MONITORING AND MITIGATION OF TRAM STRAY CURRENT EFFECTS ON BURIED ASSETS

Dr David Buxton
PhD, MICorr
Intertek Production & Integrity Assurance,
Manchester Technology Centre,
Units 12-15, Longwood Road,
Manchester
M17 1PZ

Abstract

Stray current from DC transit systems is inevitable in all cases and can lead to interference on nearby buried metallic structures and increase the risk of corrosion. Assets at risk include the rails, transit system and third party structures, utility pipelines and cables. To verify that the interference is acceptable (and not detrimental) to the facilities, monitoring of the corrosion potential of the facility can be undertaken, and the results assessed against agreed criteria. To obtain the best results a monitoring strategy should be developed and monitoring performed in a controlled manner.

Examples of monitoring data collected from several UK light rail systems are given, and methods of mitigation discussed. Control of stray current at source is considered the best approach, and to minimise stray current the primary parameter to consider is the rail to earth resistance (conductance per unit length between track and earth).

1 Introduction

Current leakage from DC railway systems is an inevitable consequence when the running rails are used for both the vehicle mechanical support / guideway and for the return circuit of the traction supply system. Current leakage from the rails is commonly referred to as stray current and is defined as *'Part of the current caused by a dc traction system which follows paths other than the return circuit'* [1]. The stray current path may include buried assets in the vicinity of the rail tracks, as illustrated in Figure 1.

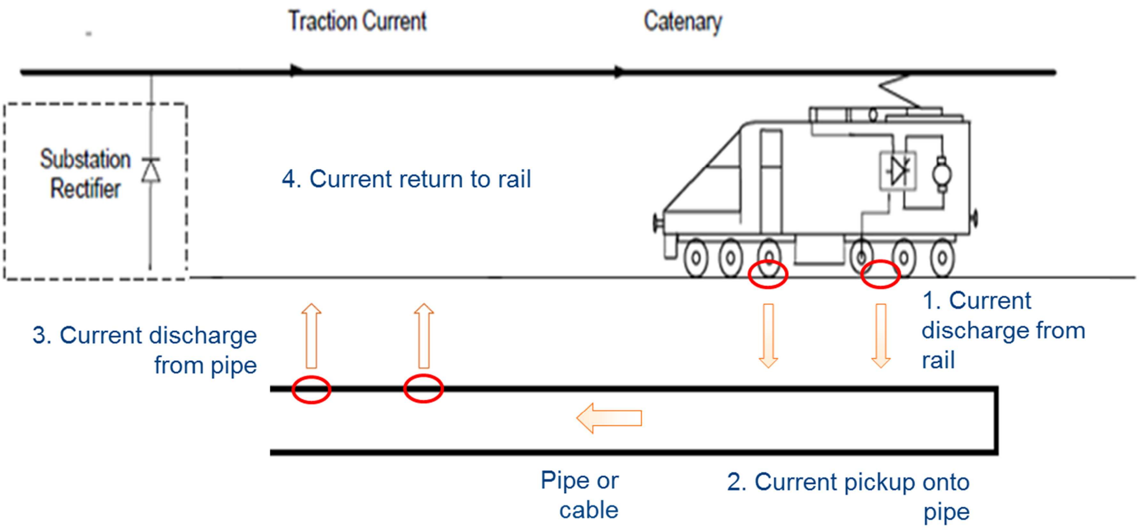

Figure 1 **Schematic showing stray current path**

Where current leaves a metallic item and enters an electrolyte, e.g. the ground, there is an electron to ion transfer; an electrochemical reaction. The reaction is an anodic or oxidation reaction (electron producing) and may involve corrosion:

$$Fe \rightarrow Fe^{2+} + 2e^{-} \qquad \text{Eqn (1)}$$

or alternative anodic reactions:

$$Fe^{2+} \rightarrow Fe^{3+} + e^{-} \qquad \text{Eqn (2)}$$

Where current is picked up onto a metallic item there is a cathodic or reducing reaction (electron consuming). In an oxygenated environment this will typically be:

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-} \qquad \text{Eqn (3)}$$

Alternative cathodic reactions include hydrogen evolution or reduction of water:

$$2H^{+} + 2e^{-} \rightarrow H_2 \qquad \text{Eqn (4)}$$

$$2H_2O + 2e^{-} \rightarrow 2OH^{-} + H_2 \qquad \text{Eqn (5)}$$

For buried assets without cathodic protection (CP), or where CP is applied, but due to environmental conditions high pH passivity is not established, the dominant anodic reaction is likely to be the corrosion reaction resulting in metal loss (Eqn 1). In these situations the amount of metal loss can be assessed using Faraday's electrolysis formula:

$$\Delta m = \frac{M \times Q}{z \times F} \qquad \text{Eqn (6)}$$

Where:

Δm	mass loss (g)
M	atomic weight (56 g mol^{-1} for iron)
Q	charge transferred (C)
z	metal ion valence (2 for iron)
F	Faraday constant, 96485 C mol^{-1}

For iron, if 1 A flows continuously for 1 year and the only anodic reaction is eqn (1) then the metal loss is 9.1 kg.

There is, therefore, a requirement for stray current control to minimize the impact of the stray current on the rail system, supporting infrastructure and third party infrastructure. It should be the responsibility of those designing and building new DC rail systems to ensure that sufficient stray current mitigation measures are incorporated. It is then the system maintainer's and operator's tasks to manage interference during service.

This paper describes the approach used for monitoring stray current, presents several examples of stray current interference from UK DC transit systems and discusses how stray current can be minimised.

2 Stray current monitoring

2.1 Stray current monitoring strategy

Where a new DC system is being installed, or an extension to an existing line developed, the impact of stray current on buried utility services in the vicinity should be considered. A carefully prepared monitoring strategy is fundamental to obtaining reliable results and should include the following [2]:

- **Selection of sites** – it is not practical to monitor every buried asset across their entire length, so a risk assessment process is undertaken to prioritise assets and locations for monitoring. The risk assessment includes:
    - Location of asset in relation to the track
    - Type of structure
    - Track type
- **Data at a frequency of up to 1 Hz, typically over a one week period** - it is not practical to record data continuously on an ongoing basis, at the required frequency to capture the potential fluctuations, without considerable expenditure. However, data can be collected practically & economically using temporary data loggers (as part of a *monitoring campaign*). This allows day-to-day variability arising from changing weather conditions or system operations to be assessed.
- **Collection of data before major construction works** – to establish a baseline or background level (specifically to be able to distinguish any interference from the DC rail system from other possible sources of interference).
- **Repeat monitoring at key times** - during the project further monitoring to capture energisation and tram testing, driver training and passenger service.

Where a DC rail system has a permanent monitoring facility, e.g. rail voltage, the system parameters can be bench marked against the utility corrosion potential data.

2.2 Test sites

Test sites are constructed in a consistent manner to give as far as possible reliable and reproducible data from the repeated monitoring campaigns. Ideally a site includes:

- A permanent buried reference electrode (typically saturated copper sulfate electrode, but other reference electrodes could be used) in close proximity to the utility service to minimise IR.
- A combined reference electrode and coupon probe (when CP is applied) to allow coupon instant OFF measurements to minimise IR.

All the data in this paper is reported with respect to saturated copper sulfate electrode.

The procedure that has been developed and used across numerous DC rail systems in the UK is to assess the data using various criteria such as the so-called *Metrolink Interference Criteria* (MIC) [3], company standards such as National Grid Gas [4] and established National / International standard such as EN 50162 [5]. Because of the very large amounts of data collected at each site, they are normally analysed using in-house software.

For example, the *Metrolink Interference Criteria* (MIC), which was developed for the assessment of data collected when Manchester Metrolink was opened in 1992 [6] uses time-weighted potential calculations based on the 20 mV criteria applied to cathodic protection stray current. A facility is considered to "*fail*" if the dataset exhibits either of the following potential changes in any one day:

- exceeds 60 mV anodic potential shift for 2½ hours or more;
- exceeds 20 mV anode potential shift for 7 hours or more.

The calculations to determine the extent of the transient anodic or cathodic shift are based on a night time, steady unaffected corrosion potential reading (E_{corr}), determined when vehicles are not running on the main line.

Typically, MIC is applied as a *first line assessment*, and if a fail is reported then additional assessment and further measurements are required to determine if there is a risk of corrosion including:

- Measurement of the unaffected potential (E_{corr}) of the structure and assessment taking into account seasonal and historical variations
- Confirmation that the potential recordings indicate interference from the rail network and that there are not additional sources
- Comparison with previous results from the same or adjacent sites, and consideration of exceptional conditions (e.g. heavy rainfall or temporary works)
- Review of the materials the structure is constructed from and the type of structure, including continuity
- Review of corrosion protection measures are applied to the structure - CP, coating type and quality
- IR drop effects on the measured potential
- The degree the MIC levels are exceeded
- Current flow measurements at bonding locations
- Repeat monitoring at sites in the locality
- Potential gradient measurements and 'over-line survey' to locate the area of maximum potential change
- System measurements (e.g. rail voltage) at traction substations and other accessible locations
- Track inspection, lineside equipment checks and rail to earth measurement
- Addition of specific protective measures to an affected structure (only after efforts to locate the source of the stray current leakage and reduce its magnitude have been unsuccessful).

Where coupons are available, the instant OFF potential data is also assessed against criteria for the protective potential range, i.e. more negative than -850 mV (copper sulphate electrode).

3 Case Study Examples

3.1 Case study 1 - Inadvertent bond to rail

Routine monitoring was undertaken at an electricity substation, located approximately 75 m from the tracks of a 750 V tram system. The level of stray current interference was observed to have increased significantly when compared to previous data; the corrosion potential fluctuations had increased from ten's of mV's to almost 1 V. The potential fluctuations were predominantly in the anodic direction, and as no cathodic protection is applied to this network, there was concern over corrosion to the asset in the area.

The substation monitored was typical of the UK electricity network in urban areas, in that there were multiple old hessian wrapped lead sheathed 6.6 kV & 11 kV power cables running into the substation, with straps connecting the lead sheaths to the substation earth (likely to be a mix of copper rods and reinforced concrete slab). The cable lead sheath is around 1 to 1.5 mm thick, and if the sheath integrity is lost, the cable is likely to fail rapidly due to water ingress and a phase to phase fault.

The operator was alerted of a possible issue and a track inspection was undertaken in the area. A bond to a redundant earth system was found to have been connected to the rail. Current returning to the rail was measured for a short duration, and peaks of up to 80 A were recorded. Data loggers were re-installed at the nearby electricity substation, and arrangements were made for the bond to be disconnected several days later. The plots in Figure 2 show the data collected when the loggers were re-installed and include the moment the bond was removed. There was a clear and significant change in the interference level.

Data was collected from two reference electrodes, both located within the small compound, one at the gate further away from the tracks, the other behind the brick substation building, closer to the tracks. The level of interference is different at the two locations, with the higher level of interference at the location closer to the tracks.

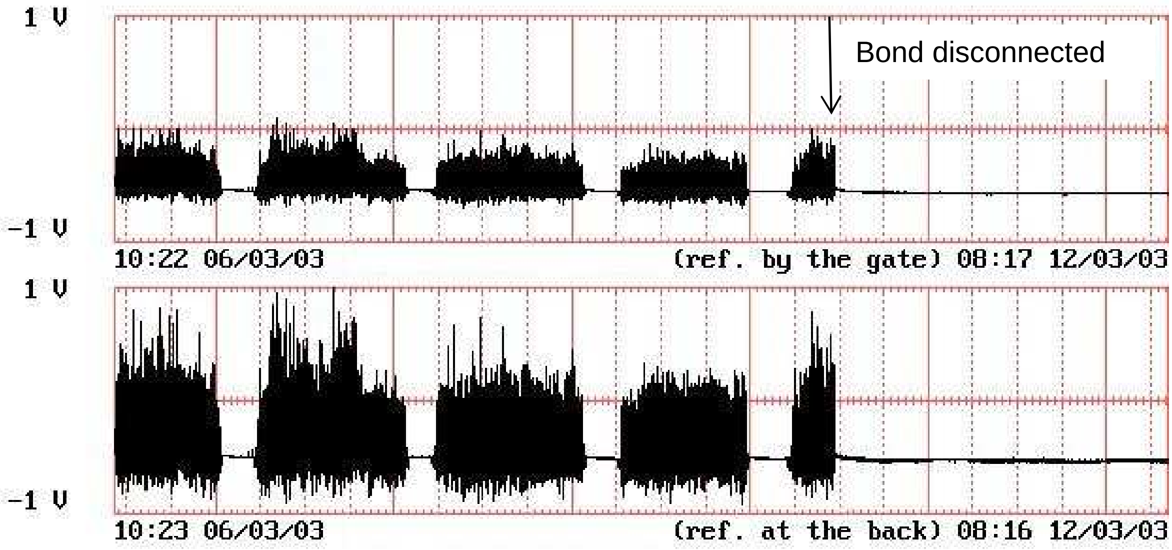

Figure 2 Corrosion potential data at electricity substation

3.2 Case Study 2 - Pipe with cathodic protection

Stray current monitoring has been carried out on a gas pipe network in the UK. Data from two sites on the same 600 mm pipe are discussed. The pipe is protected by an impressed current cathodic protection (ICCP) system with an automatic potential controlled transformer rectifier, close to site 1. The ON pipe corrosion potential data from site 1 is shown in Figure 3 (left plot) whilst the coupon instant OFF results are plotted on the right. The night time ON potential was relatively stable most nights (approximately -1380 mV), when the trams were not running. During the day there were significant potential fluctuations and assessment of the CP level by manual readings at the test post is virtually impossible. The interference level was very high at this site, but the risk of corrosion was considered low as the coupon instant OFF readings indicated good levels of protection. At night the corrosion potential was circa -1045 mV, and although there were a few excursions to potentials more positive than -850 mV they were of short duration. The total time more positive than -850 mV was less than 1%, but it is recognised that in some environmental conditions there is a risk of corrosion, even with minor anodic shifts [7].

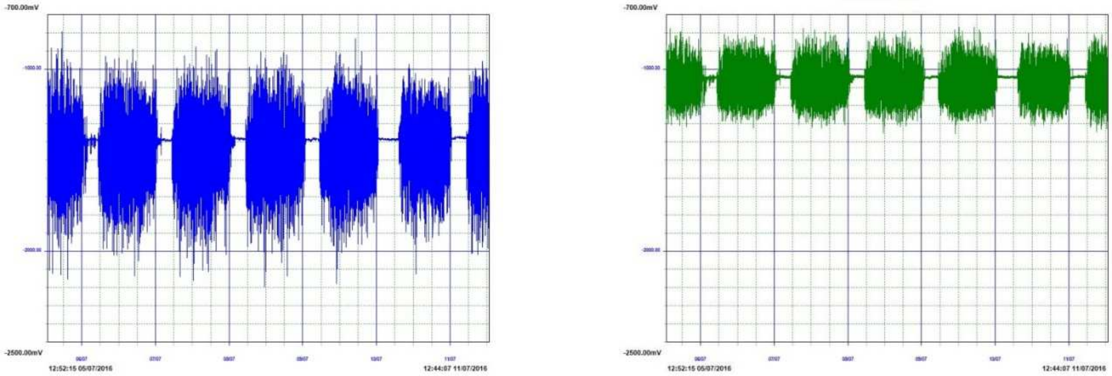

Figure 3 **Site 1 Pipe corrosion potential data**

The data collected on the coupon gave much smaller potential fluctuations which is considered to reflect the reduced level of IR error in the coupon readings. It is recognised that there may some remaining IR as both CP and stray current will still be flowing in the ground around the coupon. The coupon data was collected at a lower frequency compared to the ON potential values (0.2 Hz against 1 Hz) and this could also cause some reduction in the degree of potential fluctuations. The coupon OFF data is measured 200 ms after the coupon is disconnected and reducing this time has been reported to provide more accurate instant OFF readings [8].

Although the TR is potential controlled, a stable potential during the day could not be achieved due to the magnitude of the interference. During periods of cathodic interference the output of the TR reduced to zero and during anodic interference the output increased to the maximum current limit. Typical potential shifts are shown in Figure 4.

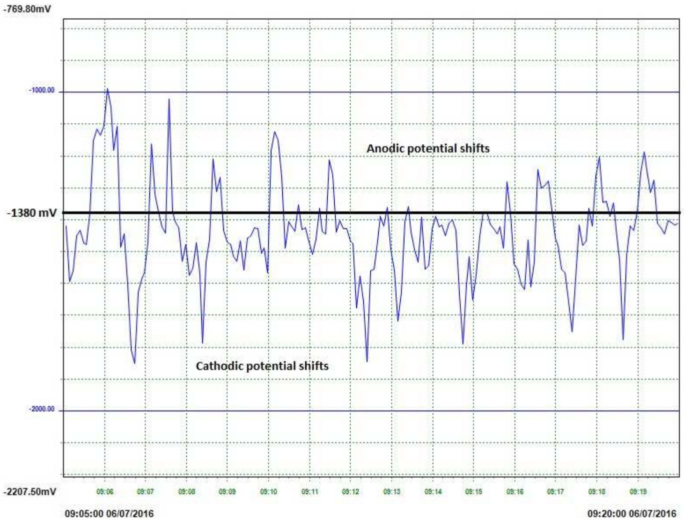

Figure 4 **Site 1 Anodic and cathodic potential shifts**

The TR has a local reference electrode close to site 1, which provides the feedback for automatic control. However, the influence of the TR potential on the pipe some distance away may be different to that at site 1. In Figure 5, data from a second site, around 650 m further along the pipe is shown, alongside Site 1 data for the same short time period. In this location the pipe runs alongside the tracks, however Site 2 is closer to the rails than Site 1. The stray current interference pattern was similar in that anodic peaks occurred at the same time, however the magnitude of the fluctuations was greater at site 2, and therefore an increase in protection levels was recommended.

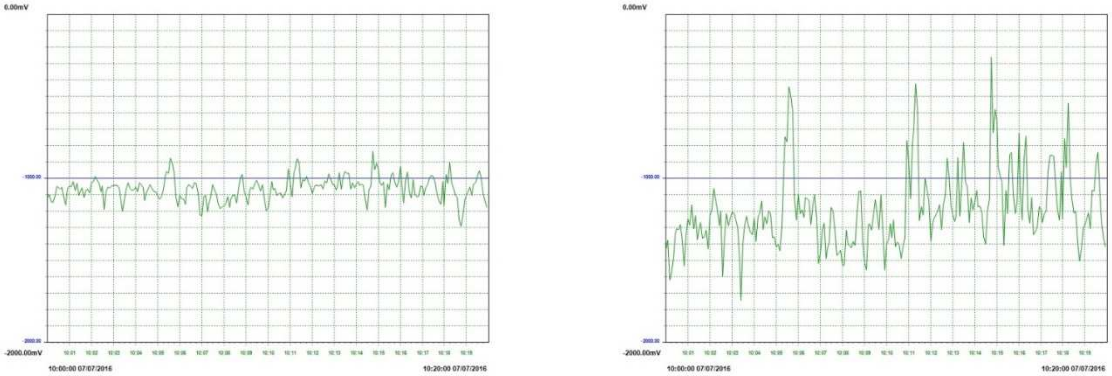

Figure 5 **Results from Site 1 (left) and Site 2 (right)**

The higher fluctuations at Site 2 could be the result of:

- The location of Site 2 being closer to the track than Site 1
- A reduced influence of the auto TR
- Poor track insulation at the Site 2 location increasing interference levels
- The location of Site 2 being closer to a traction substation where the rail potential will tend to be more negative and where stray current will tend to return resulting in higher levels of anodic interference in the area.

In the example above the interference patterns were ‘in-phase’ at both sites, i.e. showed potential shifts in the same direction. However, it is possible that whilst one site exhibits cathodic interference another location may be anodic and then the effectiveness of an automatic TR may be reduced.

4 Stray current mitigation

Where stray current levels are deemed to be unacceptably high, the first course of action is to control the stray at source. Inspection of the rail system should be undertaken to check for:

- Inadvertent bonds or failure of components such as voltage limiting devices that create a path from the rail to earth.
- Breakdown of rail insulation, for embedded sections contact between rail and track slab steel reinforcement bar
- Blocked drainage resulting in prolonged standing water in contact with the rails
- Buildup of leaves, ballast and debris

A stray current collection system is often installed in embedded sections during track construction. The mat sections may be left un-connected with the intention that a cable and bonding is installed as and when needed. Where high levels of interference persist it may be advantageous to utilise the stray current mat. When a stray current collection system is used on a ‘floating’ earth system it should be recognised that the mat may suffer accelerated corrosion where the current returns to the rail and this can be assessed by computer modelling [9]. Direct stray current monitoring of the current flow in the stray current collection system can provide an alternative to rail potential monitoring. There is the possibility that a mat can act to distribute stray current and where known rail insulation fault exists it may be advantageous to isolate the section of mat in the area of the fault.

In cases where it has not been possible to control stray current at source and the interference generated is a real issue, the application of CP to the utility asset or structure is considered a primary means of control. However, if galvanic anodes are used, the risk of additional stray current pickup via the anode should be considered.

As utility pipe and cable networks are being replaced and upgraded, many services are being replaced with plastic or plastic sheathed products. Not only are sections of plastic pipe immune from stray current, the electrical continuity of the network will be broken up, and where this occurs the network becomes a less attractive stray current path.

Unidirectional bonding (diode) of a utility asset to the rail is not favoured and only considered as a last resort, due to the risk of secondary interference. The increase in cathodic interference on the bonded structure will increase the total stray current and increase the risk of anodic interference on nearby structures. An example of modelling results of secondary interference on a steel sewer crossing a gas pipe diode bonded to a rail system is shown in Figure 6. The plot shows the predicted sewer pipeline current that result from a particular rail voltage configuration. A negative pipeline current indicates a flow that is towards the start of the pipeline at chainage 0 m (a positive value is in the opposite direction). The level of current is higher when the diode is connected. Where there is a change in the value of current it indicates current is either entering or leaving the pipe into the surrounding environment. When the diode is connected the negative current flow peaks at around the crossing point and also shows a variable slope, suggesting an uneven rate of current discharge.

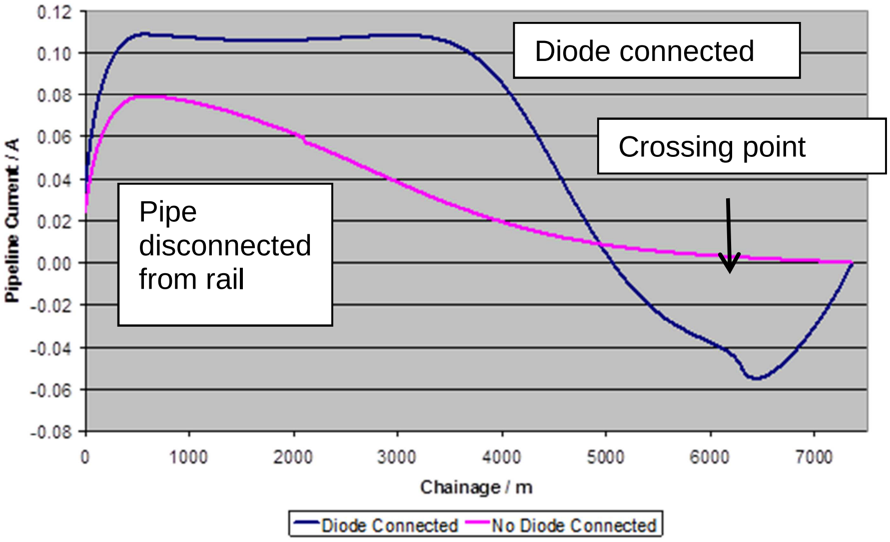

Figure 6 Modelling results showing secondary interference

5 Summary

Stray current monitoring of utility services and structures in the vicinity of DC rail systems allows the corrosion risk to be assessed and the effectiveness of any mitigation measures employed to be verified. Monitoring data requires careful interpretation, with assessment against agreed criteria. As it is not practical for the monitoring to cover entire networks, discrete monitoring points are selected, with permanent facilities, which allow repeated and consistent measurements to be taken with minimal IR errors.

6 References

1. EN 50122-1:2011 *Railway applications — Fixed installations — Electrical safety, earthing and the return circuit - Part 1: Protective provisions against electric shock*

2. P Aylott, '*Stray Current is for Life, not just for Christmas*', IEE Railway Industry Group Seminar DC Traction Stray Current Control, October 1999.

3. The Metrolink Interference Criteria, Greater Manchester Passenger Transport Executive, 1995.

4. National Grid, Management Procedure for The Management Of Stray Current On Buried Metallic Pipelines From Direct Current Transit Systems, T/PM/ECP/3.

5. EN 50162:2004 *Protection against corrosion by stray current from direct current system*.

6. P Aylott, D G John, '*Monitoring Stray Current Interference From Metrolink*', UK Corrosion 1992.

7. M. Büchler, B. Ackland and U. Angst, '*The historic evolution of cathodic protection criteria'*, Paper 9, CEOCOR 2016, Slovenia.

8. I.Magnifico et al , *Instant OFF Measurements on coupon: Practical advantages of a continuous remote monitoring and rectifier remote control based on Eoff, improving effects on cathodic protection efficiency evaluation and maintenance operations*, CEOCOR 2016, Paper 17.

9. C Charalambous et al, *Stray Current Calculation and Monitoring in DC Mass-Transit Systems*, IEEE Vehicular Technology Society, Volume 11, Issue 2, June 2016.