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Real time remote monitoring and control of the cathodic protection for mitigation of interference

Télécontrôle de la protection cathodique pour minimiser la corrosion sous condition d'interférence

Fernwirktechnik zur Kontrolle des kathodischen Korrosionsschutzes unter Fremdbeeinflussung der Rohrleitung

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Abstract

The EN 15280 and ISO 18086 provide clear criteria with respect to the control of the risk of a.c. corrosion. However, meeting these requirements in the case of strong variation of a.c. and d.c. interference over time is often difficult in the practical application. The real time application of remote monitoring of the interference conditions in combination of active control of the rectifier allows for dynamically reacting on the interference conditions. This results in an optimized cathodic protection while minimizing the risk of a.c. corrosion. The results of an extended field test on six pipelines are presented and the details of the numerical calculation models for the remote control are discussed. Moreover the issues related to external real time calibration of reference electrodes are addressed.

Résumé

La norme EN 15280 et la ISO 18086 définissent des critères clairs pour le contrôle du risque de corrosion a.c.. Cependant, respecter ces critères lors d'une variation importante d'interférence a.c. et d.c. au cours du temps n'est pas chose facile en pratique. L'application en temps réel de la télésurveillance des conditions d'interférence en lien avec le contrôle actif du redresseur de courant permet de contrôler dynamiquement ces conditions d'interférence. Il en résulte une protection cathodique optimisée tout en minimisant le risque de corrosion a.c.. Il sera présenté les résultats de tests sur site sur six conduites et il sera discuté les détails des modélisations par calculs numériques pour un télécontrôle. En plus les problèmes associés à la calibration the l'électrode de référence est adressée.

Zusammenfassung

Die EN 15280 und ISO 18086 geben Kriterien für den Schutz von Rohrleitungen vor Wechselstrominduzierter Korrosion vor. Es zeigt sich nun aber, dass die Einhaltung dieser Vorgaben bei zeitlicher Variation von Gleich- und Wechselspannung schwierig sein kann. Durch Einsatz der Fernwirktechnik ist es möglich in Echtzeit dynamisch mit einer aktiven Steuerung der Schutzstromgeräte auf die Beeinflussung zu reagieren. Dies führt zu einem optimierten kathodischen Korrosionsschutz und einem verminderten Korrosionsrisiko. Die Ergebnisse einer umfassenden Felduntersuchung und die Details der numerischen Berechnungsgrundlage werden diskutiert. Darüber hinaus wird die Möglichkeit der Kontrolle der Bezugselektrode in Echtzeit diskutiert.

1. Introduction

By means of laboratory and field investigations in Switzerland and Germany, it was possible to determine the critical interference limits with respect to a.c. corrosion [1, 2]. It was demonstrated that the evaluation of the corrosion risk is possible by means of a.c. and d.c. current densities that were determined on coupons. With the help of numerical models, it was also possible to calculate the expected current densities from the set on-potential, the induced a.c. voltages and the present soil resistance [3, 4]. This now allows for the first time to assess the a.c. corrosion risk at each measuring point, without necessarily having to install coupons. Experience gained with the application of EN 15280 has shown so far that the required limits cannot be implemented on any pipeline. Their observance is particularly difficult at high a.c. voltages and high protection current requirements, high soil resistivity and d.c. current interferences. This is due to the comparatively positive on-potentials that may be required in the case of cathodic protection at less negative cathodic protection levels to meet the requirement of J_{dc} < 1 A/m^2 according to EN 15280 [1, 2]. They allow only little flexibility in adjusting the rectifier. This way, the a.c. corrosion risk can be eliminated. There is, however, in certain cases, the risk that the protection criteria for CP according to EN 12954 are not met.

The situation is further exacerbated by the often high, and especially strongly time-varying a.c. voltages. In addition to ensuring a sufficient cathodic protection, the question of the procedure for its setting and its monitoring arises.

The current procedure for setting up and monitoring a cathodically protected pipeline is based on regular control measurements (e.g. every 3 years according to EN 12954 for detailed and comprehensive assessment of the cathodic protection). Based on these data, the cathodic corrosion protection is set to a certain value. Now, if the a.c. or the d.c. influence varies strongly over time, this must be taken into consideration when setting the parameters.

If the influencing situation changes a lot, it may take some time until the deviation from the target values of the a.c. interference is determined and corrective measures can be taken. Due to the deregulated electricity market and the increasing share of wind, energy and thus the increasing current transport will increase this risk, because a.c. currents in power lines will strongly have variations in short period of time. The EN 15280 doesn’t provide any support in this respect, since the operator is encouraged to capture the influence over a representative time period. A specific example of these time variations of the interference is shown in fig. 1. It is clear that within a month, the a.c. voltage can vary between negligibly and considerably increased. The 24 hour mean values, which are often used, clearly do not represent representative values

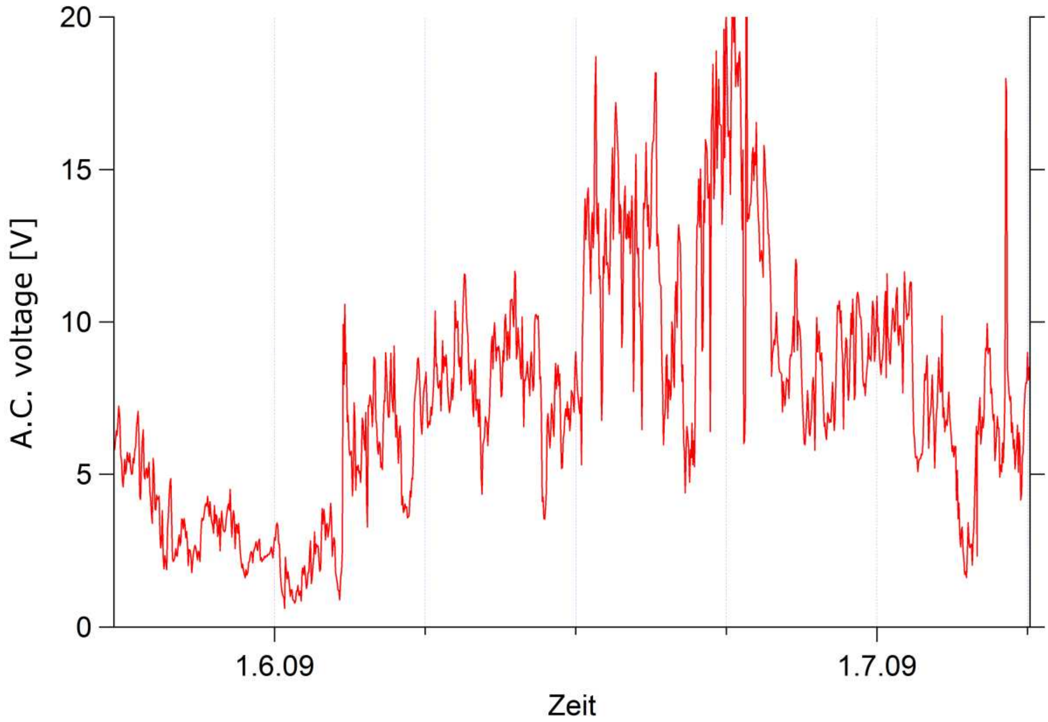

Fig. 1: **a.c. voltage induced in the pipeline over a period of one month.**

It is possible, that the situation arises in which the on-potential must be shifted to positive values due to high a.c. interference during a few weeks in the year, which then can lead to a reduction in the effectiveness of the cathodic protection. Conversely, if the on-potential is too negative, generally a sufficient cathodic protection can be achieved which however during the periods of high a.c. voltage influence leads to a.c. corrosion. Through active adaptation of the cathodic protection to the particular situation, a significantly improved protection could be achieved.

From the perspective of setting the CP, but also from the perspective of surveillance, the reasonable solution is an active cathodic corrosion protection, which can respond to the different time varying interference situations. The recovered findings out of the research project from the DVGW are presented and discussed here.

2. Control parameters

2.1. Introduction

Essential aspects of a.c. corrosion are understood due to laboratory and field experiments as well as theoretical considerations. In addition, the relevant limits could at least partly be explained with the help of thermodynamic and kinetic models [5, 6].

Concerning the limits it basically must be considered, that a.c. corrosion can be prevented by two complementary strategies. On the one hand this is the cathodic protection at low protection current density, where the on-potential must typically be more positive than -1.2 V_{CSE}. On the other hand this is the cathodic protection at high protection current density, where the on-potential must be more negative than -2.5 V_{CSE} in most cases, but depends on the upcoming a.c. voltage. In the following, the two different strategies to protect in terms of a.c.

corrosion are referred as "positive" and "negative" on-potential. The basic relationships are described in [2] in detail.

Currently not only limits based on current densities are defined, but also limits based on potential and a.c. voltage values. This represents a substantial improvement of the situation for assessing the risk of corrosion by a.c. interference, as these can be measured directly, while the current densities must be calculated from current measurements obtained on coupons. Thus, it is possible to determine the fundamental threat to the pipeline in terms of a.c. corrosion at every potential measuring point. The uncertainty, which arises from the current density, which is related to the coupon's surface size, its geometry and positioning, can be eliminated.

2.2. Control parameters

Based on the discussed criteria, for the active control, protective current densities determined on coupons as well as on-potentials can be used. The advantages and disadvantages of the two approaches are listed in the following:

Current densities: According to the current model concepts, a.c. corrosion is controlled by the effectively occurring current densities. So it might make sense to use the current densities for the control of the active CP. With this approach, however, the following problems arise:

- The current densities can only be determined with the help of coupons. During the assessment it must always be assumed that the coupons are installed in the most critical locations along the pipeline. If this is not the case, a misjudgement of the corrosion risk may occur. This is for example the case when the coupons calcify and thus get high impedance.
- Soil conditions can vary a lot over short distances. In order to capture the critical case correctly, a wide variety of coupons must be installed.
- The measured current must be based on an assumed surface. The area may be overestimated in those cases where heterogeneous current distribution exists, a partial calcification, or loss of contact to the soil of the metal surface occurred. In contrast, the surface can also be underestimated if corrosion has led to an increase of the metal surface. These uncertainties are inherently associated with the use of coupons and cannot be solved easily.
- The current densities are controlled not only by the soil resistance and the voltages, but also by modification of the pH value at the metal surface. It is known that the spread resistance can only adjust to changing on-potentials by slow mass transfer processes. Since it can take days until a steady state is reached, it is a high challenge to control the current density in a given range based on a number of coupons.

On-potentials: The on-potentials can easily be measured at each measuring point and a change in the settings of the rectifier immediately leads to a correction at all measuring points. This makes it also possible to react to short-term effects. In addition to the advantage of easy adjustment and control, the assessment of the a.c. corrosion risk using the on-potential and the a.c. voltage has the great advantage that these values can be measured easily along the entire pipeline. But also the assessment based on the on-potential has certain disadvantages:

- The assessment of the corrosion risk is based on the assumption of the worst case. Under certain conditions, the on-potentials are therefore set to unnecessarily negative resp. positive values. This is for example the case when defects on a pipeline in the a.c.-affected area are covered with a high-resistance layer of lime.
- To calculate the tolerable interference values the soil resistivity is required. Although this can easily be measured along the line, due to the heterogeneous conditions there will be an uncertainty. In contrast, coupons are capable to represent the actual local soil conditions corresponding to the area where they are installed.
- The a.c. corrosion is controlled by the current densities. The currents passing through a defect arise from the on-potential, the a.c. voltage and the spread resistance. The spread resistance is a function of the protective current and hence also of the on-potential. The lowering, but mainly the increase of the spread resistance, caused by changing the setting of the rectifier, is a slow process. In the calculation to find the optimum operating conditions the polarization time is assumed to be infinitely long, which inevitably cannot be true in real operation. The given findings indicate that this problem can be eliminated by taking simply the average [7, 8] value of the on-potential and the a.c. voltage. In this way, temporary fluctuations of the on-potential due to controlling, telluric, stray currents, grounding measures, intensive measurements and fault location etc. can at least partly be corrected.

Based on these explanations, it is clear that controlling the potentials has decisive advantages. In particular, the issue of using coupons, which provide only local information and are required in big numbers, is bypassed.

2.3. Optimizing the control parameters

The discussion shows that in terms of controlling it makes sense to use the on-potential as a control variable for the active CP. Current densities and potentials, however, are related by Ohm's Law. Taking into account the following primary relations, it is possible to calculate the current densities for a given metal surface in contact with soil from the potential values [3, 4].

- The pH at of the steel surface of the coating defect depends on the protective current density,
- The distribution of the pH value in the soil is determined by migration and diffusion,
- The spread resistance of the defect depends on the soil resistance, the pH as well as its distribution in the soil,
- The IR-free potential of the defect is a function of the protective current density and the pH,
- The a.c. current density influences the IR-free potential and thus the protective current density due to the Faraday rectification.

Under consideration of the thermodynamic [9] and kinetic [10, 11] parameters as well as a mathematical description of the lowering of the spread resistance due to the increase of the pH value [5] at the steel surface as a result of the cathodic protection, the corrosion process under the influence of a.c. current can be described [3, 4].

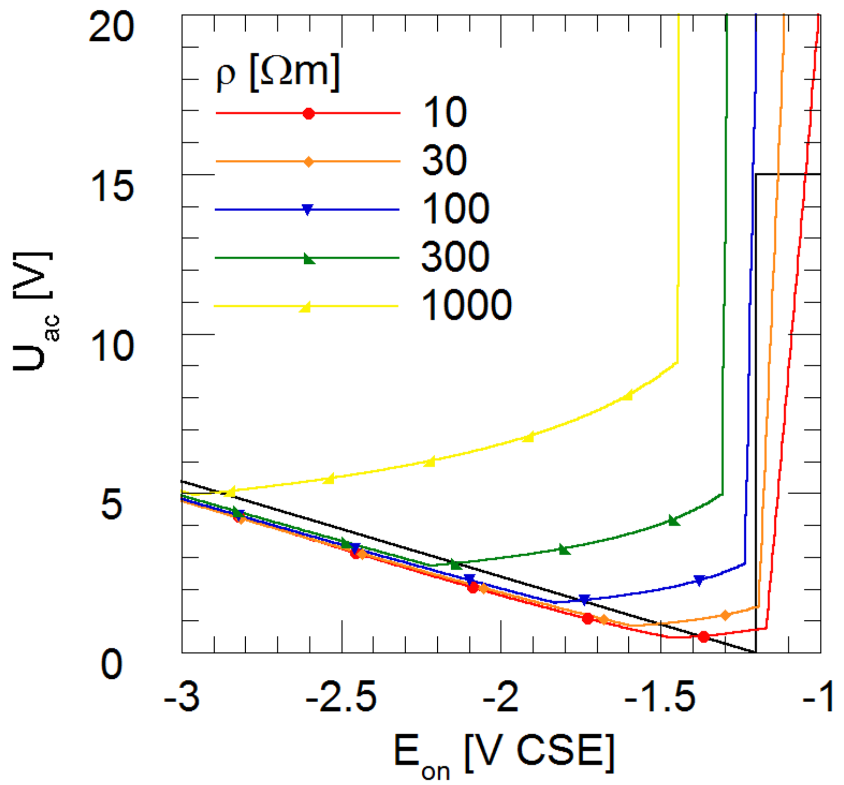

Fig 2: **Influence of the soil resistivity on the limit value curve of a defect of 1 cm^2 calculated taking into account the influences of thermodynamics, kinetics and mass transfer on the CP**

The results of the calculation for various soil resistances are shown in fig 2. The black line represents the limit values according to AfK Recommendation No. 11 [12] and EN 15280. The data in fig. 2 show that at low soil resistivity, the on-potential must be shifted to more positive values. In contrast, it can be concluded that at elevated soil resistivities highly increased a.c. voltages can be tolerated at on-potentials more positive than -1.2 V_{CSE}.

2.4. Conclusions

Based on these explanations, it is clear that for controlling the CP the on-potential is a useful parameter. Using the calculated thresholds according to fig. 2, the influence of the local soil resistivity is taken into account. This makes it clear that in principle each measuring point has a maximum tolerable a.c. voltage. Thus, it is expected that not necessarily those pipeline sections with the highest a.c. interference exhibit the highest corrosion risk.

3. Control parameters

3.1. Introduction

Based on the discussion of the various influencing factors, a procedure for setting the CP can be derived. This applies regardless of whether the CP is equipped with an active control, or whether the remote monitoring data is evaluated automatically using the current findings.

3.2. Preliminary investigations

For an ideal setting of the CP in order to prevent a.c. corrosion, at least the following values must be recorded at all measuring points:

a) Mean on-potential determined over a representative period.

b) Average a.c. voltage determined over a representative period.

c) Soil resistivity at pipe depth.

Based on the soil resistivity, the threshold value according to fig. 2 is determined. By comparing these values with the on-potential and the a.c. voltage the corrosion risk is evaluated. Based on this analysis the regions with maximum risk can be identified. These are not necessarily the sections with the highest a.c. voltage interferences, as also the soil resistivity and foreign voltage gradients have a significant impact.

3.3. Choice of the protection strategy

In a next step, the decision should be made whether the pipeline is in principle protected at a less negative or more negative on-potential. This assessment could be based on the statements in [4, 12].

3.4. Installation of the remote monitoring

Based on the protection strategy and the field measurements, the critical areas of the pipeline can be determined and should be equipped with a remote monitoring. In general, this should be areas with the most negative or the least negative on-potential, minimal soil resistivity and increased a.c. interference. Ideally, each line section having a different source of influence should be equipped with a remote monitoring system, in order to capture time dependence. The required sampling rate is determined by the interference situation. In many cases it may be sufficient to record the values every hour, or even at a daily interval. In other cases with fast changing influence, it should be checked whether the collection of data, has to be made every five minutes for example.

3.5. Adjustment of the cathodic protection

As the starting condition, the cathodic corrosion protection should be adjusted in a way that the on-potential is more negative than -1 V_{CSE} in all sections of the pipeline. Based on the available knowledge under certain circumstances also mean on-potentials to -0.85 V_{CSE} can be tolerated [13].

3.6. Control of the cathodic protection

Based on the 24-hour mean values of the remote monitoring data, compliance with the limit value curves according to fig. 2 is assessed. In the ideal case, no critical influence occurs at any point. If it does, the corrosion situation can be improved by automatic or manual adjustment of the on-potentials. A shift of the on-potentials in positive direction shall only be allowed, if the permitted mean maximum value (e.g. -0.85 V_{CSE}) is always maintained at all points in order to respect the CP criteria (see EN 12954) and the a.c. criteria (see EN 15280).

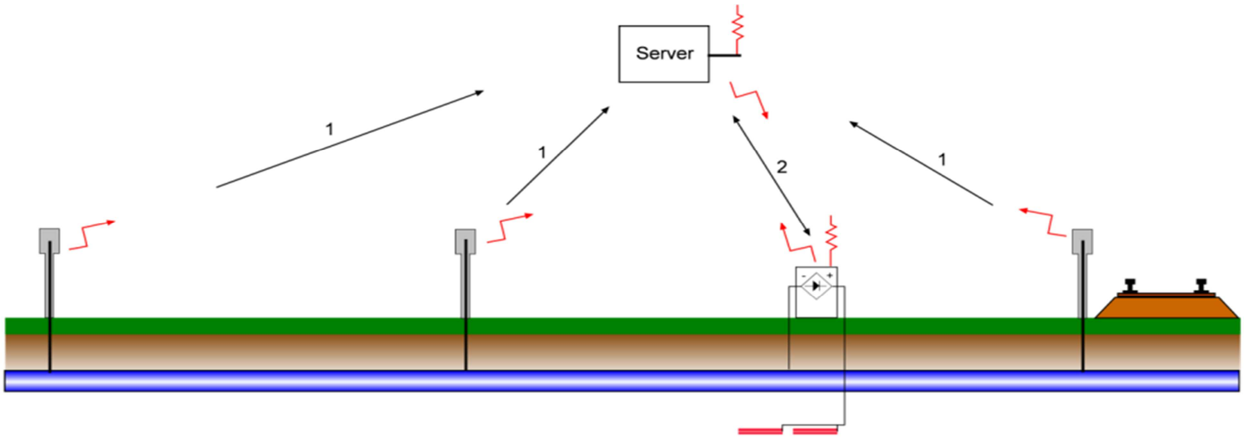

Fig. 3: **Structure of the control of the active CP**

The measurement setup as shown fig. 3 was used for the controlling. The data of the measuring points are sent to a server via a remote monitoring via connection 1. The server calculated the optimal CP settings and sent the parameters via connection 2 to the rectifier. The protection current device then sent the setting data to the server via connection 2. The setup of the individual measuring points corresponded to the one in [1]. In addition, the off-potential of the coupons was recorded.

4. Results and discussion

4.1. The control process

An example of the control procedures of the active cathodic corrosion protection system is shown in fig. 4. At the measuring site in question, there is a strong time-varying interference. Overnight, the influencing power plant is often out of service, while during the day strong a.c. interference occurs.

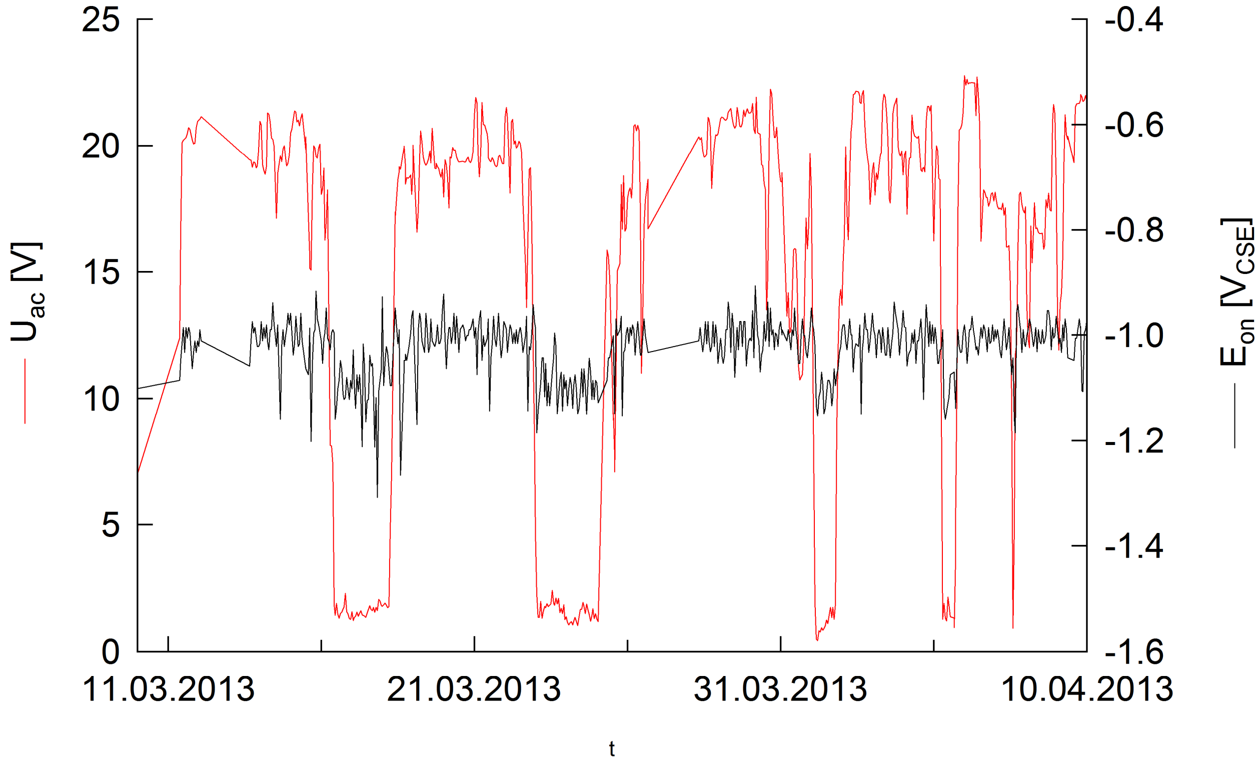

Fig 4: **A.c. voltage interference and the by the server controlled on-potential over time.**

The data clearly shows that the control of the cathodic protection actively adapts to the interference situation. The variation in the on-potential is only 100 mV. The thresholds according to fig. 2 for the corresponding location are shown in fig. 5. This clearly demonstrates that the controller has used the effective range in relation to the a.c. corrosion. The actual possible on-potential variations are very limited due to the low soil resistivity at the site. Since damage caused by a.c. corrosion has occurred already in the past in this section of the pipeline, the compliance with the limits is of importance.

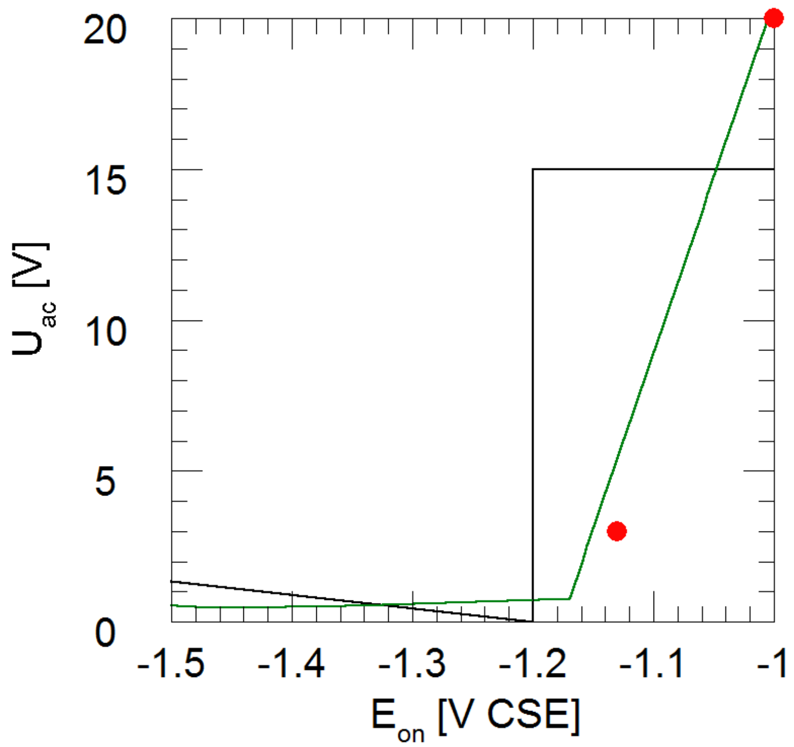

Fig 5: **Limit value curve calculated for the location with the soil resistivity of 13.5 Ωm. Additionally, the two interference situations from fig. 4 are shown.**

The shown examples demonstrate how the active CP operates on one specific measuring point. Often the locations with the lowest soil resistivity dominate the overall control. As clearly can be seen in fig. 4, the situation may change a lot with changing interference conditions, especially since different pipeline sections are influenced by different high voltage transmission lines resulting in changing measuring sites that control the CP setting.

4.2. Effectiveness of the cathodic protection

The analysis of the obtained data showed that corrosion of the coupons was successfully prevented on all pipelines in the case of a properly functioning control system. This was possible even though in many cases increased a.c. voltages, with average values over 15 V have occurred. This clearly shows the effectiveness of the active control, the application of the calculated limit values as shown in fig. 2, and the importance of the potential values for mitigation of a.c. corrosion.

The evaluation of the electrical resistance data of the coupons, which allow for detecting the corrosion rate in real time, and the associated methodology are essential for the evaluation of the results, the discussion of the limit values and the assessment of the model. The same analysis procedures were used as in the first field study of the DVGW [2]. These include the following basic principles:

1. The data acquisition every hour.

2. The evaluated period to determine the corrosion rate on the ER probes had to be at least one week.
3. The corrosion rate was determined by linear regression of the coupon thickness over a period of at least one week.
4. The averaging of the current densities, the a.c. voltage and the on-potentials was performed over a period of at least one week.

The data from the study confirm the results of the previous research. As long as the on-potential was more positive than -1.2 V_{CSE} and the a.c. voltage lower than 15 V in no case corrosion occurred. Severe corrosion only took place when the protection current density was higher than 1 A/m^2, the a.c. current density was higher than 30 A/m^2 or the ratio of a.c. to d.c. current density was bigger than 3.. The requirements of the regulations are thus confirmed by the current data. In the following, the results are discussed on the basis of an example.

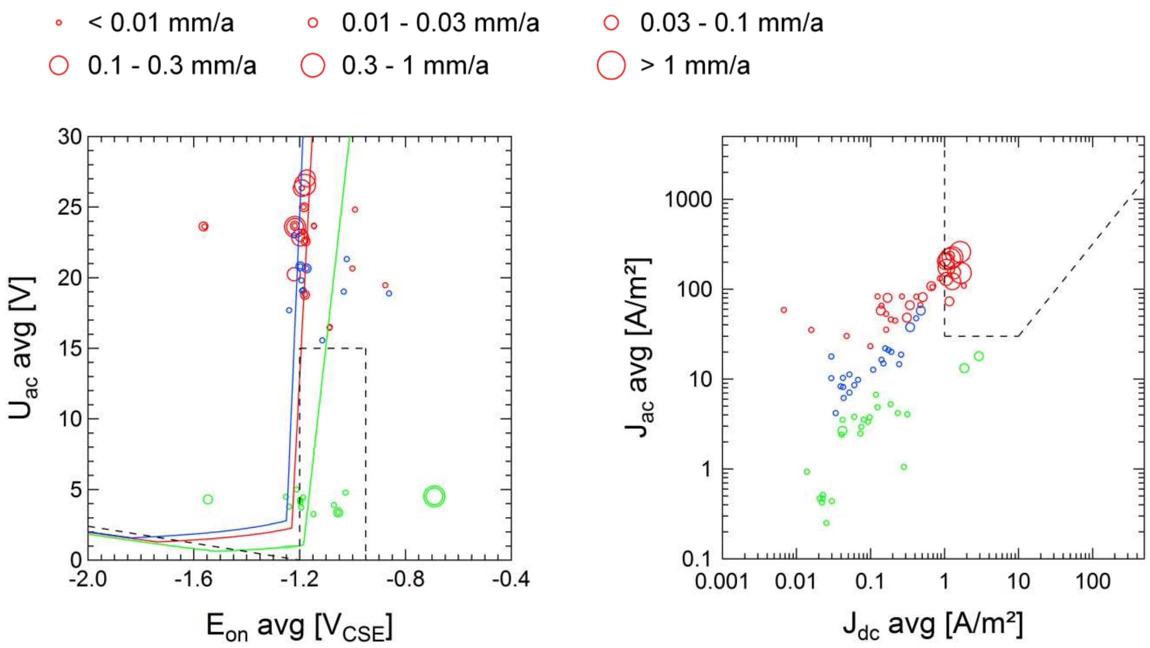

Fig 6: **Corrosion rate at the three locations of the pipeline 1. Left: dependence of on-potential and a.c. voltage; Right: dependence of protection and a.c. current density. Red: MK A; green: MK B; blue: MK C.**

The evaluated data of a pipeline are shown in fig. 6. The limit value curves for the allowable voltage values corresponding to their soil resistance for the different measuring points are shown there. It can be seen that the active control has usually been working properly and that the potential was within the specified range. The data of MK A show that strong a.c. voltage interference was present. When the on-potentials were at -1.2 V_{CSE} critical current densities and increased corrosion had occurred as expected. Once the on-potential was shifted in positive direction, the current densities reduced and the corrosion stopped. At MK C, the a.c. voltages were also increased. Due to the sufficient positive on-potentials the current densities were always uncritical as expected. Before the active control was put into service, at MK B too negative on-potentials and increased a.c. voltages occurred in several cases. The threshold values for the current densities were not exceeded in these cases. The calculations in fig. 2 are based on the assumption of the worst possible case. If there is an increase of the spread resistance by formation of calcareous deposits, the effective corrosion situation can be better than expected from the calculation.

The discussion clearly shows that there is an optimization problem of the cathodic protection. On one hand, the protection criteria for the CP must be met and on the other hand the on-potential must be not too negative to prevent a.c. corrosion. The currently available insight suggests that the a.c. corrosion rate will decrease with increasing corrosion depth [3, 4]. This is a consequence of the increase defect surface and the associated reduction of the current density with increasing corrosion depth. Mathematically, this results in a maximum corrosion depth at which it will stop. This theoretical effect is discussed in [3, 4]. It may explain the fact that most pipelines were protected in Europe for decades at on-potentials, which should have led to corrosion perforation to the current guidelines of the AfK Recommendation No. 11 and EN 15280. Repetitively strong a.c. corrosion attacks were found on coupons but on the pipelines no leaks were observed. This is due to the fact that the coupons often are much thinner than the pipelines.

Considering these findings, the on-potential must in any case be set in a way that the protection criteria for the CP are fulfilled, while taking into account a certain extent of a.c. corrosion. This model concept has just been validated [14]. This not only allows for more negative on-potentials but also explains the relatively high number of a.c. corrosion attacks and the limited number of leaks.

4.3. Controlling the reference electrodes

The key problem encountered during the field test was caused by correctly transmitted, but erroneous taken data. This was not caused by erroneous calibration of the measurement devices, but by strong deviation of the reference electrodes or defective over voltage protection. The close feedback loop between measured data and active control lead immediately to a non-suitable adjustment of the rectifier. This can cause operation conditions of the pipeline’s cathodic protection that are critical from the corrosion point of view.

For the safe operation of an active monitoring and control system for cathodic protection, the checking of the obtained data for plausibility is therefore of utmost importance. The key problem in this respect is the independent verification of the reference electrodes. Since the on-potential must be maintained in various pipeline sections within a precision of a hundred millivolts, even small deviations of a reference electrode has an important consequence on the operation of the system and hence the corrosion protection. It has to be considered that not all reference electrodes provide stable values and that deviations in the range of 10 mV can easily occur. For the long term operation of the system, a control mechanism is required that is able to identify erroneous reference electrodes and that is ideally able to automatically correct their deviation. Such a procedure is not only relevant for active control loops, but for all monitoring systems that do not have a monthly checking of the reference electrode values.

The chosen procedure for the remote validation of reference electrodes was based on the big amount of monitored potential data along the pipeline and the concurrent protection current taken with a very high time precision within one millisecond. The controlling mechanism changed the rectifier output in steps of 50 mV every hour to adjust the average on-potential value in the long term view, and thus caused small variations of the rectifier current and the on-potential within the range of a few hours. This low frequent potential variation provided enough time for the charging and discharging of all the capacitor based decoupling devices installed along the pipeline. The linear regression of the on-potential of every single test point versus the protection current allowed determining a slope and an extrapolation to zero current.

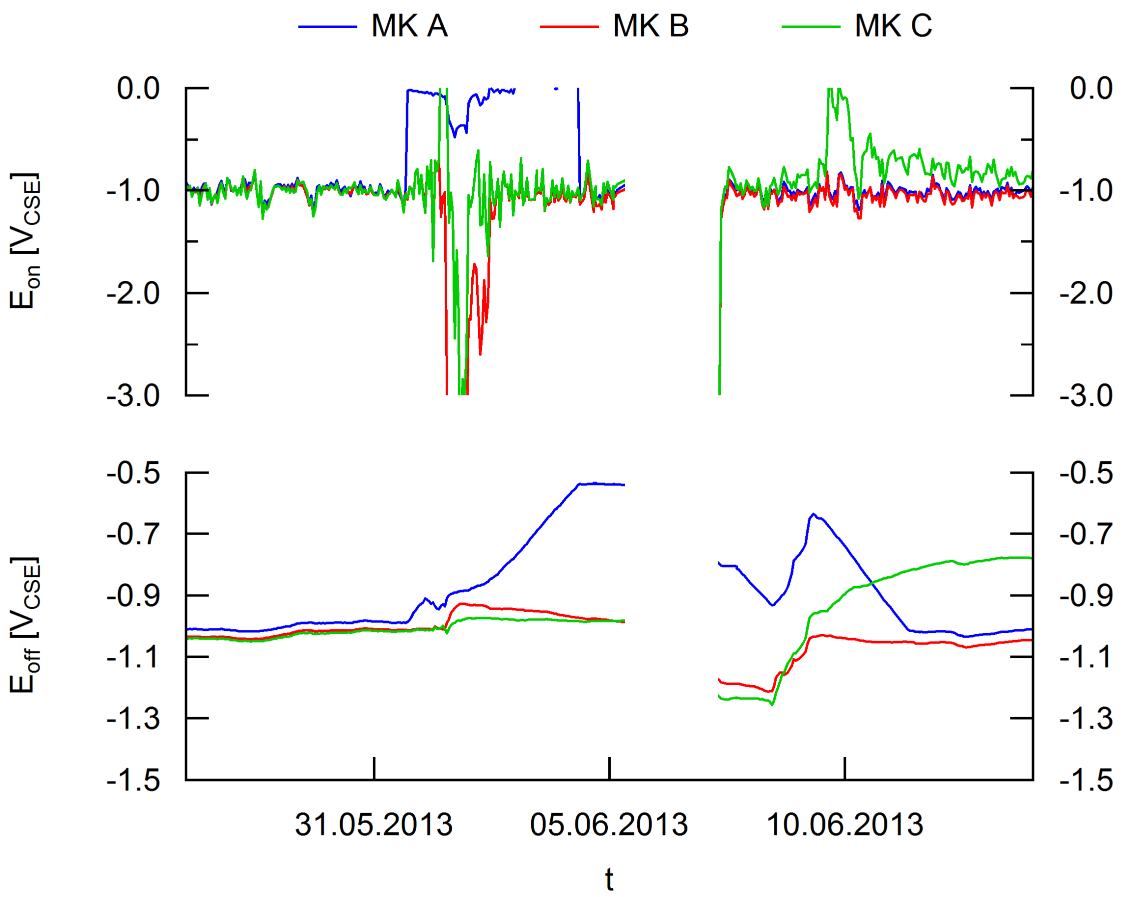

Fig. 7: **On-potential and extrapolated off-potential of a pipeline obtained during a period of three weeks.**

The potential value extrapolated to zero current is close to the off-potential determined at the specific position of the pipeline. Assuming the ohmic drop on the pipeline to be negligible at zero protection current, all extrapolated off potentials must be identical if measured versus remote earth. Deviations can only be caused by a deviation of the reference electrode or by voltage gradients either caused by coating defects or foreign current sources. If the coating defects and the foreign gradients are not changing, a deviation of the extrapolated values is bound to be caused by a deviation of the reference electrode. An example is shown in fig. 7 recorded during the period of three weeks. Originally the extrapolated off-potentials at all three locations showed a parallel behavior. Only the values from MK A had a certain constant deviation. Due to a thunderstorm the over potential protection at MK A was damaged causing significantly too positive values measured at this location. This sudden change in the potential readings is picked up by the extrapolated off-potentials at MK A. The control feedback mechanism, increased the output current of the rectifier. After repairing the overvoltage protection device, reasonable potential readings at MK A were obtained again. Since the extrapolation of the off potential values was based on the data of over one week it took some time for the calculated off potential values to recover to the original level.

After the failure in the data transmission between the 6th and the 8th of June an error in the reference electrode reading at MK C was observed. The deviation of the on-potential is not significant, but the calculated off-potential shows a gradual deviation. Contrary to the defective overvoltage protection device this deviation is caused by a deviation of the reference electrode at the given location.

The discussion demonstrates that a monitoring of reference electrodes is possible based on a big amount of data and their corresponding averaging. Based on the calculated off-potentials it was possible to identify erroneous potential readings caused by defective overvoltage protection devices and deviating reference electrodes. While the plausibility and the validity of the data can be checked with this procedure, it is not possible to determine the exact value of the individual reference electrodes. Effects of local voltage gradients cannot be determined and thus not be corrected. The checking of the reference electrode by means of a manual measurement on site cannot be replaced. Based on this evaluation method an increase of the measurement interval can be justified.

4.4. Summary

Based on the conceptual models and with the help of computational simulation, influence limits could be determined, which can be used as a basis for the active control of cathodic protection systems. The experimental results confirmed the applicability of this approach since on all six pipelines and on all 36 ER probes corrosion could be stopped even at strongly increased a.c. voltages as long as the active CP system was operating.

5. Conclusion

The threshold values determined during the investigations are based on on-potential and a.c. voltage and have shown to completely inhibit the a.c. corrosion. This is true even in cases with highly increased a.c. voltages. It was confirmed that the operation mode allowed for using time averaged values. The current model concepts are taking into account the kinetics, thermodynamics and mass transfer all, which allows for describing all relevant parameters. Thus, for defects in different soil conditions and with different geometries, it is not only possible to determine the respective permissible a.c. voltage as a function of the on-potential, but also to calculate the respective maximum depth at which corrosion is expected to stop.

By performing the evaluation of the remote monitoring data based on these calculation models the critical corrosion situations can be determined. From the real time operation data and the threshold values, the correction settings for the CP are calculated. By appropriate adjustment of the on-potential, the corrosion risk of the pipeline can be eliminated or at least reduced.

The advantage of proposed procedure, regardless of the degree of automation, is the prompt detection of the interference situation. Since this is determined in real time, the expenses for the effectivity control can be reduced. Given the expected increase in the temporal variations of the interferences, an optimized use of CP and thus an improved corrosion protection can be achieved.

The results obtained on several pipelines clearly show that an effective CP is the primary condition for the protection of the pipeline. An effective CP often requires a shift of the on-potential to more negative values, resulting in an increased risk of a.c. corrosion. Based on the current results this risk has to be taken into account since an effective CP is always required. Based on the model calculations, this does lead to a certain a.c. corrosion, which, however, with increasing depth should slow down and eventually stop at a defined depth. To date, the evidence for this effect is absent. Since most of the investigated pipelines were operated for years in an on-potential range that reproducibly leads to corrosion on coupons, but never resulted in a detectable leak, this conclusion is confirmed. This empirical observation supports the demand for an optimum cathodic protection and justifies the tolerance of a certain amount of a.c. corrosion.

The calculation of the off-potential based on the remote monitoring data allows for a control of all reference electrodes in the system against each other. This allows for increasing the control interval for manual control on site.

6. Acknowledgements

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