Approaches for Lightning Return Stroke Current Reconstruction by Numerical Regularization and Artificial Intelligence Techniques

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Abstract – Instrumentation development for lightning phenomena characterization may now enhance inverse procedures for the identification of the lightning return stroke current, from the electro-magnetic fields that occur. We intend to approach this, both spatial and temporal reconstruction, with an improved regularization procedure and a genetic algorithm optimization method. All the preliminary evaluations appear to be in good agreement with the actual characterization current models for the lightning.

I. ON LIGHTNING AND EMC

Lightning induced voltages in power and communication systems are one of the main causes of power quality and electromagnetic compatibility (EMC) [1], [2].

An inverse procedure is presented for identifying and reconstructing the wave form of the lightning return stroke current. It is based only on the acquisition of the electro-magnetic field generated by the discharge channel, in various locations on the ground and at various frequencies.

For the engineering return stroke models, the current distribution along the lightning channel is given as the sum of the integral contributions of the current pulses propagating into the channel with different speeds, or as an equivalent contribution of a quantity of accelerating moving charges [3], [4].

II. LIGHTNING PARAMETERS

Lightning parameters for the base current (peak value, front-steepness, duration) have been obtained, from direct measurements using instrumented towers or triggered lightning. In Fig. 1 it is presented the geometry of the lightning engineering model, with the return stroke regarded as a vertical antenna:

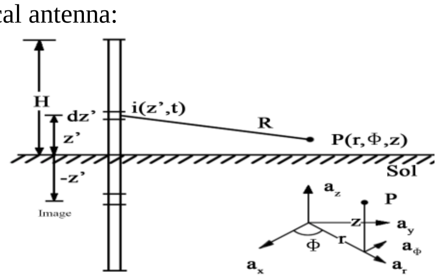

Fig. 1 Geometry model of the return stroke current – engineering model [5]

As related to this model, there is an entire panel of versions for the current identification: starting from only one sensor for the electric/magnetic field, and various sampling frequencies, or by means of the measurement of the electric or magnetic field at various distances from the lightning channel, and at various frequencies. The mathematical background relies on Fredholm integral equations of the first kind, as in relations (1) – (2), with the Green functions given in [5], for the radial component of the electric field intensity and azimuthally magnetic flux density:

$$E_r(r,z,\omega)=\frac{1}{4\cdot\pi\cdot\varepsilon_0}\cdot\int_{-H}^{H} G_r(r,z,z',\omega)\cdot\exp\left(-j\cdot\omega\cdot\frac{\sqrt{r^2+(z'-z)^2}}{c}\right)\cdot I(z',\omega)dz' \quad (1)$$

$$B_\varphi(r,z,\omega)=\frac{\mu_0}{4\cdot\pi}\cdot\int_{-H}^{H} G_\varphi(r,z,z',\omega)\cdot\exp\left(-j\cdot\omega\cdot\frac{R}{c}\right)\cdot I(z',\omega)dz' \quad (2)$$

$$I(z',\omega)=I(0,\omega)\cdot P(z')\cdot\exp(-j\cdot\omega\cdot|z'|/v) \quad (3)$$

The unknown return stroke electrical current function it is represented by relation (3), with separate variables of spatial distribution and frequency – temporal distribution.

Existing mathematical techniques to identify only the spatial function of the return current, on the height of the channel, consists in an attempt to match by *trial and error* methods, the measured field values with the calculated field values, by imposing exponential models, MTLE, or square root ones, MTLL. These models introduce generally accepted errors in the range of about 16 to 20% [1]-[2]-[5].

III. INVERSE RECONSTRUCTION BY REGULARIZATION

For our problem the integral equation of the first kind, may be generically expressed by relation (4):

$$\int K(r,z,\omega)\cdot I(r,z,\omega)drdzd\omega=u(r,z,\omega) \quad (4)$$

where the kernel K and the right hand side u field measurements are known functions, at least in principle, while I is the unknown, the causal return stroke function.

We emphasize that a strong topic of this paper deals with numerical tools for treating ill-posed problems, in the sense that we assume the problem has already been meshed and that we are faced with a matrix problem:

$$A\cdot I=u \quad (5)$$

We classified the regularization procedures as follows: Tikh, a penalty method, based on Tikhnov theory; DVSTA (or TSVD), a projection method, called damped truncated decomposition of the singular values – harmonic reconstruction; DVST (or TSVD) on/off, projection method, called truncated singular value decomposition with on/off filter factors; GCS, conjugate gradient method; TRA, algebraic reconstruction technique; GCV, generalised crossed validation; LC, the L curve criterion; QV, cvasi-optimality, methods for the regularization parameter. One can find their detailed formulation in [6].

IV. INVERSE RECONSTRUCTION BY GENETIC ALGORITHMS

The proposed genetic algorithms (GA) starts with a population of 50 randomly generated individuals, each of them representing a possible solution for the lightning return stroke current. These possible solutions are then evaluated using an average mean square error J_{av}:

$$J_{av} = \frac{1}{q} \cdot \sum_{p=1}^{q} J^{p} \quad (6)$$

where N is the number of the (r,z,ω) input vectors used to train the proposed FLS and J^p is the mean square error for a given training input vector:

$$J^{P} = \frac{1}{2} \cdot \left[E_{GA}^{p}(r,z,\omega) - E_{measured}^{P}(r,z,\omega) \right]^{2} \quad (7)$$

in which $E_{GA}^{p}(r,z,\omega)$ and $E_{measured}^{P}(r,z,\omega)$ are the calculated by using the determined lightning return stroke current with the proposed genetic algorithm method and respectively the measured electric field values, electric E, or magnetic flux density B.

To find the optimum rule base solution, the starting population is trained by an iterative process consisting in the following steps: all the individuals of the current population are evaluated and the best individual is selected and put in the population of the next generation (iteration); two individuals are randomly selected as parents of a crossover process to get two new individuals for the next generation populations; all the individuals from the new population except the best solution from current population are subjected to a mutation process.

This iterative process is repeated until the average mean square error for the best solution is smaller than an imposed value. Thus, the minimization of the mean square error leads to an optimum solution for the return stroke current.

V. NUMERICAL RESULTS – INITIAL VALIDATION

We used several input data regarding the placement of the sensors, the height of the measurements, the height of the current channel and the sampling frequencies of the measured fields. All of these cases, applied to the integral models (1) - (2) conducted to ill-posed initial systems of equations. As a consequence, the above mentioned regularization procedures are requested.

Below it is represented a sample result for the re-construction of MTLE model, from simulated field measurements (with added perturbation), fig. 2, with less than 5.5% reconstruction error:

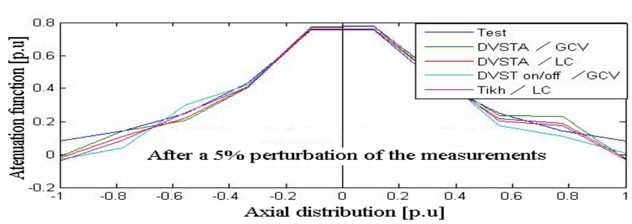

Fig. 2 Inverse reconstruction of return current spatial distribution with projection and penalty methods

We reflected also the combination of the models – measured fields and the applied regularization procedures. A sample of the solution errors yields the optimum situations:

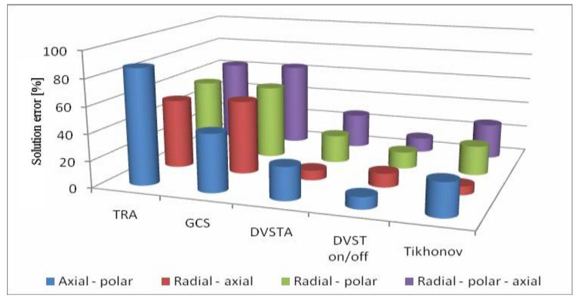

Fig. 3 Sensitive analysis of the regularization applied on the combination of the integral models

VI. PRELIMINARY CONCLUSIONS

The proposed inverse regularization method can be of interest for calculating the actual current and the consequent simulation of the electro-magnetic field to be used in "coupling" calculations.

The contribution of the authors refers to the introduction and validation of the regularization techniques in this reconstruction problem of lightning identification, and will be followed by the reconstruction approach of the combined genetic algorithm and fuzzy logic systems for the minimization of a mean square error between an evaluated field and the measured one.

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