REPORT

Fault Level and Protection Studies for ALVIN Installation

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Executive summary

Background to the Project

As part of the OpenLV project trials, EA Technology is seeking to install ALVIN LV network automation devices at a number of 11/0.433kV substations within the Western Power Distribution's (WPD) network area. The ALVIN units will enable network automation and have the capability of temporarily meshing LV substations to alleviate network stress.

Traditionally, WPD's LV networks have been designed and operated in a radial manner. If these networks are meshed as part of the network automation offered by ALVIN, the circuits in question will change from radial to ring operation. This change in network topology has an impact on the fault level and protection operation in the network. This report evaluates the fault level and protection operation performance at a number of 11/0.433kV substations provisionally selected for ALVIN installation to enable temporary network meshing.

Key Project Learning

Evaluation of several network pairs led to their exclusion from the trials due to either excessive fault levels (fed from 1000kVA transformers) or excessive fault clearance times (very long main or branch feeder cables).

If more extensive operation of meshed networks is considered in future, it may be advantageous to create acceptance/rejection rules for potential circuit pairs, based upon criteria such as transformer rating, main and branch cable types & lengths, rather than calculation or modelling for each individual circuit being considered.

Conclusions

C1. Fault levels at all ten substation busbars, and at all customer cutout positions modelled in this report, remain in compliance with EREC P25/2 when operating in meshed configuration at the maximum possible HV system fault level. A theoretical non-compliance close to R.A.V.C. substation is not considered to be feasible in practice.

C2. HV and LV fault clearance times for ALVIN rated at 400A (Chapel Street, Pilgrim Drive and R.A.V.C.) and 315A (at the other 7 substations) are within the specified WPD limits when operating in meshed configuration at the lowest possible HV system fault level.

Recommendations

R1. These five circuit pairs are suitable for operation in meshed configuration when 315A and 400A ALVIN devices are employed as specified in this report.

R2. WPD LV Networks Templates Classification Tool indicates that 315A fuses would be adequate to supply assessed feeder loadings at Cosira, Lotherton Close, East Road and Wygate Road (maximum fuse rating for a 500kVA transformer is 400A). Actual circuit loadings should be verified before any existing 400A fuses are replaced by 315A ALVINS.

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1. Background & Introduction

As part of the OpenLV project trials, EA Technology is seeking to install ALVIN LV network automation devices at a number of 11/0.433kV substations within the Western Power Distribution's (WPD) network area. The ALVIN units will enable network automation and have the capability of temporarily meshing LV substations to alleviate network stress.

Traditionally, WPD's LV networks have been designed and operated in a radial manner. If these networks are meshed as part of the network automation offered by ALVIN, the circuits in question will change from radial to ring operation. This change in network topology has an impact on the fault level and protection operation in the network. This report evaluates the fault level and protection operation performance at a number of 11/0.433kV substations provisionally selected for ALVIN installation to enable temporary network meshing.

2. Study Methodology

2.1 Network Configurations

A number of 11/0.433kV substations have been provisionally chosen to conduct the fault level and protection grading studies. From this set, those substations which are supplied from the same 11kV network have been paired together as potential candidates for LV meshing. Typically, outgoing LV feeders from both substations (i.e. Substation A and B) from the pair would end in a normally open point (NOP). This is the normal network operating configuration where each transformer supplies the load up to the NOP and this represents a radial network arrangement. In case of a transformer outage at either Substation A or Substation B, the NOP can be closed and supply to the entire LV feeder is re-routed from the other transformer. This temporary condition is a radial network arrangement too which lasts for the duration of the transformer outage. **However, it should be noted that during the operations to both enable the back feed and then to restore normal network operation following the transformer restoration, the network is in a mesh configuration for a period of time.** In the case of the proposed meshed configuration, both transformers would be in service and the NOP will be closed – resulting in both transformers sharing the load in the interconnected feeder. This is a ring network arrangement and to be used as a temporary measure – for the time duration the network is under stress.

Table 1 below lists the abovementioned network configurations and Figure 1 to Figure 4 overleaf show the network diagrams for these networks.

Table 1 Description of different network configurations

Network Configurations	Description
Normal Configuration (Radial Network)	This network configuration depicts the existing configuration of the network where outgoing feeders from both Substation A and B terminate at a network open point. This is a radial network.
Outage Tx B: Fed from Sub A (Radial Network)	This network configuration envisages a transformer outage at substation B. Substation B outgoing feeder circuits breakers are open while loads are fed from Substation A by closing the normally open point. This is a radial network.
Outage Tx A: Fed from Sub B (Radial Network)	This network configuration envisages a transformer outage at substation A. Substation A outgoing feeder circuits breakers are open while loads are fed from Substation B by closing the normally open point. This is a radial network.
Meshed Configuration (Ring Network)	This network configuration depicts an interconnected network configuration where the normally open point is closed while both substation transformers are in service. Load between Substation A and B are shared. This is a ring network.

For this exercise, a power system calculation tool 'IPSA' has been utilised to build these network models and conduct the necessary fault level and protection clearing time calculations. IPSA is widely used across the UK by Distribution Network Operators and offers calculation capabilities such as load flow and fault level. Images shown in Figure 1 to Figure 4 are extracts from the IPSA software.

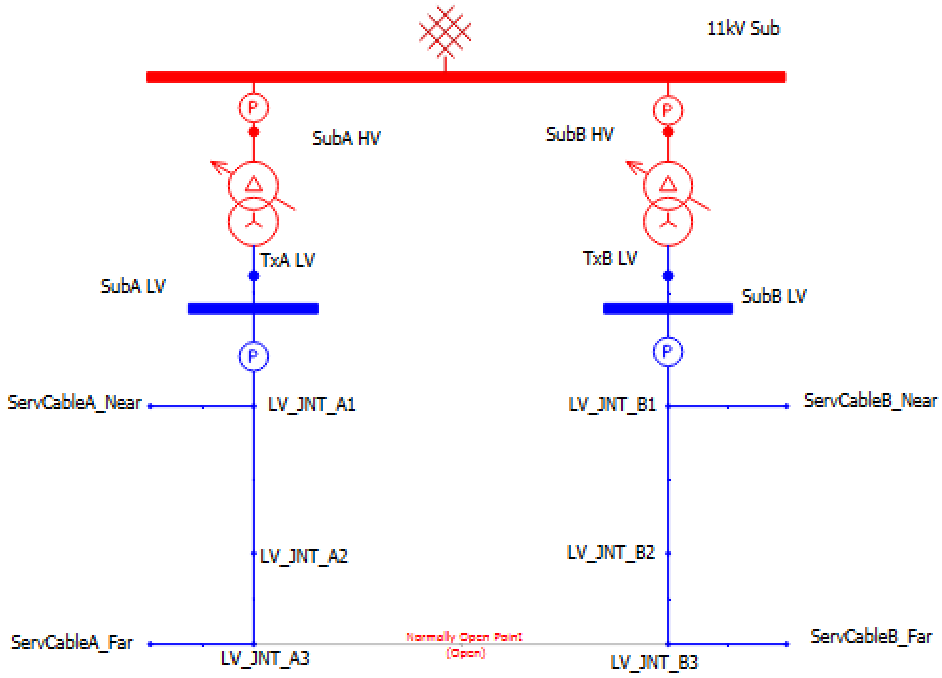

Figure 1: Normal Configuration (Radial Network)

Figure 1 above shows the normal network running arrangement where the NOP is open.

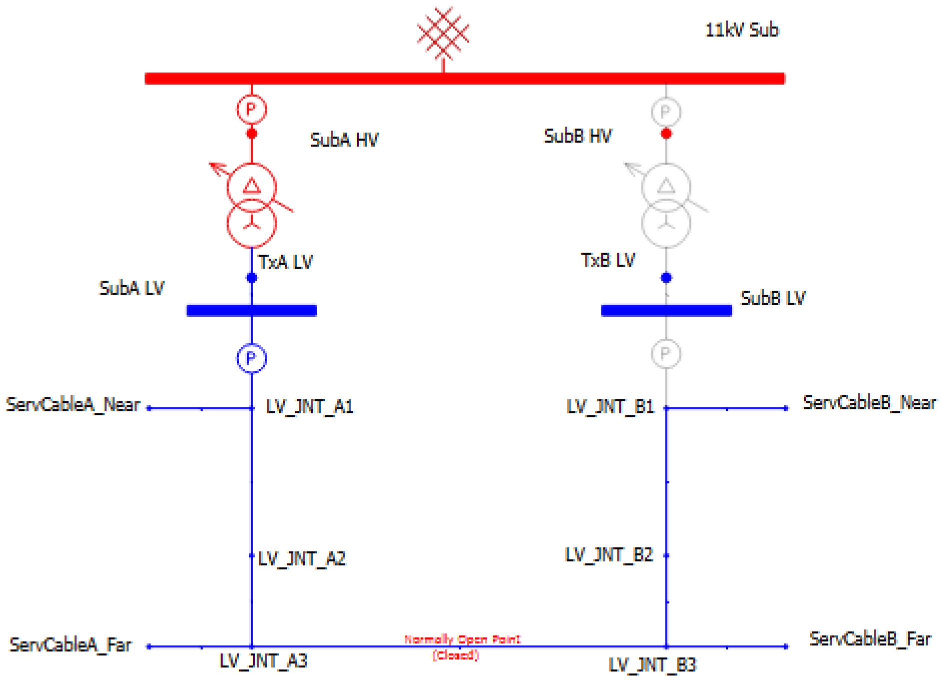

Figure 2: Outage Tx B: Fed from Sub A (Radial Network)

Figure 2 above shows an outage condition where the transformer at substation B is out of service. The NOP has been closed to re-route supply to the entire LV feeder from Substation A.

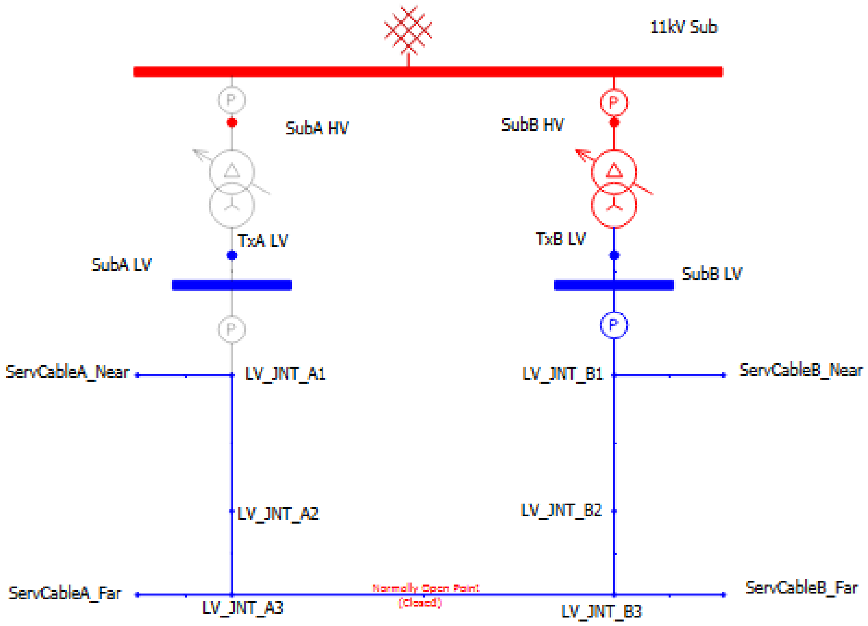

Figure 3: Outage Tx A: Fed from Sub B (Radial Network)

Figure 3 above shows another outage condition where the transformer at substation A is out of service. The NOP has been closed to re-route supply to the entire LV feeder from Substation B.

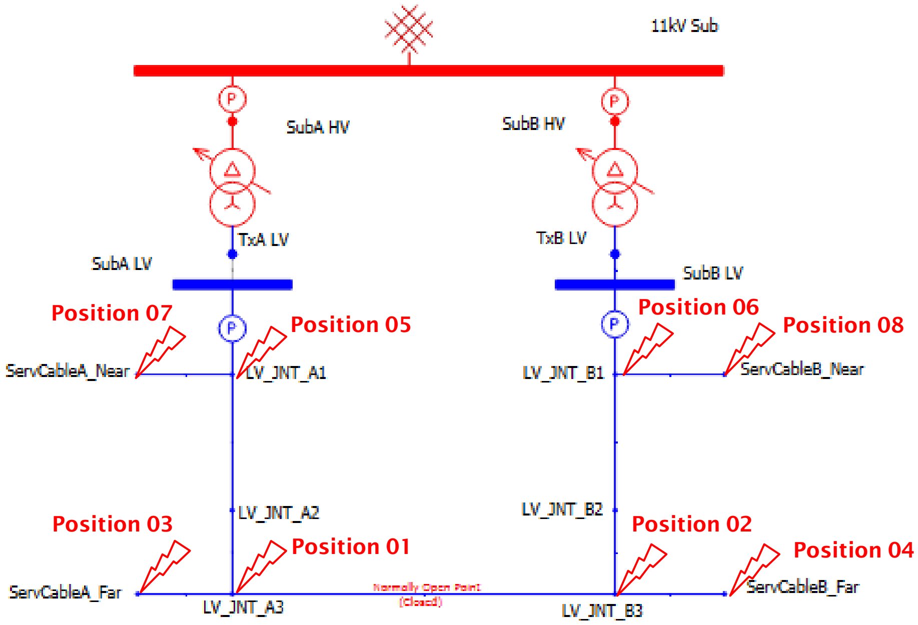

Figure 4: Meshed Configuration (Ring Network)

Figure 4 shows the proposed meshed network condition where the NOP is closed and both transformers are sharing the load on the LV ring. Several fault level and protection co-ordination studies have been performed at key network positions to evaluate worst case fault level and protection clearance times. These network positions are marked in Figure 4 and explained in Table 2 overleaf. These positions are applicable to networks shown in Figure 1 to Figure 3.

N.B. The actual networks modelled are usually more complex than these Figures suggest. All significant branches from main cables have been included in the individual circuit IPSA models along with the most remote service cables from the branches.

Table 2 Network positions considered for fault level and protection studies

Network Positions	Description
Position 01 and 02	These positions are the end of the three-phase LV mains cables from the substation. These could be either at the a) both sides of the NOP, which are the termination point for the three-phase LV main feeders during normal operating configuration or b) at the end of the longest three-phase branch from the mains cable. These network points would have the lowest three-phase fault current and highest fault clearance time under normal operation (Figure 1).
Position 03 and 04	These positions are at the end of the longest possible single-phase service cables connected at the end of the three-phase LV mains cables (Position 01 and 02). The service cables have been modelled as 20m in length to produce worst case results.
Position 05 and 06	These positions are 7.5m along the LV mains cable from the substations which have been considered as the nearest feasible service cable tapping positions. These network points would exhibit highest fault current at a service point tapping under normal operating condition (Figure 1). However, under outage conditions (Figure 2 and Figure 3), these points would become the effective termination point for the three-phase LV main feeder and might exhibit the lowest three-phase fault current and longest fault clearance time. Under meshed condition (Figure 4), a fault at these points would also exhibit longest fault clearance time.
Position 07 and 08	These positions are at the end of the service cables connected at the nearest customer tapping position (Position 05 and 06) from the substation. Two different length of service cables have been considered for both points. For prospective fault currents where highest fault current is considered worst case, the shortest possible service cable of 2m in length is considered. For protection clearance time where lowest fault current is considered worst case, the longest possible service cable of 20m in length is considered. Under normal operating condition (Figure 1), these points would exhibit highest prospective fault current at customer cut-out. Under, outage conditions (Figure 2 and Figure 3), these points might result in lowest fault current and longest fault clearance time. Under meshed condition (Figure 4), a fault at these points would also exhibit longest fault clearance time.

2.2 Fault Level and Protection co-ordination studies

For fault level, the IPSA's methodology has been used to calculate prospective fault currents across the network. The IPSA method is based on the guidelines set out in Engineering Recommendation G74 (ER G74). The G74 fault level method has been in use for many years by all UK Distribution Network Operators in the calculation of fault levels and has empirical validation.

For protection studies, IPSA's overcurrent protection co-ordination analysis has the capability to calculate the operating times of relays and other protection devices when a fault occurs on the network. A fault can be simulated by the user at any point of the network and then IPSA calculates the actual fault currents around the network seen by different protection devices and the subsequent protection operating times.

Network data required for construction of these network models has been collected via a combination of site visits and communication with relevant WPD staff. The fault levels at the 11kV voltage level have been provided by WPD as listed in Table 3 overleaf.

Table 3 Fault Level Infeed Data

	Three-Phase MVA	Three-Phase kA	Single-Phase MVA	Single-Phase kA
Maximum Fault Level	250	13.12	57.15	3
Minimum Fault Level	50	2.62	9.5	0.5

Several fault level calculations and protection co-ordination studies have been performed to evaluate the worst-case results under different network configurations. In terms of fault level calculations, the worst-case scenario would be the prospective higher fault current after the LV feeders have been meshed. To evaluate this, maximum fault level values quoted in Table 3 have been used as the source fault infeed. Three-phase faults have been studied at the substation LV terminal and at the end of the LV feeder. In addition, single-phase faults have been studied at the service cables nearest to the substation (7.5m LV main and 2m service cable) and at the end of the LV feeder (at the end of the LV mains and 20m service cable). This combination of studies at different network positions and under different configuration enabled greater understanding of prospective fault currents within the network. The following fault types have been calculated:

- Prospective three-phase symmetric fault current at 100ms
- Prospective single-phase fault current at 100ms

WPD have specified that the maximum PSCC at customer service positions should be assessed against the guidance given in ENA EREC P25/2.

In terms of protection device operation, the worst-case scenario would be longer fault clearing times under meshed/outage network condition. To evaluate this, minimum fault level values quoted in Table 3 have been used as the source fault infeed. Several protection studies at different network points have been conducted to evaluate worst case protection clearing times. These studies and associated network points are marked in Figure 4 and listed in Table 4 below:

Maximum protection operation times have been advised by WPD (60s for faults at service cutout positions and 3s for backfed transformer faults). The studies have also been conducted with existing network radial configurations and conventional BS88_5 fuses to demonstrate the difference in protection performance under meshed conditions and also indicate the integral backup fuse operating time in the event of an ALVIN device failing to operate correctly.

Table 4 Protection Study Result Plot References

	Minimum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
3P Longest Clearance Time for LV Mains Feeder from Sub A	Study 01 (Position 01)	Study 05 (Position 06)	N/A	Study 09 (Position 06)
3P Longest Clearance Time for LV Mains Feeder from Sub B	Study 02 (Position 02)	N/A	Study 07 (Position 05)	Study 10 (Position 05)
1P Longest Clearance Time for LV Service Cable from Sub A	Study 03 (Position 03)	Study 06 (Position 08)	N/A	Study 11 (Position 08)
1P Longest Clearance Time for LV Service Cable from Sub B	Study 04 (Position 04)	N/A	Study 08 (Position 07)	Study 12 (Position 07)

2.3 Network Data

The network data required for the construction of IPSA's network models has been collected via a combination of site visits and communication with relevant WPD staff. Where some required data was not available from any sources, reasonable assumptions have been put in place to complete the studies. The key data sources and assumptions are described below:

2.3.1 Transformer Data

The transformer nameplate data has been collected via site survey by EA Technology staff. The nameplate information included transformer MVA rating, positive sequence impedance, voltage levels and vector group settings. All these data have been inputted into the IPSA network models.

Unfortunately, transformer zero sequence impedance data is not typically included in nameplate information and is required for single-phase fault calculations. Zero sequence impedance values are not routinely supplied for individual transformers and there is no universally acknowledged value ascribed to them. For core-type transformers (as generally used in DNO secondary substations), the suggested values tend to lie within the range of 85 – 95% of the positive sequence value.

We have therefore adopted a ratio of 90% for these studies, a value which aligns with the IPSA library values for similar type of transformers.

2.3.2 Cable Data

Data regarding the outgoing LV feeders from the substations has been sourced from WPD's Online Data Portal. It was possible to identify individual LV feeders from this portal and extract the cable type and length for each section of the LV mains cables under consideration. The Data Portal also provided information about the location of the NOP along the feeder.

For each cable type, the positive sequence impedance data was sourced from manufacturer data sheets. Unfortunately, zero sequence impedance data for cables is not routinely supplied by the manufacturer, and there is plenty of evidence that the actual installed zero sequence impedance depends significantly on the ground conditions etc. which is a reason why manufacturers do not normally quote a value.

Investigation into the databases supplied with industry standard power system analysis software (IPSA, ERACS, PowerFactory DIgSILENT etc.) point to R0/R1 being between 2 – 4 and X0/X1 between 1-2. From these, we have deduced the following assumptions for the zero sequence impedance for LV cables:

- Zero Sequence Resistance (R0) = 3.5x Positive Sequence Resistance (R1) (for 3-core cables)
- Zero Sequence Resistance (R0) = 2.5x Positive Sequence Resistance (X1) (for 1-core cables)
- Zero Sequence Reactance (X0) = 1.5x Positive Sequence reactance (X0)

Reliable zero sequence data for single-phase service cables is even more difficult to come by. In order to align the results with EREC P25/2, service cable impedance values were calculated from Table 1 of EREC P25/2. The resultant impedance values are significantly higher than values from all other sources and therefore represent the absolute worst-case outcomes for protection operating times.

2.3.3 Feeder Protection Data

WPD staff advised the following HV and maximum LV fuse sizes for different sized transformers. Where possible, these fuses have been modelled within the IPSA network models constructed for these studies. Where protection operating times are seen to be in excess of the WPD advised limits, the next lower rating of ALVIN & LV fuse has been selected. In these cases, feeder loadings were checked against the WPD LV Networks Templates Classification Tool, however actual loadings should be validated on site before reducing any existing fuse ratings.

Table 5 Protection fuse sizes

Transformer Size	TLF Rating	CT Ratio	TLF Type	LV Outgoing Fuse
1000 kVA	7.5A or 10A	100/5	XF	400A (maximum)
750 & 800kVA	5A or 7.5A	100/5	XF	400A (maximum)
500kVA	10A or 12.5A	50/5	XF	400A (maximum)
300 & 315kVA	5A or 7.5A	50/5	XF	315A (maximum)
200kVA	3A	50/5	XF	200A (maximum)

3. Plymouth: Chapel Street Bere Alston (330326) and Pilgrim Drive (331615)

Chapel Street Bere Alston (Substation ID: 330326) and Pilgrim Drive (Substation ID: 331615) are situated in the Plymouth region. Both substations are supplied from the same 11kV network and have one 500kVA transformer installed each. Table 6 below lists the electrical asset data utilised for the fault current and protection studies:

Table 6 **Network Data for Substation Pair 330326 and 3316152**

	Substation A (330326)	Substation B (331615)
Transformer Rating	500kVA	500kVA
Transformer Impedance	4.86%	4.61%
HV Transformer Fuse	TLF 12.5A or 10A on 50:5 CT	TLF 12.5A or 10A on 50:5 CT
LV Outgoing Feeder Fuse	400A BS88-5 Fuse	400A BS88-5 Fuse
LV Outgoing Alvin Fuse	400A	400A

A series of fault level and protection studies under different network configuration to evaluate the impact on fault level and protection operation times for the proposed re-configurations. The results are discussed in section 3.1 and 3.2.

3.1 Fault Level Results

Three-phase and single-phase fault studies have been performed as per the methodology described in section 2.2. Table 7 and Table 8 list the prospective highest three-phase and single-phase fault currents at key positions in the network

Table 7 **Prospective Maximum 3P Fault Current (in kA) at Substation Pair 330326 and 3316152**

	Maximum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
Substation A LV Busbar	13.18	13.18	N/A	14.83
Substation B LV Busbar	13.86	N/A	13.86	15.51
Service tapping position Sub A Near End	12.80	12.80	3.26	14.69
Service tapping position Sub B Near End	13.45	3.24	13.45	15.33
1P Longest Clearance Time for LV Service Cable from Sub A	3.50	3.02	N/A	4.31
1P Longest Clearance Time for LV Service Cable from Sub B	6.33	N/A	2.33	7.29

Table 8 Prospective Maximum 1P Fault Current (in kA) at Substation Pair 330326 and 3316152

	Maximum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
Substation A LV Busbar	13.80	13.80	N/A	15.06
Substation B LV Busbar	14.53	N/A	14.53	15.78
Service Cut-out Sub A Near End (2m Service Cable)	11.80	11.80	1.87	12.58
Service Cut-out Sub B Near End (2m Service Cable)	12.30	1.87	12.30	13.07
Service cable Sub A Far End (20m Service Cable)	1.53	1.37	N/A	1.75
Service cable Sub B Far End (20m Service Cable)	2.46	N/A	1.34	2.60

3.1.1 Fault levels: Normal radial configuration

The study results show that the highest three phase fault level is 13.86kA which is comfortably within the maximum value of 25.9kA quoted in P25/2. As for the fault level at the nearest feasible customer tapping position, the values are also within the P25/2 specified values.

The maximum single phase fault levels are comparatively higher at 14.53kA (due to transformer zero sequence impedance assumption; see section 2.3.1). Single-phase customers connected close to the substation experience a fault level of 12.30kA which is within the 16kA value specified in P25/2. The single phase value falls away rapidly as the distance along the feeder increases.

3.1.2 Fault levels: Transformer outage conditions

As expected, there is no change in fault levels for positions up to the normally open point. At the far end of the extended feeder, 3 phase fault levels fall to 2.33kA. This also has an impact on single-phase fault levels at customer cut-out which drops to a minimum value of 1.34kA.

3.1.3 Fault levels: Meshed configuration

Initial studies were performed to establish which fault positions produce the highest fault levels within the meshed circuit. The studies demonstrated clearly that the worst case is at the substation busbars rather than any point along the feeder cables.

Maximum three-phase fault levels at the substation busbars are increased under the meshed configuration, but only by 11.9% (15.51kA being the highest) and still comfortably within the 25.9kA value quoted in P25/2. As expected, the fault levels at the normally open point are approximately doubled compared with the radial configuration.

Maximum single-phase fault levels at the substation busbars are also higher than the radial configuration, with an increase of 8.6% (15.78kA being the highest).

3.1.4 Fault levels: Summary

It is seen that the under meshed configuration, the maximum fault level at the substation busbars increases by up to 11.9% for three-phase faults and 8.6% for single phase faults. Under meshed configuration, the highest three phase fault current at the substations was 15.51kA, demonstrating compliance with P25/2.

Fault levels at single phase service cutout positions are a maximum of 13.07kA, against the P25/2 limit of 16kA.

3.2 Protection Results

Three-phase and single-phase protection studies have been performed as per the methodology described in section 2.2. Table 9 lists the longest fault clearing times for both BS88-5 fuses and ALVIN.

Table 9 **Protection Clearance Time (in Seconds) for Substation Pair 330326 and 3316152**

	Minimum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
3P Longest Clearance Time for LV Mains Feeder from Sub A	0.24 (Fuse) 0.12 (ALVIN)	0.46 (Fuse) 0.23 (ALVIN)	N/A	1.78 (Fuse) 0.93 (ALVIN)
3P Longest Clearance Time for LV Mains Feeder from Sub B	0.02 (Fuse) 0.02 (ALVIN)	N/A	1.43 (Fuse) 0.75 (ALVIN)	0.50 (Fuse) 0.25 (ALVIN)
1P Longest Clearance Time for LV Service Cable from Sub A	9.22 (Fuse) 3.96 (ALVIN)	15.36 (Fuse) 6.37(ALVIN)	N/A	68.98 (Fuse) 25.97 (ALVIN)
1P Longest Clearance Time for LV Service Cable from Sub B	1.11 (Fuse) 0.58 (ALVIN)	N/A	52.42 (Fuse) 19.12 (ALVIN)	18.15 (Fuse) 7.77 (ALVIN)

The time-overcurrent plots for these studies are presented in Appendix I. Readers may wish to refer to Table 2 and Figure 4 while evaluating results presented in Table 9 and Appendix I.

3.2.1 Protection results: Normal radial configuration

Three-phase feeder cable faults up to the end of the longest branch would be cleared within 0.24s by the BS88-5 fuses. A substitution of the BS88-5 fuses by the proposed ALVIN device changes this maximum operating time to 0.12s.

For faults at the end of a 20-metre single-phase service located at the end of the longest branch, the BS88-5 fuse clearance times of 9.22s (A) and 1.11s (B) are accelerated to approximately half of these values when ALVINs are installed.

3.2.2 Protection results: Transformer outage conditions

When either transformer is switched out, the entire circuit is fed from either Sub A or Sub B. Three-phase faults at the remote end of the extended feeder would be cleared by the BS88-5 fuse within 1.43s. Substituting ALVINs for the BS88-5 fuses reduces the maximum fault clearance times to approximately half at 0.75s. For faults at the end of a 20-metre single-phase service located close to the remote end, the maximum corresponding clearance times are 52.42s for a BS88-5 fuse and 19.12s for the ALVIN.

Each study for this condition results in fault clearance times being reduced by some 50% by the use of the ALVIN devices.

3.2.3 Protection results: Meshed configuration

Studies were performed to establish which fault positions produce the longest clearance times within the meshed circuit. Due to the dual fault infeed paths under meshed configuration, the fault clearance is a two-stage process. The BS88-5 fuse or ALVIN closest to the fault will operate first. When this occurs, the circuit configuration reverts to that of an extended feeder, with the fault now fed from the remote substation (as per section 3.2.2). Therefore, the total fault clearance time is the sum of the local fuse/ALVIN operating time added to the operating time of the remote fuse/ALVIN. Two plots (a & b) are presented for each fault under the meshed configuration to illustrate the two-stage fault clearance.

Three-phase faults at either circuit end would be cleared by BS88-5 fuses within 1.78s, but substituting ALVINs for the fuses reduces the fault clearance times to a maximum of 0.93s.

For faults at the end of a 20-metre single-phase service located close to either circuit end, the corresponding maximum clearance times are 68.98s for the existing fuse and less than 25.97s for the ALVIN.

HV faults at both A and B substations whilst operating meshed result in the fault being backfed through the transformer at that site. The total fault clearance time for this condition is less than 0.65s where 400A fuses are employed and less than 0.34s for the ALVIN. The maximum permitted time for this condition, as advised by WPD, is 3s.

These operating times show a clearance time reduction of approximately 50% when the ALVIN devices are deployed in place of BS88-5 fuses.

All modelled total fuse clearance times for the meshed condition are pessimistic; they do not take account of the effect of the initial fault current flowing through the second Fuse/Alvin device which trips, which would accelerate the true device operation time compared to the calculated value.

3.2.4 Protection results: Summary

The use of 400A ALVIN results in a reduction in fault clearance times of approximately 50% compared to the equivalent-rated BS88-5 fuses for all single-and three-phase faults.

Though the main feeder and service cutout fault clearance times are increased when the network is operating meshed configurations, they are still within the WPD design limit of 60s (LV faults) and 3s (HV faults) when the proposed ALVIN device is employed.

All fault clearance times stated in these studies are applicable to the minimum possible HV network fault level, as specified by WPD. A normal, higher, fault level will result in a general reduction in these times.

4. Nottingham: Cosira Sleaford (912548) and East Road Sleaford (912807)

Cosira Sleaford (Substation ID: 912548) and East Road Sleaford (Substation ID: 912807) are situated in the Nottingham Region. Both substations are supplied from the same 11kV network and have one 500kVA transformer installed each. Table 10 below lists the electrical asset data utilised for the fault current and protection studies:

Table 10 Network Data for Substation Pair 912548 and 912807

	Substation A (912548)	Substation B (912807)
Transformer Rating	500kVA	500kVA
Transformer Impedance	4.85%	4.61%
HV Transformer Fuse	TLF 12.5A or 10A on 50:5 CT	TLF 12.5A or 10A on 50:5 CT
LV Outgoing Feeder Fuse	315A* BS88-5 Fuse	315A* BS88-5 Fuse
LV Outgoing Alvin Fuse	315A*	315A*

(* The maximum permissible 400A fuse/ALVIN rating for these circuits would result in excessive fault clearance times, hence a 315A rating has been selected)

A series of fault level and protection studies under different network configuration to evaluate the impact on fault level and protection operation times for the proposed re-configurations. The results are discussed in following subsections.

4.1 Fault Level Results

Three-phase and single-phase fault studies have been performed as per the methodology described in section 2.2. Table 11 and Table 12 list the prospective highest three-phase and single-phase fault currents at key positions in the network

Table 11 Prospective Maximum 3P Fault Current (in kA) at Substation Pair 912548 and 912807

	Maximum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
Substation A LV Busbar	13.20	13.20	N/A	15.29
Substation B LV Busbar	13.86	N/A	13.86	15.94
Service tapping position Sub A Near End	12.79	12.79	3.66	15.15
Service tapping position Sub B Near End	13.40	3.63	13.40	15.76
Lowest fault current along the LV Feeder from Sub A	3.69	1.94	N/A	3.95
Lowest fault current along the LV Feeder from Sub B	2.27	N/A	2.42	2.50

Table 12 Prospective Maximum 1P Fault Current (in kA) at Substation Pair 912548 and 912807

	Maximum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
Substation A LV Busbar	13.83	13.83	N/A	15.41
Substation B LV Busbar	14.53	N/A	14.53	16.10
Service Cut-out Sub A Near End (2m Service Cable)	11.74	11.74	2.16	12.78
Service Cut-out Sub B Near End (2m Service Cable)	12.21	2.16	12.21	13.23
Service cable Sub A Far End (20m Service Cable)	1.57	0.93	N/A	1.63
Service cable Sub B Far End (20m Service Cable)	1.06	N/A	1.13	1.14

4.1.1 Fault levels: Normal radial configuration

The study results show that the highest three phase fault level is 13.86kA which is comfortably within the maximum value of 25.9kA quoted in P25/2. As for the fault level at the nearest feasible customer tapping position, the values are also within the P25/2 specified values.

The maximum single phase fault levels are comparatively higher at 14.53kA (due to transformer zero sequence impedance assumption; see section 2.3.1). Single-phase customers connected close to the substation experience a maximum fault level of 12.21kA which is within the 16kA value specified in P25/2. The single phase value falls away rapidly as the distance along the feeder increases

4.1.2 Fault levels: Transformer outage conditions

As expected, there is no change in fault levels for positions up to the normally open point. At the far end of the extended feeder, 3 phase fault level falls to 1.94kA. This also has an impact on single-phase fault levels at customer cut-out which drops to a minimum value of 0.93kA.

4.1.3 Fault levels: Meshed configurations

Initial studies were performed to establish which fault positions produce the highest fault levels within the meshed circuit. The studies demonstrated clearly that the worst case is at the substation busbars rather than any point along the feeder cables.

Maximum three-phase fault levels at the substation busbars are increased under the meshed configuration, but only by 15% (15.94kA being the highest) and still comfortably within the 25.9kA value quoted in P25/2. As expected, the fault levels at the normally open point are approximately doubled compared with the radial configuration.

Maximum single-phase fault levels at the substation busbars are also higher than the radial configuration, with an increase of 10.8% (16.1kA being the highest).

4.1.4 Fault levels: Summary

It is seen that the under meshed configuration, the fault level at the substation busbars increases by up to 15% for three-phase faults and 10.8% for single phase faults. Under meshed configuration, the highest three phase fault current at the substations was 15.94kA, demonstrating compliance with P25/2.

Fault levels at single phase service cutout positions are a maximum of 13.23kA, against the P25/2 limit of 16kA.

4.2 Protection Results

Three-phase and single-phase protection studies have been performed as per the methodology described in section 2.2. Table 13 lists the longest fault clearing times for both BS88-5 fuses and ALVIN.

Table 13 **Protection Clearance Times (in Seconds) for Substation Pair 912548 and 912807**

	Minimum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
3P Longest Clearance Time for LV Mains Feeder from Sub A	0.06 (Fuse) 0.02 (Alvin)	1.01 (Fuse) 0.34 (Alvin)	N/A	0.52 (Fuse) 0.17 (Alvin)
3P Longest Clearance Time for LV Mains Feeder from Sub B	0.47 (Fuse) 0.16 (Alvin	N/A	0.47 (Fuse) 0.16 (Alvin)	3.69 (Fuse) 1.33 (Alvin)
1P Longest Clearance Time for LV Service Cable from Sub A	2.28 (Fuse) 0.84 (Alvin)	28.66 (Fuse) 10.01 (Alvin)	N/A	18.31 (Fuse) 6.66 (Alvin)
1P Longest Clearance Time for LV Service Cable from Sub B	14.14 (Fuse) 5.35 (Alvin)	N/A	14.14 (Fuse) 5.35 (Alvin)	190.2 (Fuse) 54.6 (Alvin)

The time-overcurrent plots for these studies are presented in Appendix II. Readers may wish to refer to Table 2 and Figure 4 while evaluating results presented in Table 13 and Appendix II.

4.2.1 Protection results: Normal radial configuration

Three-phase cable faults up to the end of the longest branch would be cleared within 0.47s by BS88-5 fuses. A substitution of the 315A BS88-5 fuses by the proposed 315A ALVIN device changes this maximum operating time to 0.16s.

For faults at the end of a 20-metre single-phase service located at the end of the longest branch, the maximum BS88-5 fuse clearance times of 2.28s (A) and 14.14s (B) are accelerated to 0.84s and 14.14s when ALVINs are installed.

4.2.2 Protection results: Transformer outage conditions

When either transformer is switched out, the entire circuit is fed from either Sub A or Sub B. Three-phase faults at the remote end of the extended feeder would be cleared by BS88-5 fuse within 1.01s. Substituting ALVINs for the BS88-5 fuses reduces the maximum fault clearance times to 0.34s.

For faults at the end of a 20-metre single-phase service located close to the remote end, the corresponding maximum clearance times are 28.66s for a BS88-5 fuse and 10.01s for the ALVIN.

Each study for this condition results in fault clearance times being significantly reduced by the use of the proposed ALVIN devices over the BS88-5 fuses.

4.2.3 Protection results: Meshed configurations

Studies were performed to establish which fault positions produce the longest clearance times within the meshed circuit. Due to the dual fault infeed paths under meshed configuration, the fault clearance is a two-stage process. The BS88-5 fuse or ALVIN closest to the fault will operate first. When this occurs, the circuit configuration reverts to that of an extended feeder, with the fault now fed from the remote substation (as per section 3.2.2). Therefore, the total fault clearance time is the sum of the local fuse/ALVIN operating time added to the operating time of the remote fuse/ALVIN. Two plots (a & b) are presented for each fault under the meshed configuration to illustrate the two-stage fault clearance.

Three-phase faults at a circuit end would be cleared by BS88-5 fuses within 3.69s, but substituting ALVINs for the fuses reduces the maximum fault clearance times to 1.33s.

For faults at the end of a 20-metre single-phase service located close to either circuit end, the corresponding maximum clearance times are 190.2s for the existing fuse and 54.6s for the ALVIN.

HV faults at both A and B substations whilst operating meshed result in the fault being backfed through the transformer at that site. The total fault clearance time for this condition is less than 0.15s where 315A fuses are employed and less than 0.05s for the ALVIN. The maximum permitted time for this condition, as advised by WPD, is 3s.

Operating times show a clearance time reduction of 50% or greater when the ALVIN devices are deployed in place of BS88-5 fuses.

All modelled total fuse clearance times for the meshed condition are pessimistic; they do not take account of the effect of the initial fault current flowing through the second Fuse/Alvin device which trips, which would accelerate the true device operation time compared to the calculated value.

4.2.4 Protection results: Summary

The use of 315A ALVINS results in a reduction in fault clearance times of approximately 50% compared to the equivalent-rated BS88-5 fuses for all single-and three-phase faults.

Though the feeder and service cutout fault clearance times are increased when the network is operating meshed configurations, they are still within the WPD design limit of 60s (LV faults) and 3s (HV faults) when the proposed ALVIN device is employed.

All fault clearance times stated in these studies are applicable to the minimum possible HV network fault level, as specified by WPD. A normal, higher, fault level will result in a general reduction in these times.

5. Plymouth: Canefields Ave (332853) and Lotherton Close (332770)

Canefields Ave (Substation ID: 914721) and Lotherton Close (Substation ID: 915800) are situated in the Plymouth region. These substations are supplied from the same 11kV network and are equipped with 315kVA and 500kVA transformer respectively. Table 14 below lists the electrical asset data utilised for the fault current and protection studies

Table 14 Network Data for Substation Pair 332853 and 332770

	Substation A (332853)	Substation B (332770)
Transformer Rating	315kVA	500kVA
Transformer Impedance	4.54%	4.69%
Transformer HV Protection	TLF 7.5A or 5A on 50:5 CT	TLF 12.5A or 10A on 50:5 CT
LV Outgoing Feeder Fuse	315A BS88-5 Fuse	315A* BS88-5 Fuse
LV Outgoing Alvin Fuse	315A	315A*

(* The maximum permissible 400A fuse/ALVIN rating for this circuit would result in excessive fault clearance times, hence a 315A rating has been selected)

A series of fault level and protection studies under different network configuration to evaluate the impact on fault level and protection operation times for the proposed re-configurations. The results are discussed in following subsections.

5.1 Fault Level Results

Three-phase and single-phase fault studies have been performed as per the methodology described in section 2.2. Table 15 and Table 16 list the prospective highest three-phase and single-phase fault currents at key positions in the network

Table 15 Prospective Maximum 3P Fault Current (in kA) at Substation Pair 332853 and 332770

	Maximum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
Substation A LV Busbar	9.00	9.00	N/A	10.88
Substation B LV Busbar	13.63	N/A	13.63	15.44
Service tapping position Sub A Near End	8.83	8.83	3.19	10.87
Service tapping position Sub B Near End	13.23	2.99	13.23	15.23
Lowest fault current along the LV Feeder from Sub A	3.39	2.99	N/A	3.35
Lowest fault current along the LV Feeder from Sub B	2.01	N/A	1.82	3.41

Table 16 Prospective Maximum 1P Fault Current (in kA) at Substation Pair 332853 and 332770

	Maximum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
Substation A LV Busbar	9.39	9.39	N/A	10.79
Substation B LV Busbar	14.29	N/A	14.29	15.66
Service Cut-out Sub A Near End (2m Service Cable)	8.51	8.51	1.87	9.55
Service Cut-out Sub B Near End (2m Service Cable)	12.13	1.83	12.13	13.03
Service cable Sub A Far End (20m Service Cable)	1.54	1.48	N/A	1.52
Service cable Sub B Far End (20m Service Cable)	0.96	N/A	0.89	1.50

5.1.1 Fault levels: Normal radial configuration

The study results show that the highest three phase fault level is 13.63kA which is comfortably within the maximum value of 25.9kA quoted in P25/2. As for the fault level at the nearest feasible customer tapping position, the values are also within the P25/2 specified values.

The maximum single phase fault levels are comparatively higher at 14.29kA (due to transformer zero sequence impedance assumption; see section 2.3.1). Single-phase customers connected close to the substation experience a maximum fault level of 12.13kA which is within the 16kA value specified in P25/2. The single phase value falls away rapidly as the distance along the feeder increases.

5.1.2 Fault levels: Transformer outage conditions

As expected, there is no change in fault levels for positions up to the normally open point. At the far end of the extended feeder, 3 phase fault levels fall to 1.82kA. This also has an impact on single-phase fault levels at customer cut-out which drops to a minimum value of 0.89kA.

5.1.3 Fault levels: Meshed configurations

Initial studies were performed to establish which fault positions produce the highest fault levels within the meshed circuit. The studies demonstrated clearly that the worst case is at the substation busbars rather than any point along the feeder cables.

Maximum three-phase fault levels at the substation busbars are increased under the meshed configuration, but only by 13% (15.44kA being the highest) and still comfortably within the 25.9kA value quoted in P25/2.

Maximum single-phase fault levels at the substation busbars are also higher than the radial configuration, with an increase of 9.6% (15.66kA being the highest).

5.1.4 Fault levels: Summary

It is seen that the under meshed configuration, the fault level at the substation busbars increases by up to 13.3% for three-phase faults and 9.6% for single phase faults. Under meshed configuration, the highest three phase fault current at the substations was 15.44kA, within the P25/2 recommended value of 25.9kA.

Fault levels at single phase service cutout positions are a maximum of 13.03kA, against the P25/2 limit of 16kA.

5.2 Protection Results

Three-phase and single-phase protection studies have been performed as per the methodology described in section 2.2. Table 17 lists the longest fault clearing times for both LV fuses and ALVIN

Table 17 **Protection Clearance Times (in Seconds) for Substation Pair 332853 and 332770**

	Minimum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
3P Longest Clearance Time for LV Mains Feeder from Sub A	0.09 (Fuse) 0.02 (ALVIN)	0.15 (Fuse) 0.04 (ALVIN)	N/A	1.50 (Fuse) 0.51ALVIN)
3P Longest Clearance Time for LV Mains Feeder from Sub B	0.87 (Fuse) 0.29 (ALVIN)	N/A	1.29 (Fuse) 0.45 (ALVIN	1.18 (Fuse) 0.39 (ALVIN)
1P Longest Clearance Time for LV Service Cable from Sub A	2.50 (Fuse) 0.92 (ALVIN))	2.89 (Fuse) 1.07 (ALVIN)	N/A	42.16 (Fuse) 14.27 (ALVIN)
1P Longest Clearance Time for LV Service Cable from Sub B	23.92 (Fuse) 8.62 (ALVIN)	N/A	36.82 (Fuse) 12.27 (ALVIN	33.08 (Fuse) 12.12 (ALVIN)

The time-overcurrent plots for these studies are presented in Appendix III. Readers may wish to refer to Table 2 and Figure 4 while evaluating results presented in Table 17 and Appendix III.

5.2.1 Protection results: Normal radial configuration

Three-phase cable faults up to the end of the longest branch would be cleared within 0.87s by the BS88-5 fuses. A substitution of the BS88-5 fuses by the proposed ALVIN device changes this maximum operating time to 0.29s.

For faults at the end of a 20-metre single-phase service located at the end of the longest branch, the BS88-5 fuse maximum clearance times of 2.50s (A) and 23.92s (B) are accelerated to 0.92s and 8.62s when ALVINs are installed.

5.2.2 Protection results: Transformer outage conditions

When either transformer is switched out, the entire circuit is fed from either Sub A or Sub B. Three-phase faults at the remote end of the extended feeder would be cleared by the BS88-5 fuse within 1.29s. Substituting ALVINs for the BS88-5 fuses reduces the maximum fault clearance times to significantly 0.45s.

For faults at the end of a 20-metre single-phase service located close to the remote end, the corresponding maximum clearance times are 36.82s for a BS88-5 fuse and 12.27s for the ALVIN.

Each study for this condition results in fault clearance times being significantly reduced by the use of the proposed ALVIN devices over the BS88-5 fuses

5.2.3 Protection results: Meshed configurations

Studies were performed to establish which fault positions produce the longest clearance times within the meshed circuit. Due to the dual fault infeed paths under meshed configuration, the fault clearance is a two-stage process. The BS88-5 fuse or ALVIN closest to the fault will operate first. When this occurs, the circuit configuration reverts to that of an extended feeder, with the fault now fed from the remote substation (as per section 3.2.2). Therefore, the total fault clearance time is the sum of the local fuse/ALVIN operating time added to the operating time of the remote fuse/ALVIN. Two plots (a & b) are presented for each fault under the meshed configuration to illustrate the two-stage fault clearance.

Three-phase faults at either circuit end would be cleared by BS88-5 fuses within 1.50s, but substituting ALVINs for the fuses reduces the maximum fault clearance times to 0.51s.

For faults at the end of a 20-metre single-phase service located close to either circuit end, the corresponding maximum clearance times are 42.16s for a BS88-5 fuse and 14.27s for the ALVIN.

HV faults at both A and B substations whilst operating meshed result in the fault being backfed through the transformer at that site. The total fault clearance time for this condition is less than 0.28s where 315A fuses are employed and less than 0.10s for the ALVIN. The maximum permitted time for this condition, as advised by WPD, is 3s.

Operating times show a fault clearance time reduction of 50% or greater when the ALVIN devices are deployed in place of BS88-5 fuses.

All modelled total fuse clearance times for the meshed condition are pessimistic; they do not take account of the effect of the initial fault current flowing through the second Fuse/Alvin device which trips, which would accelerate the true device operation time compared to the calculated value.

5.2.4 Protection results: Summary

The use of 315A ALVINS results in a reduction in fault clearance times of approximately 50% compared to the equivalent-rated BS88-5 fuses for all single-and three-phase faults.

Though the feeder and service cutout fault clearance times are increased when the network is operating meshed configurations, they are still within the WPD design limit of 60s (LV faults) and 3s (HV faults) when the proposed ALVIN device is employed.

All fault clearance times stated in these studies are applicable to the minimum possible HV network fault level, as specified by WPD. A normal, higher, fault level will result in a general reduction in these times.

6. Peterborough: Mariette Way Spalding (911747) and Wygate Park Spalding (911748)

Mariette Way Spalding (Substation ID: 911747) and Wygate Park Spalding (Substation ID: 911748) are situated in the Peterborough region. These substations are supplied from the same 11kV network and are equipped with 315kVA and 500kVA transformers respectively. Table 18 below lists the electrical asset data utilised for the fault current and protection studies.

Table 18 **Network Data for Substation Pair 911747 and 911748**

	Substation A (911747)	Substation B (911748)
Transformer Rating	315kVA	500kVA
Transformer Impedance	4.79%	4.6%
Transformer HV Protection	TLF 7.5A or 5A on 50:5 CT	TLF 12.5A or 10A on 50:5 CT
LV Outgoing Feeder Fuse	315A BS88-5 Fuse	315A* BS88-5 Fuse
LV Outgoing Alvin Fuse	315A	315A*

(* The maximum permissible 400A fuse/ALVIN rating for this circuit would result in excessive fault clearance times, hence a 315A rating has been selected)

A series of fault level and protection studies under different network configuration to evaluate the impact on fault level and protection operation times for the proposed re-configurations. The results are discussed in following subsections.

6.1 Fault Level Results

Three-phase and single-phase fault studies have been performed as per the methodology described in section 2.2. Table 19 and Table 20 list the prospective highest three-phase and single-phase fault currents at key positions in the network

Table 19 **Prospective Maximum 3P Fault Current (in kA) at Substation Pair 911747 and 911748**

	Maximum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
Substation A LV Busbar	8.54	8.54	N/A	9.56
Substation B LV Busbar	13.89	N/A	13.89	14.88
Service tapping position Sub A Near End	8.37	8.37	2.0	9.49
Service tapping position Sub B Near End	13.77	1.90	13.77	14.80
Lowest fault current along the LV Feeder from Sub A	3.24	1.89	N/A	3.98
Lowest fault current along the LV Feeder from Sub B	3.17	N/A	1.54	4.17

Table 20 Prospective Maximum 1P Fault Current (in kA) at Substation Pair 911747 and 911748

	Maximum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
Substation A LV Busbar	8.91	8.91	N/A	9.68
Substation B LV Busbar	14.56	N/A	14.56	15.32
Service Cut-out Sub A Near End (2m Service Cable)	8.09	8.09	1.15	8.65
Service Cut-out Sub B Near End (2m Service Cable)	12.91	1.12	12.91	13.32
Service cable Sub A Far End (20m Service Cable)	1.54	0.94	N/A	1.89
Service cable Sub B Far End (20m Service Cable)	1.41	N/A	0.78	1.70

6.1.1 Fault levels: Normal radial configuration

The study results show that the highest three phase fault level is 13.89kA which is comfortably within the maximum value of 25.9kA quoted in P25/2. As for the fault level at the nearest feasible customer tapping position, the values are also within the P25/2 specified values.

The maximum single phase fault levels are comparatively higher at 14.56kA (due to transformer zero sequence impedance assumption; see section 2.3.1). Single-phase customers connected close to the substation experience a maximum fault level of 12.91kA which is within the 16kA value specified in P25/2. The single phase value falls away rapidly as the distance along the feeder increases.

6.1.2 Fault levels: Transformer outage conditions

As expected, there is no change in fault levels for positions up to the normally open point. At the far end of the extended feeder, 3 phase fault levels fall to 1.54kA. This also has an impact on single-phase fault levels at customer cut-out which drops to a minimum value of 0.78kA

6.1.3 Fault levels: Meshed configurations

Initial studies were performed to establish which fault positions produce the highest fault levels within the meshed circuit. The studies demonstrated clearly that the worst case is at the substation busbars rather than any point along the feeder cables.

Maximum three-phase fault levels at the substation busbars are increased under the meshed configuration, but only by 7% (14.88kA being the highest) and still comfortably within the 25.9kA value quoted in P25/2.

Maximum single-phase fault levels at the substation busbars are also higher than the radial configuration, with an increase of 5% (15.32kA being the highest).

6.1.4 Fault levels: Summary

It is seen that the under meshed configuration, the fault level at the substation busbars increases by up to 7% for three-phase faults and 5.2% for single phase faults. Under meshed configuration, the highest three phase fault current at the substations was 14.88kA, within the P25/2 recommended value of 25.9kA.

Fault levels at single phase service cutout positions are a maximum of 13.32kA, against the P25/2 limit of 16kA.

6.2 Protection Results

Three-phase and single-phase protection studies have been performed as per the methodology described in section 2.2. Table 21 lists the longest fault clearing times for both LV fuses and ALVIN.

Table 21 **Protection Clearance Times (in Seconds) for Substation Pair 911747 and 911748**

	Minimum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
3P Longest Clearance Time for LV Mains Feeder from Sub A	0.11 (Fuse) 0.02 (ALVIN)	1.13 (Fuse) 0.38 (ALVIN)	N/A	2.64 (Fuse) 0.96 (ALVIN)
3P Longest Clearance Time for LV Mains Feeder from Sub B	0.12 (Fuse) 0.02 (ALVIN)	N/A	2.55 (Fuse) 0.94 (ALVIN)	0.85 (Fuse) 0.29 (ALVIN)
1P Longest Clearance Time for LV Service Cable from Sub A	2.50 (Fuse) 0.92 (ALVIN)	27.45 (Fuse) 9.71 (ALVIN)	N/A	84.45 (Fuse) 25.19 (ALVIN)
1P Longest Clearance Time for LV Service Cable from Sub B	3.62 (Fuse) 1.32 (ALVIN)	N/A	82.66 (Fuse) 24.55 (ALVIN)	27.81 (Fuse) 10.54 (ALVIN)

The time-overcurrent plots for these studies are presented in Appendix IV. Readers may wish to refer to Table 2 and Figure 4 while evaluating results presented in Table 21 and Appendix IV.

6.2.1 Protection results: Normal radial configuration

Three-phase cable faults up to the end of the longest branch would be cleared within 0.12s by the BS88-5 fuses. A substitution of the BS88-5 fuses by the proposed ALVIN device changes this maximum operating time to 0.02s.

For faults at the end of a 20-metre single-phase service located at the end of the longest branch, the BS88-5 fuse maximum clearance times of 3.62s (A) and 2.5s (B) are accelerated to 1.32s and 0.92s when ALVINs are installed.

6.2.2 Protection results: Transformer outage conditions

When either transformer is switched out, the entire circuit is fed from either Sub A or Sub B. Three-phase faults at the remote end of the extended feeder would be cleared by the BS88-5 fuse within 2.55s. Substituting ALVINs for the BS88-5 fuses reduces the maximum fault clearance times significantly to 0.94s.

For faults at the end of a 20-metre single-phase service located close to the remote end, the corresponding maximum clearance times are 82.66s for a BS88-5 fuse and 25.45s for the ALVIN.

Each study for this condition results in fault clearance times being significantly reduced by the use of the proposed ALVIN devices over the BS88-5 fuses.

6.2.3 Protection results: Meshed configurations

Studies were performed to establish which fault positions produce the longest clearance times within the meshed circuit. Due to the dual fault infeed paths under meshed configuration, the fault clearance is a two-stage process. The BS88-5 fuse or ALVIN closest to the fault will operate first. When this occurs, the circuit configuration reverts to that of an extended feeder, with the fault now fed from the remote substation (as per section 3.2.2). Therefore, the total fault clearance time is the sum of the local fuse/ALVIN operating time added to the operating time of the remote fuse/ALVIN. Two plots (a & b) are presented for each fault under the meshed configuration to illustrate the two-stage fault clearance.

Three-phase faults at either circuit end would be cleared by BS88-5 fuses within 2.64s, but substituting ALVINs for the fuses reduces the maximum fault clearance times to 0.96s.

For faults at the end of a 20-metre single-phase service located close to either circuit end, the corresponding maximum clearance times are 84.45s for a BS88-5 fuse and 25.19s for the ALVIN.

HV faults at both A and B substations whilst operating meshed result in the fault being backfed through the transformer at that site. The total fault clearance time for this condition is less than 1.53s where 315A fuses are employed and less than 0.55s for the ALVIN. The maximum permitted time for this condition, as advised by WPD, is 3s.

Operating times show a fault clearance time reduction of 50% or greater when the ALVIN devices are deployed in place of BS88-5 fuses.

All modelled total fuse clearance times for the meshed condition are pessimistic; they do not take account of the effect of the initial fault current flowing through the second Fuse/Alvin device which trips, which would accelerate the true device operation time compared to the calculated value.

6.2.4 Protection results: Summary

The use of 315A ALVINS results in a reduction in fault clearance times of approximately 50% compared to the equivalent-rated BS88-5 fuses for all single-and three-phase faults.

Though the feeder and service cutout fault clearance times are increased when the network is operating meshed configurations, they are still within the WPD design limit of 60s (LV faults) and 3s (HV faults) when the proposed ALVIN device is employed.

All fault clearance times stated in these studies are applicable to the minimum possible HV network fault level, as specified by WPD. A normal, higher, fault level will result in a general reduction in these times.

7. Nottingham: R.A.V.C. (910065) and St Bartholomews Way (910066)

R.A.V.C. (Substation ID: 910065) and Bartholomews Way (Substation ID: 910066) are situated in the Nottingham region. Both substations are supplied from the same 11kV network and are equipped with 800kVA and 315kVA transformers respectively. Table 22 below lists the electrical asset data utilised for the fault current and protection studies:

Table 22 Network Data for Substation Pair 910065 and 910066

	Substation A (910065)	Substation B (910066)
Transformer Rating	800kVA	315kVA
Transformer Impedance	4.85%	4.81%
Transformer HV Protection	TLF 7.5A or 10A on 100:5 CT	TLF 7.5A or 5A on 50:5 CT
LV Outgoing Feeder Fuse	400A BS88-5 Fuse	315A BS88-5 Fuse
LV Outgoing Alvin Fuse	400A	315A

A series of fault level and protection studies under different network configuration to evaluate the impact on fault level and protection operation times for the proposed re-configurations. The results are discussed in following subsections.

7.1 Fault Level Results

Three-phase and single-phase fault studies have been performed as per the methodology described in section 2.2. Table 23 and Table 24 list the prospective highest three-phase and single-phase fault currents at key positions in the network

Table 23 Prospective Maximum 3P Fault Current (in kA) at Substation Pair 910065 and 910066

	Maximum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
Substation A LV Busbar	20.63	20.63	N/A	23.30
Substation B LV Busbar	8.51	N/A	8.51	11.80
Service tapping position Sub A Near End	18.74	18.74	3.85	21.83
Service tapping position Sub B Near End	8.35	4.67	8.35	11.82
Lowest fault current along the LV Feeder from Sub A	7.02	4.25	N/A	9.19
Lowest fault current along the LV Feeder from Sub B	3.73	N/A	3.73	5.63

Table 24 Prospective Maximum 1P Fault Current (in kA) at Substation Pair 910065 and 910066

	Maximum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
Substation A LV Busbar	21.76	21.76	N/A	23.87
Substation B LV Busbar	8.87	N/A	8.87	11.28
Service Cut-out Sub A Near End (2m Service Cable)	8.37	8.37	2.27	8.48
Service Cut-out Sub B Near End (2m Service Cable)	8.53	2.89	8.53	10.64
Service cable Sub A Far End (20m Service Cable)	3.09	2.06	N/A	3.63
Service cable Sub B Far End (20m Service Cable)	2.07	N/A	2.07	2.56

7.1.1 Fault levels: Normal radial configuration

The study results show that the highest three phase fault level is 20.63kA which is comfortably within the maximum value of 25.9kA quoted in P25/2. As for the fault level at the nearest feasible customer tapping position, the values are also within the P25/2 specified values.

The maximum single phase fault levels are comparatively higher at 21.76kA (due to transformer zero sequence impedance assumption; see section 2.3.1). Single-phase customers connected close to the substation experience a maximum fault level of 8.53kA which is within the 16kA value specified in P25/2. The single phase value falls away rapidly as the distance along the feeder increases

7.1.2 Fault levels: Transformer outage conditions

As expected, there is no change in fault levels for positions up to the normally open point. At the far end of the extended feeder, 3 phase fault levels fall to 3.73kA. This also has an impact on single-phase fault levels at customer cut-out which drops to a minimum value of 2.06kA

7.1.3 Fault levels: Meshed configurations

Initial studies were performed to establish which fault positions produce the highest fault levels within the meshed circuit. The studies demonstrated clearly that the worst case is at the substation busbars rather than any point along the feeder cables.

Maximum three-phase fault levels at the substation busbars are increased under the meshed configuration, but only by up to 12.9% (23.30kA being the highest) and still comfortably within the 25.9kA value quoted in P25/2.

Maximum single-phase fault levels at the substation busbars are also higher than the radial configuration, with an increase of 9.7% (23.87kA being the highest). It was observed that single-phase fault levels on the main cable close to R.A.V.C substation are slightly high compared to the indicated 19.6kA maximum suggested in EREC P25/2. However, the network plans indicate that no customers could be connected closer than the existing nearest connection which has a 15m service cable from a tapping 15m along the main cable from the substation. The maximum fault level at this service cutout is 8.48kA, well within the 16kA maximum as per EREC P25/2. Accordingly, this is considered to be acceptable.

7.1.4 Fault levels: Summary

It is seen that the under meshed configuration, the fault level at the substation busbars increases by up to 7% for three-phase faults and 5.2% for single phase faults. Under meshed configuration, the highest three phase fault current at the substations was 23.30kA, within the P25/2 recommended value of 25.9kA.

During meshed operation, single phase fault levels on the main cable very close to R.A.V.C. can exceed the 19.6kA suggested as a typical maximum value in EREC P25/2, however connection of a customer such that it would result in excessive fault levels at the cutout is not feasible in this location. Actual maximum fault levels at modelled single phase service cutout positions are a maximum of 10.64kA, against the P25/2 limit of 16kA.

7.2 Protection Results

Three-phase and single-phase protection studies have been performed as per the methodology described in section 2.2. Table 25 lists the longest fault clearing times for both LV fuses and ALVIN.

Table 25 **Protection Clearance Times (in Seconds) for Substation Pair 910065 and 910066**

	Minimum 11kV Fault Level			
	Normal Configuration (Radial Network)	Outage TxB: Fed from Sub A (Radial Network)	Outage TxA: Fed from Sub B (Radial Network)	Meshed Configuration (Ring Network)
3P Longest Clearance Time for LV Mains Feeder from Sub A	0.02 (Fuse) 0.02 (ALVIN)	0.11 (Fuse) 0.05 (ALVIN)	N/A	0.07 (Fuse) 0.04 (ALVIN)
3P Longest Clearance Time for LV Mains Feeder from Sub B	0.06 (Fuse) 0.02 (ALVIN)	N/A	0.06 (Fuse) 0.02 (ALVIN)	0.48 (Fuse) 0.18 (ALVIN
1P Longest Clearance Time for LV Service Cable from Sub A	0.40 (Fuse) 0.20 (ALVIN)	2.41 (Fuse) 1.22 (ALVIN)	N/A	1.71 (Fuse) 0.82 (ALVIN)
1P Longest Clearance Time for LV Service Cable from Sub B	0.74 (Fuse) 0.25 (ALVIN)	N/A	0.74 (Fuse) 0.25 (ALVIN)	10.44 (Fuse) 4.27 (ALVIN)

The time-overcurrent plots for these studies are presented in Appendix V. Readers may wish to refer to Table 2 and Figure 4 while evaluating results presented in Table 25 and Appendix V.

7.2.1 Protection results: Normal radial configuration

Three-phase cable faults up to the end of the longest branch would be cleared within 0.06s by the BS88-5 fuses. A substitution of the BS88-5 fuses by the proposed ALVIN device changes this maximum operating time to 0.02s.

For faults at the end of a 20-metre single-phase service located at the end of the longest branch, the BS88-5 fuse maximum clearance times of 0.40s (A) and 0.74s (B) are accelerated to 0.20s and 0.25s when ALVINs are installed.

7.2.2 Protection results: Transformer outage conditions

When either transformer is switched out, the entire circuit is fed from either Sub A or Sub B. Three-phase faults at the remote end of the extended feeder would be cleared by the BS88-5 fuse within 0.11s. Substituting ALVINs for the BS88-5 fuses reduces the maximum fault clearance time to 0.05s.

For faults at the end of a 20-metre single-phase service located close to the remote end, the corresponding maximum clearance times are 2.41s for a BS88-5 fuse and 1.22s for the ALVIN.

Each study for this condition results in fault clearance times being significantly reduced by the use of the proposed ALVIN devices over the BS88-5 fuses.

7.2.3 Protection results: Meshed configurations

Studies were performed to establish which fault positions produce the longest clearance times within the meshed circuit. Due to the dual fault infeed paths under meshed configuration, the fault clearance is a two-stage process. The BS88-5 fuse or ALVIN closest to the fault will operate first. When this occurs, the circuit configuration reverts to that of an extended feeder, with the fault now fed from the remote substation (as per section 3.2.2). Therefore, the total fault clearance time is the sum of the local fuse/ALVIN operating time added to the operating time of the remote fuse/ALVIN. Two plots (a & b) are presented for each fault under the meshed configuration to illustrate the two-stage fault clearance.

Three-phase faults at either circuit end would be cleared by BS88-5 fuses within 0.48s, but substituting ALVINs for the fuses reduces the maximum fault clearance times to 0.18s.

For faults at the end of a 20-metre single-phase service located close to either circuit end, the corresponding maximum clearance times are 10.44s for a BS88-5 fuse and 4.27s for the ALVIN.

HV faults at both A and B substations whilst operating meshed result in the fault being backfed through the transformer at that site. The total fault clearance time for this condition is less than 1.19s where 315A fuses are employed and less than 0.55s for the ALVIN. The maximum permitted time for this condition, as advised by WPD, is 3s.

Operating times show a fault clearance time reduction of 50% or greater when the ALVIN devices are deployed in place of BS88-5 fuses.

All modelled total fuse clearance times for the meshed condition are pessimistic; they do not take account of the effect of the initial fault current flowing through the second Fuse/Alvin device which trips, which would accelerate the true device operation time compared to the calculated value.

7.2.4 Protection results: Summary

The use of 400A (R.A.V.C.) and 315A (St Bartholomews Way) ALVIN results in a reduction in fault clearance times of approximately 50% compared to the equivalent-rated BS88-5 fuses for all single- and three-phase faults.

Though the feeder and service cable fault clearance times are increased when the network is operating meshed configurations, they are still within the WPD design limit of 60s (LV faults) and 3s (HV faults) when the proposed ALVIN device is employed.

All fault clearance times stated in these studies are applicable to the minimum possible HV network fault level, as specified by WPD. A normal, higher, fault level will result in a general reduction in these times.

8. Conclusions

C1. Fault levels at all ten substation busbars, and at all customer cutout positions modelled in this report, remain in compliance with EREC P25/2 when operating in meshed configuration at the maximum possible HV system fault level. A theoretical non-compliance close to R.A.V.C. substation is not considered to be feasible in practice.

C2. HV and LV fault clearance times for ALVIN rated at 400A (Chapel Street, Pilgrim Drive and R.A.V.C.) and 315A (at the other 7 substations) are within the specified WPD limits when operating in meshed configuration at the lowest possible HV system fault level.

9. Recommendations

R1. These five circuit pairs are suitable for operation in meshed configuration when 315A and 400A ALVIN devices are employed as specified in this report.

R2. WPD LV Networks Templates Classification Tool indicates that 315A fuses would be adequate to supply assessed feeder loadings at Cosira, Lotherton Close, East Road and Wygate Road (maximum fuse rating for a 500kVA transformer is 400A). Actual circuit loadings should be verified before any existing 400A fuses are replaced by 315A ALVINS.

Appendix I Chapel Street Bere Alston (330326) and Pilgrim Drive (331615) Protection Result Plots

Please see attached electronic file

Appendix II Cosira Sleaford (912548) and East Road Sleaford (912807) Protection Result Plots

Please see attached electronic file

Appendix III Canefields Ave (332853) and Lotherton Close (332770) Protection Results Plots

Please see attached electronic file

Appendix IV Mariette Way Spalding (911747) and Wygate Park Spalding (911748) Protection Result Plots

Please see attached electronic file

Appendix V Nottingham: R.A.V.C. (910065) and St Bartholomews Way (910066) Protection Result Plots

Please see attached electronic file

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