‘Stray current is for life – not just for Christmas’

Stray current corrosion management strategies for d.c. traction systems

P.J. Aylott
CAPCIS Ltd, CAPCIS House, 1 Echo Street, Manchester, M1 7DP

The construction of a new light rail or tramway in an urban landscape presents a series of corrosion risks to an often densely-packed buried utility infrastructure. The corrosion risk does not simply go away once the system has been built, commissioned and de-snagged, but continues unseen in the background. Good inspection and testing practices at the start of the railway’s life may reduce the chances of major pipeline and cable failures to a very low level but unless the railway is well-maintained unexpected corrosion failures may start to occur several years later. Whilst such failures may lead to minor (utility) service disruption, more catastrophic failure can also occur with severe consequences.

Good control of stray current is also of direct benefit to the railway; it reduces rail corrosion and reduces infrastructure corrosion. Corrosion costs money - A recent report included a survey of the cost of transit system stray current corrosion to both transit and third-party infrastructure and concluded that the annual cost to the US economy was US$500 million. (Every year the US spends approximately $10 billion because of corrosion and its detrimental effects). Whilst the $500m figure did not provide a breakdown between rail corrosion and utility corrosion, the report did suggest that “the low cost to the (transit system) agencies suggests that the major cost of corrosion attributed to stray current annually is being borne by the neighbouring infrastructure”. Given that corrosion is estimated to cost 3% to 5% of GDP for industrial economies, the annual cost to the UK economy of rail system stray current corrosion could be £80m.

Whilst the phenomenon and consequences of stray current have been understood since the turn of the century, and many of the problems have been contained and reduced by better system design, by changes to pipeline and cable networks and by better corrosion protection schemes the problems are still occurring and will continue to occur for as long as dc rail systems are in use. Stray current cannot be simply ‘designed out’. In the emerging era of ‘polluter pays’ how should railways respond?

What can and should be done to respond to this, and by whom? This paper addresses the corrosion management issues surrounding the addition of a tramway into a previously tram-free environment.

Tramway projects are covered by a variety of design specifications, codes of practice, national and international standards. Within the UK tramway construction has been subject to stray current codes of practice and so far each new scheme has had a unique code developed for it. Codes of practice do more than set out the design parameters for the tramway, they act as an agreed framework around which utility companies can develop a corrosion management strategy and define the level of corrosion risk that the companies agree to accept across their infrastructure. They are a double-edged sword; the codes impose obligations on the tramway contractors and operators and on the utilities. There needs to be a realism on both sides that accepts there are limits to what can be achieved

Corrosion management philosophy

In broad terms, design issues that impact on stray current can be placed into ten categories:

(i) conductivity of the return circuit (i.e. the rails)
(ii) insulation of the return circuit from earth,
(iii) operating voltage between the track and the overhead line,
(iv) insulation of the overhead line,
(v) conductivity of the overhead line,
(vi) spacing of supply substations,
(vii) train current demand,
(viii) regenerative braking,
(ix) substation and system safety earthing,
(x) signalling requirements.
Corrosion management has to start with the initial design of the system where many of the parameters in the above list will be set. Substation spacing, for example, is often constrained by land availability and by a desire to limit the initial costs of a project. Once the land requirements have been identified there is often little scope for radical change.

The overall corrosion management philosophy for the project needs to be defined at an early stage; what is the project balance between minimising stray current by design to control by direct protection of utility services? Wherever the balance is struck – and the appropriate position will depend on the proximity of other d.c. railways and the density of utility services – it needs to be achievable. The design philosophy chosen sets the corrosion risk to the railway infrastructure and to the utilities and later strategies will be based on this.

UK schemes have gone for a “minimise by design” approach, often setting themselves unrealistic goals that could not be achieved. This has particular relevance to two areas: achievement and maintenance of high levels of rail to earth resistance, and limiting criteria for corrosion damage. In a system that aims to minimise stray current, control of the rail to earth resistance is the most important and most variable parameter. (Whilst other design parameters may give a x2 or x4 improvement in stray current, rail to earth resistance can vary have a x1000 impact.)

**Inspection and monitoring for stray current**

The requirements here fall into several categories:

- inspection and testing of tramway construction
- monitoring of utility services
- monitoring of tramway operation
- operation of active corrosion management practices once the tramway is open

The construction performance against critical stray current control parameters should be monitored throughout the course of the construction process. Results should be made available to all parties as they happen in order to build confidence between the Contractor, his Client and Utilities. Engineering managers from the eventual Operator should be involved at an early a stage as possible to allow them time to build up their procedures and system knowledge well before handover.

Contractors should be encouraged to develop stray current models for their systems that predict the likely rail potentials and stray current levels thus allowing the performance of the system to be measured. Whilst power feed studies are carried out, the behaviour of the current return is given less attention except to ensure that the rail potential remains within safe limits.

**Utility monitoring programmes**

Utility monitoring programmes should be designed once the overall philosophy and key stray current design parameters have been set.

Where the design aims to minimise stray current leakage, utility monitoring should adopt a holistic approach and look at the ‘systems’ as a whole. Where it is a design expectation that some utility services will require protective measures, then a more individual or pipe-by-pipe approach should be taken.

For the systems approach, predicting exactly which pipelines and cables will suffer the most stray current is difficult. In practice it is reasonably safe to assume that stray current effects will be measurable on every buried service within a broad corridor around the tramway – most of these effects will be negligible and of no concern. With a reasonably uniform rail insulation across the system, most buried services will show the same interference patterns but with a variable peak amplitude dependent upon service materials.

Data on a number of utility test sites along an 8 km Manchester Metrolink route collected during commissioning in 1992 following the line’s conversion to Metrolink service, shows the same interference patterns at sites over a large geographical area (Figure 1). If the corrosion potential vs. time record is normalised for each site it becomes clear that there is a consistent interference ratio between the sites.
The planning of corrosion management strategies in oilfield systems, for example, is frequently based on the use of corrosion risk matrices. An example of this is shown in Figure 2.

![Figure 2: Corrosion risk matrix from API RP580 — Likelihood category (ordinate) vs. Consequence category (abscissa)](image)

Such schemes can be applied to oil production platforms, process plants etc where the corrosion risk can be categorised (because the internal and external environments are predictable or controllable), and where the failure consequences can be estimated. In the tramway stray current case, the pre-tramway internal and external environments are known and materials chosen to give very long (>60 years) life. Determining the added risk from stray current requires assessment of stray current models of the system and these, necessarily, assume that the as-built tramway is homogeneous. Hidden construction faults, areas of lower rail-to-earth insulation and undetected insulator failure all add random corrosion risks. The likely stray current interactions are then complicated by sharing and passing of current between adjacent services, owned and operated by different companies. Categorising failure consequence in urban areas, where seemingly benign pipeline leaks can cause knock-on failures in other services, is equally difficult. A gas leak into open air may be low risk; the same leak into a confined space such as a cellar or underground car park would be very high risk.

As examples of these phenomena, Figure 3 shows the location of corrosion failures on lead-sheathed telephone cables thought to be due to railway stray current across a small area of north Manchester.

![Figure 3: Corrosion failures on telephone cables in the vicinity of the Manchester to Bury 1200V d.c. rail service 1960 to 1969 — Failure sites are shown in numbered circles. Rail line runs from top left corner through area marked Heaton Park.](image)

The failure locations show a number of clusters close to and up to 1 km distant from the rail line. Whilst it is not known whether all of the failures are directly attributable to railway stray current, supporting interference records support the case.

Given this type of behaviour, together with published evidence from elsewhere, we can develop a monitoring strategy for a new system.

This strategy is based on a number of fundamental principles:
i. It is not possible to monitor every buried facility, across their entire length. Hence monitoring is restricted to a selection of “critical” sites. This implies there is a risk that significant interference is not detected on specific pipelines / cables which are not monitored and/or at locations distant from the monitoring points on pipelines / cables that are monitored.

ii. It is not practical to record data at each monitoring point continuously (without considerable expense). Hence, there is a risk that stray current effects that are variable (for example due to seasonal variations or due to effect of irregular maintenance activities) may not be detected.

iii. The effect of stray current corrosion will vary from facility-to-facility and from industry-to-industry.

Given this, a network of monitoring sites should be developed between all utility companies with a commitment to actively share data between the companies and with the tramway parties. Test sites should be assessed on a collective basis to give an overall stray current health indicator for the system. It should be assumed that if one service is showing high levels of interference in an area then other proximate services will also – hence the tramway design objective to minimise stray current.

By rationalising test sites across utilities the numbers required can be minimised. Tests on a single service are then used as an indicator of likely interference on other local services from all utilities. At some locations a number of different service types are monitored to provide the ratio between effects on different materials, eg. ratio between cast iron pipes, steel pipes and lead-sheathed cables.

Where a new line is a first step in a larger network, thought should be given to locating a small number of test sites remote from the first line but adjacent to a future route. Where cross-interference from a separate rail system is a possibility, test sites should be selected to measure this and allow discrimination between interference from the two systems.

For this strategy to work, the tramway authorities must accept the systems rationale behind it.

Test sites should be constructed in a consistent manner to give reliable and reproducible data from repeated visits over many years. Ideally sites should use permanently buried reference electrodes in close proximity to the target services. The use of multiple electrodes at known spacing to give potential gradient information and allow extrapolation to an IR-free condition should be considered at critical and representative sites. Soil resistivity probes should also be buried at pipeline or cable depth in the vicinity of these sites.

Combined reference electrode and coupon probes should be used on existing cathodic protection schemes and direct measurements made of pipe-to-coupon current.

**Tramway monitoring programmes**

The stray current performance of tramways can be measured using rail to earth potential information collected at regular intervals across the network. Whilst the minimum interval should be substations, measurement points at tramway stops should also be considered. Given that the rail potential varies across the system with changes in tram positions and time, it is necessary for the potential data to be transmitted to a central collection point – such as the control SCADA – in real time. The use of substation and stop measurement points should minimise the additional cost as telemetry systems will already be required at these locations. Analysis of the network raw data for a single instant can show up discontinuities in the rail potential profile and thus help identify stray current leakage points. Calculation and trending of daily variations in peak and rms levels provides condition monitoring information.

Where trackbed reinforcement exists this can be utilised as a stray current monitoring system and also fed back into the SCADA system. This also applies where the reinforcement is deliberately bonded as a stray current collection system.

Where diode-earthing systems are used then the direct measurement of stray current return at substation earth mats can also be incorporated.

The direct inclusion of utility monitoring information into the tramway systems provides a useful feedback on both cause and effect and should be given strong consideration at the design stage. (Figure 4 shows an example of this over a 2 week period).
Monitoring systems should be designed into the tramway system at the start to ensure that the operations staff have the tools necessary to understand and respond to changes in the stray current performance of a system.

Operational stray current management

The utility monitoring schemes should be functioning throughout the tramway construction process and before system commissioning commences. The tramway systems should come on-stream in parallel with the energisation programmes. Data from each programme should be shared across parties and collectively analysed and discussed.

Some caution should be applied to the data at an early stage of tramway commissioning, especially if the system opening is phased. The stray current behaviour of tramways will change with each new track extension and energisation and the data assessment needs to make allowances for this. This changing behaviour can lead to construction faults being masked by the growing system; conversely high levels of stray current interference can be wrongly attributed to faults when they are merely system artefacts.

Data handling

Stray current monitoring generates large volumes of data requiring specialist software systems to store and collate the information. Systems should present information from multiple sites geographically and bring utility and tramway data together.

Data should be measured against design targets (for the tramway) and corrosion criteria.

Corrosion potential criteria should respond to the systems approach and treat both anodic (or positive) and cathodic (or negative) potential changes separately and equally. Whilst the cathodic reactions at the metal surface (Eqn. 1 and 2) do not lead to direct corrosion damage, and do not reverse the anodic dissolution reaction (Eqn. 3), they are balanced by anodic effects elsewhere on the structure.

\begin{align*}
O_2 + 2H_2O + 4e^- &\rightarrow 4OH^- \quad (1) \\
2H^+ + 2e^- &\rightarrow H_2 \quad (2) \\
Fe &\rightarrow Fe^{2+} + 2e^- \quad (3)
\end{align*}

Given our basic premise that it is not possible to measure everywhere, then cathodic changes should have equal weight to anodic as long as neither is used as a sole indicator of corrosion damage. Traditional criteria aim to provide limits for corrosion damage at the monitored location on the service and need modification to support the system management approach.

CAPCIS have developed a criteria that is currently agreed for the Greater Manchester Metrolink and Midland Metro systems and provides for both a systems approach and an individual site assessment10:

(i) The continuous potential change at any part of a secondary structure, resulting from energisation of the railway, should not exceed 20 mV, and

(ii) The potential change at any part of a secondary structure, resulting from operation of the railway, should not exceed 60 mV for greater than 2.5 hours in a day or be greater than 20 mV and less than 60 mV for more than 7 hours in a day.

In addition to applying equal weight to anodic and cathodic changes, these criteria allow for the fluctuating nature of railway stray current and the logarithmic nature of the corrosion reaction’s potential vs. current response. For low potential changes this response is given by the Tafel equation:

\[ \eta_{act} = a + b \log i \quad (4) \]

In equation (4) – which applies to an error-free measurement - the Tafel constants \((a, b)\) relate to the particular metal / environment combination; \(\eta_{act}\) is the activation overpotential or potential shift and \(i\) is the current per unit area of metal surface. For steel in
soils, the main Tafel constant ($b$) is typically 0.060 V (60 mV). This means that if the current density increases by a factor of 10x the potential will increase by 60 mV. The 20 mV and 60 mV values used in the criteria above reflect this behaviour. (The original 20 mV criteria\textsuperscript{11} for cathodic protection stray current has been related to a doubling of corrosion rate\textsuperscript{2}.)

Whilst it is arguable that no explicit criteria should be necessary as long as all parties are willing to discuss issues, they do provide an agreed framework around which discussion can be based.

**The longer term**

If a minimise-by-design approach has been adopted and carried through then it is unlikely that corrosion failures due to stray current will occur within the first couple of years of operation. Following successful commissioning and fault rectification, monitoring systems on both the tramway and utilities should therefore be continued and operated at a lower intensity throughout the life of the tramway to detect degradation in performance long before corrosion failures start to occur.

The primary focus of activity should be on the system operators. They should actively maintain the stray current performance of the system. The condition monitoring information can be used to document the stray current performance and drive the maintenance process. The tramway should be given the tools to detect its own emerging stray current faults from worn rails, damaged rail insulation, etc. before they can cause significant corrosion damage to buried infrastructure.

**Conclusions**

Corrosion management systems and practices have a role to play from the early design discussions about new systems. Where a ‘minimise by design’ approach to stray current control has been taken, corrosion management does not simply stop on successful completion of the system but has an active role throughout its operation life if the corrosion risks to infrastructure are to be avoided.

**References**


[6] Information taken from failure maps collated by the General Post Office and provided to CAPCIS by British Telecommunications plc


