Possible Reasons Why Calculations Of Inductive Interference Pipeline Voltages Are Higher Than Conducted Measurements

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Abstract: Due to bundled energy routes, high voltage energy systems (e.g. overhead lines) are often located near buried isolated metallic pipelines. Thus, a possible high inductive interference from energy systems may produce hazardous AC pipeline voltages. High induced voltage levels can cause dangerous high touch voltages and AC material corrosion. Therefore, European standards limit the allowed maximum voltages for long and short term interference. Consequently, pipeline interference calculations are necessary to survey if given limits are exceeded. Unfortunately, the results of these – standardized – calculations are often higher than conducted measurements on pipelines, despite using state of the art calculation parameters. Investigations on this discrepancy are needed to bring calculations and measurement data closer together to avoid excessive measures which are often cost-intensive.

Even with experience, it is difficult to identify the very well hidden, but crucial factors for the discrepancy on specific calculated and measuring positions. The following factors are suspected to have different degrees of impact on induced pipeline voltages and have to be considered individually and with each other:

- Load current instead of using the maximum operational currents
- Reduction effect of global earthing systems
- Reduction effect of local earthing systems
- Reduction effect of practically achievable pipeline earthing systems
- Reduction effect of pipelines, running in parallel
- Reduction effect of parallel high voltage power systems with grounding conductors
- Incorrect or inadequate pipeline coating parameter
- The influence of the model-conform specific soil resistivity

Classification: Inductive interference, AC corrosion, pipeline safety

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1 Introduction

Because of bundled energy routes, high voltage energy systems (HVESs), e.g. AC overhead lines or AC traction power supply systems, are located in the vicinity of buried isolated metallic pipelines. Due to rising demand for HVESs, existing equipment is being refurbished or newly constructed and producing a higher inductive interference. Consequently, the calculation of the inductive interference is important because the possible high inductive interference from electric energy systems may produce hazardous pipeline AC voltages. High AC voltage levels can cause personal injuries (touch voltages) and damages to pipeline system components (overvoltage, AC material corrosion). This increased risk of material corrosion has an impact on the operation and safety of pipelines due to the higher possible risk of the worst case scenario, a leakage. This results in rising inspection and maintenance costs to prevent such leakages.

For minimizing the risk of personal injuries and material corrosion, European and Austrian standards and guidelines (EN 50443 [1], EN 15280 [2]) exist which limit the maximum voltage for long term and short term interference. For touch voltages, the limit is 60 Volt in normal operations and 1500 Volt in short-circuit-situations while the limit for AC corrosion is 15 Volt. If the pipeline interference voltage is within given limits, the risk for personnel and material is acceptable and no further measures, e.g. AC earthing systems, special working methods or additional isolating joints along the pipeline are required and no further mitigation costs are generated.
For this reason it is necessary to calculate the induced pipeline voltages already in the planning stage or in the case of significant changes in the pipeline or HVESs to specify necessary protection measures, particularly in areas where the pipeline interference voltage is already near the given limit.

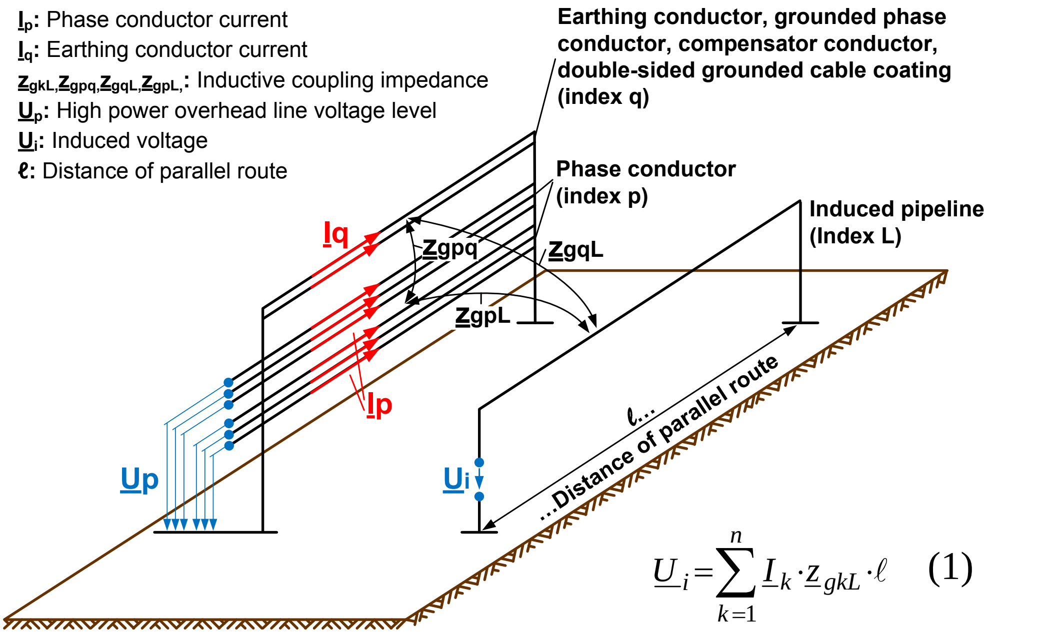
Even when all calculations are done very carefully by established and generally accepted calculation methods, conducted measurements on pipelines show lower pipeline voltage levels up to a factor of 7, than have been calculated for the same pipelines and pipeline locations before. Investigations on this discrepancy are needed to bring calculations and measurement data closer together by analysing the parameters for the calculation of induced voltages. Our current mathematical models and simulations are compared with real measurement examples, and show how different factors can influence calculations and how difficult it is to bring these and measurement data in accordance, optimizing further measures for pipeline and high voltage equipment. This can help avoid unacceptable pipeline voltages and their mitigation costs.

2 Inductive interference on pipelines

Inductive coupling appears when a magnetic field between an interfered buried isolated metallic pipeline system and an interfering HVES exists. The essential parameter for a high inductive interference is a strong inductive coupling. This occurs when a geographical closeness between a pipeline and an energy system over a longer distance exists and results in a high pipeline interference voltage.
However, there exist other important parameters. First, the HVES parameters: e.g. the load current and the phase conductor arrangement. These are major factors because the value of the load current is a direct impact factor in the voltage calculation formula (see Figure 1). A poor phase conductor arrangement produces an inhomogeneous inductive rotating field which can increase the inductive interference significantly (see also PTC paper from 2014 [3]). Second, certain pipeline parameters such as the pipeline diameter, material or coating are also important. The third parameter, which basically cannot be controlled by technical equipment, is the ambience soil resistivity which varies within a large spectrum, depending on location, material, weather and the time of the year. The fourth and final important parameter is the influence of several known and unknown grounded conductors, located near influenced or influencing systems. These conductors produce a voltage reduction on the induced pipeline and can be e.g. the PEN conductor of low voltage power lines, metal rails and compensation conductors of AC traction power supplies, conducting pipelines, foundation earth electrodes and global earthing systems.

The inductive coupling impedances $\underline{z}_{gkL}$ are affected by all of the above-described parameters and can be calculated with e.g. the formula of Dubanton [4].

Figure 1: Inductive interference between a pipeline and a two-circuit overhead line



$$\underline{U}_i = \sum_{k=1}^{n} \underline{I}_k \cdot \underline{z}_{gkL} \cdot \ell \quad (1)$$

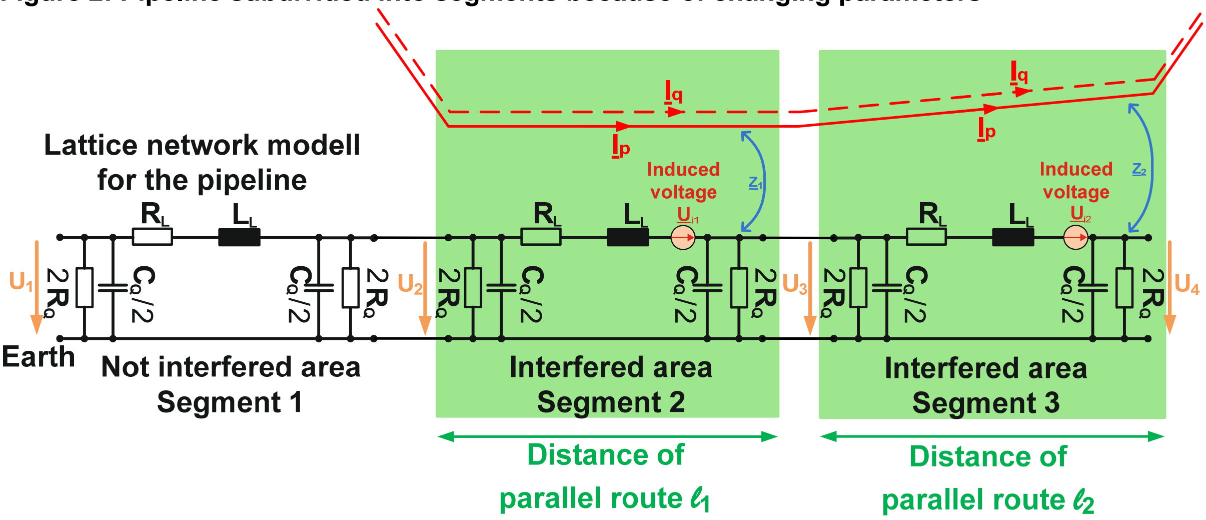
Figure 1 shows the inductive interference between an interfered pipeline and an interfering two-circuit high voltage overhead line. The phase conductor current $\underline{I}_p$ is set by the current for normal operations and short-circuit-situations, all other currents $\underline{I}_q$ flow through other conductors and cable coatings. The following matrix (2) leads to the currents $\underline{I}_q$ (3).

$$\left\| \begin{matrix} \underline{U}_p \\ 0 \end{matrix} \right\| = \left\| \begin{matrix} \underline{z}_{gpp} & \underline{z}_{gpq} \\ \underline{z}_{gqp} & \underline{z}_{gqq} \end{matrix} \right\| \cdot \left\| \begin{matrix} \underline{I}_p \\ \underline{I}_q \end{matrix} \right\| \qquad (2)$$

$$\underline{I}_q = -\underline{z}_{gqq}^{-1} \cdot \underline{z}_{gqp} \underline{I}_p \qquad (3)$$

If all currents and inductive coupling impedances $\underline{z}_{gkL}$ for one segment ℓ are known, the induced voltage $\underline{U}_i$ can be calculated for a segment. Segmenting is needed because of the fact that the geographical closeness and other parameters are not constant over the whole interfering distance and therefore the value of $\underline{z}_{gkL}$ is always changing as depicted in Figure 2. Also, other segments are not influenced as can also be seen in Figure 2. When all induced voltages $\underline{U}_i$ have been determined, the induced pipeline interference voltage over the whole interfering distance is calculated with the lattice network model. As a requirement for using this model, all parameters must be (approximately) homogenous within one segment.

Figure 2: Pipeline subdivided into segments because of changing parameters



$\underline{I}_p$,$\underline{I}_q$: High voltage energy system with interfering currents
$U_{1...4}$: Pipeline interference voltage alongside the pipeline
$\underline{U}_{i1...i2}$: Induced voltage
$\underline{z}_{1...2}$: Inductive coupling impedance

In this network model, the parameters represent the longitudinal impedance (R_L, $\underline{L}_L$), which stands for the pipeline material characteristics and the shunt admittance ($\underline{C}_Q$, R_Q), which is a combination of the pipeline coating value, ambience soil resistivity, reduction conductors and reducing earthing systems. Finally, the pipeline interference voltage alongside the pipeline can be calculated with the node admittance matrix [5].

3 Different possible impact factors on pipeline voltages

The following factors are suspected to have different degrees of impact on the induced pipeline voltage and the difference between calculated and measured pipeline interference voltages and have to be considered individually and with each other:

- Load current instead of using the maximum operational currents
- Reduction effect of global earthing systems
- Reduction effect of local earthing systems
- Reduction effect of practically achievable pipeline earthing systems
- Reduction effect of pipelines, running in parallel
- Reduction effect of parallel high voltage power systems with grounding conductors
- Incorrect or inadequate pipeline coating parameter
- The influence of the model-conform specific soil resistivity

3.1 Impact of the load current

As stated above, the value of the load current is a direct proportionality factor in the voltage calculation formula (1). Normally it is common practice to use the maximum operational currents from the influencing systems in order to cover worst case scenarios for touch voltages or, depending on the type of the influencing system, 60 to 95 percent of this maximum load current for AC corrosion.
In reality, these operational currents rarely occur because of load flow situations or safety or reliability reasons like the commonly agreed (n-1)-criteria which prevent HVES overload situations in case of a failure of other coupled systems [6]. But for the comparison of a one week lasting measurement and its associated calculations on the same pipeline locations it is indispensable to use the correct actually used load currents to get comparable results. The difference between such currents and the maximum operational currents is illustrated for two examples, for an overhead line in Figure 3 and a railroad system in Figure 4 [7].

Figure 3: Difference between maximum operational currents and load currents for overhead lines

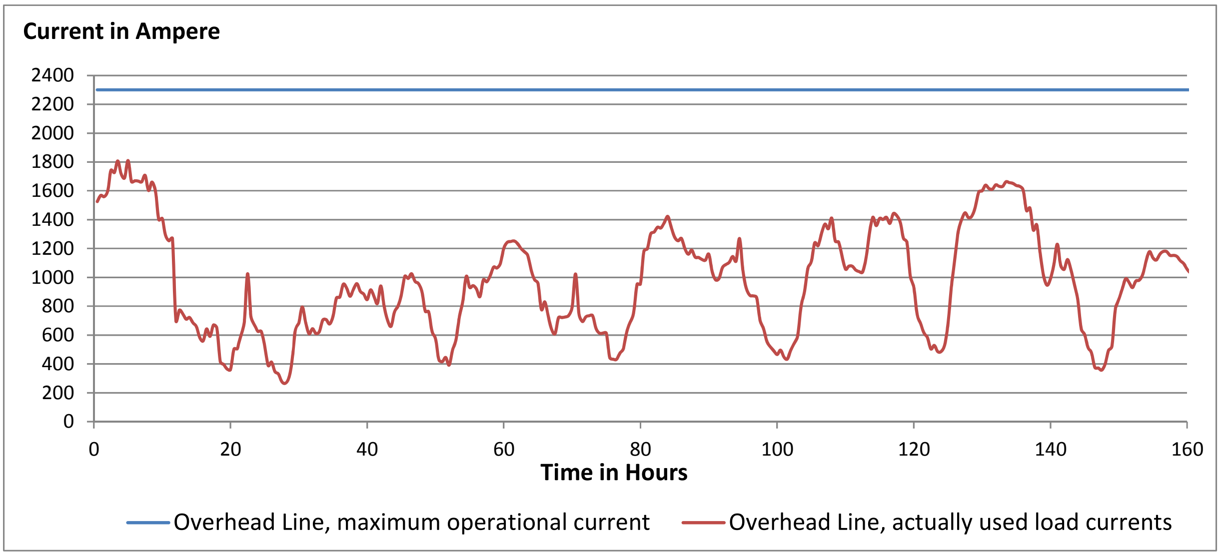
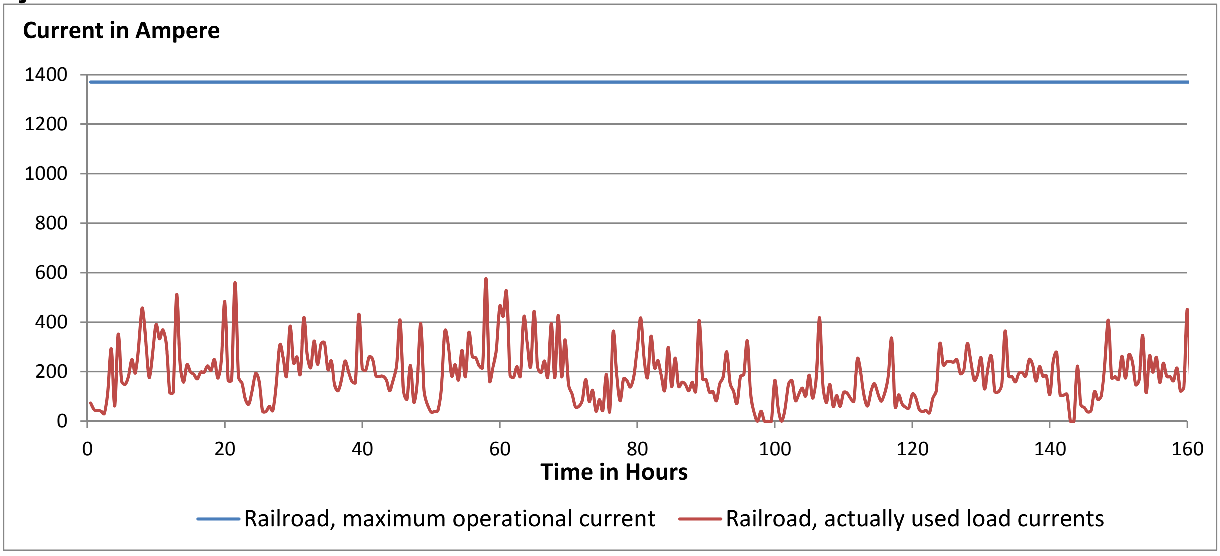


Figure 4: Difference between maximum operational currents and load currents for railroad systems



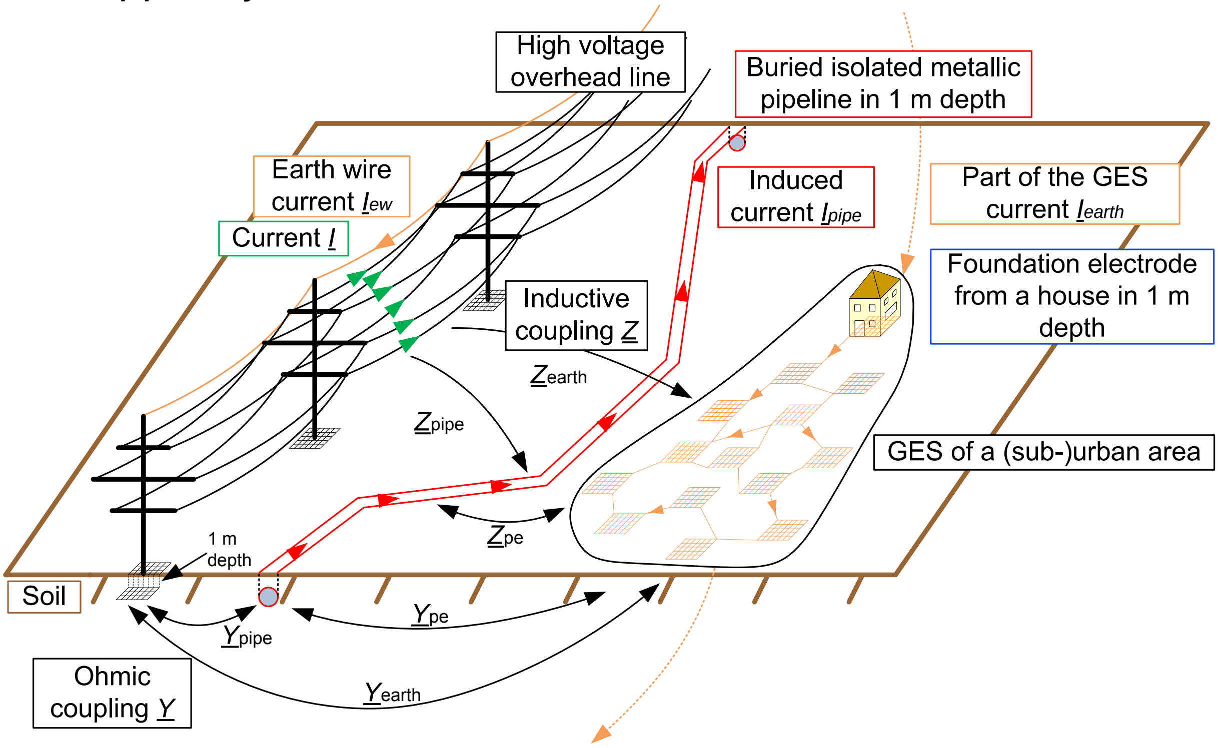
3.2 Possible voltage reduction effect of GESs, HVESs and pipelines

Bigger pipelines usually run over long distances which means that they are unavoidably built near (sub-) urban areas or inside energy routes for route optimization and cost control. Therefore, other known and unknown buried conductive material can be located near the influenced pipeline. For long term interference, if the geographical distance between interfered (pipeline) and interfering (conductive material) systems is less than 1000 (suburban and rural) or 300 meters (urban), standards and guidelines say that a significant inductive coupling between both systems can be expected and has to be investigated by calculation [1].
Depending on the geographical situation, the conductive material can be e.g. GESs, PEN conductors of low voltage power lines, earthed shields of LV-, MV- or HV-cable systems, foundation earth electrodes or conducting pipelines (water, local gas supply) in or near (sub-) urban areas as well as other transportation pipelines or HVESs (e.g. metal rails and compensation conductors of A.C. traction power supplies, earthing conductors or foundation electrode of pylons) in energy routes. All of these influencing systems and components have one thing in common: In case of inductive interference, they can result in a pipeline voltage reduction which leads to reduced pipeline interference voltages.

3.2.1 Global earthing systems (GESs)

In short, GESs consist of connected foundation electrodes and other conductive material buried in the soil within a (sub-) urban area. This connection can be realised intentionally or unintentionally either directly via conductive materials or in the common sense via the electric flow field. If a HVES is located near a pipeline and a GES, a configuration arises as depicted in Figure 5.

Figure 5: The complex interference and reduction situation between high voltage power line, GES and pipeline system



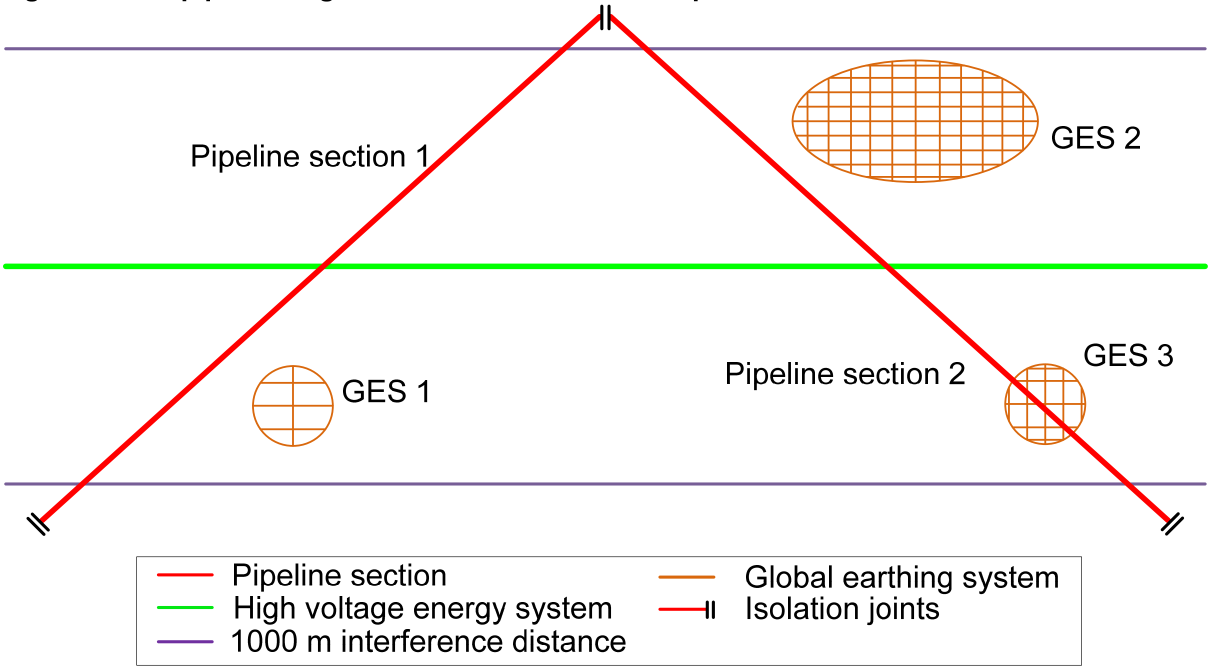
In these cases, pipeline and GES are more or less parallel metallic conductors and the inductive coupling impedances $\underline{z}_{gkL}$ from the energy system turn into a parallel connection of the pipeline coupling $\underline{z}_{pipe}$ and the GES coupling $\underline{z}_{earth}$. As a result, the coupling impedance to the pipeline is reduced with the effect of a lower pipeline voltage. This means that GESs have a reduction effect, how great it is depends on the expansion, grid structure as well as the material- and soil-conductivity. Finally, as a result of the inductive coupling, the pipeline voltage $\underline{U}_i$ is induced with consideration of this reduction effect [7].

But as written before, this induced voltage $\underline{U}_i$ is only valid for a segment ℓ, where all parameters are constant. The resulting current $\underline{I}_{pipe}$ can be calculated by linking all these segments, modelled by a chain conductor, which finally represents the pipeline. Every influenced segment is inducing the voltage $\underline{U}_i$ which drives a current whose value is depending on the pipeline's impedance (R_L, $\underline{L}_{L'}$ $\underline{C}_Q$ and R_Q) for this segment. All single segment currents are summarised and lead to the pipeline overall current $\underline{I}_{pipe}$, which flows alongside the pipeline. The same procedure is applied on the GES and leads to the current $\underline{z}_{earth}$ [7].

This results in additional inductive coupling $\underline{z}_{pe}$ between pipeline and GES. The coupling $\underline{z}_{pe}$ exists because for the respective system, the other system is an active energy system with its own magnetic field due to the additional current ($\underline{I}_{pipe}$ or $\underline{I}_{earth}$). Depending on the current flow direction, the current in the GES can additionally increase or reduce the current in the pipeline and thus the pipeline interference voltage [7].

The following simplified calculation example, which is depicted in Figure 6, shows the impact of such interference between an HVES, two pipeline sections and three differently sized GESs with a 1000 m wide interference distance parallel on both sides of the HVES.

Figure 6: Two pipeline segments with different GES-impacts

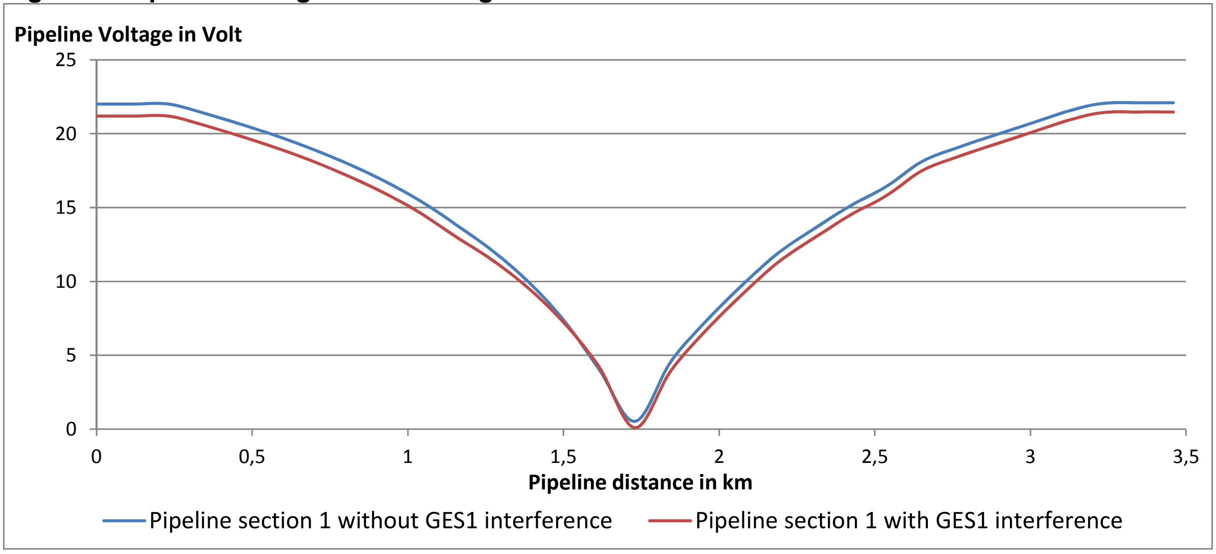


GES 1 represents a small village with a low, GES 2 a small town with a high and GES 3 a village with a medium density of conducting grounded material. Additionally, the pipeline runs directly through GES 3. The size and the amount of buried conducted metal leads to an accordingly high voltage reduction effect. Known parameters of a GES are the general geographical alignment and the expansion because these can be determined easily with GIS-Systems. This knowledge is important because, usually, rising expansions of a GES often mean more parallelism to energy systems and pipelines, resulting in higher reduction effects. Unfortunately, even with this knowledge it is not simple to calculate the reduction effect. Often, the materials and conductive structures within GESs are unknown. Today, even with expert knowledge it is only possible to make a rough estimation [7].

Beside the knowledge about the GES expansions, the geographical closeness to HVESs and pipelines is an important parameter. Normally, when the GES lies between both systems or directly in the pipeline run, the reduction factor is higher (see GES 3) than outside of the direct coupling (see GES 1). A GES has also a higher impact on the pipeline interference voltage when in near vicinity to a pipeline. The inductive coupling impedance depends on the distance between the conductors in a nonlinear manner – with less distance the coupling impedance is greater [4]. Finally, how great the reduction or increasing effect on the pipeline interference voltage is, depends on the geographical situation and has to be calculated or measured [7].

The example in Figure 6 shows the small GES 1 next to the pipeline segment 1. The result of the calculation is depicted in Figure 7 and shows a small voltage reduction effect which means that the pipeline interference voltage remains almost unchanged.

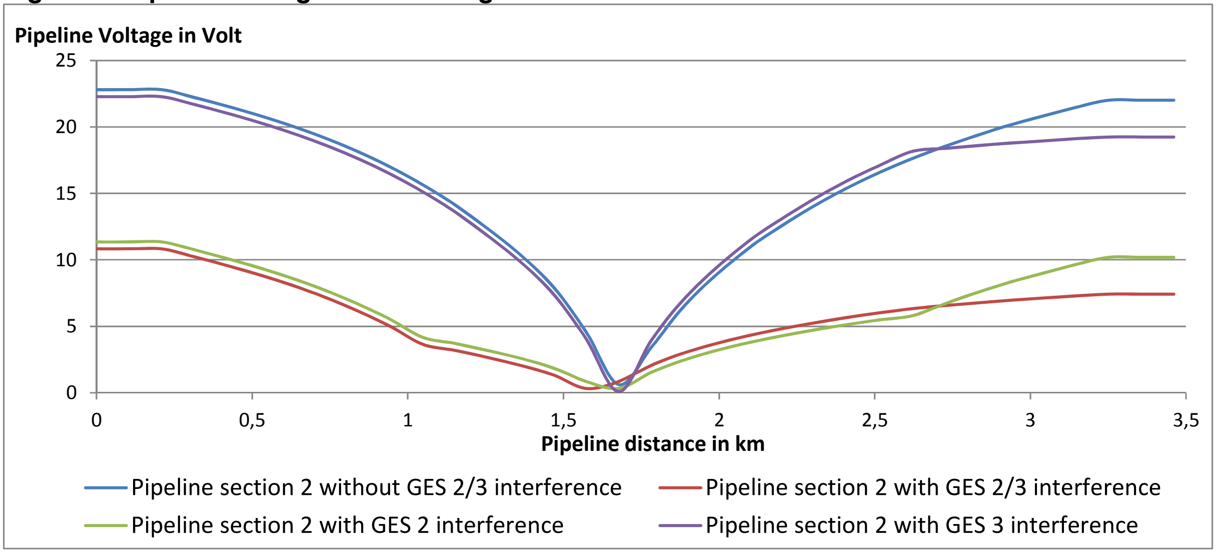
Figure 7: Pipeline voltage from the segment 1



As can be seen in Figure 8, the pipeline voltage calculation in the pipeline segment 2 shows a considerably lower value when considering GES 2 and 3 (red line) than when not (blue line). This high reduction factor results from the bigger extension and higher conducted grounded material density of the GES 2. In detail, is the calculation only done with the GES 2 (green line), the pipeline voltage is very similar to the calculation considering both GESs.

Very interesting is the effect of GES 3. With a smaller suburban extension but a close vicinity of HVES and pipeline, it has a notable reduction effect at the end of pipeline segment 2. It is important to understand that this knowledge is very crucial in cases when pipeline voltages are calculated higher than the given national limits without considering the voltage reducing effect of the GES. With consideration of these reduction factors in calculations, pipeline voltages may not be exceeding the given national limits anymore [7].

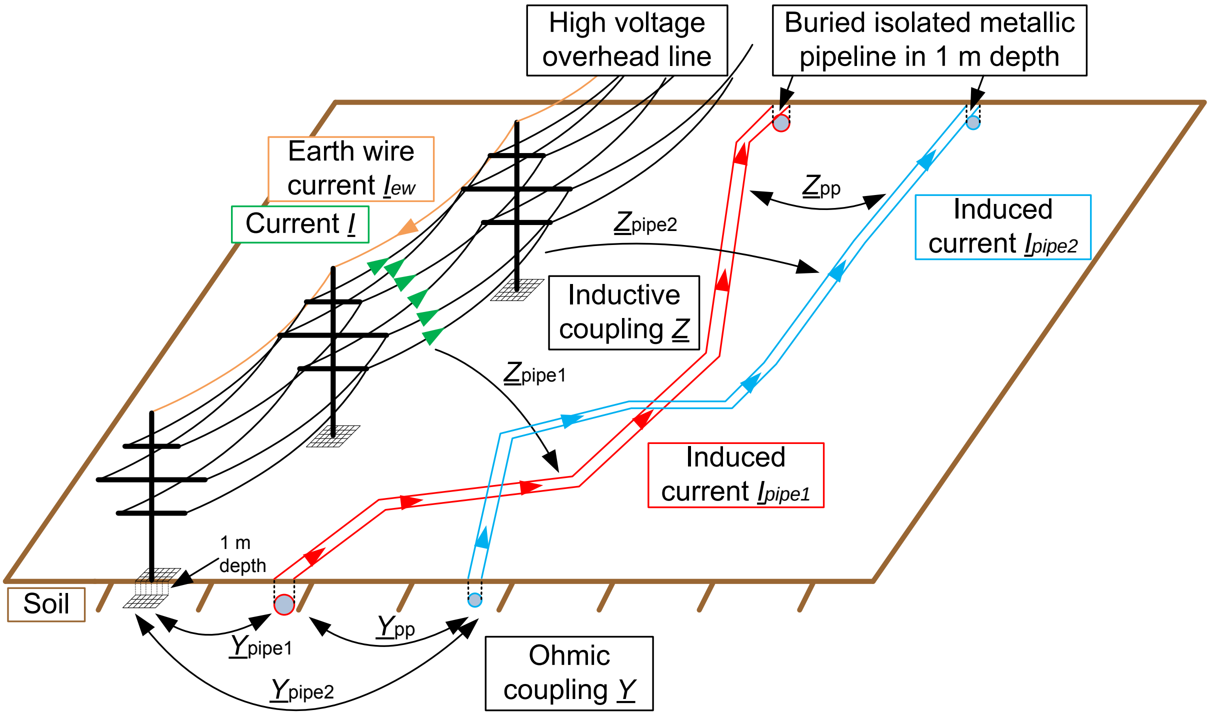
Figure 8: Pipeline voltage from the segment 2



3.2.2 Other pipelines

Because of bundled energy routes, transport pipelines are built near other pipelines. This means that two or more pipelines can have a long parallel routing or can cross each other often. If an HVES is located near a configuration with two pipelines, a setup appears as can be seen in Figure 9 and two interference effects have to be noted.

Figure 9: The complex interference and reduction situation between high voltage power line and two pipeline systems



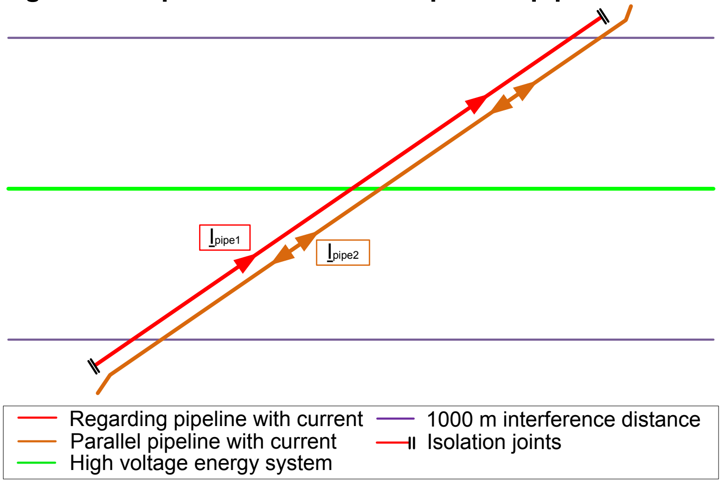
In this configuration, the same mathematical description from the GES calculation in Chapter 3.2.1 is valid, as long as different calculation parameters are considered. The coupling $\underline{Z}_{pp}$ exists because for the respective pipeline, the other pipeline is again an active energy system with its own magnetic field, caused by the additional current ($\underline{I}_{pipe1}$ or $\underline{I}_{pipe2}$) arising from the inductive interference of the HVES.
The first interference effect is due to the inductive coupling between the HV power line and the pipeline causing currents in the second pipeline. Depending on the current flow direction, the current from the second pipeline can increase or reduce the current in the regarding pipeline and vice versa. Figure 9 shows an example, where both pipeline currents flow in the same direction and thus increase the regarding pipeline current.

The second interference effect is based on the circumstance that the second pipeline works as a reduction conductor (see Chapter 3.2.1) on the regarding pipeline. This means that both factors have to be considered to be able to state whether the pipeline current and interference voltage is increased or reduced.

To illustrate how this reduction or increasing factor from a parallel pipeline works, a simplified calculation example is done. The following Figure 10 shows an example with two parallel pipelines, influenced by an HVES within the 1000 m wide interference distance.

While the regarding pipeline current direction (I_{pipe1}) is fixed, the second current direction (I_{pipe2}) is varied. If both pipelines are situated close to each other, the coupling effect has to be considered. This can be realized using the node admittance matrix.

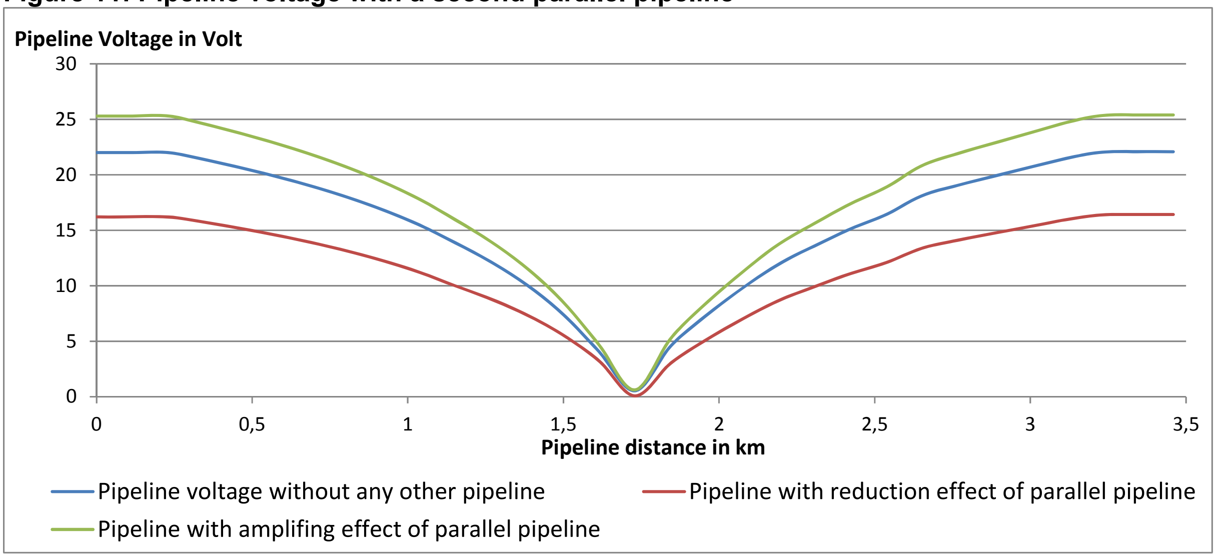
Figure 10: Pipeline with a second parallel pipeline



The degree of the parallel pipeline reduction effect depends mainly on the pipeline diameter ratio. For example, is the parallel pipeline diameter smaller, the effect on the regarding pipeline is substantially smaller with the effect of a much smaller parallel pipeline reduction effect.

Figure 11 shows three different calculations which depict the influence of the current directions on the regarding pipeline voltage. The blue line shows the calculation of the pipeline voltage of the regarding pipeline without any other parallel pipeline; the other two lines already include the parallel pipeline reduction effect. This example shows that when both pipeline currents flow in the same direction, the regarding pipeline current and therefore, the pipeline voltage, are increased (green line). Furthermore, it is clearly shown that a reduction effect is present when the currents flow in opposite directions (red line).

Figure 11: Pipeline voltage with a second parallel pipeline

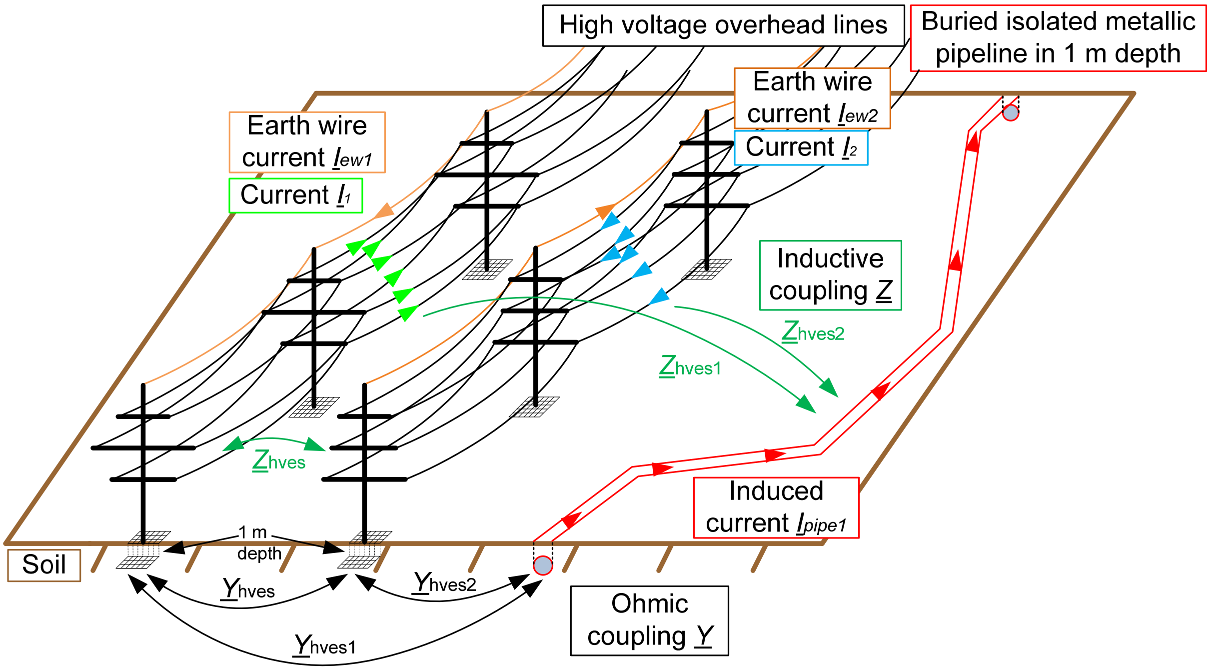


3.2.3 Parallel high voltage energy systems (HVESs)

Especially, high voltage power lines but also railway systems are bundled on energy routes and therefore they have often a longer parallel routing. Consequently, configurations can arise as depicted in Figure 12. In this figure, two power lines have a parallel routing with a pipeline and thus a potentially high inductive interference can appear. The induced voltage within one segment ℓ can be doubled with the help of formula (4) if the coupling impedance $\underline{z}$, the load current, the flow direction $\underline{I}$ and all other parameters are kept constant.

$$\underline{U}_i = \ell \cdot \left(\underline{z}_{pipe1} \cdot \underline{I}_1 + \underline{z}_{pipe2} \cdot \underline{I}_2\right) \tag{4}$$

Figure 12: The complex interference and reduction situation between two high voltage power lines and a pipeline system

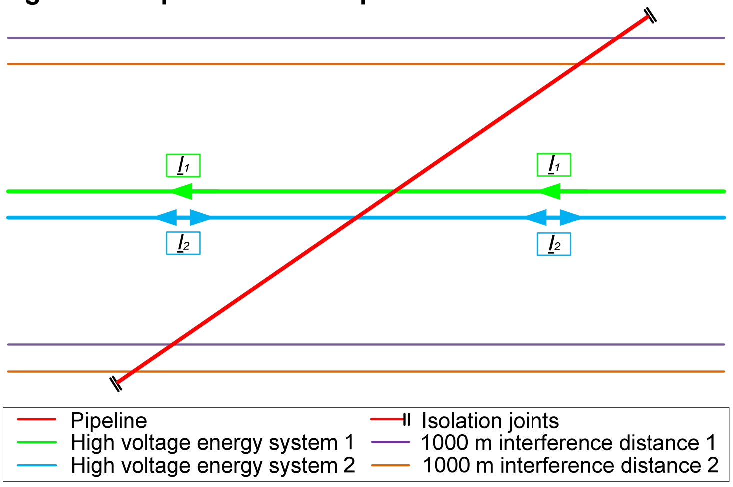


General HVES parameters, such as the pylon configuration or phase conductor arrangement, can vary but the coupling impedances always differ due to the geographical arrangement of HV lines and pipelines. Another major impact factor is the load current which is varying all the time (see Chapter 3.1) and is never the same in different HVESs, even the load flow directions can be opposite. The HVESs have the same inductive coupling effect $\underline{z}_{hves}$ to each other as shown in the previous chapters 3.2.1 and 3.2.2. In this case, the active phase conductors of one system induce currents in the phase and earthing conductors and can influence the currents in the other system. So it is possible that the coupling $\underline{z}_{hves}$ reduces or increases the active currents of both HVESs in the area with the interfered pipeline. This results in reduced or increased inductive interference and induced voltage on the pipeline as well as the induced current $\underline{I}_{pipe}$. This leads to a reduced or increased pipeline interference voltage.

To understand this situation, the following Figure 13 shows the interfering example with two parallel HVESs next to a pipeline. For easier understanding all parameters for both HVESs are equal except the current value and flow direction.

The situation is almost the same as in the chapter before except that the currents now flow in the HVESs. The increasing and reduction factor of the HVES load current flow situation is substantially higher than with two parallel pipelines because both HVESs are always active systems and their currents are added or subtracted to a resulting current, which affects the pipeline.

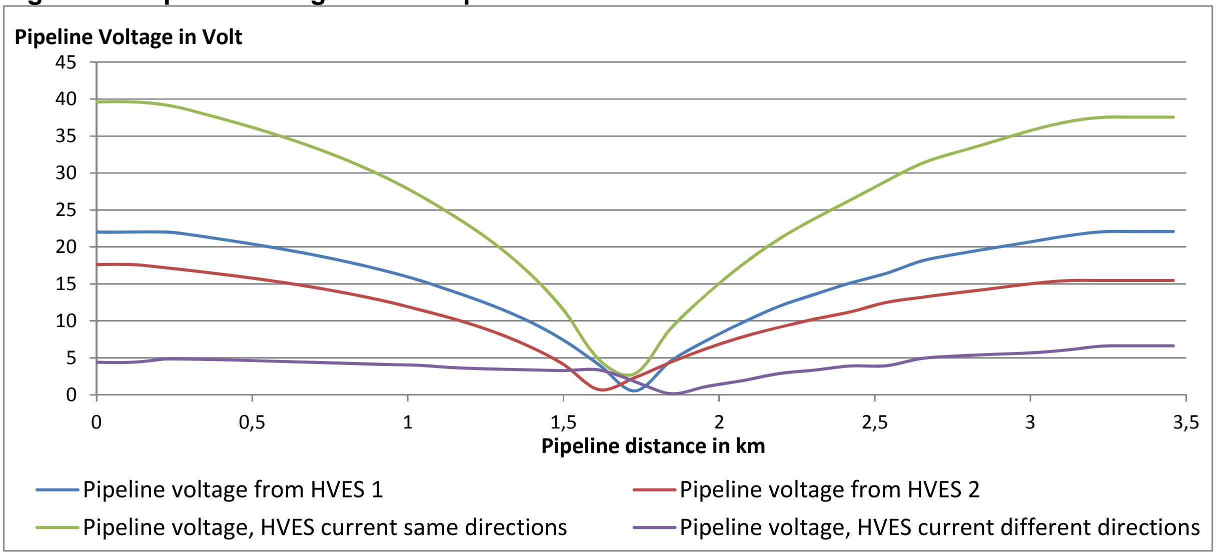
Figure 13: Pipeline with two parallel HVESs



If both HVESs are situated close to each other, the coupling effect has to be considered. This can be realized using the node admittance matrix.

Figure 14 shows the impact of the current flow direction. The blue and red line represent the pipeline interference voltage of each system with different current values. Due to slightly different interference areas, there is a small voltage shifting, so HVES 2 (red line) has a higher peak at the beginning of the pipeline than at the end. More interesting is the current flow situation. When both currents $\underline{I}_1$ and $\underline{I}_2$ flow in the same direction, the inductive interference of both energy systems is added and a higher pipeline voltage appears (green line). If the load currents flow in different directions, the pipeline voltage is massively lower (purple line). For worst case scenarios in calculations, all load flow currents are flowing in the same direction causing a maximum induced pipeline voltage.

Figure 14: Pipeline voltage with two parallel HVESs



3.2.4 Local earthing systems

Local earthing systems are conducted materials buried in the soil. This can be e.g. connecting water pipelines, extended foundation electrodes or earthed cable shields. Normally, it is difficult to detect them and so they go unnoticed and therefore, are not considered in calculations. But they can still act as reduction systems in the vicinity of HVESs and pipelines. This can lead to hardly explainable reduced pipeline voltages because of the circumstance that the physical effects and the calculations are very similar to the previous points.

3.2.5 Ohmic-inductive coupling

An ohmic coupling $\underline{Y}$ exists between all interfered and interfering systems due to their earthing systems. In normal and fault operation conditions of HVESs, earth currents can flow through their earthing systems (e.g. pylons or transformer stations) into their ambience soil and in case of the vicinity of a GES, pipeline or other conductive material, they can catch these currents and spread them to other regions. This results in a higher $\underline{I}_{earth}$ component with the effect of a higher influence on the current $\underline{I}_{pipe}$ and the resulting pipeline voltage. This can also happen due to a pipeline coating holiday in the vicinity of the grounding systems of the HVES. Then an additional current is caught up by the pipeline and can increase or reduce the current $\underline{I}_{pipe}$.

3.3 Incorrect or inadequate pipeline coating parameter

It is generally known that the pipeline coating is very important to avoid material corrosion. Corrosion on pipelines is a chemical reaction between the bare steel and the ambient soil and can only happen in locations, where coating holidays exist. Coating holidays occur due to material defects or disadvantageous environmental conditions (e.g. sharp stones, ground vibration). Due to this direct contact between steel and soil, the value of the coating resistance decreases and thus two effects happen: the cathodic protective current rises and more importantly for AC measurement and calculation, the pipeline interference voltage decreases (as can be seen in the paper of 2014 [3]). It is problematic that the value of the coating resistance can vary within a wide range. On the one hand, the material has been changed from bitumen with a low value (1 MΩm) to polyethylene with a high value (100 MΩm). One the other hand, with time, the resistance value can fall to 10 kΩm (bitumen) or 50 kΩm (polyethylene) due to coating holidays. This means that the resistance value has to be measured carefully and regularly because the value varies along the pipeline and over time. Otherwise calculations are not accurate from the outset. Then, measurements and calculations can show remarkable differences in pipeline voltage. To summarise, with a lower coating resistance value, a lower pipeline interference voltage can be expected which one should bear in mind when comparing measurements and calculations [3].

3.4 Varying the specific soil resistivity

The specific soil resistivity along a pipeline is usually not constant because the different types of soil along the route of the pipeline have a different soil resistivity. However, this is not the only factor: weather and time of the year also influence the soil resistivity by changing the soil moisture and the soil temperature. The soil resistivity is lower when the soil moisture is high (e.g. due to high precipitation) and/or the soil temperature is high (e.g. during the summer). Therefore it is difficult to find the correct value of the soil resistivity along a pipeline.

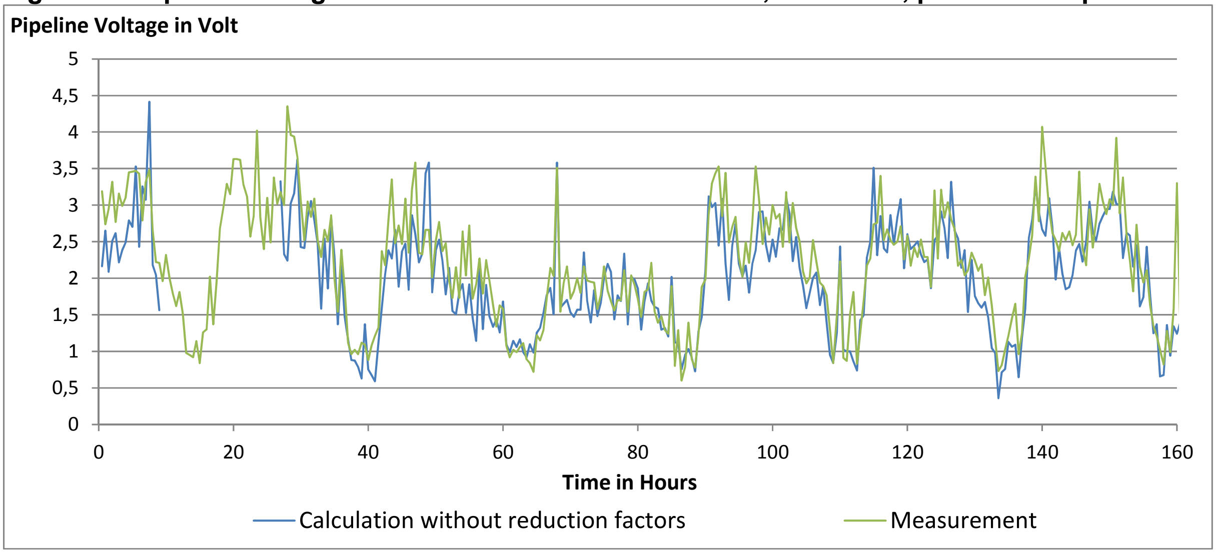
Generally, the specific soil resistivity ranges between 25 Ωm and 10000 Ωm but there also exist extreme conditions like very wet marshy ground with a very low value of down to 1 Ωm or rock made of a lot of granite with a very high value of up to 50000 Ωm. Based on this wide range of values and the fragmenting of the different types of soil, the value for the representative respective ambient soil resistivity along the pipeline can be very diverse. Considering this variation is essential, both for calculations and measurements, especially where measurements are conducted a detailed soil analysis is indispensable. The soil resistivity has a very strong influence on the pipeline interference voltage (as is shown in the paper of 2014 [3]). In areas with lower values, lower pipeline interference voltages can be expected.

For low induced pipeline voltages, the best case is, when both, soil resistivity and coating resistance are very low. Otherwise high pipeline interference voltage can be expected. Thus it is pointed out that both parameters have to be determined very carefully, otherwise it is impossible to bring calculations and measurement data closer together [3].

4 Practical results

The following figures show different examples of calculations using the actually used load currents and comparing them to measurements during a measurement period of 140 to 160 hours at different pipeline locations. The following demonstrates how the reduction effects shown in chapters 3.2 to 3.4 work. Figure 15 shows a nearly identical voltage characteristic between measurement and calculation since the model parameters reflect the real conditions very well.

Figure 15: Pipeline voltage calculation versus measurement, location 1, perfect example



Unfortunately, perfect conditions rarely appear. There exist many examples where the comparisons show different results. This chapter presents some of them and states which factors are crucial in the respective locations.

In some cases, only reduction factors from conducted material have an impact, as can be seen in Figure 16 and Figure 17 (which represent two different locations). The calculations without reduction effects show much higher results by a factor of up to 7, compared to calculations considering conductive material nearby. These two figures show an intense voltage reduction, which is based on the geographical closeness of two different things: in location 2, another pipeline in combination with the reduction factor of two parallel high voltage overhead lines and in location 3, a rural area with a well-developed and extended GES. As shown in chapter 3.1, the load currents from railway and overhead line systems are different, which can be shown clearly in these two figures. Because of the non-abrupt change of the current, it is clear that in location 2 only an overhead line induces the pipeline voltage. In location 3 a railway system is the reason, typically causing the value of the current to change very fast.

Figure 16: Pipeline voltage calculation versus measurement, location 2, HVES

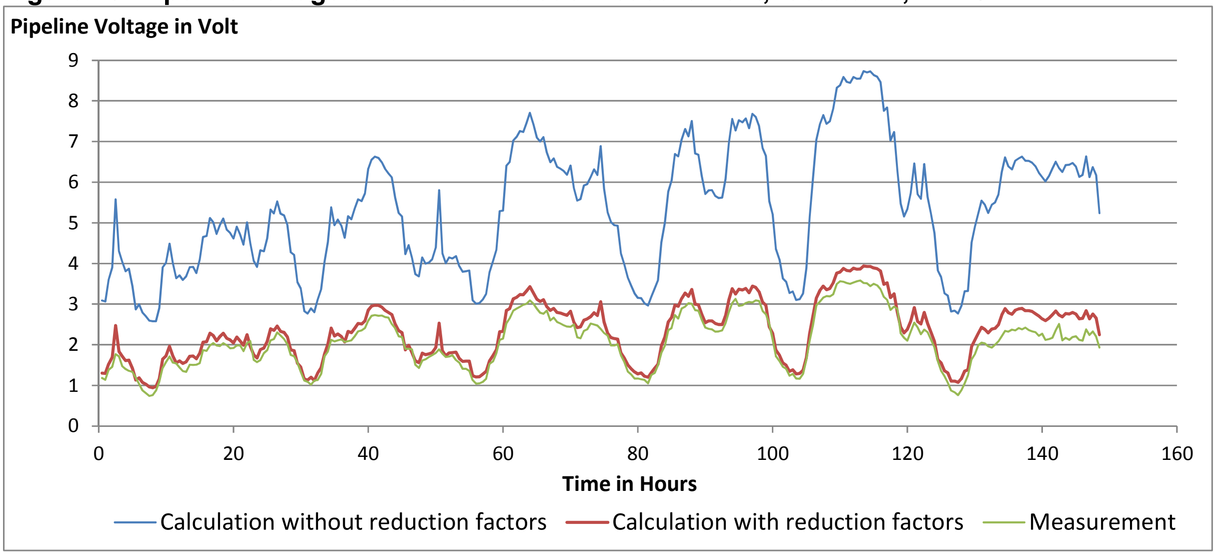
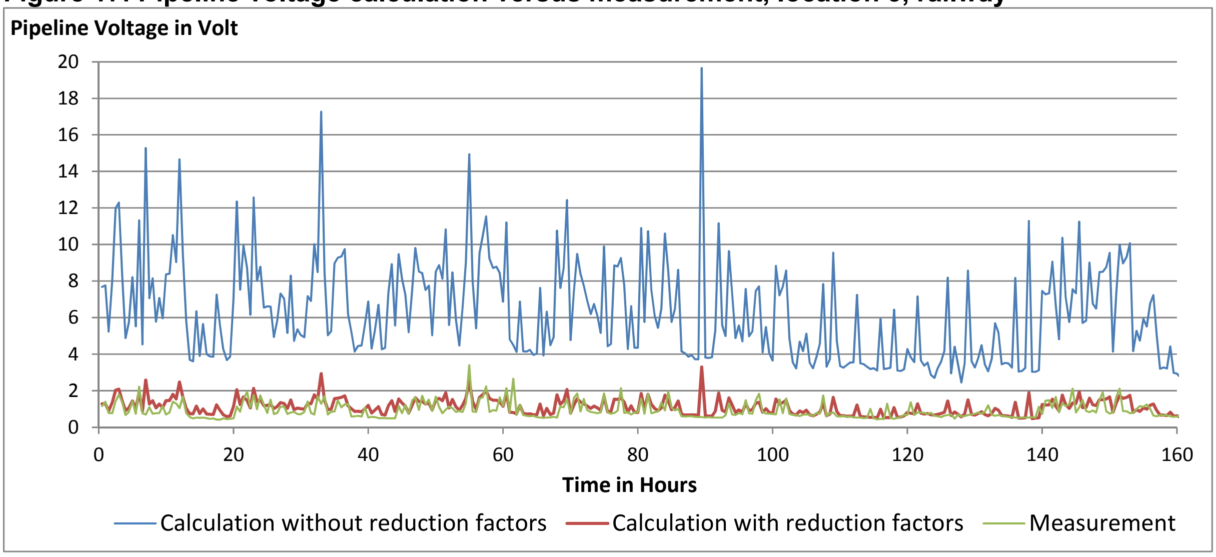


Figure 17: Pipeline voltage calculation versus measurement, location 3, railway



At a first glance, it seems that Figure 18 and Figure 19 have a similar reduction effect as shown in the two figures before. In fact, however, it is a combination of two effects: the voltage reduction effect due to conductive material and also a voltage shift due to inadequate soil resistivity.
It can be seen that both figures have nearly the same voltage progression due to close measuring points. Consequentially, the pipeline voltage reduction effect is based on the parallel pipeline. However, the impact of the reduction effect shown in Figure 18 and Figure 19 is differently high because the distance between both pipelines is varying. In addition, the impact of the soil resistivity in these examples is even more interesting because of the geographical closeness of the measuring points of less than 1 km. In location 4, the specific soil resistivity was essentially smaller than expected but in location 5, the value was higher. This can be clearly seen in Figure 18 because the calculation result is massively lower than before and in location 5, the average value is remaining on the same level. These two examples show how difficult it is to gain correct calculations in case of fast changing soil resistivities.

Figure 18: Pipeline voltage calculation versus measurement, location 4, parallel pipeline with low soil resistivity

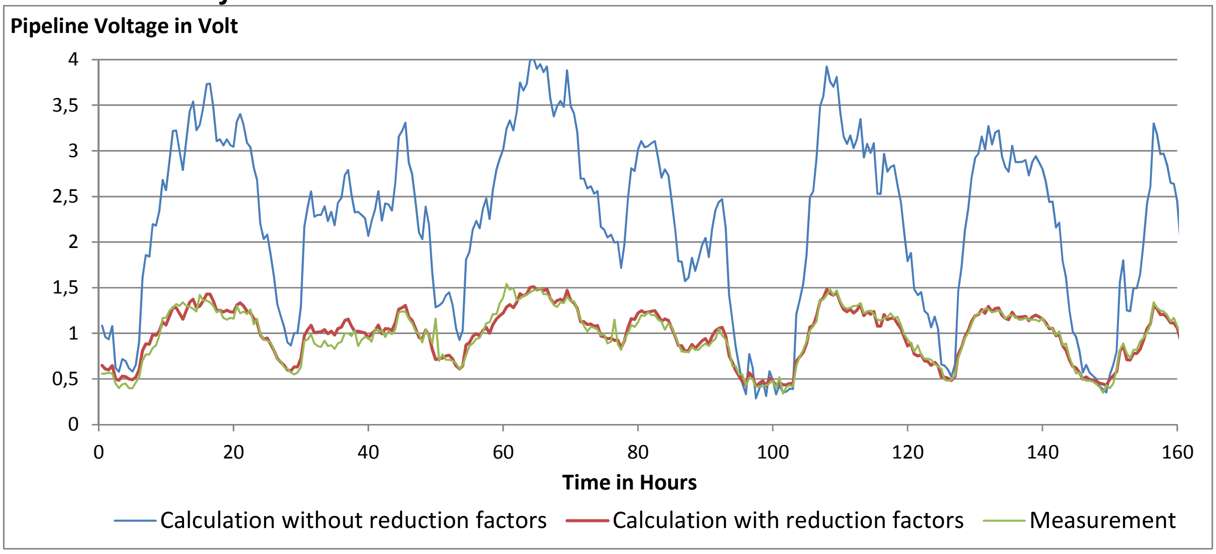
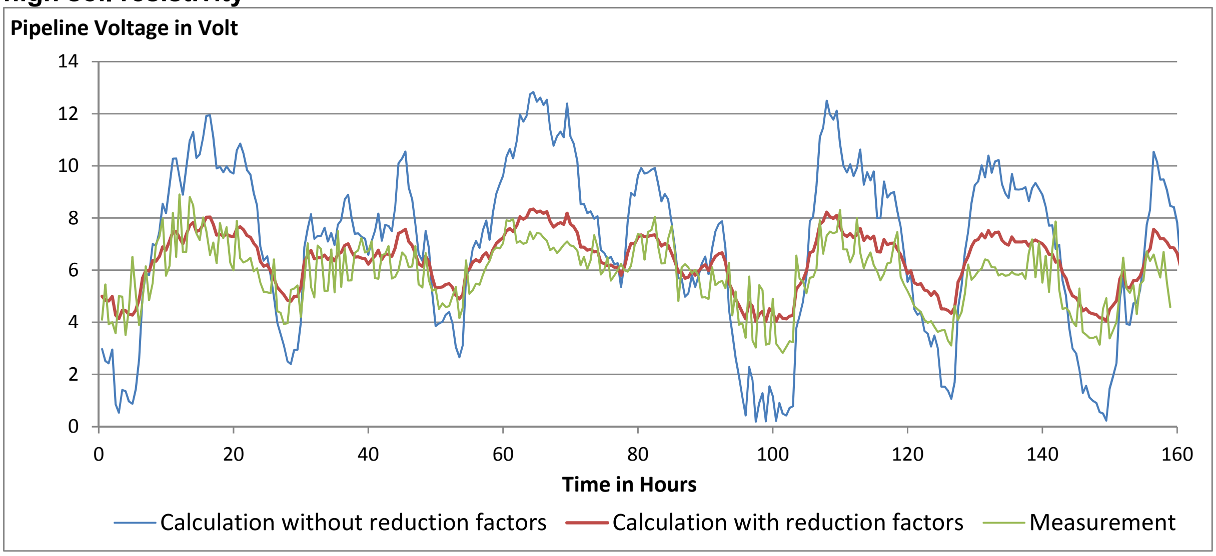


Figure 19: Pipeline voltage calculation versus measurement, location 5, parallel pipeline with high soil resistivity



Another example for a comparison between conducted measurement and calculation is shown in Figure 20. In this case, a low specific soil resistivity and two parallel HVESs (overhead lines) are located close to each other with the result of reduced pipeline voltages. As can be seen, despite using these correction effects, the resulting calculation is finally double as high as the conducted measurement. Possible reasons can be unnoticed earthing systems or measurement errors as the pipeline voltage levels are already very low.

Figure 20: Pipeline voltage calculation versus measurement, location 6, unnoticed earthing systems

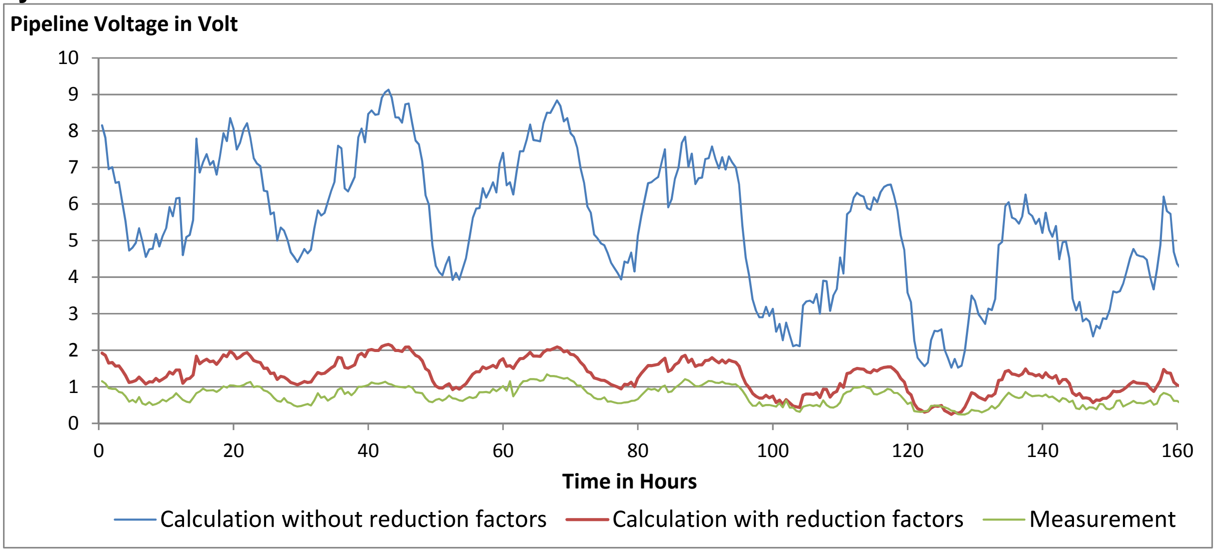
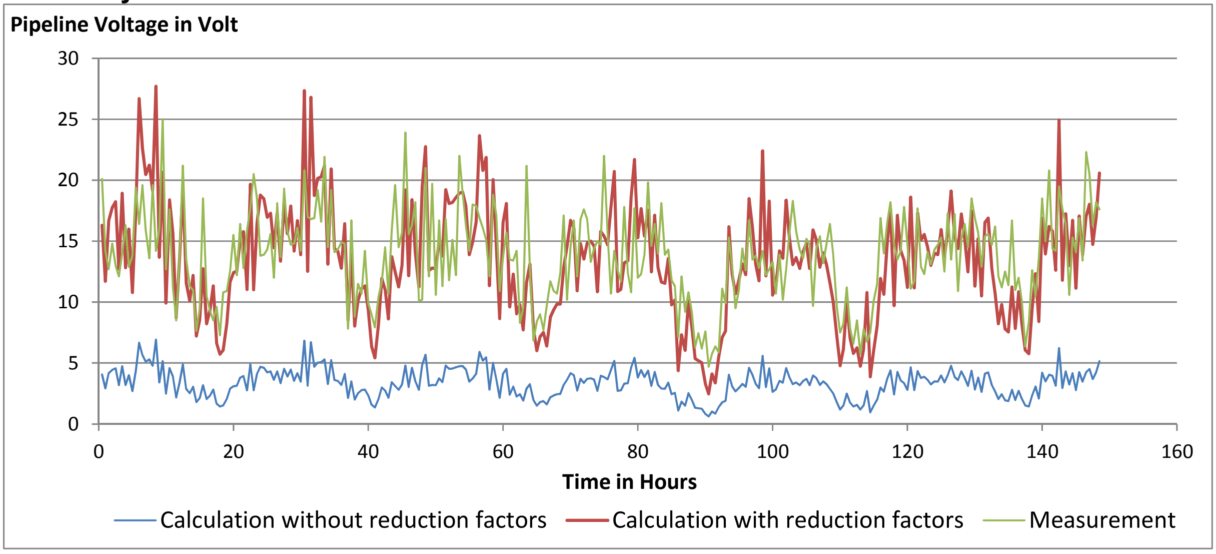


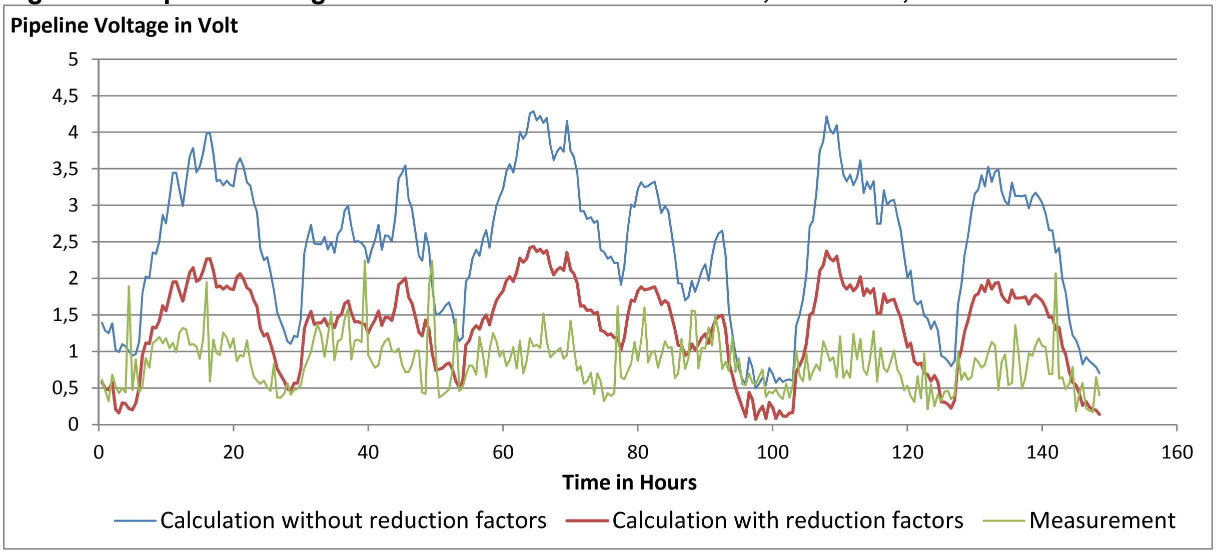
Figure 21 shows an example where the first calculation, without the reduction effect, is much lower than conducted measurements. In this case, there is no reduction effect but an amplifying effect. Investigations in this measurement location finally showed that the specific soil resistivity was substantially higher than in the surrounding area, whereof the value for the calculation was based and led to incorrect results.

Figure 21: Pipeline voltage calculation versus measurement, location 7, unexpected high soil resisitivity



Even with knowledge of all known parameters, there exist some examples where the difference between measurements and calculations can range from “low” to “unacceptably high”, see Figure 22. Possible factors can be unnoticed connected earthing systems which reduce the pipeline voltage in this location, measurement errors or other unknown factors.

Figure 22: Pipeline voltage calculation versus measurement, location 7, still unknown effects



5 Summary

Even if calculations are done very carefully with established and generally agreed calculation methods, conducted measurements on pipelines show mostly lower voltage levels than the calculated ones for the same pipelines and pipeline locations. With the consideration of the reduction – or even increasing – effects presented in this paper, most of the discrepancies between measurement and calculation can be explained when all important parameters are known. Knowledge of the correct specific soil resistivity and pipeline coating resistance is a precondition because both parameters can influence the pipeline voltage in the measuring position. The value of the load currents during the measuring period must be known because the currents are essential to understand the measurement data and to draw the right conclusion. A much more complicated area are conducted materials within the interference area because they can act as a reduction factor decreasing pipeline voltages. They can also produce influencing voltages and in an unfavourable case, they can increase the pipeline voltages too. But as can be seen in the examples, with consideration of all presented effects, most of the conducted measurements can be explained and even better, they can help to calibrate the calculation. With the help of these investigations it is possible to reduce or to avoid unnecessary measures and necessary actions, e.g. AC earthing systems or special safety working methods along the pipeline, can be used more effectively and efficiently as well.

6 References

[1] EN 50443:2012, "*Effects of electromagnetic interference on pipelines caused by high voltage a.c. electric traction systems and/or high voltage a.c. power supply systems*", CENELEC, Brussels

[2] EN 15280:2013, "*Evaluation of a.c. corrosion likelihood of buried pipelines applicable to cathodically protected pipelines*", CENELEC, Brussels

[3] C. Wahl, 2014, "*Impact of High Voltage Overhead Lines on Pipeline Security*", 9th Pipeline Technology Conference, Berlin, Germany

[4] C. Dubanton, 1970, "*Calcul approche des parameters primaires et secondaires d'une ligne detransport. Valeurs homopolaires*", CIGRE

[5] E. Schmautzer, 1991, "*Ein Beitrag zur Berechnung der niederfrequenten induktiven Beeinflussung von Rohrleitungsnetzen*", Dissertation, Graz University of Technology, Graz, Austria

[6] J. Backes, 2013, "*Bewertung der Versorgungszuverlässigkeit: Neue Ansätze zur Verwendung probabilistischer Zuverlässigkeitskenn-größen in der Netzplanung und -optimierung*", 2nd Edition, Hertbert Utz Verlag, Munich, Germany, ISBN: 978-3-8316-8018-4

[7] C. Wahl, 2015, "*Impact of Global Earthing Systems on the Inductive Interference on Buried Isolated Metallic Pipelines*", 23nd International Conference on Electricity Distribution, Lyon, France