K-BIK Power Pty Ltd

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SUBSTATION COMMON FAILURES ASSESSMENT REVIEW

Site: United Energy - Victoria

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K-BIK Power Pty Ltd

PO Box 3204
Darra Qld 4076
Australia

MOBILE: **+61(0)409 582 263**
PHONE: **+61(07) 3466 4580**
EMAIL: **Kerry.Williams@kbikpower.com.au**
WEBSITE: **www.kbikpower.com.au**

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PREPARED FOR

United Energy
PO Box 449
Mount Waverley
VIC 3149

RESPOND TO

Kerry Williams

Director – Principal Engineer
K-BIK Power Pty Ltd
PO Box 3204, Darra, Qld 4076, Australia

T: +61(0)7 3466 4580 | **M:** +61 (0)409 582 263

E: Kerry.Williams@kbikpower.com.au

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EXECUTIVE SUMMARY

United Energy have engaged K-BIK Power Pty Ltd to investigate, analyse data and perform a third-party review of a selection of substation Common Failures within the United Energy network.

United Energy have advised that they had a need for a specialist critique, validation and provide third-party review a series of failures within zone substations that appear to have common failure causes. This report reviews a sample of failure investigation reports provided by United Energy. The report steps through United Energy's review process, the findings, the recommendations and actions and makes comment on the likelihood that there are non-common and common-cause failures.

The report includes detailed outcomes of the following:

- Performing a brief Failure Mode Effect Analysis (FMEA) on zone substation critical assets and based on the United Energy data provided.
- Research common- cause failure modes on the equipment/asset types across the industry[1] and assess the likelihood that some of these modes align with those experienced by United Energy.
- Provide an assessment of maintenance strategies and where applicable interventions undertaken that have reduced the risk of failures.
- Review of all supplied documentation and where applicable make comment on the actions recommended by United Energy and if their implementation can reduce the risk of similar failures.
- Assess the failure reports and provide comment on any perceived differences between how United Energy has performed the investigation and how K-BIK Power or others would have investigated.
- Where applicable, comment on any United Energy actions or conclusions that are contained in the reports, the reasoning behind the comments, and what the likely impact to United Energy would be.
- Assess the likelihood that some common failures are unpredictable and caused by random events.

The method of performing the above scope has included an assessment of each of the reports supplied, identification of commonalities within the investigation outcomes, and the United Energy intervention strategies with respect to failure prevention and criticality of operation and any other such important criteria. Additionally, work was done on researching other failures from around the world for these types of assets and common causes that impact multiple assets within a zone substation.

Summation of Review Findings and Recommendations

The above review objectives and requirements are discussed in detail in the relevant sections of this report however as a general summation of the findings, the following is provided:

1. Common-cause failures occur in not only substations, but across the whole of a power network. They can be random and undetected until more than one event presents itself. They can show themselves as an increasing trend within an asset class, but the overarching issue is that they will have some trend and generally affect one asset type or batch.

[1] The information is sourced from IEC, IEEE, CIGRE and EPRI failure modes, statistics, probabilities and common asset failures

2. Item specific risk assessments should be performed to understand more about individual items of plant and the risks they present – these can then roll up into the higher level assessments.
3. Review the condition monitoring strategies for all individual items of plant and what on-line and off-line methods would best support the risk reduction. It is well proven that some levels of condition monitoring can reduce the risks of failures by the early warning indicators.
4. When failures occur, an in-depth forensic investigation should be undertaken to find the root cause of the failure. Once that is found, other assets of the same family and manufactured batch should be reviewed for their risk of susceptibility to similar events and likelihood of failure. If a common-cause failure is noted, then the asset risk model needs to be reviewed and re-applied according to the type of failure and asset.
5. The findings within this review are that United Energy has a structured approach to failure investigations which has some room for improvement if appropriately funded. It has also been recognised that United Energy has experienced a number of common-cause failures which could not have been detected by any normal monitoring. These types of failures may happen again and without warning and so United Energy needs to be able to recognise such events and implement a risk model unique to that asset type and family to manage any further risk of failure.

Important Commercial note about this report

The purpose of this report and the associated services performed by K-BIK Power Pty Ltd is to undertake a review of common-cause failures within United Energy zone substations in accordance with the scope of services set out in the agreement between K-BIK Power Pty Ltd and United Energy. That scope of services, as described in this report, was developed with United Energy.

In preparing this report, K-BIK Power Pty Ltd has relied upon, and presumed accurate, information (or confirmation of the absence thereof) provided by United Energy and/or from other sources. Except as otherwise stated in the report, K-BIK Power Pty Ltd has not attempted to verify the accuracy or completeness of any such information. If the information is subsequently determined to be false, inaccurate or incomplete then it is possible that the observations and conclusions as expressed in this report may need to change.

K-BIK Power Pty Ltd derived the data in this report from information sourced from United Energy (if any) and/or available in the public domain at the time or times outlined in this report. The passage of time, manifestation of latent conditions or impacts of future events may require further examination of the project and subsequent data analysis, and re-evaluation of the data, findings, observations and conclusions expressed in this report. K-BIK Power Pty Ltd has prepared this report in accordance with the usual care and thoroughness of the consulting profession, for the purpose described above and by reference to applicable standards, guidelines, procedures and practices at the date of issue of this report. For the reasons outlined above, however, no other warranty or guarantee, whether expressed or implied, is made as to the data, observations and findings expressed in this report, to the extent permitted by law.

This report should be read in full and no excerpts are to be taken as representative of the overall findings. No responsibility is accepted by K-BIK Power Pty Ltd for use of any part of this report in any other context. This report has been prepared on behalf of, and for the exclusive use of, United Energy or associated parent Companies, and is subject to, and issued in accordance with, the provisions of the agreement between K-BIK Power Pty Ltd and United Energy. K-BIK Power Pty Ltd accepts no liability or responsibility whatsoever for, or in respect of, any use of, or reliance upon, this report by any third-party.

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ABBREVIATIONS

This is a listing of any abbreviations or acronyms that are used within the document.

Term	Description
HV	High Voltage (>/= 66kV)
MV	Medium Voltage (< 66kV but generally >1kV)
LV	Low Voltage (generally <1kV)
CB	Circuit Breaker
CT	Current Transformer
VT	Voltage Transformer
ES	Earth Switch
Tx	Transformer
DS	Disconnector
CVT	Capacitor Voltage Transformer
SA or LA	Surge Arrester or Lightning Arrester
DDF	Dielectric Dissipation Factor
PD	Partial Discharge
DGA	Dissolved Gas Analysis
TDCG	Total Dissolved Combustible Gas
DLA	Dielectric Loss Angle
pF	Power Factor
mH	milli-henry
uF	microfarads
ºC	Degree Celsius
ONAN	Oil Natural Air Natural
ONAF	Oil Natural Air Forced
kV	Kilovolts
Ez%	Impedance in %
MVA	Mega-Volt-Amperes
MW	Mega-Watts
MVAr	Mega-Volt-Amperes Reactive Power
AVR	Automatic Voltage Regulation
SLD	Single Line Diagram
FMEA	Failure Mode and Effects Analysis
MFL	Maximum Foreseeable Loss
RRR	Residual Risk Rating
UE	United Energy
AER	Australian Energy Regulator
SLD	Single Line Diagram
BTOS	Bus Tie Open Scheme

1. INTRODUCTION

Background

United Energy has approximately 47 zone substations across its network. The loads on each site vary but between 1 July 2010 and 30 June 2018 the average load across all substations was in the order of 18.6MW with the heaviest loaded substations averaging load of 36.7MW. The loss of the entire supply from any one substation has the immediate impact of increasing load on the other interconnected substations until all or part of the affect substation is returned to service. Some load shedding is necessary to manage such occurrences until all customers have their supply restored.

The bulk of the zone substations within the United Energy network have aged equipment, with a number of sites having primary assets that could be considered as beyond the industry accepted operating life. This age profile is taken into consideration when United Energy reviews its maintenance strategies and associated asset risk profiles in order to extend the asset life, manage the risk of failure and reduce the level of safety risk as far as practicable.

When K-BIK Power reviewed the supplied and publicly available documentation it was noted that some of the assets are among the oldest in Australia and considered as obsolete. A typical example is the Gardiner (K) zone substation MV switchboard which is an Email J18 oil type which are considered as obsolete and highly susceptible to failures due to aging insulation. It follows that with the obsolescence of in-service equipment there would be a lack of serviceable critical spares and as the manufacturers no longer support the equipment with spares. This means that the assets would eventually get to a point where it will not be possible to replace components even by reverse engineering the parts. Therefore, the equipment has undoubtedly reached its viable or serviceable end of life and the risk of catastrophic failures increases.

Like many Australian utilities, United Energy has recognised that they have difficulty obtaining maintenance outages and so careful planning is required to ensure the work can be done in a safe and appropriately timed manner. When there is a lack of ability to secure a planned outage, it places greater demands on the equipment and so the risk of being able to operate safely and reliably under any fault or switching event is diminished considerably.

Failure mechanisms for transformers and switchgear are generally well understood and most utilities have some level of monitoring through inspection and maintenance visits. Certain manufacturer's types of switchgear will start to rapidly show signs of deterioration through the on-set of partial discharge and increasing component wear on operating mechanisms. With transformers, there can be signs of external deterioration of sub-components while internally, the condition of the insulating oil can accelerate the deterioration of the paper insulation.

With older switchgear (e.g. greater than 45 years) the insulation systems, resin encapsulated components, operating mechanisms and arc venting capabilities are all affected by aging. The risk profiles of these assets are increased further as fault levels and load profiles increase and so the risk of a catastrophic failure increases as does the possibility of an injury to an operator.

In the latter sections of this report several aspects of aged asset risks and condition assessments are discussed and compared in the K-BIK Power FMEA and with recommendations based on the outcomes.

Scope of Work

As mentioned in the Executive Summary, United Energy has engaged K-BIK Power Pty Ltd to investigate, analyse data and perform a third-party review of possible Substation Common Failures within the United Energy network.

United Energy advised there was a need for a specialist critique, validation and provision of a third-party review of a series of failures within zone substations that appear to have had common failure causes. This report outlines the review process, the findings, gaps, and where necessary recommendations with respect to the likelihood that there are common failure modes and some of which are completely unpredictable.

The report includes detailed outcomes of the following:

- Performing a brief Failure Mode Effect Analysis (FMEA) on zone substation critical assets and based on the United Energy data provided.
- Research common- cause failure modes on the equipment/asset types across the industry[2] and assess the likelihood that some of these modes align with those experienced by United Energy.
- Provide an assessment of maintenance strategies and where applicable interventions undertaken that have reduced the risks of failures.
- Review of all supplied documentation and understand the risk criteria applied to these assets by United Energy as a result of failures.
- Assess the failure reports and provide comment on any perceived differences between how United Energy has performed the investigation and how K-BIK Power or others would have investigated.
- Where applicable, comment on any United Energy actions or conclusions that are contained in the reports, the reasoning behind the comments, and what the likely impact to United Energy would be.
- Assess the likelihood that some common failures are unpredictable and caused by random events.

United Energy have supplied K-BIK Power with a small range of failure investigation reports as a sample of the types of events that they have investigated and may fit the profile of common-cause failures. United Energy has advised that whilst the majority this sample of failures appear to be common-cause failures, there were some random events and other secondary defects that were identified and corrected.

The method of performing the above scope has included an assessment of each of the reports supplied, identification of commonalities within the investigation outcomes, and the United Energy intervention strategies with respect to failure prevention and criticality of operation and any other such important criteria. Additionally, work was done on researching other failures from around the world for these types of failures and common causes that impact a utility's assets within a zone substation.

The deliverable from K-BIK Power to United Energy is this report summarising the events studied and United Energy reports compiled, then provides a considered view as to whether United Energy are justified in classifying these as common-cause failures or whether these types of failures could be avoidable or not.

As part of the scope United Energy have provided information including:

- United Energy – K#3 11kV Bus Failure Incident Report of 25/05/2015
- K Bus Explosion Photos (embedded in email dated 09/03/2004)
- Fault Incident Report – 11kV Bus explosion at Gardiner (K) Zone Substation (4/03/04 @ 11:18am)
- Lyndale (LD) 22kV Bus No. 3 trip dated 21/05/2015
- NB13 11kV CT Failure – Incident Investigation dated 12-09-2013
- NW Transformer #1 Failure Report dated 13/09/2016
- NW No. 2 Transformer Failure Incident Report dated 11/8/2015
- UED Significant Secondary Asset Incident Summary for STO
- STO #1, #2 On-load Tap Changer Overhaul – Signed Business Case

[2] The information is sourced from IEC, IEEE, CIGRE and EPRI failure modes, statistics, probabilities and common asset failures

- STO #1 Trans 22kV CB Bushing Failure – Incident Investigation.
- BTOS Protection Setting Review dated January 2019
- UE PL 2028 ZSS Transformer Life Cycle Strategy – Version no. 6 dated August 2019

This report is structured on the basis of a review of the documentation supplied and the recommendations made are based primarily on the facts of data presented, publicly available information, general industry knowledge and the known risks of such equipment in the electrical industry.

2. ANALYSIS OF SUPPLIED DATA

United Energy Common Failure Causes Risk Review

As part of the review of the supplied data, K-BIK Power undertook a FMEA for general zone substation equipment typical of that installed within United Energy substations. Whilst it includes the primary plant only the relays are included as secondary systems. The FMEA has been performed at a high level where the assumption of one asset failure can affect other assets. The FMEA has been used to underpin the review of the United Energy reports on incidents, outages and common failure causes. Each assessment was undertaken independently of the other to assess if there are issues that have not been addressed and if the failure incident reports provided by United Energy were in line with industry norms. The outcomes and actions within the incident reports generally aligned with the FMEA and events that occur within other utilities.

As a component of each assessment common cause failures were investigated and it will be shown in this report that United Energy has had a number common cause failures within their network.

The types of faults that set off the chains of events that led to the some of the United Energy failures are common occurrences within any utility network. Plant failures are also generally a normal occurrence however, as the asset ages and more through-faults are encountered, their ability to withstand the forces and stresses are diminished. Therefore, given the age and type of assets being dealt with, some of the lower level risks identified in the incident reports and FMEA may need to be reviewed to ensure that United Energy has formal processes or procedures in place to maintain the risks at acceptable levels. Without such measures in place, the focus on the significant risks can overshadow the lower level risks and then quickly turn those lesser risks into significant risks. The United Energy ZSS Transformer Life Cycle Strategy provides a clear direction for the company to manage their risks at acceptable levels that balance safety, reliability, cost, environment and statutory requirements collectively.

The outcomes of the incident reports provided clear actions for United Energy to address for the future; however, it is not a part of the scope of this report to investigate if the actions in the reports have been completed.

Loss of Supply Risk:

When a system event (or fault) occurs, it is quite common for a loss of supply to occur. This may be anything from a momentary loss of a few second to an extended outage of a few hours. In the very short duration events, the fault is generally cleared quickly, and equipment damage is often nil or very minor. In more extended outages it is likely that equipment has been damaged or needs to be checked before supply can be restored. If an asset fails, then the load must be transferred to other parts of the network whilst the equipment is replaced or repaired.

Within many of the United Energy substations there are two or more transformers, thereby providing a level of redundancy that is required to meet the customer needs for reliability of supply. In these substations it is likely that the total loss of any one asset would not trigger a total substation outage. Some random events can trigger a total substation outage, but restoration is generally quite fast once the fault is isolated. There are other random events that can trigger additional faults, and these can often go on to cause a total substation loss of supply. Generally, these types of secondary and tertiary faults create a scenario involving many items of plant and so requires a greater level of investigation before restoration can commence.

United Energy has experienced events that have led to partial and (occasional) total loss of supply from a substation. The following summary of the supplied incident reports provides a quick overview of equipment failures that have led to the outages. This summary is also used in the latter part of this report to provide commentary on whether the events were common-cause failures.

Summary of United Energy Incident Reports:

United Energy has provided a sample of incident investigation reports to analysis as possible common-cause failures. The incidents caused partial and, in some cases, a total loss of supply from a substation. The following is a short summary of each of the incidents along with comments on the whether the events were common-cause failures and if the root cause analysis performed by United Energy was in line with industry practices.

- United Energy – K#3 11kV Bus Failure Incident Report of 25/05/2015
- Fault Incident Report – 11kV Bus explosion at Gardiner (K) Zone Substation (4/03/04 @ 11:18am)
- K Bus Explosion Photos (embedded in email dated 09/03/2004)

Overview of Incident:

There were two incident reports provided from this substation and both associated with the same switchboard. The 2 events were somewhat linked and so the summary below is based primarily around the event of May 2015 which was the failure of the No.3 11 kV bus at Gardiner (K) Zone Substation on the 25th May 2015.

The report states that the fault occurred almost immediately after the isolation of the No.3 Transformer during a planned field operator switching event. The 11 kV switchboard is the oldest Westinghouse/Email J18 switchboard on the UE network and had undergone a major refurbishment in 2002. In 2004, a flashover occurred in the No.2 11 kV bus as a result of a high resistance busbar connection as per the incident report of 4/04/2004).

The May 2015 report states that the arc fault initiated from a red-phase connection on the busbar in the No.3 11 kV bus compartment of the No.2 Transformer No.3 11 kV bus cubicle, and subsequently flashed over to white-phase, to ground, or both. The protection relays did not record any of the fault event and so vital data was not available and during the initial fault the Residual Bus protection (X Scheme) and Bus Inverse Time Overcurrent protection (Y Scheme) did not operate. The fault was cleared after the 66kV line pilot differential scheme relay operated.

The report goes on to say that there was evidence that a second 3 phase-ground fault occurred in the No.3 11 kV bus compartment of the 2-3 11 kV bus tie CB cubicle due to the rapid build-up of ionised gasses in the chamber from the initial fault.

United Energy identified the cause of the fault as a high resistance joint/connection within the No.2 Transformer No.3 11 kV bus CB cubicle as was likely introduced during the refurbishment of the switchgear in 2002. The step change in load current flow through the poor connection during the switching sequence to isolate the #3 Transformer has caused the fault.

Following the failure of the No.2 bus in 2004, a number of recommendations were made by the United Energy Asset Management group, including the testing of all connections of the switchgear and rectification of protection defects. The defects were still present when the 2015 fault occurred, and United Energy identified that the implementation of the recommendations may have prevented the fault.

Comments on Incident Report:

The report showed a detailed investigation had occurred and in general is in line with industry investigation norms. It has highlighted that there needs to be a level of follow up on any actions arising from the reports. In this case the previous incident in 2004 should have had protection changes made and so the failure may have been prevented. It is also not clear as to whether the recommendations at the end of this report have been actioned (not in the K-BIK Power scope). The report could be improved slightly by assignment of actions from the commendations so that implementation is more likely to occur.

The overall incident (preventable or not) has all the signs of the secondary event as a common-cause failure. The reasoning being that the secondary incident was triggered by the ionised gasses and particles being forced into another part of the bus chamber. The J18 switchgear like may other types of the same era did not have bus segregation between panels and so when an incident occurred in the bus chamber it often caused damage to other parts of the bus and joints. Additionally, the initial fault was likely caused by defective workmanship during the refurbishment process, these type of occurrences are also quite common if the level of expertise and attention to quality details on very old switchgear is not effective.

- Lyndale (LD) 22kV Bus No. 3 trip dated 21/05/2015

Overview of Incident:

This incident relates to an outage of 22kV bus No.3 occurred at Lyndale (LD) zone Substation which was believed to have correlated with the switching of a feeder line capacitor on LD32 which suffered an internal fault. The trip was initiated by the operation of stage one and stage two back-up earth fault (BUEF) protection at LD, which isolated 22kV bus No.3 without either the LD32 or LD33 feeder circuit breakers operating.

Assessment of plant at LD zone substation following the fault uncovered that the terminal boxes located on the neutral current transformers (CTs) for all transformers were insufficiently sealed and had allowed a significant amount of water to ingress. An insulation impedance test carried out using a Megger uncovered that the water resulted in solid short circuits over the terminals inside the terminal boxes on the neutral CTs. The water which was present in the neutral CT termination box had flowed through the control cables into the termination board within the zone substation and affected a number of terminal strips.

The above caused a high impedance earth fault which was detected by the LD32 feeder protection relay, and the recorded waveforms identified that the fault was found to be almost exclusively fed by the white phase. The report states that the MEF relay did not pick up for long enough to allow the feeder to trip the fault due to the intermittent nature of the fault. The LD32 feeder protection relay needs to detect an earth fault with current above $9A_{rms}$ and it must also receive a continuous SEF trip enable signal for 2 seconds or more from the MEF relay. While the LD32 feeder relay detected the earth fault with current above $9A_{rms}$ it did not receive a continuous SEF trip enable signal from the MEF relay. This prevented the feeder relay from tripping LD32. The BUEF relay did not rely on the station MEF relay, and therefore was able to identify and trip for the earth fault.

The report concluded that it was most likely that the high harmonic content in the fault waveform that caused the MEF relay to not operate correctly and therefore why feeder LD32 did not trip. This was due to the MEF relay being unable to sustain a consistent output for long enough to allow the interlocked LD32 feeder relay to trip. It is concluded that the BUEF relay operated correctly.

This event may have been compounded by the water ingress into the terminal boxes on the neutral CTs at LD. However, it is believed that the likelihood of this impacting the operation of the feeder relay is low due to the low voltage which would have been present between terminals in the junction box thus resulting in very little current tracking through the water.

Comments on Incident Report:

The report showed a detailed investigation had occurred and what was first thought to have been the issue was only part of the total cause. In general report, is quite detailed and investigated a wider than expected number of related issues. The recommendations looked at other sites to ensure that any common-causes could be investigated and prevented. Whilst a common-cause failure had not actually occurred, there was the propensity for it to happen by way of the moisture ingress and the neutrals of relay CTs being terminated in the same box. It is therefore concluded that this was a common-cause failure that was preventable but only after the first incident and the above thorough investigation. Implementation of the actions arising from the incident report should prevent this happening again.

- NB13 11kV CT Failure – Incident Investigation dated 12-09-2013

Overview of Incident:

This report details an incident where an 11kV CT failure within the NB 11kV switchboard failed and caused damage to the CT chamber, but left the rest of the switchboard unaffected.

The circuit breaker was a Reyrolle LMT switchboard and these switchboards date back to the mid-1950s. The CT that failed was believed to be dated late 1960s, when the station and switchboard was converted from 6.6kV to 11kV but there was no identifying year of construction on the switchboard or other components.
United Energy investigators found multiple points within the debris of the solid epoxy insulation where discharge had created internal voids. For this to occur, an air gap must be present for the fault to manifest itself. Voids are likely to occur when an air bubble is trapped during the forming of the resin insulation. Due to the voltage stress around the HV stem a discharge is likely to commence and over time, it will migrate to the surface of the CT where, in this case, a flashover occurred from the HV stem to the switchboard cubicle.

The report stated that the root cause of the fault was a void in the epoxy insulating medium of the CT. It is believed that the void was present from initial manufacture of the CT. Discharge within the void over many years resulted in its expansion until it eventually reached the outside of the CT where it flashed over to the chamber. Other evidence suggests that the manufacturing quality of this specific CT was poor.

Comments on Incident Report:

The report was quite thorough in the way it was presented and looked at all factors affecting the CTs. Within the Conclusions and Recommendations there were actions which were assigned to groups within United Energy. This is a recommended way of ensuring the outcomes of any investigation have some level of benefit to the business by improving the condition or monitoring other assets to prevent further failures.

This particular incident is a common-cause failure and as industry experience shows it is directly related to the quality of manufacture. These types of defects are difficult to detect without specific condition monitoring tests being carried out. When one of these events occurs in a switchboard CT there is generally another CT that has also started to deteriorate as they often come from the same batch and hence the quality is often the same.

- NW No. 2 Transformer Failure Incident Report dated 11/8/2015
- NW Transformer No.1 Failure Report dated 13/09/2016

Overview of Incident:

There were two incident reports provided from this substation (Nunawading) and both incidents had very similar initiation causes and outcomes. In both instances the events which triggered the faults was caused by a vehicle affecting the lines outside the substation.

In the 2015 incident it was a car that crashed into a pole on the NW23 feeder and in the 2016 incident it was a truck connecting with overhead lines on the NW14 feeder. In both instances the Bus Tie Open Scheme (BTOS) operated and isolated two of the three transformers on site. The United Energy BTOS helps reduce the fault levels in the bus during an event. It has inherent draw backs one of which is a longer fault clearing time and therefore allows all the fault current to flow through only one transformer. In this type of event the substation would generally only lose supply from one transformer and likely one section of the switchboard. Supply is then normally transferred, and customers restored. It would require a number of sequential or simultaneous events to cause a three transformer substation to have a complete loss of supply to customers.

In both cases the transformers which were on the same design, manufacture and age suffered an internal fault due to the through fault. The investigations concluded that on the first event in 2015 the BTOS was not set at a level that could trip the transformer fast enough to prevent extensive internal damage. The BTOS settings were checked and adjusted to ensure this would be effective in the future. The second event in 2016 saw the scheme operate in the correct time and sequence, however it is believed that this transformer was already weakened by past events and so the winding failed.

It is known that during the years from 1960 and 1980 a number of power transformers manufactured by a past Australian transformer manufacturer had design defects that under particular fault scenarios had windings that tended to buckle and eventually collapse. In some instances, the core frames and mechanical bracing were not adequate for the design fault levels and winding movement was a consequence.

Comments on Incident Report:

Both reports were very thorough in the way the faults were investigated. In both instances the transformer failures were secondary events caused by the manner in which the protection schemes operate and inherent weaknesses in the specific transformer type. The recommendations from each report are comprehensive and actions from the first report appeared to have been implemented as can be seen by the way the systems operated on the second incident.

Common-cause failures do occur, and these incidents clearly show that a specific “batch or design” of transformers from one manufacturer has a weakness that will have a common-cause failure. By recognising the issue United Energy has recommended some actions to reduce the risk to other units of that same type.

It is not cost effective to consider total replacement prior to normal end of life nor is it practical to try any design changes to the internals. Therefore, by implementing the specific recommendations made United Energy can manage as far as possible the risk of incurring another failure under similar conditions.

As part of the documentation supplied to K-BIK Power, United Energy supplied the following documents which were produced as a result of the Nunawading incidents:

- BTOS Protection Setting Review dated January 2019
- UE PL 2028 ZSS Transformer Life Cycle Strategy – Version no. 6 dated August 2019

The BTOS review was produced out of the Nunawading incident reports which recommended that if a distribution feeder’s protection is not fast enough, it is possible to damage the transformer if a through-fault current is allowed to flow for a significant time. The document states that to reduce the risk posed to UE assets by extended fault duration, the feeder protection settings in BTOS enabled stations were reviewed to ensure that the distribution system behaved in a way that is consistent with the design considerations of the plant and equipment installed on the distribution system, and that transformers were not operated beyond their design capabilities.

The Transformer Life Cycle Strategy was developed to define the specific approach to, and principles for, the safe and efficient management of Power Transformers and ancillary devices owned by United Energy.

The document identifies strategies employed by United Energy aim to identify and address potential problems before the condition of transformers deteriorates so as to:

- prevent and minimise expensive damage to valuable strategic assets;

- avoid interruption of customer supply;
- secure transformation capacity;
- mitigate the hazard or risk to personnel and to the public, and;
- maximise investment value to United Energy and aligning with the Strategic Asset Management Plan.

The strategy defines the specific approach to, and principles for, the management of zone substation transformers. It is intended to provide a justified and evidence-based approach that is used to develop forecasts of the volumes and types of intervention - and the associated costs and risks - required to achieve a defined level of asset performance for zone substation transformers. As such, it provides a whole-life, whole-system (WLWS) based intervention and cost/risk analysis for zone substation transformers which optimises total life cycle costs.

The document states that United Energy has adopted a performance target of no catastrophic in-service asset failures due to asset deterioration per year. The target was set to reflect the risk profile of the asset and United Energy’s desired outcome of least-cost whole-of-life implementation. United Energy have also set a target availability of 98.5% for its transformer asset group and was identified as being consistent with maintaining recent levels of performance.

The document is listed as being a “live” document implying that it is subject to change at anytime and that it is to be utilised as far as possible in all transformer decision making. This type of strategy is highly recommended as it allows an organisation to continuously improve their knowledge and actions associated with the lessons learned for any system incident.

- STO #1 Trans 22kV CB Bushing Failure – Incident Investigation.
- UED Significant Secondary Asset Incident Summary for STO

Overview of Incident:

The incident investigation report above details a 22kV switchboard bushing failure at Sorrento (STO) zone substation on the evening of 4 January 2013. The bushing fault resulted in the loss of supply to the station, with the majority of customers restored within two hours. The SD24 air-insulated switchboard was manufactured in the late 1970s by Brown Boveri (which later became ABB). The switchboard is the only one of its’ kind on the UE network.

During the day, an incident occurred on the RBD-STO #2 line. This line was out for the day to clear a tree located close to a subsidiary 22kV line that was smouldering, either through intermittent contact or induction from 22kV conductor. This resulted in the entire station load being placed on the RBD-STO #1 line, #1 transformer and #1 22kV Transformer CB.
In the evening, the RBD 66kV circuit breakers D and E tripped, isolating supply to the RBD-STO #1 line. The disturbance records captured by the protection systems at RBD showed an initial 22kV phase-ground fault which quickly evolved into a balanced three phase fault. Numerous protection schemes operated in response to the fault, indicating a fault within the 22kV switchboard.

The root cause of the fault was a breakdown of the paper insulation in the red-phase 22kV bushing within the #1 transformer 22kV Circuit Breaker cubicle, upstream of the circuit breaker. The underlying fault was likely to have been present for some time. The significant increase in loading due to the high temperatures on the day, compounded by the radial operation of the substation due to the outage on the RBD-STO No.2 line during the day appears to have accelerated the deterioration of the paper exponentially, rapidly decreasing the dielectric strength resulting in plant failure. The load current through the faulted bushing at the time was

930A and the cubicle had a rating of 1250A. Therefore, the load was nearing the maximum levels.

The report conclusions state the fault was a random event, not related to age or poor overall condition of the switchgear. The fault was not detected via online condition assessment techniques employed, and even if more comprehensive condition assessment techniques had been used, the fault would have remained undetected.

Comments on Incident Report:

The report is very thorough in the way it was investigated however, this fault may not have occurred if the load had not been increased. Therefore, it is considered as a secondary incident that occurred as a random event and dependant on the earlier event (the tree clearing on RBD-STO #2 line). The bushing manufacture may have had some part to play in the event however, the key was the overall load and electrical stress due to the outage of the RBD-STO #2 line.

The report states that there is almost no method of detecting these faults and so they will always go undetected until the component deteriorates enough or a coincidental event acts as a catalyst for it to fail.

The recommendations in the report suggest looking at additional switching capacity at the 66kV side and whilst this is an option this type of event may not be restricted to only this type of switchboard. Therefore, it is not feasible to look at numerous options for load transfer every time an asset is to be heavily loaded.

- STO #1, #2 On-load Tap Changer Overhaul – Signed Business Case

Overview of Business Case:

This document is a business case for the overhaul and maintenance of a Ferranti type ES3 On-load Tapchanger (OLTC). At the Sorrento zone substation there were two Ferranti type ES3 OLTCs that had of high gas levels indicating abnormal heating, arcing and paper degradation has occurred. This type of gas signature is associated with significant contact wear with fixed and moving contacts in the OLTC.

The report states that the moving contacts were replaced on the spot, and the transformers returned to service, however the fixed contacts still needed to be replaced as they are well beyond their wear limits. This task is not easy, as the contacts are not detachable - they are fixed bushing-like contacts that form a direct connection to the main tank and cannot be rotated to defer their replacement. In addition, the contact damage leads to increased wear and damage into the tap changer gearing & mechanisms and requires the components to be replaced or refurbished.

Comments on the Business Case:

The On-Load Tapchanger (OLTC) is the only true moving mechanism in a transformer, and it is particularly prone to the effects of wear and component degradation. An On-load Tapchanger needs to fulfil two basic functions: the load current flowing through the transformer must not be broken and no section of the transformer winding can be short circuited during a tap change operation. To facilitate these functions, tapchanger designs have used a range of different types of mechanisms and arrangements. The most common designs are the high-speed types that use either diverter resistors or reactors and with newer tapchangers being vacuum switching rather than moving contacts. Older transformers often have low speed types where the contacts suffer an increase level of wear due to the current flowing through them. This increase in wear is greater when the OLTC is subjected to reverse power flows. Three common and one emerging types of tap changer failures are due to:

- mechanical failure;

- Contact wear;
- Build-up of carbon deposits between contacts;
- Vacuum bottle failures (emerging failure mode).

Industry data shows that around 60 per cent of tap changer failures are due to mechanical malfunction. Older type transformers in general are equipped with low speed tap-changers such as Ferranti ES and DS types. The low speed tap-changers present a greater maintenance burden than high speed units. Their design is such that the diverter contacts are subject to a high degree of current related wear and their roller contacts suffer with both current and mechanical wear. With these units maintenance should be undertaken at shorter intervals than for a high speed tapchanger. The increased level of intervention mitigates the risk these assets present. United Energy has found at Sorrento zone substation that excessive wear has required the change in maintenance practices to being more frequent on these older types of tapchangers. In most substations the tapchangers operate in parallel using a master-follower system and so the wear on the tapchangers tend to be the same across the same tapchangers at that site. Therefore, any defect found in one tapchanger is likely to be found in the same units at the same site. This is the case for the Tapchangers at the Sorrento zone substation.

It is not clear from any data supplied by United Energy that the higher rate of contact wear can be contributed to an increase in reverse power flows, but this is an issue that has emerged over recent years. A number of Australian utilities are experiencing load constraints due to this and recognise that a new common failure mode in older tapchangers is caused by the excessive current wear generated by the reverse power flow.

Asset Defect Risks

Transformers

The failure of a transformer is always a credible risk in any network. The probability of a failure increases with the number of transformers in a network. Additionally, the higher the number of through faults the greater the mechanical stress on a transformer and the higher the risk of failure. In general, the fault rate for United Energy transformers is low with events being infrequent in nature and below Australian industry[3] averages.

What is evident from the data presented in the supplied transformer incident investigation reports, is that United Energy has a number of transformers that have a higher than normal potential of failure. This is due in part to the substation bus protection schemes which allowed the identification of inherent weaknesses in the original transformer designs. The second transformer failure at Nunawading zone substation showed that even though the protection schemes are correctly configured along with the correct trip settings then the weakness in the transformer would still have been found due to the nature of the design. Therefore, it can be stated that any common-cause failure needs to have some type of catalyst to either set it off or allow it to be detected. This can be operational conditions, environmental, maintenance, design, manufacture or many other contribution factors.

As fault levels generally increase in substations over time, there is a need to ensure the transformer is adequately designed to cater for the future needs. Future planning is not an exact science for any utility and so it goes without saying that the design must suit the system based on the best known data at the time. This does not preclude the asset manufacturer from providing an asset that whilst it meets the specified requirements may not meet future demands and so have an unintentional built-in flaw. The United Energy ZSS Transformer Life Cycle Strategy document provides a method of addressing some of the issues and as it is a live

[3] D Martin and N R Watson: "Statistical analysis of Australian and New Zealand Power Transformer Catastrophic Fires". United Energy was a contributor to the statistical data within the publication;

document it allows for the continuous capturing of any data that can help improve the management of these assets throughout their life cycle.

One further risk associated with these transformers is the possibility that they could fail in a way that starts a fire. This could be due to a HV bushing failure and the consequences of this type of failure is that the debris from the exploding bushing could damage other equipment such as the CBs, VTs or CTs. In some instances, throughout the world the LV buckling starts a turn to turn arcing fault that ruptures the tank and causes a fire.

Bushing manufacturers have published engineering papers that state the expected operational life span of an OIP bushing is 25 years. There are numerous instances where bushing failures have occurred before and after that time period and many more instances where the OIP bushings have been in service for 40 years without any issues. What is certain is that HV bushings have been an increasing risk of failure. This is mainly due to aging of the internal insulation systems. Older type bushings had synthetic resin bonded paper (SRBP) and their failure modes were based around the surface tracking between the bonded paper and the outer porcelain. The tracking would find its way to earth and generally explode spreading porcelain debris. The Oil Impregnated Paper (OIP) type bushings have a greater variation in failure modes but most commonly the capacitive foil layers would breakdown causing an increase in internal voltage stress and eventual breakdown. If not removed before breakdown the bushing could explode and the transformer catch fire through the bushing flange. Testing the bushings for DDF (or Tan Delta), Capacitance and DFR (Dielectric Frequency Response) on a regular basis can help avoid such failures.

Instrument Transformers

The loss of instrument transformers are generally assessed as being moderate risks with reasonable controls in place, this may need to be reconsidered as national and international statistics indicate that aged instrument transformers have a higher failure rate than many other items of plant of similar age. The fact that almost no units have monitoring, or maintenance done other than electrical testing places them at high risk of internal faults going undetected. The failure mode is generally one of a catastrophic failure. K-BIK Power has had first-hand experience with such failures and cannot understate the need to review maintenance and condition monitoring of such units to reduce the risk of failure. Typical failure modes are paper degradation, internal combustible gasses building to extreme levels and insulating oil quality/ dielectric failure. These are normally not tested and are not detected in most electrical testing.

Medium Voltage Instrument transformers in switchgear tend to develop partial discharge due to moisture and defects in the resins used in their solid insulation. These types of failures are not common but when instrument transformers in switchboards from any one manufacturer start to display signs of PD then it is likely that many more of the same type with start to exhibit the same. This is an area that is truly a common-cause failure as these resin cast blocks can start to show signs of degradation at almost any stage of their operational life. It is K-BIK Power's industry experience and knowledge that can state that these types of issues can be quite random. As an example, a utility that had two identical but separate buildings on the same site with the same switchgear fitted. One switchboard had instrument transformers that deteriorated quickly after a few years of service, yet the second switchboard had no such issues. No specific causes were found despite an exhaustive investigation and series of tests. The common cause in that one board could only be identified as a problem with the batch as the only difference was the manufacturing date.

The conclusion here is that common causes may not present immediately and may not affect every unit however, history has shown that a number of common-cause failures in utilities are linked to batches or families of assets manufactured at the same time or some component that has been affected during an intervention.

Switchgear

Across a utility's major substation sites are a range of individual circuit breakers, instrument transformers, disconnect switches and power transformers that need to be managed effectively to their end of life. These assets come in a variety of types that present a range of generic and specific condition or performance issues that must get managed according to the risk that is presented.

There are a range of different types of switchgear used in the United Energy network which is a function of how switchgear design has changed over the years and the wide range of manufacturer's types that have been commercially available.

In the past switchgear design employed at higher voltages such as 66kV and above, and some lower voltages required the construction of plant to perform a specific function and the substation sites generally had all their switchgear located outdoors. This allowed individual items of plant to be replaced and extensions to be relatively straightforward. So, for example, individual circuit breakers could be replaced leaving isolators or earth switches in situ. Modern designs involve the use of gas insulated switchgear that is normally located indoors or dead tank SF6 switchgear located outdoors.

Whereas most metal clad switchboards at 33kV and below have switchgear that is located indoors and can perform multiple functions in a single unit such as circuit breakers, isolators and earth switches. These units tend to comprise a fixed portion and moving portion, although more modern types that are termed fixed pattern switchgear do not have any withdrawable elements.

Regardless of the type, the fixed portion generally contains the cable terminations, busbars, voltage transformers, current transformers, and any control equipment and protection relays mounted on the unit, whilst the moving portion (classed by the moving parts) contains the circuit breaker or withdrawable voltage transformers. Industry experience shows that the fixed portions have the majority of catastrophic failures due insulation degradation, although there are many older switchgear types that are starting to show signs of circuit breaker mechanism wear and internal insulation deterioration.

The fixed and moving portions are more difficult to replace on an individual basis due to space constraints and the use of bespoke cable compartments or busbar configurations. Therefore, when a number of units of switchgear on a switchboard require replacement, it is usually more cost effective to replace the entire switchboard section. Retrofitting circuit breaker units to replace the moving portion have been used to replace old oil type breakers and reduce the risk of oil fires and blasts; however, this is not a permanent fix as the unaltered fixed portions may well be deteriorated and fail.

In general, the fault rates for switchgear are low with events being infrequent in nature. By measuring the fault rates a utility can show signs of volatility and then trend the results against both internal and industry averages. This can help introduce a planned investment program to maintain the fault rate performance over the medium term. Therefore, a planned asset replacement program can be determined on the basis of current asset condition and forecast asset degradation, which is underpinned by the fault performance for the asset base. This way specific assets that are assessed to be poorly performing can be justifiably targeted for asset refurbishment or replacement.

United Energy has in the past refurbished switchboards to extend the life, only to have partial failures a number of years later due to workmanship defects by refurbishment contractors. Old switchboards do not have parts that are easily obtained as spares and often have to be re-engineered. Therefore, any refurbishment requiring such work has an element of risk.

The failure mechanisms within Switchgear can be quite varied but there are some common underlying failure modes or causes. It is important to note a few key issues:

- The failure mechanisms for switchgear are mostly understood and can be monitored through inspection and maintenance visits.
- Common-cause failures do occur across the same fleet of manufacturer switchgear types. Where these have a safety impact, a utility may want to rollout some type of modification, otherwise the operating experience has to be built into the assessment of the switchgear health.
- Significant rises in the probability of failure can normally be forecast in an asset risk indicator where changes in state and indicators for older assets present themselves as they start to show signs of asset degradation and common failure causes.

There are no right or wrong answers for switchboard refurbishments or replacements it is basically down to risk versus cost. What is evident from industry experience and based on the supplied reports United Energy's experience that switchboard families tend to have common-cause failures whereas single boards or specialist plant tend to have more random failures. These occur at various stages throughout the life of the board and can be accelerated by operating conditions, environmental conditions, age related deterioration, or a manufacturing defect.

3. PERFORMANCE OF FMEA

The paragraphs below summarise the K-BIK Power independent FMEA for general zone substation equipment. Whilst it includes the main primary plant, only the relays are included as secondary systems equipment. The FMEA has been performed at a high level for individual assets and where the assumption of one asset failure can also affect other assets. To include all asset failure modes and all secondary systems control equipment would require significant time to compile.

Process for the Reviews

This process for reviewing and compilation of this report has generally been as follows:

- Receive and review all existing documentation, noting key findings and issues from existing reports;
- Research data on similar and other common failures within zone substations for applicability to this case;
- Perform an independent Failure Mode and Effects Analysis (FMEA) on the major assets of a zone substation;
- Consider all external influences that can influence the operation and reliability of the substation equipment;
- Review United Energy risk assessments in the reports and actions arising from incidents as mentioned in the supplied incident reports and make comments as applicable;
- Perform a Gap analysis between the FMEA, the risk assessments and actions arising for incident reports to identify any gaps in either or both;
- Make comment on the methodology for performing the investigations and outcomes of the incident reports;
- If applicable, identify any areas of priority in terms of risk and any mitigation strategies that could reduce the likelihood of such failures.

K-BIK Power FMEA

A detailed explanation of the FMEA (Appendix C & attached spreadsheet) and the above ratings with risks is given in Appendix B – FMEA Methodology in this report.

In the assessment it was recognised that United Energy had recorded failures and therefore not only is the probability high but so are the consequences and severities. In some cases, the detection methods are quite good however the other criteria determine that the impact of the failure would be significant. The severity of the failures varies depending on the cause, but the consequences have generally been the loss of supply. Therefore, depending on the failure the restoration time may be quite short to several hours. Additionally, in a number of assessments total loss of the asset is considered and this in reality means a network configuration to cover the loss of the asset for possibly several months.

As an example of assessing an asset's role in a substation the following was obtain from some of the background research into main circuit breakers in a switchyard. International statistics show the average that circuit breakers within a substation are switched in a 2 year period is up to 50 times by operators for planned outages and generally 1 protection trip for an unplanned event. When relating this to United Energy it follows that United Energy could have as many as 47 unplanned events within a 2 year period. It also follows that the more switching the greater the risk of a failure during the switching event.

The highest risk with an unplanned event is when there is someone either visiting or working in the substation. The risk that an asset fails to operate or catastrophically fails after a planned maintenance event has a high consequence such as an explosion or fire. It is assumed, and generally normal practice, to perform planned switching events remotely and have all persons vacate the switchyard or switchroom and then only re-enter 2 to 3 minutes after the switching event. This is because the additional time is considered as sufficient for any alarms, primary or back-up protection to operate and the unplanned event to occur.

Items assessed as in the lowest risk category:

These did have a wide range of severities, probabilities and consequences and whilst quite a few had low or poor effectiveness of detection controls the probability of the failure was low enough to reduce the risk of the failure to an acceptable level. In the cases where the overall risk is higher and few detection methods are used, there are comments that indicate that condition monitoring can have a profound impact on the outcomes of the assessments.

What the assessment sheet it does not highlight is that regardless of the overall score being low the probability of a failure can still be very high and if the controls are relaxed only slightly then a risk of failure increases significantly. Add to this that to prevent the failure an intervention must occur, and this may well be the reason why there are generally very few failures on assets that are well monitored. For United Energy, some of the causes of the failures have been unpreventable and regardless of any monitoring devices the failure would have likely occurred anyway. This is primarily due to such issues as common-cause failures within batches of the same equipment.

The problem here though is that in most cases an outage is required for any prevention of a failure, and it is likely that parts or a total asset replacement will be required. This has a cost implication along with the likely reduction in asset availability. Therefore, it should be recognised that whilst the assessment outcome may have a lower score and most assets are well managed, the longer term implications are that the score will increase as the assets age and the number of required interventions increases.

Medium risk scores (between 50 and 100) all have lower levels of detection controls and the probability of a failure occurring is quite high (80 to 96) along with very high consequence ratings. The ability to maintain assets so they remain in good working order is possibly one of the highest priorities for United Energy however, as stated earlier if the equipment is beyond normal operating life then there is little possibility of lowering the risk. Where there are unpredictable external events that create large fault currents, the aged asset is at a higher risk of failure due to the weakened insulating materials and mechanical strength.

The under-lying outcome here is that all substation assets can have a high number of failure modes that have the potential to cause substantial impacts on the United Energy operations and people. It is also noted that most of the failure modes and effects are based around good maintenance strategies being in place. Having said that, the ability to maintain an item of plant is only as good as the skills of the maintenance staff, the availability of components and the ability of the plant to remain fit for purpose.

As stated earlier, it is recognised that there are times that failures occur as a result of an unpredictable event. For example, the case of the transformer failure at Nunawading (MW) zone substation on 16th March 2007 where a truck incident cause a power pole to be bought down, causing a 3-phase fault. The end consequence was that the No 1 transformer in the substation failed due to the operational characteristics of the protection scheme, the likely transformer design inadequacies and the number of feeder faults in that area.

The effect can be termed as the "Swiss Cheese Effect" where in any given instance every hole in the "cheese slices" lines up to allow an incident to occur. It is also known that in many instances the removal of any one of those "slices" would not have the same end result.

It is the experience of K-BIK Power and recorded by many utilities that such events occur regularly throughout Australia. Events such as traffic incidents can be assessed by plotting the location of the event. As with the general vehicle accident statistics there can be clusters were the vehicle make contact with the power network more often than in other areas. The same can be said for weather events such as lightning strikes that tend to pass through certain locations throughout the year.

The closer the cluster is to a zone substation the greater the number of faults detected within the substation. Depending on the voltage level of the line affected the assets may see the fault current on the lower or higher voltage side of the substation. This has an impact on the fault clearing times due to the protection schemes and relay co-ordination. The assets then suffer some level of weakening of it capability. Where there are families or batches of the same design and manufacture of equipment there can be common-cause failures. Typically, these are design or manufacturing weaknesses that normally are undetectable under normal operating conditions.

An outcome here is that regardless of maintenance, design or risk reduction methods, there will always be unpredictable events that will create a series of subsequent events that have an adverse impact on the assets.

4. RECOMMENDATIONS

The following are recommendations based on the requested review of the supplied documentation, the performance of the FMEA, industry engineering literature and other associated primary plant risk assessments:

Substation Asset Considerations:

The following substation asset recommendations and common-cause failures made in this report take into account:

- Asset age, aging rates and condition
- Operating characteristics and environments
- Possible design, manufacturing and refurbishment defects
- Maintenance requirements and skills to perform the maintenance
- Failure modes and frequency of failures and defects
- Safety of people, assets and the environment
- Reliability of supply to United Energy's customers and business impacts
- Probability or likelihood of any specific event causing an asset failure

Comments and Recommendations

When considering the overall work done to deliver the data analysis and FMEA assessments there are two basic recommendations:

- Perform item specific risk assessments to understand more about individual items of plant and the specific risks they present – this can then roll up into the higher level assessments.
- Review the condition monitoring strategies for all individual items of plant and what on-line and off-line methods would best support the risk reduction. It is well proven that some levels of condition monitoring can reduce the risks of failures by the early warning indicators.

A third recommendation is made with respect to protection schemes:

- Perform a detailed scenario modelling exercise on the protection schemes individually and collectively when a change to the network has been made. This will assist to better understand the operating characteristics and the fault levels that the assets will realise.

This recommendation has time and cost constraints that could make it unviable. Additionally, it may not be possible to envisage and then model every possible fault scenario that any one asset could see in its operating life. Therefore, ensuring the protection systems are designed correctly, operate as intended and the settings are routinely checked would offer a risk profile as low as reasonably practical (ALARP).

Comments on Common-Cause Failures:

Within the data provided by United Energy and that obtained externally and reviewed by K-BIK Power clearly demonstrates that almost any substation asset can have a common-cause failure that goes undetected for some time. That is, any one occurrence cannot necessarily be stated as a common-cause failure on its own. Where two or more events occur that yield the same end result and properly investigated can be stated as common-cause failures.

The latter is generally derived after a trend of similar failures occurs and a common cause has been found. Addressing the issue is significantly more difficult and needs specific modelling of an asset under specific conditions. Once that has been done then any intervention that needs to be undertaken to reduce the risk of a failure or the event scenario occurring needs to be implemented.

Industry examples of common-cause failures have being provided in Appendix A of this report. In this appendix examples of typical substation equipment have been provided along with a short background on each example. In all the examples there were common-cause failures that generally started at manufacture but were not detectable until either a failure occurred or were found during maintenance inspections. Nonetheless they were all classed as common-cause failures as they were present in all equipment of the same batch, manufacture and age. In most cases the network conditions allowed the "defects" to grow until found or they failed.

This type of failure mode requires a different approach to the normal asset risk modelling that provides solutions and actions for industry wide known failure modes. When realised these common-cause failures may require separate and quite different risk modelling to that of all other asset families of the same class in the same network.

The fourth recommendation is:

- Where failures occur, an in-depth forensic investigation should be undertaken to find the root cause of the failure. Once that is found, other assets of the same family and manufactured batch should be reviewed for their risk to similar events and likelihood of failure. If a common-cause failure is noted, then a new risk model needs to be applied according to the type of failure and asset.

Other Comments

The following are additional comments are made based on the general quality and structure of the data and reports provided for the review.

I. The method of performing the incident investigations appears to be quite sound overall. There does appear to be an element of constraint on the ability to do full detailed forensic investigations into the primary plant failures e.g. power transformers. This needs to be reviewed as the data obtained from such detailed investigations can be used as a basis for maintenance strategy changes and to underpin any actions to prevent further events that may be common-cause failures.

II. The switchgear failures reviewed for the compilation of this report were primarily on older types of switchboards. This suggests that most MV switchboard failures at United Energy are on older switchboards. This may well be the case but there needs to be a clear condition monitoring and management plan for those switchboards that are less than 20 to 30 years old. These more modern types have issues that may not be immediately detectable and eventually start to show as common-cause failures. Whilst older boards need more attention there is a point at which these medium aged boards will start to require as much attention and cause system faults. The recommendation is that any lessons learnt from older switchboard maintenance needs to be applied as practically as possible on younger switchboards.

III. Investigations into failures should always follow general guidelines to establish a root cause. The use of fish-bone diagrams, bowtie diagrams and the like are ways of covering all aspects of a failure. K-BIK Power typically follows the "Apollo Root Cause Analysis" principles and looks at all possible causes and their effects. This way any possible cause that has had no effect on the asset can be reviewed and eliminated as part of the root cause. When this type of method is used there are quite often additional pieces of evidence found that have contributed to an event that were previously not considered or not known. It is by this type of structured approach that many common-cause failures can be found and action for future prevention or intervention can be implemented.

5. CONCLUSION

The findings within this review are that United Energy has a structured approach to failure investigations which has some room for improvement if appropriately funded. It has also been recognised that United Energy has experienced a number of common-cause failures which could not have been detected by any normal monitoring. This type of failure may happen again and without warning and so United Energy needs to be able to recognise such events by performing detailed investigations and implementing a risk model unique to that asset type and family to manage any further risk of failure.

In conclusion, K-BIK Power recommends the regular testing and maintenance of HV and MV equipment is carried out to predict any deterioration in condition of the asset. This is regardless of age or type of equipment as early intervention can reduce the risk of failure. It follows that by monitoring tends over time a planned intervention can reduce network risks, maximise corrective measures at minimal cost and at times extend the life of the asset. These recommendations should also be considered with respect to the return on investment and risk appetite of any organisation, however, all HV equipment have finite serviceable lives and must be replaced when they present an unacceptable risk or have excessive costs to maintain the reliability. It is within the findings of this report that at some United Energy zone substations the assets are rapidly nearing the end of life and therefore it is strongly recommended that a replacement priority plan be implemented to ensure the assets are replaced in due course. For those sites that need an extended life, suitable maintenance strategies and personal risk assessments should be implemented.

APPENDIX A Common Cause Failure Examples

This appendix provides some basic examples of failures from other utilities that had common-causes and they also highlight the dangers to persons and other equipment.

(locations and owners of this equipment are intentionally omitted.)

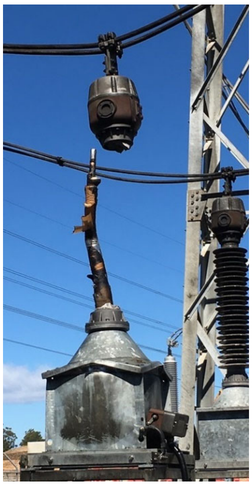

Figure 1| 132kV Voltage Transformer Failures (different substations)

These voltage transformers (Figure 1 above) had a weakness with the oil quality and as a result the dielectric strength deteriorated over time and cause internal flash- overs under switching and lightning events.

The Voltage Transformer (VT Figure 2) that was connected to this transformer had a lightning impulse level of 75kV where as the main transformer 11kV side had 95kV. The failure occurred after a lightning strike at the substation and the VT failed and caused a fire. When sister units were investigated the issue was then discovered. During factory impulse testing the VT was disconnected and so the issue remained undetected until the lightning event.

Figure 2| VT on Fire in Transformer Cable Box.

Figures 3 and 4 below show the remnants of failed CTs. These were 2 of 9 separate failures. All failures had a common-cause being they were over filled and created internal pressures during the daily load cycles. The internal pressures generated hydrogen gas from the insulation which then formed a tracking path along the stem of the CT. With an increase in system voltage in the early hours of the morning there would be an internal flashover from the line side head to the DLA tap which was the only earth point internally.

The utility had several hundred units in service and when all were checked it was found that only a batch of units made in one calendar year had the problem and was cause by a change in manufacturing process. This is an example of a common-cause failure that cannot be detected without a trend of failures developing and then the root cause being exhaustively investigated.

Figure 3| 132kV Current Transformer Explosive Failures

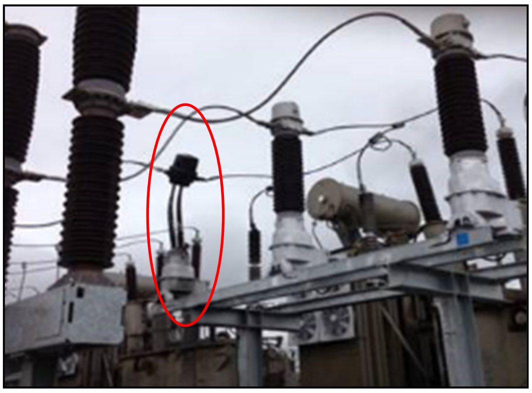

Figure 4| 132kV Current Transformer Explosive Failures

In Figure 5 below the windings of the transformer had suffered a number of through faults that were of low magnitude. This transformer hen suffered a close in fault where the fault level rose to almost the substation fault rating. The transformer had been specified with a fault rating on this winding and should have withstood all the faults. The failure occurred after a number of local lightning storms and the winding flashed over between turns then carried on through the winding. The winding had been damaged by the through faults and local fault and was evidenced by the buckling of the windings. When the design was checked for strength during the failure investigation it was discovered that the fault rating was in fact half of the specified fault rating. Upon discussion with the OEM it was found that they had had an error (of a factor of 2) in their fault calculations and consequently the transformer was constructed with a weak winding. The utility had 7 transformers of this design in service and was forced to install fault current limiting devices and change the protection to faster trip speeds to ensure the transformers could remain in service as far as possible. These units were made in 1978 which was during a period where the design of some power transformers had design and manufacturing weaknesses.

Figure 5| Transformer buckled winding resulting in internal damage then failure

Figure 6| Old Pitch-Insulated Busbar Joints with Voids

Figure 6 shows a top view of a 3 phase busbar arrangement where the joints were originally encased in pitch to improve the lightning impulse level. Over a period of more than 40 years the hardener in the pitch decomposed and the pitch slowed leaked leaving large voids and exposed bar busbars. The investigation found that many utilities within Australia and the UK had the same problem. As the busbars are in a continuous chamber an whole of switchboard outage is required for any inspection or repair. Complete loss of the pitch caused phase to phase failures and so extensively damaged the switchboards.

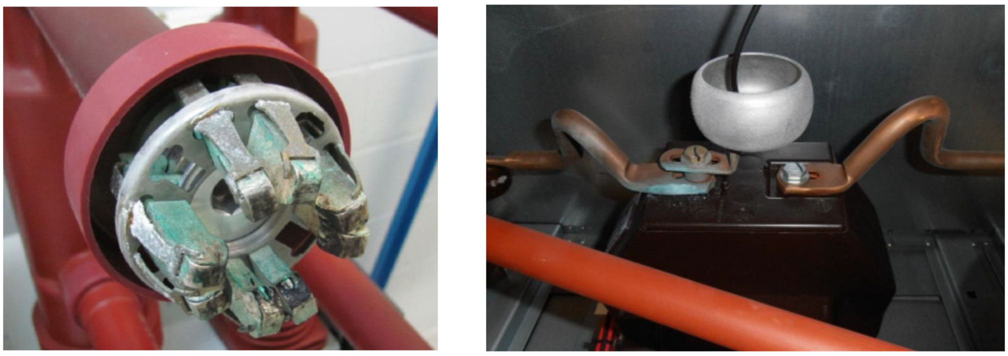

Figure 7| Contact Partial Discharge due to corrosion.

Figures 7 show a circuit breaker cluster and a fixed switchboard CT both with green coloured corrosion on the copper contacts. The ingress of moisture can cause the corrosion and that in turn produces the PD. Whilst this is can happen in high humidity areas it is not common in dry environments such as in this switchboard. The investigation showed that the humidity was less than 50% over the entire year and so the cause was not moisture. It was found that the supplier had changed the type of surface treatment to the contacts and this had a reaction with copper. The issue was found in 8 switchboards in one utility and it was advised that other utilities had had the same problem without knowledge of the underlying cause.

General Comment:

In all the examples above there were common-cause failures that generally started at manufacture or through some maintenance activity but were generally not detectable until either a failure occurred or were found during maintenance inspections. Nonetheless they were all classed as common-cause failures as they were present in all equipment of that batch, manufacture and age. In most cases the network conditions allowed the “defects” to grow until they were detected, or as in most cases, they failed.

APPENDIX B FMEA Methodology

Assessing the operation, maintenance and reliability of any zone substation can be difficult as each asset has several failure modes, some of which affect only the asset, some have a small impact on other assets and substation supply and other failures can cause a total substation outage or consequential loss of other assets. In the scope of this assignment the individual asset failure modes considered are those that have a high overall likelihood of causing a total substation outage. K-BIK Power has developed and performed an FMEA for a typical zone substation and has added an element of risk assessment in addition to the failure modes.

The setting up of the FMEA has included Failure modes based on information sourced for IEC, IEEE, CIGRE and EPRI failure modes, statistics, probabilities and common asset failures.

To add to the above, an assessment of a good deal of other engineering was done in order to develop the best assessment criteria for the FMEA, with the outcomes being applied as below.

To assess the impact on United Energy of each of the asset failure modes would require an exhaustive assessment of failure reports across all failure experiences for at least the last 15 years. This is not possible and so a small sample of investigation reports was supplied and is upon which this FMEA has been based.

For the assessment of the United Energy sample of investigation reports listed previously the failure causes have been reviewed. Additionally, four (4) columns have been added with a weighted value for each. This provides a method of assessing the severity, probability and consequence of an event then applies a factor that assesses what type of detection controls are in place to detect or prevent the incident. The details are as follows:

Severity of the Failure Mode (S) – this is based on the impact of the event and given a ranking of 1 (None impact) to 5 (Critical).

Probability of Occurrence (O) – This probability is based on a statistical analysis of whether the event occurs from 1 in 1.5 million (Unlikely) to 1 in 2 (Almost certain) and is directly related to risk likelihood.

Consequence of Failure (C) – in this criteria the consequence does relate to the risk matrix consequence but has 4 areas of concern, People, Environment, Asset, and Business. These vary across the range of failure modes and the ranking score is from 10 (highest level) to 1 (the lowest level)

Effectiveness of Detection Controls (D) – This criteria looks at the controls that are in place or can be put in place to detect a failure mode prior to an event. The ranking from 10 as most effective to 1 as ineffective.

The following provides details of the methodology for the development and outcomes of the FMEA used in this report. This assessment does not just use the normal risk matrix of Likelihood x Consequence but takes into account the Severity of the risk to the network and business and the controls in place to manage it. This allows a short summation of the highest to lowest risks associated with the assets, site, business and other factors.

In reference to the FMEA the following have been adapted:

Column D: Zone Substation Typical Failure Modes (CIGRE % of failures)

These failure modes are detailed in a range of documents such as IEEE, IEC, EPRI and CIGRE guidelines as well are industry known failures modes that have been detailed in many engineering papers.

Column E: Failure Effect – What happens

With each failure mode there is a reason behind it and this summation is provided to quantify what happens with each failure mode. It should be noted that what happens can vary for each failure mode due to the influences that trigger the failure and so these remain in separate columns.

The cause of the failure mode and the failure effects of how it happens are added for clarity around the type of failure being assessed. These are not taken from any standard and are free text that are based on the industry knowledge held by K-BIK Power and from researched data.

Column H: Severity of Failure Mode – (S)

As mentioned above IEC, IEEE and CIGRE literature has been used in providing this information. There are 5 severity modes used in this table they are:

- **A.** Critical: This is a safety hazard and causes or can cause injury or death and requires highest priority - system is non-operational.
- **B.** Major: This requires immediate attention as the system is non-operational
- **C.** Minor: This requires attention in the near future or as soon as possible. In this instance the system performance is degraded but operations can continue – possibly with work-arounds or reconfigurations.
- **D.** Insignificant: There is no immediate effect on system performance.
- **E.** None: If there is a failure the effect will be undetected or regarded as insignificant. In this type the failure is generally a functional failure such as a non-system component (eg cubicle heater)

These Severity ratings have been given a numerical rating with Critical being the highest at a rating of 5. This (S) rating is used in calculating the Risk Priority Number.

Column J: Probability of Occurrence (O)

This probability has been adopted from the guides for the statistical analysis of electrical failures & insulation breakdowns. They are taken from standards such as IEC and IEEE along with CIGRE Technical brochures. They look at all the failures and rank them from 1 to 10 with the lowest ranking being the most unlikely event. The guides have given statistical probabilities based on Weibull analysis and these define the probability of such a failure. It is noted that the data is wide ranging and is more asset based than total substation or network based.

When used in this FMEA some of the assessments were based on the frequency of known causes of failures so that a correlation between the probability and the actual could be used to understand how likely is it that the failure will occur.

The ranking from 1 to 10 is used as the (O) in the calculating of the Risk Priority Number.

Column L: Consequence of Failure (C)

The consequence of the failure has been adopted from industry risk assessment methodologies that look at the consequences to 4 key areas:
People – Death, Injury. or Disability
Environment – from Extensive to no impact
Assets – the extent of damage to the asset
Business impact – This can be a financial cost or branding/ image cost.

There are combinations of these consequences that have been included as the types of failures can have varying impacts on each of these areas.

The rating or score from 1 to 10 with 1 being the lowest ranking or consequence and 10 the highest. This ranking number is used as a multiplier in the Risk Priority number calculation so as to balance the risks against the consequence.

Column N: Effectiveness of Detection Controls (D)

The effectiveness of controls is based around the ability to generally detect any emerging faults. This may be by testing, on or off-line monitoring, processes, procedures or general maintenance. The rankings range from excellent at a ranking of 10 to completely ineffective at a ranking of 1. The rankings are used as the denominator in the Risk Priority number, so it reflects the risk reduction according to the controls in place.

Column P: Risk Priority Number - (S x O X C)/D

The Risk Priority number allows a quick overview of the highest priority risks assessed. The method looks at a simple calculation of

Severity (S) x Probability of Occurrence (O) x Consequence (C) all divided by the Effectiveness of the controls (D)

This number will range from the very smallest risk (negligible) at 0.1 through to the highest possible risk of 500. The majority of risks in industry are below 100 if appropriate controls are in place. Therefore, those Risks above 100 are shown in red and should be addressed as the highest priorities.

The amber coloured risks are between 50 and 100 and whilst have a reasonable level of control need to be addressed as some can easily and quickly move to the high risk area. This is most likely where the risks are above a Priority number of 80.

Below 50 the risks are considered as low risk. Whilst some have an extremely low probability, they can have high consequences. All can be managed according to the specifics of each risk.

APPENDIX C General Substation Failure Mode and Effects Analysis (FMEA) Data

Failure Causes/Mode & Effects Analysis - Data Sheet	High Risks Risk Priority >/= 100	Medium Risks Risk Priority >50 & <100	Lowest Risks Risk Priority <50
Client: United Energy	Equipment: Typical Zone Substation		

Item	Component Description	Component Function	Typical Failure Modes	Failure Effect - what happens	Cause of Failure Mode	Failure Causes - how it happens	Severity of Failure Mode S	Probability of Occurrence O	Consequence of Failure C	Effectiveness of Detection Controls D	Risk Priority Number (S x O X C)/D	Actions to Reduce Risk of Failure Mode	Comments & Additional Notes
1	Transformer - Power	Transform power from one voltage to another	A - Internal Failure (Thermal or Dielectric)	16 - Alarm + Trip + Internal Damage + Requiring Asset Replacement	Through faults, Overloading or aged insulation - no external damage	System fault is seen by Tx, aged asset, continual overloading, bad joints etc	Major - Requires immediate attention. System is non-operational.	Moderate (infrequent failures) 1 in 400 (0.25%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Moderate; controls effective under certain conditions.	28.3	On-line & off-line condition monitoring	Through faults cannot be totally prevented but can be reduced by fast acting protection schemes (I^2t reduction)
2	Transformer - Power	Transform power from one voltage to another	B - Major Component Failure (bushing, Tapchanger etc)	12 - Alarm + Damaged Component + Replacement	Component deterioration not detected	Bushings not tested or have internal breakdown. Damaged by external forces, build up of dust, moisture & bad connections	Critical - Safety hazard. Causes or can cause injury or death. Requires highest priority - system is non-operational.	Low (few failures) 1 in 15, 000 (= .01%)	Single Fatality / Permanent Disability Extensive Environmental Damage Extensive Asset Damage Major Business Impact	Very low. Some general controls but mostly ineffective	33.8	Bushing monitoring devices, Tapchanger testing & off-line testing of all major components	Without on-line bushing monitoring these failures can occur. Off-line testing can trend but can only be done with outage plans & maintenance at set intervals.
3	Transformer - Power	Transform power from one voltage to another	C - Minor Component failure (wiring, control etc)	08 - Fail to Operate + Repair	generally control circuit wiring or component failure. Age related or bad connection	Poor connections or broken wires, aged components, heater failures etc	Minor - Requires attention in the near future or as soon as possible. System performance is degraded but operation can continue.	Moderate (occasional failures) 1 in 2,000 (0.05%)	No Injury Negligible Environmental Damage Minor Asset Repair Cost Negligible Business Cost	Low. Few controls in place - more luck than controls for detection	2.4	Checking of minor components during routine checks & maintenance. Act on any alarms or operational issues	Mostly reactive than proactive. Minor components can be checked routinely without outage.
4	Transformer - Power	Transform power from one voltage to another	B - Major Component Failure (bushing, Tapchanger etc)	12 - Alarm + Damaged Component + Replacement	Poor maintenance practices, silver sulphide, component fatigue	Maintenance is not done correctly or on time, Oil is corrosive, component fatigue not detected	Major - Requires immediate attention. System is non-operational.	Moderate (occasional failures) 1 in 2,000 (0.05%)	Single Fatality / Permanent Disability Extensive Environmental Damage Extensive Asset Damage Major Business Impact	Very poor. Almost no controls in place - Failure is likely to go undetected	72.0	Only testing during routine maintenance.	Need on-line monitoring for imminent failure detection
5	Transformer - Power	Transform power from one voltage to another	A - Internal Failure (Thermal or Dielectric)	18 - Alarm + Trip + Disruptive Failure + Internal & External Damage + Fire + Replacement	Internal Short Circuit causing tank/ bushing rupture and fire	The transformer suffers an internal fault that allows oil to be expelled and ignites	Critical - Safety hazard. Causes or can cause injury or death. Requires highest priority - system is non-operational.	Low (very few failures) 1 in 150, 000 (= .001%)	Single Fatality / Permanent Disability Extensive Environmental Damage Extensive Asset Damage Major Business Impact	Moderate; controls effective under certain conditions.	15.0	Condition monitoring of transformers to assess internal condition of windings.	
6	HV Circuit Breaker	Interrupt power supply generally under fault conditions	B - Major Component Failure (bushing, Tapchanger etc)	12 - Alarm + Damaged Component + Replacement	Operating mechanism fails and CB does not operate	Operating mech fails & fault current exceeds design limits, or current overloading.	Major - Requires immediate attention. System is non-operational.	Moderate (occasional failures) 1 in 2,000 (0.05%)	Major Injury/ Health Effects Major Environmental Impact Major Asset Damage Minor Business Impact	Low. Few controls in place - more luck than controls for detection	22.4	Routine testing of CB to assess condition	
7	HV Circuit Breaker	Interrupt power supply generally under fault conditions	E - Asset fails to conduct continuously	10 - Reduced Capability + Alarm + Loss of Voltage Control + Fail to operate + replacement	CB opens & closes with or without command. Chattering	Continual restrikes deteriorate contacts & CB chatters	Major - Requires immediate attention. System is non-operational.	Low (very few failures) 1 in 150, 000 (= .001%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Moderate; controls effective under certain conditions.	11.3	Routine testing of CB to assess condition of contacts & monitor type of loads being switched	
8	HV Circuit Breaker	Interrupt power supply generally under fault conditions	F - Asset Operates without command	09 - Reduced Capability + Alarm + Loss of Voltage Control + Fail to operate + Repair	False signals send trip commands or operating mech is worn	If wiring is incorrect or modified, relay may be faulty or there is mechanical wear on CB operating mech.	Minor - Requires attention in the near future or as soon as possible. System performance is degraded but operation can continue.	Moderate (occasional failures) 1 in 2,000 (0.05%)	No Injury Negligible Environmental Damage Minor Asset Repair Cost Negligible Business Cost	Moderately high. Some controls in place	1.7	Commissioning checks after modifications & inspections of mechanisms during maintenance intervals.	
9	MV Circuit Breaker	Interrupt power supply generally under fault conditions	I - Asset fails to operate (locked in position)	08 - Fail to Operate + Repair	Operating mechanism siezed or open circuit in wiring, relay fails	Lack of CB maintenance on operating mech or relay or wiring is damaged.	Minor - Requires attention in the near future or as soon as possible. System performance is degraded but operation can continue.	Low (very few failures) 1 in 150, 000 (= .001%)	No Injury Negligible Environmental Damage Minor Asset Repair Cost Negligible Business Cost	Moderate; controls effective under certain conditions.	1.0	Inspections of mechanisms and wiring during maintenance intervals. Regular relay testing to prevent failures	
10	MV Circuit Breaker	Interrupt power supply generally under fault conditions	G - Breakdown between phases	16 - Alarm + Trip + Internal Damage + Requiring Asset Replacement	Internal failure of insulation between phases	excess voltage stress between phases leads to a breakdown between phases	Major - Requires immediate attention. System is non-operational.	Low (very few failures) 1 in 150, 000 (= .001%)	Single Fatality / Permanent Disability Extensive Environmental Damage Extensive Asset Damage Major Business Impact	Moderate; controls effective under certain conditions.	12.0	Routine testing of CB to assess condition	PD detected when testing
11	MV Circuit Breaker	Interrupt power supply generally under fault conditions	H - Breakdown 1 phase to earth	18 - Alarm + Trip + Disruptive Failure + Internal & External Damage + Fire + Replacement	1 pole fails and tracks to earth	Partial Discharge builds carbon tracks and allows arc to travel to earth	Major - Requires immediate attention. System is non-operational.	Low (very few failures) 1 in 150, 000 (= .001%)	Single Fatality / Permanent Disability Extensive Environmental Damage Extensive Asset Damage Major Business Impact	Moderate; controls effective under certain conditions.	12.0	Routine testing of CB to assess condition	PD detected when testing
12	MV Switchboard	Provide a method of distributing a single power to a number of circuits	G - Breakdown between phases	16 - Alarm + Trip + Internal Damage + Requiring Asset Replacement	Internal failure of insulation between phases	Excess voltage stress between phases or entry of vermin leads to a breakdown between phases	Major - Requires immediate attention. System is non-operational.	Moderate (infrequent failures) 1 in 400 (0.25%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Poor; control is insufficient and causes or failures are extremely unlikely to be prevented or detected.	56.7	Ability to control voltage stresses and vermin proof the switchroom.	Monitoring in the bus chamber or other areas is not cost effective on old switchboards
13	MV Switchboard	Provide a method of distributing a single power to a number of circuits	H - Breakdown 1 phase to earth	18 - Alarm + Trip + Disruptive Failure + Internal & External Damage + Fire + Replacement	1 pole fails and tracks to earth	Partial Discharge builds carbon tracks and allows arc to travel to earth	Major - Requires immediate attention. System is non-operational.	Moderate (increasing rate of failures) 1 in 80 (1.25%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Very low. Some general controls but mostly ineffective	51.0	Ability to detect PD is essential to prevent tracking. Most components eg CTs discharge before failure.	General hand held PD meters can detect increasing levels and should be used at general site inspections.
14	MV Switchboard	Provide a method of distributing a single power to a number of circuits	B - Major Component Failure (bushing, Tapchanger etc)	12 - Alarm + Damaged Component + Replacement	mechanisms fail or components fail and render switchboard / CB inoperable.	As switchboards & CBs age the parts are not replacable so may fail beyond economic repair	Minor - Requires attention in the near future or as soon as possible. System performance is degraded but operation can continue.	Low (few failures) 1 in 15, 000 (= .01%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Moderate; controls effective under certain conditions.	12.8	When switchboards and Parts are no longer available then consideration on a planned end of life is needed. In most cases only 1 panel is affected and so load can be shifted until repairs or replacement.	Some boards can be removed and parts used for life extensions on other boards until economic replacements can be made.
15	MV Switchboard	Provide a method of distributing a single power to a number of circuits	E - Asset fails to conduct continuously	08 - Fail to Operate + Repair	Mechanism may be faulty or component has failed. No serious damage	General aging & component wear causes many old switchboards to have these failures	Minor - Requires attention in the near future or as soon as possible. System performance is degraded but operation can continue.	Moderate (infrequent failures) 1 in 400 (0.25%)	No Injury Negligible Environmental Damage Minor Asset Repair Cost Negligible Business Cost	Low. Few controls in place - more luck than controls for detection	3.0	Component failures can happen. If the load is affected then it can be switched to other feeders until repairs are made.	The frequency of these minor repairs needs monitoring as they can become very frequent and start to impact operational functionality of the board.
16	MV Switchboard	Provide a method of distributing a single power to a number of circuits	I - Asset fails to operate (locked in position)	08 - Fail to Operate + Repair	A CB may not operate & remains racked in & switched on.	CB can have mech fail and not open & therefore cannot be removed without whole board outage.	Major - Requires immediate attention. System is non-operational.	Low (few failures) 1 in 15, 000 (= .01%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Poor; control is insufficient and causes or failures are extremely unlikely to be prevented or detected.	34.0	If a CB mech is not maintained it can fail and so the CB will not open when required. Whole bus outage is needed.	This can happen with older switchboards due to vertical racking wear and alignemnt.
17	Protection Relay	Device for detecting a fault & sending signals to circuit breakers to interrupt fault	J - Circuit Board Failure within Electronics	15 - Alarm + Trip + Internal Damage + Requiring Asset Repair	Internal circuit board has failure & watchdog alarm is triggered	The circuit board may overheat and componets burn out. Some are manufacturing defects.	Major - Requires immediate attention. System is non-operational.	Moderate (occasional failures) 1 in 2,000 (0.05%)	No Injury Negligible Environmental Damage Minor Asset Repair Cost Negligible Business Cost	Moderate; controls effective under certain conditions.	2.7	Generally a faulty circuit board will be detected when relay testing. Some failures are random but do not cause significant loss.	

Failure Causes/Mode & Effects Analysis - Data Sheet			High Risks Risk Priority >/= 100	Medium Risks Risk Priority >50 & <100	Lowest Risks Risk Priority <50
Client:	United Energy	Equipment:	Typical Zone Substation		

Item	Component Description	Component Function	Typical Failure Modes	Failure Effect - what happens	Cause of Failure Mode	Failure Causes - how it happens	Severity of Failure Mode S	Probability of Occurrence O	Consequence of Failure C	Effectiveness of Detection Controls D	Risk Priority Number (S x O X C)/D	Actions to Reduce Risk of Failure Mode	Comments & Additional Notes
18	Protection Relay	Device for detecting a fault & sending signals to circuit breakers to interrupt fault	K - Component Functional Failure	16 - Alarm + Trip + Internal Damage + Requiring Asset Replacement	Some relays of older type can have componets fail due to age wear or damage.	Relay becomes old and component wear increases, internal part are weakened so do not operate correctly.	Major - Requires immediate attention. System is non-operational.	Moderate (occasional failures) 1 in 2,000 (0.05%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Moderate; controls effective under certain conditions.	22.7	When old relays start to fail replacement with new relays requires extensive work on protection system.	Planned replacements are needed.
19	Protection Relay	Device for detecting a fault & sending signals to circuit breakers to interrupt fault	L - Out of Tolerance Failure	09 - Reduced Capability + Alarm + Loss of Voltage Control + Fail to operate + Repair	Relay settings drift due to system influences.	New equipment may be introduced, old relays can have wear, inadvertant operator error etc	Minor - Requires attention in the near future or as soon as possible. System performance is degraded but operation can continue.	Low (very few failures) 1 in 150, 000 (= .001%)	No Injury Negligible Environmental Damage Minor Asset Repair Cost Negligible Business Cost	Moderate; controls effective under certain conditions.	1.0	Regular relay testing can detect out of tolerance. Relay remains operational but not as effective as needed.	
20	Protection Relay	Device for detecting a fault & sending signals to circuit breakers to interrupt fault	M - Operator Error/ Maintenace Issue	05 - Unwanted Alarm + Trip	Test personnel make an error and send trip signal during relay testing	Test personnel do not full isolate the relay into test position and trigger an alarm of trip without warning.	Minor - Requires attention in the near future or as soon as possible. System performance is degraded but operation can continue.	Moderate (occasional failures) 1 in 2,000 (0.05%)	No Injury Negligible Environmental Damage Minor Asset Repair Cost Negligible Business Cost	High; unlikely the cause or failure will go undetected.	1.5	Test persons are trained correctly but occassionally make mistakes.	
21	Protection Relay	Device for detecting a fault & sending signals to circuit breakers to interrupt fault	N - External Fault - unpredictable (eg car vs Pole)	09 - Reduced Capability + Alarm + Loss of Voltage Control + Fail to operate + Repair	Relay operates for no specific reason. Fault current is very high and causes asset damage.	Fault external to substation has impact that triggers relay operation eg car vs pole, fires, lightning strikes. etc.	Major - Requires immediate attention. System is non-operational.	Moderate (infrequent failures) 1 in 400 (0.25%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Ineffective; causes or failures almost certainly cannot be prevented or detected.	170.0	External factors that trip relays etc can have large fault currents and cause damage in the substation.	Credible failure cause - examples at United Energy & western Power.
22	Current Transformer	Current measuring device	A - Internal Failure (Thermal or Dielectric)	16 - Alarm + Trip + Internal Damage + Requiring Asset Replacement	Overload or Internal fault	Overload of CT and repeated saturating causing internal breakdown	Critical - Safety hazard. Causes or can cause injury or death. Requires highest priority -	Low (very few failures) 1 in 150, 000 (= .001%)	Single Fatality / Permanent Disability Extensive Environmental Damage Extensive Asset Damage Major Business Impact	Very low. Some general controls but mostly ineffective	22.5	Correct Engineering design, additional redundant protection, routine testing & monitoring	
23	Current Transformer	Current measuring device	B - Major Component Failure (bushing, Tapchanger etc)	Major Component failure - explosion - loss of asset	Dielectric failure on insulation or oil	Excessive moisture content, Oil quality deteriorates	Critical - Safety hazard. Causes or can cause injury or death. Requires highest priority -	Low (few failures) 1 in 15, 000 (= .01%)	Single Fatality / Permanent Disability Extensive Environmental Damage Extensive Asset Damage Major Business Impact	Very poor. Almost no controls in place - Failure is likely to go undetected	67.5	Testing of oil and DLA	Most utilities do not do oil sampling of instrument transformers and failures can occur.
24	Current Transformer	Current measuring device	H - Breakdown 1 phase to earth	Major Component failure - explosion - loss of asset	Internal fault with breakdown to earth	Internal gas build up causing a tracking path to earth	Major - Requires immediate attention. System is non-operational	Moderate (occasional failures) 1 in 2,000 (0.05%)	Single Fatality / Permanent Disability Extensive Environmental Damage Extensive Asset Damage Major Business Impact	Very low. Some general controls but mostly ineffective	36.0	Electrical testing at routine maintenance intervals.	This scenario does occur but not as often as oil breakdown
25	Voltage Transformer	Voltage measuring device	A - Internal Failure (Thermal or Dielectric)	Transformer has internal failure causing loss of Asset	Switching or lightning event causes extreme voltage stress and internal failure	Lightning surge breakdown dielectric strength of oil or paper and flashover occurs	Major - Requires immediate attention. System is non-operational.	Moderate (infrequent failures) 1 in 400 (0.25%)	Single Fatality / Permanent Disability Extensive Environmental Damage Extensive Asset Damage Major Business Impact	Very low. Some general controls but mostly ineffective	45.0	Electrical testing at routine maintenance intervals.	Prefer oil sampling to be added to checks
26	Voltage Transformer	Voltage measuring device	H - Breakdown 1 phase to earth	Transformer has internal failure causing loss of Asset	HV or LV winding has failure and short to earth	Insulation breakdown or moisture ingress causes short to earth	Major - Requires immediate attention. System is non-operational.	Moderate (occasional failures) 1 in 2,000 (0.05%)	Single Fatality / Permanent Disability Extensive Environmental Damage Extensive Asset Damage Major Business Impact	Low. Few controls in place - more luck than controls for detection	28.8	Electrical testing at routine maintenance intervals.	Oil sampling & ensure surge arrestors are close by in substation
27	Voltage Transformer	Voltage measuring device	B - Major Component Failure (bushing, Tapchanger etc)	Major Component failure - explosion - loss of asset	Internal fault causes bushing insulator to rupture and starts fire	An internal fault cause pressure build up to damage insulator	Critical - Safety hazard. Causes or can cause injury or death. Requires highest priority - system is non-operational.	Moderate (infrequent failures) 1 in 400 (0.25%)	Single Fatality / Permanent Disability Extensive Environmental Damage Extensive Asset Damage Major Business Impact	Very low. Some general controls but mostly ineffective	56.3	Electrical testing at routine maintenance intervals.	Oil sampling & ensure surge arrestors are close by in substation
28	Busbar - Switchyard	Open bar connector for transmitting power from one device to another	P - Others	03 - Reduced Capability	Hot joints & Environmental damage to busbars	Rust a & aging of old Busbars	Minor - Requires attention in the near future or as soon as possible. System performance is degraded but operation can continue.	Low (very few failures) 1 in 150, 000 (= .001%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	High; unlikely the cause or failure will go undetected.	6.4	Busbars are exposed and visual inspections can assess condition.	
29	Busbar - Switchyard	Open bar connector for transmitting power from one device to another	G - Breakdown between phases	05 - Unwanted Alarm + Trip	Vermin or debris falling onto busbars	Possible vermin, Debris or overhead earth wire fall across busbars and cause 3 phase fault.	Major - Requires immediate attention. System is non-operational.	Unlikely 1 in 1.5 million (= .0001%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Ineffective; causes or failures almost certainly cannot be prevented or detected.	34.0	Faults of this type are rare but can cause significant damage. They cannot be predicted & almost unpreventable.	
30	Busbar - Switchyard	Open bar connector for transmitting power from one device to another	H - Breakdown 1 phase to earth	05 - Unwanted Alarm + Trip	1 busbar fails & causes a fault.	a post insulator may fail and the busbar arcs to earth causing an outage.	Major - Requires immediate attention. System is non-operational.	Low (few failures) 1 in 15, 000 (= .01%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Very low. Some general controls but mostly ineffective	25.5	Inspection of post insulators is visual only and failures occur. Busbar damage is slight. Cost is in post insulator but outage costs are high.	
31	Switch Isolator/ Disconnector	Switching device for opening power circuits.	L - Out of Tolerance Failure	08 - Fail to Operate + Repair	Switch does not open or close correctly and contact do not make properly.	Linkage mechanisms get loose with operation and need adjustment. Can get out of tolerance & misalignment occurs	Minor - Requires attention in the near future or as soon as possible. System performance is degraded but operation can continue.	Moderate (occasional failures) 1 in 2,000 (0.05%)	No Injury Negligible Environmental Damage Minor Asset Repair Cost Negligible Business Cost	Very low. Some general controls but mostly ineffective	3.0	Most controls are visual inspections & switching operator advice. Cost is minor if performed with maintenance.	
32	Switch Isolator/ Disconnector	Switching device for opening power circuits.	B - Major Component Failure (bushing, Tapchanger etc)	08 - Fail to Operate + Repair	Switch lever/ operating mechanism fails	Old operating mechanisms can rust at oints and break when trying to operate.	Major - Requires immediate attention. System is non-operational.	Low (few failures) 1 in 15, 000 (= .01%)	Major Injury/ Health Effects Moderate Environmental Impact Moderate Asset Damage Minor Business Impact	Very low. Some general controls but mostly ineffective	18.0	Most controls are visual inspections & switching operator advice. Cost is minor if performed with maintenance.	
33	Switch Isolator/ Disconnector	Switching device for opening power circuits.	I - Asset fails to operate (locked in position)	12 - Alarm + Damaged Component + Replacement	One or more phases fails to open	Insulator may fail and pole stays closed with others operating correctly.	Major - Requires immediate attention. System is non-operational.	Low (very few failures) 1 in 150, 000 (= .001%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Very poor. Almost no controls in place - Failure is likely to go undetected	34.0	Most controls are visual inspections & switching operator advice. Cost is minor if performed with maintenance.	
34	Transformer - Station Services	Small transformer for providing local power within the substation	A - Internal Failure (Thermal or Dielectric)	16 - Alarm + Trip + Internal Damage + Requiring Asset Replacement	Through faults, Overloading or aged insulation - no external damage	System fault is seen by Tx, aged asset, continual overloading, bad joints etc	Major - Requires immediate attention. System is non-operational.	Moderate (infrequent failures) 1 in 400 (0.25%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Moderate; controls effective under certain conditions.	28.3	Station services transformers get little maintenance & if they fail can cause whole of site outage.	
35	Transformer - Station Services	Small transformer for providing local power within the substation	B - Major Component Failure (bushing, Tapchanger etc)	12 - Alarm + Damaged Component + Replacement	Component deterioration not detected	Off circuit tapchangers cause internal breakdown. Bushings may get damaged by external forces, build up of dust, moisture & bad connections	Critical - Safety hazard. Causes or can cause injury or death. Requires highest priority - system is non-operational.	Low (few failures) 1 in 15, 000 (= .01%)	Single Fatality / Permanent Disability Extensive Environmental Damage Extensive Asset Damage Major Business Impact	Very low. Some general controls but mostly ineffective	33.8	Station services transformers get little maintenance & if they fail can cause whole of site outage.	

Failure Causes/Mode & Effects Analysis - Data Sheet

High Risks Risk Priority >/= 100	Medium Risks Risk Priority >50 & <100	Lowest Risks Risk Priority <50

Client: United Energy **Equipment:** Typical Zone Substation

Item	Component Description	Component Function	Typical Failure Modes	Failure Effect - what happens	Cause of Failure Mode	Failure Causes - how it happens	Severity of Failure Mode S	Probability of Occurrence O	Consequence of Failure C	Effectiveness of Detection Controls D	Risk Priority Number (S x O X C)/D	Actions to Reduce Risk of Failure Mode	Comments & Additional Notes
36	Post Insulator	Device for supporting busbars on structures	B - Major Component Failure (bushing, Tapchanger etc)	16 - Alarm + Trip + Internal Damage + Requiring Asset Replacement	Internal of post insulator tracks to earth & fails	Moisture & leakage current track inside post insulator until a path to earth is created the failure occurs.	Major - Requires immediate attention. System is non-operational	Low (few failures) 1 in 15, 000 (≈ .01%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Very poor. Almost no controls in place - Failure is likely to go undetected	51.0	Internal leakage is almost not detectable onlt some corona & PD can detect a possible fault.	
37	Post Insulator	Device for supporting busbars on structures	H - Breakdown 1 phase to earth	17 - Alarm + Trip + Disruptive Failure + External Damage + Replacement	Dirt dust & damage to insulator causes failure	Debris, dirt dust and other contaminates including vermin can short out a busbar at the top of post	Major - Requires immediate attention. System is non-operational	Low (very few failures) 1 in 150, 000 (≈ .001%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Very poor. Almost no controls in place - Failure is likely to go undetected	34.0	External factors eg vermin & debris are almost impossible to prevent	
38	Surge Arrestor	Device for reducing voltage spikes on power lines and equipment	H - Breakdown 1 phase to earth	17 - Alarm + Trip + Disruptive Failure + External Damage + Replacement	Corrosion, cracks manufacturing defects, incorrect design application	Degradation of grounding mechanism - fails to ground	Major - Requires immediate attention. System is non-operational.	Low (very few failures) 1 in 150, 000 (≈ .001%)	Major Injury/ Health Effects Moderate Environmental Impact Moderate Asset Damage Minor Business Impact	Low. Few controls in place - more luck than controls for detection	9.6	Testing, Inspections & maintenance/ replacement	Review cost vs testing as it may be more cost effective to replace surge arrestors after 15 years
39	Capacitor Bank	Device for proving Power factor correction or capacitance into a power circuit	B - Major Component Failure (bushing, Tapchanger etc)	17 - Alarm + Trip + Disruptive Failure + External Damage + Replacement	Bushing or busbar failure causes capcan failure	Bushings & connections can get damages or broken under a fault	Minor - Requires attention in the near future or as soon as possible. System performance is degraded but operation can continue.	Moderate (occasional failures) 1 in 2,000 (0.05%)	No Injury Negligible Environmental Damage Minor Asset Repair Cost Negligible Business Cost	Ineffective; causes or failures almost certainly cannot be prevented or detected.	12.0		
40	Capacitor Bank	Device for proving Power factor correction or capacitance into a power circuit	A - Internal Failure (Thermal or Dielectric)	16 - Alarm + Trip + Internal Damage + Requiring Asset Replacement	Internal failure of capacitor layers fail & internal rupture occurs	Internal capacitive layers can break down and short out causing internal failure	Minor - Requires attention in the near future or as soon as possible. System performance is degraded but operation can continue.	Moderate (increasing rate of failures) 1 in 80 (1.25%)	No Injury Negligible Environmental Damage Minor Asset Repair Cost Negligible Business Cost	Ineffective; causes or failures almost certainly cannot be prevented or detected.	18.0		
41	Capacitor Bank	Device for proving Power factor correction or capacitance into a power circuit	N - External Fault - unpredictable (eg car vs Pole)	17 - Alarm + Trip + Disruptive Failure + External Damage + Replacement	Vermin or debris hit busbars or cans & cause failure	Vermin - snakes etc - can crawl between live bars & earth causing a short	Major - Requires immediate attention. System is non-operational.	Moderate (occasional failures) 1 in 2,000 (0.05%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Very poor. Almost no controls in place - Failure is likely to go undetected	68.0		
42	Cable	Used for transmitting power supplies between connected devices	D - Cable joint failure	08 - Fail to Operate + Repair	Cable joint fails in-line or at termination	Moisture ingress & PD tracking at poor cable terminations.	Minor - Requires attention in the near future or as soon as possible. System performance is degraded but operation can continue.	Moderate (increasing rate of failures) 1 in 80 (1.25%)	No Injury No Environmental Damage Major Asset Repair Cost Substantial Business Cost	Low. Few controls in place - more luck than controls for detection	30.6	Visual inspections & PD checks on cable terminations is best option.	
43	Cable	Used for transmitting power supplies between connected devices	H - Breakdown 1 phase to earth	15 - Alarm + Trip + Internal Damage + Requiring Asset Repair	Cable insulation failure or Damage caused to cable	Moisture ingress damages cable insulation & it tracks to earth or cable is damaged by external influences.	Major - Requires immediate attention. System is non-operational.	Moderate (infrequent failures) 1 in 400 (0.25%)	Single Fatality / Permanent Disability Major Environmental Damage Major Asset Damage Moderate Business Impact	Very low. Some general controls but mostly ineffective	40.0	Selection of cable type can prevent moisture ingress.	Dial-before-you-dig to prevent cable damage from excavations
44	Cable	Used for transmitting power supplies between connected devices	G - Breakdown between phases	15 - Alarm + Trip + Internal Damage + Requiring Asset Repair	3phase cable insulation damage or moisture ingress	Moisture ingress damages cable insulation & causes phase to phase fault or cable is damaged by external influences.	Minor - Requires attention in the near future or as soon as possible. System performance is degraded but operation can continue.	Low (few failures) 1 in 15, 000 (≈ .01%)	Single Fatality / Permanent Disability Major Environmental Damage Major Asset Damage Moderate Business Impact	Very low. Some general controls but mostly ineffective	18.0	Selection of cable type can prevent moisture ingress.	Dial-before-you-dig to prevent cable damage from excavations
45	Overhead Line	Used for transmitting power supplies between connected devices	D - Cable joint failure	17 - Alarm + Trip + Disruptive Failure + External Damage + Replacement	Line splices fail & line comes down	Line fatigue, vegetaion pressure on lines, poor splicing, pole degradation	Critical - Safety hazard. Causes or can cause injury or death. Requires highest priority - system is non-operational.	Moderate (increasing rate of failures) 1 in 80 (1.25%)	Single Fatality / Permanent Disability Major Environmental Damage Major Asset Damage Moderate Business Impact	High; unlikely the cause or failure will go undetected.	30.0	Line inspections & defect management reduces failures	
46	Overhead Line	Used for transmitting power supplies between connected devices	B - Major Component Failure (bushing, Tapchanger etc)	12 - Alarm + Damaged Component + Replacement	Pole fails or insulator fails	age & degradation of pole and componets can cause failures	Critical - Safety hazard. Causes or can cause injury or death. Requires highest priority - system is non-operational.	Moderate (increasing rate of failures) 1 in 80 (1.25%)	Single Fatality / Permanent Disability Major Environmental Damage Major Asset Damage Moderate Business Impact	Moderate; controls effective under certain conditions.	40.0	Pole & line inspections reduce failures	
47	Overhead Line	Used for transmitting power supplies between connected devices	N - External Fault - unpredictable (eg car vs Pole)	17 - Alarm + Trip + Disruptive Failure + External Damage + Replacement	Vehicle or other damages pole or line	vehicle incident or other damage to pole or line to cause a fault. Includes lightning strikes.	Critical - Safety hazard. Causes or can cause injury or death. Requires highest priority - system is non-operational.	Moderate (increasing rate of failures) 1 in 80 (1.25%)	Single Fatality / Permanent Disability Major Environmental Damage Major Asset Damage Moderate Business Impact	Very poor. Almost no controls in place - Failure is likely to go undetected	120.0	Vehicle accidents cannot be predicted for any site	
48	Overhead Line	Used for transmitting power supplies between connected devices	G - Breakdown between phases	05 - Unwanted Alarm + Trip	line clashing or debris on line	Lightning, debris or adverse weather conditions can cause lines to clash & trip supply.	Major - Requires immediate attention. System is non-operational.	Moderate (increasing rate of failures) 1 in 80 (1.25%)	Single Fatality / Permanent Disability Major Environmental Damage Major Asset Damage Moderate Business Impact	Moderate; controls effective under certain conditions.	32.0	Use of spreaders and vegetaion manage helps reduce risks	
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Table 1| K-BIK Power FMEA Spreadsheet.

End of Report