Line Voltage Regulators

AMS – Electricity Distribution Network

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Disclaimer

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1 Executive Summary

This document is part of the suite of Asset Management Strategies relating to AusNet Services' electricity distribution network. The purpose of this strategy is to outline the inspection, maintenance, replacement and monitoring activities identified for economic life cycle management of line voltage regulators in AusNet Services' Victorian electricity distribution network.

This strategy applies to 89 medium voltage (MV) line voltage regulators (VR) locations installed on the electricity distribution network lines. This strategy excludes station located 66kV voltage regulators.

Condition assessment shows that about 35% of VR sites are in good condition (C1 or C2) as being in line with the current standard. The remainder are three phase VR units are in various condition states with 18% of the fleet in "Average" condition, 30% in "Poor" condition and 17% in "Very Poor" condition.

Criticality analysis of line voltage regulators, by assessing the economic impact of a failure, was developed. Apporximately 45% of the fleet, fall into high and very high criticality bands. Risk analysis was developed by analysing criticality and condition over the fleet. The risk analysis recommended a proactive replacement forecast for the 2022-26 regulatory period.

Ongoing proactive management of line voltage regulators installation, inspection, maintenance and replacement practice is required to ensure AusNet Services meet stakeholder expectations of cost, safety, reliability and environmental performance. The summary of proposed asset strategies is list below.

1.1 Asset Strategies

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1.1.1 New Assets

- All new line voltage regulators shall be installed with SCADA monitoring and control
- Continue replacing three-phase line voltage regulators with three single-phase units
- Adopt standardisation of single phase line voltage regulator sizes

1.1.2 Condition Monitoring

In conjunction with other maintenance works:

- Continue the effort to align line voltage regulator condition assessment with zone substation power transformer condition assessment (AMS 20-71)
- Record additional condition assessment metrics or health indices during routine maintenance
- Inspect line voltage regulators at three-month intervals (non-SCADA monitored line voltage regulators), as per PGI 02-01-04
- Use the auto-diagnostic capability of new single-phase line voltage regulators and map more diagnostic parameters to SCADA
- Continue using Advanced Meter Interval (AMI) 'smart meter' data to validate line voltage regulator performance
- Review existing fault reporting methodologies and codes

1.1.3 Maintenance

- Continue routine maintenance works; oil testing, oil reconditioning, oil replacement, overhaul and tank works as per PGI 02-01-04
- Expand current library of standard maintenance instructions (SMI) to incorporate the remaining on load tap changers without an existing SMI
- Implement regular training of maintenance personnel by manufactures of primary units and secondary relay employed including regular interface with manufacturers to understand fleet performance issues.

1.1.4 Obsolescence and Spares Management

- Undertake strategic spare stock level assessment
- Maintain sufficient spare components for existing three-phase units
- Maintain sufficient spares policy for single-phase units to allow complete replacement and maintenance at the depot.

1.1.5 Replacements

- Replace 15 three-phase line voltage regulators with three single-phase line voltage regulators in the 2022-26 regulatory period
- Prioritise the future replacements so to address the future reverse flow regulation requirements on each feeder as required due to increased embedded solar generation capacity.

2 Introduction

2.1 Purpose

The purpose of this document is to outline the inspection, maintenance, replacement and monitoring activities identified for economic life cycle management of line voltage regulators assets. The document is intended to inform asset management decisions and communicate the basis for activities.

In addition, this document forms part of the Asset Management System for compliance with relevant standards and regulatory requirements. This document demonstrates responsible asset management practices by outlining economically justified outcomes.

2.2 Scope

This strategy applies to medium voltage (MV) line voltage regulators installed on the electricity distribution network.

This strategy excludes station located 66kV voltage regulators, which are addressed in AMS 20-71.

2.3 Asset Management Objectives

As stated in *AMS 01-01 Asset Management System Overview*, the high-level asset management objectives are:

- Comply with legal and contractual obligations;
- Maintain safety;
- Be future ready;
- Maintain network performance at the lowest sustainable cost; and
- Meet customer needs.

As stated in *AMS 20-01 Electricity Distribution Network Asset Management Strategy*, the electricity distribution network objectives are:

- Improve efficiency of network investments;
- Maintain long-term network reliability;
- Implement REFCL's within prescribed timeframes;
- Reduce risks in highest bushfire risk areas;
- Achieve top quartile operational efficiency; and
- Prepare for changing network usage.

3 Asset Description

3.1 Asset Function

The voltage along a distribution line decreases as the distance from the zone substation increases. The voltage on the distribution line also decreases as the load increases.

Low voltages can occur during periods of heavy electrical demand, such as during heat waves, when air conditioners are running. High voltages can occur during periods of low electrical demand, such as during the middle of the day in residential areas when many people are at work and this problem may be exacerbated when high levels of residential solar is installed.

The Electricity Distribution Code prescribes the range within which voltages must be maintained. Overvoltage and under voltages (that is voltages outside the range prescribed in the Electricity Distribution Code), may cause appliances to operate less efficiently or to overheat and fail prematurely.

Line voltage regulators are installed on distribution feeders to raise or lower the voltage to compensate for the voltage drop along the feeder to ensure all customers receive a voltage within the range prescribed in the Electricity Distribution Code. Very long feeders may require multiple voltage regulators between the zone substation and the end of the feeder.

3.2 Asset Population

AusNet Services has three line voltage regulator configurations on the distribution network:

1. One three-phase regulator;
2. Three single-phase regulators; and
3. One single-phase regulator.

There are 89 line voltage regulator sites on the electricity distribution network. This relates to 141 regulator tanks[1]. Each site has one of the three configurations listed above.

The three-phase regulator units are inclusive of mechanism, on load tap change (OLTC), winding's tank, controller.

The three single-phase units are an assembly of three individual single phase units each with its own mechanism, OLTC and winding tank. They may have one controller for each single-phase unit (CL6 or CL7) or one controller (CL7) controlling all three single-phase units.

[1] RIN 2018 AusnetServcies Category Analysis

The one single-phase units have their own mechanism, OLTC, winding tank and one controller (CL6 or CL7). They are pole mounted and are used on single-phase networks.

All new installations, except those on single-phase networks, are three single-phase regulators. Three single-phase regulators present advantages when compared to the older three-phase units.

Some of the advantages include:

- greater voltage control, achieved by the single-phase units ability to tap on individual phases);
- SCADA connectivity;
- reverse flow regulation functionality; and
- increased maintenance efficiency, achieved by swapping a defective single-phase unit with one in good working order on site and returning the defective one to the depot to perform maintenance, investigation and repair.

One three-phase regulator | Three single-phase regulators | One single-phase regulator

Figure 1 – Line Voltage Regulator Configurations

The breakdown of population by regulator configuration is presented in Figure 2.

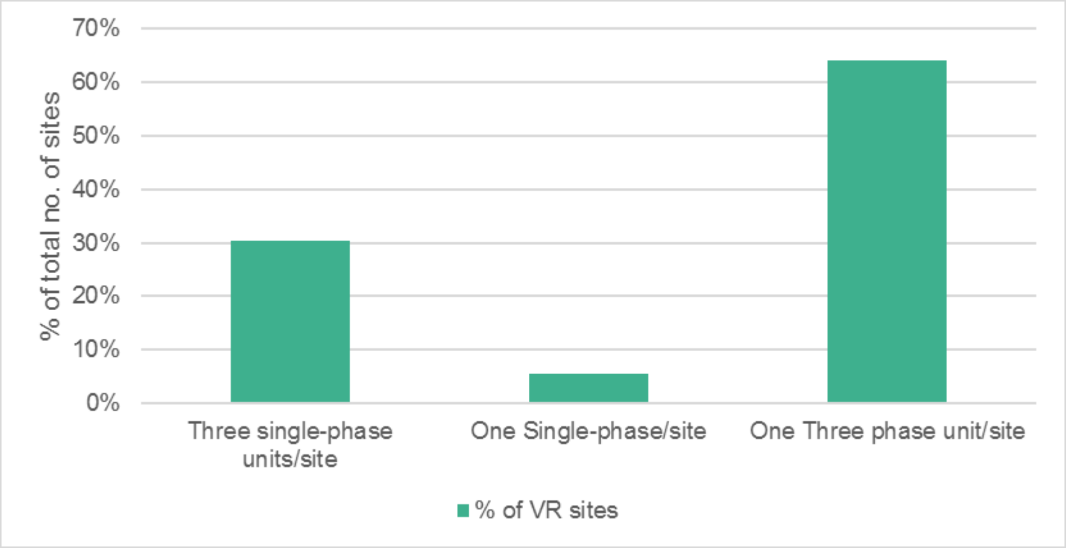

Figure 2 – Voltage regulator sites by configuration

On feeders where Rapid Earth Fault Current Limiter (REFCL) technology is mandated (refer to Section 4.3), the voltage regulator configuration is different than on the rest of feeders by installing a single controller (CL7) to ensure the tapping of all three phases is done at the same time. This is required so that the three phases are voltage balanced for the use of REFCL.

The reminder of the feeders may have individual controllers (CL6 or CL7) for each phase thus allowing a greater voltage control.

3.3 Asset Age Profile

The service age profile for voltage regulators in Figure 3 is based on the known and derived installation dates.

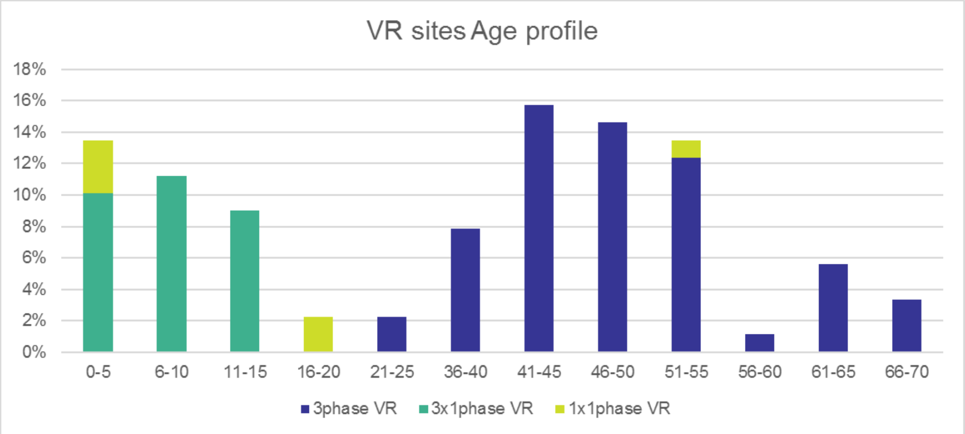

Figure 3 – Services Age of Voltage Regulators as of end of 2017

3.4 Condition

A condition rating is assigned to each line voltage regulator unit as a score per site. Line voltage regulator units are scored following a similar process used for station power transformers.

The process includes measurements and assessments. Measurements used in the condition assessment include:

- Oil samples for DGA and oil quality tests (reported in condition colour: green, amber, red)
- Number of tap operations
- Number of faults (based on work order records)
- Environmental deterioration (oil leaks, corrosion, cabling)

Assessments are made by subject matter experts (SME) and include interpretation of the measurements, regulator site condition, make and vintage (to account for known issues with specific makes and vintages).

The condition score is a five point scale ranging from “Very Good” (C1) to “Very Poor” (C5). Table 1 provides further details of the condition scores.

Table 1 - Condition Score definition

Condition Score	Condition Description	Condition	Summary of Condition Score Main Characteristics	Remaining Life
C1	Very Good	Initial service condition.	• Oil sample green • Low (significantly under 1800) number of tap operations • Zero fault work orders	95%
C2	Good	Deterioration has minimal impact on asset performance. Oil samples green or amber,	• Oil sample green • Low to medium (under 1,800) number of tap operations • Maximum one fault work order	75%
C3	Average	Functionally sound showing some wear with minor failures, but asset still functions safely at adequate level of service.	• Oil sample green • Medium to high (under 3,600) number of tap operations • Between two and six fault work orders	45%
C4	Poor	Advance deterioration – plant and components function but require a high level of maintenance to remain operational.	• Oil sample amber or green • Very high (over 3,600) number of tap operations • More than six fault work orders	25%
C5	Very Poor	Extreme deterioration, approaching end of life with failure imminent.	• Oil sample amber or red • Very high (over 3,600) number of tap operations • More than six fault work orders	15%

For further information regarding the condition assessment framework, specific issues, conditional maintenance activities and discussion of failures, refer to the condition scoring methodology, which can be found in the Asset Health Report AHR 20-68.

Figure 4 shows the distribution of condition scores by line voltage regulator configuration as a percentage of total number of line voltage regulator sites.

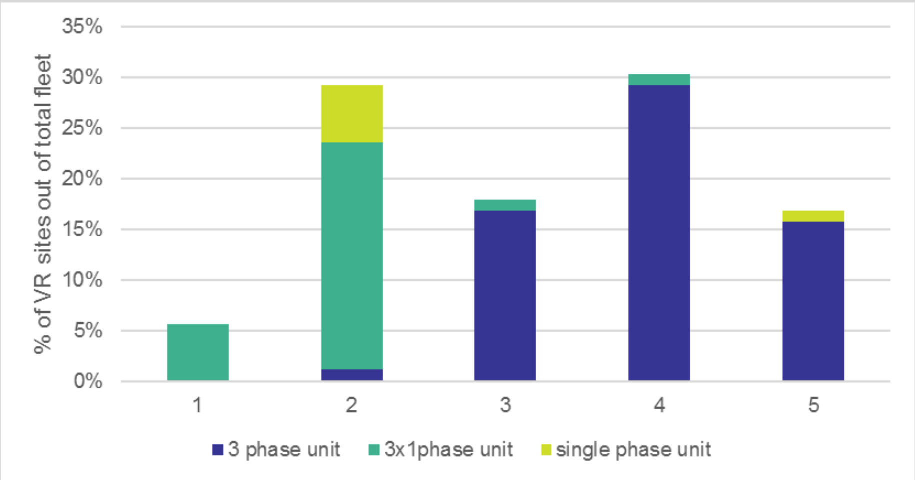

Figure 4 – Condition score by line voltage regulator configuration

The three-phase units are in the worst condition. The single-phase line voltage regulators, whether one unit per site or three units per site, are in good condition given they are recently installed and the repair is made by replacing a complete defective unit with one in good working order. The repair of the defective single-phase units is made at the depot rather than on site.

3.5 Asset Criticality

The consequences of voltage regulator failure are allocated into five criticality bands based on their economic impact as the result of the failure. These asset criticality or consequence impacts are irrespective of the likelihood of the actual failure.

The following failure impact were considered;

- Supply Risk – interruptions to customer supplies;
- Bush fire ignition – risk of fire ignition in summer months due to overloading of downstream plant;
- Public safety and environmental – risk of electrical shock due to high volts at customer end;
- Compliance – failure to supply electricity to the quality required by the code hence attracting penalties; and
- Collateral damage – appliance damage due to low/high volts at customer end.

3.5.1 Supply Risk

A line voltage regulator mal-operation can trip the upstream feeder circuit breaker taking thousands of customers out of supply.

Line voltage regulators are usually required on remote locations towards the end of the feeders where the voltage drop occurs. Thus, intervention time (travelling to site only) to restore power supply may take up to 3 hours.

Such an event may incur a significant reliability incentive scheme penalty.

3.5.2 Bushfire Ignition

There is no record of fires started by line voltage regulators in the past.

Bush fire ignition is mitigated in later designs using single-phase units with covered conductor, concrete bunded foundation area, maintained bare earth surrounds to fence.

3.5.3 Public Safety and Environment

A mal-operation of the line voltage regulator can result in high volts at the customer end.

The most significant environmental risk is accidental oil spill. This hazard is mitigated by design. All ground mounted line voltage regulator sites are have bunded spill barriers. Major leak would require clean up of surrounding soil.

3.5.4 Compliance

Line voltage regulators are required in the network to ensure that all customers and particularly remote customers receive electricity at a quality within the code (Clause 4 of the Electricity Distribution Code).

A mal-operation of the line voltage regulator may result in high or low volts at the customer end hence out of code voltage.

3.5.5 Collateral Damage

A line voltage regulator maloperation can result in high/low volts at the customer end. This in turn can result in customer appliance damage. AusNet Services are liable for all damaged customer appliance due to voltage fluctuation.

3.5.6 Criticality bands

The criticality of a line voltage regulator site has been assigned into bands using factors above and ;

- maximum yearly load (MVA);
- contingency scenario; and
- power utilisation factor (PUF)

The limitation of providing reverse power flow capability has not been factored into this assessment. This is treated as a separate business driver.

Figure 5 shows the combined distribution of criticality scores, with 1 being low impact and 5 being very high impact.

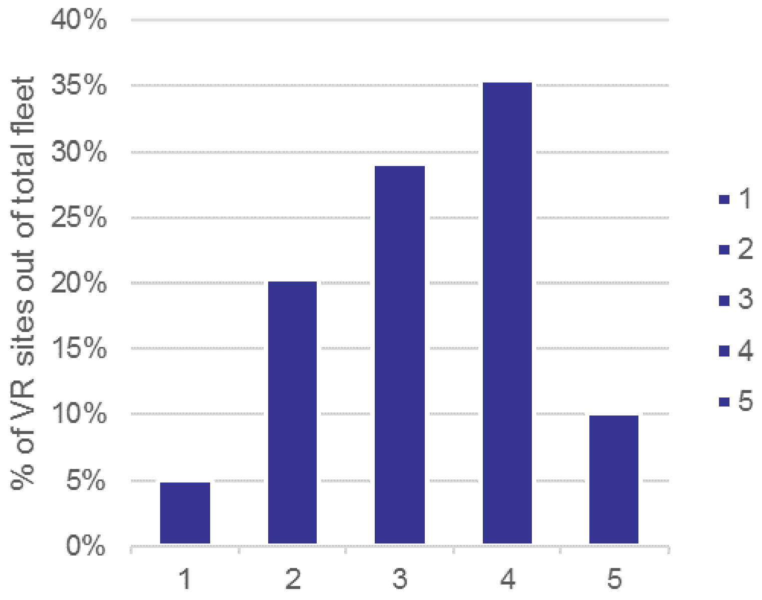

Figure 5 – Line voltage regulator site criticality score

3.6 Asset Performance

Asset performance is assessed by analysing the defects and unassisted failures of the line voltage regulators. The analysis includes failure trend, damage component and number of corrective maintenance work orders.

3.6.1 Work Order Analysis

Figure 6 illustrates the yearly corrective maintenance (CM) trend by line voltage regulator component.

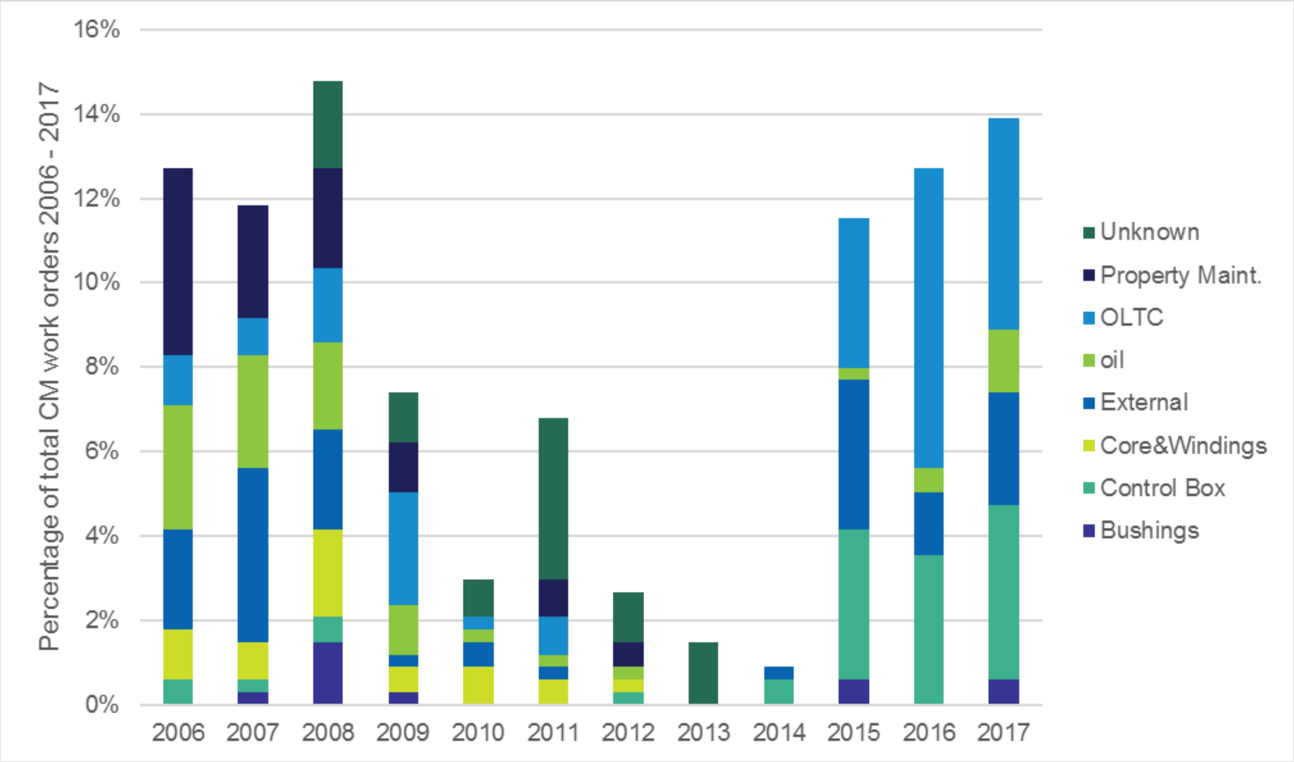

Figure 6 – Component failure trends 2006-2017

Figure 6 shows a change in component type failure between the older three-phase line voltage regulators and the modern three single-phase line voltage regulator.

As the line voltage regulator fleet is being renewed and new line voltage regulator sites are built to new standard there are less issues with oil leaks, core and windings and property maintenance. However, new component failures have appeared, such as issues with cables connecting the single-phase line voltage regulators and control box together and control box software troubleshooting.

The reduction of work orders from 2008 to 2014 is due to a number of new zone substations being installed. This changed the criticality of voltage regulators for several years. This change was accompanied by a considerable experience loss in fitter skills thus maintenance reporting and practice were greatly reduced. The increase in the number of work orders starting 2015 is assumed to be due to a better maintenance work management with the migration from the old asset management software to SAP.

Figure 7 illustrates the volume of corrective maintenance work orders as a percentage of total number of corrective maintenance work orders by line voltage regulator component from 2006 to 2017.

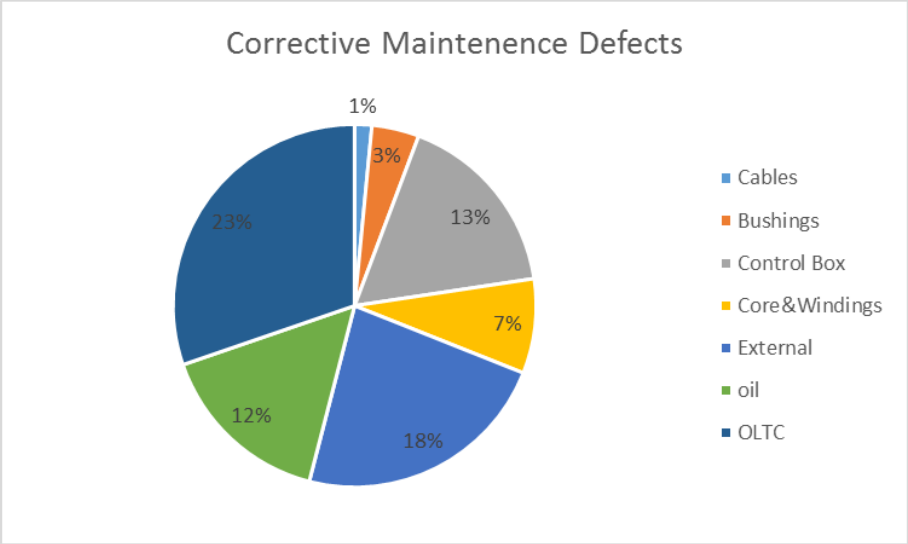

Figure 7 – Line voltage regulator components affected by failures (2006-2017)

4 Other Issues

4.1 Asset Inspection

Condition assessments involving regular oil and non-invasive investigations, as well as planned overhauls are performed in accordance with the SAP maintenance cycles as stated in PGI-02-01-04.

Given the complexity of the equipment, it is not possible to assign an overall condition score upon a site visit. The condition scores are calculated by a subject matter expert taking into account various inputs such as visual inspection of the external part of line voltage regulator components, oil sampling investigation results, number of tap operations and past work orders.

An opportunity exists to improve the inspection process on the new generation line voltage regulators. The controller has auto-diagnostic capability and is SCADA connected. This opens the opportunity to receive a set of predefined parameters via SCADA, such as the number of tap operations and percentage of contact wear.

4.2 Compliance

The Electricity Distribution Code regulates the distribution of electricity by a distributor to its customers. Clause 4 details the regulatory obligations for the quality of supply for a number of parameters, including voltage.

Table 2 is reproduced from the Electricity Distribution Code and lists the standard nominal voltage variations allowed.

Table 2 – Standard Nominal Voltage Variations

STANDARD NOMINAL VOLTAGE VARIATIONS				
Voltage Level in kV	**Voltage Range for Time Periods**			**Impulse Voltage**
	Steady State	**Less than 1 minute**	**Less than 10 seconds**	
< 1.0	+10% - 6%	+14% - 10%	Phase to Earth +50%-100% Phase to Phase +20%-100%	6 kV peak
1-6.6	± 6 % (± 10 % Rural Areas)	± 10%	Phase to Earth +80%-100% Phase to Phase +20%-100%	60 kV peak
11				95 kV peak
22				150 kV peak
66	± 10%	± 15%	Phase to Earth +50%-100% Phase to Phase +20%-100%	325 kV peak

Line voltage regulators are key assets in managing voltage levels to maintain compliance with the Electricity Distribution Code.

4.3 Rapid Earth Fault Current Limiter (REFCL)

In line with the Victorian Electrical Safety (Bushfire Mitigation) Amendment Regulations 2016 AusNet Services needs to install the Rapid Earth Fault Current Limiter (REFCL).

The installation and application of REFCL technology are governed by two key legislations:

1. Electricity Safety (Bushfire Mitigation) Regulations 2013
2. Electricity Safety Act 1998

With the introduction of REFCL on designated zone substations and feeders there is a requirement to perform network capacitance to earth balancing. AusNet Services is utilising several methods to achieve minimal capacitive unbalance (or network capacitance to earth imbalance). The key aspect involving new design three single-phase line voltage regulators is maintaining the downstream feeder phases balanced by employing a single controller, which ensures the on load tap changers on each phase are tapping at the same time. The older three-phase line voltage regulator design are not impacted by REFCL design requirements.

4.4 Emerging Capacity/ Reverse Power Flow

An issue which is having an increasing impact is installation of residential rooftop solar panels. The main consequences, which will impact the voltage regulation philosophy on distribution networks:

- Due to electricity circulating on both directions through the network (zone sub to customer and vice versa) all line voltage regulators need to be capable for reverse flow regulation,
- Due to the lack of legislative regulation and network automation on customers generating electricity to the grid the line voltage regulators need to be more sensitive. Thus, the tapping range needs to be narrowed resulting in more tap operations per year, an increased maintenance cost and a reduced life span of line voltage regulators.

5 Risk and Options Analysis

5.1 Overview

As outlined in Section 3.1 the fundamental function of the line voltage regulators in the distribution network is to compensate for the voltage drop along a feeder to ensure all customers receive voltage within the range prescribed in the Electricity Distribution Code.

Table 3 presents the risk matrix condition score versus criticality for the entire line voltage regulator fleet. Those included in current replacement program to be completed prior to 2021 have been excluded.

The risk matrix highlights in red colour the worst condition and highest consequence line voltage regulator sites.

Table 3 – Line Voltage Regulator Risk Matrix

		Condition					
		C1	C2	C3	C4	C5	**Total**
Criticality	5		3	2	3		**8**
	4	5	10	3	9	1	**28**
	3		10	4	7	2	**23**
	2		3	6	5	2	**16**
	1				2	2	**4**
	Total	**5**	**26**	**15**	**26**	**7**	**79**

The risk matrix suggests it is economic to replace 15 line voltage regulators between 2022 and 2026. The line voltage regulators selected for replacement are in the red section of the risk matrix are the criticality 5 in condition C4, Criticality 4 in condition C4 and C5, Criticality 3 in condition C5. The Criticality 5 assets in condition C3 are not planned for replacement.

It has been established that the line voltage regulators in the red section of the risk matrix are largely of same make with those in the amber section. Thus, proactively replacing the high risk line voltage regulator units can achieve a double benefit; it mitigates the highest risk sites and it mitigates the next highest risk by providing some emergency breakdown spares for the line voltage regulators in the amber risk section.

An emerging driver for line voltage regulator replacement is the requirement for reverse flow regulation (refer Section 4.4). This type of replacements were not included in this proactive replacement program and are considered separately under network planning augmentation.

5.2 Summary of Proactive Replacement Forecast

The next regulatory period, 2022-26, proactive replacement program includes the replacement of 15 three phase line voltage regulators with modern equivalent of three single-phase line voltage regulators. This represents an average three VR sites replacement per year, which is consistent with the past, reset period replacement.

6 Asset Strategies

The following strategies shall be used to manage risks associated with line voltage regulators

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6.1 New Assets

- All new line voltage regulators shall be installed with SCADA monitoring and control
- Continue replacing three-phase line voltage regulators with three single-phase units
- Adopt standardisation of single phase line voltage regulator sizes

6.2 Condition Monitoring

In conjunction with other maintenance works:

- Continue the effort to align line voltage regulator condition assessment with zone substation power transformer condition assessment (AMS 20-71)
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- Continue routine maintenance works; oil testing, oil reconditioning, oil replacement, overhaul and tank works as per PGI 02-01-04
- Expand current library of standard maintenance instructions (SMI) to incorporate the remaining on load tap changers without an existing SMI
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- Undertake strategic spare stock level assessment
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- Prioritise the future replacements so to address the future reverse flow regulation requirements on each feeder as required due to increased embedded solar generation capacity.