Implementation & Optimisation of Resonant Networks

for

Victorian REFCL Applications

Previously the titled:

Selection of Arc Suppression Coils for Victorian REFCL Applications

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1 Executive Summary

The Victorian Electrical Safety (Bushfire Mitigation) Amendment Regulations 2016 impose stringent earth fault detection requirements on nominated 22kV polyphase electricity networks. These regulations motivate the installation of Rapid Earth Fault Current Limiters (REFCLs) to mitigate the risk of fire ignition as a result of single-phase-to-ground faults.

Current REFCL systems are based on the principles of resonant earthing, which is a popular earthing principle used extensively across Europe, China and Russia. Resonant networks offer enhanced detection sensitivity and a means of limiting earth fault currents to a much lower level than the solidly earthed systems currently used in Australia.

The sensitivity to earth faults in a resonant network is definitive; it is calculable with knowledge of system parameters and can be reasonably estimated during the scoping phase based on previous experience with similar Victorian networks. All of which were built to a common standard by the State Electricity Commission.

The requirements of the regulations can in some cases exceed the mathematical or practical capabilities of large resonant networks, particularly those with a high penetration of underground cable. In scoping the program of works for the implementation of the REFCLs, consideration to the number of Arc Suppression Coils (ASCs), a REFCL system component, is required to ensure the performance capacity defined within the regulation is practically achievable.

Three (3) important parameters determine the ultimate earth fault capability in a resonant network;

- Network Size
    - Defined as the phase-to-ground capacitive charging current in Amperes
- Damping
    - An Ohmic value expressed as a percentage of the Network Size
- Dissymmetry
    - The residual phase-to-ground charging current (capacitive imbalance) present as a steady state neutral voltage

Experience with Victorian networks indicates damping values are typically in the order of 2.5% - 3.5%, a relatively low figure when compared to European networks. Victorian networks also contain inherent challenges with dissymmetry due to extensive single phase networks and asymmetric load induced voltage drop.

When determining the number of Arc Suppression Coils required for REFCL applications, calculations and practicalities support a maximum network capacitive size of 93 – 130 A before separation of the network must be considered to ensure compliance with the regulations.

2 Purpose

The purpose of this document is to provide guidance on the quantity of Arc Suppression Coils required for Rapid Earth Fault Limiter (REFCL) applications adhering to the Victorian Electrical Safety (Bushfire Mitigation) Amendment Regulations 2016.

An Arc Suppression Coil is the fundamental component of a resonant grounded electricity network.

3 Background

3.1 Performance Standard

The performance standard required for REFCL systems in prescribed areas is as follows;

In the event of a phase-to-ground fault on a polyphase electric line, the ability—

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 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 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, 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;

Where;

- **high impedance faults**[1] means a resistance value in ohms that is equal to twice the nominal phase-to-ground network voltage in volts;
- **I^2t** means a measure of the thermal energy associated with the current flow, where **I** is the current flow in amps and **t** is the duration of current flow in seconds;
- **low impedance faults**[2] means a resistance value in ohms that is equal to the nominal phase-to-ground network voltage in volts divided by 31·75;
- **polyphase electric line** means an electric line comprised of more than one phase of electricity with a nominal voltage between 1 kV and 22 kV;

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[1] Target value is 25,400Ω

[2] Target value is 400 Ω

4 Compensated Networks

4.1 The Resonant Point

The Arc Suppression Coil (ASC) is the primary component in a resonant grounded power network. The ASC is fundamentally a variable single phase inductor connected between the power transformer neutral and earth.

When the inductance is adjusted to match the three (3) phase, phase-to-ground capacitance of the network, the system is considered in resonance or tuned.

The neutral voltage and angle is used to determine the tune point, which is found at the point of maximum neutral voltage.

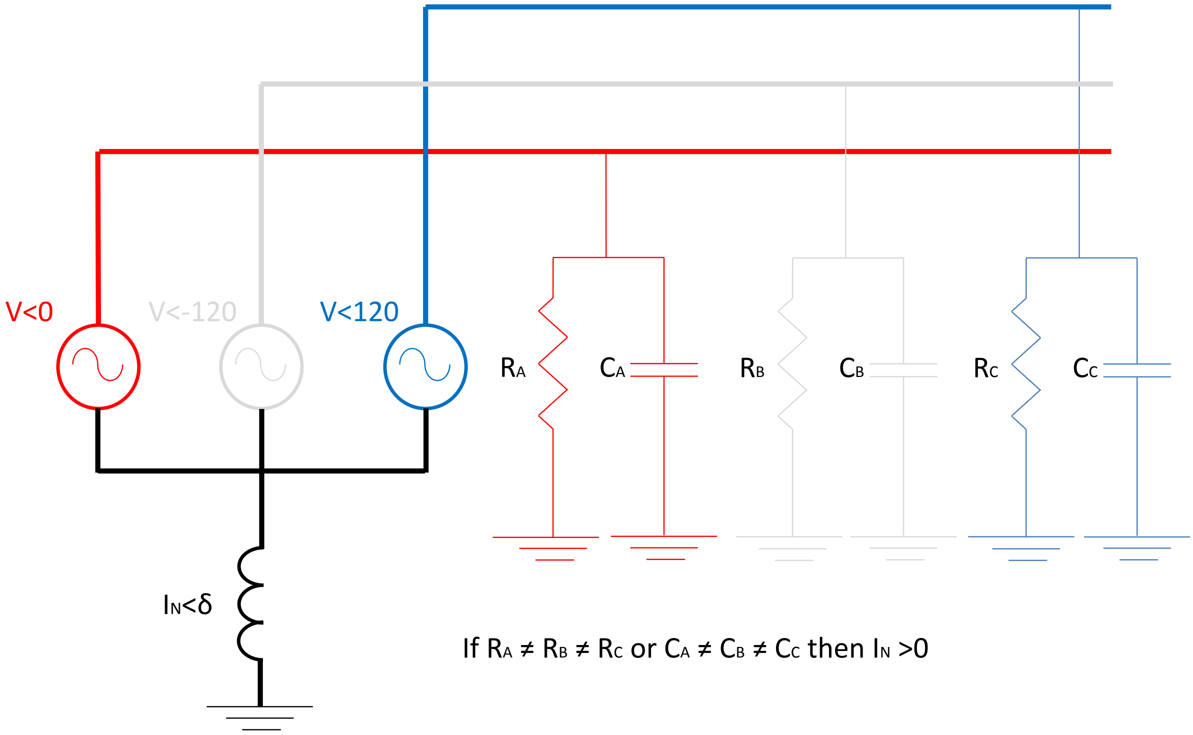


Figure 1 - Generic System Model

The total amount of capacitance present on the system is dependent on the assets which make up the network.

- Overhead line capacitance
  - A general rule of thumb for overhead lines on a 22kV network is 0.06 A/km.
  - Variance is introduced depending on the construction type, height from the ground and the presence of subsidiary circuits or aerial earths
- Underground cable capacitance

    - The contribution to capacitive charging currents is a little easier to define, as it is a standard parameter in cable datasheets. Typically 22kV cable exhibits around 1.8-2.5 A/km.
    - The variance in cable capacitance is typical to the size, design, amount of insulation and construction method used.
- Distribution Assets
    - Assets such as transformers, surge arrestors and other items will exhibit some capacitive leakage. As variances can be large between different assets, experiences show that the combined value may represent 5-10% of the total capacitance however this may appear as a smaller percentage in large cable networks.

4.1.1 Example Network

Take a 22kV network with the following parameters;

- 450 km of overhead line
    - 0.06 A/km capacitive charging current
- 45 km of underground cable
    - 2.4 A/km capacitive charging current

The calculated resonant point of the network is therefore;

- $450 \times 0.06 + 45 \ \times 2.4 \ = 135A$
- $135 \times 1.1 = 148.5A$
    - Allowance of 10% for distribution assets

Therefore an Arc Suppression Coil of 148.5A (85.5Ω) at 12.7kV is required in the system neutral to achieve resonance on this network.

4.2 The Neutral Voltage

The magnitude of the neutral voltage at the point of resonance is a function of network dissymmetry and damping.

Dissymmetry arises from unequal capacitive charging currents on a three (3) phase symmetrical power system.

This asymmetrical system current returns to the system star-point as a zero sequence quantity. The impedance of the ASC and the magnitude of this current are responsible for the neutral voltage.

The damping impedance of the network will have reducing effect on the neutral voltage; however for Victorian Networks we can assume a constant 2-3% for damping and therefore neglect its influence.

- The neutral voltage is therefore proportional to the network imbalance at the point of resonance.

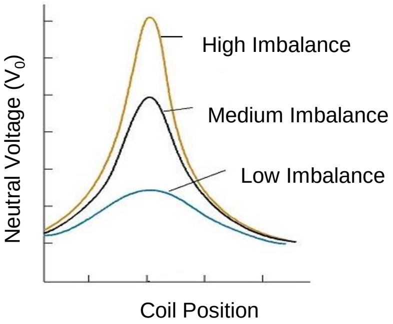


Figure 2 - Neutral Voltage as a Function of Coil Position

4.3 Earth Faults

When a fault occurs on a resonant network, the capacitive coupling current at the fault location is of equal and opposite polarity to the inductive current in the faulted phase. This results in a drastic reduction of fault current at the site of the fault, since the summation of reactive components is zero.

The resistive leakage driven by both the healthy phases creates a resultant current that is in phase with V_N. This quantity is known as the residual and is further eliminated by enhanced REFCL systems which use inverter technology.

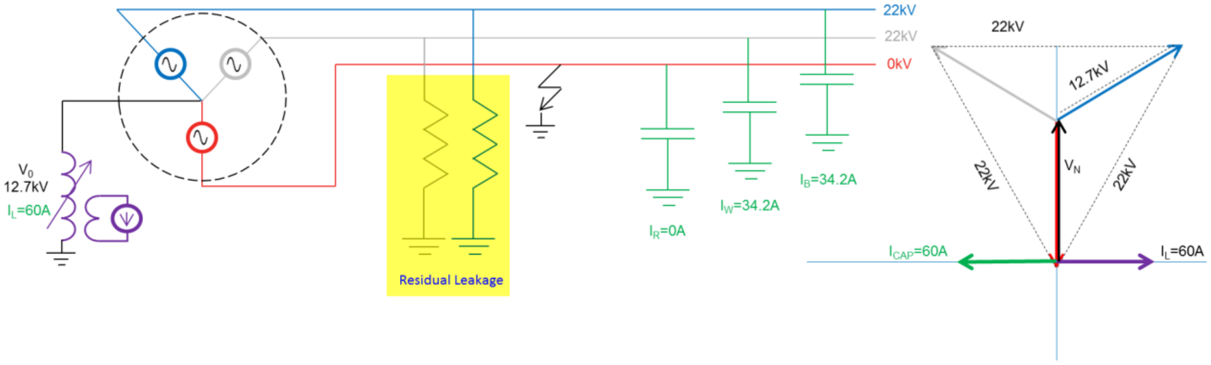


Figure 3 - Earth Fault in a Resonant System

4.3.1 Detection

In a resonant network, earth faults are detected through an increase in the **neutral voltage.** This voltage is measured either through a dedicated neutral VT, from a 22kV three phase Bus VT connected in open delta, or a calculated vector summation ($3V_0$).

Since this voltage is common to the network, a neutral voltage trigger does not provide identification of the faulted feeder.

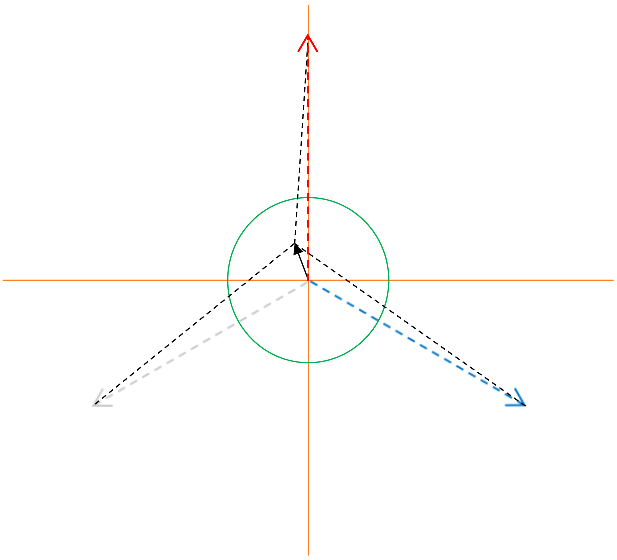


Figure 4 - Neutral Voltage Detection

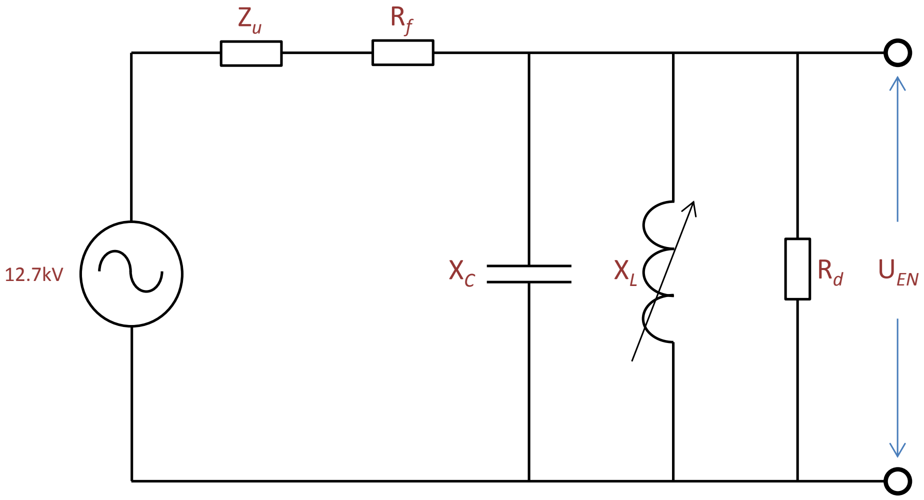
Figure 4 - Neutral Voltage Detection provides a graphical representation of the neutral voltage with respect to the minimum operating voltage quantity.

- The black arrow represents the system neutral voltage which is the product of the zero sequence capacitive leakage current, or more simply the dissymmetry (capacitive imbalance)
- The green circle represents the neutral voltage magnitude threshold for which defines the earth fault condition
- Under fault conditions the neutral voltage moves from the steady state position due to displacement caused by the faulted phase
- The angle of the neutral voltage corresponds to the faulted phase
- The magnitude of the neutral voltage shift is proportional to the fault impedance

In the Figure 4 - Neutral Voltage Detection example, one can observe that sensitivity is greatest for Red phase faults, then for White and then for Blue due to the magnitude of the required displacement in neutral voltage to trigger fault detection. The black dotted lines define the neutral voltage displacement path for earth faults. The displacement magnitude required for detection is the distance to the green circle (minimum operating voltage)

For fault detection to incorporate unbalance, the available phase voltage for fault detection must overcome the imbalance voltage in addition to the constraints imposed by system damping.

4.3.2 Equivalent Circuit



Z_U	Impedance presented by unbalance
R_f	Fault Resistance
X_c	Network Capacitance
X_L	Arc Suppression Coil Reactance
R_d	Damping Resistance
U_{EN}	Neutral Voltage

Figure 5 - Equivalent Circuit of a Faulted Resonant Network during an Earth Fault

Before attempted to solve for R_f, the circuit can be further simplified with some assumptions;

- $X_C = X_L$ – the network is tuned
- $Z_U = 0$ – assume the network is perfectly balanced

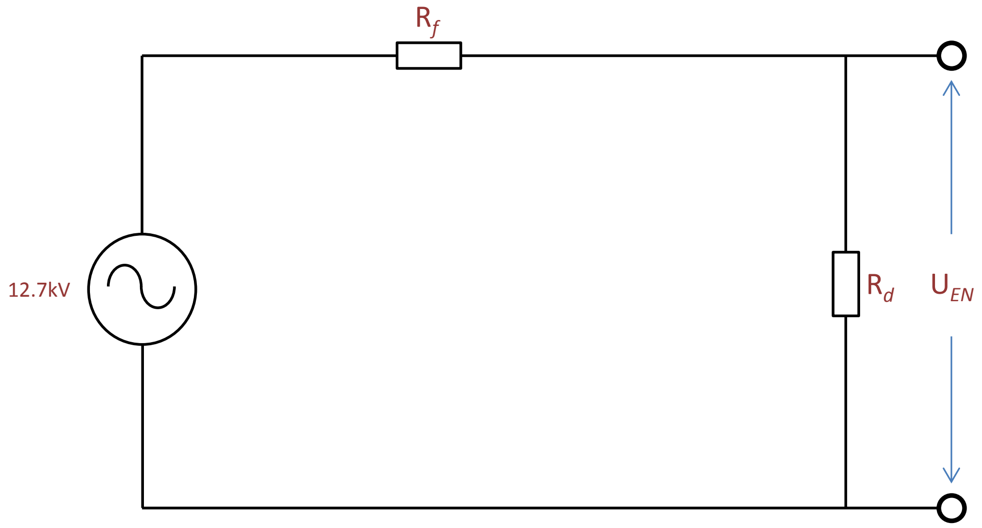


Figure 6 - Simplified Equivalent Circuit ($Z_u = 0$)

From the simplified circuit above, a basic voltage divider equation can be used to solve for the $U_{EN\ (MIN)}$ required for 25.4kΩ detection.

$$U_{EN} = \frac{R_d}{R_f + R_d}$$

Where R_f = 25,400Ω + 5%

In section **Error! Bookmark not defined.** - **Error! Reference source not found.** rules are introduced which define basic requirements to ensure dependable, secure and selective earth fault detection.

5 REFCL Implementation

The following section explains the derivation of the network parameters required to achieve 25.4kΩ sensitivity in a resonant network.

Refer to 3.1 Performance Standard for sensitivity requirements.

5.1 System Parameters

In a typical resonant network the system parameters formulate the earth fault detection capability. Network size, damping impedance and system dissymmetry values are considered and a typical minimum operating voltage of approximately 0.3pu is often applied. In small or asymmetric networks a damping resistor might be used to control dissymmetry issues. With very little consideration, earth fault sensitivities of up to 6-10kΩ can be easily obtained.

Victorian Networks are aiming to achieve a particular and onerous sensitivity; therefore it is the network which must be manipulated in order to achieve the requirements.

5.1.1 Neutral Operating Voltage

To achieve 25.4kΩ sensitivity, the minimum neutral voltage operating quantity must be set to incorporate the following;

- Worst case dissymmetry
    - Maximum displacement due to load asymmetry at an angle geometrically opposite to a phase voltage
- Worst case damping
    - Evaluation of historical resonant/locus curves
- A safety margin to guarantee detection at the ultimate sensitivity
    - Suggest a target of least 5% higher than the required capacity

5.1.2 Damping

Existing trial installations on the Powercor Network have indicated damping values in the range of 2.0 – 4.0%. These figures are consistent with United Energy’s Frankston South and AusNet Services networks at Kilmore South and Woori Yallock which are all based on the design philosophies of the State Electricity Commission Victoria.

Variances in operational damping experienced by a particular system appears to be most affected by environmental conditions with days of high humidity, light rain and mist resulting in increased leakage and subsequently higher damping values, which are derived from locus calculations within existing REFCL systems.

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.

For the purposes of these calculations, figures of **2.0, 3.0, 4.0 and 5%** will be used in order to present a sensitivity analysis on the effect that damping has on detection capability.

5.1.3 Dissymmetry

To ensure earth fault sensitivity is both achievable and stable, the minimum operating voltage must be configured with consideration to the worst case dissymmetry.

Providing a metric with to the worse case dissymmetry is difficult, however work to date has shown that a combination of transpositions and low voltage capacitive correction can favourably manipulate the neutral voltage to appropriate levels.

In addition, there is an element however of load induced asymmetric voltage drop which has a second order effect on capacitive imbalance by introducing variance in the total per phase charging current. Ultimately this leads to a fluctuating dissymmetry value which varies with load and cannot be eliminated using static balancing techniques.

In this document a dissymmetry range of **250** - **400V** will be used. This could be considered a realistic figure given adequate attention and investment in network balancing, however it is highly dependent on the inherent characteristics and **should not** be assumed attainable in all circumstances.

5.2 System Design Guidelines

The minimum operating voltage ($U_{EN\ (MIN)}$) is the threshold of neutral voltage used as the determinant for earth faults. As is the case when setting over-current devices, the value we select must carefully consider a number factors to ensure the dependability, security and selectivity of the protection scheme. The following rules of thumb are proposed to ensure these objectives are met;

- $U_{EN\ (MIN)}$ shall be at least **5 x** the standing neutral voltage
    - Provides an adequate margin of safety to prevent false detection from switching, single phase fuse operation and neutral voltage fluctuations
    - Ensures a more balanced earth fault sensitivity across all phases
- $U_{EN\ (MIN)}$ shall be at least **1000 V** primary
    - Corresponds to a 5V secondary voltage on typical VT’s
    - Ensures fault detection relays do not “bottom out” and challenge their minimum levels of sensitivities

  - Ensures the primary VT and any auxiliary open delta VT are operated within their specified accuracy range
  - Provide immunity to low level transient voltages on secondary circuits and high burden relay inputs
- $U_{EN\ (MIN)}$ shall be set to detect an impedance that is at least **5%** greater than the prescribed impedance (25.4kΩ)
  - This provides a margin of safety to ensure capacity requirements can be satisfactorily met
  - The target for $U_{EN\ (MIN)}$ can therefore be set with respect to a minimum impedance of 26.67kΩ
- $U_{EN\ (MIN)}$ shall be set to incorporate the impedance presented by unbalance on the least sensitive phase **in addition to the above constraints**

5.2.1 Optimum Network Sizing

The table below presents three (3) plausible U_{EN} set points which are compliant with section **Error! Reference source not found. Error! Reference source not found.**. At each of the set points, the minimum damping impedance is calculated for which the mathematical detection of earth faults (R_f) at the required capacity is possible.

The calculated resistance values (Ω) are then translated into per unit values at 2.0%, 3.0%, 4.0% and 5.0% to find the **maximum network size** (capacitive charging amps) at which the required capacity is achievable.

U_{EN} (V)	Min Damping (Ω)	Maximum Network Size (A)					
		2.0%	**2.5%**	**3.0%**	**3.5%**	**4.0%**	**5.0%**
1,250	2,912	218	174	145	125	109	87
1,625	3,913	162	130	108	93	81	65
2,000	4,985	127	102	85	73	64	51

Table 1 - Network Parameters for Required Capacity

The area shaded green represents the optimum and most practicable system parameters in pursuit of the regulations based on the requirements of section **Error! Reference source not found. Error! Reference source not found.** and the expected damping range of Victorian 22kV networks.

5.3 Capacitance Mitigation

To ensure the objectives of the regulations are met, the capacitive charging current of the network being protected should be kept to within **93 – 130A** provided;

- Damping coefficients remain in the expected 2.5% - 3.5% range
- Adequate capacitive balancing solutions are implemented and maintained

Many Victorian 22kV networks are much larger than the suggested range and so additional augmentation work is required in order to practically achieve the required capacity. These augmentation works are aimed at reducing the total charging capacitance on the network.

5.3.1 Bus Splitting

In zone substations with multiple transformers installing multiple REFCL systems, segregating neutrals and opening bus tie circuit breakers is considered the most appropriate approach. This creates two smaller independent networks and improves the mathematics behind fault detection capability.

Consider the network below with eight (8) feeders and two transformers;

- Total network charging current is 200A with a 25A contribution per feeder

The installation of a REFCL system on both transformers and segregating operation of the substation across the bus tie alters the system into two (2) networks of 100A in size. This significantly alters the earth fault detection capability of the network.

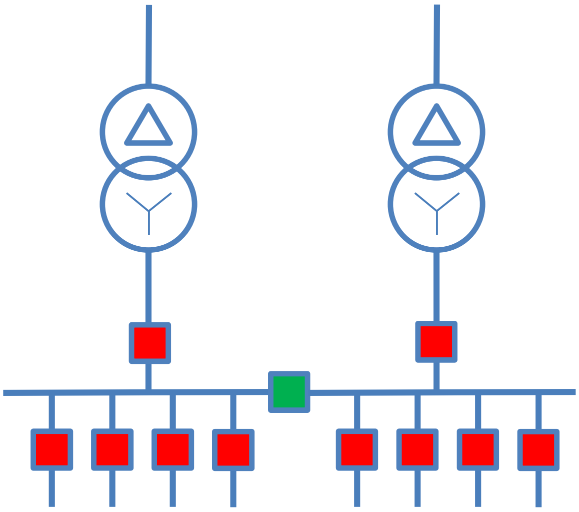


Figure 7 - Open 22kV Bus Tie Arrangement

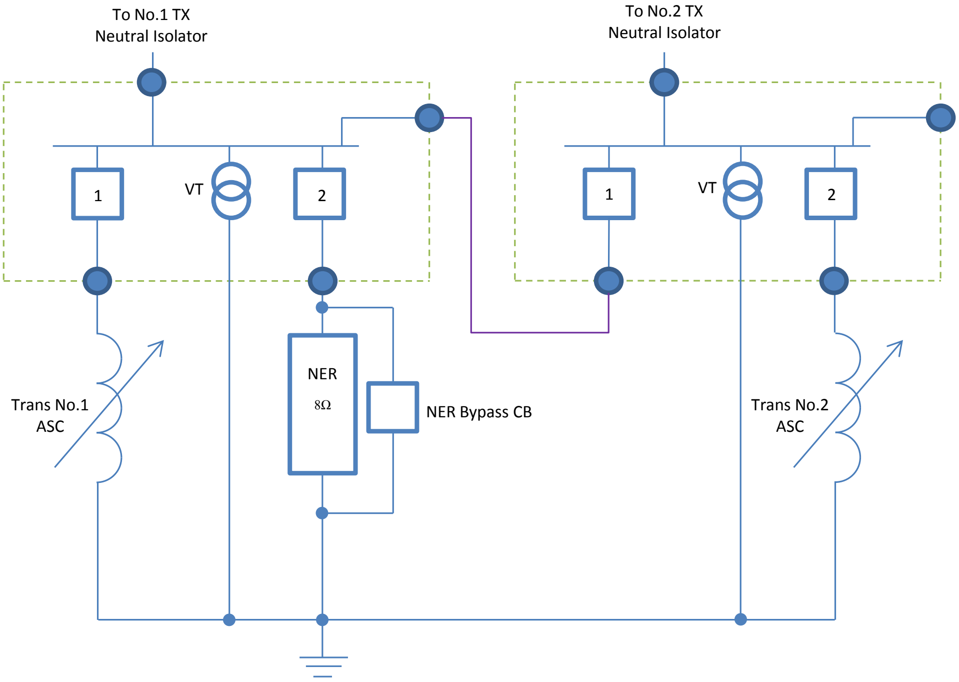


Figure 8 - Dual REFCL Neutral System Arrangement

Summary

Advantages	Disadvantages
Most effective reduction in charging current	Additional plant and equipment
Optimal earth fault sensitivity	Requires replacement of traditional substation transformer and voltage control schemes
	Imposes a reliability risk for loss of transformer
	Requires splitting of capacitor banks or additional reactive support

5.3.2 Isolation Transformer

The 22kV charging current referred to in a resonant network is the phase-to-ground charging current of the network. It is this current which creates the resonant circuit with the arc suppression coil under earth fault conditions.

One method of potentially reducing the size of the network is to isolate large sections of cable via a delta winding, thus presenting the network downstream as a phase-to-phase load to the main system and reducing the total zero sequence charging current.

The application of isolation transformers is only applicable to sections of the system with 100% underground cable, as any overhead would lead to non-compliance of the regulations. Finding large sections of bulk underground cable on rural 22kV network would also be challenging and so multiple installations would be required in order to have a tangible effect on the total capacitance.

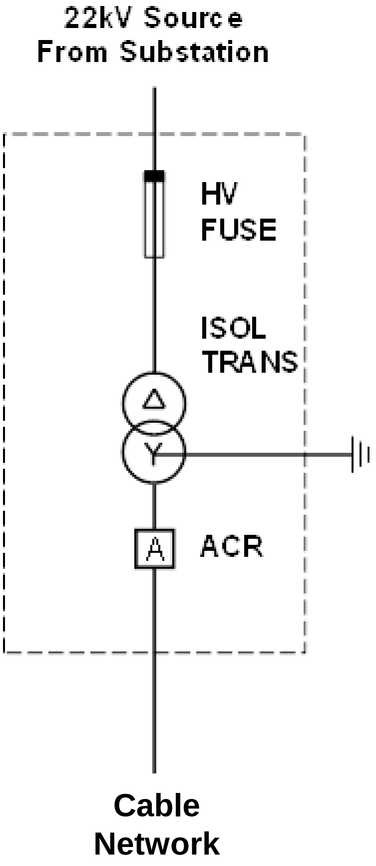


Figure 9 - Isolation Transformer Concept

Summary

Advantages	Disadvantages
Provides reduction in overall charging current	Requires upfront development and investment to bring the product to market
Discrete use may defer future substation augmentation due to capacitive growth following initial REFCL deployment	Multiple units required per site due to the distributed nature of the network and underground sections.
	Any overhead network downstream the isolation transformer will be in breach of required capacity within the regulations
	Each unit would require the acquisition of land and associated civil costs

5.3.3 Parallel and/or Distributed Coils

In many European networks it is common practice for utilities to deal with large cable networks or capacitive growth through the installation of parallel or distributed arc suppression coils working in a fixed tap configuration.

These networks rely on these additional coils to provide bulk reactance support to the primary arc suppression coil within the substation. This coil remains variable and is responsible for the tuning function.

Two fundamental differences exist between the objectives of these network owners and the objective of Victorian networks who must comply with the required capacity defined in the regulations.

1. There is no requirement to treat the residual component from a fire ignition perspective
2. Fault detection sensitivity requirements are not as onerous as those prescribed

This solution permits a smaller coil to be used as the primary coil within the substation for the purposes of tuning; however it does not address the ever diminishing damping resistance which decreases proportionally with network size. It must be remembered that it is not network size which determines fault detection capability, but the magnitude of the damping impedance in real terms.

The use of additional or distributed coils will mask the effect of a large network on the substation coil but it will not hide the associated decrease in damping impedance associated with large networks. It is the damping impedance which has the ultimate influence on earth fault detection sensitivity.

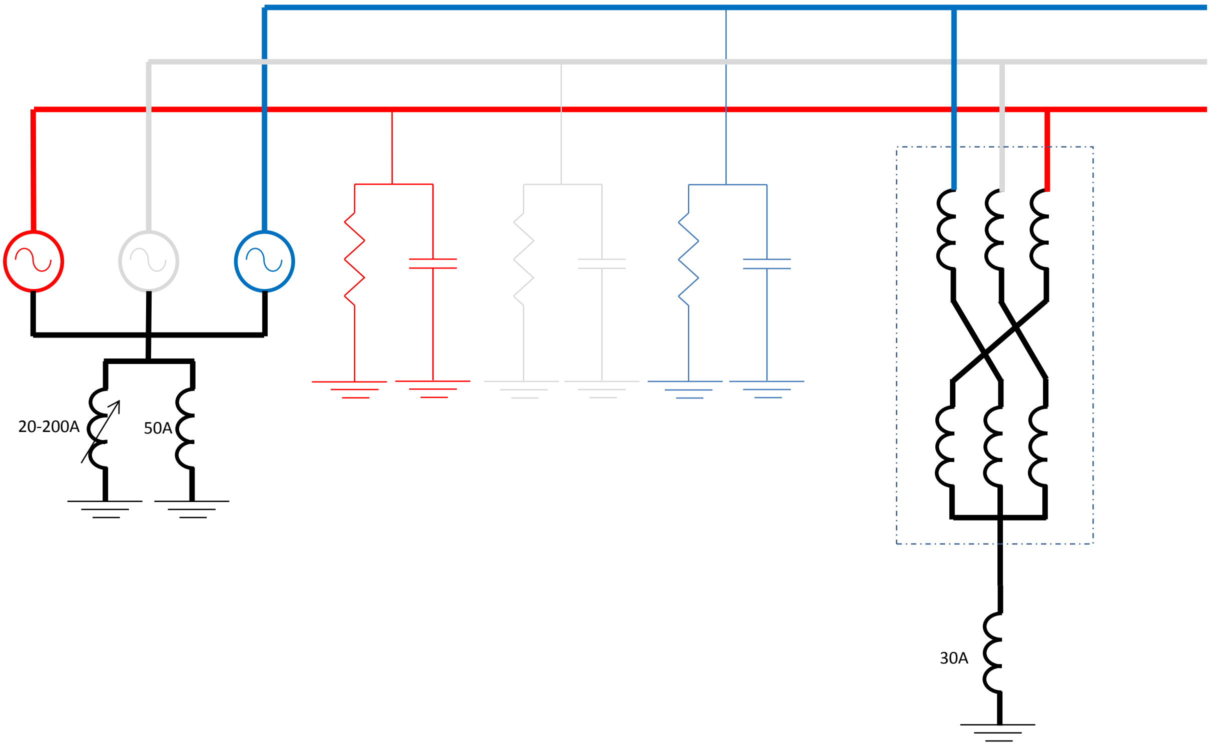


Figure 10 - Parallel and/or Distributed Coil Concept

Figure 10 - Parallel and/or Distributed Coil Concept presents a sample network with;

- One (1) fixed 50 amp arc suppression coil connected in parallel to;
- One (1) variable arc suppression coil with a tapping range of 20-200A.
- One (1) fixed 30A arc suppression coil connected on the distribution network via an earthing transformer

The example network has a tune point due to total capacitive charging of 260A. Under this scenario;

- The fixed coils contribute 50A + 30A = 80A
- The variable coils tunes the remainder of the network and arrives at a position of 180A
  - 50A + 30A + 180A = 260A
- The network damping coefficient of the complete network is 3.0%
  - The damping impedance is approximately 1628Ω
  - With reference to Table 1 - Network Parameters for Required Capacity, fault detection at the expected capacity is not obtainable.

Note: The tuning relay on the variable ASC will calculate a damping value of a much higher percentage than the actual value. This is due to the total damping impedance expressed as a percentage of coil position.

Summary

Advantages	Disadvantages
Cost effective implementation	Does not address the requirement of the regulations when applied to large or growing networks
Preferred method for dealing with network growth	

6 Appendices

6.1 REFCL Optimisation Examples

6.1.1 Woodend Zone Substation

Overhead Line	0.06 A/km	885 km
Underground Cable	2.4 A/km	40 km
Calculated Charging Current	Inclusive of 10% distribution asset margin	164 A
Actual Tune Point		162A
Actual Damping		3-4%
Achievable Balancing		250 - 500V
Theoretical Min Op for required capacity[1]		984V @ 3.5% R_d
No. of ASC's required[2]		2
Practically Confirmed?		No

6.1.2 Gisborne Zone Substation

Overhead Line	0.06 A/km	350 km
Underground Cable	2.4 A/km	31 km
Calculated Charging Current	Inclusive of 10% distribution asset margin	105 A
Actual Tune Point		113A
Actual Damping		2-3%
Achievable Balancing		<250V
Theoretical Min Op for required capacity[1]		1832V @ 2.5% R_d
No. of ASC's required[2]		1
Practically Confirmed?		No

6.1.3 Castlemaine Zone Substation

Overhead Line	0.06 A/km	888 km
Underground Cable	2.4 A/km	19 km
Calculated Charging Current	Inclusive of 10% distribution asset margin	109 A
Actual Tune Point		Unknown
Actual Damping		Unknown
Achievable Balancing		250-500V
Theoretical Min Op for required capacity[1]		1409V @ 3.5% R_d
No. of ASC's required[2]		1
Practically Confirmed?		No

6.1.4 Colac Zone Substation

Overhead Line	0.06 A/km	1288 km
Underground Cable	2.4 A/km	35 km
Calculated Charging Current	Inclusive of 10% distribution asset margin	177 A
Actual Tune Point		Unknown
Actual Damping		Unknown
Achievable Balancing		500 - 800V
Theoretical Min Op for required capacity[1]		907V @ 3.5% R_d
No. of ASC's required[2]		2
Practically Confirmed?		No

6.1.5 Camperdown Zone Substation

Overhead Line	0.06 A/km	917 km
Underground Cable	2.4 A/km	0.4 km
Calculated Charging Current	Inclusive of 10% distribution asset margin	56 A
Actual Tune Point		Unknown
Actual Damping		Unknown
Achievable Balancing		500 - 800V
Theoretical Min Op for required capacity[1]		2482V @ 3.5% R_d
No. of ASC's required[2]		1
Practically Confirmed?		No

6.1.6 Maryborough Zone Substation

Overhead Line	0.06 A/km	943 km
Underground Cable	2.4 A/km	4 km
Calculated Charging Current	Inclusive of 10% distribution asset margin	73 A
Actual Tune Point		Unknown
Actual Damping		Unknown
Achievable Balancing		500 - 800V
Theoretical Min Op for required capacity[1]		1995V @ 3.5% R_d
No. of ASC's required[2]		1
Practically Confirmed?		No

6.1.7 Winchelsea Zone Substation

Overhead Line	0.06 A/km	365 km
Underground Cable	2.4 A/km	114 km
Calculated Charging Current	Inclusive of 10% distribution asset margin	325 A
Actual Tune Point		Unknown
Actual Damping		Unknown
Achievable Balancing		500 - 800V[3d]
Theoretical Min Op for required capacity[1]		510V @ 3.5% R_d
No. of ASC's required[2]		3
Practically Confirmed?		No

6.1.8 Eaglehawk Zone Substation

Overhead Line	0.06 A/km	892 km
Underground Cable	2.4 A/km	43.5 km
Calculated Charging Current	Inclusive of 10% distribution asset margin	174 A
Actual Tune Point		Unknown
Actual Damping		Unknown
Achievable Balancing		500 - 800V
Theoretical Min Op for required capacity[1]		921V @ 3.5% R_d
No. of ASC's required[2]		2
Practically Confirmed?		No

6.1.9 Terang Zone Substation

Overhead Line	0.06 A/km	1107 km
Underground Cable	2.4 A/km	4.6 km
Calculated Charging Current	Inclusive of 10% distribution asset margin	85 A
Actual Tune Point		Unknown
Actual Damping		Unknown
Achievable Balancing		500 - 800V
Theoretical Min Op for required capacity[1]		1752V @ 3.5% R_d
No. of ASC's required[2]		1
Practically Confirmed?		No

6.1.10 Ballarat South Zone Substation

Overhead Line	0.06 A/km	1298 km
Underground Cable	2.4 A/km	70 km
Calculated Charging Current	Inclusive of 10% distribution asset margin	246 A
Actual Tune Point		Unknown
Actual Damping		Unknown
Achievable Balancing		500 - 800V
Theoretical Min Op for required capacity[1]		666V @ 3.5% R_d
No. of ASC's required[2]		3
Practically Confirmed?		No

1 Calculated assuming zero dissymmetry and one (1) ASC. Actual tune point used when available
2 Based on calculated minimum operating voltage
3 Achievable balancing target based on total overhead length.
    a. <400km - <250V
    b. 400 – 900km – 250V – 500V
    c. >900km – 500V – 800V
    d. Winchelsea has had extensive single phase cabling installed as part of PRF works