Rapid Earth Fault Current Limiter (REFCL) Program

22kV/√3 Arc Suppression Coil Sizing Policy

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1 PURPOSE AND BACKGOUND

1.1 Purpose

The purpose of this document is to explain AusNet Services' policy in relation to sizing of Arc Suppression Coils (ASCs) required for Rapid Earth Fault Current Limiter (REFCL) applications adhering to the Victorian Electrical Safety (Bushfire Mitigation) Amendment Regulations 2016.

1.2 Background

The 2009 Victorian Bushfire Royal Commission made several recommendations with respect to fires initiated from distribution electricity networks. Subsequently, the Victorian Government established the Powerline Bushfire Safety Program to research the optimal way to deploy REFCLs for bushfire prevention. This research led the Government to introduce Electricity Safety (Bushfire Mitigation) Amendment Regulations 2016, which requires AusNet Services to install REFCL technology in 22 nominated zone substations.

The REFCL technology must comply with the performance criteria stipulated below.

In the event of a phase to ground fault, the REFCL system shall have the following abilities:

(a) to reduce the voltage on the faulted conductor in relation to the station earth when measured at the corresponding zone substation for high impedance faults (25,400 Ohms) to 250 volts within 2 seconds; and

(b) to reduce the voltage on the faulted conductor in relation to the station earth when measured at the corresponding zone substation for low impedance faults (400 Ohms) to-

  (i) 1900 volts within 85 milliseconds; and

  (ii) 750 volts within 500 milliseconds; and

  (iii) 250 volts within 2 seconds; and

(c) during diagnostic tests for high impedance faults (25,400 Ohms), to limit-

  (i) fault current to 0·5 amps or less; and

  (ii) the thermal energy on the electric line to a maximum I^2t value of 0·10;

REFCL technology proven to date that complies with the above criteria, consists of three core components; an Arc Suppression Coil, Compensation device (inverter) and a control system.

An ASC introduces a resonant grounding philosophy and is the basis of REFCL technology explained further in the next section.

1.3 Resonant Earthing Philosophy

Resonant grounding involves the installation of an inductance on the zone substation transformer neutrals, creating a high impedance path between the neutral point and earth. See below representation of three-phase network model.

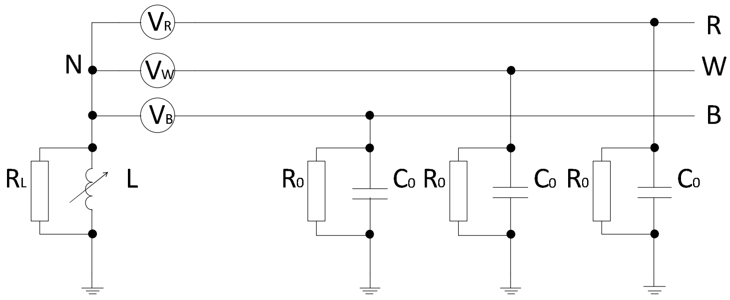

Figure 1 Three Phase Network Model

Where: C_0 = Phase-to-ground capacitance
R_0 = Phase-to-ground resistance
L = Arc Suppression Coil Inductance
R_L = Arc Suppression Coil Resistance
$V_{R,W,B}$ = Phase to ground voltage source

When a ground fault occurs, the fault current will consist of a reactive component and residual component with the former being the more dominant factor due to the large presence of network capacitance. If the ASC is perfectly tuned (at resonance point), the ASC will eliminate the capacitive component of the fault current, as the two quantities (inductive current and capacitive current) effectively cancel each other leaving only residual current flowing through the circuit as shown below.

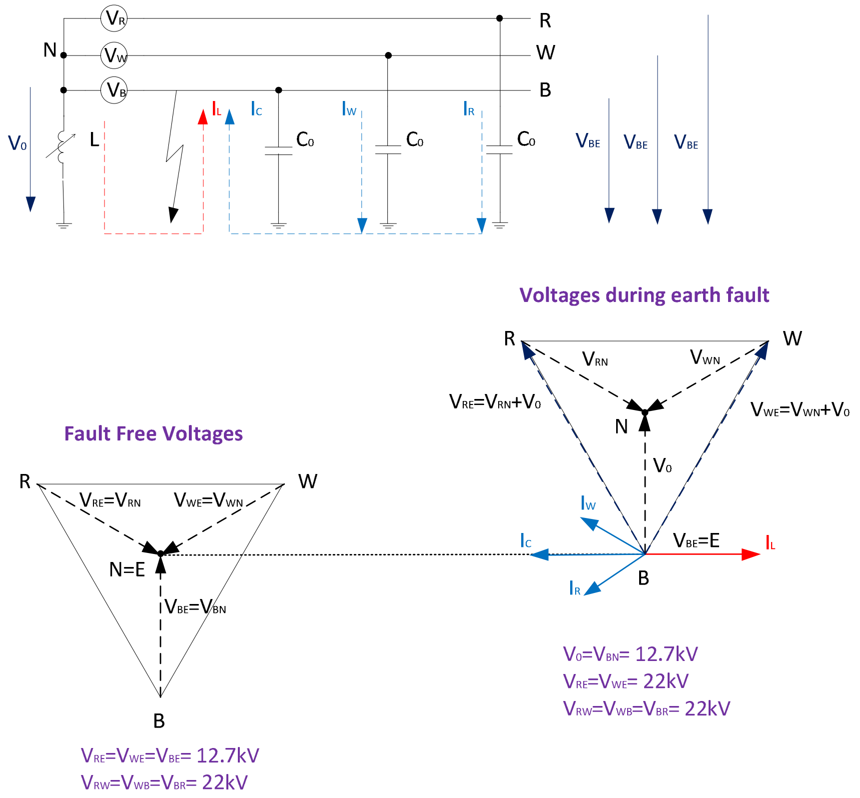

Figure 2 Voltage and Current Response on resonant earthed networks

Where: R,W,B = Phases
C_0 = Phase to ground capacitances
L = Arc suppression coil inductance
I_L = Inductive Fault current
I_C = Total Capacitive Fault current
$I_{W,B}$ = Phase Fault current contribution
$V_{RE,WE,BE}$ = Phase to ground voltages
$V_{RN,WN,BN}$ = Phase to neutral voltages
V_0 = Neutral voltage

The three-phase network model can further be simplified into a zero sequence model as per below.

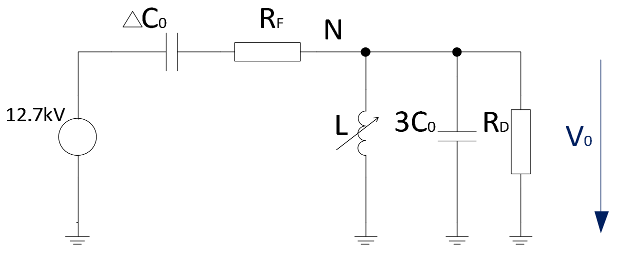

Figure 3 Zero Sequence Model

Where: $3C_0$ = Total Phase-to-ground capacitance
ΔC_0 = Unbalance due to individual phase capacitances
R_F = Fault impedance
L = Arc Suppression Coil Inductance
R_D = Total damping

As mentioned above, the resonance point results in maximum neutral voltage displacement with the magnitude a function of network size, dissymmetry and damping. In order to ensure the ASC is effective, these three quantities need to be understood.

Network size is defined as the equivalent network phase to ground capacitive current of the network and is used as the base when quantifying dissymmetry and damping. The phase to ground capacitive current used to determine network size vary depending on the conductor type i.e. overhead conductor or cable.

Network dissymmetry arises from unequal capacitive charging currents on a three (3) phase symmetrical power system. This asymmetrical system current returns to the system neutral point as a zero sequence quantity. The impedance of the ASC and the magnitude of this current are then responsible for the magnitude of the neutral voltage. The presence of dissymmetry will then lead to a standing neutral voltage in system normal conditions. Since network dissymmetry consists of unequal capacitive charging currents, solutions can be applied on the physical three phase network to manage its influence. For more information, refer to the REFCL Program Network Balancing Strategy (REF 20-06) and Capacitive Balancing Policy (REF 30-06).

Network damping is the effective impedance seen across the zero sequence network. The impedance cannot be influenced, as it represents the real losses of the network and affected by environmental conditions with days of high humidity, light rain and mist resulting in increased leakage current. The variance in the total amount of damping between different systems is generally due to the mix of overhead line and underground cable. Underground cable systems inherently have higher shunt resistive losses than the overhead line, and so networks with a high penetration of underground cable are likely to exhibit higher levels of damping.

2 Achieving Performance

The following section explains the derivation of the network parameters described in section 1.3 required to achieve the performance criteria. In addition to the size, dissymmetry and damping of the network the minimum operating voltage (trigger) also needs to be selected to ensure detection reliability.

2.1 Network charging currents

Network charging data is provided by conductor manufacturers for their products however general rules of thumb are typically applied depending on the rating of the conductor when determining ASC sizing prior to any installation. However, since the installation of the ASC at the Woori Yallock zone substation (WYK), actual tune point data has become available and used to rationalise the network charging values. The below table summarises these values.

	Three-phase Charging Current in Amps per km	
Conductor Type	**Typical**	**Rationalised**
22kV overhead	0.06	0.085
22kV cable	3	2.5

Table 1 Charging Current Values

In order to calculate the total ASC size for a zone substation the above charging currents are multiplied by the summated conductor route kilometres. The following table compares the actual ASC tune point at WYK[1] against its predetermined value using the above charging current values.

	Typical	**Rationalized**	**Actual**
Coil Tune point (A)	182	166	168

Table 2 WYK ASC Tune Point with rationalised charging current values

The WYK network is considered to be a typical AusNet Services network therefore the rationalized values have been used to forecast network size for the remaining zone substation requiring an ASC to be installed. Refer to sections 3 and 4 for network size information for tranche 1 and tranche 2 zone substations.

2.2 Damping

Typically, Victorian networks will have a 2-4% damping factor. The variance of network damping can be due to weather conditions which impact the real losses seen i.e. a dry and dirty asset may have a higher resistive path to earth compared to a rain washed asset which may have a lower resistive path to earth. The type of conductor in the network will also influence the damping factor as cables for instance have larger resistive losses than overhead cable meaning networks with large amounts of cable sections will result in larger damping factors. The damping factor will also be proportional to the network size.

As seen in Figure 3 Zero Sequence Model, the damping factor limits the neutral voltage rise of the system. REFCL systems use the neutral voltage to determine if a fault has occurred, higher levels of damping reduce the sensitivity that can be achieved.

For the purposes of understanding the impact of damping, the following table demonstrates the equivalent neutral voltage rise for given damping factors across for a variety of coil sizes.

	Maximum Voltage Rise (V)				
Coil Tune Point (A)	**2% Damping**	**3% Damping**	**4% Damping**	**5% Damping**	**6% Damping**
90	3,528	2,352	1,764	1,411	1,176
120	2,646	1,764	1,323	1,059	882
150	2,117	1,411	1,058	847	706
180	1,764	1,176	882	706	588

Table 3 Maximum Voltage Rise based on Damping

Observations from above tables suggest that a larger coil and higher damping factor results in a lower permissible neutral voltage rise consequently applying more pressure to ensure network

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[1] Actual tune point at WYK taken during commissioning in January 2017

dissymmetry is minimized. The damping factor will be the biggest influence in achieving detection sensitivity and hence is the main determinant of the size of the network that can be protected by a single REFCL.

2.3 Dissymmetry

Network dissymmetry plays an influential role as it directly relates to the standing neutral voltage once the ASC is in service. As described in the previous section, the major factor influencing the standing neutral voltage is the unequal capacitive charging currents on the three (3) phase symmetrical power system. Load induced asymmetrical voltage drop may affect the standing neutral voltage as unbalance in phase to ground voltages is seen at the neutral point.

The unequal capacitive charging current can be offset by the installation of low voltage capacitor banks, which reflect a phase to ground charging capacitance onto the distribution network. The ‘LV balancing capacitors’ can be installed on three phase sections and or single phase sections of the network.

To date, AusNet Services and Powercor have proven the effectiveness of these devices on the WYK and Gisborne networks resulting in reducing standing neutral voltages to less than 500V.

For the purposes of this document a dissymmetry range of 300V to 500V will be assumed.

It must be noted that network dissymmetry must also be kept to a minimum considering the trigger level selected is uniform across all phases. This means the angle of dissymmetry will impact the earth fault detection ratio as it will likely be aligned to a particular phase.

2.4 Neutral Voltage Set Point

Based on industry best practice the standing neutral voltage must be less than one third of the trigger level selected. The above assumption for standing neutral voltage then correlates to a set point between 900V and 1500V. The light green cells in the following table highlight the combination of coil tune point and damping factors that satisfy this requirement.

		Maximum Voltage Rise (V)				
Coil Tune Point (A)	**Maximum dissymmetry allowed (V)**	**2% Damping**	**3% Damping**	**4% Damping**	**5% Damping**	**6% Damping**
90	588	3,528	2,352	1,764	1,411	1,176
120	441	2,646	1,764	1,323	1,059	882
150	352	2,117	1,411	1,058	847	706
180	294	1,764	1,176	882	706	588

Table 4 Maximum Voltage Rise based on Dissymmetry

To validate this further the 900V – 1500V set point range can be evaluated on the equivalent circuit.

Should we assume the three individual phase to ground capacitances are balanced and the ASC is perfectly tuned then the equivalent circuit can further be simplified into a voltage divider circuit as per below.

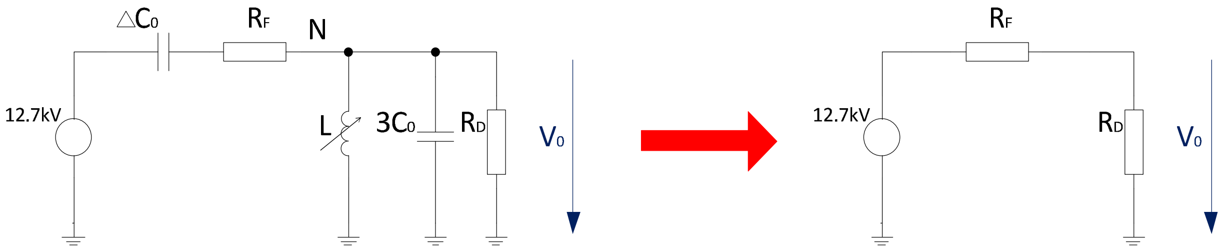

Figure 4 Simplified equivalent circuit

Where:
R_F = Fault impedance
R_D = Total damping

Note:
$3C_0$ and L have cancelled each other out
ΔC_0 has been ignored to assume no phase to ground unbalance

Given the fault current sensitivity target of 0.5A and the nominal operating voltage of 12.7kV, the respective fault impedance detection threshold is found to be 25,400 Ohms. It would be prudent to add a safety and reliability margin to the targeted fault impedance (R_F) to ensure the performance criteria is met. As such an additional 5% will be used resulting in an R_F of 26,672 Ohms.

Using the simplified equivalent circuit and predetermined damping resistances for a range of ASC sizes, the following table can be created which captures the maximum ASC size and corresponding network damping to meet the detection target. The light green highlighted cells represent the most practicable system parameters.

V_0 Set Point (V)	**Arc Suppression Coil Size (A) At various damping ratios**								
	2%	**2.5%**	**3%**	**3.5%**	**4%**	**4.5%**	**5%**	**5.5%**	**6%**
900	312	249	208	178	154	138	124	113	104
1200	228	182	152	130	114	101	91	82	76
1500	177	142	118	101	88	79	71	64	59

Table 5 Arc Suppression Coil Sizes to meet detection performance

From the above table based on the assumed dissymmetry values and the neutral voltage set point of 1500V, the tune point coil size must be limited to 142A for a network damping ratio no greater than 2.5% which would be a best case scenario

2.5 Solution

As described above, network size, dissymmetry, damping and the V_0 set point will impact the ability to detect the fault impedance target of 26,672 Ohms. All these factors can be influenced except for network damping other than by physically changing the network, such as by replacing underground cable with overhead, which is impractical.

Chart 1 below translates information in Table 5 to provide a visual interpretation on the relationship between coil size and network damping.

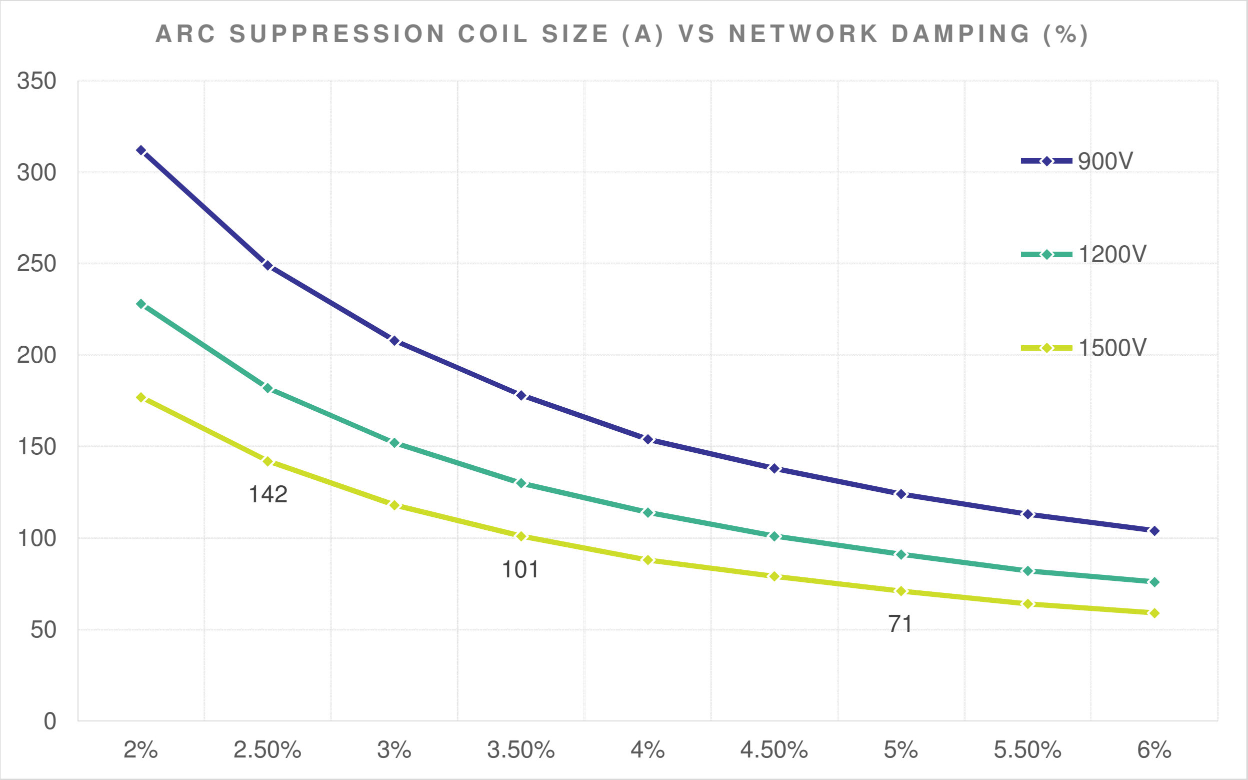

Chart 1 Arc Suppression Coil Size (Amps) vs Network Damping (Percentage)

With a network damping range from 2.5% to 5% and the assumption we can limit the dissymmetry to 500V (1500V V_0 set point), we can achieve performance with an ASC tuned at 68A. The tune point of the ASC can then be increased up to 142A on the proviso that the network damping ratio is no greater than 2.5%.

Consequently, where the total tune point for the zone substation has exceeded this 142A threshold it will be necessary to develop engineering solutions to keep within this limit. Reducing our network operating size is the preferred solution as it involves well understood design and network operating procedures. Woori Yallock is an example where this solution will be adopted as an additional ASC at the zone substation will be installed allowing the whole network to be divided on an ASC per bus arrangement reducing the network operating size that each ASC protects.

Another means to reduce the effective tune point of the ASC at the zone substation would be to install parallel or distributed coils throughout the network. This is quite common in Europe however it must be noted that the application in that market is different which has no obligation to detect extremely high impedance faults to mitigate fire ignitions. Nevertheless, the installation of further coils will increase the apparent damping at the zone substation and further constraint the ability to detect the targeted fault impedance. Hence is a need to split the network into smaller zones in order to meet fault detection sensitivity targets.

3 Tranche 1 Sizing

Zone substation	Overhead Bare Conductor	Cable	Calculated Charging Current (+10%)	Tune Point	Damping	Achievable Dissymmetry	Theoretical Uen Trigger @ 3.5% Damping	No. of ASCs	Practically Confirmed
WYK	379	85	270	229[2]	4.50%	<500V	1346	2	No
RUBA	504	10	75	Unknown	Unknown	<500V	2394	1	No
BWA	276	18	75	41[3]	4.0%	<500V	2409	1	No
WGI	595	25	125	Unknown	Unknown	<500V	1454	1	No
KLK	119	65	72[4]	Unknown	Unknown	<500V	2520	1	No
SMR	979	27	165	Unknown	Unknown	<500V	2182	2	No
WN	1448	26	207	Unknown	Unknown	<500V	1752	2	No
MYT	425	8	62	Unknown	Unknown	<500V	2955	1	No
KMS	226	18	70	Unknown	Unknown	<500V	2610	1	No

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[2] Woori Yallock tune point taken with two ASC in parallel as of March 2018

[3] Initial BWA commissioning (November 2017) excluding single phase spur off BWA22 (downstream of manual switch 829758) and BWA23 HV customer connection (downstream of WO002)

[4] Kinglake forecast excluding PRF and 56M works have reduced forecast from 196A

4 Tranche 2 Sizing

Zone substation	Overhead Bare Conductor	Cable	Calculated Charging Current (+10%)	Tune Point	Damping	Achievable Dissymmetry	Theoretical Uen Trigger @ 3.5% Damping	No. of ASCs	Practically Confirmed
RWN	149	45	108	Unknown	Unknown	<500V	1676	1	No
ELM	239	45	223	Unknown	Unknown	<500V	1628	2	No
FGY	124	75	255	Unknown	Unknown	<500V	1423	2	No
BGE	258	69	266	Unknown	Unknown	<500V	1363	2	No
LDL	423	60	196	Unknown	Unknown	<500V	1851	2	No
MOE	883	21	133	Unknown	Unknown	<500V	2720	2	No
BDL	1455	44	234	Unknown	Unknown	<500V	1554	2	No
WOTS	1437	39	223	Unknown	Unknown	<500V	1630	2	No