ESSENTIAL SERVICES COMMISSION

Review of the Victorian Electricity Distribution Code

for Bushfire Mitigation

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Review of the Victorian Electricity Distribution Code for Bushfire Mitigation

Essential Services Commission

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DEFINITIONS

AS	Australian Standard
CT	Current Transformer
DNSP	Distribution Network Service Provider
ESB	Electricity Supply Board
ESC	Essential Services Commission
EPR	Earth Potential Rise
ESR	Electricity (Safety) Regulations
GFN	Ground Fault Neutraliser
HV	High Voltage
IEC	International Electrotechnical Commission
REFCL	Rapid Earth Fault Current Limiter
SIR	Services and Installation Rules
VEDC	Victorian Electricity Distribution Code
VT	Voltage Transformer

EXECUTIVE SUMMARY

WSP has been engaged by the Essential Services Commission (ESC) to review the voltage standards in the Victorian Electricity Distribution Code (VEDC). Our review is in the context of distributors' being required to install Rapid Earth Fault Current Limiters (REFCL) technology in response to changes to the Electricity Safety (Bushfire Mitigation) Regulations 2013.

The implementation of REFCL changes the system neutral earthing method to a compensated arrangement, which requires connected equipment to be suitably rated to withstand up to phase-to-phase voltages between phases and neutral. This allows distributors to meet their obligations under the Electrical Safety (Bushfire Mitigation) Regulations 2014.

The objective of modifying the VEDC is to allow operation of REFCL technology without violating the voltages standards set out in the VEDC. Our findings should be read in conjunction with the assumptions and limitations of this Report.

WSP's method in assessing the VEDC resulted in an initial review of international standards followed by an assessment of equipment capabilities. This led to our suggested recommendations in consultation with the ESC on amending the VEDC.

Key Findings

— Our initial review of international standards concluded that there are no explicit requirements for phase-to-earth voltage withstand requirements (magnitude and duration). The focus of these standards seems to be supply variations for phase-to-phase voltages rather than phase-to-earth voltages. Our detailed findings are provided in Section 3.

— When reviewing plant standards for selected equipment, we identified the ability for equipment to be specified to withstand up to phase-to-phase voltages between phase and neutral. The withstand duration varies depending on the type of equipment selected but the maximum permitted time is around eight hours. High voltage cables, when specified as Category B, have 125 hours overall limit of exposure to high voltages per year. Items such as surge arrestors, where not specified to withstand full phase-to-phase voltage, would require replacement. Our detailed findings are provided in Section 4.

— There have been some cases documented internationally where networks with REFCLs deployed have resulted in higher than phase-to-phase voltages between phase and earth. These are not normal operating conditions. Further detail is provided in Section 5.3.

Amending the VEDC

— Our review of international jurisdictions did not reveal any limits on phase-to-earth voltage limits where REFCLs are installed. Removing the phase-to-earth voltage limits in the VEDC for areas of REFCL operation would be consistent with our findings.

— The maximum expected phase-to-earth voltage on a network where a REFCL is operating be limited to the maximum phase-to-phase voltage level (this is equivalent to approximately 1.9 times the nominal phase-to-earth voltage on an effectively earthed system).

— Equipment operating on a REFCL network be specified to withstand the maximum expected phase-to-phase voltages between phases and earth.

USE OF CONTENT AND LIMITATION

This report is a product of work undertaken by WSP for the Essential Services Commission (the Client) as technical consultant for the review of the Victorian Electricity Distribution Code for Bushfire Mitigation (the Project). This report cannot be relied upon in any circumstance by any other party.

To the best of WSP's knowledge, the facts and matters described in this Report indicate the Client's intentions in relation to the Project at the time of issuing of this Report. However, the passage of time, the manifestation of latent conditions or the impact of future events (including a change in applicable law) may result in changes to the Project. To the fullest extent permitted by law, WSP, its related bodies corporate and its officers, employees and agents assumes no responsibility and will not be liable to any third party for any loss, expense or damage (including any indirect, consequential or punitive losses or damages or any amounts for loss of income or profits, of any kind (arising in contract, tort or otherwise) suffered or incurred by a third party arising from any matter dealt with in the report, or conclusions expressed in the report. The information contained within the report have not been independently verified and checked by WSP. If the material set out in these documents is inaccurate or incomplete, it may impact the conclusions or recommendations in this Report. WSP takes no responsibility for the accuracy and completeness of this information.

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1 BACKGROUND

1.1 PROJECT BACKGROUND

In response to recommendations of the 2009 Victorian Bushfires Royal Commission, the Victorian Government established a Powerline Bushfire Safety Program that resulted in new measures to reduce bushfire risks from electricity networks. The Electricity Safety Act 1998 (VIC) imposes bushfire mitigation requirements on Victorian electricity distributors. As part of these requirements, on 1 May 2016, amendments to the Electricity Safety (Bushfire Mitigation) Regulations 2013 (VIC) came into effect. The Bushfire Mitigation Regulations mandates the installation of bushfire mitigation equipment on certain sections of the Victorian distribution network.

In response to the amended bushfire mitigation regulations, Victorian distributors are proposing the installation and operation of a proprietary variant of Rapid Earth Fault Current Limiter (REFCL) called Ground Fault Neutraliser (GFN). This proprietary REFCL is an enhanced version of the resonant neutral earthing system based on the arc suppression coil scheme with a residual current compensator that utilises power electronics. However, the normal operation of the REFCL, which is new to Australia, may exceed certain provisions of the VEDC's current technical standard leading to distributor non-compliance.

WSP has been engaged by the ESC to assist reviewing the voltage standards in the VEDC. The review is being undertaken in the context of distributors' likely installation of REFCLs technology in response to the new bushfire mitigation requirements.

1.2 OBJECTIVE

This report addresses the following objectives in our scope of engagement with the ESC for modifying the VEDC to allow REFCL operation:

- Task 1: Desktop study of REFCL operation and international approach for setting voltage limits in REFCL networks
- Task 2: Provide draft options in amending the VEDC
- Task 3: Provide a final recommendation in amending the VEDC

2 TECHNICAL AND REGULATORY CONTEXT

2.1 CATEGORISATION OF POWER QUALITY PHENOMENON

In assessing the impacts of REFCL operation on power system voltages it is important to quantify the nature and type of phenomenon. Table 2.1 provides an overview of the main power quality phenomenon including magnitudes and durations.

Table 2.1 Categorisation of Power Quality Phenomenon [1]

Category	Subcategory	Sub Subcategory	Typical Duration	Typical Voltage Magnitude
Transients	Impulsive	Nanosecond	< 50 ns	
		Microsecond	50 ns - 1 ms	
		Millisecond	> 1 ms	
	Oscillatory	Low frequency	0.3 - 50 ms	0 - 4 pu
		Medium frequency	20 us	0 - 8 pu
		High frequency	5 us	0 - 4 pu
Short-duration variations	Instantaneous	Interruption	0.5 - 30 cycles	< 0.1 pu
		Sag (dip)	0.5 - 30 cycles	0.1 - 0.9 pu
		Swell	0.5 - 30 cycles	1.1 - 1.8 pu
	Momentary	Interruption	30 cycles - 3 s	< 0.1 pu
		Sag (dip)	30 cycles - 3 s	0.1 - 0.9 pu
		Swell	30 cycles - 3 s	1.1 - 1.4 pu
	Temporary	Interruption	3 s - 1 min	< 0.1 pu
		Sag (dip)	3 s - 1 min	0.1 - 0.9 pu
		Swell	3 s - 1 min	1.1 - 1.2 pu
Long-duration variations	Interruption, sustained		> 1 min	0.0 pu
	Undervoltages		> 1 min	0.8 - 0.9 pu
	Overvoltages		> 1 min	1.1 - 1.2 pu

2.2 VICTORIAN REQUIREMENTS

2.2.1 VICTORIA ELECTRICITY DISTRIBUTION CODE

Temporary increase in phase-to-earth potential is well documented in a resonant grounded network [2]. The standard voltage and voltage variation requirements set out by the VEDC Version 9, as shown in Figure 2.1, specifies that the 22 kV system phase-to-earth quantity shall not exceed +80 per cent for 10 seconds.

4.2 Voltage

4.2.1 Subject to clause 4.2.2, a ***distributor*** must maintain a nominal ***voltage*** level at the ***point of supply*** to the ***customer's electrical installation*** in accordance with the *Electricity Safety (Network Assets) Regulations* 1999 or, if these regulations do not apply to the ***distributor***, at one of the following standard nominal ***voltages***:

(a) 230V;

(b) 400 V;

(c) 460 V;

(d) 6.6 kV;

(e) 11 kV;

(f) 22 kV; or

(g) 66 kV.

4.2.2 Variations from the relevant standard nominal ***voltage*** listed in clause 4.2.1 may occur in accordance with Table 1.

Table 1

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%	Phase to Earth +80%-100%	60 kV peak
11	(± 10 %		Phase to Phase +20%-100%	95 kV peak
22	Rural Areas)			150 kV peak
66	± 10%	± 15%	Phase to Earth +50%-100% Phase to Phase +20%-100%	325 kV peak

Figure 2.1: VEDC Voltage Variations

The voltage unbalance limit is shown in Figure 2.2.

4.6 Negative sequence voltage

4.6.1 Subject to clause 4.6.2 a ***distributor*** must maintain the negative sequence ***voltage*** at the ***point of common coupling*** to a ***customer's*** three phase ***electrical installation*** at a level at or less than 1%.

4.6.2 The negative sequence ***voltage*** may vary above 1% of an applicable ***voltage*** level, but not beyond 2% for a total of 5 minutes in every 30 minute period.

Figure 2.2: VEDC Voltage Unbalance Limit

2.2.2 SERVICE AND INSTALLATION RULES

WSP examined the Victorian Services and Installation Rules (SIR) to consider how these regions incorporate the increase in phase-to-earth voltage caused by REFCLs. Extracts of the relevant sections are reproduced below.

6.1.1 Supply Systems

Electricity supplied throughout Victoria is in the form of alternating current of approximately sinusoidal waveform at a frequency of 50 Hz. Electricity Distributors' endeavour to maintain the voltage at the Point of Supply in accordance with the Electricity Distribution Code (Refer Table 6.1 and the Code) and may superimpose control signals on the normal supply voltage.

Standard nominal voltages are 230 V, 400 V, 460 V, 6.6 kV, 11 kV, 22 kV and 66 kV.

Standard Low Voltage Systems are 3 phase 4 wire 400/230 V, Single phase 2 wire 230 V and 3 wire 460/230V Systems.

Table 6.1-1 Standard Nominal Voltages and 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

Figure 2.3: Victorian Standard Voltage Variation

2.2.2.1 METERING

The Victorian SIR considered the effect of REFCLs on metering class instrument transformers, as seen in Section 9.13.3 of the rules and shown in Figure 2.4. The Victorian SIR requirements for metering Voltage Transformers (VTs) are AS 60044.2 for three-phase transformers and Australian Standard (AS) 1243 for one-phase transformer. AS 1243 is a superseded by AS 60044.2.

It is worth mentioning the Victorian SIR only specifies requirements for metering class instrument transformers. For protection class transformer insulation coordination, there is no equivalent performance requirements stated in the SIR. The Victorian SIR refers AS 2067 and AS 1824.1 for protection Current Transformers (CTs) and VTs, and AS1824.1 is a cancelled document.

Table 9.13-1 Metering Transformers Performance Requirements

DESCRIPTION	REQUIREMENT
Voltage Transformers	
ratio – 11 kV	11 000 / 110 V
ratio – 22 kV	22 000 / 110 V
class	0.5 M
rated burden	4 mS for three phase units or 12 mS for single phase units
rated output	50 VA (min) per phase
voltage factor GFN* not installed	1.9 / 30 s
voltage factor GFN* installed	1.9 / 8 h
insulation level – 11 kV	28 kV (PFWV), 95 kV (LIWV)
insulation level – 22 kV	50 kV (PFWV), 125 kV (LIWV)
Current Transformers	
ratio	100 – 200 / 5 A or 200 – 400 / 5 A
class	0.5 M
rated burden	0.6 ohm
rated output	15 VA
thermal limit current	
100 – 200 / 5 Amps	300 A
200 – 400 / 5 Amps	600 A
rated short time current – 11 kV	18.4 kA / 2 s
rated short time current – 22 kV	13.1 kA / 2 s
insulation level – 11 kV	28 kV (PFWV), 95 kV (LIWV)
insulation level – 22 kV	50 kV (PFWV), 125 kV (LIWV)

Ground Fault Neutraliser GFN

Figure 2.4: Victorian SIR on Metering Class VTs and CTs

2.3 CHANGE TO PHASE-TO-EARTH VOLTAGES

The implementation of REFCLs, has the effect of causing a neutral shift such that the faulted phase shifts to near earth potential, and the neutral point rises to the normal phase-to-earth voltage. Consequently, the other two phases then experience the normal phase-to-phase voltage above earth.

Additionally, in rural parts of the Victorian network variations of up to ten per cent voltage is allowed under the VEDC. Thus, under REFCL operation the potential of non-faulted phases above earth may rise to ten per cent above the phase-to-phase voltage, which is approximately $\sqrt{3} * 1.1 = 1.9$ pu.

As the VEDC presently only allows for +80 per cent rise of phase to earth voltages for 10 seconds, this limit requires revision in order to ensure REFCL operation is compliant with the VEDC.

3 NETWORK REGULATIONS, STANDARDS AND GUIDELINES

3.1 OVERVIEW

The first task that WSP undertook was to carry out a high-level document search to identify countries that have REFCLs installed and the applicable voltage standards. The initial focus was around New Zealand and Europe where REFCL technology is known to be implemented. During the search, information regarding Russian and Chinese practices were discovered (but not focussed on in depth), but have been included as appropriate for completeness.

The following countries are known to employ resonant earthing in their distribution system:

— **New Zealand:** REFCLs are employed predominately to improve supply reliability and in extensive use by distributors such as Orion and North Power.

— **Europe**: European Committee for Electrotechnical Standardization's EN50160 provides the basis of voltage variation regulation implemented by the connected parties across Europe. Due to the large number of connection parties and various network characteristics, the standard is written in general, the members of connected parties in the network often set their requirements to be stricter than those given in EN50160.

— **Ireland:** The distribution voltage levels are 10 kV, 20 kV and 38 kV. The 38 kV system predominantly consists of long overhead transmission lines prone to single-line-earth faults [3]. Many of the 38 kV systems are resonant earthed using arc suppression coils.

— **Sweden:** Due to severe month-long snowfall, Sweden is known to utilises resonant earthed networks with REFCL technology extensively for reliability purposes.

— **Russia:** The 6-35 kV distribution network in Russia can be either insulated, resistance or and resonant grounded [4].

— **China:** REFCL implementations are used extensively throughout the Chinese distribution network. Overvoltage due to resonant grounded system are known to cause damage to equipment and is managed by controlling the degree of compensation [5].

3.2 NEW ZEALAND

3.2.1 STANDARDS AND REGULATION

The New Zealand sub-transmission and distribution system consists largely of 29 local distribution companies with voltages that can vary from 11 kV to 110 kV. All distribution companies design and operate their network to Part 3, Section 28 of the Electricity (Safety) Regulations 2012 (ESR) with regards to supply voltage regulation.

> **28 Voltage supply to installations**
>
> (1) The supply of electricity to installations operating at a voltage of 200 volts AC or more but not exceeding 250 volts AC (calculated or measured at the point of supply)—
>
> (a) must be at standard low voltage; and
>
> (b) except for momentary fluctuations, must be kept within 6% of that voltage.
>
> (2) The supply of electricity to installations operating at other than standard low voltage (calculated or measured at the point of supply)—
>
> (a) must be at a voltage agreed between the electricity retailer and the customer; and
>
> (b) unless otherwise agreed between the electricity retailer and the customer, and except for momentary fluctuations, must be maintained within 6% of the agreed supply voltage.

Figure 3.1: ESR Specification on Voltage Supply to Installations

The definition of *voltage* in Section 28 of ESR is not clearly defined to distinguish phase-to-earth and phase-to-phase values. Moreover, the definition of *momentary* has also not been defined. To provide reference to this definition, IEEE C62.41-1991 defines the duration of momentary in the context of voltage swells as 30 cycles to 3 seconds.

An exception to this network operating and design philosophy is from Network Tasman, whose Asset Management Plan stated the network is designed to give ±5 per cent voltage variation at the consumers' switchboard.

3.2.2 DISTRIBUTOR EXPERIENCE

Orion, an electricity distribution company, is known to own and operate REFCLs through its network. We understand that Orion's experience with REFCLs to be broadly as follows:

- Neutral voltage displacement during REFCL operation had been similar to that found where neutral earthing resistors are installed.
- The time to clearing fault can vary between 1 to 3 hours and Orion has implemented some hardening to its network.
- Equipment connected to parts of the network with REFCLs is specified to withstand 1.8 pu voltage (phase-to-earth) for eight hours.
- Surge arrestors required replacement for parts of the network with REFCLs installed.

3.3 EUROPE

With regards to the relevant supply voltage variation, the requirements are set out in Section 5 of EN50160: Medium-voltage supply characteristics, which encompasses voltage levels from 1 kV to (and including) 36 kV. The standard supply voltage variation shall not exceed ±10 per cent.

5.2.2 Supply voltage variations

5.2.2.1 Requirements

Under normal operating conditions, excluding the periods with interruptions, supply voltage variations should not exceed ± 10 % of the declared voltage U_c.

In cases of electricity supplies in networks not interconnected with transmission systems or for special remote network users, voltage variations should not exceed + 10 % / - 15 % of U_c. Network users should be informed of the conditions.

NOTE 1 The actual power consumption required by individual network users is not fully predictable, in terms of amount and simultaneity. As a consequence, networks are generally designed on a probabilistic basis. If, following a complaint, measurements carried out by the network operator according to 5.2.2.2 indicate that the magnitude of the supply voltage departs beyond the limits given in 5.2.2.2, causing negative consequences for the network user, the network operator should take remedial action in collaboration with the network user(s) depending on a risk assessment. Temporarily, for the time needed to solve the problem, voltage variations should be within the range + 10 % / - 15 % of U_c, unless otherwise agreed with the network users.

NOTE 2 Identification of what is a "special remote network user" can vary between countries, taking into account different characteristics of national electricity supply systems as, for instance, limitation of power on the supply terminal and/or power factor limits.

Figure 3.2: EN50160 on Supply Voltage Variations

The definition of *supply voltage* is shown in the figures below:

3.2
declared supply voltage
U_c
supply voltage U_c agreed by the network operator and the network user

NOTE Generally declared supply voltage U_c is the nominal voltage U_n but it may be different according to the agreement between the network operator and the network user.

Figure 3.3: EN50160 Declared Supply Voltage Definition

3.21
supply voltage
r.m.s. value of the voltage at a given time at the supply terminal, measured over a given interval

Figure 3.4: EN50160 Supply Voltage Definition

EN50160 differs from the VEDC such that it does not make the distinction on how the voltage is measured (i.e. phase-to-phase or phase-to-earth). However, it would be safe to assume that it is phase-to-phase for medium voltage applications.

EN50160 allocates a higher phase-to-phase voltage variation (+10 per cent and -15 per cent) for remote networks, which is akin to the rural areas the REFCLs are installed in the Victorian network.

5.3.2 Supply voltage dips/swells

5.3.2.1 General

Voltage dips are typically originated by faults occurring in the public network or in the network users' installations.

Voltage swells are typically caused by switching operations and load disconnections.

Both phenomena are unpredictable and largely random. The annual frequency varies greatly depending on the type of supply system and on the point of observation. Moreover, the distribution over the year can be very irregular.

Figure 3.5:EN50160 Voltage Swells

According to Figure 3.6 while EN50160 understands and considers voltage swell due to ground faults and defines a swell to be voltages exceeding 110 per cent of reference voltage, EN50160 does not make hard recommendations for the maximum overvoltage swell level or the acceptable swell duration or distinguish against phase-to-phase versus phase-to-earth voltages.

3.18
reference voltage (for interruptions, voltage dips and voltage swells evaluation)
a value specified as the base on which residual voltage, thresholds and other values are expressed in per unit or percentage terms

NOTE For the purpose of this standard, the reference voltage is the nominal or declared voltage of the supply system.

Figure 3.6: EN50160 Reference Voltage Definition

3.4 IRELAND

The transmission and distribution network in Ireland is owned by the Electricity Supply Board (ESB) and operated by System Operator Northern Ireland and EirGrid. The ESB Distribution Code [6] and the EirGrid Grid Code [7] both make references to EN 50160, which is ±10 per cent. The only instance when the code specifies phase-to-earth values with regards to operating voltages are at low voltage level; this can be seen in Figure 3.7.

DPC4.2 Voltage

DPC4.2.1 The **Distribution System** includes networks operating at the following nominal voltages:

TABLE 1 – DISTRIBUTION NOMINAL VOLTAGES

Low Voltage (LV)	230 volts – phase to neutral 400 volts – phase to phase
Medium Voltage (MV)	10,000 volts (10kV) 20,000 volts (20kV)
High Voltage (HV)	38,000 volts (38kV) 110,000 volts (110kV)

DPC4.2.2 The **DSO** shall operate the **Distribution System** so as ensure that the voltage at the supply terminals, as defined in EN 50160, complies with that standard. The **Low Voltage** range tolerance shall be 230V +/- 10%. The resulting voltage at different points on the system depends on several factors, but at the **Connection Point** with **Customers** can be expected to be in accordance with Table 2 under steady state and normal operating conditions.

TABLE 2 – OPERATING VOLTAGE RANGE

Nominal voltage	Highest voltage	Lowest voltage
230V	253V	207
400V	440V	360
10kV	11.1kV	Variable according to operating conditions. Information on particular location on request by the User concerned
20kV	22.1kV	
38kV	43kV	
110kV	120kV	

Higher maximum voltages can arise at the **Connection Point** with **Generators** as per Table 5 in clause **DCC**10.5.

Figure 3.7: ESB Distribution Code

CC.10.13 Power Quality

Users shall ensure that their connection to the **Transmission System** does not result in the level of distortion or fluctuation of the supply **Voltage** on the **Transmission System**, at the **Connection Point**, exceeding that allocated to them following consultation with the **TSO.** Distortion and fluctuation limits are outlined in IEC/TR3 61000-3-6 (Harmonics) and IEC/TR3 61000-3-7 (Voltage fluctuation). **Users** shall also operate their **Plant** in a manner which will not cause the requirements contained in CENELEC Standard EN 50160 to be breached.

Figure 3.8: EirGrid Grid Code

3.5 SWEDEN

REFCLs are widely adopted by the Swedish medium and high voltage transmission network companies for reliability reasons as well as to reduce the risks of collateral damage during cable faults [8]. Although Sweden is known to implement REFCLs in its distribution network, the country’s distribution network standard follows EN 50160 closely [9], where the slow voltage variation is specified to not exceed ±10 per cent at all voltage levels. It is interpreted that this refers to phase-to-phase values.

In terms of voltage swells, no voltage swell requirements are set for nominal voltages above 1 kV.

3.6 CHINA

Many grounding techniques exist within the Chinese distribution network. Generally, they are ungrounded, grounded through arc suppression coils, or grounded with low resistance [10] [11] [12] [13].

Equipment installed in the compensated system in the distribution networks of Xining (capital of Qinghai Province) have previously sustained damaged from overvoltage during ground faults. This led to the complete bypass of the resonant grounding system [5]. In 2017, Siemens and State Grid Xining Power Supply Company (Xining PSC) collaborated to develop an appropriate grounding technique to mitigate overvoltage.

The existing REFCLs in Shanghai Fengxian are widely overcompensated to avoid overvoltage issues [14].

The main Chinese distribution network standard is given in GB/T 12325-2008 Power quality – admissible deviation of supply voltage, and the electricity supply law is governed by Power Supply and Business Rules 1996 (direct translation of 供电营业规则). The original text for the Chinese voltage regulation is shown in Figure 3.9 and the translation is shown in Figure 3.10.

第五十四条

在电力系统正常状况下，供电企业供到用户受电端的供电电压允许偏差为：

1.35千伏及以上电压供电的，电压正、负偏差的绝对值之和不超过额定值的10%；

2.10千伏及以下三相供电的，为额定值的±7%；

3.220伏单相供电的，为额定值的+7%，-10%。

在电力系统非正常状况下，用户受电端的电压最大允许偏差不应超过额定值的±10%。用户用电功率因数达不到本规则第四十一条规定的，其受电端的电压偏差不受此限制。

Figure 3.9: Chinese Power Supply and Business Rules on Voltage Regulation

ARTICLE 54:

Under power system normal condition, the allowable deviations supplied by the power company at the user's receiving end is:

1. 35 kV and above: the sum of the absolute values of voltage positive and negative deviations does not exceed 10% of the rated value;

2. 10 kV and below: three phase power supply, ±7 % of rated value;

3. 220 volts shingle-phase power supply, +7%, -10 % of rated value.

In the abnormal condition of the power system, the maximum allowable voltage deviation of the user's receiving end should not exceed ±10 % of the rated value. If the user's power factor does not meet the requirements of article 41 of this rule, the voltage deviation at the receiving end is not limited by this.

Figure 3.10: Chinese Power Supply and Business Rules on Voltage Regulation (Translated)

Moreover, GB/T 12325-2008 Chapter 4 specifies:

4 供电电压偏差的限值

4.1 35 kV 及以上供电电压正、负偏差绝对值之和不超过标称电压的 10%。

注：如供电电压上下偏差同号(均为正或负)时，按较大的偏差绝对值作为衡量依据。

4.2 20 kV 及以下三相供电电压偏差为标称电压的±7%。

4.3 220 V 单相供电电压偏差为标称电压的+7%，-10%。

4.4 对供电点短路容量较小、供电距离较长以及对供电电压偏差有特殊要求的用户，由供、用电双方协议确定。

Figure 3.11: In GB/T 12325-2008 on Voltage Deviation Limit

4. Power supply deviation limits

4.1 35 kV and above: the sum of the absolute values of the positive and negative deviation shall not exceed 10% of the rated voltage value.

Note: if the upper and lower deviations of the power supply voltage are the same side, (i.e. all positive or negative), the absolute value of the larger deviation is used as the basis for measurement.

4.2 20 kV and below: the three-phase power supply voltage deviation shall not exceed +/- 7% of the rated voltage value.

4.3 220 V single-phase power supply voltage deviation shall not exceed +7%, -10% of the rated voltage value.

4.4 for small short-circuit capacity at the power supply point, long distance power supply, or user requires specific supply voltage deviation*, the voltage deviation shall be defined by the agreement between the supplier and the user*.

Figure 3.12: GB/T 12325-2008 on Voltage Deviation Limit (Translated)

3.7 RUSSIA

In the Russian Federation, the neutral points of distribution networks from 6-35 kV can be isolated, resistive, or compensated [15]. Russia's 6-35 kV network standard is set out by *GOST 13109-97: Electric Energy – Electromagnetic Compatibility of Technical Equipment – Power Quality Limits in Public Electrical Systems*.

The voltage deviation is specified by normal deviation and maximum permissible deviation, which is ±5 per cent and ±10 per cent of U nominal as per Table 3 of GOST 13109-97. Section 5.2 and Table 3 of the standard shows the standardised voltage dip duration, which is the voltage outside of ±10 per cent, to be 30 seconds. The voltage is denoted by U_y of the standard, and it is unclear whether phase-to-phase or phase-to-earth values are specified (but presumed to be phase-to-phase).

4 EQUIPMENT STANDARDS

4.1 TERMS OF ANALYSIS

The effect of voltage variations on equipment is analysed in this section within the context of phase-to-earth voltages reaching up to phase-to-phase values.

WSP analysed the AS and International Electrotechnical Commission (IEC) standards. Most electrical equipment used in Australia is manufactured to these standards. We noted that in several cases the AS standards are often a slightly modified version of an equivalent IEC standard, with the published version being a marked-up version of the IEC.

This section only considers current standards and new equipment installed should reasonably be expected to comply. A plant already in service on the network is likely to have been designed and constructed to older standards or earlier versions of the same standards. When REFCLs are to be used in areas with existing equipment in service, their ratings and performance against the revised VEDC will require assessment on a case-by-case basis.

4.2 VOLTAGE TRANSFORMERS

Manufacturing and testing of VTs is defined in AS 60044.2. It requires (in Table 2, clause 5.3) VTs on isolated neutral and resonant (impedance) earthed systems to be able to operate at phase-to-earth voltage factors of 1.9 pu for 8 hours. There is no specific reference to REFCL; however, the definition of *impedance earthed systems* is, ‘a system whose neutral point(s) is(are) earthed through impedances to limit earth fault currents’ as defined in the same standard. We infer that it includes REFCLs.

VTs to AS 60044.2, where it has been specified that they operate on an impedance earthed systems, should be suitable for the proposed amended voltages and durations as per Table 2 of the standard (voltages of up to 1.9 pu between phase-to-earth and durations from 30 seconds up to 8 hours.

We note the purchaser needs to specify the earthing condition of VT use. So simply complying with AS 60042 does not confirm that a VT will be suitable for use on a REFCL system. The specification also needs to cite the relevant requirements of Table 2 in the standard.

For capacitive VTs in accordance with AS 60044.5, equivalent requirements and definitions apply. Refer to Table 2 in clause 6.4 of that standard. For brevity, it is not reproduced here, as capacitive voltage transformers are not normally utilised at distribution voltage levels.

4.3 POWER TRANSFORMERS

Manufacturing and testing of power transformers is defined in the AS 60076 multipart suite of standards that are heavily based on the IEC 60076 equivalents.

The latest version of AS/NZS 60076.3 (2017) is based substantially on IEC 60076-3:2013. This Part 3 of the suite provides requirements for insulation levels.

Generally, the load end transformers on a 22 kV distribution network will be delta-connected without an earth reference. All windings and bushings should therefore be rated for phase-to-phase rating levels. Neutral point shift is not of significant concern.

Where the transformer is star-connected, usually at the point of supply to the 22 kV network portion, the rated voltage of the neutral point must be considered. This will allow it to rise to at least the phase-to-earth voltage due to neutral point displacement when a phase voltage approaches earth potential.

The standard requires that the neutral terminal is tested at the applied test voltage for the line terminals of transformers with rated voltage less than or equal to 72.5 kV. To achieve this in a practical sense, the construction of the transformer should ensure the neutral terminal (and therefore the lower end of the winding) has the same insulation requirements as the line terminals (noting that for $U_m \leq 72.5$ kV the standard only allows uniform winding insulation). Therefore, a transformer constructed to this standard should be able to operate continuously with phase-to-earth voltage experienced at the neutral.

Furthermore, the standard requires that for U_m of 24 kV, the 60-second applied voltage test is conducted at 50 kV (per Table 2 in clause 7.2.2). This test should be undertaken as a phase-to-earth value (second sentence of clause 7.2.2), which is 393 per cent of the nominal phase-to-earth rating.

New power transformers compliant with the latest versions of AS and IEC 60076 should be suitable for operation in REFCL areas when specified to withstand phase-to-phase voltage levels between phase and earth.

The terms of analysis in Section 4.1 noted that considerations only include present standards. Given the long asset life of transformers, assets already in service are likely to have been manufactured to a different standard. They need to be evaluated on a case-by-case basis. AS/NZS 60076.3 has recently been updated (2017 for the AS version and 2013 for the IEC version) with changes made to the sections relevant to this situation. Caution is required in assuming recently manufactured assets are compliant to the latest standard.

4.4 CABLES

The manufacturing and testing process of cables is defined in AS 1429.1-2006 for 3.6 kV to 36 kV systems. The standard identifies three categories of cables (A, B and C) and outlines operating conditions. Category B cables are used for:

> *"… systems which, under fault conditions, are operated for a short time with one phase earthed. This period should not exceed 1 hr … a longer period, not exceeding 8 hrs on any occasion can be tolerated. The total duration of earth faults in any year should not exceed 125 hrs."*

To meet this requirement, Category B cables are capable of operating on REFCL systems with one phase earthed (and the other phase experiencing phase-to-phase voltages between phase and earth) for a period of 8 hrs in each instance.

Where category B cables are used, it would be prudent to maintain a register of time spent under REFCL operation each year to manage the 125 hrs per year requirement where category B cables are specified.

Category C cables are typically specified when operating with a permanent earth fault. These cables are typically the next voltage rating up (e.g. for a 22 kV system 33 kV cables would be specified as per Table 1.1 of AS 1429.1-2006).

4.5 SURGE ARRESTERS

Surge arresters are typically specified in accordance with the relevant part(s) of AS 1307 and/or IEC 60099 in accordance with a phase-to-earth voltage. Therefore, when specifying surge arresters for REFCL areas, it is important to consider the likelihood of phase-to-phase voltage between phase and earth during REFCL operation. Higher voltage rated surge arresters will be required for systems that do not experience sustained grounding of phases.

International experience shows that surge arresters have required replacement in areas where REFCLs have been installed [16].

4.6 SWITCHGEAR

The switchgear and control gear standard typically used in Australia is AS 62271.1-2012, which is similar to IEC 62271-1, Ed 1.1. (2011). Unlike the standards described in the sections above for transformers and cables, AS62271.1 does not specify a long-time overvoltage withstand duration, only a 60-second short-duration for power-frequency withstand voltage test.

For 24 kV equipment (this the equipment typically specified on a 22 kV system), the required 60-second short-duration power frequency voltage withstand test is 50 kV phase-to-earth[1] as per Table 1a in AS 62271.1-2012.

Based on the switchgear standard rated voltage values in AS 62271.1-2012, the equivalent phase-to-earth voltages are provided below in Table 4.1 (this is the rated phase-to-phase voltage divided by the square root of three).

For a 22 kV system with a compensated neutral the phase-to-earth voltage can rise up to 24.2 kV (110 % of 22 kV). This would infer requiring 48.3 kV (Series II) or 52 kV (Series I) rated voltage switchgear.

It is noted that the Series II voltages are based on practices adopted primarily in areas outside of Australia including North America. These series II voltages are normally based on ANSI/IEEE standards and installed on 60 Hz networks. Suppliers do not normally provide these products unless they have been type-tested to meet relevant AS and/or IEC standards.

Table 4.1 AS62271-1 Switchgear rated phase-to-phase and phase-to-earth voltages

SWITCHGEAR RATED VOLTAGE (P-P KV)	RATED VOLTAGE (P-E KV)
Voltages - Series I	
12	6.9
24	13.9
36	20.8
52	30.0
72.5	41.9
Voltages - Series II	
27	15.6
38	21.9
48.3	27.9

It is noted that Annex G of AS62271 ("Information and technical requirements to be given with enquiries, tenders and orders") section G.2 ("Ratings") allows the customer to specify the "Type of system neutral earthing (Effectively or non-effectively)".

WSP consulted with a switchgear supplier to understand if 24 kV switchgear could be utilised on an unearthed neutral network with a nominal voltage of 22 kV. The switchgear supplier's advice was that they would likely offer higher voltage rated switchgear in such an application such that phase-to-earth voltages are not exceeded and in order to warrant their equipment. Their view was that switchgear designed to AS 62271 is not type-tested such that phase-to-phase

[1] The value U_d in Table 1a of the standard is defined as phase-to-earth, and U_r is defined as phase-to-phase.

voltage could be applied between phases and earth for more than 60 seconds. Further consultation with suppliers is recommended to understand if 24 kV rated switchgear can be used on a 22 kV network.

It is noted that the WSP literature review did not produce in any evidence that higher voltage rated switchgear is utilised in such applications.

4.7 SUMMARY

The current AS for VTs, power transformers and HV cables specifies or gives options to allow the specification of equipment suitable for the above-nominal voltage rises that are likely to be experienced during REFCL operation. The standard specifies the 1.9 voltage factor for VTs, that the neutral terminal must be capable of withstanding the phase-voltage for power transformers and cables should be suitable for operation with a phase grounded. We note that in the case of power transformers this standard has recently changed, so even recently manufactured equipment may not be as resilient.

Surge arresters are typically specified via a phase-to-earth rating, so when used in REFCL areas would need to be specified in accordance with an anticipated phase-to-earth voltage rise to phase-to-phase levels.

For switchgear, the AS and IEC standard does not explicitly specify operation with phase-to-phase voltages between phase and earth, other than a 60 second test requirement. Discussions with a supplier revealed that they would likely nominate a higher voltage rating where switchgear is to be operated on a non-effectively earthed neutral system for a 22 kV nominal voltage. Further consultation with switchgear suppliers is recommended to see if 24 kV rated switchgear can be utilised on a 22 kV network.

5 ADDITIONAL CONSIDERATIONS

The following section covers additional considerations either raised during the public consultation or brought up during discussions with the Essential Services Commission (but not specifically related to Table 1 of the Victorian Electricity Distribution Code (VEDC)).

5.1 PROTECTION

Protection requirements are not specifically covered in Section 4 of the VEDC, however existing schemes would require review.

A stakeholder advised that some changes to protection settings related to their embedded generation (neutral voltage displacement protection) were required following REFLC implementation [17]. Impacts on protection were also identified in the Marxsen reports [18].

5.2 VOLTAGE UNBALANCE

The impact of REFCL operation on voltage unbalance limits was raised during the Stakeholder Forum on 6 April 2018. Rotating plant (generators and motors) are sensitive to voltage unbalance and draw excessive negative sequence current in that scenario.

Voltage imbalance during the operation of REFLC operation will not be significant. The voltage imbalance between the three phase conductors arises because of the voltage change along the faulted line caused by the fault current. As the fault current is very low, the voltage imbalance will be extremely low.

WSP is not aware of this being an issue based on the literature review carried out to date.

5.3 POTENTIAL FOR ABNORMAL PHASE-TO-EARTH OVERVOLTAGES

With regards to the VEDC voltage standards for phase-to-earth levels, the worst-case scenario is where the phase-to-earth voltage rises up to line-to-line potential. This would be an increase of 1.73 pu over the nominal voltage for the case of a solidly earthed neutral network.

There are cases documented where higher than line-to-line potential has been recorded between phase-to-earth. This has been due primarily to open circuits and the degree of compensation applied [19] [20]. Further investigations are carried out in *Evaluation of neutral voltages in arc suppression coil systems* [21].

In practice, the voltage rise does not quite reach the line-to-line potential and the allowable voltage variation in line potential from nominal should also be considered.

5.4 HIGH VOLTAGE CUSTOMERS WITH EMBEDDED GENERATION

Equipment is specified to be appropriately rated where a HV system is designed to operate with an isolated or compensated neutral. This may be the case for customers with embedded generation such that hardening may not be required.

HV customers with embedded generation face potential rise of phase-to-earth voltage levels to phase-to-phase values under fault conditions when generators are connected via transformers with a delta on the HV side. This situation would occur until the fault on the network is cleared and/or the generator is tripped. Neutral voltage displacement is often provided at customer connection points to detect this situation and trip the generator.

Given the potential for such a scenario, customer equipment would be specified accordingly (e.g. voltage transformers, surge arrestors, etc.) and additional hardening may not be required.

5.5 EARTH POTENTIAL RISE

Following an earth fault, a REFCL will largely reduce the earth fault current and consequently the voltages between the faulted conductor and ground to much lower levels compared to a solid or impedance grounded system.

The impact of earth potential rise is related to step and touch voltages and electrocution risk where the magnitude and duration of current through the body determine the risk.

Although the duration of the fault would be longer while the REFCL operates (up to 60 seconds), it is noted that the greatest risk for public safety is after a period of at least 10 seconds, by which time the REFCL would have reduced voltages to a level that provides a lower risk over existing neutral earthing practices as highlighted in the Marxsen report [22].

Tests were also carried out by Westpower in New Zealand where an earth fault was simulated and EPR measured [23].

A ‘cross country fault’ can occur during operation of the REFCL[2]. This is where there is an insulation failure in the system due to one of the healthy phases being exposed to elevated phase-to-earth voltages. During a ‘cross country fault’ involving more than one location, the fault current path involves earthing media at each location causing associated earth potential rise. Depending on the location and system parameters, the ‘cross-country’ fault current in the REFCL installed network could be more than, or less than, a phase-to-earth fault in the present network. It should be noted that the REFCL will not limit a ‘cross-country’ fault.

In summary, the operation of REFCLs on high voltage networks should provide safety benefits to the public due to the ability to reduce the voltage between the conductor and ground to levels generally much lower than without a REFCL.

[2] A ‘cross country' fault refers to a second fault that occurs on the same system as the first fault while the first fault is still active.

6 CONCLUSIONS

6.1 KEY FINDINGS

WSP's key findings are as follows:

- A review of international voltage standards did not reveal specific limits (magnitudes or durations) for phase-to-earth voltages in a similar fashion to Table 1 of the VEDC.
- A review of most plant standards for equipment generally showed alignment in terms of the maximum expected voltage magnitude for phase-to-earth voltages where equipment is specified to operate on an isolated or compensated network. This value was no more than the highest expected phase-to-phase levels between phases and earth in the absence of any earth faults.
- Switchgear does not have an explicit withstand for higher than nominal phase-to-earth voltages and discussions with one supplier indicated that higher rated switchgear may be required. Further consultation with switchgear suppliers is recommended. There is however no evidence that higher than nominally rated switchgear is utilised when used on a compensated or isolated network.
- There have been some documented cases where phase-to-earth voltage levels exceeded phase-to-phase values which resulted in equipment damage. This outcome appears to be primarily due to open circuits and/or the degree of compensation provided and not necessarily a normal operating scenario. Specifying a limit of phase-to-phase voltages between phases and earth would provide certainty to HV customers that they are not required to design their equipment for such conditions. Refer to Section 5.3 for further details.

6.2 VICTORIAN ELECTRICITY DISTRIBUTION CODE MODIFICATIONS TO ACCOMMODATE RAPID EARTH FAULT CURRENT LIMITERS

WSP's key recommendations are that:

- The maximum expected phase-to-earth voltage on a network where a REFCL is operating be limited to the maximum phase-to-phase voltage level (this is equivalent to approximately 1.9 times the nominal phase-to-earth voltage on an effectively earthed system).
- Equipment operating on a REFCL network be specified to withstand the maximum expected phase-to-phase voltages between phases and earth.

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