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Methods and instruments for stray current verification in DC rapid transit and railway systems

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ABSTRACT

Modern electrified transportation systems feature increasing installed power and performance and correspondingly stray current phenomena and corrosion are receiving more attention in terms of contractual specifications and request of final validation of proposed solutions, as well as a maintenance program that can actively tackle stray current issues. The problem is complex for the system physical extension, difficult measurement conditions and variability of electrical parameters. This work considers validation of stray current protection performance, in terms of track voltage, track leakage and collected current, and impressed potential on structures along the right-of-way. The exemplification of the specifications of a hypothetical instrument and setup support the discussion.

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1. INTRODUCTION

Stray current and induced corrosion are a significant problem of electrified transportation systems (ETSs), especially if operated at DC [1]-[9], although some impact may be expected also for ac railways [10]-[13]. There has been a significant modeling and simulation effort to better understand the dynamics, identify the relevant factors and optimize the design solutions [2], [3], [5], [14]-[18]. It is nevertheless true that an accurate simulation result stems from a comprehensive description of the system, fed with accurate estimates of all relevant parameters. Low-frequency phenomena can be in principle accurately modeled, but there are approximations when the system is quite extended and its electrical parameters are not fully and accurately documented, and they may vary with time and environmental conditions [19]-[28]. In addition the validation of simulation models and project requirements needs a comparison with experimental data [29], [30] obtained with suitable and accurate methods, so to demonstrate compliance for contractual and system assurance purposes. Compliance to standards [31], [32] is generally required, but for this specific case they give a limited description of methods, leaving details and implementation to good engineering. An example of results variability and of necessary precautions is given in [21], [22] for track insulation. This work aims at clarifying approaches for stray current assessment by measurement, discussing the specifications of a virtual instrument and setup, as the result of the engineered requirements and good practice, controlling external factors and thus including the expected variability and uncertainty.

2. DESCRIPTION OF THE RAILWAY SYSTEM AND RELATED QUANTITIES

For the phenomena of stray current and corrosion the relevant part of the ETS are the track and structural elements nearby, including metal works and platform. Such system is the typical metro or rapid transit system featuring tunnel or viaduct sections, platform screen doors, visible cable trays and walkways and some other electrical equipment located wayside. An overall sketch of such system is shown in Figure 1, including the elements and measurements that are discussed in the following.

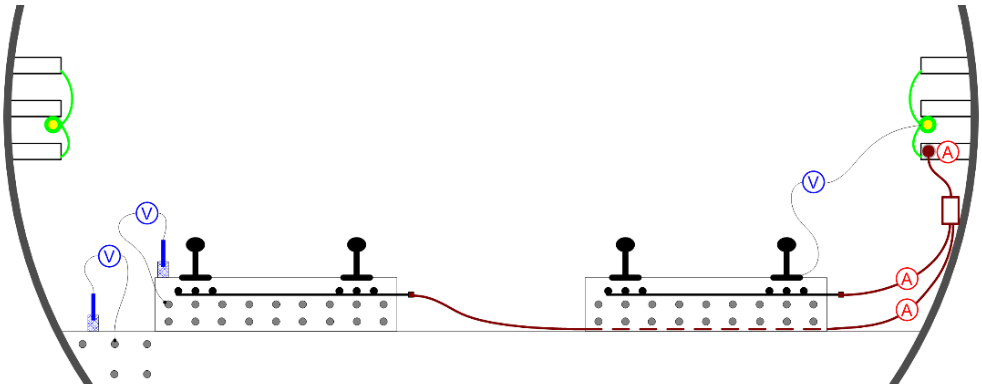


Figure 1. Sketch of ETS tunnel section subject to verification of stray current and corrosion potential: running rails and SCD rebars (black), other reinforcement (gray), connecting cables and SCC (brown), earthing equipotential conductor (yellow/green), voltmetric measurements and half-cells for concrete potential reading (blue), and amperometric measurements (red)

Focusing on stray current (SC) and impressed potentials (IPs) the circuit is composed of the track with its mechanical fastening to the track bed (or sleepers) that is a first leakage path, backed up by a stray current protection (SCP) system, devised in modern projects to intercept part of the leakage current leaving the rails, capturing through stray current drainage (SCD) sections and collecting it into the wayside stray current collector (SCC) back to the traction power station (TPS) [33], [34]. The SCP may be connected only when significant track leakage occurs or can be operated continuously for stray current reduction.

The quantities to measure to the aim of stray current assessment are (in line with standards):

- Potential of track V_{te} and conductive parts V_{ce} with respect to earth are an indication of chance of corrosion (besides an estimate of touch potential issues), each compared to suitable thresholds: the 5 V average V_{te} value of EN 50122-2 to specify the track-to-earth conductance limit for protection of the track, a range of limits between about 100 to 300 mV for steel in soil for variable soil resistivity, with 200 mV for steel in concrete (EN 50162 [32]); these latter limits may apply both as potential to earth or potential shift of steel with respect to concrete, where soil or concrete are the reference material containing the electrolyte and representing the negative reference for anodic corrosion to occur;
- Longitudinal voltage on conductive parts, such as reinforcement V_{cl}, again to estimate chance of corrosion, as per Annex C.2 of EN 50122-2 [31];
- Stray current leakage from a track section I_{tl} , drainage current I_{scd} or collected current I_{scc} flowing in the SCP at longitudinal position x. Accessible SCP quantities I_{scd} and I_{scc} may be used to determine the amount of captured stray current, and thus indirectly the amount of track leakage, allowing indirect monitoring of track insulation and the assessment of the SCP system efficiency [14]: $E_{SCP} = I_{scd}/I_{tl}$;
- Current flowing in specific conductive parts, to analyze relevance of leakage, although the measurement of the potential shift is preferable from a normative viewpoint (direct comparison with limits);
- Track insulation resistance (versus earth) is usually covered by specific tests [22], but can be estimated having available both track potential V_{te} and track leakage current I_{tl} quantities.

3. MEASUREMENT AND ASSESSMENT METHODS

The measurement of electrical quantities at low frequency is quite consolidated in terms of methods, instrumentation and data processing, especially in laboratory and at industrial sites using permanent installations. Conversely the application to ETSs is not immediate, especially if such measurements are going to be performed as part of the test and commissioning activities, and are thus based on a temporary setup.

Examples of installations onboard rolling stock for the purpose of power quality measurements can be seen in [35], [36]. The main concerns for track and wayside measurements of stray current phenomena regard:

- The physical extension of the system and the noise pick up on long wires, especially running in parallel to power cables and the traction circuit; exploiting the rejection of common-mode disturbance (CMRR) by the outer cable screen and cable balance does not work in all configurations, when there is only one wire connected to either polarity. In this case the wire should be protected against induction by running it first against conductive parts (common mode shielding) and in particular as close as possible to the conductive part under measurement (minimization of the loop area and reduction of differential mode noise pickup).
- The opportunity of an estimate by difference of measured values for the total current leakage of a track span, and for the voltage drop across a wayside longitudinal conductive part as the reinforcement of a viaduct or tunnel; as known, an estimate by difference of two larger quantities is more exposed to errors in the respective measurements: the absolute uncertainty of the difference $v_l=v_1-v_2$ is the square root of the sum of squares of the original uncertainties of v_1 and v_2, but the relative uncertainty is ratioed on the difference v_l, that is a smaller quantity (see sec. 0).
- The correct identification of an earth reference for potential measurements that does not suffer of an uncontrolled potential shift due to train passage or variable electrolytic potentials; this is usually addressed by selecting a power system earth conductor that in normal conditions has a minimal flowing current as 3-phase systems are usually balanced and well insulated.
- The input impedance of the measuring system necessary for impressed potentials and electrochemical potentials; as we will see such measurements necessitate a very large input impedance (in the range of hundreds of MΩ) and unavoidably this increases the input noise because the large input impedance does not effectively terminate (or load) the measuring circuit that remains "floating".
- The sampling rate, dynamic range and resolution of the acquisition channel for each type of measurement.

Other aspects related to the design and practical realization, such as mechanical robustness, susceptibility to vibrations and shocks, and index of protection, are not considered.

3.1. Measurement of potential (voltage to earth)

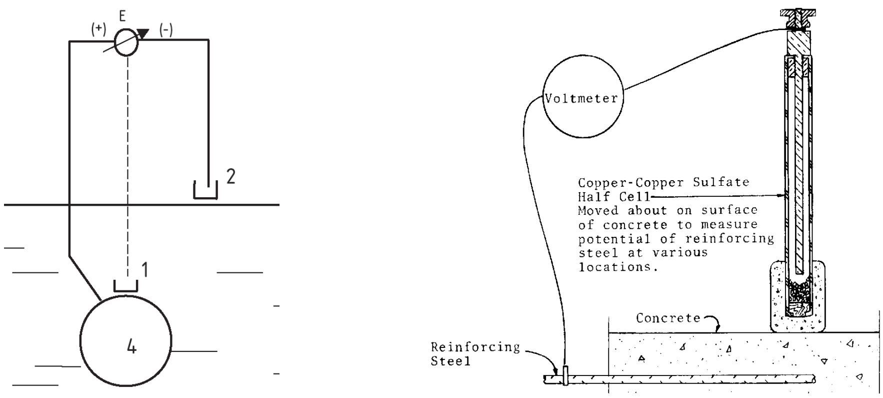
Track to earth potential. Track to earth potential is the most easily measurable quantity and corresponds to the difference of potential between the track and a local earth reference, such as an equipotential earthing conductor.

The dynamic range of the reading should accommodate for the typical variations, that is dc rapid transit and railway can be as high as 130-140 V [37], in cases of significant line exploitation and in particular if the return circuit or traction power stations are not significantly oversized. It is to remember that slightly negative values of the track potential cannot be excluded, as predicted by stray current models, e.g. near the TPS [2]: a bipolar channel is thus necessary with about ±200 V range or higher. Data acquisition systems should interface by using an attenuating probe, such as a resistive voltage divider with a ratio of 20:1 or, better, 50:1, to match the channel range. Multimeters and data loggers may be directly connected.

Resolution is not a concern as small values are not of relevant for the calculation of the threshold for the application of a stricter conductance requirement, i.e. 5 V (see EN 50122-2, sec. 5.2). Conversely, if potential measurements are used to estimate indirectly differences of potential as for longitudinal voltage, then resolution is an important factor, as discussed in sec. 0. The source impedance is very low (the total track-to-earth resistance amounting to less than a few Ω) and is not a problem. A minimum sampling rate is not expressly required any longer by the EN 50122-2, but usual values in dc railways are 1 to 10 Sa/s. Aiming at applying the setup to ac railways we must distinguish between the sampling of the waveforms (at 50 or 60 Hz), possibly internal to each instrument and channel, and the reporting of the resulting rms, usually done every period in industrial installations.

Structure impressed potential. The impressed potential IP (or potential shift) of structures is the difference of potential between the metal and the surrounding medium: for reinforced concrete the interface is established between the reinforcement (steel) and concrete (in which steel is encased); for metallic pipes and reservoirs the interface is with the surrounding soil. Corrosion may occur depending on the difference of potential and the type and concentration of ionic species present at the interface, as well as the moisture %.

Measuring the potential shift is complicated by the fact that the source impedance is high and variable, depending on a mix of ionic species, oxide barriers and conductive materials [38]. The way the electric contact is formed is another source of instability: whereas direct connection to a clean rebar is possible, to read the potential on the concrete surface, the electrochemical half-cell used for the reading introduces its own potential difference and internal resistance; for pipes and reservoirs, finally, if they are not directly accessible as for reinforcement, the reading is done as in the EN 13509 [39], using half cells above the pipe and at some distance away (usually > 10 m). The various arrangements are shown in Figure 2.



(a) (b)

Figure 2. Potential measurements; (a) Pipe or buried structure, (b) Reinforcement rebar in concrete

When performing measurements of concrete IP the ASTM C876 standard [40] requires the use of an instrument with suitable input impedance, 10 to 200 MΩ, requesting a verification of the stability between successive readings while increasing the input impedance value; for extreme cases a galvanometer with some GΩ input impedance should be used. In general 10 MΩ is really a minimum and 50-100 MΩ are common.

A suitable CMRR is also necessary, since such IPs (between a hundred mV to about 1 V) must be measured under a significant induction on connecting wires, caused by power cables and traction circuit [41], [42], or overhead power lines [43]. A minimum CMRR at mains frequency is 80 dB: a 100 V induced voltage translates into a 10 mV superposed ac noise, that agrees with the resolution of the ASTM C876 [40]. These two requirements on input impedance and CMRR are common to other applications, such as impedance spectroscopy, and biological and medical measurements, and are usually satisfied using a FET or MOS instrumentation amplifier input stage [44].

Last, it is noted that the reference negative terminal of the acquisition channel should be in principle connected to the concrete surface potential, in good electric contact with the soil, but measured by means of a chemical half cell, whose rest potential amount to some hundreds mV depending on the cell type: for the saturated $Cu/CuSO_4$ electrode, the potential for temperatures of 5 to 45 °C ranges between 315 and 320 mV (316 and 318 mV usually taken as “official” reference values) [45], [46]. For measurements involving water and sea water the Ag/AgCl electrode may be used, that has a wider variability of cell potential (approx. between fresh water and sea water the cell potential changes between 250 and 350 mV) [39].

Earth potential reference. The identification of a suitable earth potential is far from trivial in at least a couple of situations, i.e. at viaducts or in tunnels. At viaducts the problem is that the soil is reachable several meters beneath and that if necessary this must be accomplished with a separate wire and not by using the reinforcement of the pylon for the connection, as small voltage drops, but relevant for IP measurements, may occur. Track voltage instead is large enough not to be appreciably influenced.

Inside tunnels the soil potential is not directly accessible. The available tapping points are the equipotential conductors of the earthing system: in normal operating scenarios these conductors have a negligible voltage drop as the current flow is minimal, and is mainly at mains frequency (50/60 Hz), as caused by some power imbalance and small differences of utility earth potential. In this case the presence of mains frequency noise may be obviated by applying time averaging of successive readings, of course necessitating a correspondingly higher sample rate in excess of some hundreds Sa/s.

3.2. Measurement of longitudinal voltage

The potential difference across longitudinal conductive elements is a relevant quantity if related with provisional calculations as per Annex C, sec. C.2, of the EN 50122-2 [31]. It can in principle be measured directly, by assigning a local voltage channel at one of the two ends and running back a wire from the other end quite close to the measured part (to minimize the loop area and the picked-up induced voltage). For practical reasons it may be instead preferred estimating such a longitudinal voltage as difference of the terminal voltages measured at each end, using the local earth as reference. This approach has three issues:

- The two terminal voltages V_{1e} and V_{2e} must be measured using the same earth potential reference, that might not be if they are far away: longitudinal earthing conductors may undergo slight voltage drops due to current flow (the best approach is to check for negligible current flow); suitable earth references in a dc transit systems are cable trays and equipotential earthing conductors.

– The two measured voltages must be synchronized with a time resolution much better than the required sampling: considering a 2 to 10 Sa/s sampling, suitable synchronization is in the range of 1 to 10 ms, compatible with the real time clock and system clock resolution of a microprocessor (1 ms).
– The difference of two similar readings increases the resulting relative uncertainty: with V_{1e} and V_{2e} measured with a channel range of ±10 V to avoid out-of-scale readings, assuming a standard uncertainty u_1=u_2=1%, the resulting difference V_{12} presumably in the range of 100 mV (for compliance with corrosion limits) will be affected by $\sqrt{(0.1\mathrm{V})^2+(0.1\mathrm{V})^2}=141\,\mathrm{mV}$, that corresponds to an unacceptable relative uncertainty of 141%, too large compared with the corrosion limits.

3.3. Measurement of current in conductors and conductive parts

Not all the relevant current quantities can be directly measured as they do not flow in conductors, but they leak though extended interfaces (such as the track leakage I_{tl} through fasteners and supporting pads). I_{scd} and I_{scc} can be measured by using current probes located on the respective conductors: assuming a 2.5 mA/m track leakage (the EN 50122-2 limit), 200 m of SCD give a total leakage of 0.5 A and I_{scd} will be very close to it (for an efficiency of about 80-90%); the SCC collects leakage over inter-TPS separation of 2-5 km so I_{scc} ranges between 5 and 12.5 A; larger values may be expected in case of track insulation failure.

For the track leakage and current flow in conductive parts the following approaches may be used:

– The current leaving the track in a section of s meters can be estimated as the difference of the track currents at the two ends x_1 and x_2 of the section (s=x_2–x_1); for each rail $I_{tl} = I_{r1}–I_{r2}$; for the measurement of the rail currents current sensors are needed that do not embrace the running rail and stay off the area occupied by the train wheels and train shape:
  a) A current sensor of the close-up type can be used, located next to the central part of the running rail and supported at the rail foot, as described in [47];
  b) With mechanical joints in the running rails, the rails electrical continuity is ensured by short bonding conductors bridging the mechanical joint, where a probe can be placed to read the rail current.
– The current flowing in extraneous conductive parts (ECPs) is more difficult to capture, depending on the geometry of the circuit: viaduct tendons, handrails, and bonding cables connecting platform screen doors (PSDs) to the track can be measured with a clamp-on probe with some issues of sensitivity.

4. COMPARISON AND BENCHMARKING

Methods and specifications are now compared with the performance of typical instrumentation available to implement such a virtual measuring system (although the characteristics for comparison are taken from real products, commercial names are omitted as far as possible).

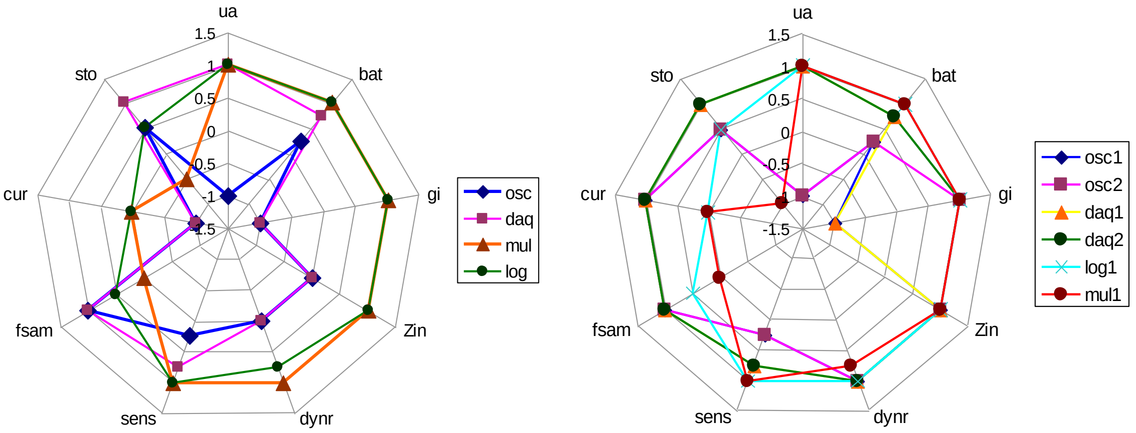
The comparison criteria, with the weighting coefficients K and the objective function (1), are:

– Possibility of unmanned acquisition "ua" gets $x_{ua} = +K_{ua}$, $–K_{ua}$ otherwise;
– Operation on battery (tolerating power shortages and ensuring galvanic insulation) "bat" gets $x_{bat} = +K_{bat}$, for full autonomy (>1 day), lower values to 0 for smaller capacity, $–K_{bat}$ without battery;
– Galvanic insulation ("gi"), necessary to avoid ground loops and false reading and to ensure safety;
– Input impedance "Zin" is insufficient ($x_{zin} = –k_{zin}$), sufficient ($x_{zin} = 0$), over-performing ($x_{zin} = +0.5k_{zin}$);
– Channel dynamic range "dynr" fits the expected variability in normal conditions ($x_{dynr} = 0$), it has margin for abnormal fluctuations without compromising resolution ($x_{dynr} = +0.5K_{dynr}$), or cannot ($x_{dynr} = –K_{dynr}$);
– Combined sensitivity and resolution "sens" allow accurate reading compared to limits: $L_{sens,min}$=10% barely sufficient ($x_{sens} = 0$), below it ($x_{sens} = K_{sens} \log_{10}(L_{sens,min}/L_{sens})$), above it ($x_{sens} = –K_{sens}$);
– The sampling rate "fsam" is insufficient ($–K_{fsam}$), barely sufficient (0), or over-performing, and allows e.g. For noise reduction and enhanced resolution techniques ($+K_{fsam}$);
– Measurement of current ("cur"): dso or daq are not designed for this ($x_{cur} = 0$) and must interface through a current probe (when used $x_{cur} = K_{cur}$); mul and some logs have limited current measurement capability (usually one or few Amperes), so $x_{cur} = 0.5K_{cur}$;
– Storage ("sto") is important for long-term acquisition in ua conditions and when the sampling frequency is increased to improve data quality: $x_{sto} = 0.5K_{sto}$ if autonomy >1 day, $=K_{sto}$ if >1 week, 0 otherwise;
– The cost in k$ is assigned to each device and then estimated for one complete setup at one location, that is able to measure the quantities shown in Figure 1: 2 impressed potentials, 3 currents and 1 track voltage; since the two IP measurements have different reference potentials, they must be carried out with galvanic insulation or two (or more) different instruments isolated from earth; this has a significant impact on cost.

$$J = x_{ua} + x_{bat} + x_{gi} + x_{Zin} + x_{dynr} + x_{sens} + x_{fsam} + x_{cur} + x_{sto} - x_{prc} \quad (1)$$

The instrumentation subject to this comparison is described below and results of the 9 performance criteria are shown in Figure 3, whereas the price and the objective function *J* are in Table 1:

- Standard 8-bit digital oscilloscope ("osc"): channel full scale (FS) up to 50 or 100 V; resolution limited to ±FS/128; enhanced resolution up to about n=12÷14 bits available by increasing the sampling rate by $2^{(n-8)}$; very slow sampling rate (e.g. <100 Sa/s) is difficult or impossible to achieve as many instruments go in "roll-on mode"; number of channels 2 or 4; models with battery quite expensive; channels not galvanically insulated, except for very few industrial data recorders (e.g. Yokogawa);
- Portable data acquisition system ("daq"): channel full scale (FS) usually up to 10 V; resolution of ±FS/1024 (10 mv) to ±FS/32768 (0.3 mv) for 12 to 16 bits; enhanced resolution available; all necessary sampling rates available; number of channels 2 to 8; PC operated, so battery supplied, but unmanned operation is achieved by deploying laptop or single-board computer; channels not galvanically insulated;
- Multimeter with data logging ("mul"): FS up to 500 V so direct connection is possible; resolution of 4½ digits (avoiding cheap 3½ models), sensitivity about 0.05-0.1% so ≤100 mv on FS=100 V; sampling rate up to a few Sa/s; battery operated; possible logger operation as standalone unit;
- Specialized mini data logger ("log"): with peculiar characteristics such as GPS location and sync, and GSM network, battery supplied with easy control functions, built-in filters for mains noise rejection, but often have a limited input range for V_{te} and number of channels; the price is higher than a daq;
- Clamp-on current probe ("concp"): to use for i) cables (SCD, SCC, PSD) and ii) ecps, with different FS and sensitivity requirements; robust industrial-grade Hall effect probes (considered here) have a lowest 20-50 A FS, so well suited for I_{scd} and I_{scc}; lab-grade probes (flux gate and active compensating probes) have 10 to 50 smaller FS and correspondingly better sensitivity, so a forced choice for many ecps; industrial-grade probes are usually swiftly characterized by the manufacturer with 1% FS sensitivity, although real performance is much better (for which ad-hoc calibration is strongly recommended);
- Close-up current probe ("cupcp"): no commercial products, used to measure rail current compatible with passing trains; they are based on two principles, transformer with the rail as part of the magnetic circuit, or magnetic field sensor (coil for ac, hall effect or GMR for dc+ac) positioned next to the rails;
- High-impedance standard voltage probe ("stdvp"): standard oscilloscope probe that ensures a 10 MΩ Zin if connected to a 1 MΩ Z_{in} channel and extends the input voltage range of a 10x factor (with protection of channel thanks to the large series resistance);
- Differential voltage probe ("difvp"): galvanic insulation; Z_{in} = 1-10 MΩ; CMRR @ 50 Hz = 80 dB; S/N > 60 dB assuming a 100 V FS with 100:1 ratio and less than 1 mvrms noise at the output.



	K_{ua}	K_{bat}	K_{gi}	K_{Zin}	K_{dynr}	K_{sens}	K_{fsam}	K_{cur}	K_{sto}
cfg1	10	10	10	5	5	5	5	10	5
cfg2	10	10	10	10	10	10	10	10	10

Figure 3. Multi-criteria comparison of instruments (left) and setups (right) with values of weights (below)

Without the use of additional probes, it is evident that the data logger is as expected the best instrument for this kind of measurements, although it has e.g. a limited current capability (and not all models). However, the flexibility, performance and lower overall price of daq solution emerge when the complete setup shown in Figure 1 must be implemented.

Table 1. Multi-criteria objective function J for selected setups (including instruments and probes to carry out the measurement shown in Figure 1)

Instrument	Acronym	Price	O.F. *J* (cfg1)	O.F. *J* (cfg2)
osc (×2) + stdvp (×3) + concp (×3)	osc1	7.05	4.3	23.1
osc (×2) + difvp (×3) + concp (×3)	osc2	8.4	22.9	41.6
daq + stdvp (×3) + concp (×3)	daq1	2.85	38.5	62.3
daq + difvp (×3) + concp (×3)	daq2	4.2	**57.1**	**80.8**
mini data logger (×3)	log1	7.8	42.2	62.2
multimeter (×6)	mul1	4.8	34.0	42.7

5. CONCLUSION

Methods, specifications and setups for stray current protection measurements on-site have been discussed considering normative requirements and common practice, and going into the details of the setup, identifying a range of suitable instruments and devices. Layout of connections and other practical aspects were considered too. Peculiar characteristics of this kind of measurements are: unsupervised acquisition, long battery autonomy and galvanic insulation. Besides discussing performances and best practice for specific measurements (track voltage, impressed voltage, stray current leakage), a set of “virtual setups” was built starting from the best selections among four types of instruments (oscilloscope, data acquisition system, multimeter and data logger) together with suitable probes. Results of the analysis were synthesized in radar plots showing 9 performance criteria and one objective function that includes the price in the final judgment.

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