Evaluation of techniques for the determination of the corrosion risk caused by induced AC-currents on cathodically protected pipelines

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Abstract

Different techniques used for the determination of the AC-corrosion risk of cathodically protected pipelines were investigated in laboratory and field tests. The reproducible attack of the AC corrosion was possible within 24 hours, by taking into account the specific effect of the soil composition, allowing the test of the different available techniques under laboratory conditions. The AC-Voltage, the AC-current density and the Highspeed measurement proved to be sensitive to the AC-corrosion. Additionally, these techniques were used for the characterization of coupons at 12 different locations in Switzerland. In some cases the different techniques yielded contradictory results regarding the risk of AC-corrosion. After at least 2 years of exposure, the coupons were excavated. On two samples corrosion attack was found, which was not detected by any of the available techniques used for the evaluation of the AC-corrosion risk. This failure of the available methods was related to the formation of chalk layers covering only a part of the sample surface and fluctuations of the induced AC-power.

Zusammenfassung

Die verschiedenen Verfahren, welche heute für die Beurteilung der Gefährdung von kathodisch geschützten Rohrleitungen gegen Wechselstromkorrosion eingesetzt werden, sind in Labor- und Feldversuchen untersucht worden. Durch Berücksichtigung der Bodenzusammensetzung gelang es Wechselstromkorrosion innerhalb von 24 h reproduzierbar zu erzeugen. Dies ermöglichte die Überprüfung der verschiedenen Verfahren zur Feststellung der durch Wechselstrom verursachten Korrosionsgefährdung im Labor. Die Vorgänge sind komplex, sodass es nicht möglich ist, ein einziges Messverfahren in allen Böden einzusetzen. Die heute verfügbaren Methoden wurden zudem an einer neu entwickelten Messprobe in Feldversuchen getestet. Während mindestens 2 Jahren waren solche Messproben an 12 durch Wechselströme beeinflussten, kathodisch geschützten Rohrleitungen angeschlossen. Nach dem Ausgraben der Messproben wurde festgestellt, dass die in der Schweiz getroffenen Massnahmen zur Verringerung der Gefährdung nur zum Teil wirksam sind. An zwei Stellen wurden Korrosionsangriffe festgestellt. Diese Angriffe konnten mit keinem der eingesetzten Beurteilungsverfahren detektiert werden. Die Abklärungen ergaben, dass das Wechselstromdichte-Kriterium keine Vorhersage erlaubte, da die Messoberflächen teilweise verkalkt waren. Dadurch wird die Wechselstromdichte lokal erhöht. Wie schon die Laboruntersuchungen zeigten, ist die heute zur Verfügung stehende Highspeed-Messung zu langsam und die Ergebnisse sind deshalb nicht eindeutig zu interpretieren.

Résumé

Différentes techniques utilisées pour la détermination du risque de corrosion AC de pipelines dotés d'un dispositif de protection cathodique ont été évaluées à l'aide de test en laboratoires et sur le terrain. Une attaque de corrosion AC sur une période de 24 heures à pu être effectuée de façon reproductible en laboratoire, permettant de tester la réponse des différentes techniques disponibles et ce en tenant compte les effets spécifiques de la composition du terrain. Les mesures de tension alternative, de densité de courant alternatif et les mesures à vitesse élevée se sont révélées sensibles à la présence de corrosion AC. En plus, ces techniques ont été utilisée pour la caractérisation de coupons à 12 différents endroits en suisse. Dans certains cas les différentes techniques ont produits des résultats contradictoires concernant les risques de corrosion AC. Après au moins 2 ans d'exposition, les coupons ont été excavés. La présence d'une attaque de corrosion sur deux échantillons n'a été détectée par aucune des techniques à disposition pour l'évaluation du risque de corrosion AC. Cet échec des techniques de détection standards peut être expliqué par la présence de couches de craie recouvrant partiellement la surface de l'échantillon ainsi que par des fluctuations de la puissance alternative induite.

Introduction

With the observation of the first corrosion damages induced by AC corrosion on cathodically protected pipelines in the 1988 [1, 2] the confidence in the efficiency of cathodic protection was shaken. As a consequence, the phenomenon "AC corrosion" was investigated very detailed.

AC corrosion on cathodically protected pipelines has so far mainly occurred on tubes with a polyethylene coating. The reason for this effect is the high number of defects in the bitumen coating, which resulted in a deviation of the induced AC current. First investigations demonstrated, that the AC corrosion can only occur if the AC current density exceeds 30 A/m^2 [4-6]. The electrical and physical parameters, which influence the current density, are the induced AC voltage and the soil resistivity in at the defect in the coating. The current density is proportional to the reciprocal value of the radius of the defect. Hence, large defects are less critical than small ones. Most corrosion damages were found on defects with an area of about 1 cm^2.

In the present work the influence of chemical parameters on the AC corrosion was investigated. The chemical properties determine the soil resistivity around the defect in the coating. They depend on the soil composition and the modification of the soil due to the cathodic protection. The cathodic protection results in the formation of OH^- and causes the migration of cations to the defect. It was shown that both effects influence the spreading resistance. Sodium and potassium hydroxides are readily soluble and form a highly conductive electrolyte while the formation calcium and magnesium ions result in the formation of insulating covers [7, 8, 9].

Based on the obtained experience it was possible to reproduce ac-corrosion under laboratory conditions within 24 hours. Hence, it was possible to characterize the available measuring techniques and corresponding criteria.

Additionally to the laboratory investigation coupons were places in 12 possible critical locations in Switzerland. For this characterization a new probe was developed that allowed the determination of the weight loss, the potential, and the current independent on external factors. The methods tested in the laboratory were applied on these coupons in regular intervals. After exposure, it was possible to characterize the validity of the characterization techniques. Additionally, the efficiency of mitigation for the ac-corrosion risk was tested.

Experimental

Laboratory investigations

Cylindrical samples of mild steel were embedded in epoxy resin. The exposed area was 1 cm^2. These samples were embedded in quartz sand, which was soaked with various electrolytes of well-defined composition. This allowed for the simulation of the behavior in soil. By means of an AC and DC source a cathodic protection and an influencing AC-current were simulated. The highspeed measurement was performed with the Modata of Weilekes. A detailed the description of the experimental set-up is given in [8].

Field investigations

For the field investigations it was necessary to develop a suitable probe. The main requirement was a controllable reference electrode close to the sample, the possibility to mount several samples for statistical control and a sample orientation that would exclude the loss of contact to the soil due to ground movements after installation. The probe is schematically shown in Fig. 1. Three metal cylinders with a surface area of 1 cm^2 and an orientation of 45° were mounted in the probe. The reference electrode was introduced through the tube and has electrolytic contact to the soil through Bentonit and porous glass. Hence the reference electrode could easily be controlled and exchanged.

Twelve probes were positioned on sites with possible ac corrosion risk and connected to the cathodically protected pipelines. Hence it was possible to characterize the behavior and the available techniques under real conditions.

After excavation the weight loss of the samples was determined by etching of the surface with an inhibited acid. In combination with the density of steel it was possible to calculate the material loss in μm/year.

Results and discussions

The off-potential

The off potential allows characterizing the quality of the cathodic protection. With exception of three locations the threshold of -0.85 V_{CSE} was fulfilled. It was found that there is a correlation between the off potential and the spreading resistance of the samples. Since the formation of insulating covers was demonstrated in laboratory investigations the increase of the spreading resistance in the field investigations can also be correlated with the formation of chalk layers on the metal surface. These covers prevent the access of the cathodic protection current and result therefore in an increased off potential. The spreading resistance is changing over time. This can be explained with alternating formation and disbonding of the insulation cover on the metal surface as a function of time. The disbonding results in a decreased resistance and a lower off potential due to the better access of the current to the metal surface. Hence, the cover can be subject to continuos formation and destruction This phenomena might be caused by the decreased current density and a loss of the alkalinity of the soil, which results in the redissolution of the cover.

AC-current density

In the laboratory investigations the critical value of 30 A/m^2 was confirmed. Higher ac-current density resulted in corrosion attack, which increased with increasing current density [8]. In the field investigations the critical value of 30 A/m^2 was only exceeded once. Therefore, based on this criterion no corrosion attack on any of the 12 locations was expected.

The fast measured off-potential (Highspeed measurement)

Under laboratory conditions the influence of the ac-current density, the cathodic protection current density and various cation were investigated [8]. With increasing current density an increased maximum value in the fast measured off potential was found (Fig. 2). This is in agreement with theoretical considerations demonstrating the correlation between the current density and the highspeed measurement.

In literature the threshold is at -0.85 V_{CSE}. However, the results in Fig. 2 clearly show, that this value is not exceeded, although ac-corrosion occurred on the samples. This result demonstrates that the method or the threshold need to be checked carefully.

The cathodic protection can result in the formation of a chalk layer on the metals surface. Its influence on the results obtained with the highspeed measurement was investigated by experiments in $Ca(OH)_2$. The results were less reproducible and exhibited a significant scatter. Additionally a significant time effect was observed which could result in a shift of the results in anodic direction (Abb. 3). After the experiment the formation of a chalk layer was found on the surface. Which might be responsible for the time effect and the significant shift of the potentials.

On the probes in the field measurements similar results were obtained. Consecutive measurements resulted in a good reproducibility within 10% of the maximum value. A typical result is shown in Fig. 4 for two measurements. The threshold of is exceeded for both samples. Clearly a phase shift between the on- and off potential was found for one of the samples, while the other showed a linear behavior. The phase shift can be explained with capacitive charging at the electrochemical double layer. However, the reason for the different capacitive contributions for samples measured in the same location in the same time period is not clear. Apparently the induced voltage on the pipeline is not responsible for the difference.

The laboratory experiments demonstrated that an increased ac-current density results in increased values in the highspeed measurement (Abb. 4). The analogous experiment was performed in the field, by running the highspeed measurement with and without AC-deviator connected to the pipeline (Fig. 5). The threshold of -0.85 V_{CSE} was exceeded with the deviator connected to the pipelines. Without the deviator the values significantly increased demonstrating the correlation between ac-current density and values determined in the highspeed measurement in the field application. Since the current density is linked with the ac-corrosion risk, the values obtained with the highspeed measurement should indicate a possible corrosion risk as well.

Based on these observations a correlation between the ac-current density and the maximum value determined in the highspeed measurement is expected. The results of all measurements at all locations are shown in Fig. 6. It is clear that the expected correlation between the ac-current density and the off potential is not given. The highest off-potentials are clearly observed at small ac-current densities.

In the laboratory investigations it was found that the increased off potential is linked to the formation of an insulating chalk layer on the metal surface. A similar conclusion seems to be possible in the case of the field measurements. The insulating layer causes a low current density but is responsible for the high values in the highspeed measurement. Apparently additional processes influence the discharging of the surface. Therefore the highspeed measurement is not applicable in the presence of chalk layers.

Excavation of the probes

The excavation allowed the visual inspection of the samples, the determination of the corrosion state and the weight loss, as well as the degree of corrosion attack. The visual inspection showed clearly that the formation of a chalk layer could occur even in cases where the calcium content of the soil is comparable small. The deposition of chalk could result in the formation of covers with a thickness of several millimeters. It was found that the samples that had maximum values above +1 V_{CSE} in the highspeed measurement exhibited a chalk layer on the metal surface. The corrosion rate of most samples was clearly smaller than 10 µm/year. Only on two samples from two locations this value was exceeded.

In one case local grooves were found with a depth of up to 140 µm. Locally, more than 50 µm steel were lost per year. In the second case a weight loss of 1.3 grams was found, which corresponds to a uniform material loss of 580 µm/year. In Fig. 7 an image of the corresponding sample is shown. As the attack was not uniformly, the observed depth was up to 1 mm/year.

The evaluation of the data of these samples makes clear that none of the criteria, which are currently used for the assessment of the ac-corrosion risk, indicated a possible corrosion attack. The ac-current density was below 10 A/m^2, with the values of the highspeed measurement and the off-potentials always were below -0.85 V_{CSE}. Additionally the ac-potentials were below 2.5 V. this is an indication that the surface of both samples was not completely covered with chalk.

A possible explanation for the failure of the available criteria to detect the corrosion attack or at least the possible corrosion risk is the partial covering of the surface with the chalk. This could result in a decreased surface area and an underestimation of the actual current density. This partial covering oft the surface was indeed observed.

The soil at both locations had a low specific resistivity of 10-30 Ωm and the hardness of the water contained in the soil was higher than the carbonate hardness. Hence, apart of the observed chalk formation also hygroscopic hydroxides were formed. This resulted in a decreased spreading resistance of the surface areas, which were not covered by the chalk layer and a locally strongly increased current density.

Influence of soil composition

In the laboratory investigation a good agreement between soil composition and spreading resistance measurements was found. Based on these observations a similar behavior was expected in the field tests. The soil resistivity, the pH-value, the water content the hardness and the buffer capacitance with respect to alkalinity was investigated for the soils at the different locations. The observed behavior is complex. This may be caused by the complexity of the processes in the soil as waterflow, temperature change, soil inhomogeneity and the problems with the determination of the soil composition. However a the following general conclusions are possible:

- Soil with a resistivity of more than 100 Ωm and a carbonate hardness which is higher than the overall hardness does not offer e significant risk of ac-corrosion. This is due to the formation of a dense chalk cover, which results in a small spreading resistance.
- Soil with a resistivity of more than 100 Ωm and a carbonate hardness, which is comparable with the overall hardness, represents a possible risk of ac-corrosion. In this case no significant chalk layer will be formed and the spreading resistance will decrease over time.
- Soil with a resistivity of less than 25 Ωm and carbonate hardness, which is smaller than the overall hardness represents a possible, a possible risk of ac-corrosion. In

this case the surface is partially covered with a chalk layer with locally increased current density.

Conclusions

AC-corrosion could be reproducibly generated within 24 hours allowing for the reliable investigation of the critical parameters and the testing of the characterization techniques. Most of the investigated sites are protected against ac-corrosion. The mitigation measures taken in Switzerland are efficient. Out of 12 Locations corrosion attack was only found at two sites. None of the currently available techniques could detect the corrosion attack found at those sites.

The critical current density of 30 A/m^2 was confirmed. However, this criterion is problematic if the surface area is decreased by the formation of a chalk layer on the surface. In this case the current density is underestimated. This could have caused the corrosion attack in the field tests.

Both, in the field tests and the laboratory investigations the values of the highspeed measurement were found to correlate with the ac-current density. Hence, the highspeed measurement is basically suited for the assessment of the corrosion risk caused by the ac-influence. The advantage is that it is independent on the surface area and the problems created by the decreased surface area should be excluded. However, it was found that the formation of a chalk layer strongly affects the results in the highspeed measurement. Therefore the technique can only be used in the absence of the covering layers. Additionally it was found that the threshold or the data an additional problem is hat the threshold of -0.85 V CSE is too high as neither in the field measurements for in the laboratory investigations the value was exceed although corrosion was occurring. Therefore the problem of the highspeed measurement is the overestimation of the corrosion risk in the case of chalk layers and the underestimation in the case of the standard threshold. The effect of increased measuring speed is subject to current investigations.

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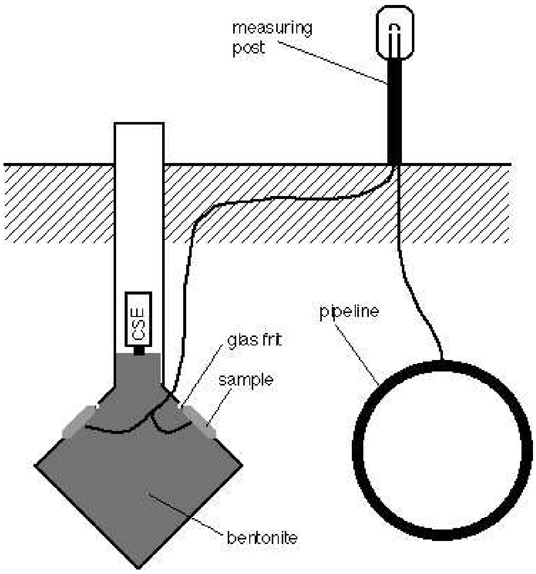

Fig. 1: Schematic set-up of the probe.

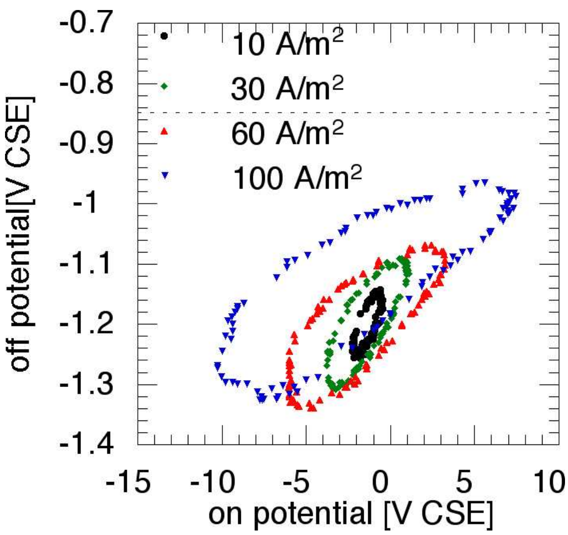

Fig. 2: Highspeed measurement with in NaOH and quartz sand.

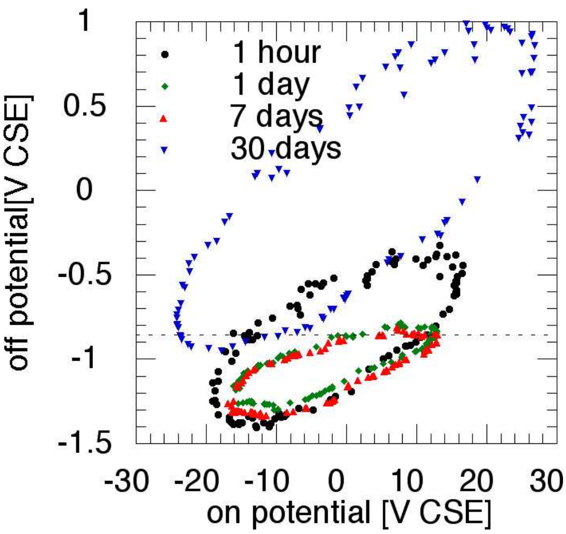

Fig. 3: Highspeed measurement at 100 A/m^2 in $Ca(OH)_2$-solution and quartz sand.

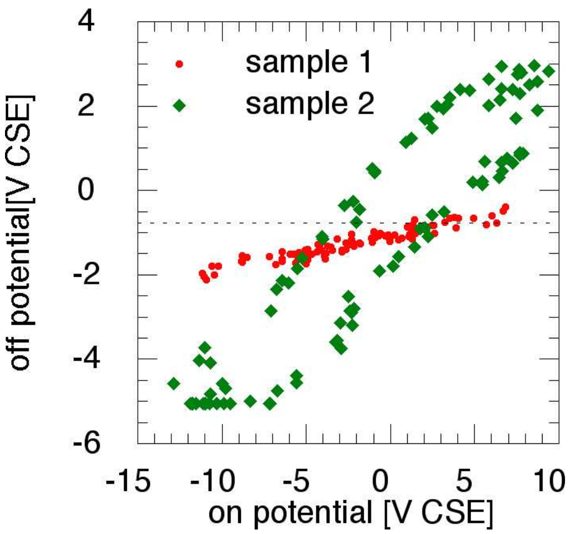

Fig. 4: Highspeed measurement on two samples at one location in the field.

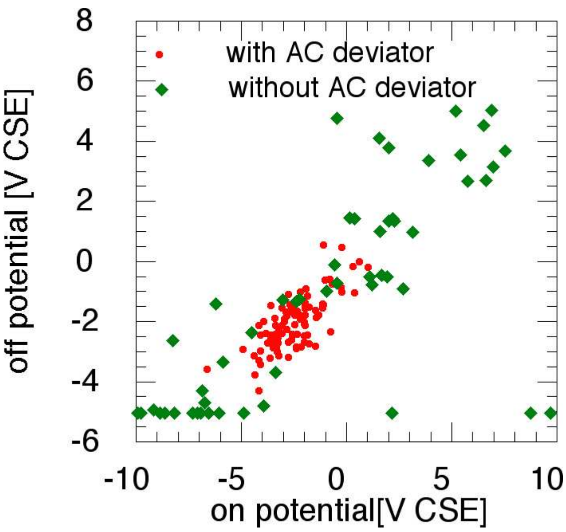

Fig. 5: Highspeed measurement on a field sample with connected and disconnected ac deviator.

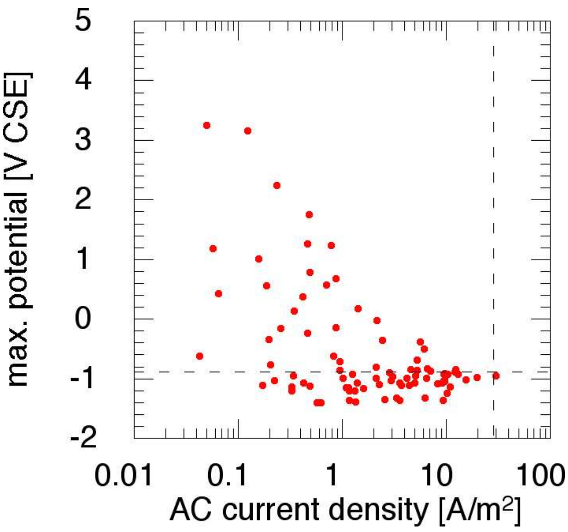

Fig. 6: Correlation between ac current density and max. off potential determined with the highspeed measurement.

Fig. 7: Corrosion attack on a field sample The diameter is 11.5 mm.