Title Wellington's Trolley Bus Overhead Electrical Network – Introduction of Electrical Fault Protection

Authors Simon Fleisher (Wellington Cable Car Limited)
Steve Read (ProTechtion Consulting Limited)

Presenter Simon Fleisher (Wellington Cable Car Limited)

Conference EEA Conference and Exhibition 2014,
18 – 20 June, Auckland

Abstract

Wellington Cable Car Limited (WCCL) operates and maintains Wellington's venerable Trolley Bus DC overhead electrical network. This network covers 80 Km of road with 160 Km of Copper contact wire suspended above the streets providing 550V DC electrical power for Trolley Bus traction motors that use a collector head system to establish positive electrical contact. The origins of the system date back to the days of Trams and have been modified over successive decades by multiple owners to give us the system that is in place now. Fifty feeder pillars that supply network sections form the demarcation point between WCCL's network and Wellington Electricity Lines Limited's (WELL) fifteen DC substations.

Because of its historical lineage and evolution from Trams to Trolley Buses, there is a lack of sensitive short circuit detection, earth fault protection and discrimination that would be utilised if the system had been designed and installed recently. In particular, it doesn't meet the full requirements of the Electrical Safety Regulations, 2010. This leaves WCCL and Greater Wellington Regional Council (GWRC) who fund the network exposed from a risk management and legislative perspective. WCCL needs to be able to ensure that personnel in the vicinity of the system are not exposed to any potential risk arising from fault conditions (the system design renders it vulnerable to occasional contact wire breaks for a variety of reasons, particularly in network sections that haven't been replaced in the past 5 years).

WCCL, in conjunction with Protechion Consulting (and funded by GWRC) have successfully designed and installed a prototype electrical fault protection system that provides the requisite short circuit detection, earth fault protection and conventional electrical safety functionality required to meet modern-day standards. This system takes into account the transient electrical characteristics of the system under normal and fault conditions, including the effects of accidents, vehicle collisions and weather-related events. The prototype performance thus far indicates that the design (with some minor changes to facilitate batch manufacture methods) is suitable for wider implementation across the network. This is a really good example of innovative design combined with a high degree of expert knowledge in a field where the overall skill base and availability of electric components is rare (Wellington's Trolley Bus network is the only one in the southern hemisphere). This is seen as a role model for effective asset management and risk mitigation.

Introduction

Wellington Cable Car Limited (WCCL) is a Wellington City Council-owned Council Controlled Organisation that was incorporated in its current structure in 1991. As well as running Wellington's historic Cable Car (a funicular railway), WCCL operates and maintains the city's iconic Trolley Bus 550V DC overhead electrical network.[1] The network is the only one of its type in the southern hemisphere and is maintained under contract to Greater Wellington Regional Council. Four WCCL employees oversee and provide specialist engineering support for network operations and maintenance, including project managing the replacement of degraded sections due to wear and tear, mechanical and electrical degradation of the contact wire. WCCL’s main subcontractor for maintenance operations and section replacement is Transfield Services Limited.

The Trolley Bus network has operated in its current form since 1949 and covers the CBD, eastern, southern and western suburbs. It provides electrical power for 62 Trolley Buses that operate 819 scheduled bus services per working day (Go Wellington operates 324 buses in total, including the Trolley Buses). The network covers 80 Km of road with 160 Km of Copper contact wire suspended above the streets providing 550V DC electrical power for the Trolley Bus traction motors. A collector head system is used to establish positive contact with the contact wire instead of the pantograph system that is used on Trains or Trams.

Figure 1: Go Wellington Trolley Bus

[1] In DC traction there is a very large variation of voltage above and below the nominal voltage and this is acknowledged in international standards and literature. 550V was the original British nominal value for Trolley Busses, while Europe used 660V and more recently 750V nominal systems.

The origins of the system date back to the days of Trams and have been modified over successive decades by multiple owners to give us the system that exists now. The deregulation of the New Zealand electricity industry and the privatisation of publically owned transport infrastructure left its legacy in the form of a fragmented approach to system ownership that Greater Wellington Regional Council (GWRC) now has to deal with. Wellington's Trolley Buses and their supporting power systems are provided by three companies that are all completely independent of each other – WCCL, Wellington Electricity Lines Limited (WELL) and Go Wellington (the local subsidiary of NZ Bus).

The whole network including the power supply arrangements has been historically underinvested in, but GWRC have provided significant funding over the past 10 years to improve its material state. There is one significant legacy issue arising, however, as a result of the history of fragmented ownership and previous lack of investment. The network lacks the requisite discrimination, earth fault protection and electrical safety capability that would be considered standard operating procedure if a new overhead electrical network using modern equipment and protection devices was to be designed and installed. Also a modern system could be non-earthed, but this is not feasible with the existing equipment. The only electrical fault protection available is overcurrent located upstream at the WELL DC substations, and this does not provide adequate detection of short circuits or any earth fault protection.

This is a significant omission because the physical design of the network and local road conditions mean that the Trolley Buses occasionally pull down lengths of network contact wire, albeit accidently (this happens 10 – 15 times per year). Other common causes of contact wire faults include mechanical impact from unauthorised high loads, vehicle collisions with poles and extreme weather conditions. This gives rise to the remote possibility that a bystander could come into contact with a broken live contact wire and inadvertently form a path to earth, potentially causing electric shock.

This leaves WCCL and GWRC (who fund the network) exposed from a risk management and legislative perspective. However, it is good to know that there have been no serious incidents or accidents in over 40 years of operations. However, the changes to the Electrical Safety Regulations in 2010 and the more restrictive health and safety environment pervasive nowadays led to the requirement to investigate and determine the technical feasibility of an earth fault protection system. In particular, WCCL needs to be able to ensure that personnel in the vicinity of the system are not exposed to any potential risk arising from electrical fault conditions. This is the genesis of the TBOP (Trolley Bus Overhead Protection) project.

The aim of this paper is to describe the technical rationale behind the TBOP system design, comment on how a prototype protection cabinet installed on one network section has performed, and discuss the implications for earth fault protection of the wider network.

Trolley Bus Network Description and Protection Requirements

The system comprises 15 WELL-owned DC substations of varying power outputs that supply 50 WCCL feeder pillars; the connection point to each feeder pillar forms the demarcation point between the two systems. The nominal voltage for the Trolley Bus network is 550V DC and the current generation of Trolley Buses have a maximum power output of 130 KW (a physical schematic diagram of the WCCL network is at Figure 2).

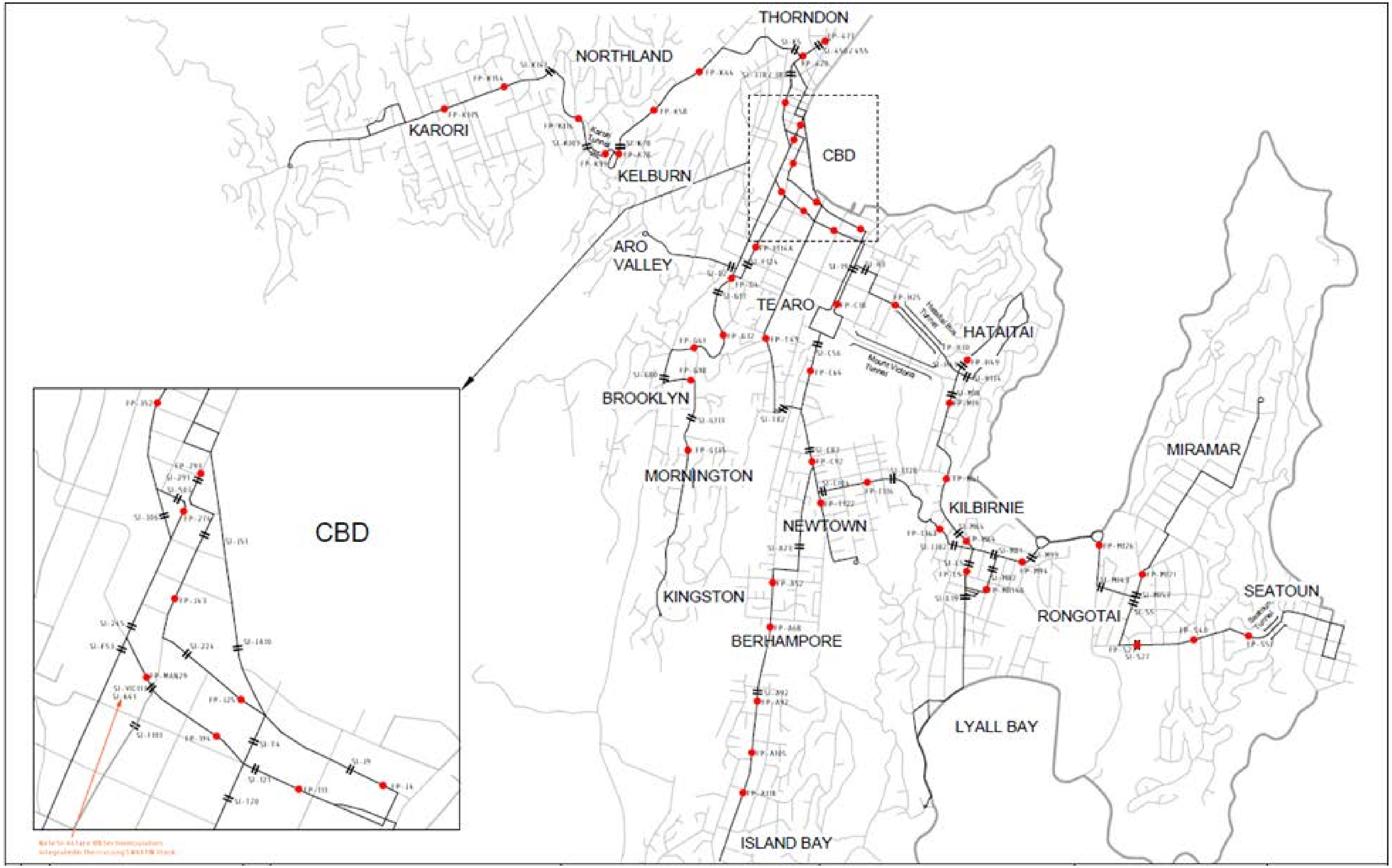

Figure 2: Physical Schematic Diagram of Wellington Cable Car Trolley Bus Overhead Electrical Network

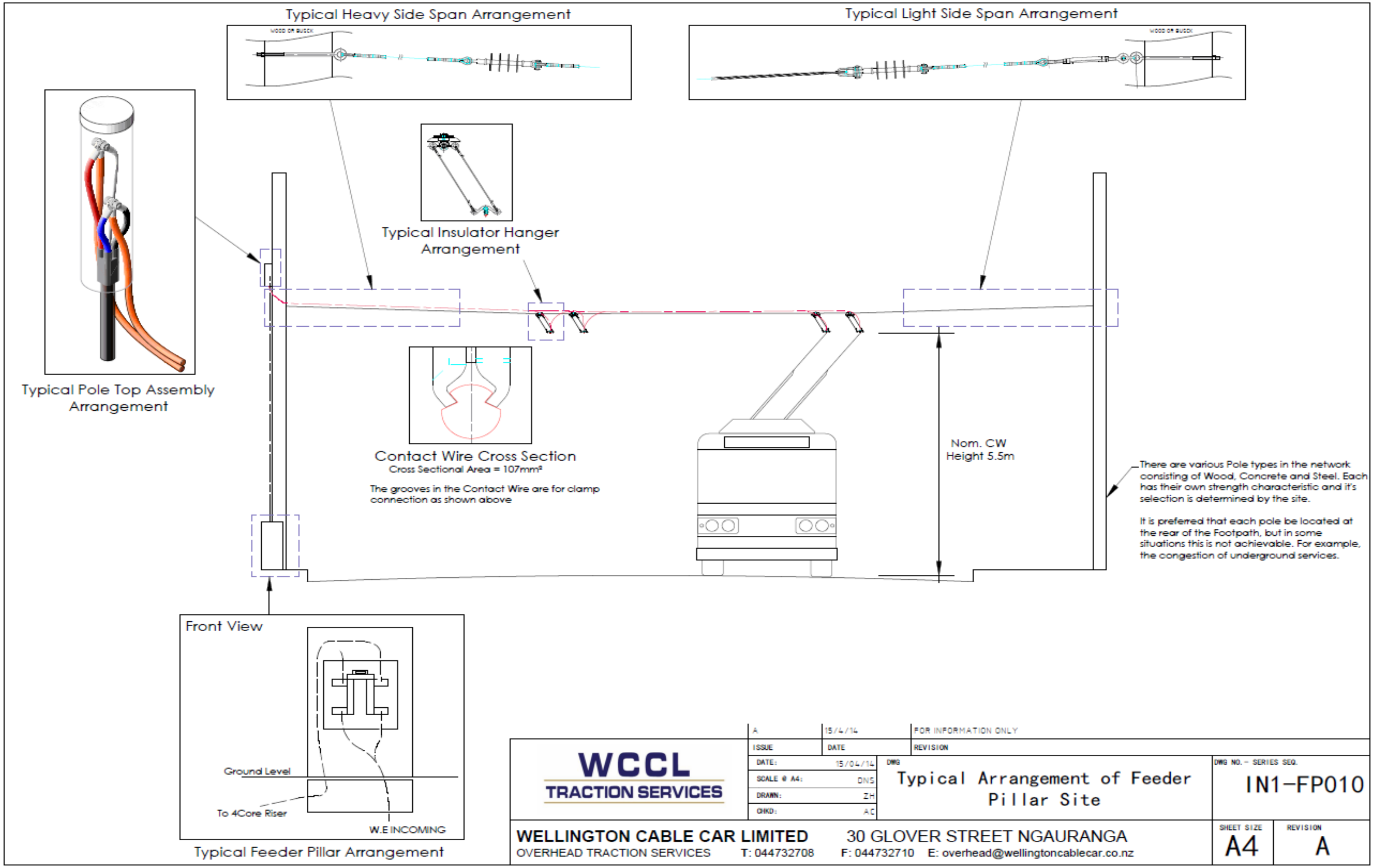

Figure 3: **Typical Arrangement of Feeder Pillar Site**

The feeder pillars connect to the overhead contact wires via knife switches that enable offload isolation. The longest distance between a feeder pillar and the farthest extent of a network section is approximately 2.4Km and the diameter of contact wire utilised (when new) varies from 80mm^2 for the oldest sections to 107mm^2 for new sections. The pre-tensioned copper contact wire is suspended via section insulators below steel wire rope, located on poles that are spaced approximately 25m apart (Figure 3).[2]

Short Circuit

Network short circuit and a degree of overcurrent protection before TBOP implementation is provided at a high level by the DC breakers located at the WELL substations within the range 1,200A – 1,500A. Immediate short circuit trip is provided for currents above 1,500A, and for some WELL feeders a degree of overload tripping exists in the range 1,200A – 1,500A with time delays up to 25s. Analysis of the Trolley Bus nominal operating voltage and maximum power output indicates a nominal steady state running current of 236A with theoretical maximum starting current of 490A set by on-board protection, but there are much higher transient currents observed when buses cross "special works".

The design and physical layout of the network makes the following examples the main potential causes of a short circuit:

(a) Broken contact wire(s) that touch the opposite polarity contact wire;
(b) An over-height unauthorised load (for example, a lorry with a high load) travelling through the streets that inadvertently touches both wires and creates a short circuit;
(c) Impact damage to the supporting infrastructure due to vehicle damage or extreme weather / earthquakes that causes the +ve and –ve wires to touch; and
(d) Defective Trolley Buses with degraded internal impedance that cause a short circuit by providing a low impedance path between the +ve and –ve wires.

The size of the short circuit varies dependent upon the location and the nature of the defect, and it is the lower short circuit current faults that are problematic as they are below the WELL breaker fault threshold settings. Figure 5 shows a fault at the terminus at the end of a route remote from the feeder pillar.

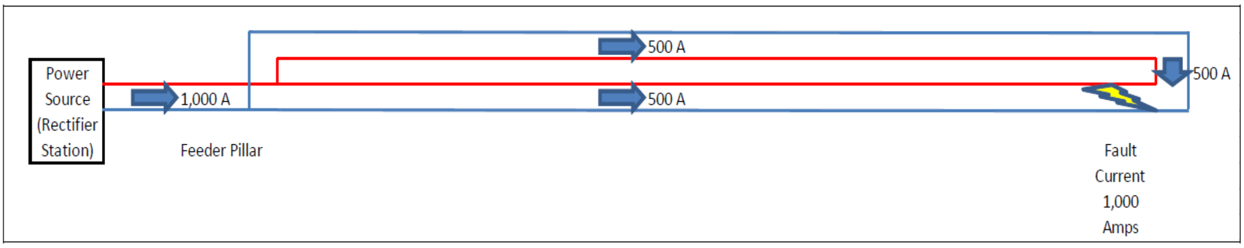

Figure 4: Short Circuit Fault Close to Terminus, Current Flows in Two Parallel Paths

Even though the fault current flows down two parallel paths to the short circuit point there is a problem as 1,000A is still too low to be detected by the existing protection at the rectifier station set to 1,500A. Realistic calculations have an allowance for contact wire wear, rectifier source impedance, protection errors, etc.

[2] The network physical installation is maintained in accordance with BS EN 50119:2009 (Railway applications – Fixed installations – Electric traction overhead contact lines); (British Standards Institution, 31 January 2010).

Earth Faults

Earth leakage current is the normal day-to-day current flowing over the surface of insulators and down the many support structures to earth. Earth fault current is that which flows to earth due to a fault such as a fallen wire, vehicle in contact with the wire, or a person in contact with the wire and earth. The main risk emanates from broken +ve contact wires that are still live. The risk of fallen wires is managed by maintaining the network at a good level and keeping the number of in-situ crimp joints in contact wires to a sensible level (the approved repair method in the event of a wire tear down).

The risk of electrocution is assessed based on IEC Standard TS 60479-1[3] "*Effects of current on human beings and livestock*". This is a reference standard for the NZ Electricity (Safety) Regulations.[4] It provides tables and diagrams to quantify the risk of electrocution that results from electric current flowing through the body. This risk depends on:

(a) Is the current AC (alternating current = normal mains power) or DC (direct current = trolley bus power),
(b) The duration of the current (how fast is the protection),
(c) The amount of current flowing (how many mA), and
(d) The path of the current (for example from hands to feet).

The risk can be further quantified based upon the following extracts from TS 60479-1:

Zones	Boundaries	Physiological effects
DC-1	Up to 2 mA curve a	Slight pricking sensation possible when making, breaking or rapidly altering current flow
DC-2	2 mA up to curve b	Involuntary muscular contractions likely especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects
DC-3	Curve b and above	Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected
DC-4 1)	Above curve c_1	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time
	c_1-c_2	DC-4.1 Probability of ventricular fibrillation increasing up to about 5 %
	c_2-c_3	DC-4.2 Probability of ventricular fibrillation up to about 50 %
	Beyond curve c_3	DC-4.3 Probability of ventricular fibrillation above 50 %
1) For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed. As regards ventricular fibrillation this figure relates to the effects of current which flows in the path left hand to feet and for upward current. For other current paths the heart current factor has to be considered.		

Figure 5: Table 13 - Time/Current Zones for DC for Hand-to-Feet Pathway (Summary of Zones of Figure 22)

[3] (International Electrotechnical Commission, 2005-07).
[4] (NZ Government, 01 March 2010).

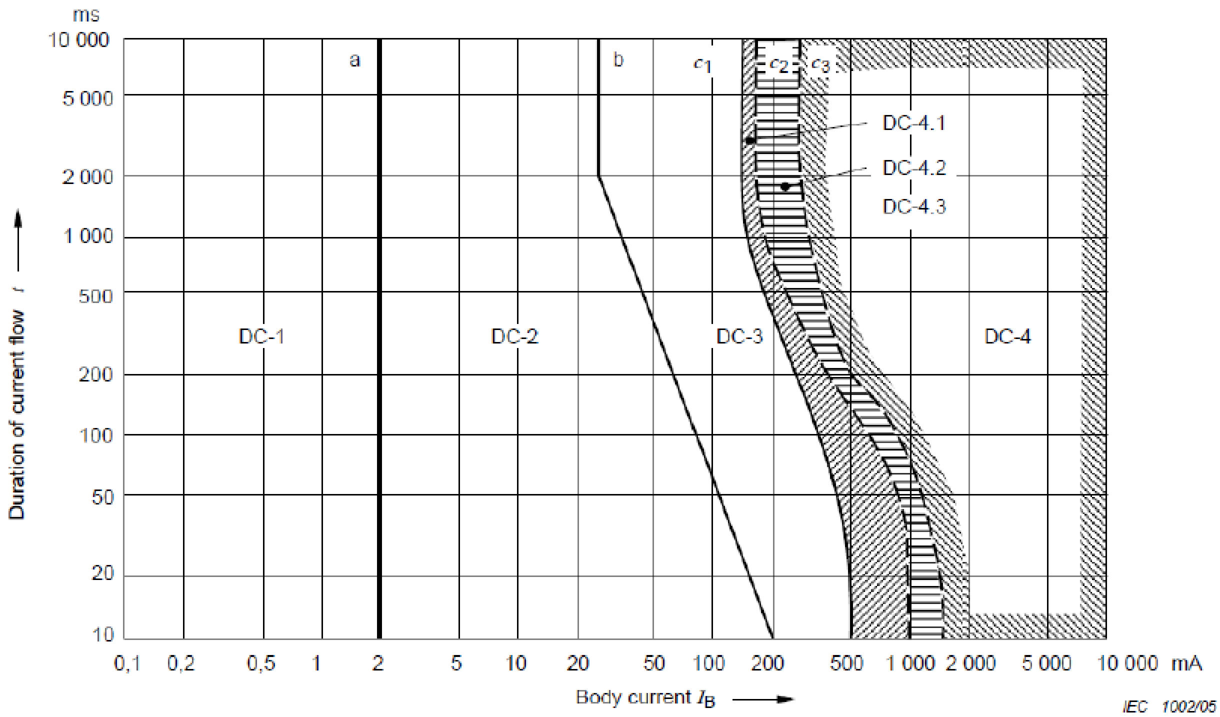

Figure 6: Figure 22 – Conventional Time/Current Zones of Effects of DC Currents on Persons for a Longitudinal Upward Current Path (refer to Table 13)

The ideal scenario is to completely eliminate the potential for electric shock. However, in the event that this cannot be achieved, the aim must be to keep people in zone DC-3 or below (DC current is painful but doesn't prevent movement so people have the opportunity to break free). From the shape of the zone DC-3 there is a greater risk if the person is carrying current for a longer time. This is significant because:

(a) DC current allows people more opportunity to move their limbs and body than with AC current (as per clause 6.2 of the standard), and
(b) We can consider a two stage protection, faster when the current is high and slower for low current. This could reduce the risk of unwanted earth fault protection tripping on stormy or very wet days.

A person in contact with two live wires is rare due to the system design and the type of incidents that cause wire tear downs. Typically with two fallen wires a short circuit occurs between the positive and negative. This is fortunate because a person in contact with both positive and negative wires might not be detected by any form of protection (if the person is reasonably insulated from earth) and could readily receive a fatal shock if they are unable to pull away from touching the contact wires. There is little that can be done about this low probability scenario so our focus below is on the normal case of a person in contact with a single wire.

Safety of a Fallen Wire on an Uncracked Road Surface

Tests undertaken in Wellington during prototype development have shown that the earth fault current flowing in a single live contact wire lying on an uncracked road surface (either wet or dry, but not deeply cracked) will be too small to detect by practical earth fault protection. The current may be 15 to 50 mA if the roadway is wet and much less if the roadway is dry (the measurement was less than 1 mA on a dry roadway). This non-fatal current is not detectable in a practical system because it is well less than the insulator leakage current.

Safety of a Fallen Wire on a Cracked or Excavated Road Surface

A cracked surface will provide direct paths from the top of the roadway into the earth below especially when the road has been soaked with a long period of rain or salt water. These conditions will greatly increase the earth fault current. From a human safety point of view the aim is to:

(a) Choose a *pickup setting*[5] that detects any earth fault current that could be fatal, and
(b) Choose a *delay setting*[6] that disconnects potentially fatal current within zone DC-3 or DC-2 (see Table 13 and Figure 22).

A distinction must be made between *upward* and *downward* current as Figure 22 from IEC 60479-1 is plotted for upward current. This is not the case for the network since the WELL supply has the negative connected to earth therefore the live contact wire is the positive wire and the earth fault current is downward through the body. For longitudinal downward current (feet negative), the curves have to be shifted to a higher current magnitude by a factor of approximately 2. Adjusting the curves as described, the c1 curve is at 300mA (and higher for short duration faults), and this is the intended threshold for earth fault current for use within the CBD. In the suburban routes such a setting will not be possible due to the longer length of the sections (more and older insulators = more earth leakage on stormy days).

In summary, there is more risk for persons on cracked pavements (especially in the wet) or in excavations immediately adjacent to a broken live contact, principally if they touch the wire unless:

- The person can remove themselves from the live wire, **OR**
- There is fast and sensitive earth fault protection (for example, in zone DC-3).

[5] Pickup setting - the point at which the earth fault current becomes detectable.
[6] Delay setting – this is the time delay normally used with this type of earth fault protection to avoid unwanted tripping for momentary occurrences.

Protection Cabinet Design

The TBOP cabinet has the following main **components**:

- Berm- mounted polyester cabinet
- Incoming DC circuit breaker: rated to interrupt current in the range 200A to 40kA
- Outgoing DC line contactor(s): rated to interrupt current in the range 0A to 4kA
- Line test contactor and 500Ω resistor to test line (voltages each side of resistor) before closing and auto-reclosing
- Multi-function protective relay(s) designed for DC traction systems.
- Transducers for line current and voltage measurements
- Differential (residual) current transducer for earth fault measurement.
- Remote earth reference and Transducer for frame voltage protection.
- Equipment for local, control, testing, indication, isolation & lockout for safe working
- 48V battery, 550V sourced charger, MCBs and regulated power supplies
- Filtered ventilation and heating equipment, thermostats etc.
- Real Time Automation Controller for local control + future SCADA & Intertrip
- PC+3G Modem to log oscillograms, Sequence of Event data and for interim control

Figure 7: Prototype TBOP Cabinet

The TBOP cabinet has the following main **functions**:

- To detect short circuit faults and earth faults in the WCCL network and respond with a Trip => Wait => Line-test => Auto-reclose sequence.
- To detect loss of supply from the WELL network and respond with an Open => Wait => Sense return of supply => Line-test => Auto-restore sequence.
- To interrupt load and fault current using the most appropriate device with interlocking to prevent the CB from interrupting small load currents and the contactor from interrupting fault current above 3.5kA.
- To "Major-Lock" for operation of CBFail or ContactorFail protection and from Frame Volts protection; this enforces an on-site inspection prior to resetting.
- To extract and save oscillograms in COMTRADE format and SOE records in auto-named files for performance analysis and trouble shooting.
- To manage the 48V battery by sequenced shutdown and restoration in the absence of incoming 550V supply.
- To remove ozone, regulate temperature and avoid condensation via fans and heater.

Faults in the overhead network are detected by the following **protection elements/functions**:

- **1Ig>** (Earth fault) is set at 320mA and trips the line contactor only. Setting range is 80mA to 8A, from earlier trials we expect that a setting of 320mA is only possible in shorter sections that have modern insulators.
- **1I> (Hi-Set Overcurrent)** is set at 3.5kA/10msec and trips the CB first followed by the line contactor. These short circuits would be less than 100m or so from TBOP.
- **3I>** (Overcurrent) is set at 1.6kA and trips the line contactor only. This has the same approximate sensitivity as the WELL protection. 3I> is blocked by 1I> to ensure the contactor doesn't attempt to interrupt faults above 3.5kA (it is rated 4kA).
- **2I>/1dI** (Overcurrent enabled by 1dI current step window) is set at 800A and trips the line contactor only. The **1dI** current step element has di/dt triggers in combination with a complex set of time delays to define the current steps. In combination with correctly placed cross bonds **2I>/1dI** has the sensitivity to detect broken wire short circuit faults.

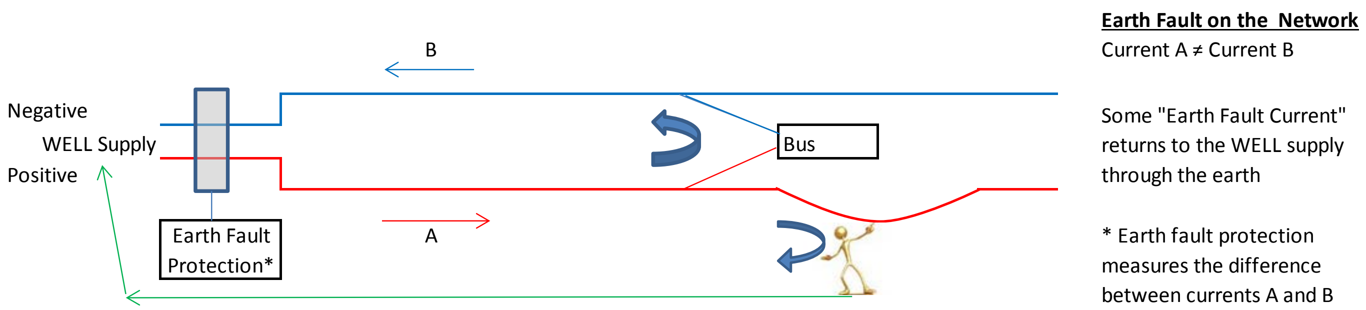

Figure 8: Operating Principle of EF Protection 1Ig>

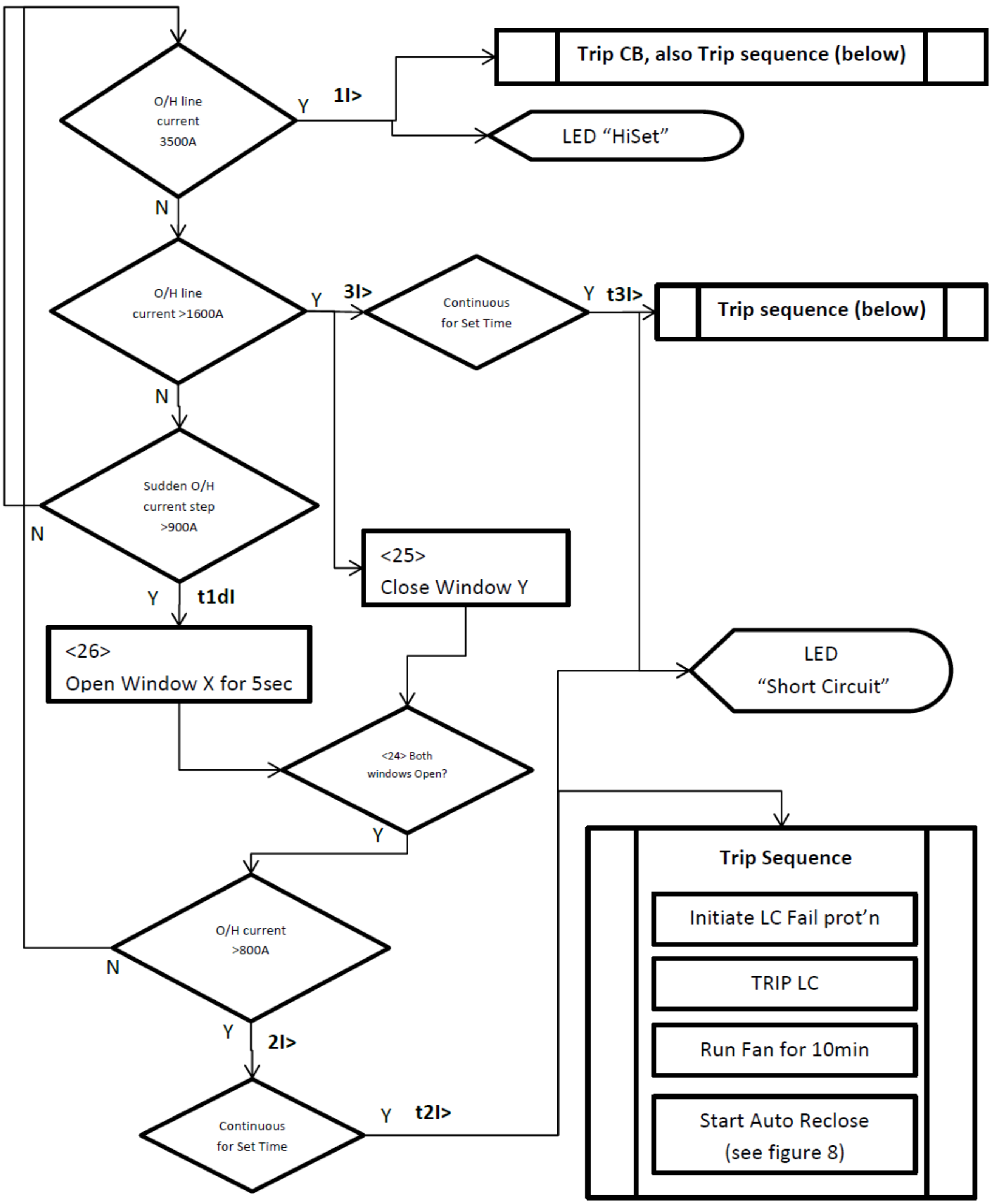

Figure 9: Flow Diagram of Short Circuit Protections 1I>, 3I> and 2I>/1dI

Installation and Prototype Performance

The prototype TBOP has been in service since mid-March 2014 at position M64, a location chosen for its very busy intersection with many "special works" (Switches and Merges) because it is these components that generate the troublesome transients as the buses pass through.

Figure 10: Prototype TBOP Cabinet in Anti-Tagging Camouflage

This brief period has included two major storms and generated a number of related trippings plus a wealth of disturbance/event records. Overall the TBOP has performed well and is building our understanding of the interactions between buses, WCCL overhead network and the WELL supply network.

- There have been brief earth fault protection pick-ups (< 100msec duration) as buses move across section insulators, but only one earth fault tripping and it was followed by successful auto-reclose.
- There have been many bus transients (≈ 20msec duration) as buses move across "special works" the maximum observed so far is 1,100 Amps.
- The performance to date suggests that 3I> will not operate for bus transients and time delays of 1Ig>, 2I>, 3I> can be reduced for faster more reliable protection.

- As expected it has not been possible to grade (discriminate) with upstream WELL protection because their short circuit protection doesn't have a time delay feature.
- WELL protection although old is observed to be very fast, a further blow to discrimination.
- Several short circuit trippings have been followed by persistent low voltage in the WELL supply that has blocked the line-test process (see Figure 10 below). We are working to understand the reasons for this.

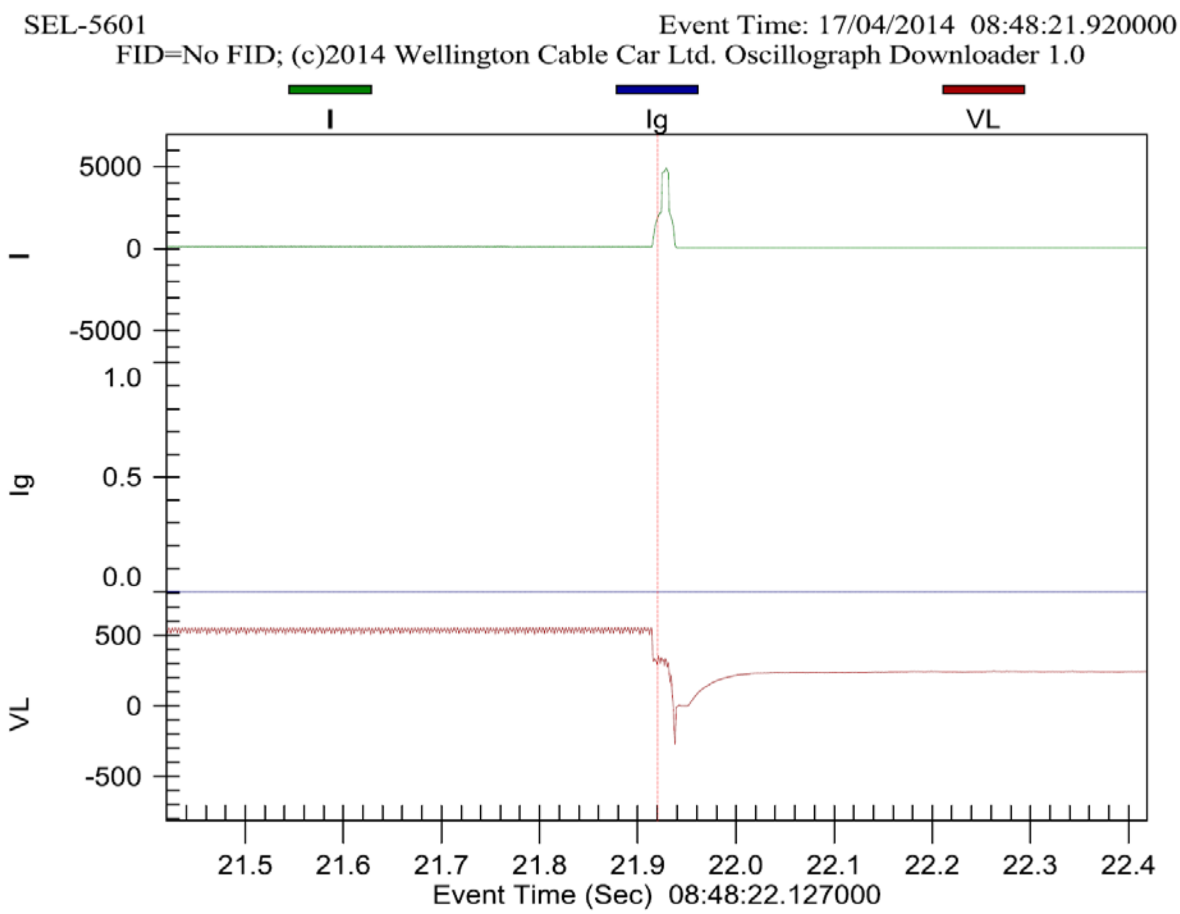

Figure 11: Example Oscillogram of a Short Circuit Fault

Cross Bonds

Cross bonds are an essential component of the TBOP initiative, they make it possible to detect broken wire short circuits (see below) and also improve bus performance.

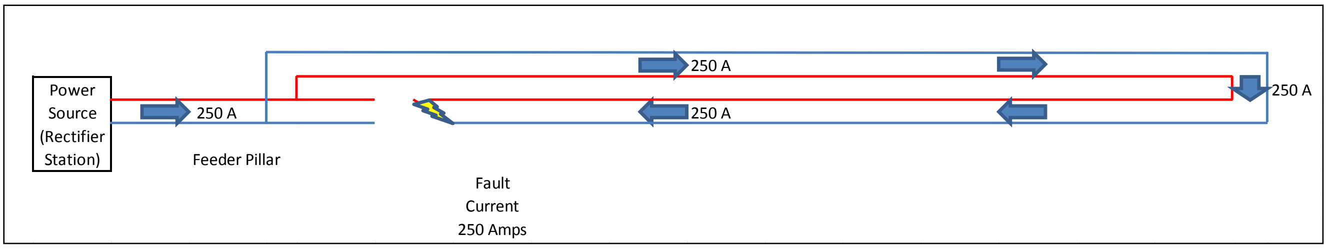

Figure 12: Worst-Case Broken Wire Short Circuit (without Cross Bonds)

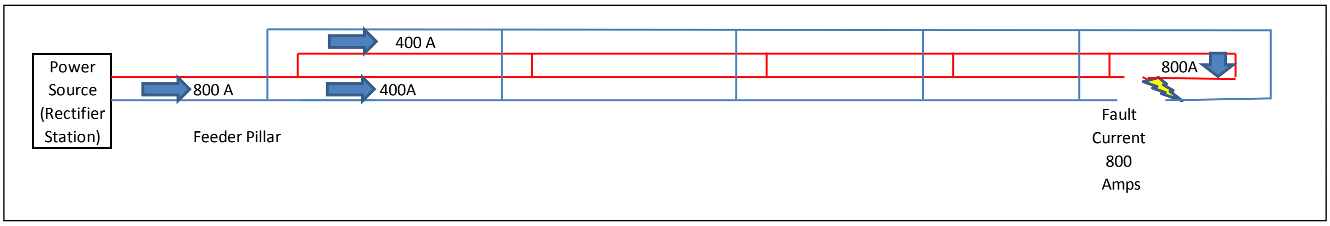

Figure 13: Cross Bonds Increase Worst Case Short Circuit from 250 to 800 Amps

Summary

To meet the challenges of the physical, organisational and regulatory environment a berm-side protection concept has been developed and embodied in a prototype TBOP cabinet that has been in service since mid-March 2014. Performance to date suggests that the TBOP project technical and operational objectives can be achieved by a combination of TBOP cabinets and cross bonds. It will not be possible for TBOP to clear all faults before upstream protection unless this is also upgraded, but adjustments of TBOP settings will be trialled to improve discrimination and therefore the number of successful auto-recloses.

This project is viewed as a good example of innovative design combined with a high degree of expert knowledge in a field where the overall skill base and availability of electric components is rare (Wellington's Trolley Bus 550V DC overhead electrical network is the only one in the southern hemisphere). The prototype performance thus far indicates that the design (with some minor changes to facilitate batch manufacture methods) is suitable for wider implementation across the network. This significantly reduces WCCL and GWRC's risk exposure and is seen as a role model for effective asset management and risk mitigation.

Bibliography

British Standards Institution. (31 January 2010). Railway applications - Fixed installations - Electric traction overhead contact lines. *BS EN 50119:2009*.

International Electrotechnical Commission. (2005-07). Effects of current on human beings and livestock – Part 1: General aspects. *IEC/TS 60479-1*, Edition 4.0.

NZ Government. (01 March 2010). *Electricity (Safety) Regulations 2010*. Retrieved 21 April 2014, from http://www.legislation.govt.nz/regulation/public/2010/0036/25.0/whole.html?search=qs_act_resource_resel#DLM2763624