement for the years 2013/14 to 2017/18, November 2013.

loading conditions for St Andrews feeder 25 (and for Anstruther feeder 12). As discussed in section 1.2, feeder 25 peak loading is within 2% of maximum loading of St Andrews primary and thus the calculated values of headroom are viewed as valid.

Table 4-1 Additional capacity headroom at St Andrews and Anstruther with deployment of AVR on feeder 25 (existing circuit configuration)

		St Andrews			Anstruther	
	NOP	Feeder 25 (MVA)	Demand Reduction (MVA)	% Capacity Headroom Added*	Feeder 12 (MVA)	Demand Increase (MVA)
Peak Feeder Load		3.34			1.26	
AVR Location						
1. Cambo Lodge	Grange NOJA	1.039	2.301	11%	3.666	-2.406
2. On main line near to Troustrie ABSW	Grange NOJA	1.039	2.301	11%	3.663	-2.403
3. Sypsies ABSW	Grange NOJA	1.039	2.301	11%	3.652	-2.392
4. Crail Soule	Harbour Pumping Station	0.569	2.771	13.2%	4.269	-3.009

Table 4-1 shows that up to 13% additional capacity headroom at St Andrews is achievable (if the AVR is located at Crail Soule), above the existing demand capacity headroom of 7% (20% total capacity headroom). However, if the proposed load transfer is carried out at times of peak demand at Anstruther (9.2MVA), this may take the total load on Anstruther primary above its firm rating. This will limit the allowable magnitude and duration of the load transfer to the short term overload rating for the transformer. Thus, an important consideration for implementation of load transfer is the intact loading of Anstruther primary substation at the time of the intended transfer and the ability to utilise the Anstruther short term transformer rating of 13MVA for 3 hours. Investigation into the implications for use of dynamic thermal ratings on primary transformers as part of Flexible Networks Work Package 2.1 suggests that use of this short term rating should be acceptable. However, further analysis of the Anstruther transformer load and ambient temperature profiles would be required to verify this.

The total maximum load transfer to Anstruther will be up to approximately 3MVA, as shown in Table 4-1, if the AVR is located at Crail Soule. For the timestamp of peak aggregate loading in 2013 on the feeders analysed, the total Anstruther primary loading is 5.9MVA, indicating that maximum load transfer would be perfectly acceptable under these conditions.

Considering Anstruther primary load data from PI throughout 2013, the total load exceeds 7MVA for 26 half-hour readings (i.e. about 0.15% of the time). This suggests that the desired load transfer from St Andrews feeder 25 may not always be possible if the Anstruther primary substation is already close to peak loading, as it may result in firm capacity being exceeded.

By way of illustration, for these timestamps (> 7MVA), the loading on feeder 25 is up to 3MVA. If up to approximately 83% of the load on feeder 25 can be transferred during backfeed (with the AVR located at Crail Soule) and if additional losses due to the backfeed configuration are in the order of 10%, as per Table 4-1, there will still be 8 half-hourly periods where load transfer is constrained (circa 60% load transfer) unless the short-term rating of the Anstruther transformers is utilised. Given that concurrent loading conditions on St Andrews feeder 25, Anstruther feeder 12 and Anstruther primary will vary from year to year, it may be necessary to manage the load transfer during backfeed to ensure that the loading of Anstruther primary transformers does not exceed the appropriate thermal rating.

4.3 Generation

It is recommended that discussions are held with the St Andrews Bay Hotel to ensure that generation export does not take place in the future as it may affect the operation of the AVR.

5 Key Learning Outcomes

5.1 Network Modelling

A clear methodology has been developed for modelling the 11kV network, including a set of rules for load scaling. This modelling approach was shown to reproduce the measured voltage profile from network monitoring equipment installed as part of the Flexible Networks project. The key learning outcomes from this process include:

- Use of GIS information imported into IPSA2 to model the 11kV Network, supplemented with SPEN equipment rating information. This will be documented in further detail in a report providing recommendations for future techno-economic modelling of the HV and LV networks.
- The loading at each secondary substation can be determined using an initial value which is then refined to match the overall feeder current, as extracted from by PI.
- Initial load values at each secondary substation can be taken as follows;
  - For ground mounted substations: 80%-100% of the recorded MDI value for that year.
  - For pole mounted substations: 20%-35% of transformer rating.

  Although measured loads at secondary substations vary from assumed loads (following refinement to match the overall feeder current) at any measurement timestamp, loads were found to be broadly comparable which provides confidence in the loading assumptions applied.
- The loading profile along a particular feeder has been validated by modelling the voltage drop along the feeder, and comparing this to voltage measurements at secondary substations or control points where monitoring is available (for example NOJA, Gridkey or Subnet monitors). Possible reasons for deviation from the measured profile were postulated; for example, large, intermittent point loads such as pumps are not well-represented by the model. These discrepancies will be explored further as part of Flexible Networks Work Package 1.4: Improved Planning Tools, which seeks to provide wider learning about the usefulness of extensive secondary substation monitoring and how it can be used to improve network modelling.
- Our network model validation assessment provides confidence that voltage profiles can be predicted using the loading assumptions described above without significant additional monitoring. This therefore provides a means of optimising, through modelling, the location of and benefits that can be gained from using AVRs. Results from network monitoring undertaken after the AVR has been deployed to St Andrews feeder 25 will be analysed when available and compared with the results of this study to

provide further learning and enable refinement of the modelling approach for AVRs.

5.2 AVR Modelling

The AVR was modelled in IPSA using a simple transformer model, with manual tap settings. A beta model of an AVR is under development in IPSA that enables selection of the appropriate control mode (Bi-directional, Co-Generation etc.) to automatically determine the required tap position. AVR performance testing will shortly take place at the PNDC and will provide a better insight into the characteristics of an AVR. This will support further development of the AVR model itself as well as refinement of the modelling approach. This will consider the various power systems software used by UK DNOs.

There are several learning outcomes that can result from the use of the simple transformer model to model an AVR:

- Manual setting of the transformer tap gives the engineer undertaking the studies a fundamental understanding of how the regulator is required to behave.
- This in turn allows a proper consideration of the selection of appropriate regulator basic settings (such as set point and band width), Reverse Power Sensing control modes and of other settable parameters, such as LDC values.

It is also noted that, by constraining the allowable tapping range of the AVR, the "load bonus" function of an AVR (referred to by Cooper Power Systems as the "ADD-AMP" capability) can also be considered. The "ADD-AMP" function permits an increase in the maximum current rating of the AVR to be achieved provided that the tapping range of the AVR (and therefore the extent of voltage control that it is able to provide) is correspondingly limited. For the purposes of this study, no benefit has been taken from the ADD-AMP feature as its use is currently pending a SPEN review in order to determine policy in this area.

5.3 AVR Deployment

This analysis has determined a range of optimal locations for an AVR to facilitate load transfer from St Andrews feeder 25 to Anstruther feeder 12. For physical installation of AVRs, there are some key locational constraints that must be observed e.g. location of AVR with respect to spurs, as this may significantly affect the influence of the AVR on network voltages.

However, it is recognised that there are practical installation limitations that must also be considered as part of the site selection process e.g. wayleaving process, radio reception for telecontrol etc.

There is therefore a need to provide some locational flexibility in the analysis to cope with these practical issues, with some iteration for example on pole ranges traded off against AVR performance.

Appendix A – Input Data

Cable Data Table for IPSA -GIS Conversion (from SPEN WinDEBUT)

CABLES		Rating	R	X
MATERIAL	CONDUCTOR DIAMETERE	(A)	(mOhms/m)	(mOhms/m)
CU	0.0125 in	73	2.287	0.118
CU	0.0225 in	100	1.260	0.109
CU	0.025 in	107	1.137	0.108
CU	0.04 in	140	0.703	0.101
CU	0.05 in	160	0.583	0.098
CU	0.06 in	175	0.464	0.096
CU	0.075 in	199	0.376	0.093
CU	0.1 in	240	0.276	0.090
CU	0.15 in	290	0.188	0.084
CU	0.2 in	345	0.142	0.082
CU	0.25 in	395	0.113	0.080
CU	0.3 in	445	0.092	0.078
CU	0.4 in	508	0.070	0.078
CU	0.5 in	570	0.055	0.078
CU	25 mm	137	0.739	0.102
CU	95 mm	287	0.193	0.085
CU	150 mm	377	0.123	0.081
CU	185 mm	432	0.098	0.078
CU	300 mm	548	0.060	0.078
AL	0.0125 in	55	3.704	0.113
AL	0.0225 in	78	2.058	0.105
AL	0.03 in	91	1.543	0.102
AL	0.04 in	108	1.158	0.099
AL	0.05 in	122	0.926	0.096
AL	0.06 in	135	0.767	0.094
AL	0.075 in	154	0.617	0.092
AL	0.1 in	185	0.456	0.090
AL	0.15 in	225	0.312	0.084
AL	0.2 in	270	0.234	0.082
AL	0.25 in	310	0.187	0.080
AL	0.3 in	350	0.152	0.078
AL	0.4 in	403	0.116	0.076
AL	0.5 in	450	0.092	0.074
AL	25 mm	103	1.257	0.102
AL	70 mm	185	0.443	0.090
AL	95 mm	225	0.320	0.087
AL	120 mm	255	0.253	0.085
AL	150 mm	290	0.203	0.082
AL	185 mm	330	0.164	0.080
AL	240 mm	381	0.126	0.078
AL	300 mm	430	0.100	0.076

OHL MATERIAL	SIZE	Rating (A)	R (mOhms/m)	X (mOhms/m)
CU	0.0225 in	149	1.201	0.383
CU	0.025 in	151	1.088	0.383
CU	0.035 in	175	0.777	0.370
CU	0.05 in	206	0.544	0.360
CU	0.075 in	256	0.372	0.340
CU	0.1 in	313	0.272	0.340
CU	0.15 in	404	0.183	0.328
CU	0.2 in	510	0.142	0.328
CU	16 mm	152	1.083	0.383
CU	25 mm	183	0.696	0.366
CU	32 mm	207	0.541	0.360
CU	50 mm	260	0.352	0.340
CU	70 mm	324	0.259	0.338
CU	100 mm	414	0.176	0.328
CU	3/0.104 in	151	1.088	0.383
AL	0.025 in	125	1.072	0.384
AL	0.05 in	193	0.541	0.373
AL	0.1 in	300	0.269	0.352
AL	0.15 in	386	0.182	0.304
AL	25 mm	125	1.100	0.382
AL	32 mm	146	0.851	0.382
AL	50 mm	193	0.542	0.373
AL	100 mm	300	0.275	0.352
AL	150 mm	385	0.183	0.304
CE AL-ALLOY	0.025 in	125	1.072	0.384
CE AL	0.05 in	193	0.541	0.373
ABC	95 mm	255	0.320	0.340
SCA	0.025 in	125	1.072	0.384
SCA	50 mm	193	0.542	0.373
HDC	0.025 in	165	1.094	0.375
HDC	16 mm	165	1.104	0.386
HDC	32 mm	250	0.557	0.364
HDC + AE	32 mm	250	0.557	0.364
ACSR	0.025 in	125	1.072	0.384
ACSR	0.05 in	193	0.541	0.373
ACSR	25 mm	125	1.100	0.382
ACSR	50 mm	193	0.542	0.373
ACSR	150 mm	420	0.181	0.291

Appendix B – St Andrews Bay Hotel Generator Data

Table B-1 St Andrews Bay Hotel Generator Data

Generator Data – Combined Heat and Power (CHP) Plant	
Type	F G Wilson Model 8230H
Rating	501kW (100% rating)
Fuel Source	Diesel
Connection Voltage	11kV
Date of First Connection	2001 probable
Operational Regime	24 hours a day

The CHP unit is solely for the hotels own demand e.g. heating, hot water and lighting. It runs all the time with output fluctuating against demand. There is also a diesel generator for emergency situations.

COGENCO DATA SHEET
CGC-500P-L-NGUK-50
Low Temperature **British Natural Gas**

Cogenco

TECHNICAL SPECIFICATION

Cogenco identification	CGC	500P	Compression ratio		12:1
Engine type	Perkins	4008-31 TRS2	Engine speed	rpm	1500
Generator type	MECC ALTE	ECO 43-1SN	Power factor		1
Cylinder configuration	In Line	8	Air fuel ratio		1.69
Exhaust manifold		Dry	Barometric pressure	kPa	100
Bore	mm	160	Exhaust gas temperature after H/E	°C	120
Stroke	mm	190	Ambient temperature	°C	25
Swept volume	litres	30.574	Gas heating value (LHV)	kJ/nm3	34710
Mean effective pressure	bar	13.8	Methane index		>80

PERFORMANCE AND EFFICIENCY		100%		75%		50%	
Fuel input	kW	1298	*100.0%*	1121	*100.0%*	816	*100.0%*
Mechanical shaft power	kW	526	*40.5%*	395	*35.2%*	263	*32.2%*
Electrical output	kW	501	*38.6%*	376	*33.6%*	250	*30.7%*
Heat output from jacket water and oil	kW	211	*16.3%*	194	*17.3%*	165	*20.2%*
Heat output from exhaust gases (120°C)	kW	307	*23.7%*	250	*22.3%*	178	*21.8%*
Total useable heat output	kW	**518**	***39.9%***	**444**	***39.6%***	**343**	***42.0%***
Total useable energy	kW	**1019**	***78.5%***	**820**	***73.2%***	**593**	***72.7%***
Intercooler heat output	kW	90	*6.9%*	43	*3.8%*	18	*2.2%*
Radiated and unaccounted for heat	kW	73	*5.6%*	60	*5.4%*	43	*5.3%*

TEMPERATURES AND FLOWS		100%	75%	50%
Fuel mass flow	kg/hr	96.8	83.6	60.9
Fuel volume flow	nm3/hr	134.6	116.3	84.6
Ventilation air volume flow (incl. comb. air)	nm3/hr	20800	20800	20800
Combustion air mass flow	kg/hr	2792	2411	1755
Combustion air volume flow	nm3/hr	2156	1862	1355
Exhaust gas mass flow (wet)	kg/hr	2888	2495	1816
Exhaust gas volume flow (wet)	nm3/hr	2271	1962	1428
Exhaust gas volume flow (wet) @ 120°C	m3/hr	3216	2777	2022
Jacket water flow	m3/hr	36	36	36
Intercooler water flow - minimum	m3/hr	24	24	24
Secondary water flow - minimum	m3/hr	46	46	46
Maximum return water inlet temperature	°C	80	80	80
Secondary water outlet temperature	°C	89.6	88.2	86.4
Maximum intercooler water inlet temperature	°C	45	45	45
Intercooler water outlet temperature	°C	48.5	46.7	45.7
Exhaust gas temperature before cooler	°C	478	492	506

WEIGHTS AND DIMENSIONS			
Weight - dry	kg	9600	Cogenco Limited
Weight - wet	kg	10000	Parsonage Farm Business Park
Length-canopy only	mm	4400	Parsonage Way
Length-canopy and controlo panel	mm	4800	HORSHAM West Sussex
Width	mm	2000	United Kingdom RH12 4AL
Height-canopy only	mm	2400	Tel: +44(0)1403 272270
Height-canopy and attenuators	mm	3600	Fax: +44(0)1403 272274
			www.cogenco.co.uk
			sales@cogenco.co.uk

Tolerance on energy input	+5%	Tolerance on heat output	+/-7%
Tolerance on power output	+/-3%	Tolerance on exhaust flow and temperature	+/-5%
Definition of ratings to ISO 3046	In order to comply with the Cogenco policy of continuous improvement the information is subject to change without prior notice		

Figure B-1 Generator Datasheet

Appendix C – Manufacturer's AVR Data

Table C-1 AVR Impedance Data

Maximum Impedance @ 16R
(Application: Closed or Open Delta Systems)

Rated Voltage	Rated Current	% Z_1	% X_1	% R_1	% Z_0	% X_0	% R_0	Base mVA
11000	50	0.56	0.51	0.22	0.57	0.53	0.22	1.0
11000	100	0.71	0.67	0.24	0.73	0.69	0.24	1.9
11000	150	0.87	0.84	0.21	0.89	0.87	0.21	2.9
11000	200	0.60	0.58	0.18	0.62	0.59	0.19	3.8
11000	300	0.65	0.63	0.18	0.67	0.64	0.18	5.7
22000	50	0.81	0.76	0.27	0.83	0.78	0.28	1.9
22000	100	0.78	0.75	0.18	0.80	0.77	0.19	3.8
22000	150	0.87	0.85	0.18	0.89	0.87	0.18	5.7
22000	200	0.67	0.64	0.17	0.68	0.66	0.18	7.6
22000	300	0.51	0.47	0.19	0.52	0.49	0.20	11.4
33000	100	0.28	0.21	0.19	0.29	0.22	0.19	5.7
33000	200	0.38	0.34	0.16	0.39	0.35	0.16	11.4

Minimum Resistance @ neutral for all designs = .01%
Minimum Reactance @ neutral for all designs = .0%

Craig A. Colopy, P.E.
9/28/2001

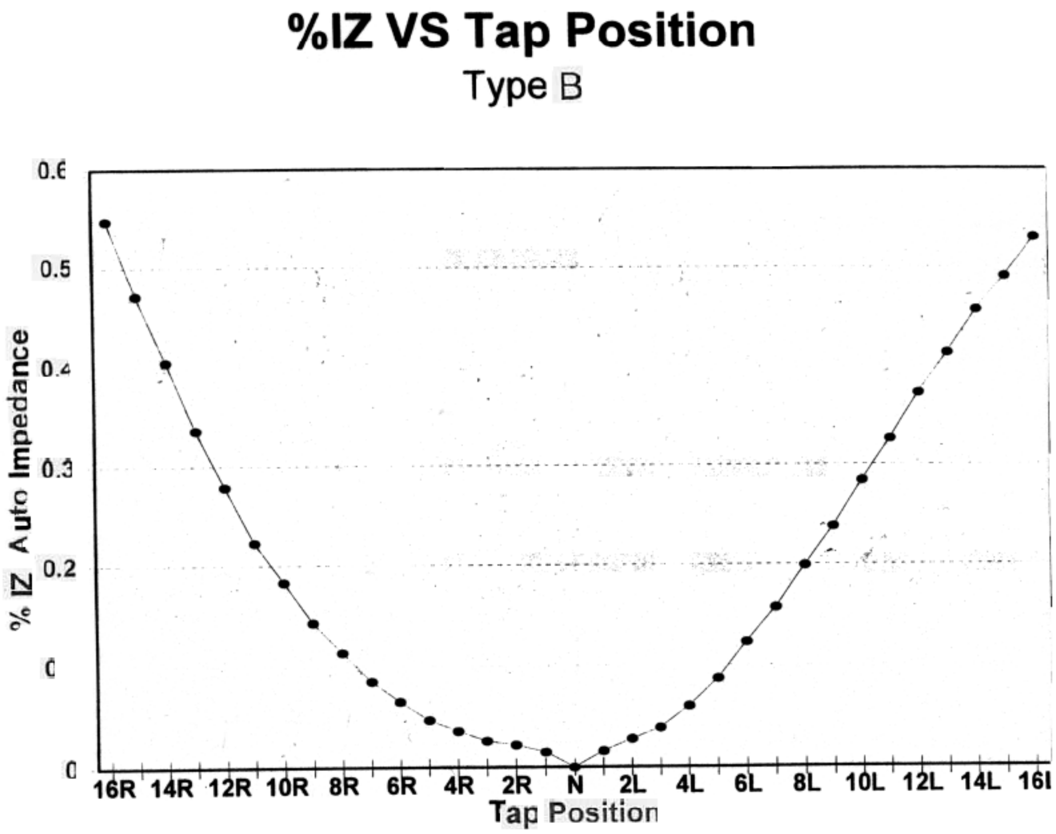


Figure C-1 AVR Type B Impedance Characteristics with Tapping Position

Table C-2 Three-Phase AVR Continuous Current Ratings (reproduced from IEEE - STD C57.15-2009[1])

Table 9—Supplementary continuous-current ratings for three-phase voltage regulators

Range of voltage regulation (%)	Continuous-current rating (%)
10.00	100
8.75	108
7.50	115
6.25	120
5.00	130