Estimation of AC Interferences on Pipelines Running Parallel to the Railway Line Prior to Changing Traction from 3 kV DC to 25 kV AC and Design of Mitigation

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Two pipelines, a crude oil pipeline and a gas pipeline running in parallel to the railway line were both cathodically protected and subject to significant DC interference that was successfully mitigated by forced drainages. It has been a concern of pipeline operators that the planned change of traction from 3 kV DC to 25 kV AC would introduce AC interference problems that required significantly different mitigation measures. The initial rough estimation of the inductive effect disregarded characteristics of the pipelines and was based on the calculation of electromotive force which turned out to be of the order of magnitude of 100 V under normal operating conditions, raising both corrosion and safety concerns. In order to estimate future AC interferences more precisely, detailed calculations have been done. In these calculations, the results of soil resistivity field measurements, pipe diameter, metallic material and coating characteristics were taken into consideration and the pipeline-to-ground voltage was calculated.
Calculation of inductive effect generally consists of two steps:
- calculating the induced electromotive force along the pipeline and
- calculating the pipeline-to-ground voltage and electric current in the pipeline.

It is necessary to see a clear distinction between the induced electromotive force and voltage that occur on the pipeline. Induced electromotive force is a virtual electric generator inside the electrical circuit, which consists of pipeline and soil that occurs as a result of the inductive effect. Pipeline-to-ground voltage is the only quantity that affects the pipeline, equipment on it, and people who come into touch with the pipeline.
Calculations pipeline-to-ground voltage is always carried out in cases of:
- earth faults (short-term impact) and
- normal operation (long-term impact).

All the calculations presented in this study were done in the technical computing software *Mathematica*.

Calculation of the induced electromotive force
The first step in calculating the induced electromotive force is to determine the zone of influence of the high voltage AC line. According to CEN / TS 15280:2006[1] and EN 50443:2011[2] in rural areas, for soil resistivity less than 3000 Ωm, the zone of influence includes the area in which the distance between the high AC voltage rail traction line and pipeline is less than or equal to 1000 m. If the resistance of the soil higher, the area of influence in which the distance is equal to the resistance of the

soil expressed in Ωm divided by 3 is considered. In urban areas, this distance can be reduced to less than 300 m, taking into account the reduction factor due to the adjacent metal structures.
The zone of influence usually consists of a series of pipeline segments approaching to, distancing from or crossing the high AC voltage line. Since the equations for calculating the electromotive force are valid for the parallel configuration, convergence, divergence and intersection are approximated by parallel configurations[3,4]. The above approximation is always possible if the pipeline is divided into short enough segments. Figure 1. shows a graph of segment lengths denoted by *L*, and the appending mean distances from the railway line, denoted by *a*, for 4.5 km of the pipeline running within 1200 m of the railway line between the adjacent electric traction stations. The entire length of the pipeline in the zone of influence was 22.3 km.

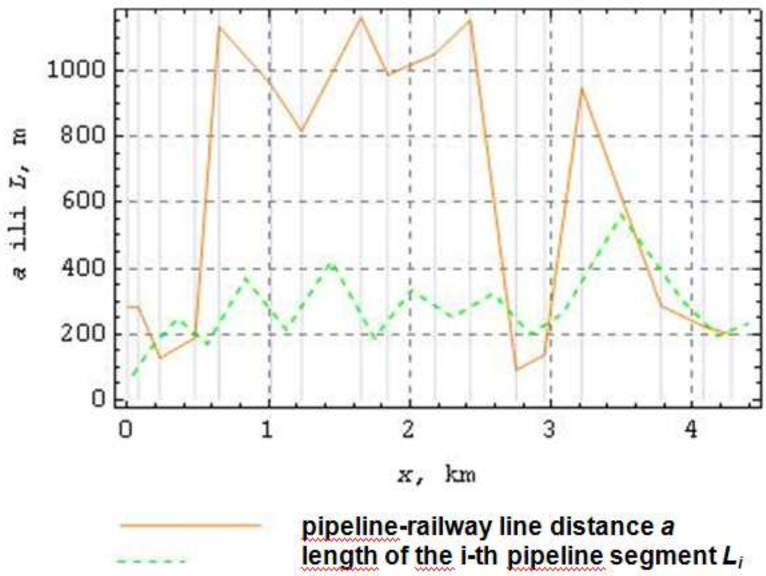


Figure 1. Division of pipeline into segments.

Electromotive force induced in the *i*-th segment of the pipeline of equivalent length L_{pi} equals to:

$$Ems_i = 2\pi fkM_iL_{pi}I$$

where *f* is the frequency of the AC voltage, *M* is the mutual inductance of the two circuits with feedback through the soil, *k* is the shielding factor and a *I* is the induction current.
According to the guide CIGRE 1995[5], and vol II. ITU-T K.26 inductance can be calculated in several ways. In a simpler case, when the pipeline is not very close to the high voltage line, one can use the polynomial formulas which are valid for any reciprocal distance between pipeline and high AC voltage line but do not take into account the distance of the high AC voltage line from the ground. *M* depends upon resistivity of the soil ρ_{soil} that may be obtained from field measurements.

In the case of AC traction, the current that flows trough well grounded conductors - rails and the return line (if it exists) reduces the effect of induction. Nominal shielding factor can be calculated from the impedance matrix of the group conductors consisting of the contact wire, feeder cable, rail tracks and the return cable. Figure 2. shows the dependence of the calculated shielding factor on the soil resistivity.

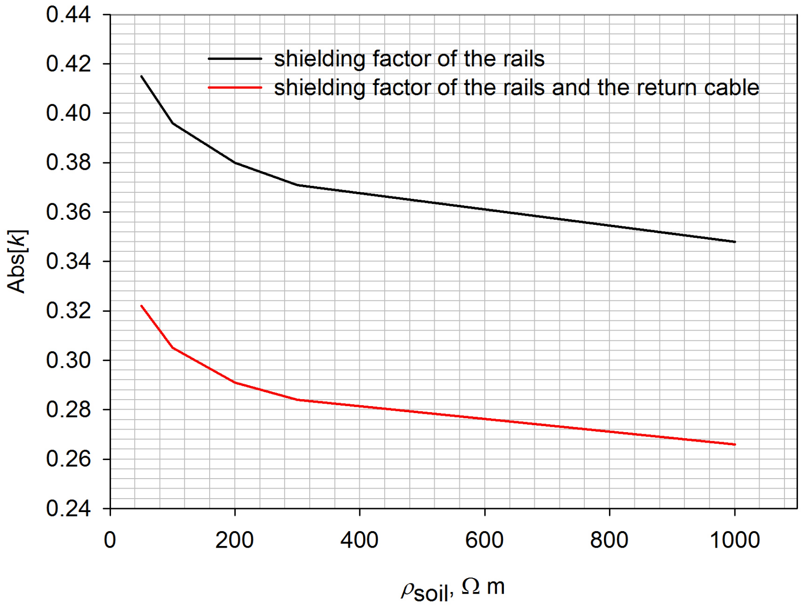


Figure 2. Calculated shielding factors of the rails without and with the return cable.

Induction current is deduced from diagrams obtained for maximum train timetable. Induction current diagram for the investigated pipeline segment is shown in Figure 3.

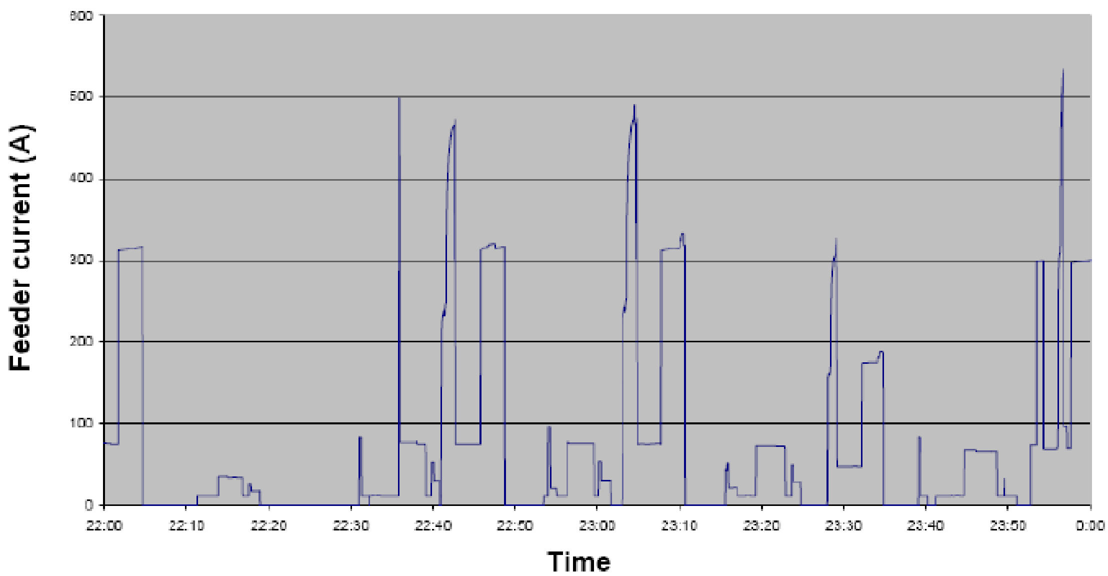
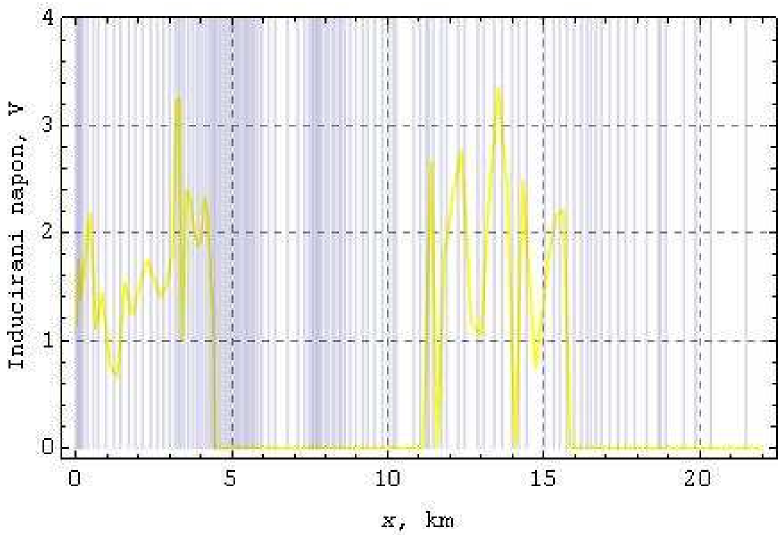


Figure 3. Induction current calculated for maximum train timetable.

According to the technical recommendations [6-8], current flowing in feeder cable is reduced with distancing of the train from the electric traction station. This is usually shown by the so called traction current diagrams. In the calculation, it is also necessary to take into account the direction of the current flow. Traction current flows to the first train at a feeder section, so the actual induced voltage depends on the position of trains on individual sections of track. Currents of electric traction are extremely variable, ranging from zero to the maximum value, depending on the driving regime, track inclines, curves, train weight, etc. Actual induced electromotive force and pipeline-to-soil voltage and their temporal and spatial distribution will depend, therefore, to a large extent on the dynamics of the railway traffic. In the present work, calculations for normal operation were carried out for the case when the current at individual feeder section reaches its maximum (at present case 0.28 kA) taking into consideration the railway timetable (two trains on present on in the area of influence but between different traction stations).

a)



b)

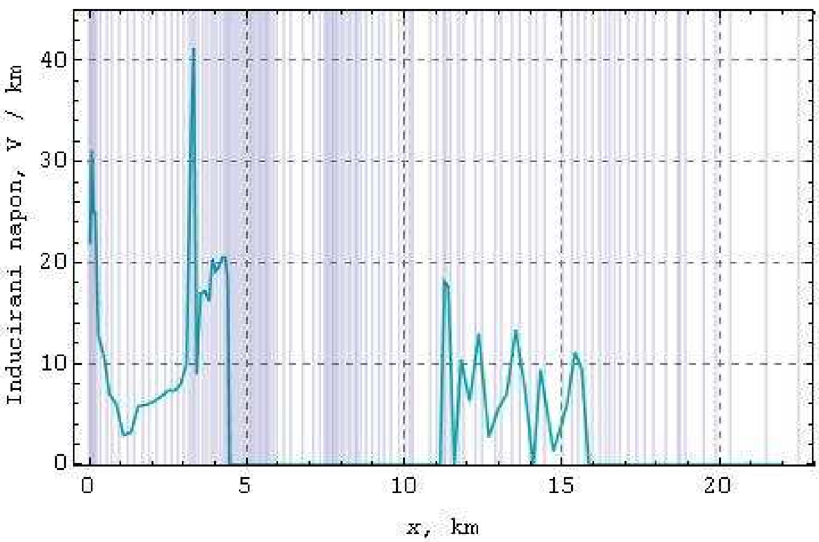


Figure 4. Induced electromotive force in a) expressed in V and b) V km^{-1}.

The sample results of the calculated electromotive force spatial distribution are shown in Figures 4 and 5. The appending total electromotive force at the investigated pipeline was calculated to be equal to 76.38V.

Calculation of the induced pipeline-to-soil voltage

The input parameters of the pipeline-to-ground voltage calculation that refer to the characteristics of the pipeline and soil, as well as the shielding factors are given in Table 1.

Table 1. Input parameters of the pipeline-to-soil voltage calculation.

Parameter	**Symbol**	**Unit**	**Value**
steel resistivity	ρ_{cel}	Ω m	0.17×10^{-6}
soil resistivity	ρ_{tla}	Ω m	700
pipeline diameter	D	m	0.508
vacuum permeability	μ_0	$H\ m^{-1}$	$4\times\pi\times10^{-7}$
relative permeability of steel	μ_r		300
frequency	ω	$rad\ s^{-1}$	$2\times\pi\times50$
insulation thickness	δ_c	m	0.0035
vacuum permittivity	ε	$F\ m^{-1}$	8.85×10^{-12}
relative insulation permittivity	ε_r		2.4
insulation resistivity	R_u	$\Omega\ m^2$	25000
pipeline impedance	z	$\Omega\ km^{-1}$	0.112217+0.639649×I
pipeline parallel admittance	y	$S\ km^{-1}$	0.0638372+0.00304264×I
characteristic pipeline impedance	Z_c	Ω	2.48916+1.99137×I
pipeline propagation factor	γ	km^{-1}	0.152842+0.134697×I
pipeline characteristic length	L_K	km	6.543
shielding factor for ρ_{soil} = 700 Ω m	k_R		0.358431
shielding factor that includes the effect of return cable for ρ_{soil} = 700 Ω m	k_r		0.274039

Estimation of the specific resistance of isolation, R_u was based on current cathodic protection system requirements. Relation between cathodic protection current j_z and insulation resistivity is given by the equation:

$$\left(\frac{j_z}{\mu \text{A m}^{-2}}\right) = \frac{3\times10^5\,\text{V}}{\left(R_u/\Omega\ \text{m}^2\right)}$$

In the simple case of pipeline and high AC voltage line placed in parallel, one can analytically express the pipeline-to-ground voltage and currents along the pipeline. For the general case of random mutual position of the pipeline and high AC voltage line in the zone of influence, the method is based on the division of the pipeline in the relatively large number of segments in order to calculate the spatial distribution of the pipeline-to-ground voltage. Each *i*-th segment is reduced to π network exposed to the induced electromotive force E_{msi}. The calculation is performed by solving the system of equations each being applicable to an individual cell. Matching results with the actual situation depends primarily on knowledge of the actual insulation resistivity including resistive and capacitive contributions.

In the segmented model, calculation of the pipeline-to-ground voltage can be simulated by placing grounding resistance R_{ground} at any point between the *i*-th and *j*-th segment. Lowering of the pipeline-to soil potentials near grounding point depends on the grounding resistance and the impedance electrical circuit pipe-soil. Grounding pipeline in several points can cause significant current flow through the grounding electrodes. This current can reach tens of amperes under normal operation or a few hundred amperes during earth faults. Segmented model enables calculation of current flowing through the grounding electrodes placed between the *i*-th and *j*-th segment. Groundings must have sufficient current capacity.

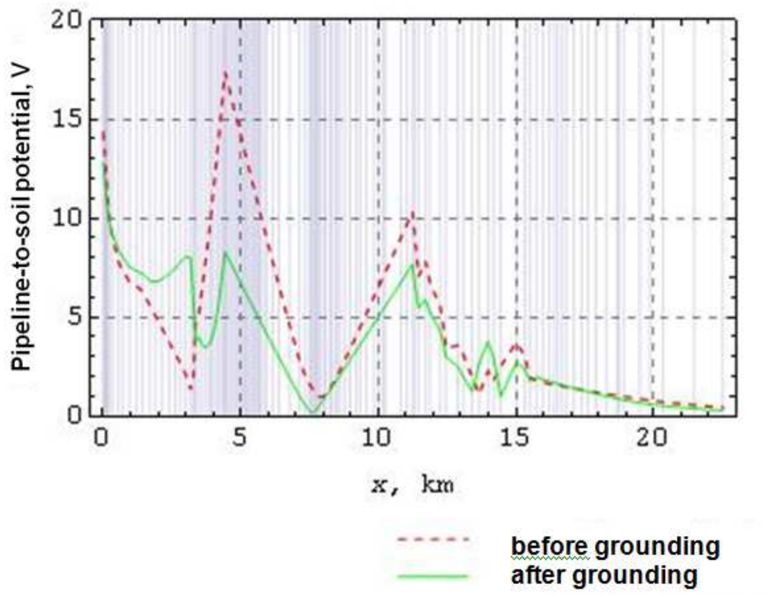


Figure 5. Pipeline-to-soil potential under normal operating conditions of AC traction before and after grounding.

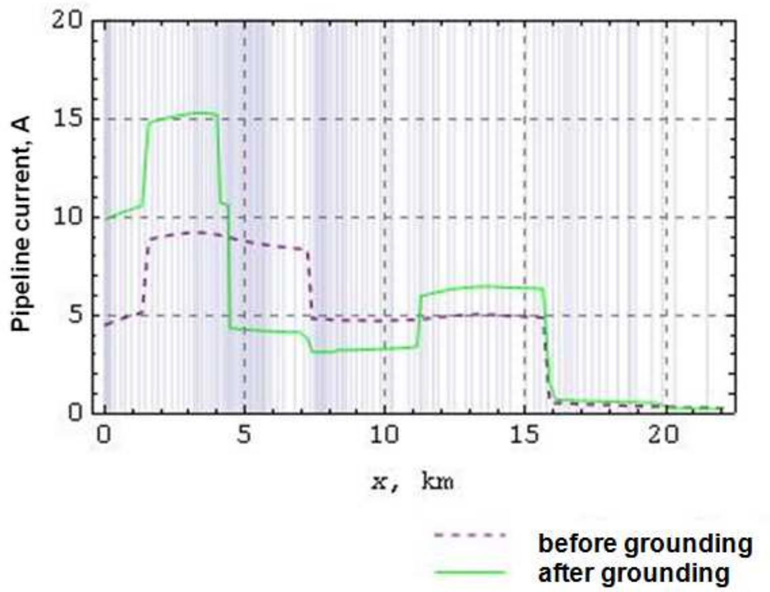


Figure 6. Pipeline current under normal operating conditions of AC traction before and after grounding.

Figures 5 shows spatial distribution of pipeline-to-soil voltage and Figure 7 shows current on the pipeline before and after grounding. Four groundings with resistances between 0.47 and 3.1 Ω were already present on the pipeline. 8 new groundings having resistances equal to 2 Ω were added. Currents flowing trough grounding electrodes were found to be between 0.23 and 9.88 A.
Positions of new groundings were primarily determined by the induced pipe-to-soil potentials at certain segments of the pipeline. The extremely significant design factor was soil resistivity since the pipeline passed through rocky terrain of very high resistivity (mean value equal to 700 Ω m). Points of low soil resistivity had to be found in order to attain sufficiently low grounding resistance.

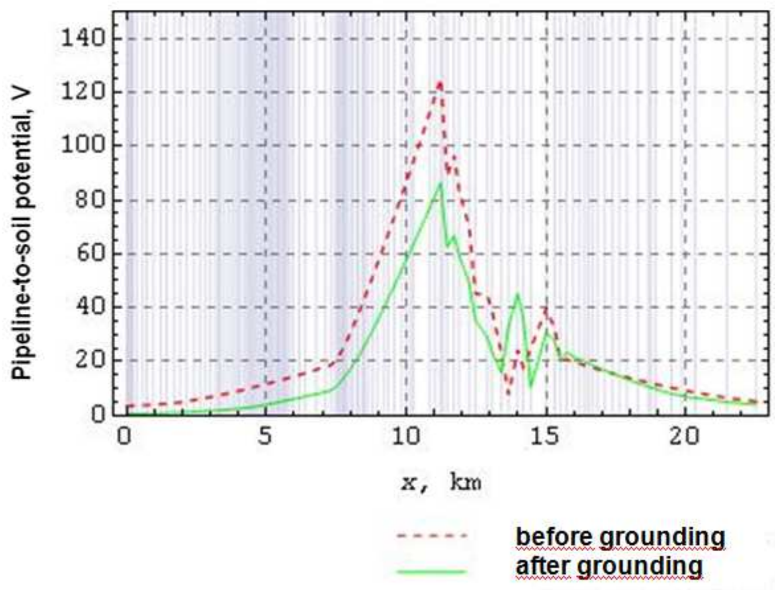


Figure 7. Pipeline-to-soil potential under earth fault conditions of AC traction before and after grounding.

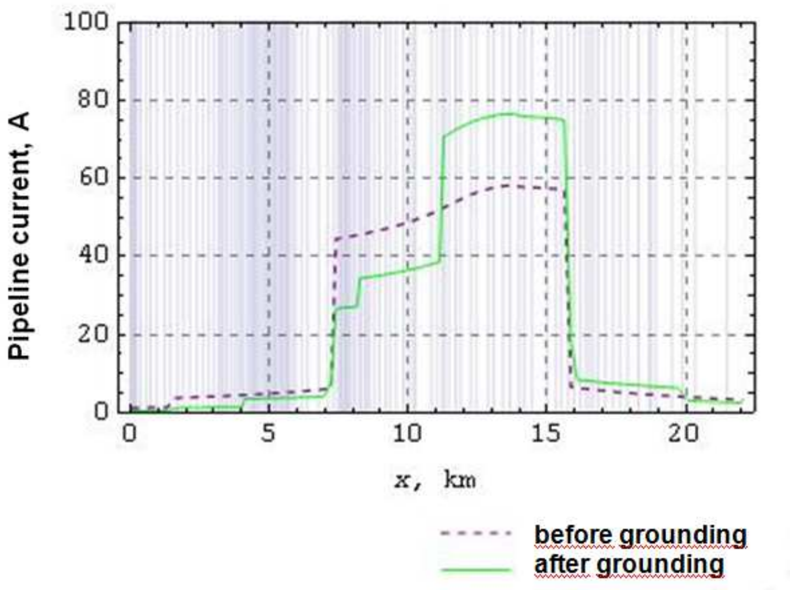


Figure 8. Pipeline current under earth fault conditions of AC traction before and after grounding.

The calculation was repeated for the case of earth fault. The induction current was estimated at 3.24 kA. Figure 7 and 8 show the results under earth fault conditions. Currents flowing trough grounding electrodes were found to be between 0.34 and 58.91 A.

Conclusions

Calculation of inductive effect on pipelines in the zone of influence of AC railway traction is a complex procedure that is dependent on a number of railway and pipeline characteristics. The calculation procedure had to combine mathematical expressions that were commonly used by railway companies for estimating inductive influence of railway on communication lines and mathematical expressions commonly used by pipeline operators to estimate inductive influence of high voltage AC power lines on pipelines.

By performing repeated calculation with various input parameters, one can obtain spatial and temporal distribution of:

- induced electromagnetic force
- induced pipeline-to-soil potential
- pipeline current
- the effect of groundings
- current trough grounding electrodes

The present calculation enabled realistic estimate of the electromagnetic induction effect and precise design of mitigation measures. Based on these calculations conclusions could be made whether induction would pose a safety and/or corrosion threat to the pipeline. The estimated extent of the inductive influence was confirmed by field measurements.

1. CEN/TS 15280:2007 Evaluation of a.c. corrosion likelihood of buried pipelines -Application to cathodically protected pipelines
2. EN 50443:2011Effects of electromagnetic interference on pipelines caused by high voltage a.c. electric traction systems and/or high voltage a.c. power supply systems
3. ITU-T K.26 vol.V:1989 ITU-T Directives 1989 Directives concerning the protection of telecommunication lines against harmful effects from electric power and electrified railway lines - Volume IV Inducing-currents and voltages in electrified railway systems
4. ITU-T K.26 vol.II:1989, ITU-T Directives 1989 Directives concerning the protection of telecommunication lines against harmful effects from electric power and electrified railway lines - Volume II Calculating induced voltages and currents in practical cases
5. CIGRE Guide on the Influence of High Voltage a.c. Power Systems on Metallic Pipelines (CIGRE:1995)
6. SBF TE 1:2006 Technische Empfehlung Nr. 1 der Schiedsstelle für Beeinflussungsfragen , Anleitung zur Berechnung der in Telekommunikations-(TK-) Leitungen durch Starkstromleitungen induzierten Spannungen
7. AfK-Empfehlung Nr. 3: Oktober 2006 or SBF TE 7:2006 „Maßnahmen beim Bau und Betrieb von Rohrleitungen im Technische Empfehlung Nr. 7 Einflussbereich von Hochspannungs-Drehstromanlagen und Wechselstrom-Bahnanlagen", Oktober 2006
8. AfK-Empfehlung Nr. 11:Januar 2003 Wechselstromkorrosion – Beurteilung der Verhältnisse bei Stahlrohrleitungen und Schutzmaßnahmen Herausgegeben
9. NACE SP0177-2007 Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems