33kV Cable Systems
HVP Reopener Application – CRC 3F
May 2019

SP Distribution Plc
SP Manweb Plc

Application for an uncertainty mechanism reopener to allowed revenue under the RIIO-ED1 price control, May 2019 reopener window.

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CONTENTS

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1. EXECUTIVE SUMMARY

This document sets out the combined submission made by SP Energy Networks (SPEN) on behalf of SP Distribution (SPD) Plc. and SP Manweb (SPMW) Plc. for an increase to allowed levels of expenditure during the RIIO-ED1 price control period.

This application is made under the High Value Project (HVP) uncertain cost reopener arrangement of Charge Restriction Condition – 3F (CRC 3F).

The proposed adjustments are submitted in light of the emergence of an asset type issue, the significance of which was not known prior to the beginning of ED1. As a result the required levels of expenditure to remediate this issue, which are of a material amount, could not be included within the SPD or SPMW ED1 business plans submissions.

The network issue is in relation to the 33kV Cable Systems in both the SPD and SPMW licence areas. A defective 33kV trifurcating cable joint, procured by SPEN between 2002 and 2010; is now exhibiting unprecedented failure rates, creating intolerable levels of system risk, stressing 33kV assets and leading to wide-scale customer supply interruptions.

During the summer of 2018, between May and July inclusive, the combined number of 33kV faults totalled 249, with 117 and 132 in SPD and SPMW respectively. At the peak of the event, SPEN managed fourteen 33kV cable faults daily; compared to a normal daily average of less than one.

Under this High Value Project submission, SPEN will return the 33kV Cable System to tolerable levels of risk through a strategic risk mitigation and intervention strategy, delivered efficiently through conventional engineering and innovation in both licences.

The HVP submission seeks adjustments to allowed levels of expenditure under a range of activities including point of failure intervention, pro-active asset replacement, monitoring equipment and additional mitigation.

The summary adjustment in each licence area to deliver the HVP is presented below.

	Proposed Adjustment £m (2012/13 Prices)
SPD	38.00
SPMW	32.07

This document includes the background to the 33kV Cable System issue and challenge in both licence areas, the needs case for effective and immediate intervention, the outputs and deliverables within the scope of the HVP and a summary of compliance against the relevant licence conditions.

Where the Authority seeks additional information to that included within the main body or appendices of this submission, SPEN welcome the opportunity to provide further information or clarity through bi-lateral meetings or supplementary questions.

2. REGULATORY CONTEXT

The RIIO-ED1 electricity distribution price control is a form of ex ante regulation, meaning allowed revenues are set at the start of the period with clearly defined DNO outputs. A DNO's allowed revenue comprises:

- Base revenue - the base amount of money that a network company can earn on its regulated business in order to recover the efficient costs of carrying out its activities;
- Incentive rewards or penalties for over or under-delivery of outputs;
- Uncertainty mechanisms - mechanisms for funding elements that could not be set up front.

Uncertainty reopeners are one form recovery for uncertain costs within the RIIO model. SPD and SPMW are facing significant network costs believed to qualify for adjustment to the RIIO-ED1 allowed revenue for each licence, applying to the price control financial model (PCFM) UCHVP value, under the High Value Project (HVP) reopener arrangement.

The move to an eight-year price control period increased the chances of unidentified high-value projects arising once allowances had been determined. Whilst it is right for DNOs to manage the risks associated with variations in small projects, uncertainty reopeners provide some protection from the financial impact of high-value projects with a value greater than £25m in 2012/13 prices.

CRC 3F sets out how the HVP reopener mechanism works. This application is made in accordance with all requirements laid out in this condition.

The submission window for applications for adjustments for uncertain cost activities is open between 1 May 2019 and the 31 May 2019.

The adjustments detailed within this application are due to factors outside of SPD and SPMW control, which could not have been foreseen and/or quantified prior to the start of the price control, and materially affect and will continue to affect network management costs.

3. INTRODUCTION

This uncertain cost reopener application is made by SP Energy Networks (SPEN) on behalf of the SP Distribution Plc. (SPD) and SP Manweb Plc. (SPMW) licences under the High Value Project (HVP) arrangement of Charge Restriction Condition 3F (CRC 3F).

This submission is in relation to an emerging 33kV cable system issue in both licences. This document presents the HVP needs case, project outputs and deliverables, and a summary of compliance against licence conditions for both SPD and SPMW. All details are presented clearly for each licence and monetary values are in 2012/13 prices.

With support from the Authority, SPEN have elected to combine the submissions of both SPD and SPMW licences as the background, intervention strategies, cost derivations, output methodologies and assessment of licence compliance are equivalent. Combination allows for brevity and clarity for the Authority in reviewing SPEN's applications. The values and proposed adjustments are clearly defined for each licence.

The appendices contain additional technical information which may be of interest or value to the Authority when forming decisions.

3.1 Background

Since the start of ED1, SPEN have experienced an exceptional and increasing trend of seasonal 33kV cable faults in both the SPD and SPMW licence areas. This is attributed to the failure of a particular type of cold-shrink 33kV cable joint, manufactured by XXX and procured by SPEN between 2002 and 2010[1].

In DPCR5, SPD experienced an average of 5.2 trifurcating joint failures/annum, and SPMW experienced an average of 14.0 failures/annum. In RIIO-ED1 this has increased to 30.3 failures/annum in SPD, and 62.3 failures/annum in SPMW, an increase of 582% and 445% in SPD and SPMW respectively. These are shown in Figure 1 and Figure 2 below.

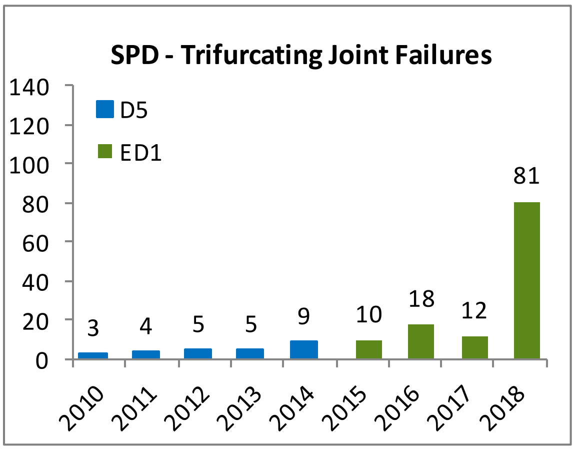


Figure 1 SPD DPCR5 to ED1 Trifurcating Joint Failures

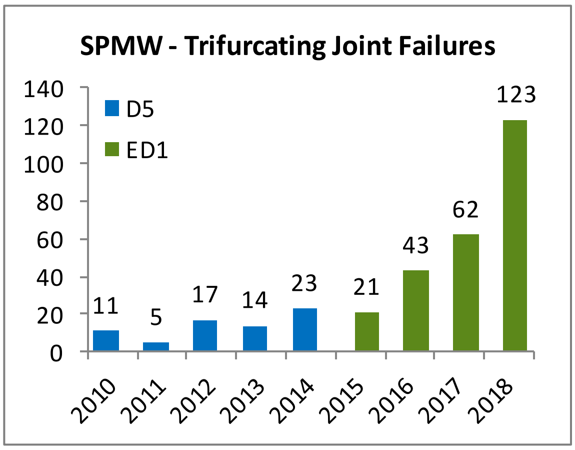


Figure 2 SPMW DPCR5 to ED1 Trifurcating Joint Failures

The challenges of managing secure customer supplies through this excessive fault activity have been enlarged by the seasonal nature of the joint failures, as they predominantly occur over the summer period. Figure 3 presents the sum of the trifurcating joint failures during ED1 by month.

[1] For brevity, throughout this document this will be referred to as the type issue trifurcating joint.

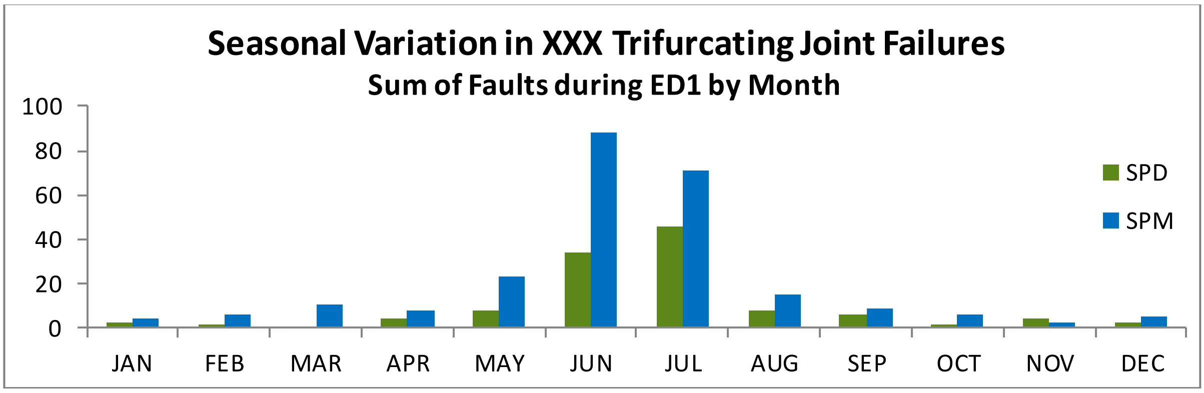


Figure 3 - Trifurcating Joint Failure Seasonal Trend

The XXX trifurcating joint suffers from a known failure mode due to a manufacturing and design deficiency, common to all joints of this particular type and date range. Investigations have concluded that all joints of this type are at risk of advanced failure by design and are subsequently end-of-life. Analysis has also determined that temperature variations contribute in part to their failure; explaining the seasonal peak.

Against an expected service life of 40-45 years, these joints exhibit failure 10-15 years after installation, with 6% of the entire population failing in the summer of 2018 alone.

3.2 High Value Project Proposal(s)

In order to manage the network risk created by this faulty equipment and to ensure a safe, secure and efficient network is provided for customers, SPD and SPMW intend to remove all affected joints within ED1 and implement additional appropriate mitigation.

Table 1 sets out the cost activities proposed for inclusion within the HVP adjustment(s).

Cost Activity	Description and Reason for Inclusion
Trifurcating Joint Fault Costs	As part of a managed end-of-life intervention programme and due to the excessive failure rate of these joints, point-of-failure intervention forms a component of the delivery programme. The fault work associated with the replacement of joints is within the scope of the HVP submissions.
Asset Intervention Costs	Where in-service underground assets e.g. cable and joints are found to be end-of-life, the only cost-effective intervention is pro-active asset replacement. The costs to replace the remaining trifurcating joints and cable assets are within the scope of the HVP submissions.
PD Monitoring Equipment Costs	The use of on-line cable partial discharge monitoring equipment enables the early identification of faults through pre-emptive detection. This informs the prioritised intervention and network re-configuration to secure supplies. Costs of this activity are within the HVP submissions.
Additional Mitigation (Voltage Reduction)	It has been determined that applying a marginal voltage reduction, may mitigate faults. Voltage reduction will be applied seasonally within both licence areas to reduce electrical stresses and fault prevalence. The cost of this activity is not within the scope of these submissions.
Incurred and Forecast Project Engineering Costs	The required project, engineering and clerical support required to deliver the above activities was previously unforeseen and allowance was not made within the price control. The costs already incurred and the forecast costs to administer the remaining fault, replacement and mitigation activities are included within these HVP submissions.

Table 1- Cost Activity and Inclusion within HVP Proposal(s)

SPD and SPMW have now commenced these projects by undertaking prioritised removal of end-of-life assets, point of failure interventions, and implementation of failure mitigation measures including additional network monitoring and voltage reduction.

The requirement and costs of these projects were not known to SPEN in advance of 2015. As such, provision was not made for them within the RIIO-ED1 business plan submissions for either licence.

4. NEEDS CASE

The root cause of increased 33kV faults on the SPEN distribution networks is attributed to a particular type of cold-shrink trifurcating-transition cable joint. This section sets out the application of these joints within distribution networks, the failure mechanism associated with the type issue trifurcating joint, the network risk created by their presence and the proposed intervention strategy.

4.1 Network Application

Cable joints are key network components used to connect cables for new connections, during fault repairs or at regular intervals on longer circuits. Trifurcating joints are installed at the transition between older 3-core paper insulated lead cables (PILC) and modern single-core cross-laminated polyethylene cables (XLPE).

Figure 4, below, illustrates a 3-core polyethylene cable entering a trifurcating joint to a single-core conductor, as shown on SPEN's geographical information system (GIS).

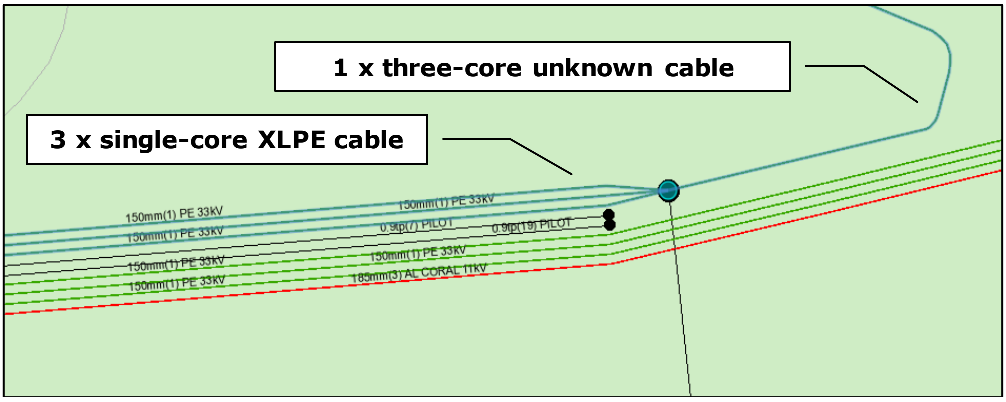


Figure 4 - GIS View of XLPE and PILC Trifurcating-Transition Joint

4.2 Fault Mechanism

The type issue trifurcating cable joints were procured by SPEN between 2002 and 2010, and installed between 2002 and 2011. The joint passed all relevant procurement tests at the time but a consistent failure mode has arisen 10-15 years after installation.

Forensic investigation of failed type issue trifurcating joints has been undertaken to confirm the root cause of failure. Early forensic analysis has found an identical failure location on all joints, at the point of highest electrical stress; as shown in Figure 5.

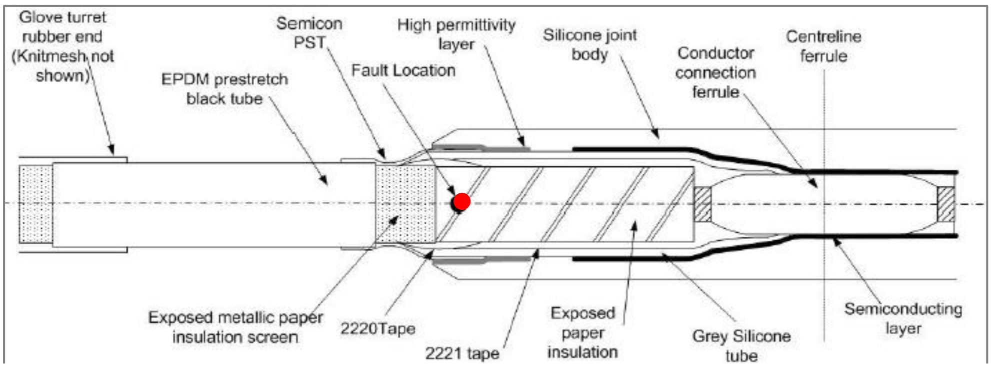


Figure 5 - Joint Construction and Failure Location (PILC Side)

The investigation has shown that the failure mechanism on all joints is also identical; moisture ingress on the paper cable side of the joint destroys the materials dielectric insulating properties, leading to the rapid onset of destructive failure. This occurs as the paper side of the joint is inadequately protected against moisture permeation; the outer layer consists of cold-shrink tubing only without an additional metallic moisture barrier. The investigation has ruled out cable deterioration or jointing techniques from contributing to the advanced failures of inspected joints.

Analysis concludes that the root cause of failure is associated with the joint design, and that all joints of this type are at risk of advanced failure.

This design was the first cold-shrink 33kV trifurcating joint procured by SPEN, and was adopted ahead of industry. This decision was taken due to the safety benefits of removing heat-shrink tools from joint bays and the utilisation of non-carcinogenic resin, used when sealing the joints. As such, SPEN is the only GB DNO affected by this issue.

At the time of submission, SPEN have contracted KEMA to undertake additional forensic analysis on recovered faulted and non-faulted joints. This work is being undertaken to confirm previous findings and to determine if there are any additional factors which influence a prioritised intervention plan.

SPEN's analysis of the seasonal nature of the enhanced failure rates shows that ambient temperature variations propagate the failure mode, with the resulting thermal-cycle causing moisture ingress and oil hysteresis, accelerating disruptive failure, Appendix 1.

SPEN have continued our commitment to use safer cold-shrink kits and now deploy a modern equivalent. Other DNOs have indicated ambitions to adopt similar solutions in our discussions with them.

In line with typical DNO procurement strategy, SPEN are unable to recover incurred costs from the supplier due to the nature of the contractual terms required to achieve unit cost in line with industry allowances.

4.3 Network Risk

In order to manage and maintain a safe, secure and reliable electricity supply, SPD and SPMW ED1 asset replacement plans are designed to remove end-of-life assets from the distribution network, and to maintain supplies under normal fault scenarios.

4.3.1 End-of-life Asset Risk

SPEN report asset replacement in the Cost and Volumes Reporting Pack (table CV7) as either Network Asset Secondary Deliverables (NASDs) or non-NASDs assets. SPD and SPMW do not currently report 33kV underground cable (33kV UG Cable (Non Pressurised)) against NASDs. Asset health is therefore not reported utilising common network asset indices methodology (CNAIM).

Despite this, CNAIM can be used to determine the health of these assets. Utilising this methodology, and application of the reliability factor, the type issue trifurcating joints are classified as health index 5 (HI5) or end-of-life. This is due to the known asset design deficiency set out in section 4.2. Had this condition been known in advance of the SPD and SPMW business plan submissions, provision would have been made for replacement of the entire population within ED1.

4.3.2 Network Fault Risk

The high prevalence of end-of-life trifurcating joints has led to exceptional network fault activity (Figure 1 and Figure 2, page 4).

The SPD and SPMW networks are designed to be secure under the requirements of Engineering Recommendation P2/6 standards. As such, EHV faults rarely result in the loss of supply to customers. However, over recent years interruptions arising from joint faults are routine; an example is set out below:

Where there is a pre-existing 33kV system outage/fault:

1. *If there **is no** interconnection at the lower voltage, a 33kV fault will result in lost supplies.*
2. *If there **is** interconnection at the lower voltage, a 33kV fault will result in inversion of the 33kV network:*
    a. *This may contravene ESQCR requirements by compromising protection operation.*
    b. *The lower voltage network may or may not be able to support the demand on the 33kV interconnector at the time of the fault.*
    c. *Where demand cannot be supported the network will trip causing interruption or equipment will deteriorate due to thermal stressing.*

The above risks increase where failures occur concurrently/coincidentally, as experienced throughout the summer months in SPD and SPMW, and can affect multiple network groups at the same time.

Table 2 sets out the number of lost supply incidents arising from trifurcating joint faults in SPD and SPMW during ED1.

	2015/16	2016/17	2017/18	2018/19
SPD	1	4	3	25*
SPMW	-	1	-	1
*22 of which are subject to one-off exceptional event application. N.B. Fewer disruptions in SPMW are due to system interconnectivity not fewer faults; in contrast network stressing and risk or large interruptions is greater in SPMW due to this interconnectivity.				

Table 2 – Lost Supply Incidents Arising from 33kV Trifurcating Joint Faults

4.4 Intervention Strategy

It is recognised that joints will continue to fail before they are all replaced, as such a portion of the asset replacement programme will be completed under fault conditions.

However, allowing these joints to fail rather than replacing them as part of a planned programme creates unnecessary stressing of the system and increases exposure to protection mal-operations and customer interruptions. The removal strategy therefore comprises of two components;

- Point of Failure Intervention – replacement of the joint upon fault and failure.
- Proactive Prioritised Replacement – removal of the joint before fault and failure either via overlay of cable sections or targeted joint replacement.

In addition to replacement of all end-of-life type issue assets, SPD and SPMW will deploy risk mitigation measures as part of a strategic risk mitigation and management programme. This includes:

- Installation of online Partial Discharge cable monitoring to prioritise interventions and enable intelligent network reconfiguration to avoid supply disruption.
- Application of a seasonal voltage reduction policy to operate at lower voltage, within statutory limits, reducing electrical stresses and failure probability.

Due to asset data challenges, there may be a quantity of joints that has not been possible to locate (section 4.4.1). These joints will continue to present network risk as they would be replaced on failure. It is therefore necessary to target all remaining identified trifurcating joints under proactive intervention.

4.4.1 Identifying Trifurcating Joint Locations

As cable joints are underground assets, they are not regularly inspected or compared against known data records. In many cases trifurcating joints have been installed during fault repairs where a cable section has been 'pieced out'. In these situations it is not uncommon for legacy asset data to have be approximate.

Trifurcating joint locations have been identified in both licence areas through purchase records, asset data records, fault records and application of an identification algorithm.

The algorithm reviews 33kV system joints against all known asset information i.e. date of manufacture, installation date, service status, joint type and number of conductors. Combining known asset markers determines the likelihood of the joint being of the type issue trifurcating design. Where the algorithm confirms or determines with Very High or High probability that the joint is of the affected type, it is positively identified as the end-of-life trifurcating-transition joint and included within the scope of this reopener.

The volume of joints replaced under ED1 will be the sum of those removed on faults to-date, and those with confirmed, high or very high likelihood type certainty. Table 3 shows the volume of 33kV joints assessed, the amount discounted by the algorithm and those identified as in-service trifurcating joints of the affected type.

Licence	Total 33kV Joints Assessed	Discounted as non-affected joint type	Identified as Affected Trifurcating Joint – In Service (April 2019)
SPD	27,288	25,483	**1,805**
SPMW	24,411	23,024	**1,387**
Total	51,699	48,507	**3,192**

Table 3 - Volume of Type Issue Trifurcating Joints in SPD and SPMW

To validate the above, logistics records for the affected joint type have been compared to the above volumes and agreed within 2.1%. The method was also verified using alternate data held in the geographical information system in SPD, which confirmed the overall volumes to within 0.1% with 95.9% accuracy. The approach is consistent in both licences.

The intervention volumes set out in section 5 will replace all of the in-service type issue trifurcating joints during ED1 through combination of reactive point-of-failure intervention and proactive asset replacement. Intervention will include targeted replacement and cable overlay where circuit integrity is compromised due to clusters of joints arising from repetitive fault repairs/joint replacements, as this is the most economic investment.

5. OUTPUTS & PROGRAMME DELIVERABLES

The proposed HVP intervention activities for the 33kV Cable System in SPD and SPMW are summarised in Table 4.

Section	Cost Activity	SPD HVP	SPMW HVP
5.1	Fault Costs	Included	Included
5.2	Asset Intervention Costs	Included	Included
-	Voltage Reduction Costs	Excluded	Excluded
5.3	Monitoring Equipment Costs	Included	Included
5.4	Incurred and Forecast Project, Engineering and Clerical Support Costs	Included	Included

Table 4 - Costs of Intervention Activities

The following sections include methodologies, justifications and breakdown of costs. As the approach is common across both the SPD and SPMW licence applications, for brevity it is presented once, and any variations are clearly highlighted.

5.1 Trifurcating Joint Fault Costs

It is recognised that joints will continue to fail before they are replaced, as such a portion of the asset replacement programme will be completed under fault conditions. The adjustment within these reopener applications include the costs of faults incurred to date and the cost of faults forecast within the remainder of the price-control.

5.1.1 Incurred Fault Cost Methodology

Faults in both licence areas are recorded within corporate data systems. Each fault is assigned unique identification linked to all associated fault repair costs. These costs are compiled by asset category for the purposes of annual reporting; Cost and Volumes Reporting (table CV26 - Faults).

Based on DPCR5 run-rates of trifurcating joint faults, ED1 allowances made inclusion for an expected volume of trifurcating joint faults. Table 5 sets out a comparison of the run-rates and scaling factor between price controls for each licence.

Licence	DPCR5 Trifurcating Joint Fault Run Rate	RIIO-ED1 Trifurcating Joint Fault Run Rate	Scaling Factor (ED1 to DPCR5)
SPD	5.2 / year	30.3 / year	582%
SPMW	14.0 / year	62.3 / year	445%

Table 5 - Run Rate of Trifurcating Joint Faults by Price Control

The proposed adjustment has been calculated as the difference between ED1 forecast costs (based on DPCR5 run-rate) and actual trifurcating joint fault costs. ED1 Forecast costs have been found by pro-rating actual in-year costs to the ED1 Forecast volumes of the same year. This method ensures costs are reflective of the activities undertaken during the current price control.

5.1.2 Forecast Fault Cost Methodology

Annual failure rate has been found by dividing in-year failed volumes by the starting population[2]. To improve statistical forecasts; SPD and SPMW failure rates have been aggregated to provide a larger data-set. As the failure mode is common this combination is reasonable.

The failure rate trend has been extrapolated using a second-order polynomial line-of-best fit. Upper and lower bands of ±25% have been applied to account for the inherent uncertainty, shown in Figure 6. Conservatively, the lower band has been adopted for cost forecasting.

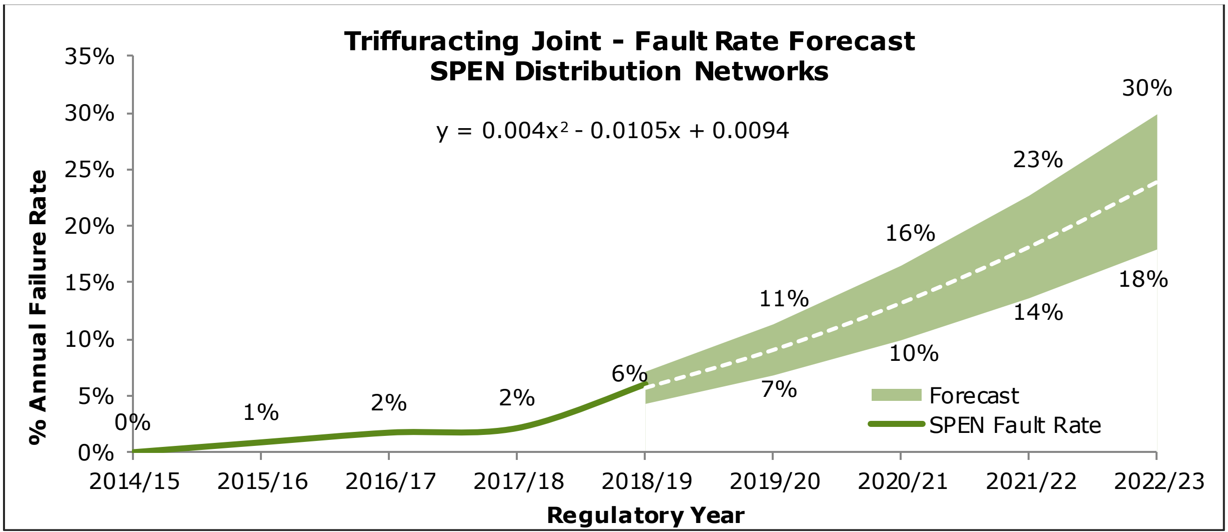


Figure 6 - Annual Trifurcating Joint Failure Rate Forecast - SPD & SPMW

5.1.3 Type Issue Trifurcating Joint Fault Cost Adjustments

The type issue fault volumes are summarised for each licence in Table 6. The proposed HVP adjustment takes account of the original (Pre-ED1) forecast fault volumes.

	Volumes RY	15/16	16/17	17/18	18/19	19/20	20/21	21/22	22/23	RIIO-ED1
SPD Fault Volume	Original ED1 Forecast	5	5	5	5	5	5	5	5	40
	Amended ED1 Forecast	10	18	12	81	117	126	113	70	547
	HVP Adjustment	**5**	**13**	**7**	**76**	**112**	**121**	**108**	**65**	**507**
SPMW Fault Volume	Original ED1 Forecast	14	14	14	14	14	14	14	14	112
	Amended ED1 Forecast	21	43	62	123	90	97	87	54	577
	HVP Adjustment	**7**	**29**	**48**	**109**	**76**	**83**	**73**	**40**	**465**

Table 6 - Proposed Adjustment Fault Volumes

The HVP adjustment costs have been calculated as the product of the adjustment volumes and peak average outturn fault costs (in 2012/13 prices), shown in Table 7.

[2] As failure volumes increase and the population declines, the forecast failure rate grows rapidly. The forecast assumes a steady planned intervention programme.

	Costs £m RY	15/16	16/17	17/18	18/19	19/20	20/21	21/22	22/23	RIIO-ED1
SPD Fault Costs	Original ED1 Forecast	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	**£xxx**
	Amended ED1 Forecast	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	**£xxx**
	HVP Adjustment	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	**£xxx**
SPMW Fault Costs	Original ED1 Forecast	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	**£xxx**
	Amended ED1 Forecast	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	**£xxx**
	HVP Adjustment	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	**£xxx**

Table 7 - HVP Adjustment Fault Costs, £m (2012/13 Prices)

5.2 Asset Intervention Costs

The remainder of type issue trifurcating joints, not replaced on fault, will be programmed for intervention during ED1, as per Table 8.

	Trifurcating Type Issue In Service Joints	Forecast to be Replaced on Fault	Joints replaced under planned Intervention
SPD	1,805	426	**1,379**
SPMW	1,387	328	**1,059**
Total	3,192	754	**2,438**

Table 8 - Trifurcating Joints replaced under planned intervention

The planned intervention activity consists of two components;

1. Cable Overlaying - removing compromised cable sections, preventing excessive joint volumes and delivering the most efficient intervention,
2. Targeted Joint Replacement – removing the remainder of the affected trifurcating joints.

These are presented in the following sections, and efficient unit cost benchmarking for both activities is provided in section 5.2.3.

5.2.1 Cable Overlaying

The most common point failure on cables is at a joint, regardless of pre-existing type issues. Subsequent to this a well-constructed network minimises joints to reduce the likelihood of disruptive customer faults.

When a trifurcating joint is replaced under fault, this introduces 4 new joints to the circuit. In most cases trifurcating joints are installed in pairs during fault repair. If these joints are replaced separately, 8 new joints are introduced to the circuit. Overlaying the cable between two trifurcating joints will result in only 2 new joints, as per Table 9.

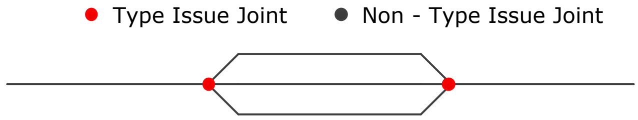
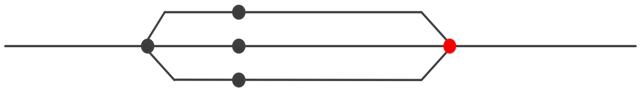
	Configuration	Description	Joint Count
1		Adjacent type issue trifurcating joints installed during fault repair between 2002 and 2011.	2
2		One type issue joint removed during fault repair during ED1.	5
3a		Second type issue joint removed as a targeted replacement.	8
3b		Second type issue joint and original fault repair overlaid.	2

Table 9 - Cable and Joint Configurations

In instances where fault repairs have been completed on one trifurcating joint as per configuration 2, intervention of the second joint will be delivered under configuration 3b.

Where circuits contain clusters of joints, or targeted joint replacement will compromise integrity (configuration 3a), overlaying cable is the preferred intervention. Table 10 shows cable lengths to be overlaid, and joints removed by this method, in each licence.

	Cable Lengths to be Overlaid (km)	Trifurcating Joints removed via Cable overlay
SPD	114.44	1,112
SPMW	85.56	712

Table 10 - Volume of Cable Overlaid and Trifurcating Joints Removed via Overlay

Table 11 presents the RIIO-ED1 schedule of works for the cable overlay interventions.

Cable Overlaying		15/16	16/17	17/18	18/19	19/20	20/21	21/22	22/23	RIIO-ED1
SPD	**Volume (km)**	0.00	0.00	0.00	0.00	28.61	28.61	28.61	28.61	**114.44**
	Cost £m	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	**£xxx**
SPMW	**Volume (km)**	0.00	0.00	0.00	0.00	21.39	21.39	21.39	21.39	**85.56**
	Cost £m	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	**£xxx**

Table 11 – Cable Overlay Cost and Volumes ED1 Schedule, £m (2012/13 Prices)[3]

5.2.2 Targeted Joint Replacement

The remainder of the type issue joints, not replaced on fault or cable overlay, will be scheduled for replacement within the remainder of RIIO-ED1. As per the outcome of forensic investigation all joints are susceptible to failure due to design deficiencies. Subsequently these joints are end of life and scheduled for pro-active replacement.

[3] Total values are correct - summation differences are due to rounding errors.

Table 12 presents the breakdown of volumes replaced under targeted joint replacement.

	Replaced via Cable Overlay	Targeted Joint Replacement	Total
SPD	1,112	267	**1,379**
SPMW	712	347	**1,059**

Table 12 - Breakdown of Joint Removal Activities

Table 13 presents the schedule of volumes and costs for targeted joint interventions.

Targeted Joint Replacement		15/16	16/17	17/18	18/19	19/20	20/21	21/22	22/23	RIIO-ED1
SPD	**Volume**	0	0	0	85	47	47	47	41	**267**
	Cost £m	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	**£xxx**
SPMW	**Volume**	0	0	0	63	72	72	72	68	**347**
	Cost £m	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	£xxx	**£xxx**

Table 13 - Targeted Joint Replacement Costs & Volumes ED1 Schedule (2012/13 Prices)

5.2.3 Unit Cost Benchmarking

<u>33kV UG Cable (Non Pressurised) - Replacement</u>

Costs for the above activity have been benchmarked against SPD and SPMW outturn unit costs, industry outturn costs, and Ofgem's expert view of unit cost for the ED1 determination; these have been compared with SPEN's internal unit cost analysis.

	Unit	SPD Average Outturn	SPMW Average Outturn	SPEN Analysis	Industry Average Outturn	Ofgem Expert View[4]	HVP Proposal
33kV UG Cable (Non Pressurised)	km	£xxx	£xxx	£xxx	£xxx	£xxx	**£xxx**

Table 14 - 33kV UG Cable (Non Pressurised) Replacement - CV7 Unit Cost Benchmarking

<u>33kV UG Cable (Non Pressurised) - Joint Replacement</u>

As per Annex A of the Regulatory Instructions and Guidance, "Replacement of cable joints and terminations (including sealing ends)" is the only reportable under Cost and Volumes table CV8 - (Refurbishment no SDI) against the 33kV UG Cable (Non Pressurised) asset category.

Prior to 2018/19, SPD and SPMW have not undertaken 33kV joint replacements; subsequently there is no internal unit cost precedent. The industry average outturn over ED1 aligns with our internal analysis and provides a reasonable baseline for estimation.

	Unit	SPEN Average Outturn	SPEN Analysis	Industry Average Outturn	Ofgem Expert View	HVP Proposal
33kV UG Cable (Non Pressurised) Joint Replacement	km	£xxx	£xxx	£xxx	£xxx	**£xxx**

Table 15 - 33kV UG Cable (Non Pressurised) Joint Replacement – CV8 Unit Cost Benchmarking

[4] Ofgem Expert View from MEAV Slow Track values provided by Ofgem in support of ED1 final determinations.

5.3 PD Monitoring Equipment Costs

Delivery of the installation of an innovative online partial discharge (PD) cable monitoring system in 12 substations in SPD and 10 in SPMW is within the scope of the reopener.

Partial discharge is an electrical phenomena in high voltage (HV) and extra high voltage (EHV) systems where dielectric insulation is deteriorating. PD provides a well-established indicator of asset condition and is a common pre-cursor of asset failure. It is used extensively for transformer and switchgear assets but has not previously been commonly used for cable assets due to challenges distinguishing between noise and legitimate PD.

Recent developments in online (energised) cable PD monitoring using artificial intelligence and self-learning algorithms have brought several online cable PD monitoring solutions to commercial readiness. SPEN have engaged two key suppliers in this field to deploy trials in the SPMW and SPD licence areas. The first trial is currently underway in SPMW; an extract of the live system report is shown in Figure 7.

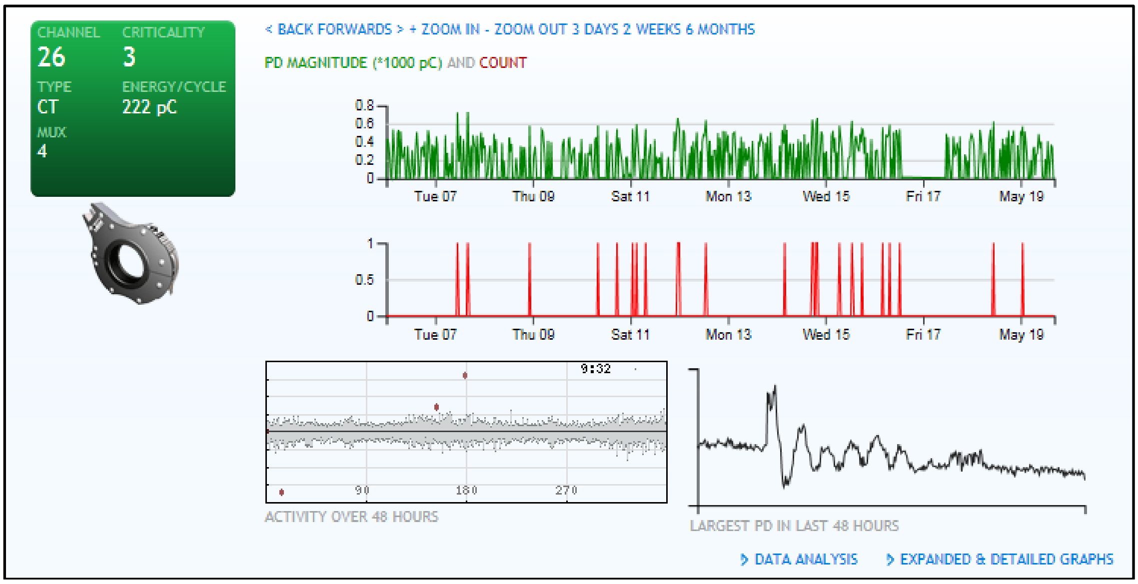


Figure 7 - Extract from Online Cable PD monitoring system –SPMW trial

The trial has determined that the equipment can be successfully installed on both EHV cable networks and marginal PD activity has already been detected. Monitored circuits have not yet faulted during the trial and accordingly no PD spikes have been recorded.

The benefits of this technology are two-fold; where significant PD activity is detected on EHV cable circuits and mapped to the location of known type issue trifurcating joints:

1. Targeted joint replacement can be accelerated to remove the asset pre-failure, preventing undue system stress and mal-operation exposure through faults.
2. Dynamic system re-configuration can be undertaken by the operational network management centre to de-energise the circuit and/or secure supplies.

In order to obtain optimum coverage, SPEN have identified sites with a high density of the type issue joint on connected circuits, for the installation of this solution.

SPEN do not have precedent of installation and have engaged with industry suppliers to understand the cost of equipment and installation at these sites. These values are commercially sensitive and have been aggregated on a licence basis for this submission.

	Number of Sites	Total Cost £m
SPD	12	xxx
SPMW	10	xxx

Table 16 - Online Cable PD Monitoring Costs, £m (2012/13 prices)

Only equipment purchasing and installation costs are included within the scope of this reopener. The ongoing service level agreements and costs of reactive works triggered by monitoring results are not included. Full installation will be scheduled for the 2019/20 regulatory year, with all cost adjustments allocated to this year.

5.4 Project Team Costs

To facilitate design and delivery of the project within RIIO-ED1 timescales, dedicated project teams will be established with 10 full time equivalent (FTE) staff in SPD and 9 in SPMW. The project team structure consists of a design and delivery component under a single project manager, as presented in Figure 8.

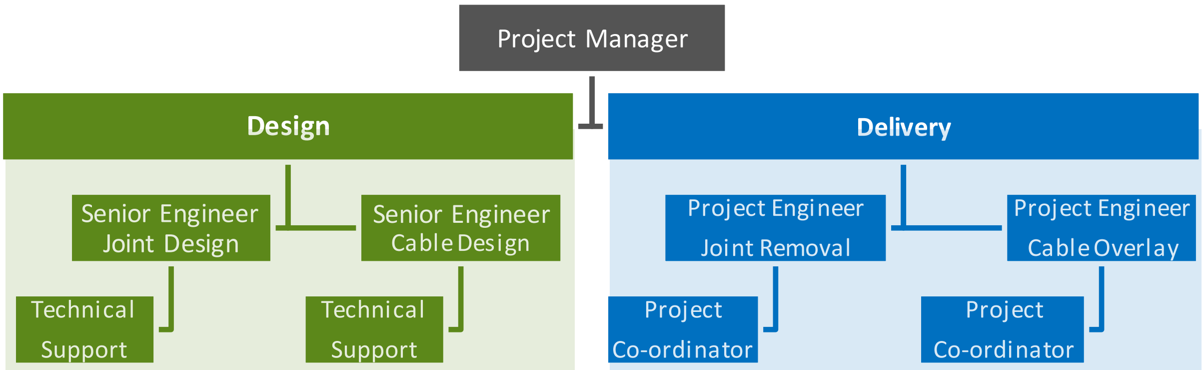


Figure 8 - HVP FTE Team Structure in SPD & SPMW

The division of labour in each licence is presented in Table 17.

Role	SPD FTE Design	SPD FTE Delivery	SPD FTE Total	SPMW FTE Design	SPMW FTE Delivery	SPMW FTE Total
Project Manager	0.5	0.5	1	0.5	0.5	1
Senior Engineer - Joint Design	1.5	0	1.5	1	0	1
Senior Engineer - Cable Design	1.5	0	1.5	1	0	1
Technical Support - GIS/Network Data	2	0	2	2	0	2
Project Engineer - Joint Removal	0	1	1	0	1	1
Project Engineer - Cable Overlay	0	1	1	0	1	1
Technical Support – Project Coordinator	0	2	2	0	2	2
Project Sum FTE	**5.5**	**4.5**	**10**	**4.5**	**4.5**	**9**

Table 17 - Project Team Division of Labour

The breakdown of costs over the price control period is shown in Table 18.

Project Team Costs	15/16	16/17	17/18	18/19	19/20	20/21	21/22	22/23	RIIO-ED1
SPD	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	**xxx**
SPMW	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	**xxx**

Table 18 - Project Team Costs over RIIO-ED1, £m (2012/13 Prices)

5.5 Statement of Costs

A summary of the HVP adjustment for the SPD licence is shown in Table 19, and a summary of the HVP adjustment for the SPMW licence is shown in Table 20. These adjustments are the minimum cost, efficient requirements to mitigate the 33kV cable system risk in SPD and SPMW. All values are presented in 2012/13 prices as per CRC 3F.3.

SPD	Close Out Precedent	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22	2022/23	RIIO-ED1
Cable Overlay	CV7	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	**xxx**
Targeted Joint Replacement	CV8	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	**xxx**
Fault Costs	CV26	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	**xxx**
PD Monitoring Equipment	CV11[5]	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	**xxx**
Project Team (EMCS)	C9[6]	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	**xxx**
Total	-	0.04	0.10	0.06	1.96	9.46	9.27	9.16	8.77	**38.00**

Table 19 - SPD Summary of HVP Adjustment, £m (2012/13 Prices)[7]

SPMW	Close Out Precedent	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22	2022/23	RIIO-ED1
Cable Overlay	CV7	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	**xxx**
Targeted Joint Replacement	CV8	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	**xxx**
Fault Costs	CV26	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	**xxx**
PD Monitoring Equipment	CV11	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	**xxx**
Project Team (EMCS)	C9	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	**xxx**
Total	-	0.06	0.25	0.37	2.61	7.25	7.10	7.00	6.61	**32.07**

Table 20 - SPMW Summary of HVP Adjustment, £m (2012/13 Prices)

[5] Costs and Volumes Table CV11 – Operational IT & Telecoms
[6] Costs table 9 – Core CAI (Closely Associated In-directs)
[7] Total values are correct - summation differences are due to rounding errors.

6. PROPOSED OUTPUT MEASURES

In addition to scheme design, project co-ordination and delivery, the project team will be responsible for the internal monitoring of programme delivery and milestone tracking. This team will also report on HVP progress under the CV23 – HVP RRP category.

6.1.1 Proposed Close out Methodologies

There are similarities between the activities within this adjustment and other regulatory areas, as such SPEN seek comparable output measures for close-out. The same close out approach is proposed for both licences.

Output	Precedent	Unit	Output Measure
Cable Overlay	**CV7**	**km**	This application sets a volume of km of cable that must be efficiently replaced to deliver intervention. Project costs have been derived as the product of volumes and efficient unit costs. It is proposed at close-out, review of actual delivered volumes is used to apply any adjustment using the agreed unit cost.
Targeted Joint Replacement	**CV8**	**Each**	This application sets a volume of targeted cable joints that must be efficiently replaced to deliver intervention. Project costs have been derived as the product of volumes and efficient unit costs. It is proposed at close-out, review of actual delivered volumes is used to apply any adjustment using the agreed unit cost.
Fault Costs	**CV26**	**Each**	This application details incurred and forecasts fault volumes. Adjusted expenditure has been derived as the product of these volumes and unit costs to date. It is proposed at close-out an adjustment is made to the actual incurred fault costs attributed to the trifurcating joints type issue.
PD Monitoring Equipment	**CV11**	**Each**	This application sets a volume of sites under which PD monitoring equipment will be installed. Costs have been derived using industry rates. It is proposed at close-out, a review of volumes of completed sites is used to scale the allowed adjustment with respect to delivered volumes proportionally. Any over delivery adjustment should be capped to +20%.
Project Team (EMCS)	**C9**	**£**	The project team costs have been derived using SPENs internal rates. The measure of the team's success is the full removal of all joints. It is proposed at closeout, allowance is reviewed against the remaining volume of type issue trifurcating joints. Any adjustment should be compared against the % of remaining trifurcating joints from Table 3. Where there are 0 joints remaining, 100% of the proposed team costs should be allowed.

The volumetric adjustments proposed are comparable to the close-out methodology applied under the Link Box reopener arrangement. SPEN endorse this simple volumetric approach, as it is readily recordable using existing reporting mechanisms and has full transparency and accountability.

<u>Efficient Delivery</u>

At each intervention SPEN strive to deliver the most cost effective solution that ensures network security. SPEN will endeavour to deliver at lowest cost whilst achieving a secure network, free from type issue trifurcating joints. At close out, any expenditure afforded under this HVP should be allowed on the basis of efficient intervention.

<u>Materiality</u>

SPEN propose that if any adjustment required under the above metrics is less than the materiality thresholds set out in Table 2 of Appendix 1 of CRC 3F, there shall be no positive or negative adjustments to the total adjustment values presented in Table 19 and Table 20 of this application.

7. SUMMARY OF COMPLIANCE AGAINST HVP LICENCE CONDITIONS

CRC 3F.8 of the SPD and SPMW electricity distribution licence sets out the conditions under which uncertain cost reopeners must be made. SPEN has considered these HVP reopener applications against the requirements set out within the condition;

a) *Is based on information about the actual or forecast level of efficient expenditure on the uncertain cost activity that was either unavailable or did not qualify for inclusion when the licensee's Open Base Revenue Allowance was derived.*

SPEN considers this HVP application meets this requirement - as the 33kV trifurcating joint issue and its impact upon the cable system had not emerged when the Opening Base Revenue Allowance was prepared for SPD or SPMW, as outlined in section 3.

Following the summer of 2018, it is clear that the volume of faults contribute to an emerging trend of an increasing peak in 33kV underground faults between May and July.

Figure 9 shows 33kV trifurcating joint faults/month since January 2013. The first noticeable increase occurred in summer 2016 in both SPD and SPMW. The trend continued in 2017 in SPMW, whilst SPD volumes were comparable with the previous year. In 2018, both licences experienced a significant increase on previous fault rates.

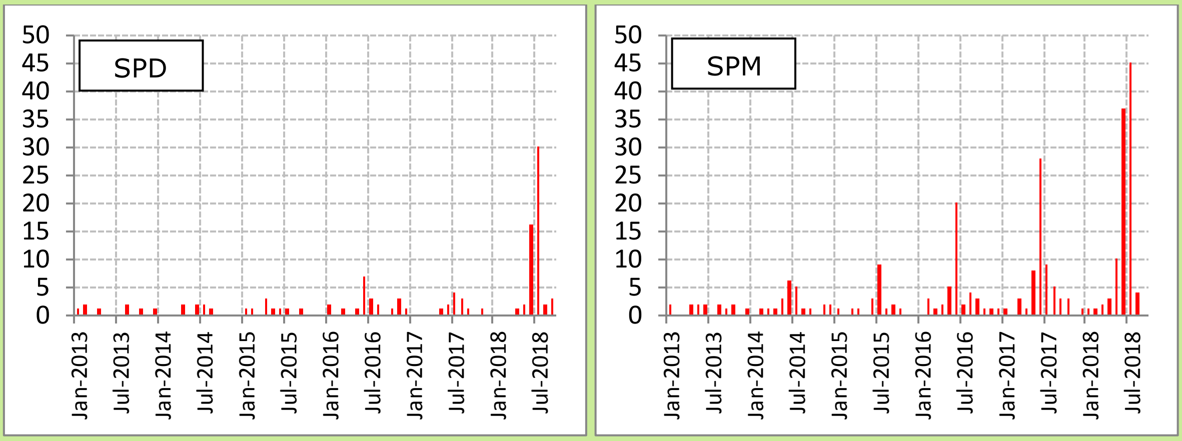


Figure 9 - SPD and SPMW Trifurcating Transition Joint Failures

Alongside this trend, analysis has confirmed that all joints are at high risk of accelerated failure, creating significant network security concerns.

It is SPEN's view that costs to address this issue during RIIO-ED1 qualify for consideration of adjustment to allowed expenditure during the RIIO-ED1 period

b) *Takes account of any relevant adjustments previously determined under this condition.*

These HVP reopener applications meet this requirement – there have been no previous relevant adjustments under this condition.

c) *For all uncertain cost activities other than High Value Project Costs, constitutes a material amount as specified for the licensee in Appendix 2, 3, 4 or 5.*

This condition is not applicable as SPEN's submission is an HVP reopener.

d) *For High Value Project Costs passes the tests set out in Appendix 1.*

These applications meet this requirement – the below checks against the tests in Appendix 1 of CRC 3F have been completed. All values are in £m, 2012/13 Prices.

A1.2

$$(\max(TUCHVPF - TUCHVPov, \quad TUCHVPov - TUCHVPF)) > MA + (20\% \ x \ TUCHVPov)$$

A1.3

The total adjustment must not exceed:

i) $TUCHVPF - TUCHVPov - (20\% \ x \ TUCHVPov)$
$Where \ TUCHVPF > TUCHVPov$; or

ii) $TUCHVPF - TUCHVPov + (20\% \ x \ TUCHVPov)$
$Where \ TUCHVPF < TUCHVPov$

Term	***Definition***	***SPD***	***SPMW***
$TUCHVPov$	*Means the total opening level of allowed expenditure that is defined as High Value Project Costs as set out in Table 2 plus any additional allowed expenditure determined under previous reopeners under this condition.*	*0.00*	*0.00*
$TUCHVPF$	*Means the proposed revised level of allowed expenditure that is defined as High Value Project costs.*	*38.00*	*32.07*
MA	*Is the material amount set out for the licensee at Table 2 of this Appendix.*	*6.47m*	*5.82m*

SPD – A1.2 Result

$\mathbf{38.00m - 0.00 > 6.47m + (20\% \ x \ 0.00)}$ **Passes**

SPD – A1.3 Result

$\mathbf{38.00 > 0.00}$

$\mathbf{38.00 - 0.00 - (20\% \ x \ 0.00) \leq 38.00}$ **Passes**

SPMW – A1.2 Result

$\mathbf{32.07 - 0.00 > 5.82 + (20\% \ x \ 0.00)}$ **Passes**

SPMW – A1.3 Result

$\mathbf{32.07 > 0.00}$

$\mathbf{32.07 - 0.00 - (20\% \ x \ 0.00) \leq 32.07}$ **Passes**

e) *Relates to costs incurred or expected to be incurred after 1 April 2015*

These applications meet this requirement – all costs will be incurred after 1 April 2015.

f) *Constitutes an adjustment to allowed expenditure that (excluding any Time Value of Money Adjustment) cannot be made under the provisions of any other condition of this licence.*

These applications meet this requirement - SPEN consider that the materiality and unforeseeable nature of the investment qualifies as a HVP and that there is no other available funding mechanism within the licence for these programmes.

The HVP uncertainty mechanism is designed to adjust a DNOs allowed expenditure where works have been identified during the price control which could not have been identified at the time opening allowed revenues were set. The likelihood of encountering uncertain HVPs has been significantly increased by the 8-year RIIO-ED1 period.

The requirements under the definition of a HVP have been met;

- The programme has clear, transparent volumetric **outputs**; km of cable, volume of joint interventions, installation of monitoring equipment and deployment of a project team to support, enable and monitor delivery. This is supported by a proposed volumetric close-out methodology.
- There is a clear **needs case** to remove end-of-life assets and the significant risk they pose to the electricity network through excessive fault activity.
- **Statements of costs** built up out of efficient proposals and have been benchmarked to out-perform industry costs.

This HVP delivery programme is comparable to previously completed high value projects; the BT 21st Century HVPs scheme of work consisted of many km of communications pilots being laid and targeted installation of marshalling kiosks and communications cabinets.

All other uncertain cost reopener arrangements are non-applicable and can be ruled out.

7.1 Ofgem's Principal Objective

SPEN have considered this submission against Ofgem's key objective of ensuring that all customers are able to access maximum value and quality of service from their energy supply. SPEN believe with certainty that accelerated, managed and strategic removal of the current exceptional level of 33kV cable system risk is in the interest of SPD & SPMW customers through reduced overall costs and improved security of supply.

The adverse creates and tolerates a situation where SPEN customers face risks of wide-scale, long-duration outages. The costs incurred through fault repair and of lost supply to customers and business is in excess of the cost of delivering an efficient intervention programme which secures customers supplies. Paired with the risk of simultaneous failure of the type issue trifurcating joints, SPEN believe this proposal obtains best value for todays and future customers.

8. APPENDIX 1 - AMBIENT TEMPERATURE INFLUENCE ON CABLE TRIFURCATING JOINT FAILURES

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AMBIENT TEMPERATURE INFLUENCE ON CABLE TRIFURCATING JOINT FAILURES

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ABSTRACT

A significant volume of 33kV cable trifurcating joint failures has prompted investigations on failure cause. Through analysing historical failure records, the majority of the failures occurred in summer and in the evening/overnight/early morning. Failures appear to occur more frequently due to a combination of a higher absolute ambient temperature and a sustained period of large day/night temperature difference. These are prospective precursors to a relative saturation hysteresis phenomenon that lowers the dielectric strength of the oil-impregnated paper insulation in the joints, increasing the probability of dielectric failures.

INTRODUCTION

SP Energy Networks (SPEN) is the owner and operator of the transmission and distribution networks in Scotland (SP Distribution), and the distribution network in the North West of England and Wales (SP Manweb).

Between May and July 2018, SPEN distribution licenses experienced an unprecedented volume of 33kV cable faults. This is also preceded by high fault volumes across the same months in the previous years, more notably from 2016 onwards.

These faults have been attributed to a type of cold shrink transition trifurcating joint procured between 2002 and 2010. In general, this joint connects older three-core oil-impregnated paper insulated lead cables (PILCs) to three single-core cross-laminated polyethylene (XLPE) cables.

As for the cold-shrink joint technology, SPEN was an early adopter realising the health and safety benefits from the use of low carcinogenic resin and the dispensability of heat-shrink tools from joint pits. Expected lifetime of this cold shrink trifurcating joint is around 40 years.

Nevertheless, as indicated by Figure 1, a significant volume of failures has arisen 10-15 years after initial installation. Forensic investigation has revealed a consistent dielectric failure mode [1].

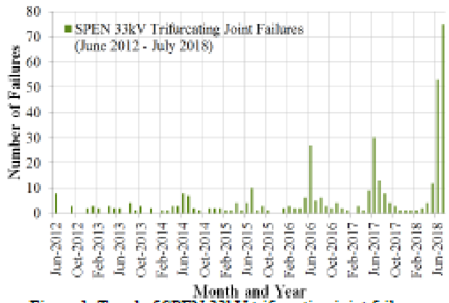

Figure 1. Trend of SPEN 33kV trifurcating joint failures (June 2012 – July 2018)

With most failures occurring between May and July, a seasonal influence is deduced. In addition, specifically to failures occurring within those months, failures appear more frequently later in the evening/overnight/early morning, suggesting a day/night influence. This is shown in Figure 2.

This paper presents findings from analysing ambient temperature records alongside historical failure records of SPEN 33kV cable trifurcating joint failures. A potential failure mechanism and an immediate remedial measure implemented by SPEN are also discussed.

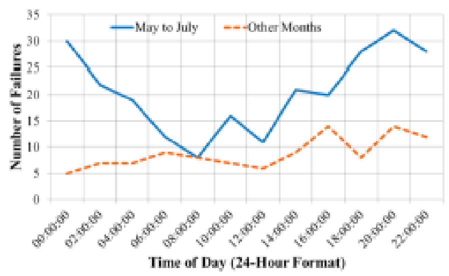

Figure 2. Time of failure of SPEN 33kV trifurcating joints (summer months versus others)

AMBIENT TEMPERATURE INFLUENCE

It is acknowledged that cable and joint temperatures can be influenced by loading level (on-load conductor loss), dielectric loss and ground temperature [2].

Although ground temperature data are not available, they can be approximated by ambient temperature as ground temperature closely follows ambient temperature variation, especially within 5m depth [3]. In addition, cables are usually installed within 1-2m depth. Thus, cable and joint temperatures can in turn be estimated from loading, dielectric loss and ambient temperature.

Typically in the UK, loading is higher in winter and lower in summer [4]. This is also perceived from Figure 3 that depicts the loading level (in terms of current) of a 33kV circuit in SP Manweb, recorded from January 2015 to July 2018.

From Figure 3, a noticeable increase in loading between October 2016 and September 2017 was due to the transfer of nearby demand to this particular circuit. Other than that, it is clear that loading is generally higher in winter and lower in summer, even during that specific period of increased loading.

Note that the summer intact MVA rating of this 33kV circuit is 20.12MVA, which equates to a current rating of 352A. With an average current loading of 62A (18% loading) as indicated from Figure 3, this circuit is lightly loaded. In fact, other 33kV circuits are also similarly lightly loaded.

Considering that a trifurcating joint is designed to be rated higher than its corresponding cable circuit, the influence of loading level on cable temperature and thus joint temperature is low.

Similar observation was also found in [5] where the temperature experienced by plant throughout a year should most likely follow the same shape (a parabolic tendency) as that exhibited by the ambient temperature, with loading generally affecting the profile more (still the same shape) during winter.

In terms of dielectric loss, it is acknowledged that it can increase from the presence of moisture or in general the ageing/degradation of the insulation (which could also be expedited by presence of moisture in case of ingress). Judging from the seasonality of the failures encountered, the more dominant influence on the failures could be from ambient temperature.

Realising the greater influence of ambient temperature, records were obtained from MetOffice for Liverpool and Crosby in the SP Manweb distribution license area. Figure 4 shows the hourly ambient temperature records (average values from both locations) from January 2015 to July 2018. The trifurcating joint failures in SP Manweb during this period are also illustrated.

With respect to Figure 4, failures seem to occur more frequently with higher ambient temperatures (during summer) and interestingly following a sustained period of large day/night temperature difference. Besides that, most failures occurred in the evening, overnight or early morning which is reflected more clearly by Figure 2.

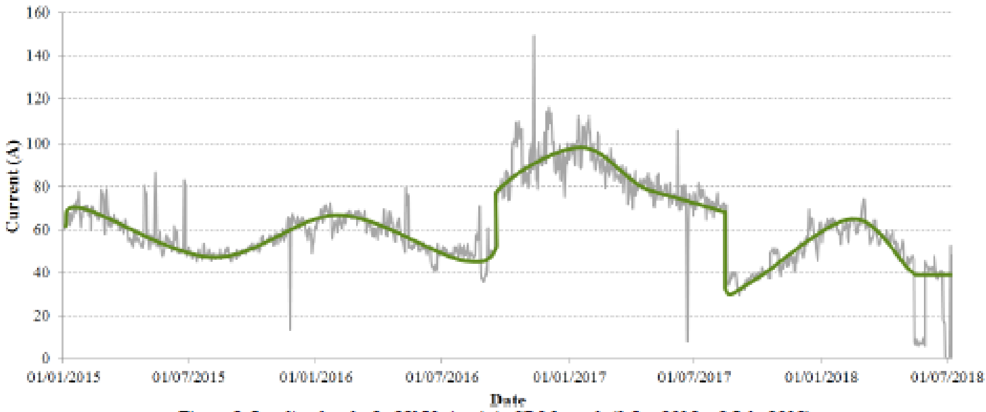

Figure 3. Loading level of a 33kV circuit in SP Manweb (1 Jan 2015 – 8 July 2018)

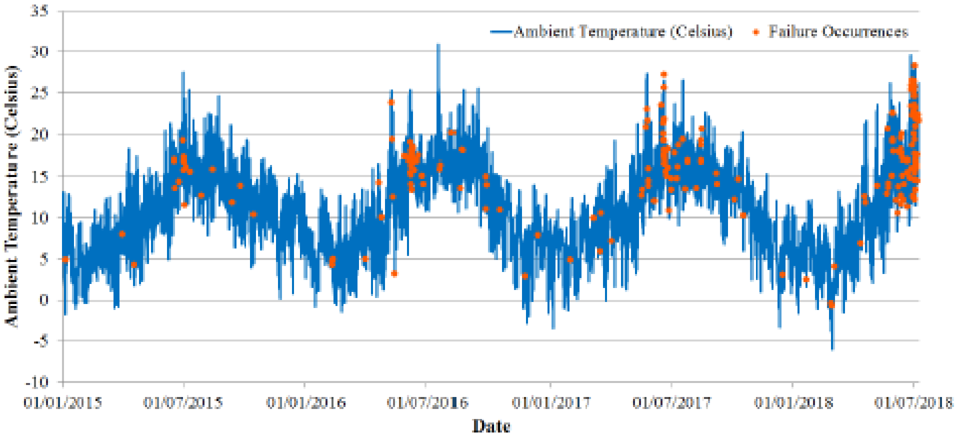

Figure 4. Ambient temperature records overlaid with failure occurrences (1 Jan 2015 – 8 July 2018)

POTENTIAL FAILURE MECHANISM

Ambient temperature is generally higher in summer than in winter. In addition, the temperature variance experienced throughout 24 hours of a single summer day is also consistently higher.

With oil impregnated paper insulation used in the joints and with temperature known to affect oil-paper moisture behaviour and properties, the temperature profile experienced by the joints could have contributed to a higher risk of failure.

Figure 5 depicts the moisture equilibrium charts for an oil-paper insulation system from [6]. In essence, an increase in temperature will induce migration of moisture from paper to oil. The reverse is also true.

Specifically on oil, Equation (1) shows the temperature dependence of moisture saturation, $M_{Saturation}$ for mineral oil as referred from IEC 60422 [7], where T_{Oil} is the oil temperature in Kelvin. Relative saturation, RS, is expressed simply as the ratio between absolute moisture in oil, M_{Oil} and the moisture saturation. This is expressed in Equation (2).

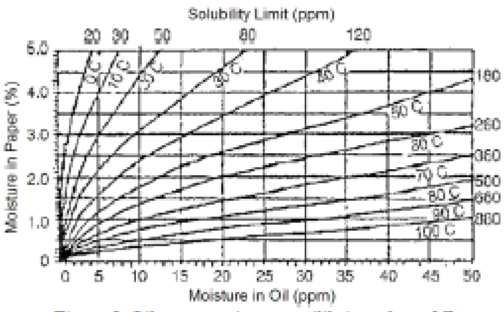

Figure 5. Oil-paper moisture equilibrium charts [6]

$$M_{Saturation} = 10^{7.0895-1567/T_{Oil}} \quad (1)$$

$$RS = M_{Oil}/M_{Saturation} \quad (2)$$

Note that moisture saturation is always the same at a given temperature (considering the same oil type and condition) [5]. Nonetheless, the RS could be different as the absolute moisture present in an insulation system varies from time to time. This together with the known oil-paper moisture migration [8] is the underlying cause behind a hysteresis phenomenon noted in [9, 10].

With reference to Figure 6 as adapted from [11], more moisture migrates from paper to oil with an increase in oil temperature. This situation resembles day time operation when ambient temperature increases to a peak on a typical summer's day.

Even with the greater moisture in oil, the oil RS can still be low as moisture saturation increases with temperature too. It is noteworthy that depending on the migration rate, the oil RS can even drop if the increase in moisture saturation is greater. This is observed from Figure 7 [11].

In the converse situation (night time operation), oil temperature drops with a decrease in ambient temperature, leading to the migration of moisture from oil back to paper. This process is slower than the migration of moisture from paper to oil. The significance of this is that the absolute moisture present in oil is still high. Together with a drop in oil temperature which causes a commensurate decrease in moisture saturation, the RS of the oil will hence be high.

In essence, higher absolute moisture and RS can be expected in the cooling phase than in the heating phase [11]. The absolute moisture and RS are also influenced by the previous temperature cycles [11]. This insinuates that such a hysteresis process can progressively cause higher absolute moisture and *RS* in oil, especially after a sustained period of high temperature difference.

Ultimately, the higher *RS* in oil means a "wetter" insulation system which translates into a notable decrease in the dielectric strength particularly in the case of free water formation (*RS* > 100%) [5]. In other words, there is a higher probability of dielectric failures.

Arguably, if a significant change in loading does occur, i.e. a further reduction in loading during night time operation when ambient temperature drops; in tandem with a further increase in loading during day time; this would exacerbate the hysteresis phenomenon.

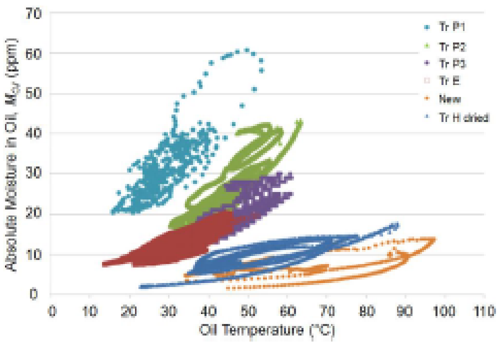

Figure 6. Absolute moisture versus oil temperature [11]

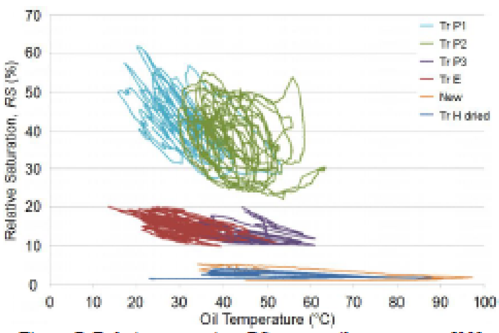

Figure 7. Relative saturation, RS versus oil temperature [11]

POTENTIAL SOURCE OF MOISTURE

Moisture needs to be present to instigate the *RS* hysteresis. With cables normally lightly loaded and even with a high ambient temperature in summer, the temperature experienced by the oil-paper insulation is unlikely to be high enough to cause severe thermal ageing/degradation which in itself is a source of moisture.

This is particularly true given that for non-thermally upgraded paper, every 6°C increase (decrease) from a reference 98°C will double (halve) the ageing rate [12]. Thus, moisture that needs to be present for instigating the *RS* hysteresis is most likely from an external source.

For the trifurcating joints under investigation, a design flaw identified via post mortem study is most likely the cause behind moisture ingress, evidenced by the discovery of moist paper insulation [1].

This initial presence of moisture could then expedite ageing/degradation of the oil-paper insulation through predominantly the auto-acceleratory hydrolysis process, which in turn produces more moisture [13]. Moreover, moisture also causes an increase in dielectric dissipation factor, directly leading to a higher dielectric loss contribution and thus a higher temperature experienced by the insulation system.

With paper being more hydrophilic than oil, more moisture would be residing in paper [8]. Eventually through the *RS* hysteresis described, more moisture will then migrate to oil, lowering the oil's dielectric strength.

This progressive increase in moisture over time from ageing/degradation is perhaps why significantly more failures occurred in the past three years (seen in Figure 1) on top of an overall seasonality nature of the failures.

IMMEDIATE MITIGATING MEASURE

The volume of faults experienced has inevitably impinged on significant risks on SPEN distribution networks. Realising the increased susceptibility to dielectric failures, SPEN employed a voltage reduction (VR) measure targeting high risk groups.

This immediate mitigating measure involved a reduction by either 3% or 5% of the standard 33kV target voltage at 132/33kV grid transformers supplying high risk urban 33kV network groups. Figure 8 shows the decreasing average failure rate following VR application in SPEN Manweb, with average failure rate dropping from 4.37 failures per day to 2.13.

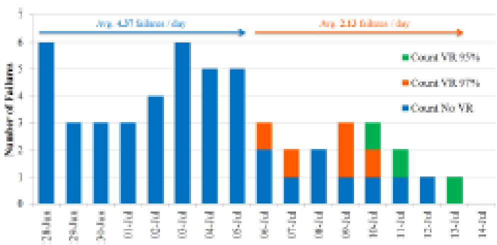

Figure 8. Voltage reduction (VR) effect on failures

Note that downstream customers are not affected by the VR application as the voltage drop is compensated by 33/11kV tap changer operation.

It is noteworthy that full unit replacement still represents the most effective intervention for underground components. Thus, in addition to increased operational readiness during summer, a systematic and risk driven approach has also commenced to replace these joints, prioritising circuits that present the most risks to network security or circuits that provide strategic significance to network operational management.

CONCLUSION

An emerging trend of 33kV cable trifurcating joint failures in SP Energy Networks (SPEN) has expedited the need for understanding potential failure cause and subsequently the implementation of remedial and pre-emptive measures.

Analysis of failure records indicated a seasonal influence, with more failures particularly from May to July. Failures also occurred more frequently in the evening/overnight or early morning.

The higher ambient temperature and the greater day/night temperature variation in summer could have most likely triggered a relative saturation hysteresis, drawing more moisture from the paper to oil in an oil-paper insulation system. This reduces dielectric strength and hence increases the probability of dielectric failures. More failures are hence to be expected, particularly with ageing/degradation of the insulation producing more moisture.

It is envisaged that accelerated ageing experiments and findings from an upcoming expert forensic analysis would aid forecasting of future fault likelihood. At present, a "summer" 33kV target voltage policy has been drafted to enact the voltage reduction measure. Concurrently, work has also commenced on prioritising joints for replacement to uphold the security of supply.

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