Rapid Earth Fault Current Limiter (REFCL) Program

22kV/√3 Arc Suppression Coil Sizing Policy

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1	24/03/2017	First Issue	J Bernardo
2	19/04/2018	Values in tables are updated	A Ziusudras
3	25/04/2019	Neutral setpoint section and appendix updated. Maximum coil size changed to 101A.	Matthew Ch'ng

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.

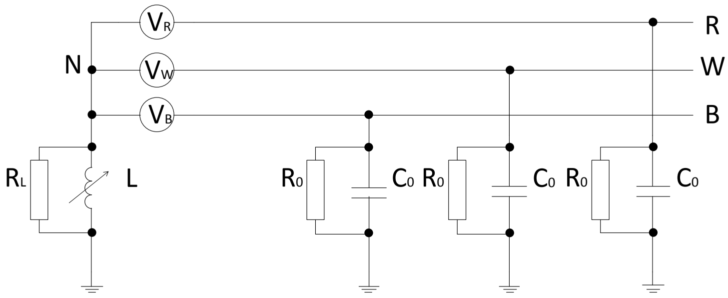


Figure 1 Three Phase Network Model

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.

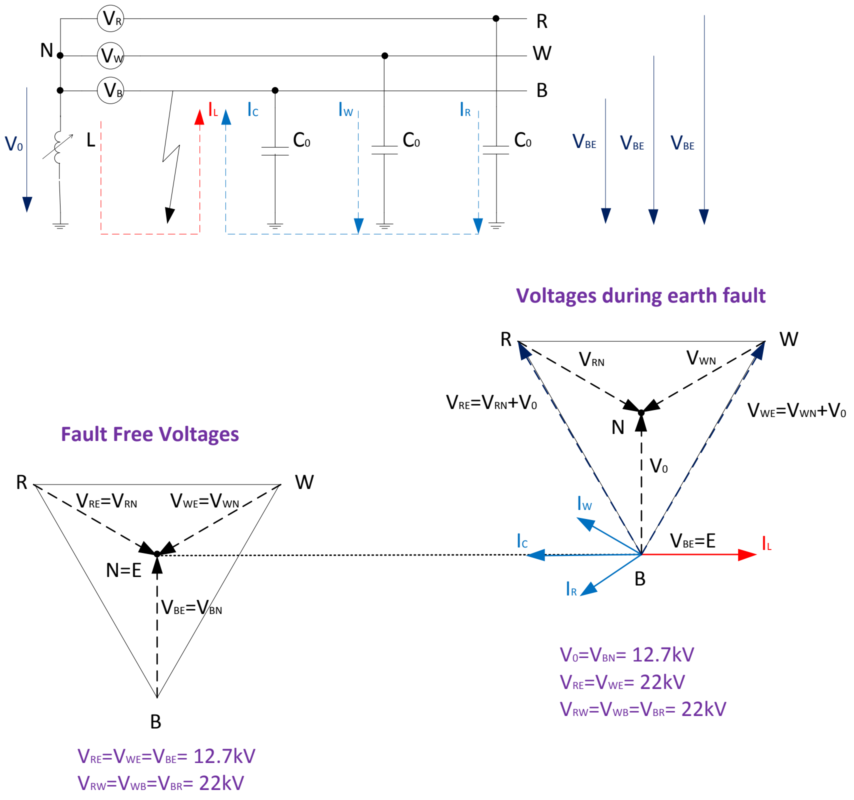


Figure 2 Voltage and Current Response on resonant earthed networks

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.

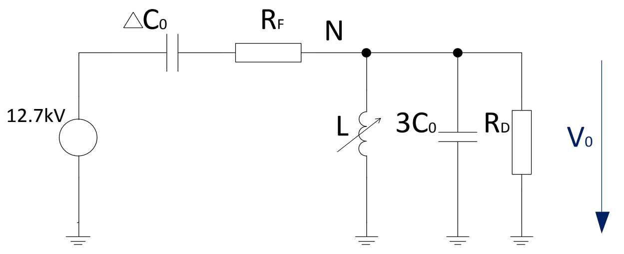


Figure 3 Zero Sequence Model

Where:

$3C_0$	= Total Phase-to-ground capacitance	R_F	= Fault impedance
ΔC_0	= Unbalance due to individual phase capacitances	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.

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	2657	1904	1484	1215	1029
120	2103	1484	1146	934	788
150	1740	1215	934	758	638
180	1484	1029	788	638	536

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 dissymmetry is minimized. The damping factor will be the biggest influence in achieving

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

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

The standing neutral voltage must generally be less than one third of the trigger level selected. This allows the GFN to discriminate between a fault and typical background capacitive network imbalance. The light green cells in the following table highlight potential combinations of coil tune point, damping factor and dissymmetry that satisfy this requirement.

		Maximum Voltage Rise (V)				
Coil Tune Point (A)	**Maximum Dissymmetry (V)**	**2% Damping**	**3% Damping**	**4% Damping**	**5% Damping**	**6% Damping**
90	400V	2657	1904	1484	1215	1029
120		2103	1484	1146	934	788
150		1740	1215	934	758	638
180		1484	1029	788	638	536

Table 4 Maximum Voltage Rise based on Dissymmetry[2]

To validate this further, the 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.

[2] It must be noted that the table outlines only a very small sample of scenarios. In reality, other combinations exist and aspects including, but not limited to, their variance in values and frequency of occurrence will require an engineering assessment before finalizing the neutral voltage set point.

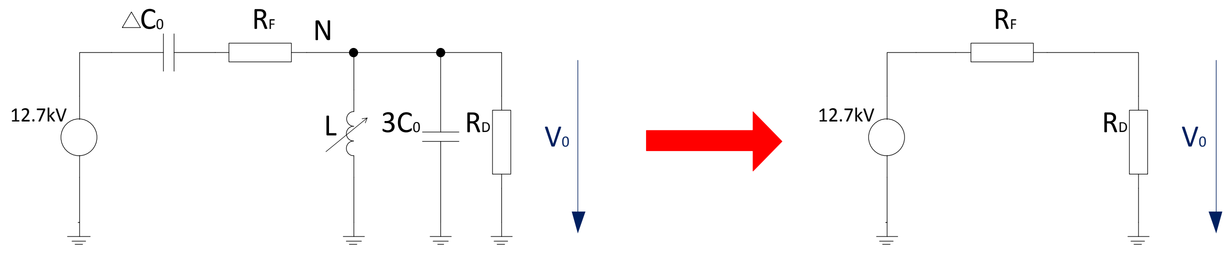


Figure 4 Simplified equivalent circuit

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

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.

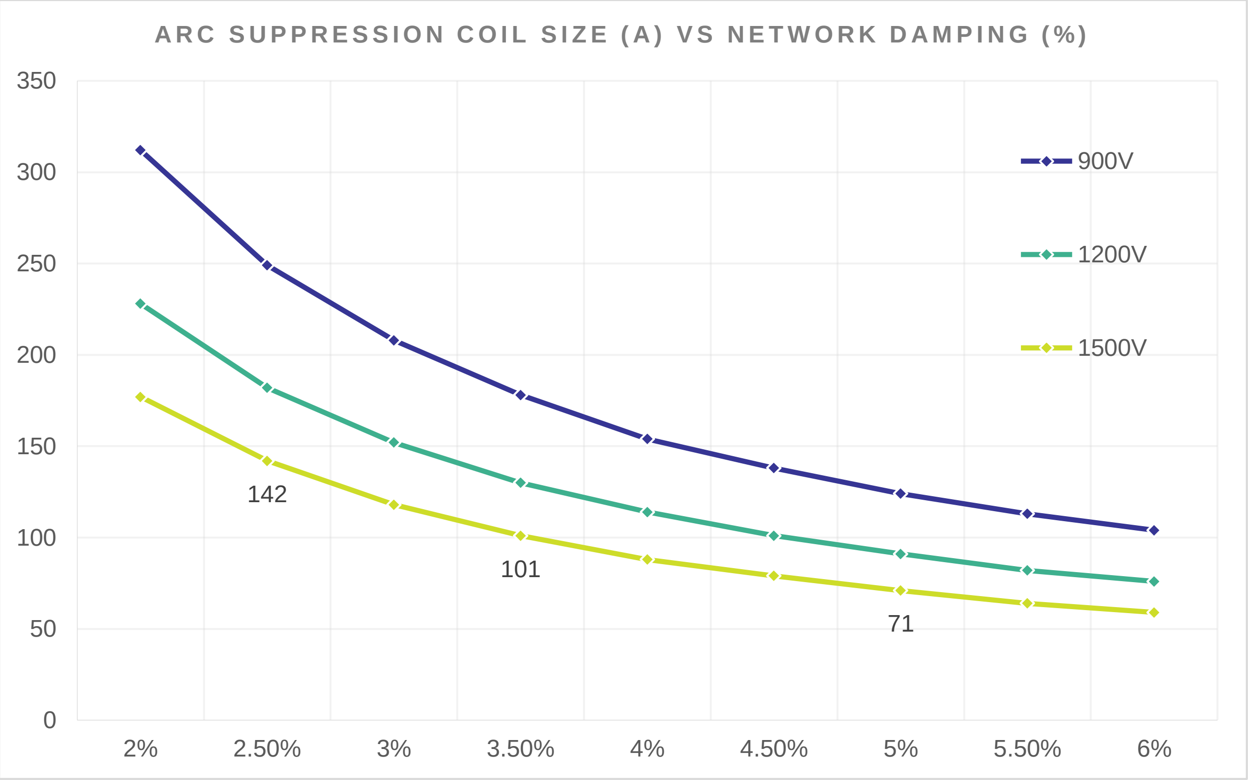


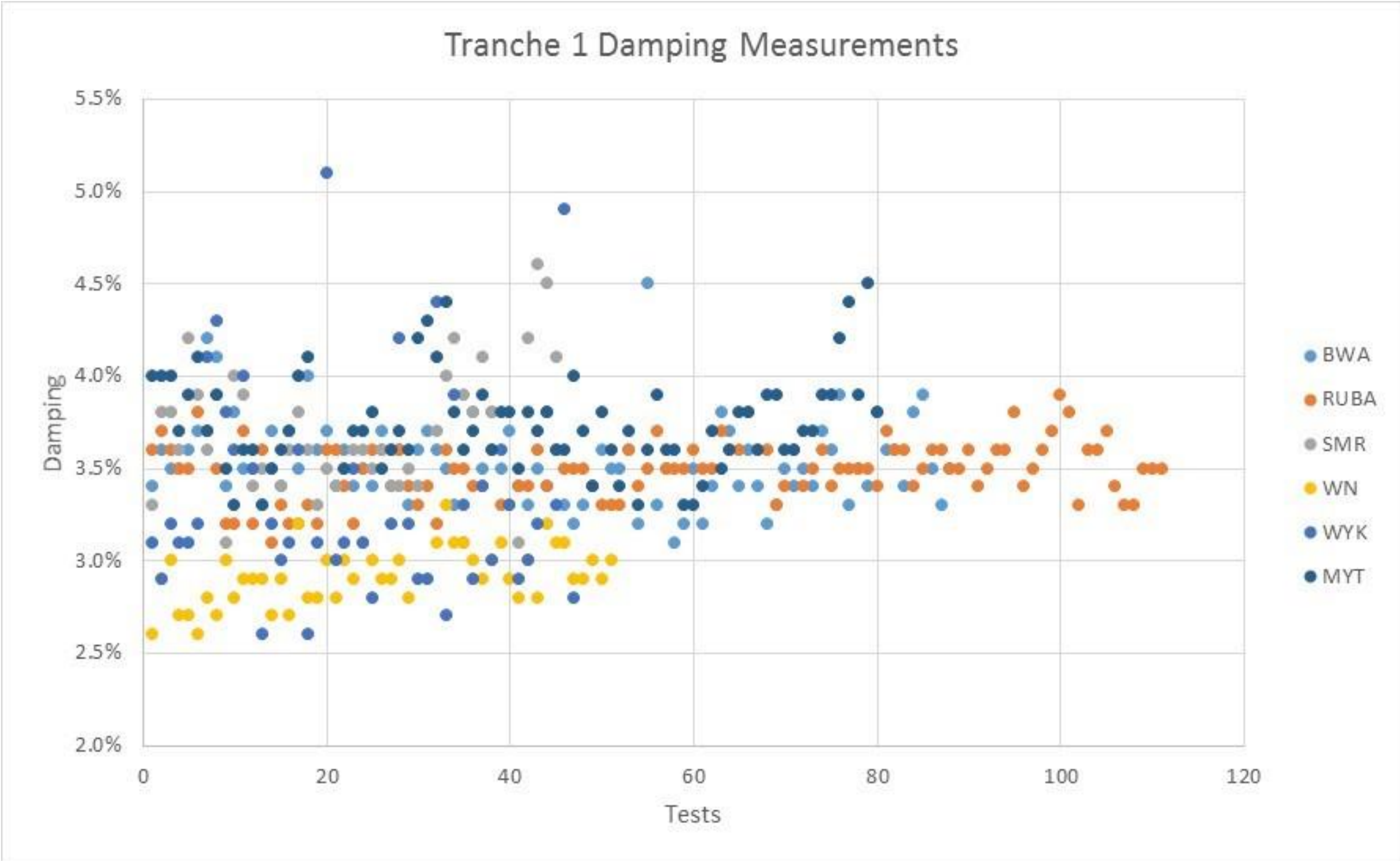
Chart 1 Arc Suppression Coil Size (Amps) vs Network Damping (Percentage)

Theoretically, 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%. However, following an analysis of empirical data obtained in Tranche 1, a damping factor of 3.5% was adopted as a more realistic value for coil sizing purposes. Refer to Section 3 which provided a summary of Tranche 1 damping measurements obtained during compliance testing.

Consequently, where the total tune point for the zone substation has exceeded the 101A 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 Appendix 1 - Tranche 1 Damping Measurements



Note:

- Kinglake Zone Substation (KLK) has been excluded due to extremely high damping factor.