**TE_253/2010_CNCSIS**
# MODELING, PREDICTION AND DESIGN SOLUTIONS, WITH MAXIMUM EFFECTIVENESS, FOR REDUCING THE IMPACT OF STRAY CURRENTS ON UNDERGROUND METALLIC GAS PIPELINES

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## The research team:

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## Project presentation:

### The importance and the relevance of the scientific content:

The acceleration of the corrosion of the underground metallic pipelines (water-lines) due to the electromagnetic pollution of the soil (the totality of currents that go through the soil and who's current lines can cause perturbation in the electric double layer of the metallic water-lines/soil system) is the determinative factor in reducing mentenability and reliability of underground metallic structures. The biggest percentage of the cases of accelerate corrosion produced by stray currents in a.c. represents those caused by the distribution and transport network of electrical energy. [1-4]

Analytical and numerical modeling of the real situation (inductive coupling – conductive coupling – real time) represents the only viable and efficient method to predict the risk areas, on which dangerous electrical potentials may arise. [5], [6], [7] [8]

From these points of view, the development of specific analysis methods, modeling instruments and collecting information about the electromagnetic interference, represents an important issue so as to solve the corrosion problem.

Developing and implementing these methods, instruments and information should ensure the integrity of the underground pipelines grid, with an immediate effect in the safety of the operating personnel and the environment protection.

The solution of the electrochemistry problem requires experimental techniques and theoretical specific to the study of electrode process, in which time the solution of the electro kinetic problem which appears is a physical-mathematical problem of the electromagnetic field in cvasistationary regime.

Researches of this domain reveal a series of algorithms to solve coupling problems, but they are restrictive and do not take account of the geometry complexity of the pipeline grids. These algorithms are based on a series of approximations that raise the particularity of the problems. [9], [10], [11]

The traditional approach in the electromagnetic field analysis around infinitely long conductors of cylinder shape situated in the vicinity dissipative hemi space (the ground) was published for the first time in a simplified way at the beginning of the last century. With all these, the first analytical methods that were elaborated and world wide spread were independently developed in the 20' by Carson and Pollaczeck using his wide known formulae [12], [13], while various other approximating formulae were introduced later. [14-18] With the advances in computer technology and the increase in computational power, more advanced and sophisticated analytical models were adopted. As a result, a technical recommendation was developed [19 - 21], based also on experimental results. During the late 1990s two research projects of the Electrical Power Research Institute (EPRI) and the American Gas Association (AGA) targeted the analysis of power line inductive coupling to gas pipelines using practical analytical expressions. [22]

A common research that analysis both the inductive and conductive coupling is realized by SES (Safe Engineering Services) and AGA (American Gas Association). The mechanisms of the inductive coupling, line-underground pipeline, are studied also by other authors for many practical cases. [26-29]

The analysis of the conductive effects is experimental; was introduced a generalized theory, which studied the conductive coupling between the high voltage systems and the underground metallic structures. [23], [24], [25]

In 1995, as part of CIGRE Working Group 36.02, the document named *Guide Concerning Influence of High Voltage AC Power Systems on Metallic Pipelines* was elaborated. This document approaches the influence of the high voltage power devices over the metallic pipelines situated in their neighborhood. This study represents a reference document in this field and it describes the simple evaluation methods of the electromagnetic interference phenomena and the method for measuring them. [30]
A separate study of the inductive coupling and of the conductive one without considering the influence of the pipelines grid on the metallic structure of the power station (grounding structure) often leads to important errors. The contributions on these topics are in [31], [32].
A group of researchers from the VUB University of Brussels, in co-operation with the firm Elsyca from Brussels, have developed a three-dimensional computation model in D.C. quasi-stationary regime. The model can analyze structures composed by wide networks of underground pipelines; can evaluate inclusively the stray currents derived from the others systems of cathodic protection or from the railway respectively. [33]
More recently, new methods employing the Finite- Element Method (FEM) or Finite Difference Method (FDM) were proposed that aims to provide an alternative calculation method of the induced voltages on the pipelines. [34-38]
In the topic of line-pipeline interference recently was proposed some artificial intelligence techniques, but the imposed solution was not unanimity accepted in the field because of the restrictive algorithms involved in the process. [39], [40], [48]
In the world, there are a few software packages, available on the market, for simulating the electromagnetic interference phenomena in quasi-stationary regime, harmonic type, between the high voltage transmission lines and the underground metallic pipelines, based on the method described above (ECCAPP–Electric Power Research Institute; CDEGS-Safe Engineering; CATPro–Elsyca). [41], [42]
In the world, exists these kinds of preoccupation to studies the metallic structures corrosion because of a.c. and d.c stray currents. Regarding the corrosion control in d.c. stray currents, the developed and settlement technical solutions [43] could be implemented relative easily and assures an adequate protection (polarized mitigation, forced mitigation, etc.). In terms of corrosion control due to a.c. stray currents, although exist much more theoretical studies [44] the performances and effectiveness of the protection solutions are not sufficient, decoupling through PCR/ ISP devices (SUA), decoupling with polarization cells (EU, SUA, Canada) etc.
In Romania, about 5 years, the Technical University of Cluj and INCDIE ICPE-CA (dr. Dan Doru Micu and dr. Iosif Lingvay) are concerns about studying the accelerating corrosion effects of the a.c. signals overlapped to metal/ electrolyte interferences, studies from which resulted efficient technical solutions for corrosion control in a.c. stray currents. [7], [45]

The experience of the project director and research team members in this domain is wide. Until now, they have bring their contribution in solving this kind of interference problems, between high voltage power lines and metallic pipelines, which can be observed from the presented list of scientific papers, published at different international conferences and from the numbers of research projects at which were participate. The papers made by the team was disseminated in frame of ID_1024 [37], and CEEX_ICEMECOS [46] research project (partnership and further international collaborations) where the members of this research team have made significant contributions. The project manager (conf.dr.Dan Micu) has also worked with an international team on the same theme within the Romanian – Flemish bilateral contract developed in collaboration with ETEC Department of the Free University of Brussels, BILA 2000. [47]

A study made over the most prestigious publications in domain (IEEE Transactions on Electromagnetic Compatibility), underlines the fact that almost 20% of articles present modeling results of some electromagnetic interference phenomena and rest of them presents results with experimental and observational nature.
To elaborate some physical models for efficient calculations and mathematical simulations of the interaction processes correlated with adequate numerical analyses for investigating and/or predicting the impact of the electromagnetic fields created by HVPL through the nearby metallic structures is a general effort of the researchers from the entire world. In this context, the proposed theme presents the chance of an important step in this domain of present interest.

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## Project objectives:

The aim of the project consist in developing knowledge in the domain of the influence of a.c. stray currents on electrochemical processes, in special the aspects regarding the corrosion of metallic gas pipelines. Based on this knowledge's we will elaborate a prediction and control method for the corrosion and also solutions and procedures to follow in the design, for decreasing the degradation of metallic pipelines by corrosion.

The project director (conf.dr.ing. Dan Doru Micu) together with team members had an international collaboration in this area with a researcher from the Aristotle University of Thessalonica (Dr. G. Christoforidis). Results have led to the development of a differential mathematical model for induced voltage value estimation in an underground metallic, gas transportation pipeline which shares the same distribution corridor with an overhead high voltage power line. [37], [38]

A similar approach based on finite element method it was also done in [26], [28]. Project manager had also an international collaboration in the same field with the ETEC department of VRIJE University Brussels, trough a Romanian-Flemish bilateral contract BILA 2000: *Development of methods and tools for analysis of the electromagnetic AC interference between high voltage transmission systems and metallic pipelines*. The aim of this project it was to determine an accurate solution for field problems using the boundary elements method [47].

Project manager and team members were partners and coordinators of CEEX inter and multidisciplinary projects. [46] Thus is reflected the implication of project manager and team members on applying field calculation numerical methods for identifying electrical potentials on pipelines, arising from inductive coupling.

Calculation assumptions of these methods are limited to deal only with pipelines which have a perfect insulation and with homogenous soil, rarely encountered in practical situations. Pipeline insulation defects are a common fact especially for older pipelines. Their dimension varies from a few millimeters up to several decimeters. If induced voltage in pipeline exceeds 1kV it may occur discharges even with sparks at damaged or porous areas. Therefore presence of defects or pores should be considered in study for the coupling between a high voltage power line and nearby pipelines.

To take a further step from current models, in the first goal of this project it will be developed a generalized hybrid method to model the common power line-pipeline distribution corridor and calculate the induced currents and voltages in pipeline. The term of hybrid model was introduced in papers and a book [7], [9] disseminated within the ID_1024 [37] and CEEX_ICEMECOS [46] project, only as a study concept of an equivalent Thévenin power line - pipeline circuit. The main advantage of this method over previous ones will consist in the fact that in the same model it will be used either field calculations booth electrical circuit theory methods being possible to take in account existing defects in pipeline insulation and heterogeneous soil. It will be given higher accuracy to results by optimizing the model through a multilayer soil type consideration. The proposed method will use the differential model (developed by 3 team members through the ID_1024 project [37] and improved in the international collaboration [38]) to determinate the magnetic vector potential on the overhead power line conductors surface being under a fault condition, and on the pipelines surface placed in the same distribution corridor. Then using a combination between Faradays laws and the results obtained for magnetic vector potential it will be calculated the self inductance of power line and pipeline and the mutual inductance between this two structures.

After that it will be gone further to develop and implement an equivalent electrical circuit to model the specific situations by considering an optimal number of sections for power line and pipeline. The equivalent circuit will contain their resistance, their self and mutual inductance and leakage resistance (to consider insulation defects).

Once these parameters are determined through the differential numerical model, the equivalent electrical circuit will

be calculated. To substantially increase the accuracy of the numerical results of this method it will be taken in account the ill conditioned nature of the impedance matrix. This hypothesis is neglected in [34], involvement of the conditioning number in the study of electromagnetic interference between power lines and nearby pipelines is partially discussed in the ID_1024 project and in papers [37].
For this first objective, the equivalent circuit will be implemented in specialized software, the PSPICE module of the ORCAD program. Due to the large number of circuit elements, the input file for this software will be obtained in txt format, eventually as a result of a MATLAB routine.

Using the data obtained through the generalized hybrid method and previously retained in a data base as I.2 si II.1 objective will be done the implementation of some resolving solutions for the electromagnetic interference problems between overhead power lines and metallic gas transportation pipelines, based on artificial intelligence techniques. Artificial intelligence techniques are methods with a growing impact in solving problems from various scientific fields. These methods go from a basic set of solutions determined by different methods (in our case results obtained with the generalized hybrid method) and scale the solutions for flexible geometry construction of the studied problem based on the training data set. The advantage of these artificial intelligence techniques (Fuzzy Logic, Neural Networks and Genetic Algorithms) is that once implemented and trained to resolve a specific problem, they provide solutions with reduced calculation effort for any other geometric configuration of the studied problem, unlike conventional numerical methods (finite difference method [36], finite element method [26], boundary element method [47]) which take a long processing time and a considerable calculation effort for each configuration in part.
There are some attempts in the specialized literature to use artificial intelligence techniques to solve these electromagnetic interference problems, between overhead power lines (OPL) and metallic pipelines (MP). Employees of the research team from Aristotle University of Thessalonica in [39] use Fuzzy Logic to study an electromagnetic interference problem between a 145 kV high voltage power line with a single-phase grounding fault and an underground gas metallic pipeline. In [48] the team of this project with a collaborator from Aristotle University brings the theoretical basis for making an interference study between an overhead power line and a metallic pipeline using artificial intelligence techniques.
In [39] and [40] it was achieved the implementation of a neural network which calculates directly the induced voltage in pipeline, but using some simplifying assumptions, like elimination of air-earth interface, considering the single-phase fault far away from the common distribution corridor.

Reevaluation of these assumptions according with the latest studies in this area constitutes the starting premises in seeking to improve these methods to solve OPL-MP interference problems.
So it can be said that there is no generalized solution to study this problem in normal OPL operation conditions, with or without cathodic protection for pipeline or in case of some more complex faults (two or three phase faults, lightning, etc). Thus, in these objectives it is considered relevant in context of international research to implement a general solution using artificial intelligence techniques (Fuzzy Logic and Neural Networks) to solve different particular OPL-MP electromagnetic interference cases, like: operation in normal conditions with or without cathodic protection, respectively in single, two or three phase fault conditions for different geometrical configurations for OPL.
The innovative idea consists in combining alternative solutions, based on the developed artificial intelligence techniques, in a main Fuzzy Block which will be created to identify parameters that define the specific operating conditions (based on a defined set of fuzzy laws) and call the solution or solutions that may solve the specific OPL-MP electromagnetic interference problem. If there are several possible solutions (close accuracy solutions) for a specific problem, this main Fuzzy Block will also have to provide a final solution by weighting the provided results (outputs) of these alternative solutions. For each particular case of OPL-MP electromagnetic interference will be created a training data base by solving that specific problem using the hybrid method (developed through the objective I.1).
For testing and validation of the generalized method, developed using artificial intelligence techniques, it will be chosen a set of real OPL-MP electromagnetic interference problems which will be solved with the proposed solution and the obtained results will be compared with in field measurements. Testing cases will be provided by the national gas transmission system operator, The National Company of Natural Gas Transportation TRANSGAZ S.A. with which the research team of this project has signed a collaboration agreement and has an ongoing research contract.

Within the objective II.2, the project proposes to develop technical solutions to minimize corrosion phenomena existent in the electromagnetic environment by reducing voltages induced in gas pipelines by an overhead electrical line that share the same distribution pipeline corridor.
In the international scientific papers identified [43, 44] using equivalent circuit is recommended for the study of galvanic corrosion, since it can lead to a simplification of the understanding mechanism behind this phenomenon. But because corrosion is not due to a single mechanism, we believe that you can use several equivalent circuits to describe exactly how physical and chemical aspects are considered relevant in the process of corrosion. For this purpose a circuit will be proposed in which the modeling of the corrosion process of metal pipes for a joint route with overhead

line be made by choosing the circuit elements designed to model parameters such as soil resistivity, resistance to leakage, corrosion rate.

To prevent voltage peaks induced in a buried pipeline, common distribution corridor of Overhead Power Line – Pipe will be designed taking into account the effect of electrical or geometrical discontinuities in the area of influence.
In order to reduce the inductive coupling in [23] it is said that an overhead electrical line could be designed to generate constant, longitudinal and minimum electric field conduction in the adjacent pipeline. In [4, 5], without a relevant demonstration, it is shown that for a particular configuration of power line is feasible to minimize the conduction of the electric field in the area of influence, through a proper sequence of phase conductors. Another possible technique to reduce the longitudinal electric field in the influence area of Overhead Power Line-CM, presented in the scientific literature [6] is to use an auxiliary grounding and shielding conductor, installed between overhead electrical line poles. In the context of this research, based on hybrid model built into the objective I.1, the efficacy and limitations of these techniques in order to reduce the longitudinal electric field for different geometries and different loading conditions of the power line will be gradually analyzed. Algorithm developed by the research team in [37] and [46], to calculate the longitudinal electric field, will be amended for this analysis, because it must include the effects of the auxiliary conductor. Calculations will be made with and without the auxiliary conductor, in order to evaluate the effectiveness of the attenuation techniques. The procedure is repeated for each geometry and power line phase conductor examined.
Within the bilateral agreement with University of Padova researchers group from the Department of Electrical Engineering (Prof. Daniele Desideri) (with who the project manager is having an ongoing research collaboration agreement for 3 years 2009-2011), it is planned to realize some simulations in specialized software (Maxwell, Comsol) to track the screening effect and the synchronization of power line conductors phases on the longitudinal electric field.

In the papers [30] and [32] it is used an approximation according to which the horizontal grounding conductors are not affected by the electric field conduction resulted from an adjacent electric line joint to pipeline route. If we ignore this case, to compute the attenuation (the equivalent circuit modeling) will have to keep in mind that the grounding conductors may have appreciable values for the induced voltages.
Since in the bibliography [26, 30, 32, 33] were identified only restrictive algorithms, in this objective algorithms will be developed to calculate the attenuation effect for each grounding conductors configuration, for conductors with arbitrary electrical conductivity and permeability, diameters up to 25 mm and for the entire range of possible soil resistivity.
In scientific literature [23, 29, 30, 32, 34] each conductor was considered as individual, thus the attenuation was made in a single point of the pipeline. In general, due to multiple discontinuities, physical or electrical from the area of influence, more voltage peaks are induced in a pipeline (more picks). Installing a single attenuation conductor can reduce local induced voltages on the pipeline, but does not affect other maximums. So, to develop a complete attenuation method, individual successive attenuation methods of voltage peaks induced in a pipeline will be implemented, in order to achieve reduced voltage values induced in the pipelines of considerable length.

In objective III.1 we will make a series of theoretical and applied research in order to design a protective device for metallic pipelines, meant to mitigate currents induced by high voltage power lines (HVPL) that share the same distribution corridor with them. In [31] one can find a study of the influence of the HVPL adjacent to buried metallic pipeline, manifested by the presence of stray currents generated by inductive coupling. This induction is dependent on the quality of insulation. Destructive phenomena produced by stray currents generated by the HVPL on the coating and tubular material of the buried pipeline material are well documented in the literature [1, 43, 44].
In previous studies, conducted by the project directors and team members within projects CEEX ICEMECOS [46] and ID_1024 [37], we show that pipelines with superior quality coating, characterized in terms of quality as good and very good insulations, will be strongly influenced in a negative way. The absence of pores in the insulation means there is no contact between the ground and the metal parts of pipes. The induction that occurs in this kind of pipelines (HVPL operation due to different loads), without mitigation towards the soil, can produce voltage spikes of 5-6 V, very harmful for the insulation of the pipeline. HV power lines induce sinusoidal currents in the natural gas transmission pipelines which are in their vicinity. If the positive component of this sinusoidal signal is drained to the ground, the negative component overlaps over the injected signal by the cathodic protection station, causing a decrease of the pipeline – soil potential. Thus, cathodic protection is more effective only on the signal induced by the HVPL into the pipeline, signal whose positive part is drained.

In Romania we know a number of devices that limit the amplitude of AC voltage positive alternation induced in the pipeline to the acceptable values in terms of reaction in time of coating. Their disadvantage is that the amplitude of the negative alternation is not limited to an acceptable level, which does not harm the insulation applied to buried pipelines. Potential whose actual values are more negative -1100 mV, measured through the electrode of Cu-$CuSO_4$,

damage insulation applied to pipes, leading to cathodic detachment [45].
World wide, there are many devices that drain stray currents induced in underground pipelines, but there is no information available regarding the instantaneous potential limitation. The disadvantage of these devices is the overall dimension, the absence of potential control of cathodic protection (potential $IR_{free}$ what should be between -850 mV and -1100 mV), and that insulation is not protected for cathodic overprotection.
Thus, the optimal solution for controlling coupling between the HVPL and a pipeline is the development and implementation of some controlled mitigation devices of stray currents that are designed to protect metallic buried pipelines, isolated from the outside.
Advantages over existing devices would be the possibility of mitigating only the positive alternation harmful cathodic protection from sinusoidal form of current induced in the soil – pipeline. The device will be designed to eliminate the cathodical overprotection due to currents induced in pipeline by HVPL, avoiding the cathodical separation of insulation, and to limit the values of the voltages induced in the pipeline, values which were estimated previously using methods developed under the objectives I and II of this project proposal. The device will have to protect any pipeline located near the HVPL, including the situation of a defect, on one phase (one phase accidentally touching the earth, outside the right-of-way region), or on two-phases (according to models developed under objective II), knowing that at the beginning of the fault an over voltage can be induced in the pipeline. Regarding this fact, it's important to ensure a good time response of the device.
Before checking the operation and efficiency of the mitigation device, this one will be subjected to functional testing and simulations in laboratory conditions. An equivalent circuit of the device will be implemented in PSpice and the behavior of the device will be simulated, for real conditions.
Finally, we will emphasize the functional efficiency of the device and of our computation and prediction methods, using on-line measurements of induced voltages and stray currents. The measurements will be performed in front of a cathodic protection station, on two gas pipeline transits having a common route with 400kV HVPL (identified case by SNTGN TRANSGAZ SA).
Note: The references are the same like in 8.1

**The estimated impact of the project**

**The scientific and technical impact:** Results of the project aim to rethink the activities of modeling, design, implementation and maintenance of transporting energy carriers (gas, liquid fuel) in an integrated context, which considers both the requirements imposed by industry (existing stray currents) and the continuous monitoring of the degradation state of metallic pipelines. The project also aims to develop methods and algorithms that allow the analysis of existing situations, in terms of the impact of electromagnetic fields created by the HVPL on metallic underground pipelines, setting risk situations and simulating the behavior of the model by introducing corrosion protection solutions. The viability of the mentioned will allow extending the adopted technical solutions in other fields of activity, mainly in the industry.
**Economic impact:** Anticipation, using the prediction of degradation state of metallic pipelines, creates the premise of an efficient and rational investment plan. Applied during the design stage, methodologies that avoid pipelines degradation represent the fundament of sustainable development, even in heavily polluted environment. We aim to recommend some modeling solutions, prediction and accurate and realistic design at low cost. This will asses the complex phenomena that arise when a physical model and a mathematical simulation of the electromagnetic field interaction with metallic pipelines is performed. A quantification of these results is easy to perform for the transmission and distribution of natural gas operators and electricity transmission operator that are forced to use right-of-ways even from the design stage. If both energy infrastructure and underground pipelines networks designers will consider the results of our research, we believe that electromagnetic incidents between the two sides will be avoided and the maintenance costs of the pipelines network will be reduced.
**Social impact:** Consist in offering solutions for optimal placement of devices and solutions for protection and safety on electromagnetic fields impact, which lead to the situation of risk and environmental pollution reduction. The results ultimately will benefit society, by providing safer and healthier living and working conditions (sustainable development).
**Environmental impact:** Knowing the polluting agents and particularly the actions of stray currents allows applying correct technical solutions that reduce the effects of pollution as well as potential sources of pollution. In this way, the occurrence of complex pollutants agents will be severely hindered and will result in improved environmental conditions.
**Opportunities for education and training:** Much of the results presented as methodologies and amendments to regulations will be the support of improving university courses and perfecting courses for specialists. Both courses and applying the monitoring of gas transmission pipelines status means new jobs, especially for young engineers.

We must also consider the opportunity of building in perspective, some gas pipelines bus that pass through our country. Inevitably, there will be right-of-ways, and hence possible corrosion problems. We intend to offer our expertise capacity in the feasibility study stage, to prevent any harmful effects that existing power lines might have on

the pipelines.
The addressed issues have an increased theoretical complexity degree and also a great practical importance. It is both inter-and multidisciplinary (electrical engineering, mathematics, electrochemistry, electrical equipment). We do not know any research center that has approached unitary and systematically this issue, so complex and so up-to-date by its implications.