Smart CCP –
Detecting Minor Damages in the Coating of Cathodically Protected Buried Pipelines

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Introduction

Cathodic corrosion protection (CCP) is a technical system which is used to reliably protect underground steel pipes against external corrosion. For high pressure gas pipelines of public gas supply with an operating pressure > 4 bar, the installation of this protection method is even stipulated. Remote monitoring systems are used to check the effectiveness of CCP based on measurements. The generated data can also be used to assess the condition of cathodically protected pipes.

The remote CCP monitoring technology used at present has been designed to collect tho measurement parameteres which are required to prove the effectiveness of CCP and send the information as raw data to the evaluation centre. This technology, however, is not suited for a permanent monitoring of cathodically protected pipelines. For a continuous monitoring, a new technology has to be applied which generates a constant stream of CCP measurement data at a high sampling rate which is processed and evaluated in situ, so that only relevant information will be transmitted to the evaluation centre. This technology, which is innovative in the field of CCP, is called online monitoring.

The motivation to advance remote monitoring technology to an online monitoring is to detect possible external impacts which may be dangerous to pipelines early, and avoid catastrophes, such as the severe gas accident on 30 July 2004 near the town of Ath in Belgium. Online monitoring is capable of detecting dangerous external impacts, such as for instance from an excavator bucket, on buried pipes with cathodic protection, and promptly transmit a danger alarm.

Current technological level of remote CCP monitoring

The current remote CCP monitoring technology meets the requirements stipulated in Code of Practice GW 16, cf. German Technical and Scientific Association for Gas and Water DVGW, GW 16 “Cathodic Protection (CP) of Buried Storage Tanks and Steel Pipes – Remote Monitoring” (2008-05). Typically, the measurement values are interrogated up to four times a day, while the data is transmitted once a day to the evaluation centre via SMS through the mobile communications network. The CCP technical staff in the control centre evaluate the received measurement data, as shown in ***Figure 1***.

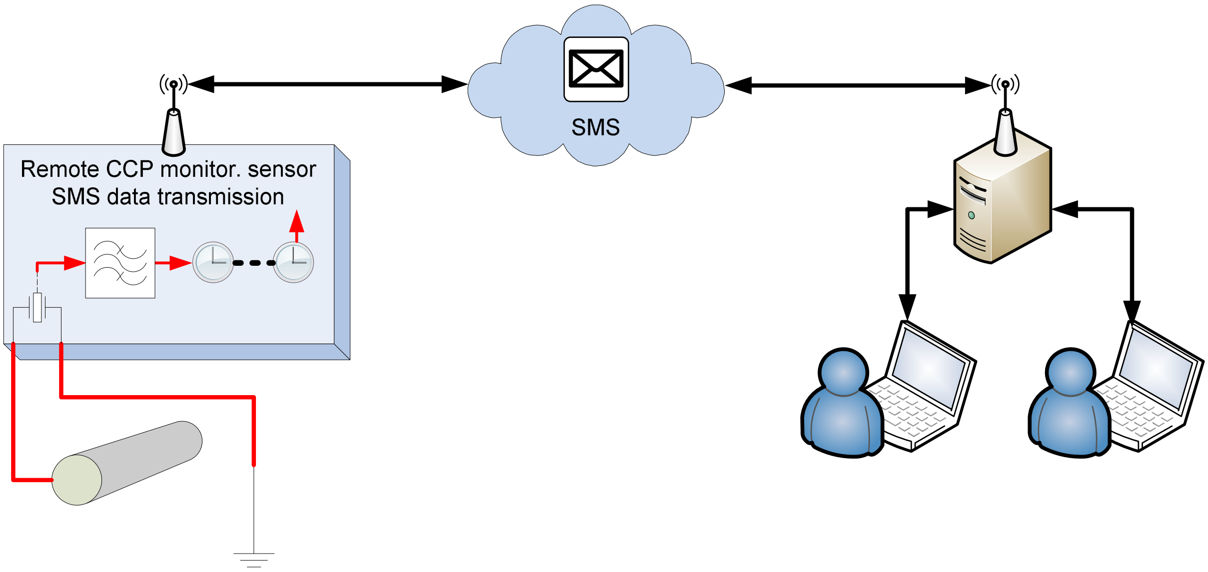

Figure 1: *Current technological level of remote CCP monitoring*

The system does not allow to interrogate and evaluate the measured data on a non-stop basis. Neither is it possible to directly process measurement data with an in-situ sensor in order to automatically analyse the measured values for irregularities or specific events. Remote monitoring technology has been designed to collect the key CCP measurement values at larger intervals (at least once a day) and transfer them to the control centre where they are compared to reference values.

For the maintenance strategy of pipeline operators, information about the condition of their networks is indispensable. Evaluating the effectiveness of CCP and the coating quality of a cathodically protected pipeline provides meaningful evidence about its condition. However, the existing remote CCP monitoring technology cannot reliably detect events, which change a pipe's coating resistance only for a short time and cannot be tracked over a longer period, but may well be critical referring to its integrity. To make matters worse, the existing online monitoring technology can only poorly detect external impacts, which – compared to the ground resistance of a pipeline – are high-resistance, or not at all.

Online monitoring: General remarks

Online monitoring represents a new concept of remote CCP monitoring. It is based on an uninterrupted collection of measurement data with a much higher resolution of value and time domains, allowing for an accurate digital mapping of the CCP measurement values, including their curves. This is followed by an evaluation of the measured data with methods of digital signal processing. By implementing algorithms in the CCP sensor software, it is possible to adapt the computation to specific tasks and ambient conditions. The direct data processing in the sensor allows for a smart evaluation of the measured data based on defined criteria. If a specific event to be detected occurs, such as for instance damage from an excavator bucket, the data will be transmitted instantly as alarm to the desired receiving station.

Online monitoring represents a non-stop monitoring of key CCP measurement parameters, such as the ON potential. In combination with the continuous collection of other measurement data, which will also be possible then, such as AC voltage induced on the pipeline by external sources like high voltage power lines, statements on the condition of cathodically protected pipelines will become more precise.

What's more, it is now actually possible to detect short-time and possibly dangerous external impacts on a buried pipeline (from an excavator bucket for instance). In order to measure impacts of this type, a much more sensitive and faster technology than the one used so far is required.

To ensure that the CCP sensors can be accessed any time and that the sensor data can also be transmitted to the control centre any time, an appropriate communication structure needs to be implemented. The existing remote monitoring sensors transmit data via SMS transfer, a method which is not suitable for a data transmission deterministic in time. In contrast, data transmission based on the TCP/IP protocol, as it is realised in Ethernet networks, on the Internet and via GPRS/UMTS in mobile telecommunications, is well suited for this task. ***Figure 2*** sketches the method.

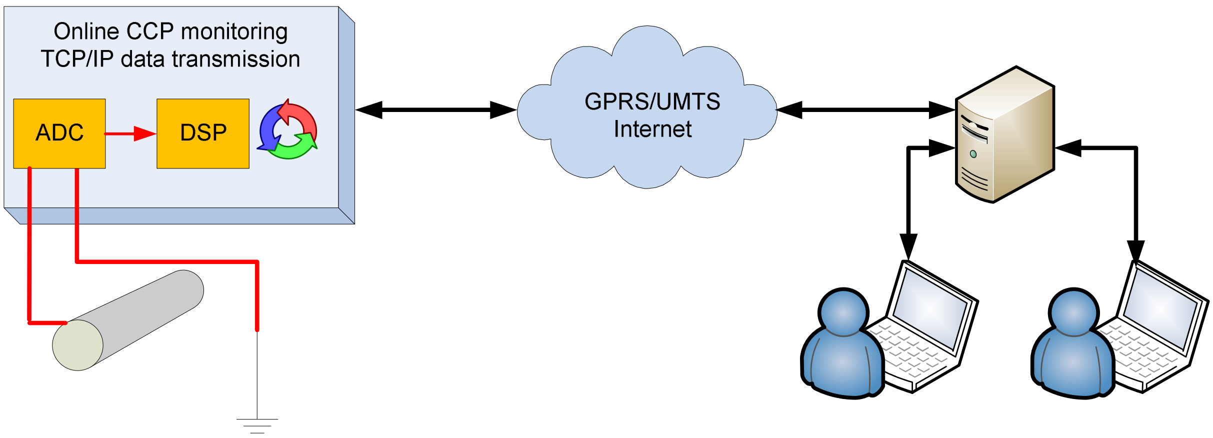

Figure 2: *Online monitoring*

Uninterrupted power supply must be ensured, as such systems cannot be supplied via battery.

Online monitoring: Technology

The major differences of the new online CCP monitoring technology compared to the existing remote CCP monitoring technology are measurement data collection and processing and data transmission/communication.

Collection of measurement data
A prerequisite of online monitoring is that the CCP measurement values are collected without loss of information for further processing. The information content of the measured signals always relates to the context of the task to be solved or the shares of a signal in the measurement signal which need to be recorded loss-free in order to evaluate them in the later signal processing.
In order to process physical parameters in a processor, the information has to be digitised via an analogue-digital converter, differentiating between the value domain and the time domain. The resolution of the value domain, specified in bits, needs to be adapted to the measurement range and the smallest amplitude variations to be recorded. The resolution of the time domain determines the upper repeat frequency up to which it is possible to record the continuous measurement signal without losing signal changes during digitisation regarding time.
The sampling rate of the continuous signal when digitising to a discrete-time signal determines the frequency up to which the signal can be reconstructed in the processor. The Nyquist-Shannon sampling theorem has to be considered for the dimensioning of the analogue-digital conversion. This theorem states that the frequency with which the continuous measurement signal is sampled, i.e. digitised, must be at least twice as high as the highest frequency which occurs in the measurement signal to be recorded. This is the mathematical, theoretical requirement for a full reconstruction of the desired signal after it has been digitised. In its technical application, however, the sampling frequency needs to be increased by a multiple in relation to the sampling theorem to ensure a safe signal recording. The sampling rate is often stated in Hertz or values/s.
The values measured by the online CCP monitoring are converted from analogue to digital with up to 1 MHz, which means that the course of the CCP measurement values is digitised with 1 million values per second, generating a very precise mapping in the processor. Analysis has shown that sampling rates of this magnitude are required for a safe detection of impacts with a very short-time effect, as they occur when a pipe is damaged by an excavator bucket.

Figure 3, ***4*** *and* ***5*** illustrate how the quality of digitising an analogue measurement signal depends on the sampling frequency. ***Figure 3*** shows the analogue input signal. ***Figure 4*** and ***5*** show the sampling of the signal with an analogue-digital converter, where the red lines indicate the moments when the values were captured. The resolution of the value domain is high which is why no information is lost. In ***Figure 4***, the resolution of the time domain in relation to the time of signal change is not high enough, i.e. the sampling frequency is too low to digitise the signal without loss of information. As a result, the high-frequency change in the signal is not detected. ***Figure 5***, in contrast, shows that the high sampling frequency records the high-frequency oscillation so that it is mapped in the digitised signal.

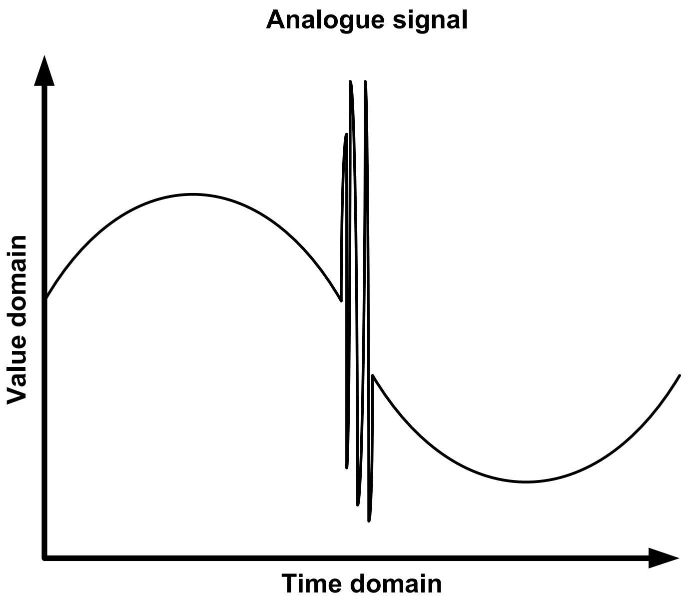

Figure 3: *Analogue signal*

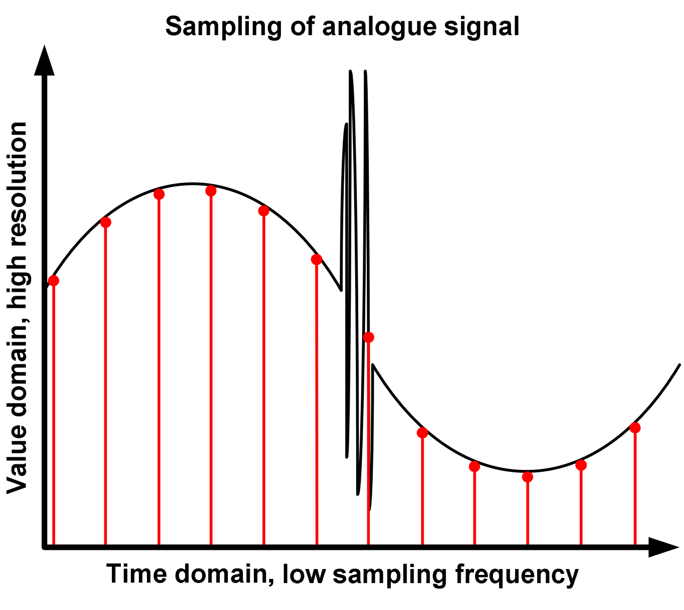

Figure 4: *Sampling of the analogue signal of Figure 3 with low sampling frequency, high-frequency signal shares are not recorded*

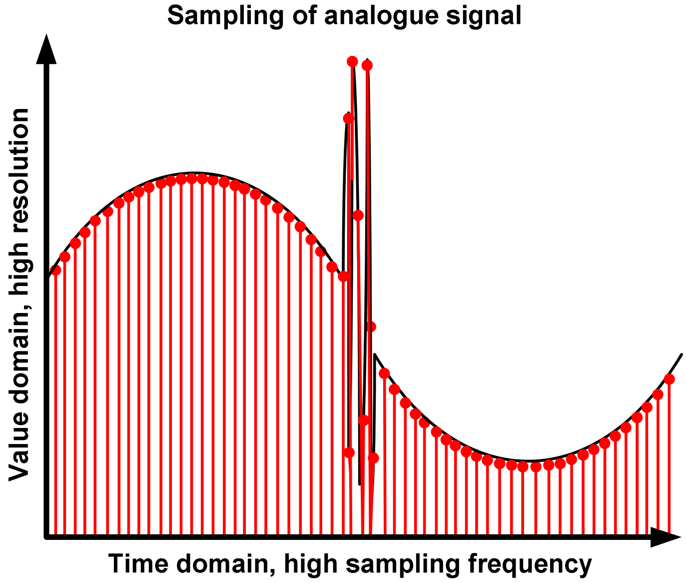

Figure 5: *Sampling of analogue signal of Figure 3 with high sampling frequency, all signal shares are recorded*

Processing of the measurement data

In a next step, the digitised measurement values are evaluated with computations. Online monitoring with its simultaneous and continuous collection of multiple CCP measurement parameters puts special demands on the performance of signal evaluation. A digital signal processor with special software algorithms and methods of digital signal processing is used for the automatic and simultaneous processing of all measurement values.

By implementing appropriate software algorithms and a non-stop evaluation of voltages and currents on a pipeline, specific signal patterns, like that generated when hit by an excavator bucket, can be detected automatically. The computation of the individual CCP measurement parameters can be requested at virtually any time.

Apart from the protective current supplied by the protective current unit, the measured voltages and currents also contain interference signals, induced into the pipeline by, for instance, high-voltage overhead lines or AC voltage railway tracks. The demands placed on online monitoring call for a recording of all components contained in the measurement signal (interference signals as well as the shares of the CCP protective current) without the use of hardware filters. This is necessary for a safe splitting of the interfering influences from those shares of the signal which are relevant for the specific evaluation and determination of the measurement parameters and the events to be detected using statistical methods.

The Fourier analysis is appropriate for signal processing tasks of this type. This analysis transforms the signals of the time domain to the frequency domain where they are analysed. Using methods of frequency selective analysis, the signal components can be investigated isolated from each other to allow for a focused examination of their changes. To analyse the continuously collected CCP measurement data, the Fourier analysis needs to be applied to permanently refreshing data. When the Fourier transform is applied to a dataset, the time information is lost since the complete dataset is broken down into its frequency shares, and the associativity of an occurring frequency to a specific point in time is lost. To avoid the loss of time information, the so-called short-time Fourier transform is applied. The Fourier transform is applied to equidistant time sections whose results are examined with their correlation of time. In this way, continuously refreshing time signals, as is the case with the non-stop recording of the CCP measurement parameters, can be analysed in the frequency domain.

Figure 6 illustrates the application of the short-time Fourier transform to a time signal. The time signal is multiplied by a window function, and this window is then Fourier transformed. The window function runs over the complete time signal, displaying the amount of the respective frequency shares in relation to the respective point in time as shown in ***Figure 7***.

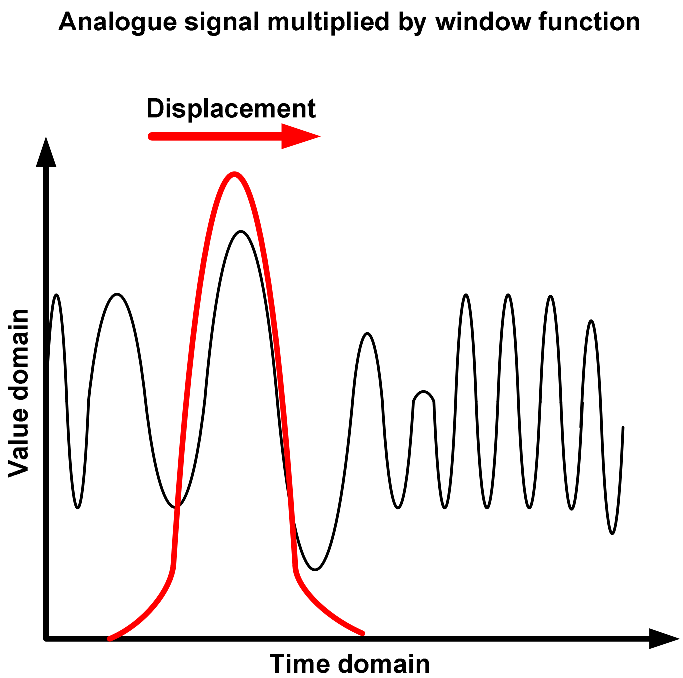

Figure 6: *Analogue signal multiplied by a window function for the short-time Fourier analysis*

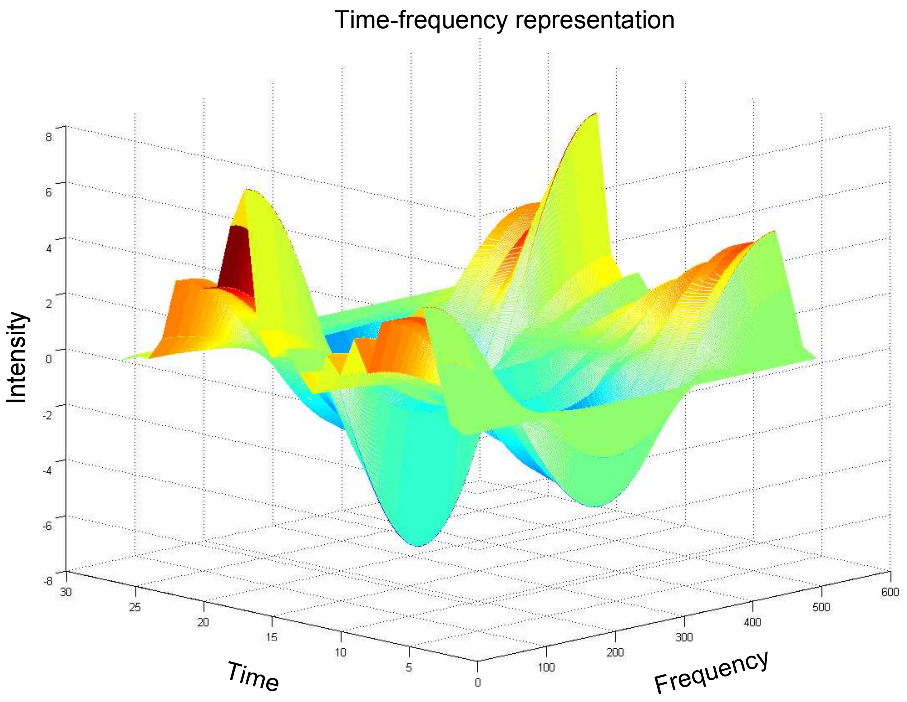

Figure 7: *Time-frequency representation of the analogue signal*

The measurement values transformed to the frequency domain are then evaluated with more algorithms in order to detect irregularities and meaningful characteristics in the curve of the measurement signal. Based on the patterns of these signal curves, it shall be possible to detect impacts, such as by an excavator bucket.
By realising an evaluation solely based on software algorithms, the system remains very flexible. Evaluation methods for future requirements can be implemented by installing software updates, which allows for an easy expansion of features based on the same hardware system.

Data transmission/communication
The CCP sensors for online monitoring are connected to the control centre via the so-called packet data transmission of the TCP/IP protocol. The bidirectional data transmission and communication allows for high transmission rates and establishes a permanent connection among all participants, so that the interlinked systems can exchange data any time. The TCP/IP protocol is the basis in Ethernet networks, on the Internet and the GPRS/UMTS standard in wireless communication. The physical transmission channel used for the communication is therefore irrelevant for the provision of information. The telecontrol protocol IEC 60870-5-104 used in control systems, which is published as DIN EN 60870-5-104 “Telecontrol equipment and systems – Part 5-104: Transmission protocols – Network access for IEC 60870-5-101 using standard transport profiles (IEC 60870-5-104:2006)” (2007-09), is also based on TCP/IP, so that the smart CCP sensors can also be integrated in a control system.
For communication and data transmission and to perform open and closed loop con-

trol processes of the protective current unit, the license-free Linux operating system is used.

Future possibilities of CCP through online monitoring

Online CCP monitoring takes full advantage of the information content provided by the CCP measurement parameters. Based on software algorithms, the digital signal processing processes the measurement data and evaluates them based on specific parameters and occurring events. This allows for an easy adaptation of the system to changing situations and requirements by simply modifying the software.
Figure 8 sketches the structure of the system, based on the implementation of features as mere software modules. Signal processing takes place in the digital signal processor DSP, while the general open and closed loop control and communication tasks are performed in the second processor GPP (general purpose processor).

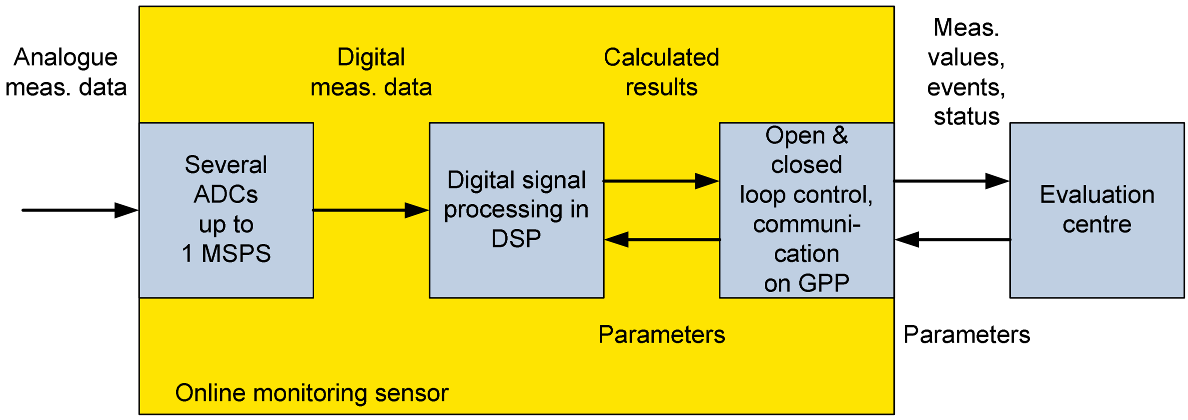

Figure 8: *Schematic illustration of the structure of the online monitoring sensor, based on the implementation of the system features as mere software modules*

With the fast and universal connection of the measuring sensors to the control centre via communication channels based on the TCP/IP protocol, it is possible to transfer measurement information, safety messages or control commands with a high transmission rate at any time without relevant delay.

Continuously adjustable output voltage of a protective current unit

With the new technology, it is also possible to perform precise open and closed loop control functions to allow for a fast and continuously adjustable setting of the output voltage of the protective current unit for instance, based on the processing of the measured values. In future, such control algorithms will certainly be required on pipelines which are subject to AC voltage in order to minimise the risk of possible AC corrosion. Related research results can be found in the DVGW research project G 2/01/08 on field tests for testing the influence of AC voltage and ON potential on AC corrosion. Swiss Society for Corrosion Protection, M. Büchler, C.-H. Voûte. June 2010, and Büchler, M.; Voûte, C.-H.; Joos, D.: Einfluss von zeitlich variierendem kathodischen Korrosionsschutz auf die Wechselstromkorrosion (Effect of pulsed cathodic protection on the a.c. corrosion process), 3R (2011), No. 6.

Reducing operational costs

Great portions of the operational costs of CCP are also influenced by the quality of remote monitoring. The less often the in-situ monitoring measurements stipulated in the DVGW Code of Practice GW 10 “Cathodic Protection (CP) of Buried Storage Tanks and Steel Pipes – Commissioning and Monitoring” (2008-05) are required, the better the operational costs for CCP can be optimised. GW 16 formulates both the requirements placed on remote CCP monitoring in relation to the selected remote monitoring category and the respective possibilities to reduce in-situ measurements.

With online CCP monitoring, an economic installation of a remote monitoring process according to GW 16 Category 2c, and thus the possibility to completely do without in-situ measurements according to GW 10, is again within the range of possibility. Extensive test measurements which were carried out in our premises have shown that this measurement technology was also able to safely detect the occurrence of new coating defects, whose ground resistance was 100 times higher than the coating resistance of the pipeline section (note: GW 16 merely stipulates a factor of 15). ***Figure 9*** shows the electrical equivalent diagram of this situation.

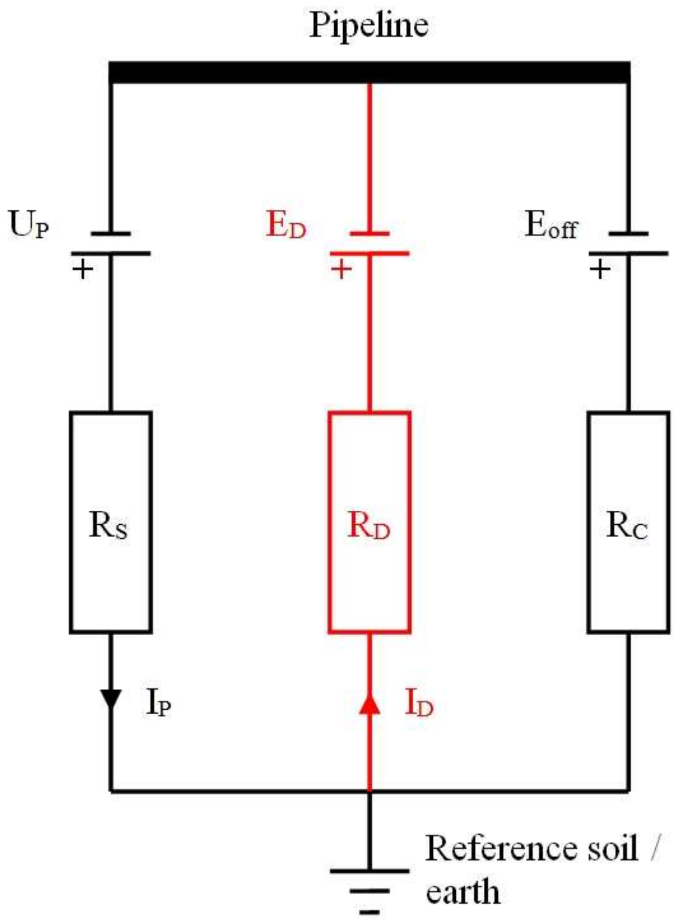

Figure 9: *Electrical equivalent diagram for a cathodically protected pipeline with additional, temporarily effective coating defect with relatively high resistance*

I_P = *Protective current without new coating defect*
U_P = *Output voltage at protective current unit without new coating defect*
R_S = *Spread resistance of anode system*
U_{off} = *OFF potential in the pipeline without new coating defect*
R_C = *Coating resistance of pipeline without new coating defect*
R_D = *Spreading resistance of new coating defect*
U_D = *Potential of new coating defect*
I_D = *Current to new coating defect*

Danger prevention

The key innovation of the online CCP monitoring technology is the possibility to prevent danger on cathodically protected buried pipelines, which has been made possible by detecting even the smallest external impact on a pipeline.

In general, the person who damaged a high pressure gas pipeline with gas leakage will notice and report this event. If, however, there is no gas leakage, but the external impact leads to a mechanical weakening of the pipeline, problematic situations may occur later. In the latter case, it is particularly important that the operator is informed about such an external impact so that appropriate countermeasures can be initiated.

Summary

In the field of CCP, the new online CCP monitoring of cathodically protected pipelines represents a ground-breaking innovation. With the continuous monitoring of important CCP measurement parameters, dangerous external impacts on pipelines, such as from an excavator bucket, can be detected promptly. These external impacts are detected and sent immediately as danger alarm, even if they did not cause an apparent destruction of the pipeline. External mechanical impacts, in particular, which do not lead to an instant gas leakage, cannot be recognised with usual measurement technologies. Up to now, network operators have to rely on that the respective person notices and reports the damage.
What's more, a detailed evaluation of the CCP measurement parameters, in combination with an improved protective current unit technology, allows for a continuously adjustable control of the CCP protective current in order to counteract possible dangers through AC corrosion.
With the fast and permanent integration of the CCP sensors to the control centre via standardised transmission protocols, as they are used in networks, wireless communication and on the Internet, information from and to the sensors can be transmitted between the systems any time.
The implementation of online CCP monitoring will help to significantly reduce the operational costs of CCP, since it makes an economic installation and operation of remote CCP monitoring according to Category 2c feasible in many cases.

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