REPORT:

OFF MEASUREMENTS 101:
FROM METROLOGY PRINCIPLES TO APPLICATION

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ABSTRACT:

IR-Free measurements are one of the hot topics in the cathodic protection industry. Obtaining correct values requires a multi-disciplinary knowledge. It is sometimes necessary to return to the principles of physics, metrology and electronics and verify that all the boundary constraints are still valid. The aim of this paper is to give a basic understanding of the theory and to pinpoint what are the current technologies, challenges and trade-offs in realizing E_{OFF} measurements.

RÉSUMÉ:

Les mesures IR-Free sont un sujet brûlant pour le secteur de la protection cathodique. Pour obtenir des mesures correctes, on nécessite d'une compétence multidisciplinaire. Il est parfois nécessaire de retourner aux principes basilaires de la physique, de la métrologie et de l'électronique et de vérifier si toutes les conditions aux limites sont encore valide. Le but de ce rapport est de donner une compréhension basilaire de la théorie et de souligner quels sont les technologies actuelles, les défies et les compromis en réalisant des mesures de potentiel OFF.

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INTRODUCTION.

Measuring is the activity of **comparing the magnitude of a phenomenon with a reference unit**, with the goal of obtaining a value that can be stored and transmitted and eventually compared against other values obtained from similar processes that take place elsewhere or from the same process at a previous or later time.

In the case of OFF potential measurements, what we are trying to do is to compare the measured potential value with a threshold (i.e. a reference value) or with its previous values; the real goal of this kind of activity is to protect a steel artifact from corrosion, by monitoring the effectiveness of its active and passive protection systems.

This seemingly simple activity has a long series of hidden assumptions and traps.

The aim of this paper is to:

- broadly analyze those assumptions
- summarize the conditions for a correct measurement
- compare the conditions found during the previous step with the current technology
- summarize the possible trade-offs in different implementations

The aim of this paper isn't to:

- discuss the different theories on E_{OFF} measurements
- discuss the nature of corrosion and corrosion protection

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SOME USEFUL DEFINITIONS.

As a first step, we can try to list some definitions:

- **Measurement**: the process of establishing the magnitude of some attribute of an object relative to some unit of measurement

- **Measure**: the output of the measurement process (sometimes, in some idioms, this term is also used as a synonym of measurement)

- **Uncertainty principle** (also known as Heisenberg principle): any kind of mathematical inequality asserting limits on the precision with which we can know pairs of related properties; it is sometimes confused with the:

- **Observer effect**: the changes that the act of observing a phenomenon produces on it; measuring is an observation activity and as such it alters the observed phenomenon

- **Metrology**: the science of measurement; one of its main activities is to define systems of reference units and to define chains of traceable operations to link the reference units with the measurement activities

METROLOGICAL ISSUES.

This seemingly basic definitions introduce the main problems that we can find during every measurement activity.

E_{OFF} measurements have their peculiar difficulties, that are well hidden behind these broad definitions.

First of all let's talk about one kind of observer effect that we have to consider when making a voltage or current measurement, the so called **loading effect**.

Every time we connect to the electrical phenomenon that we want to measure, the connection of our measure instrument alters the context (we have the same perturbation even if there isn't contact: a clamp-on ammeter has a mutual inductance with the cable where the current to measure circulates and it alters the current circulation).

In the case of a voltage or potential measurement, the insertion of the voltmeter alters the impedance of the measuring chain:

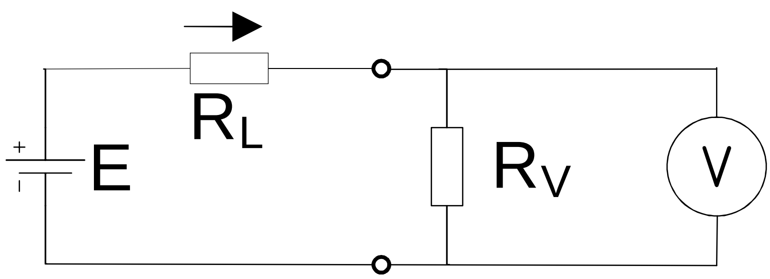

Fig. 1 - Thevenin's equivalent of the circuit

The real voltmeter can be seen as an ideal voltmeter (an open circuit with infinite resistance) and its input resistance.

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So the measured voltage is the voltage drop on R_V, produced by the current

$$\frac{E}{R_V+R_L}$$

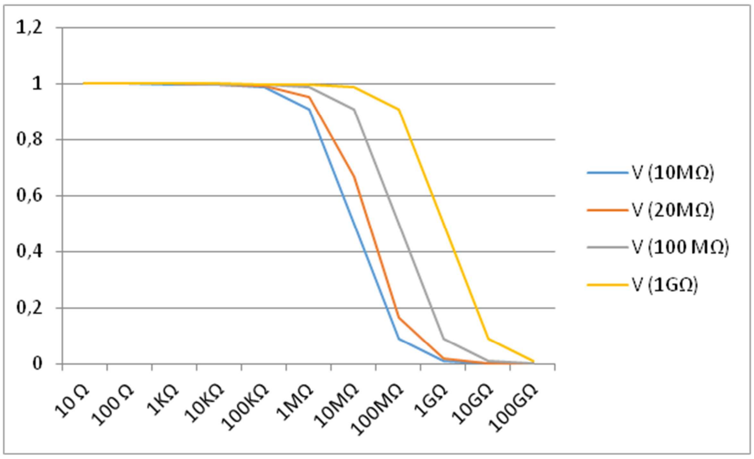
i.e.

$$V = \frac{E \cdot R_V}{R_V + R_L}$$

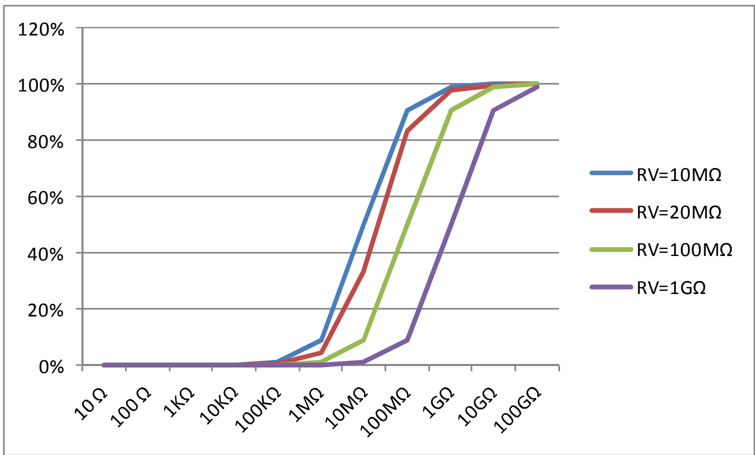
If $R_V \gg R_L$ then $V \approx E$.

If R_L is similar to R_V then we introduce an error.

The magnitude of the error, as seen from the previous formula, depends on the ratio between the load impedance and the voltmeter input impedance, as can be seen in the following figure:



a.



b.

Fig. 2 - Effect of the ratio between load and voltmeter impedance (a. value , b. error)

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Even in the simple hypothesis of a purely resistive impedance both in the meter and in the load, we can see from the graph that when the magnitude of the input resistance isn't two orders higher than that of the load, we start to appreciate an insertion error.

A consequence of this situation is that we must avoid to have an high circuit impedance, both reducing the contact resistance in the connections inside the circuit and the resistance between reference electrode and soil.

In situations where pipe-to-soil impedance is very high, we have the luck that usually the corrosion processes are slower due to the slower ion diffusion, but, if it is necessary to have a lower error, we need to increase the input impedance of our instrument. This isn't always a simple activity, because we lose accuracy and we risk to have the input circuit of the measure instrument behave as an antenna, capturing noise from the environment.

When there are capacitive or inductive components in the impedance, this introduces complexity. As an example, different harmonics can have different delays, attenuations and phases in the soil/coating/steel system; filtering the ac components, measuring them, attenuating them are all difficult problems, and they are more difficult in all the situations where you need to minimize power consumption.

But when we are making ON-OFF cycles there is another important effect: capacitive and inductive components alters the transient response of the system to the theoretical square wave produced by the cycle and they have also an influence in the magnitude and duration of the spikes produced by equalization currents.

This is one of the reason why the NACE literature about instant OFF recommends to wait 600 ms - 1s before reading the value.

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We can only control the nature of the input impedance, but the load impedance depends on a lot of different parameters outside of our control.

Even the act of filtering ac components necessarily introduces a delay, the delay of integration of the filter, and this delay grows with the ac rejection we want to obtain.

GOING DIGITAL.

Nowadays all measuring systems are digital and the analog/digital conversion introduces new sources of error in the measure, due to the sampling process and to the quantization of the result.

An 8-bit A/D converter divides its full-range in 256 sub-ranges; if they are linearly divided, every value has an average error of a half-step, i.e. 1/512 of the full range extent. A 24-bit ADC, as a comparison, has an average quantization error that is 6 orders of magnitude lower…

OFF MEASUREMENT.

The aim of an ideal E_{OFF} measurement is to obtain an IR-free potential; we stop the current injection, zeroing the voltage drop due to the current flow in a non-zero resistance path, and, immediately after that, we can measure the polarized potential of the pipe.

What are the assumptions of this ideal situation that can't be met in a real context?

First of all, the disconnection of the power source isn't instantaneous, so the input signal isn't an ideal square wave but a "rounded" one, with some possible "ringing" on top and, perhaps, an "overshoot", a spike, following the connection/disconnection.

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If we do it on a pipe, we have to account for its lack of uniformity, so we can have some kind of "equalization" between different sectors, and the different harmonics of the real square wave will have different phases and attenuations, so that the result would be even less similar to a square wave.

We will have to find a trade-off between the necessity of avoiding the transient effects and the necessity of taking the measure before the start of the depolarization.

The entity of the lack of ideality also depends on the technology used to operate the disconnection, because electromechanical relays suffer of higher rebounds and of the risk of remaining stuck.

This "real world" problems have a reflex in the wording used in the various standards and norms, not quantitative but qualitative phrases as "immediately after disconnection", where the only agreement seems to be that "immediately" means "after less than a second".

In coupons we have different issues: the transient is faster, but to have a lower IR drop the distance to the reference electrode have to be short.
A very short distance means a very low resistance; this is good both for the IR drop and for the loading effect of the voltmeter, but how about protection current?
If the coating is in good state, the spread resistance could be orders of magnitude higher than the resistance between coupon and electrode.
This low resistance path is privileged by protection current and perhaps this is a situation where the old saying "cathodic protection is only used to protect coupons" have a very sound meaning.

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CONCLUSIONS.

After this summary of metrological and practical issues, our idea is that it is still really important to have a good knowledge of the applicative context.

The good news is that current progresses in low size and low power electronics gives us the possibility of remotely monitor and control our pipes even by taking measurements on coupons and probes.

In every situation it is advisable to make an audit to decide what's the correct trade-off between cost and complexity and safety or economical considerations.

State-of-the-art technology gives us the possibility of having highly configurable remote monitoring units, that can be adapted to the vast majority of operational contexts and this produces economy of scale.
We can still have very peculiar situations where we need ad hoc solutions, but these are typically the situations when safety considerations or economical considerations allows the choice of customized solutions.

The technological trend favors the introduction of RMUs with integrated cyclic interruption and this is giving us an enormous database that the research community could use to test different measure strategies.

The results obtained are in line with the theoretical expectations in random installations. Perhaps it is a good time to start some pilot test with chosen soil/steel/coating samples, to build a taxonomy of issues and solutions and to guide in the choice of appropriate cycles, delays and instruments.

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