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Reconstruction of transient currents from magnetic data

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Abstract

Purpose – To provide a time domain formulation for reconstruction of transient currents flowing in massive parallel conductors from magnetic data collected in the dielectric space surrounding the conductors.

Design/methodology/approach – A boundary integral equation (BIE) formulation involving Mitzner's and Rytov's high order surface impedance boundary conditions (SIBCs) is used. Input data of the inverse problem are the magnetic fields at given locations near the conductors. In order to validate the inversion algorithm, the magnetic field data are computed solving the direct problem with FEM for given current waveforms.

Findings – The improvement in reconstruction accuracy of the new time domain BIE formulation employing high order SIBCs has been demonstrated numerically in a simple test case. The range of validity of the technique has been extended to current pulses of longer duration and the computational burden has shown to increase only by a factor of 4.

Research limitations/implications – The proposed formulation can be compared with other possible formulations, both in the time and in the frequency domain.

Practical implications – Based on this formulation a new current sensing technique is proposed for realization of low cost current sensors based on magnetic sensor arrays.

Originality/value – The inverse problem addressed in the paper has been solved for the first time.

Keywords Magnetic fields, Boundary-elements methods, Sensors

Paper type Research paper

Introduction

The inverse problem of reconstructing currents flowing in parallel conductors from magnetic field data around them arises in the design of innovative current sensors for protection systems (D'Antona *et al.*, 2001). Since these types of problems feature low electromagnetic penetration depth in the conductors, a natural approach in this case is to eliminate the conducting region from the numerical procedure by using surface impedance boundary conditions (SIBCs) at the conductor/dielectric interface (Godzinski, 1961).

The numerical method best suited for use with the SIBC is the boundary integral equation method (BIE) because in BIE and SIBC the functions are approximated at

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the same points on the interface between the media. Being applied to an eddy current problem consisting of conducting and non-conducting regions, the BIE yields a system of two integral equations over the conductor's surface with respect to two unknowns: the required function (for example, magnetic scalar or vector potentials) and its normal derivative at the conductor/dielectric interface (Brebbia, 1980).

Use of the SIBC allows elimination of the extra unknown and reduces the formulation to only one integral equation employing the fundamental solution of the Laplace equation. Usually, the surface integral equations are derived in such a way that the total currents flowing in the conductors are on the right-hand side so they are considered as known quantities (Barmada *et al.*, 2004). This is certainly true in direct problems, but in inverse problems the known (measured) value is the magnetic field at the location of the sensors whereas the goal is to calculate the total currents in the conductors. As a result, the surface integral equation should be supplemented by an equation relating the total currents flowing in the conductors and the field values measured by sensors outside the conductors. Di Rienzo *et al.* (2003) have developed an iterative procedure to solve both equations and analyzed its convergence.

Note that the BIE-SIBC formulation proposed by Di Rienzo *et al.* (2003) employs the time domain version of the classical Leontovich SIBC based on the assumption that the field penetrates only in the direction normal to the conductor surface. Rytov (1940) has demonstrated that the use of the Leontovich's SIBC leads to an approximation error of the order of magnitude of $O(\delta^2/D^2)$ where δ is the skin depth and D is the characteristic size of the conductor's surface. It practically means that the method developed by Di Rienzo *et al.* (2003) is applicable only if the skin depth is very thin.

Limits of applicability of the inverse BIE-SIBC formulation can be extended using the improved Mitzner (1967) and Rytov (1940) SIBCs allowing for such high order effects as curvature of the conductor surface and diffusion in directions tangential to the surface. Approximation errors due to use of Mitzner's and Rytov's SIBCs are $O(\delta^3/D^3)$ and $O(\delta^4/D^4)$, respectively (Yuferev and Ida, 1998). Boundary element formulations based on the SIBCs of high order of approximation have been developed for direct problems using the perturbation technique (Yuferev *et al.*, 2000). In the present paper the high order time domain SIBCs are implemented in the formulation developed by Di Rienzo *et al.* (2003) to improve the reconstruction accuracy and extend the application area of BIE-SIBC formulations of inverse problems. Special attention is paid to details of implementation of the iterative procedure which is main difference between inverse and direct BIE-SIBC formulations.

Statement of the problem

N parallel conductors carrying time-varying transient currents $I_i(t)$, $i = 1, 2, \ldots, N$, and M sensors located in the dielectric space surrounding the conductors are considered. The transients are so fast that the electromagnetic field has no time to penetrate deep into the conductor so that its penetration depth is shallow. This physical statement can be described mathematically as follows:

$$\delta = \sqrt{\tau/(\sigma\mu)} \ll D \tag{1}$$

where δ denotes the skin depth; D, the characteristic size of the conductor cross section; τ, the duration of the current pulse; and σ and μ are the electrical conductivity and magnetic permeability of the conductor material, respectively.

An output voltage signal supplied by the magnetic sensor can be expressed in the form:

$$V_k(t) = S_k\left(\vec{s}_k \cdot \vec{H}\left(\vec{r}_k^{\,\mathrm{sens}}, t\right)\right), \quad k = 1, \ldots, M \tag{2}$$

In the inverse problem the quantities V_k, S_k and $\vec{s}_k$ are considered to be known (measured) and the currents $I_i(t)$ need to be determined.

Surface impedance boundary conditions

The SIBCs are naturally represented in terms of a local quasi-spherical orthogonal curvilinear coordinate system related to the conductor's surface. Let coordinates ξ_1 and ξ_2 be directed along the surface and coordinate η be directed into the conductor normal to its surface so that the unit vectors $\vec{e}_1, \vec{e}_2, \vec{n}$ of the local coordinate system are related as follows:

$$\vec{e}_1 \times \vec{e}_2 = \vec{n} \tag{3}$$

The local radii of curvature corresponding to coordinate lines ξ_k are denoted as d_k, $k = 1, 2$.

With the local coordinates the SIBC can be represented in the following general form (Yuferev and Ida, 1998):

$$\vec{n} \times \vec{E} = \mu \frac{\partial}{\partial t}\vec{F} \tag{4}$$

where vector $\vec{F}$ describes the perturbation of the electromagnetic field in the free space surrounding the conductor due to the field diffusion inside the conductor and the energy dissipation. The components of vector $\vec{F}$ may take different forms depending on the approximation of the equation used to describe the field diffusion into the conductor:

$$(\vec{F}^{\mathrm{PEC}})_{\xi_k} = 0 \tag{5a}$$

$$(\vec{F}^{\mathrm{Leontovich}})_{\xi_k} = T_1 * H_{\xi_k} \tag{5b}$$

$$(\vec{F}^{\mathrm{Mitzner}})_{\xi_k} = T_1 * H_{\xi_k} - T_2 * \left[\left(d_k^{-1} - d_{3-k}^{-1}\right) H_{\xi_k}\right] \tag{5c}$$

$$\begin{aligned}(\vec{F}^{\mathrm{Rytov}})_{\xi_k} = {} & T_1 * H_{\xi_k} - T_2 * \left[\left(d_k^{-1} - d_{3-k}^{-1}\right) H_{\xi_k}\right] \\ & + T_3 * \left[\frac{3d_{3-k}^2 - d_k^2 - 2d_k d_{3-k}}{8 d_k^2 d_{3-k}^2} H_{\xi_k}\right] \\ & + T_3 * \left[\frac{1}{2}\left(-\frac{\partial^2 H_{\xi_k}}{\partial \xi_{3-k}^2} + \frac{\partial^2 H_{\xi_k}}{\partial \xi_k^2} + 2\frac{\partial^2 H_{\xi_{3-k}}}{\partial \xi_k \partial \xi_{3-k}}\right)\right]\end{aligned} \tag{5d}$$

where $*$ denotes time-convolution products and the time-dependent functions T_1, T_2, T_3 are written in the form:

$$T_1 = (\pi\sigma\mu)^{-1/2} t^{-1/2}; \qquad T_2 = U/(\sigma\mu); \qquad T_3 = 2(\pi\sigma^3\mu^3)^{-1/2} t^{1/2} \tag{6}$$

Here $U(t)$ is the unit step function.

In the particular case of the perfect electrical conductor (PEC) the field does not penetrate into the conductor and the skin depth is zero as well as the right hand side of equation (4). In the Leontovich approximation the body's surface is considered as a plane and the field is assumed to be penetrating into the body only in the direction normal to the body's surface. High order effects of the curvature of the conductor surface and the diffusion in the direction tangential to the surface are taken into account in the Rytov approximation.

BIE-SIBC formulation

The electromagnetic field distribution in the conductors and surrounding free space can be described by Maxwell's equations in the quasi-static approximation:

Non-conducting space:

$$\nabla \times \vec{H} = 0 \tag{7a}$$

$$\nabla \times \vec{E} = -\mu_0 \partial \vec{H}/\partial t \tag{7b}$$

Conducting region:

$$\nabla \times \vec{H} = \sigma \vec{E} \tag{8a}$$

$$\nabla \times \vec{E} = -\mu \partial \vec{H}/\partial t \tag{8b}$$

Here μ_0 is the magnetic permeability of the free space.

Let us introduce the magnetic scalar potential in free space as follows (Mayergoyz, 1983):

$$\vec{H} = \vec{H}_{\text{fil}} - \nabla\phi \tag{9}$$

$$\vec{H}_{\text{fil}} = \sum_{i=1}^{N} (\vec{H}_{\text{fil}})_i = \frac{1}{4\pi} \sum_{i=1}^{N} \int_{L_i} \vec{I}_i(\vec{r}', t) \times \frac{\vec{r} - \vec{r}'}{|\vec{r} - \vec{r}'|} \mathrm{d}l \tag{10}$$

Here $\vec{H}_{\text{fil}}$ is the magnetic field created by the currents I_i, $i = 1, 2, \ldots, N$, flowing through an imagined filament located inside every conductor (Mayergoyz, 1983). Substitution of equations (9) and (10) in equation (2) yield:

$$V_k(t) = \sum_{i=1}^{N} S_k \alpha_{ki} I_i(t) - S_k \vec{s}_k \cdot \nabla\phi\left(\vec{r}_k^{\,\text{sens}}, t\right), \quad k = 1\ldots, M \tag{11}$$

where α_{ki} is a coefficient depending only on the relative position of the kth sensor and the ith filamentary current and S_k are the sensitivities of the magnetic sensors (Di Rienzo *et al.*, 2003).

Substitution of equation (9) into equation (7a) yields the Laplace equation governing the scalar potential distribution in free space:

$$\Delta\phi = 0 \tag{12}$$

Application of the BIE method transforms equation (12) into the following surface integral equation (Brebbia, 1980):

$$\frac{1}{2}\phi + \sum_{i=1}^{N}\int_{S_i}\phi\frac{\partial G}{\partial \vec{n}}\mathrm{d}s = \sum_{i=1}^{N}\int_{S_i} G\frac{\partial \phi}{\partial \vec{n}}\mathrm{d}s \tag{13}$$

where S_i is the surface of the ith conductor, c is a coefficient depending on the surface shape and G is the fundamental solution of the three-dimensional Laplace equation:

$$G(|\vec{r}-\vec{r}'|) = (4\pi)^{-1}(|\vec{r}-\vec{r}'|)^{-1}$$

From equation (9) one obtains:

$$\frac{\partial \phi}{\partial \vec{n}} = \vec{n}\cdot(\vec{H}_{\mathrm{fil}} - \vec{H}) \tag{14}$$

Substitution of equation (14) into equation (13) yields:

$$\frac{1}{2}\phi + \sum_{i=1}^{N}\int_{L_i}\phi\frac{\partial G}{\partial \vec{n}}\mathrm{d}l = \sum_{i=1}^{N}\int_{L_i} G\vec{n}\cdot(\vec{H}_{\mathrm{fil}} - \vec{H})\mathrm{d}l \tag{15}$$

Equations (9), (10) and (15) contain four unknowns I_i, ϕ, $\vec{H}_{\mathrm{fil}}$ and $\vec{n}\cdot\vec{H}$ so that an additional relation between these quantities is required to render the formulation solvable. In this role, the time domain SIBC equation (4) can be used.

Taking the scalar product of equation (8b) and the normal unit vector $\vec{n}$ leads to the following result:

$$\frac{\partial}{\partial t}(\vec{n}\cdot\vec{H}) = -\mu^{-1}\vec{n}\cdot(\nabla\times\vec{E}) \tag{16}$$

Applying the vector identities to the right hand side of equation (16) and using equation (4), one obtains:

$$\mu^{-1}\vec{n}\cdot(\nabla\times\vec{E}) = \mu^{-1}\sum_{k=1}^{2}(-1)^k\frac{\partial E_{\xi_k}}{\partial \xi_{3-k}} = \mu^{-1}\nabla\cdot(\vec{E}\times\vec{n}) = -\frac{\partial}{\partial t}\nabla\cdot\vec{F} \tag{17}$$

Substituting equation (17) into equation (16) and taking into account the fact that both current and field are zero at the initial moment of time, the SIBC for the normal component of the magnetic field at the conductor's surface is obtained:

$$\vec{n}\cdot\vec{H} = \nabla\cdot\vec{F} \tag{18}$$

Substitution of equation (18) into equation (15) yields:

$$\frac{1}{2}\phi + \sum_{i=1}^{N} \int_{S_i} \left[\phi \frac{\partial G}{\partial \vec{n}} + G \nabla \cdot \vec{F} \right] \mathrm{d}s = \sum_{i=1}^{N} \int_{S_i} G \vec{n} \cdot \vec{H}_{\mathrm{fil}} \mathrm{d}s \tag{19}$$

Equations (5), (9), (10) and (19) can be solved with respect to I_i, $\vec{H}_{\mathrm{fil}}$ and ϕ using the iteration procedure proposed by Di Rienzo *et al.* (2003).

Let $I_i^{(m)}$ be the total currents at the step m. Then $I_i^{(m+1)}$ are obtained as follows:

(1) calculate $\vec{H}_{\mathrm{fil}}$ using equation (10);

(2) solve equation (19) to obtain $\phi^{(m+1)} = \phi^{(m+1)}(\vec{r}, t)$ over the conductor's surface;

(3) calculate $\phi_k^{(m+1)}$, $k = 1, \ldots, M$, in the vicinity of the sensor k according to BIE method;

(4) calculate $\nabla \phi^{(m+1)}$ at the location of each sensor; and

(5) calculate $I_i^{(m+1)}$ using equation (11).

Details of implementation are given next.

Numerical results

To illustrate the method, a system of three parallel conductors of circular cross-sections and equal diameters $D = 50\,\mathrm{mm}$ is considered (Figure 1). Nine sensors are placed at positions P_k, $k = 1, \ldots, 9$, with sensitivity vectors parallel to the x-axis.

For the sake of simplicity, suppose that the ratio of the radius of the cross section of the conductors and their length is such that the field variation along the conductors may be neglected. Thus the problem can be considered as two-dimensional in the plane of the conductor's cross section and equation (19) is reduced to the following form:

$$\frac{1}{2}\phi + \sum_{i=1}^{3} \int_{L} \left[\phi \frac{\partial G}{\partial \vec{n}} + G \nabla \cdot \vec{F} \right] \mathrm{d}l = \sum_{i=1}^{3} \int_{L} G \vec{n} \cdot \vec{H}_{\mathrm{fil}} \, \mathrm{d}l \tag{20}$$

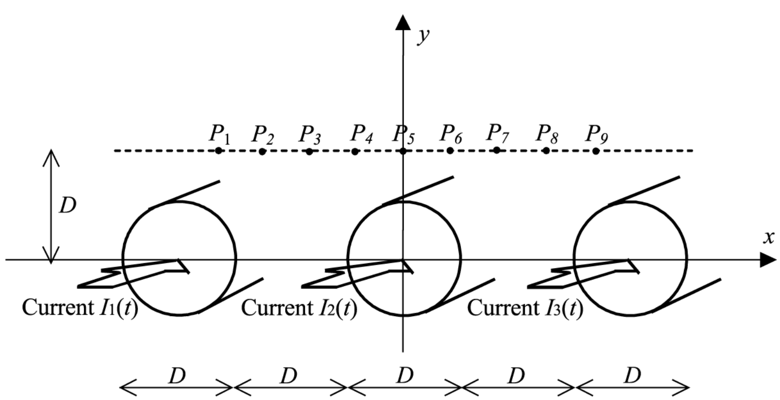

Figure 1.
Geometry of the problem ($D = 50\,\mathrm{mm}$)

where L is the cross section contour that has been discretized with constant elements and G is the fundamental solutions of the two-dimensional Laplace equation:

$$G(|\vec{r}-\vec{r}'|) = -(2\pi)^{-1}\ln(|\vec{r}-\vec{r}'|)$$

In the two-dimensional case, the SIBC equation (18) takes the form:

$$\vec{n}\cdot\vec{H} = \frac{1}{\sqrt{\pi\sigma\mu t}} * \frac{\partial H_\xi}{\partial \xi} + \frac{1}{2d}\frac{U(t)}{\sigma\mu} * \frac{\partial H_\xi}{\partial \xi} + \sqrt{\frac{t}{\pi\sigma^3\mu^3}} * \left(\frac{3}{8d^2}\frac{\partial H_\xi}{\partial \xi} + \frac{1}{2}\frac{\partial^3 H_\xi}{\partial \xi^3}\right) \quad (21)$$

where the coordinate ξ is directed along the contour of the conductor's cross section.

The waveforms of the current pulses flowing in the conductors are the following (Figure 2):

$$I_1(t) = 1-\exp\left(-\left(\frac{t}{T}\right)^2\right);\; I_2(t) = -\left(1-\exp\left(-\left(\frac{2t}{T}\right)^2\right)\right);$$
$$I_3(t) = 1-\exp\left(-\left(\frac{3t}{T}\right)^2\right); \quad (22)$$

with $T = 0.004$ s.

The magnetic fields at the locations of the sensors $P_k(x_k = -2D + k\cdot(2D/5), y_k = D)$, $k = 1, \ldots, 9$, are computed by means of a commercial FEM software

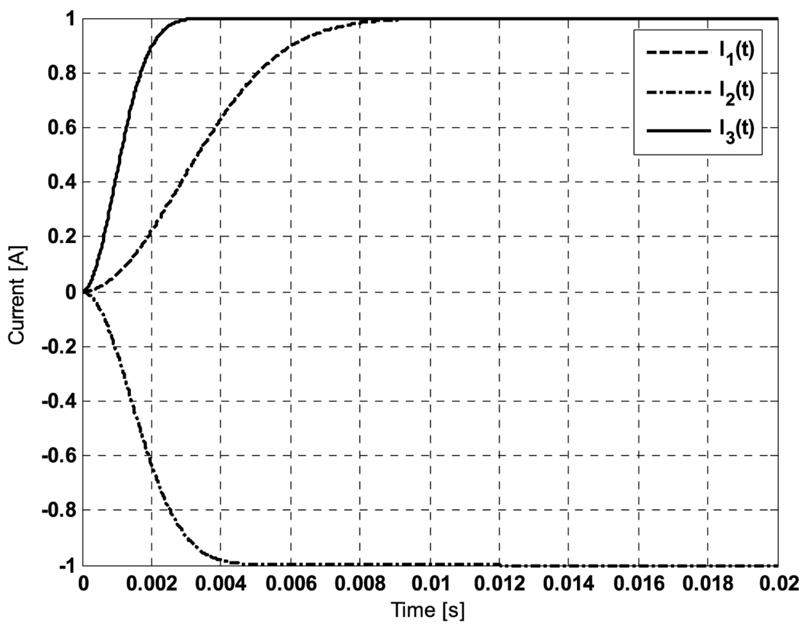

Figure 2.
Current waveforms

(Maxwell, Ansoft Co.) and are plotted in Figure 3. The FEM mesh has been refined until the relative variation of the computed magnetic fields is lower than 0.001 percent.

The inversion technique is applied in the time interval from $t = 0$ to $5T$, which is discretized into 1,000 time samples. This is the minimum temporal discretization that assures stability of the numerical results. The inverse formulation is solved for each time sample using five iterations. Convolutions are computed by means of an inverse Fourier transform algorithm. The contour of each conductor is discretized using 40 constant elements. Numerical simulations prove that increasing the number of elements does not change the results significantly.

Figure 4 shows absolute errors in the reconstruction of currents $I_1(t)$, $I_2(t)$, $I_3(t)$ starting from the x-components of the magnetic field at points P_k, $k = 1, \ldots, 9$, in the case of copper conductors (conductivity $\sigma = 5.8 \times 10^7$ S/m). As can be noted, disagreement between reconstruction using Leontovich's SIBC and Rytov's SIBC starts earlier than disagreement between reconstruction using Mitzner's SIBC and Rytov's SIBC, due to the diffusion process of the magnetic field in the conductors: adoption of higher order SIBCs increases accuracy in reconstructing the currents. The technique has proven to be robust with respect to the choice of number and position of the measurement points, as shown by Figure 5, which shows the errors when only five sensors (P_1, P_3, P_5, P_7, P_9) are used for inversion.

In order to investigate the variation in conductivity inside the conductors, the same simulations as in Figure 4 have been carried out for the case of nine sensors and of aluminum (conductivity $\sigma = 3.8 \times 10^7$ S/m) conductors (Figure 6): errors of different order of approximations are higher than the corresponding ones in the case of copper conductors, due to higher diffusion of magnetic field in the conductors for lower conductivity values.

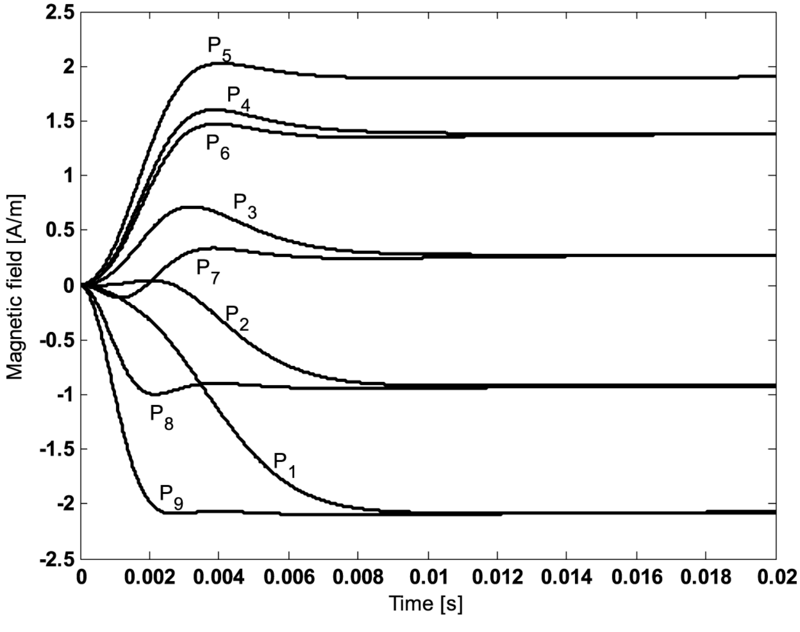

Figure 3. Amplitude of the x-component of the magnetic field at $P_1 \ldots, P_9$ generated by the currents of Figure 2 and computed by FEM

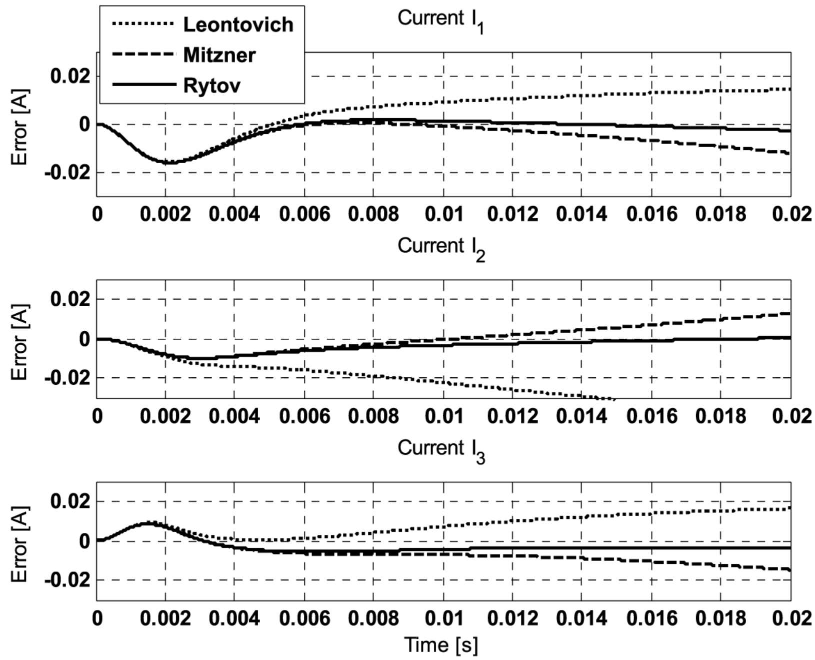

Figure 4.
Absolute errors with nine sensors and copper conductors

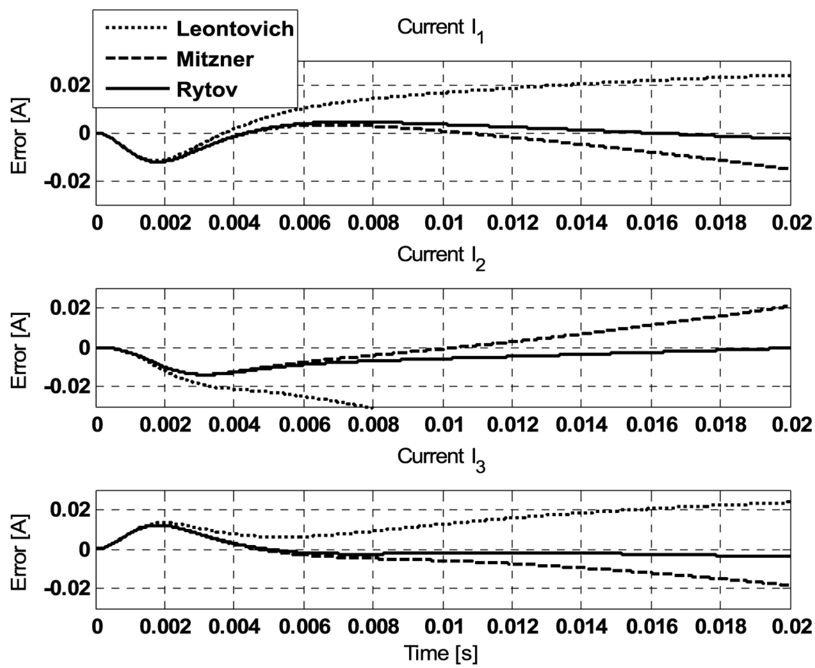

Figure 5.
Absolute errors with five sensors and copper conductors

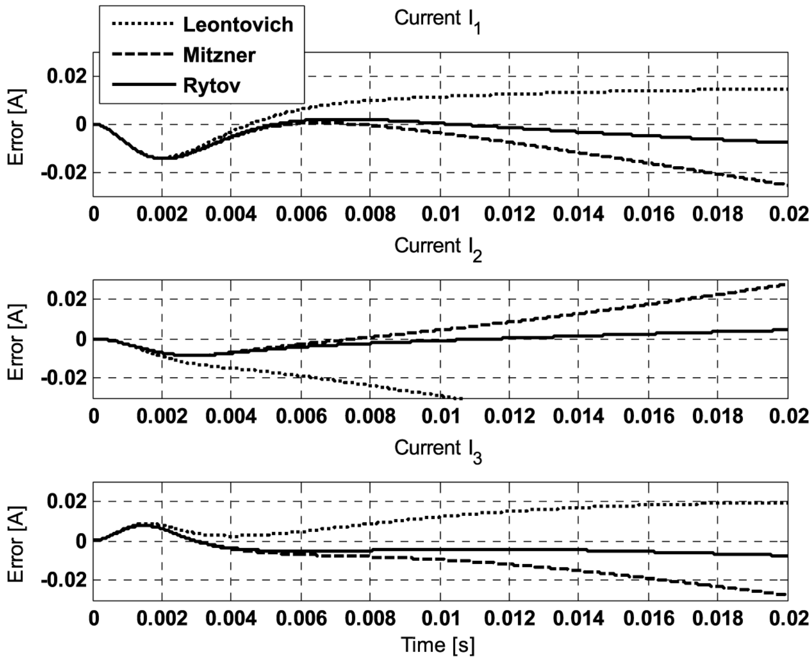

Figure 6.
Absolute errors with nine sensors and aluminum conductors

In order to investigate the dependence of the accuracy of the technique with the distances between conductors and the proximity effect, a second simulation set-up has been considered (Figure 7), with conductors nearer to each other. Reconstruction errors (Figures 8 and 9) are higher than in the first test case and only Rytov's SIBC gives rise to acceptable results.

Figure 10 shows the computational costs for numerical solution of the formulations employing SIBCs of different orders of approximation, in terms of computational times normalized to the time needed for numerical solution of the boundary element formulation employing the Leontovich SIBC. It is easy to see that the use of Rytov's SIBC leads to increase in computational time by only a factor of 4, compared with

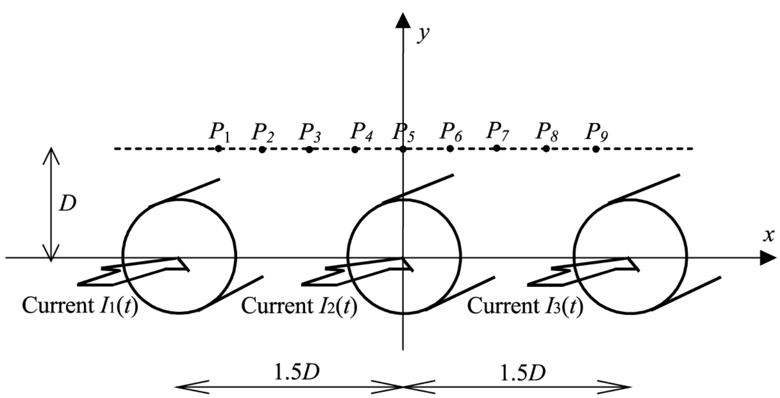

Figure 7.
Second test case with conductors nearer to each other ($D = 50\,\text{mm}$)

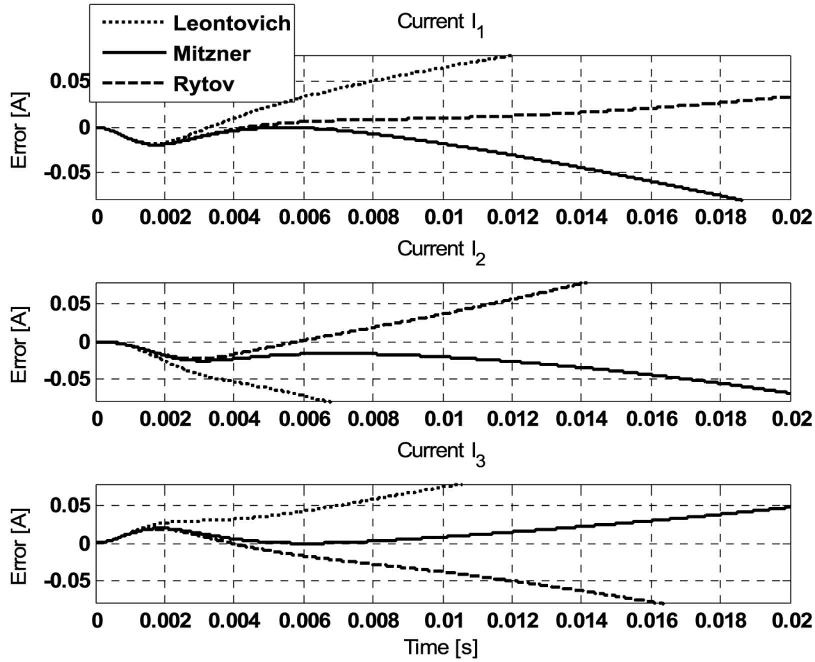

Figure 8.
Absolute errors with five sensors (P_1, P_3, P_5, P_7, P_9) and copper conductors

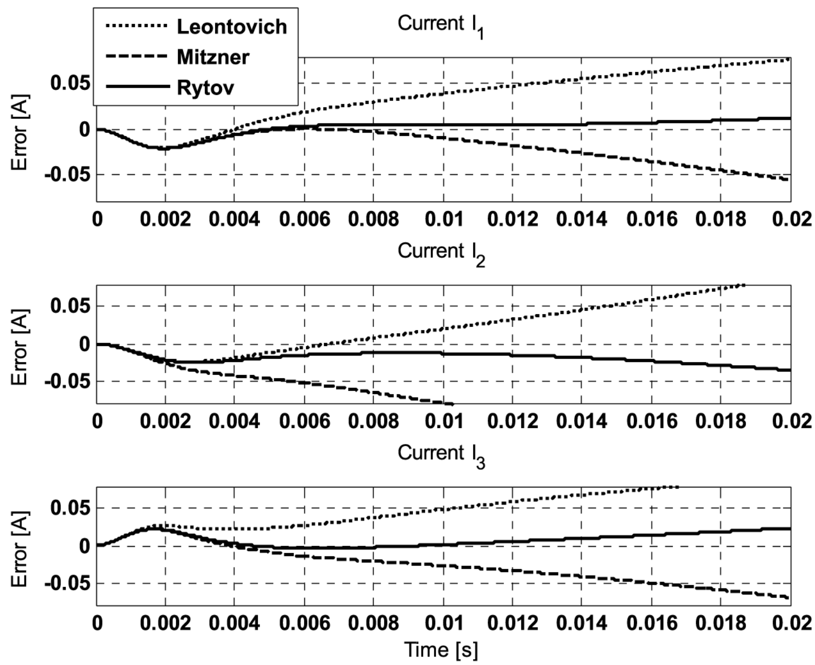

Figure 9.
Absolute errors with nine sensors ($P_1, \ldots, P_9$) and copper conductors

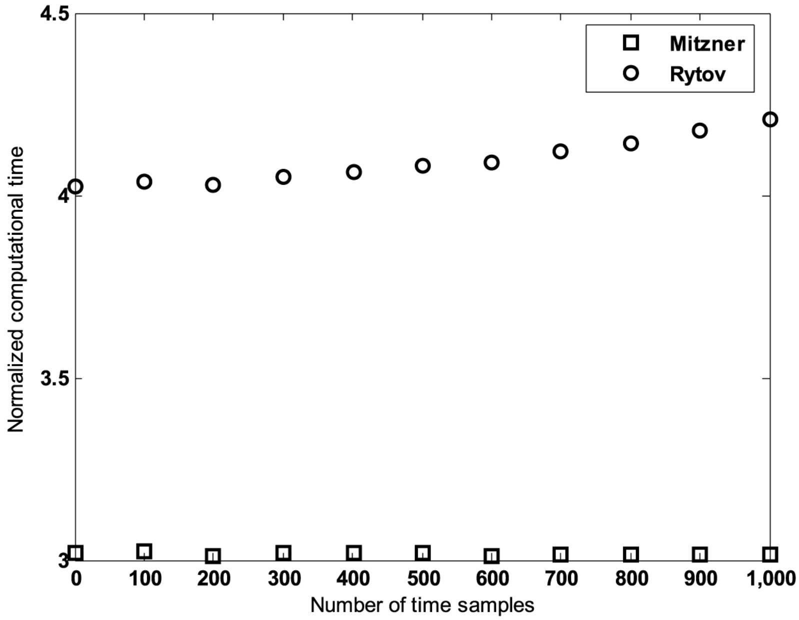

Figure 10.
Normalized computational time vs number of samples for solving BIE-SIBC formulations of different orders

the use of Leontovich's SIBC. The numerical example considered here leads us to the conclusion that the use of SIBCs of high order of approximation allows significant improvement in the accuracy of results without significant increase in the required computational effort.

Conclusions
The improvement in reconstruction accuracy of the new time domain BIE formulation employing high order SIBCs has been demonstrated numerically in a simple test case. The range of validity of the technique has been extended to current pulses of longer duration and the computational burden has shown to increase only by a factor of 4.

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