COORDINATION OF POWER AND METAL PIPELINES USING RISK BASED SAFETY PRINCIPLES

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ABSTRACT

Electrical power lines and substations impress continuous and transient voltages and currents on adjacent or parallel metal pipelines during normal operation of the power system and also during earth fault events. The impressed pipeline voltages present a potential risk of damage to the pipelines and dangerous electric shock to people in contact with the pipeline metal.

Power line towers and substation fences/enclosures are subject to dangerous touch voltages during fault events. The electrical power industry has developed a risk based approach to managing the safety risk to people in contact with such metalwork. It considers the likelihood of a person being present in the hazard zone at the same time as the fault event. This calculated likelihood is used to determine whether mitigation is required to eliminate the risk or reduce it to as low as reasonably practicable.

The requirements for managing the safety risk to people in contact with metallic pipelines is specified in AS/NZS4853, which adopted the electrical power industry's risk based approach to managing touch voltage risk in 2012. This revised approach to safety risk assessment and mitigation has now been applied to extensive buried metal pipeline networks in New Zealand.

The buried pipeline networks are generally well insulated from ground, electrically continuous along their length and unearthed as this facilitates the application of effective impressed current cathodic protection. These characteristics have however made it necessary to consider a large portion of the pipeline network when assessing the impact of changes to only small portions of the power system and complicate the coordination requirements between the electrical power and pipeline utilities.

This paper describes how risk based safety principles have been implemented on metal pipeline networks in New Zealand and what data needs to be transferred between pipeline and power utilities to facilitate effective coordination.

KEYWORDS

Safety, Earth Potential Rise, Low Frequency Induction

PRESENTER PROFILE

Rodney has a PhD in electrical engineering. He has more than fourteen years' experience as a consultant in addition to seven years research experience. Rodney has been involved in metal pipeline, power line and substation installation and upgrade projects throughout New Zealand, Australia, Asia and North America.

1 INTRODUCTION

Electrical power is reticulated throughout New Zealand via networks of transmission and distribution lines, underground cables and substations.

If the aerial lines and underground cables parallel buried metal pipelines for some distance, continuous load and transient earth fault currents along the lines will induce voltages and currents in the pipelines by the mechanism of magnetic field induction. This is referred to as Low Frequency Induction (LFI) and the peak value of impressed pipeline voltage and current depends on the parallel length, separation of the power line and pipeline and the magnitude of the power line currents.

During continuous operation of the power lines, the currents in each of the three phase conductors are 120° out of phase such that the magnetic fields associated with adjacent conductors almost exactly cancel each other out, resulting in a small net magnetic flux density at the pipeline which induces a small continuous voltage on the pipeline.

Line-to-earth faults on power lines result in a large current in the faulted phase only. There is no significant magnetic field cancellation from the other phase conductors and the impressed pipeline voltages and currents are larger than those of the continuous case. Circulating currents induced in overhead earth wires and cable screens cause magnetic field cancellation and thereby reduce the impressed pipeline voltages and currents.

An earth fault to a conductive power line pole or at a substation will cause earth fault current to return to the supply transformer via the local earth grid and remote earth. This causes an increase in the voltage of the ground, called an Earth Potential Rise (EPR), which decreases with distance from the pole or substation earth grid. An insulated metal pipeline entering the EPR zone will transfer a remote earth reference voltage into the zone, thereby creating a voltage stress across the pipeline insulation and presenting a touch voltage hazard to people in contact with the pipeline metal. This hazard also affects metal pipelines not parallel to power lines.

Photograph 1: Examples of melted Cathodic Protection (CP) cable insulation caused by LFI and pipeline telemetry equipment damaged by a power line EPR

Metal pipelines buried in soil are subject to corrosion. Protective coatings are applied to their outer surfaces to insulate them from the soil and they are made electrically continuous along their length so that impressed current cathodic protection can be applied. The combination of isolation from ground and electrical continuity along their length makes buried metal pipelines particularly susceptible to LFI and EPR hazards.

2 POWER INDUSTRY RISK BASED HAZARD ASSESSMENT

Metal power line towers, concrete poles and the metal fences/enclosures that surround substations are subject to a voltage rise during an earth fault at the tower, pole or substation. A person in contact with the earthed metalwork will experience a voltage difference between their hand and feet (i.e. a touch voltage) that will cause electrical current to flow through their body from hand to feet. Also, a person standing near the faulted tower, pole or substation with feet at different distances from its earthing system will experience a voltage difference between their feet (i.e. a step voltage) that will cause electrical current to flow through their feet and legs. In both electrical shock scenarios, a portion of the body current will flow through the person's heart region, potentially causing ventricular fibrillation, which can be fatal.

Section 61A of the New Zealand Electricity Act 1992 requires electrical power utilities to implement and maintain a safety management system in accordance with the Electricity (Safety) Regulations 2010. The safety management system must require all practical steps be taken to prevent equipment from presenting a significant risk of serious harm to persons. "Significant risk" is interpreted by the New Zealand power industry as being a level of risk that a reasonable person would consider to be unacceptable.

Power utilities are able to confine the bulk of their non-line assets and equipment, such as transformers, circuit breakers, isolators, converters, capacitors, etc. inside fenced-off, monitored substations. They therefore pose low risk of serious harm because members of the public do not have access to the substations and maintenance staff and operators are adequately trained and equipped with electrical safety gear.

Power line towers, poles and distribution kiosk substations are however generally accessible to the public. They therefore pose a more serious risk of harm to the public. The risk of serious harm is calculated by taking into account the frequency of earth faults (F_f) at an installation and the likelihood that people will be in the installation's hazard zone, known as the exposure frequency (E_f). By assuming that these two random variables are statistically independent, the probability of fatality (P) of an individual is equal to their product:

$P = E_f \times F_f$ (1)

Where:

E_f = (Total duration of exposure per year in hours) / (number of hours in a year) (2)

F_f = Average number of hazardous EPR and LFI events per year (3)

Based on the annualised risk of someone being present in the hazard zone during and earth fault event, it can be determined whether any treatment should be applied to reduce the risk. Remedial action is then taken to reduce the risk until the residual risk to people ceases to be significant, i.e. it becomes acceptable to a reasonable person. The risk assessment criteria adopted by the New Zealand power industry is summarised in Table 1.

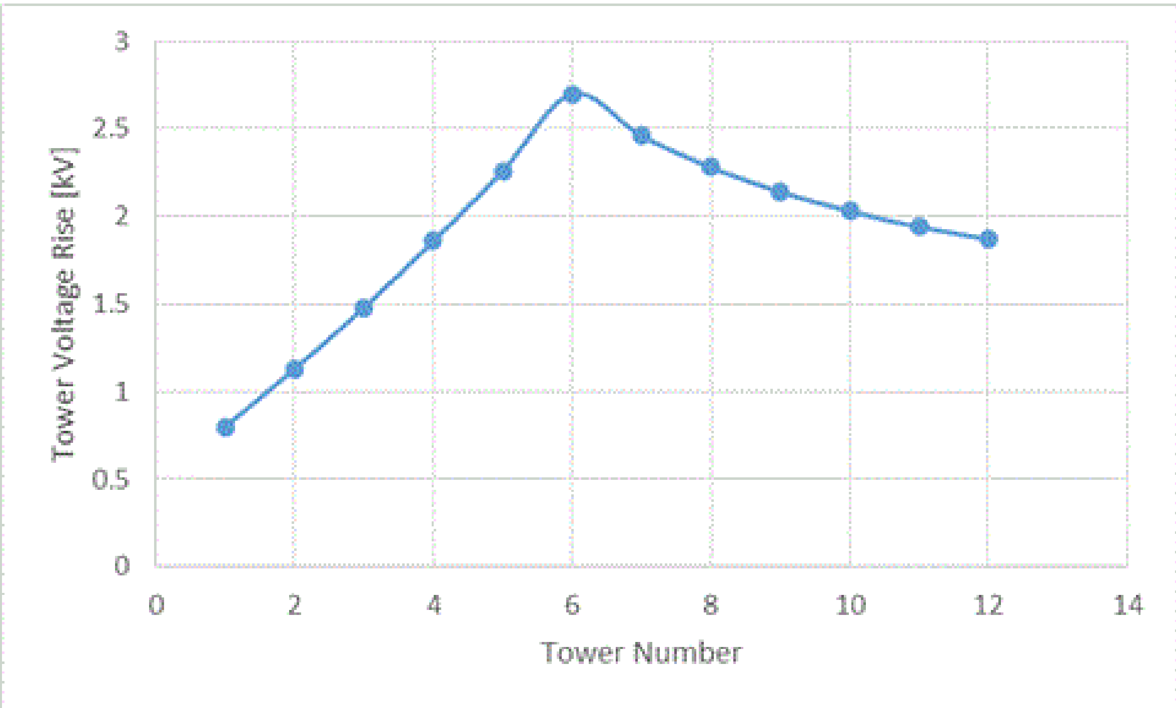
Table 1: Summary of risk assessment criteria adopted by the New Zealand power industry

Probability of fatality (per annum)	Risk classification for individual death	Requirement for hazard mitigation
> 10^{-4}	High	Risk is intolerable. Must prevent occurrence regardless of cost
10^{-4} – 10^{-6}	Intermediate	Risk is ALARP. Must minimise occurrence unless risk reduction is impractical and costs are grossly disproportionate to safety gained
< 10^{-6}	Low	Risk is low. Minimise occurrence if reasonably practical and cost of reduction is reasonable given project costs

The application of electrical hazard assessments in the New Zealand power industry generally only considers the risk to the public at a specific tower, pole or substation during a worst case earth fault at that installation. Risk to maintenance and operations staff is managed by Personal Protective Equipment (PPE) and safety procedures. Also, the risk to the public at the installation as a result of an earth fault at another installation connected to it electrically by overhead earth wires or buried earth cables is not generally considered. Similarly, the risk to the public at the installation as a result of an earth fault at another installation by the mechanism of LFI is also not generally considered.

The calculated voltage rise at towers bonded to an overhead earth wire is plotted in Figure 1 for an earth fault at a tower near the middle of the line. LFI and transfer EPR along the earth wire creates a voltage rise and therefore risk to the public at all structures along the full length of the line. Not just at the faulted tower.

Figure 1: Calculated voltage rise along an overhead earth wire during an earth fault near the middle of the line



Photograph 2: A power line tower located adjacent to a gardening shed is connected to other towers via an overhead earth wire that is also parallel to another power line

If, for example, we were considering the risk to people accessing a gardening shed that is adjacent to a transmission line structure, as pictured in Photograph 2, the calculated risk would be the likelihood someone is standing near the tower during a dangerous earth fault scenario. To determine this, we would need to calculate the voltage rise at that tower for an earth fault at every tower along that line and also for every tower along the parallel transmission line. Every fault scenario that creates a risk of fatality to the person accessing the shed would contribute to the fault frequency used to calculate the annualised probability of fatality to the individual.

The reason why the New Zealand power industry has generally not done this in the past is because most of the power lines do not have earth wires along their full length. Partial earth wires that are attached to sections of the lines are generally high resistance steel earth wires that do not transfer much voltage to adjacent towers (this is however not always the case as is evident in Figure 1).

For underground cable installations with cable screen continuity connections between installations, the regular earthing of the installations reduces the total voltage rise along the circuits for all earth fault scenarios within the supply network. EPR hazards that require risk assessment are therefore generally confined to pole top transformer installations that supply small, localised earthing networks.

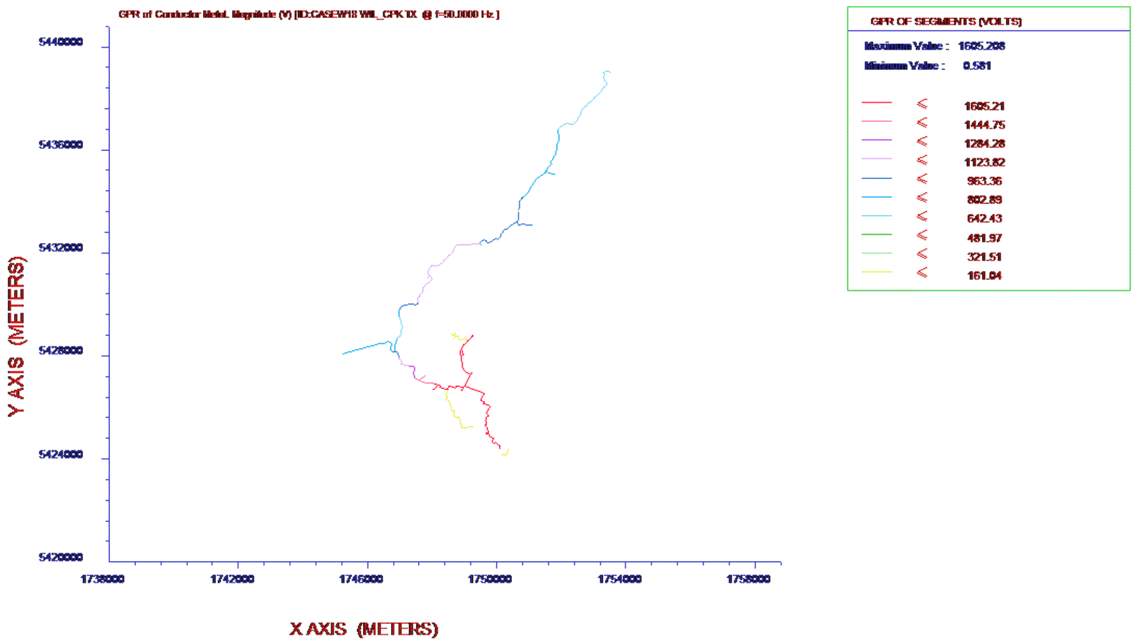
The ENA EG-0 approach used in Australia, where aluminium earth wires are more common, for assessing electrical hazards at power line structures considers an increased fault frequency to account for LFI and transfer EPR along earth wires that connect adjacent towers for up to 2 km along a transmission line.

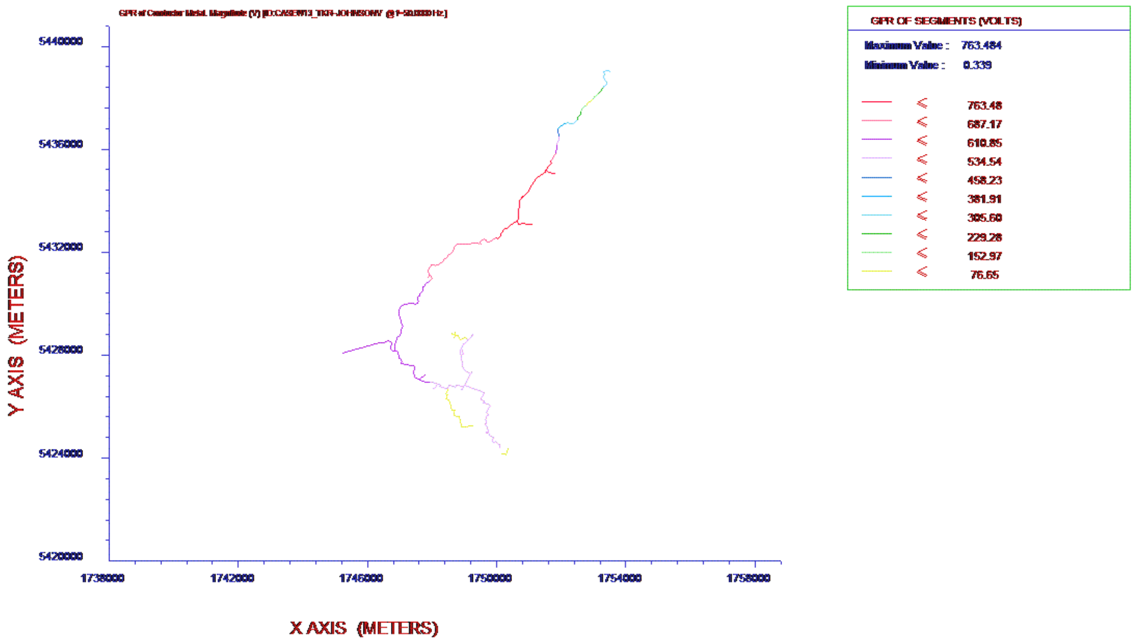
3 PIPELINE INDUSTRY RISK BASED HAZARD ASSESSMENT

Continuous load currents and transient earth fault currents on electrical power lines and at substations impress voltages and currents on metal pipelines. These pipelines are generally electrically continuous along their entire length and insulated from earth with a durable high-resistance coating to protect the pipeline from corrosion. This results in significant impressed pipeline voltages and currents along large parts of the pipeline networks for earth fault at various substation locations and also for all power lines that are adjacent or parallel to it.

An example is presented in Figure 2 of the detailed calculations that were performed in CDEGS for a continuous length of buried metal pipeline for worst case earth faults along two power lines that parallel the pipeline.

Figure 2: Calculated impressed voltages on the same pipeline for two power lines supplied by different substations more than 20 km apart





Top View of GPR of Segments (Volts)

In total, more than 30 transmission and distribution circuits were analysed to assess the touch voltage risk to maintenance staff that frequently accesses the extensive, continuous pipeline network. It is also evident in the plots that the impressed voltages vary along the length of the pipeline for each fault scenario such that staff working on certain parts of the pipeline network are subject to different touch voltage risks from the different circuits, depending on where they are working on the network and what job they were doing (e.g. the duration of contact with the pipeline is very short for a CP test and very long for a valve operation).

If, for example, we were assessing the risk to maintenance staff for a job involving an annual CP test at a test point along the pipeline, we would need to consider the duration of contact with the pipeline during the test and also the fault frequency of every fault scenario that impresses a dangerous voltage on the pipeline. That calculated risk does not however constitute the total risk of dangerous electric shock to the maintenance person, because that person may do another 200 CP tests at other locations along the same pipeline during one year.

Since a fault on a particular circuit impresses a dangerous voltage along a section of the pipeline that includes a number of test points and the single CP technician cannot be in two places at the same time, the likelihood of the fault event and the presence of the person in the hazard zone are not statistically independent for each job, as was assumed in Equation (1). The risk for a particular job must therefore consider the test person's work schedule and the annualised risk to the test person must consider all jobs during the year. This results in a complex risk calculation for assessing the risk to pipeline maintenance staff when the power utility installs a new power pole or substation near a specific test point or valve on the pipeline network. A simple risk assessment of the EPR or LFI at the closest test point alone will not suffice. The calculated risk at that test point must be fed back into the overall risk calculation to determine how the change to the power system affects the risk to people working on the entire network.

Figure 3: Standard job audit sheet used to develop the risk calculation tool for a continuous metal pipeline network

Name: ______________________ Position: ______________________

Team: ______________________

Network Region: ______________________ Date: ______________________

Installation / Work task		Shut-off valves			Main line valves (incl. bypass)			Branch valves (incl. bypass)			Air valves			Scour Valves			Pressure Reducing Valves			Flow meters	Pipelines			Telemetry (incl. electrical)	Pumps/motors
		Manhole	Chamber	Pump stations	Manhole	Chamber	Pump stations	Manhole	Chamber	Pump stations	Manhole	Chamber	Pump stations	Manhole	Chamber	Pump stations	Manhole	Chamber	Pump stations		Above ground	Buried	Pump stations		
Valve operation	Tasks/installation/year																								
	Hours/task																								
Valve maintenance	Tasks/installation/year																								
	Hours/task																								
Valve repair	Tasks/installation/year																								
	Hours/task																								
Valve replacement	Tasks/installation/year																								
	Hours/task																								
Flow meter maintenance	Tasks/installation/year																								
	Hours/task																								
Flow meter repair	Tasks/installation/year																								
	Hours/task																								
Flow meter replacement	Tasks/installation/year																								
	Hours/task																								
Leak repair	Tasks/installation/year																								
	Hours/task																								
Coating repair	Tasks/installation/year																								
	Hours/task																								
CP testing	Tasks/installation/year																								
	Hours/task																								
Telemetry maintenance	Tasks/installation/year																								
	Hours/task																								
Pump/motor maintenance	Tasks/installation/year																								
	Hours/task																								
Pump/motor repair	Tasks/installation/year																								
	Hours/task																								
Pump/motor replacement	Tasks/installation/year																								
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4 ELECTRICAL HAZARD MANAGEMENT PLAN

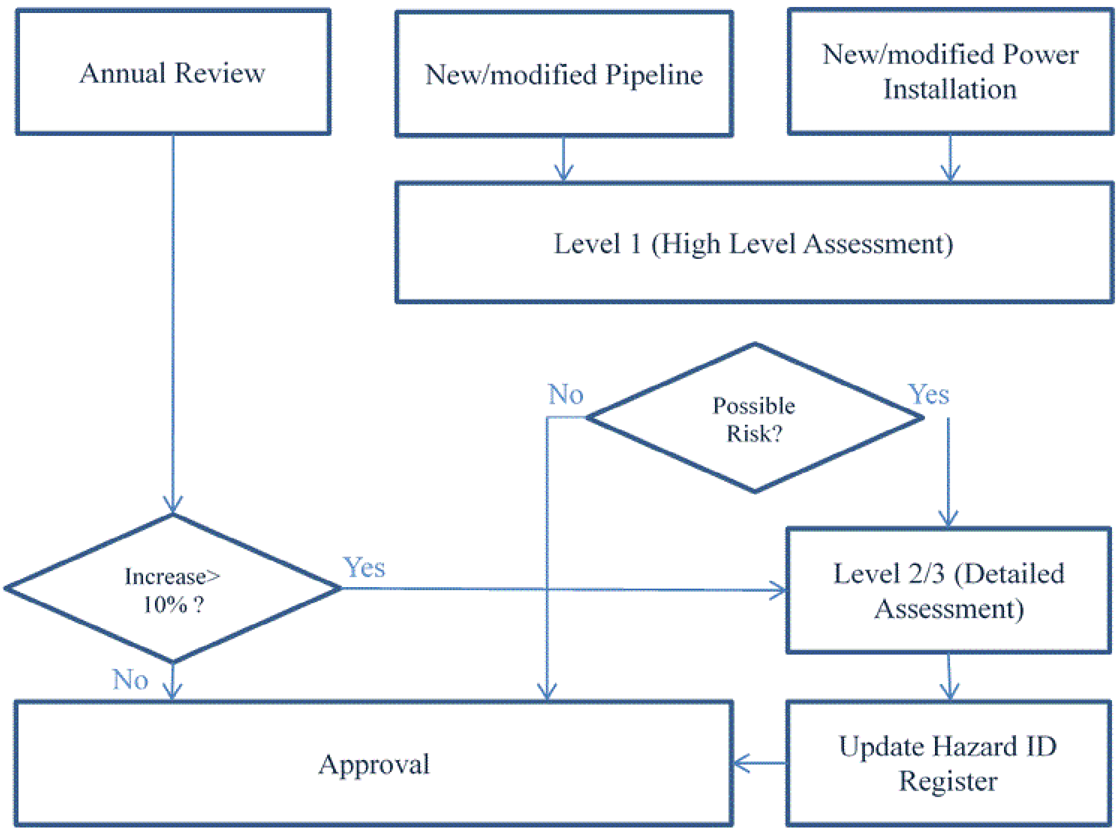
The requirements for the identification, control and risk management of electrical hazards are specified in AS/NZS4853 and are implemented in the form of an Electrical Hazard Management Plan (EHMP) for each pipeline.

The EHMP is implemented as a layer in the pipeline utility's existing GIS system. EPR hazards are defined on this layer as hazard radii surrounding the power pole or substation. LFI hazards are defined as hazards zones along the length of the pipeline.

For each hazard zone defined on or near the pipeline, the data associated with its definition includes details of the pipeline (i.e. depth, construction and insulation), power line (i.e. phase arrangement, conductor type, attachment height, sag, tower/pole earthing), substation earthing system, prospective earth fault current, earth return current and primary earth fault clearing time that were used in the assessment of the hazard. This information is readily transferable to the designer along with the relative positions of the pipeline and power system assets. It is not necessary for the designer to request long lists of specific data that may be contained in various sources and would require effort to retrieve manually.

The EHMP does not only contain hazards that have been assessed as low or intermediate risk (i.e. those with impressed pipeline voltages that exceed the tolerable limits) but also those that have negligible risk (i.e. calculated impressed pipeline voltages that are below the tolerable limits). The hazard management flowchart in Figure 7 indicates that an EHMP review is initiated either every year or by a change to the pipeline or power system. In this way, the risk treatments and controls remain current and appropriate for iterative changes or upgrades to the power system.

Figure 4: Hazard management process flowchart for metal pipeline networks



For each hazard zone defined on or near the pipeline, the data associated with its definition also includes details of the hazard mitigation measures (e.g. pipeline earth electrode maximum design and measured resistances, isolation type and surge diverter rating) and additional risk controls (e.g. minimum PPE requirements). These details are used by maintenance personnel to verify installations as part of their regular maintenance checks. It also forms part of a maintenance team's job safety plan.

At present, the complex risk calculations that require knowledge of maintenance staff work schedules and the risk components associated with each individual LFI and EPR sources are implemented on a spreadsheet calculation tool that is updated manually when either hazards or maintenance and operation schedules are reviewed and revised. It is envisaged that these calculations will in the future also be implemented in the GIS system so that they can be automatically updated when hazards or work schedules change.

When a power utility makes changes to a power line or substation that impact the level of impressed voltage on a nearby or parallel buried pipeline, the change in risk profile is not limited to pipeline maintenance staff working on the pipeline section near the power installation. The change will potentially affect the risk to maintenance and operations staff working on the entire buried pipeline network and requires a review of the entire risk model for that network. This is because, unlike power system assets, the extensive pipeline network is electrically continuous, very well insulated and generally unearthed.

5 CONCLUSIONS

Interference between metal pipelines and power system assets by the mechanisms of LFI and EPR can result in significant impressed pipeline voltages and currents that present a risk of fatal electric shock to pipeline maintenance and operation staff and also a risk of damage to the pipeline and associated equipment.

The 2012 revision of AS/NZS4853: Electrical Hazards on Metallic Pipelines has adopted a risk based approach to managing LFI and EPR risks that is consistent with the power industry. Metal pipelines are however generally electrically continuous for significant distances, very well insulated and unearthed. Earth faults on the power system therefore impact the safety of people in contact with the pipelines over a much greater extent of the network.

Whereas it is possible to assess the risk to people at a particular power system installation by considering worst case earth fault scenarios at that installation only, risk assessments on buried metal pipelines must consider the impact of power system earth faults across the network. This complicates the risk calculations, treatments and ongoing maintenance of risk management on metal pipelines.

It is not sufficient to apply the power system risk management approach to buried metal pipelines. If power utilities intend to install or upgrade assets that can impress dangerous voltages on the pipeline network, they need to coordinate analysis, risk assessment and risk treatment efforts with the pipeline owner. The pipeline utility's GIS-based Electrical Hazard Management Plan for the pipeline network will simplify the transfer of input data for the analysis and will consider the impact of change on the entire pipeline network, not just the portion that is adjacent or parallel to the new or upgraded power system asset. This coordination must be initiated at the start of the project when the Level 1 assessment has identified the potential for dangerous impressed voltages on the pipeline.

REFERENCES

New Zealand Electricity Networks (2009) *Guide to Power System Earthing Practice*, Electricity Engineers' Association (EEA).