NUMERICAL EVALUATION OF INDUCED VOLTAGES IN THE METALLIC UNDERGROUND PIPELINES

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In the paper are evaluated the induced potential in pipeline based on the subdivision of the zone of influence AC Power Lines / electric traction line / gas pipeline, in a relatively great number of sections in order to be able to determine voltages at many positions along the gas pipeline. Is presented two practical cases, of subdivision of the zone of influence in sections (a circuit model) and is created a special interpolation algorithm and global interpolation functions for the precise calculation of the induced voltages values in different points on the pipeline taking into account the measured data. Because there are only a set of available reactance measurements, for a continuous function between the magnetic permeability and electrical induced currents, it is necessary to apply numerical interpolation methods and/or nonlinear curve fitting procedures.

1. INTRODUCTION

Pipelines located near power lines, may capture a portion of the energy encompassed by the conductors' paths, particularly under unfavourable circumstances such as long parallel exposures and power fault conditions. Interference calculations consist essentially of inductive and conductive interference calculations, which are performed independently; computation results can subsequently be combined together. Inductive interference calculations are performed on a hybrid field theory/circuit theory model.

The evaluation of the induced voltage in pipeline is based on the subdivision of the zone of influence in a relatively great number of sections in order to be able to determine voltages at many positions along the pipeline using Thevenin equivalent circuits [1-3].

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2. NUMERICAL INTERPOLATION OF THE MAGNETIC PERMEABILITY

Some authors [4] approach the electromagnetic interference between power grids and neighbouring metalic structures by proposing the construction of a database to contain the corresponding values of the relative magnetic permeabilities of the metalic parts and the values of the induced electrical currents on different frequencies, both in a normal function of the power grids, and in mallfunction conditions. Thus, a reconsideration of the relative magnetic permeability, in an approximation close to the reality, leads also to relevant estimations of the electrical interference values that are to be identified. An eloquent example on this issue may be explained by one of the mathematical relations which relates the conductor impedances with the magnetic permeabilities, by Carson theory. Because there are only a set of available reactance measurements, for a continuous function between the magnetic permeability and electrical induced currents, it is necessary to apply numerical interpolation methods and/or nonlinear curve fitting procedures. Using numerical data from the consulted bibliography we implemented and tested a set of numerical interpolation instruments. Special attention was paid to the minimisation of the interpolation error, and to the stability of the proposed functions [4, 5].

The numerical interpolation of the magnetic permeability as related to the variation of the induced electrical current in the metalic structures was accomplished with a range of liniar, Lagrange and spline functions [6].

The relation below shows the cubic spline models, used in the interpolation process of this study:

$$B(x)=\begin{cases} 0 & x\le -2 \\ (x+2)^3 & -2\le x\le -1 \\ 1+3\cdot(x+1)+3\cdot(x+1)^2-3\cdot(x+1)^3 & -1\le x\le 0 \\ 1+3\cdot(1-x)+3\cdot(1-x)^2-3\cdot(1-x)^3 & 0\le x\le 1 \\ (2-x)^3 & 1\le x\le 2 \\ 0 & 2\le x \end{cases} \quad . \tag{1}$$

In order to identify the c_i coefficients from the spline interpolation function, we have to solve a tridiagonal system of equations, that without imposing any boundary conditions to the interpolation function, proves to be highly ill-conditioned. That is, a small variation of the input data can lead to great variations of the output data, the coefficients. Thus, the stability of the interpolation function is greatly affected. Numerical regularization techniques have to be applied so as to reach stable coefficients of the spline interpolation functions [6].

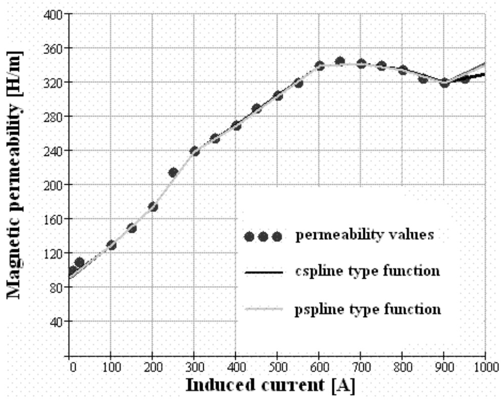

Fig. 1 – Numerical interpolation of data aqusition.

The tridiagonal equations system is presented in the above relation where the cubic spline interpolation has to be defined as a liniar combination of the $B_{\rm i}$ functions in the known interpolation knots:

$$\begin{bmatrix} 1 & 4 & 1 & & & \\ & 1 & 4 & 1 & & \\ & \dots & \dots & \dots & & \\ & & & 1 & 4 & 1 \end{bmatrix} \cdot \begin{bmatrix} c_{-1} \\ c_0 \\ \dots \\ c_{n+1} \end{bmatrix} = \begin{bmatrix} f(x_0) \\ f(x_1) \\ \dots \\ f(x_n) \end{bmatrix}; \; f(x_k) = \sum_{i=-1}^{n+1} c_i \cdot B_i(x_k) \;\; 0 \le k \le n . \qquad (2)$$

As it can be seen in (Fig. 1), the interpolation functions, linear and spline, do a great job in fitting a continuos link function between magnetic permeability and induced electrical currents. The *cspline* function interpolates with cubic functions, *lspline* approximates the boundary knots with liniar functions, and *pspline* with parabolic functions.

3. **INTERPOLATION ALGORITHMS APPLIED FOR INDUCED VOLTAGE EVALUATION**

Is made an evaluation of the induced voltages in a pipeline, which runs in the same right of way with a power line and electric traction line, for a real case, (Fig. 2). The input data are: power line and pipelines geometrical configuration; conductor and pipeline physical characteristics (including insulating and coating characteristics); environmental parameters (air characteristics, soil structure and characteristics); power system terminal (or boundary) parameters (power source voltages, equivalent source impedances) [7, 8].

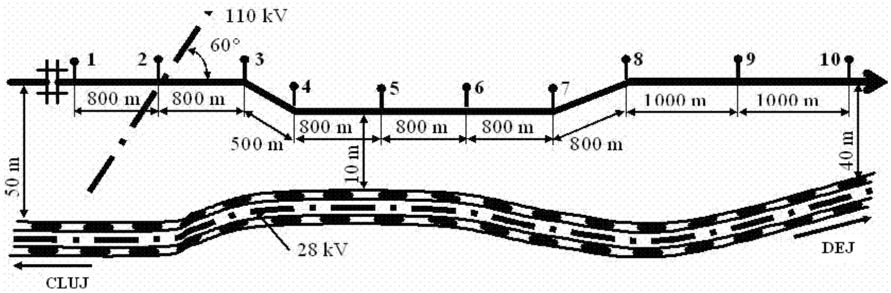

Fig. 2 – The right of way electric power line-traction line-gas pipeline.

The results demonstrates that is possible to obtain a precise evaluation of the solicitations if is known the resistance and the adduction current in the pipeline. After the determination in each point the potentials due to the right and left side of the line is applied the superposition method [2, 3].

It was measured the a.c. voltages between the pipe and soil, respectively the U_{AC} induced along the gas pipeline. We measured the induced alternative voltages in steel gas pipelines posed in different type of soil and isolated by different organic layers. In this way was determined the: induced voltages U_{CA} in a medium pressure gas pipeline (1999), with 300mm diameter and 8 mm width, isolated with polyethylene in 3 layers (total 3mm) according with the EN 10285, having the same right of way (20 km) with a double traction line and being intersected with an electric power line 110 kV; soil resistivity along the utility corridor and electrochemical potentials *E* pipeline/soil along the gas pipeline. The measured results [7] are presented in the Table 1.

Table 1

The parameters values in the points of measure

Parameter	Points of measure									
	1	2	3	4	5	6	7	8	9	10
Soil resistivity [Ω·m]	11	18	16	45	32	93	21	64	17	15
U_{AC} [$V_{ef.}$]	8.10	19.1	17.2	29.3*	15.2	26.4**	7.13	1.89	2.11	4.32
E [$V_{Cu/CuSO4}$]	- 0.353	-0.398	-0.371	-0.325	-0.394	-0.410	-0.387	-0.324	-0.352	-0.365

* – maximum value obtained when a train pass from Dej toward Cluj
** – maximum value obtained when a train pass from Cluj toward Dej

The calculus and the program made in MathCAD with the predefined functions help us to determine more precisely the values of the induced voltages on the entire influence zone. The values in volt of the induced voltages (*y*) measured on the common corridor line-pipeline at different distances in meters (*x*), are introduced in MathCAD program. The predefined functions for the spline and linear interpolation are used for the induced voltage calculus in any point of the right of way [7, 8]:

$$\begin{cases} lsp(t) := \text{interp}(\text{lspline}(x,y), x, y, t) \\ psp(t) := \text{interp}(\text{pspline}(x,y), x, y, t) \\ csp(t) := \text{interp}(\text{cspline}(x,y), x, y, t) \\ l(t) := \text{linterp}(x, y, t) \\ t := 800, 801..7450 \end{cases} \cdot \tag{3}$$

The following algorithm was developed in MathCAD program for the induced voltage calculation in different points on the pipeline based on the measured data.

$$A := \left| \begin{array}{l} X \leftarrow x := (800 \quad 1600 \quad 2400 \quad 2650 \quad 3450 \quad 4250 \quad 5050 \quad 5450 \quad 6450 \quad 7450) \\ V \leftarrow y := (8.10 \quad 19.10 \quad 17.2 \quad 29.3 \quad 15.2 \quad 26.4 \quad 7.13 \quad 1.89 \quad 2.11 \quad 4.32) \\ n \leftarrow \mathbf{last}(X) \\ \quad \mathbf{for} \quad j \in 0..n \\ \qquad A_{j,0} \leftarrow V_j \\ \quad \mathbf{for} \quad j \in 1..n \\ \qquad \left| \begin{array}{l} \mathbf{for} \quad k \in 0..n-j \\ \qquad A_{k,j} \leftarrow \dfrac{A_{k+1,j-1} - A_{k,j-1}}{X_{k+j} - X_k} \\ \mathbf{for} \quad i \in 1..j \\ \qquad A_{n-j+i,j} \leftarrow 0 \\ A \end{array} \right. \\ A \end{array} \right. \tag{4}$$

$$N(t) := \sum_j \left(A_{0,j} \cdot \prod_{i=0}^{j-1} \left[t - (x)_i \right] \right) + A_{0,0} .$$

The interpolation spline function with linear end conditions is more precise than the linear interpolation polynom but the created algorithm gives us the correct data if the interval of the influence zone is increasing.

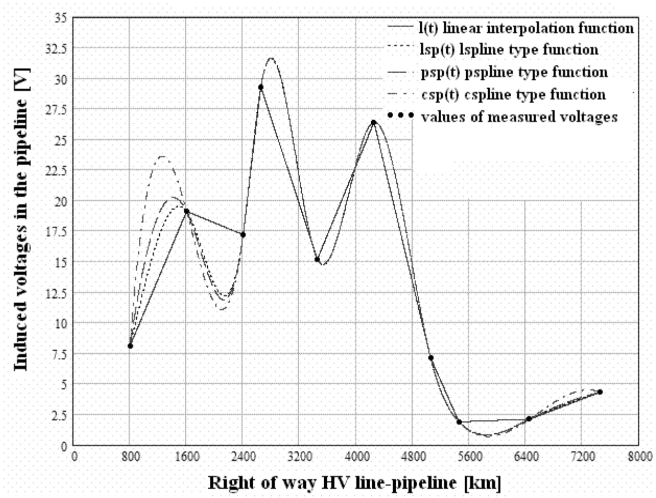

Fig. 3 – Induced voltages in the gas pipeline using special interpolation functions.

Another example presents a real case for evaluation the induced voltage in each point of the right of way power electric line (220 kV) – metallic gas pipeline, based on the measured data, was used the numerical spline interpolation method. It was developed a global interpolation function for all four corridor sectors [9].

The calculated data for induced voltages is split in four sectors taking into account the configuration of the commun coridor, presented in Table 2.

Table 2

Calculated voltages having origin the beginning of the right of way line-pipeline

Right of way corridor		Location [km]	Induced voltage estimation [V]	Right of way corridor		Location [km]	Induced voltage estimation [V]
S1	1	2	13.42	**S3**	1	35	13.49
	2	6	9.18		2	35.5	12.66
	3	7	8.68		3	42.5	68.02
	4	15	6.91	**S4**	1	43	48.09
S2	1	25.5	38.22		2	45	3.81
	2	27	41.61		3	46	2.32
					4	54	1.07
	3	28	42.42		5	55	1.18

For each zone coresponding at some distance location it was evaluated the induced voltages taking into account the inductive coupling. In the following table is shown the calculated voltages having like origin the beginning of the right of way line-pipeline.

By sectorial interpolation without imposed continuity condition on the interpolation function the results is not quite good regarding the estimated voltages so imposing continuity conditions at the separation zone limits we obtain better solutions (Fig. 4).

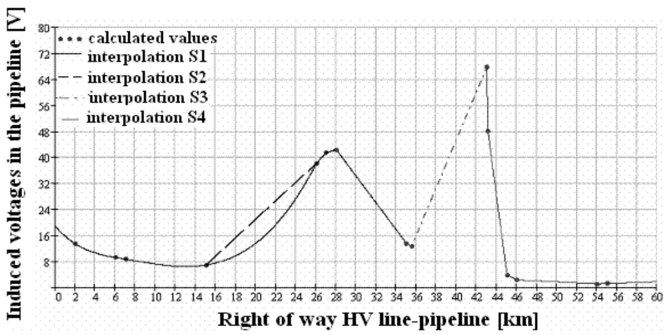

Fig. 4 – Sectorial numerical interpolation withouth add values and with imposed continuity conditions.

Another version for interpolation starts from choosing a global interpolation function followed by a numerical estimation of a first variation of the induced voltage predictor value (Fig. 5).

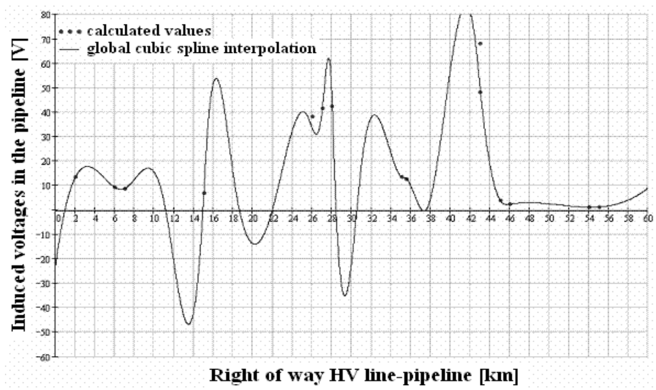

Fig. 5 – Global interpolation with spline predictor function.

Based on the obtained data from the sectorial interpolation for each set of data we could estimate by corector interpolation using a greater number of estimated voltages:

$$\begin{aligned} &Sk(z) := \mathrm{interp}(\mathrm{lspline}(xk, yk), xk, yk, z) \\ &S(z) := \mathrm{if}(z \le 15, S1(z), \mathrm{if}(z \le 28.57, S2(z), \mathrm{if}(z \le 42.5, S3(z), S4(z)))) \\ &x_i := \mathrm{if}(i \le 9, x1_i, \mathrm{if}(i \le 19, x2_{i-10}, \mathrm{if}(i \le 29, x3_{i-20}, x4_{i-30}))) \\ &y_i := \mathrm{if}(i \le 9, y1_i, \mathrm{if}(i \le 19, y2_{i-10}, \mathrm{if}(i \le 29, y3_{i-20}, y4_{i-30}))) \end{aligned} \quad . \qquad (5)$$

This last case of predictor-corector interpolation verify the real conditions of coexistence in the same right of way the metallic pipelines and electric HV lines, the continuity limits and fitts good with the estimated induced voltage values initially calculated (Fig. 6).

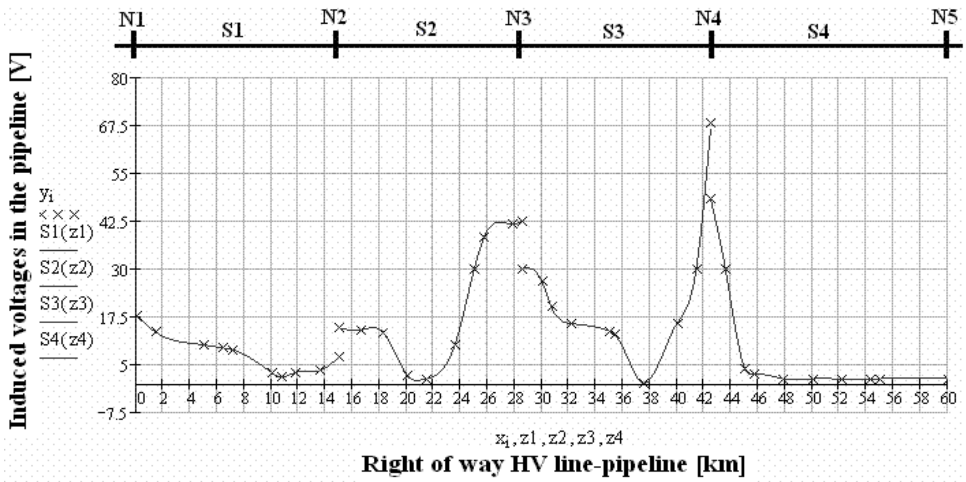

Fig. 6 – Global interpolation with predictor corector method.

4. **CONCLUSIONS**

The evaluation of the induced voltage in pipeline is based on the subdivision of the zone of influence in a relatively great number of sections in order to be able to determine voltages at many positions along the pipeline using Thevenin equivalent circuits. Is presented two practical cases of subdivision of the zone of influence in sections (a circuit model) and is made a precise evaluation of the induced voltages using some interpolation functions for the measured data. In the first case is observed that the interpolation spline function with linear end conditions is more precise than the linear interpolation polynom but the algorithm developed in MathCad gives us the correct data if the interval of the influence zone is increasing. The interpolation functions, linear and spline, do a great job in fitting a continuos link function between magnetic permeability and induced electrical currents**.** In the second case demonstrates that the predictor-corector interpolation verify the real conditions of coexistence in the same right of way the metallic pipelines and electric HV lines, the continuity limits and fitts very good with the estimated induced voltage values initially calculated. Also it is observed that the interpolation functions, linear and spline do a great job in fitting a continuous link function between magnetic permeability and induced electrical currents**.**

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