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POWER SYSTEM DYNAMIC PERFORMANCE

POWER INSTRUMENTATION AND MEASUREMENT

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Electromagnetic Transient Effects on Thermal Field for Plane Electrical Conductors

Giorgio Galli, Federico Rossi, and Andrea Nicolini

***Abstract*—Effect of fast electromagnetic transient on the thermal field in plane conductors is evaluated by means of the numerical simulation of the one-dimensional current and temperature distributions. It was found that non negligible heating may occur along the conductor edge for electromagnetic pulse time constants lower than 10^{-3} s. Also, it is shown that the heat exchange coefficient "h" produces a negligible influence on temperature distribution.**

***Index Terms*—Conductors, short-circuit currents, temperature.**

NOMENCLATURE

β	Electrical circuit time constant (s^{-1}).
d	Conductor width (in meters).
D	Thermal diffusivity (in m^2/s).
$\mathrm{D_e}$	Electrical diffusivity (in m^2/s).
E	Electrical field (in N/Coulomb).
h	Heat-exchange rate ($\mathrm{W}/^\circ\mathrm{km}^2$)
H	Magnetic field (in amperes per meter).
$\mathrm{H_c}$	Magnetic-field transient component (in amperes per meter).
H_ω	Magnetic-field harmonic component (in amperes per meter).
i	Imaginary unit.
I	Global current (in amperes).
I_1	Transient component of global current (in amperes).
I_2	Harmonic component of global current (in amperes).
J	Global current density (in $\mathrm{A/m}^2$).
$\mathrm{J_c}$	Density of global current transient component (in $\mathrm{A/m}^2$).
J_ω	Density of global current harmonic component ($\mathrm{A/m}^2$).
J*	Density of dimensionless current.
λ	Thermal conductivity (W/°km).
L^{-1}	Inverse Laplace transform notation.
φ	Initial phase of current harmonic component (in radians).
μ	Magnetic permeability (in Henries per meter).
p	Laplace transform complex variable.
q	Laplace transform complex variable.
σ	Electrical conductivity ($\Omega^{-1}\ \mathrm{m}^{-1}$)
θ	Dimensionless temperature.
t	Time (in seconds).
T	Temperature (°K).
$\mathrm{T_a}$	Environment temperature (°K).
$\overline{T}$	Temperature-field Laplace transform.
ω	Angular velocity of current harmonic component (in radians per second).
x	Space variable (in meters).
x*	Dimensionless space variable.

I. INTRODUCTION

MAGNETIC levitation, rail-guns systems and short-circuit tests on conductor bars are characterized by very high electrical power dissipation and very fast current transient [1], [2]. This paper deals with a simultaneous numerical evaluation of current and temperature transients on a rectangular conductor. The evaluation has been carried out by means of a time-dependent one-dimensional finite-difference model. The study has determined the relations between current transient characteristics and temperature distribution; in fact, it has been shown that when current is higher than 10^5 A and current rise time is shorter than 10^{-4} s, a sudden temperature increase occurs which may cause a local fusion of the conductor or a degradation of the conductor mechanical properties [3], [4].

II. CURRENT DENSITY EVALUATION

Current versus time on rectangular conductors during short circuits has been experimentally determined and is given by the following equation:

$$I = I_1 e^{-\beta t} + I_2 \cos(\omega t + \varphi), \quad I = 0 \text{ when } t \leq 0. \tag{1}$$

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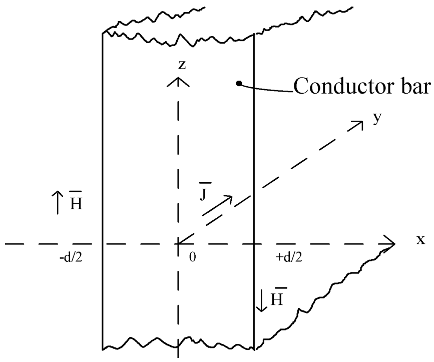

Fig. 1. Conductor slab and reference system.

I_1, I_2, and φ satisfy the following constraints:

$$I(t=0)=0. \tag{2}$$

Equation (2) means

$$\varphi = ar\cos\left(-\frac{I_1}{I_2}\right). \tag{3}$$

In order to determine the current distribution inside a rectangular cross-section conductor, the assumed hypotheses are as follows:

1) Electrical field is quasisteady. Thus, displacement current is neglected.
2) Electrical conductivity σ is constant.
3) Conductor is considered to be an infinitely long slab of thickness d (see Fig. 1). A reference system is assumed which shows x direction parallel to slab d thick section.

Hypotheses a) and b) allow one to write the next equation [5]

$$\vec{J} = \sigma\vec{E}. \tag{4}$$

Thus, the magnetic field inside the conductor is given by

$$\Delta\vec{H} = \frac{1}{D_e}\frac{\partial\vec{H}}{\partial\tau}. \tag{5}$$

$D_e = 1/(\sigma\cdot\mu)$ may be called electrical diffusivity by analogy to the thermal diffusivity.

Initial condition $(\mathrm{t}=0)$ makes $H=0$ all over the conductor. Values of H on the conductor surface depend on the current instantaneous value and the system geometry; thus, they are known when (1) is given. The current density is governed by the following relation:

$$\vec{J} = \nabla\times\vec{H}. \tag{6}$$

Hypothesis 3) determines that current density is parallel to the y direction and depends only on the x coordinate and time (see Fig. 1). In fact, the slab is considered infinitely long for y and z directions with respect to the x-direction slab dimensions (see Fig. 1). This is a suitable hypothesis when reference is made to applications relative to rail guns or power conductor bars. Thus, 1-D analysis and models are taken into account also for the successive thermal analysis. Thus, according to (6), the magnetic-field direction is parallel to the z axis (see Fig. 1).

Thus, (5) and (6) may be rewritten

$$\frac{\partial^2 H(x,t)}{\partial x^2} = \frac{1}{D_e}\frac{\partial H(x,t)}{\partial t} \tag{7}$$

$$J(x,t) = -\frac{\partial H(x,t)}{\partial x}. \tag{8}$$

The magnetic field may be written as follows:

$$H(x,t) = H_c + \mathrm{Re}(H_\omega). \tag{9}$$

Magnetic-field components are obtained by solving (7) with classical methods by using the following constraints [6]:

$$H(x,0) = 0 \tag{10}$$

$$H(0,t) = 0 \tag{11}$$

$$\int_{-d/2}^{d/2} J(x,t)dx = I(t) \quad \Rightarrow H\left(\frac{d}{2},t\right) = -\frac{I(t)}{2}. \tag{12}$$

The solution of (7) is

$$H_c = -\frac{1}{2}I_1\frac{\sin\left(x\sqrt{\frac{\beta}{D_e}}\right)}{\sin\left(\frac{d}{2}\sqrt{\frac{\beta}{D_e}}\right)}\cdot e^{-\beta t} + \\ - I_1\sum_{n=1}^{\infty}\frac{\frac{(-1)^n}{n\pi}\sin\left(\frac{2\pi n x}{d}\right)}{1-\frac{\beta d^2}{4\pi^2 n^2 D_e}}\cdot e^{-4\pi^2 n^2\frac{D_e t}{d^2}} \tag{13}$$

and

$$H_\omega = -\frac{1}{2}I_2\frac{\sinh\left[x(1+i)\sqrt{\frac{\omega}{2D_e}}\right]}{\sinh\left[\frac{d}{2}(1+i)\sqrt{\frac{\omega}{2D_e}}\right]}\cdot e^{i(\omega t+\varphi)} + \\ - I_2 e^{i\varphi}\sum_{n=1}^{\infty}\frac{(-1)^n}{n\pi}\frac{\sin\left(\frac{2\pi n x}{d}\right)}{1+i\cdot\frac{\omega d^2}{4\pi^2 n^2 D_e}}\cdot e^{-4\pi^2 n^2\frac{D_e t}{d^2}}. \tag{14}$$

Equations (13) and (14) are defined for

$$-\frac{d}{2}\leq x\leq\frac{d}{2}. \tag{15}$$

With (8), we can obtain the current density which may be written as follows:

$$J(x,t) = J_c + \mathrm{Re}(J_\omega). \tag{16}$$

The current density components are

$$J_c = \frac{1}{2}I_1\sqrt{\frac{\beta}{D_e}}\frac{\cos\left(x\sqrt{\frac{\beta}{D_e}}\right)}{\sin\left(\frac{d}{2}\sqrt{\frac{\beta}{D_e}}\right)}\cdot e^{-\beta t} \\ + 2\frac{I_1}{d}\sum_{n=1}^{\infty}\frac{(-1)^n\cos\left(\frac{2\pi n x}{d}\right)}{1-\frac{\beta d^2}{4\pi^2 n^2 D_e}}\cdot e^{-4\pi^2 n^2\frac{D_e t}{d^2}} \tag{17}$$

and

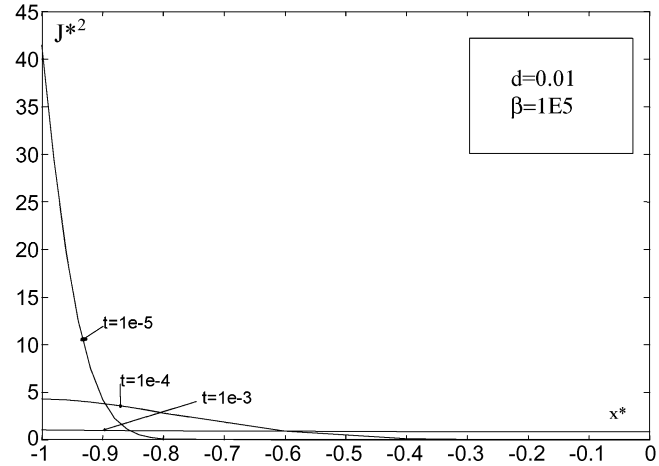

Fig. 2. Square values of dimensionless current for $\mathrm{d} = 0.01$ m and $\beta = 10^5\ \mathrm{s}^{-1}$.

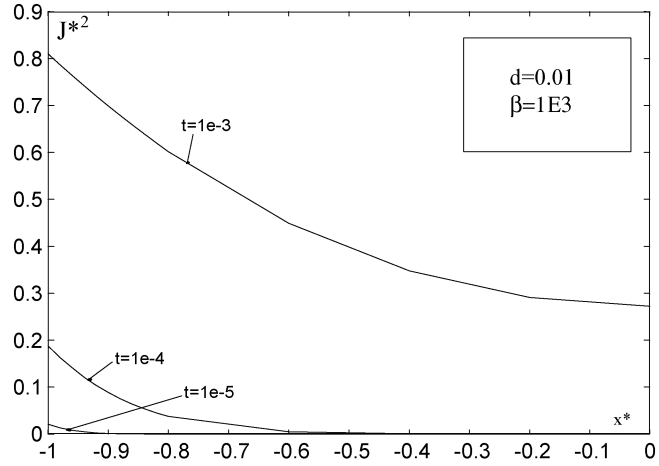

Fig. 3. Square values of dimensionless current for $\mathrm{d} = 0.01$ m and $\beta = 10^3\ \mathrm{s}^{-1}$.

$$J_\omega = \frac{1}{2} I_2 (1+i)\sqrt{\frac{\omega}{2D_e}} \frac{\cosh\left[x(1+i)\sqrt{\frac{\omega}{2D_e}}\right]}{\sinh\left[\frac{d}{2}(1+i)\sqrt{\frac{\omega}{2D_e}}\right]} \cdot e^{i(\omega t+\varphi)} + 2\frac{I_2}{d} e^{i\varphi} \sum_{n=1}^{\infty} (-1)^n \frac{\cos\left(\frac{2\pi n x}{d}\right)}{1 + i \cdot \frac{\omega d^2}{4\pi^2 n^2 D_e}} \cdot e^{-4\pi^2 n^2 \frac{D_e t}{d^2}}. \quad (18)$$

D_e may be considered as a constant whose value is approximately $10^{-2}\ \mathrm{m}^2/\mathrm{s}$ for the common conductors: it is two orders of magnitude higher than thermal diffusivity. Thus, the EM transient duration (see (16), (17), and (18)) is generally much shorter than the thermal transient duration.

Several cases of current distributions are reported in Figs. 2–5; they are shown in terms of the square value of the dimensionless current which is defined as follows:

$$J^* = \frac{d \cdot J}{I_2}. \quad (19)$$

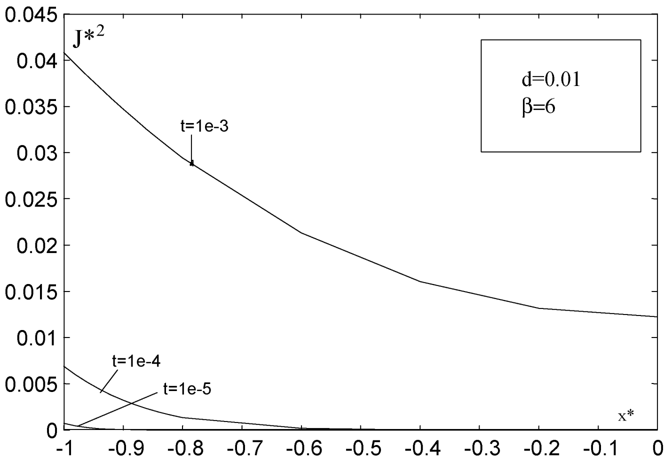

Fig. 4. Square values of dimensionless current for $\mathrm{d} = 0.01$ m and $\beta = 6\ \mathrm{s}^{-1}$.

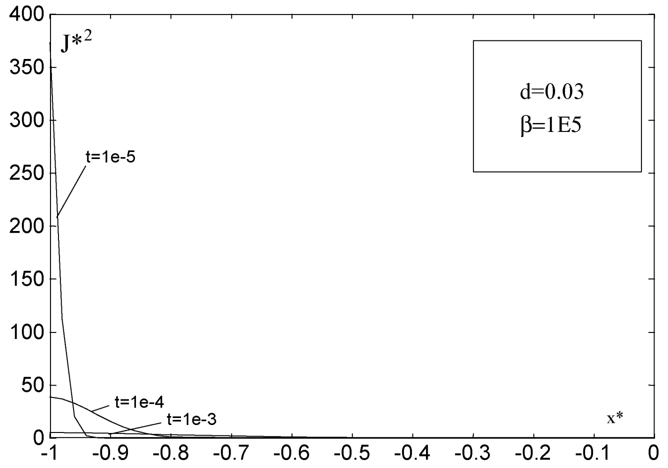

Fig. 5. Square values of dimensionless current for $\mathrm{d} = 0.03$ m and $\beta = 10^5\ \mathrm{s}^{-1}$.

Thanks to slab symmetry, current distributions are given according to half-space representation versus the following dimensionless spatial variable:

$$x^* = \frac{2x}{d}. \quad (20)$$

Current distribution evaluations were made by using typical possible values for rail guns and a short-circuit conductor bars (rail-guns: $\mathrm{I}_1 = 170\,000$ A, $\mathrm{I}_2 = 255\,000$ A, $\omega = 100\,\pi$; conductor bars: $\mathrm{I}_1 = 50\,000$ A, $\mathrm{I}_2 = 75\,000$ A, $\omega = 100\pi$). However, current distributions represented in Figs. 2–5 are the same for every case in which the $\mathrm{I}_1 - \mathrm{I}_2$ ratio is 2/3.

Results (see Figs. 2–5) show that when the conductor maximum thickness is not much greater than 10^{-2} m, the effects due to the magnetic-field penetration time already expire after $\mathrm{t} = 10^{-2}$ s. Furthermore, when $10^{-4}\ \mathrm{s} < \mathrm{t} < 10^{-3}\ \mathrm{s}$, the effects due to the current transient cannot be neglected only if the current rise time $\mathrm{T_s} = 1/\beta$ is short ($\beta > 10^3\ \mathrm{s}^{-1}$).

III. TEMPERATURE TRANSIENT

Generally, temperature steady state is reached much later than that of the current field, which is represented by the first term of

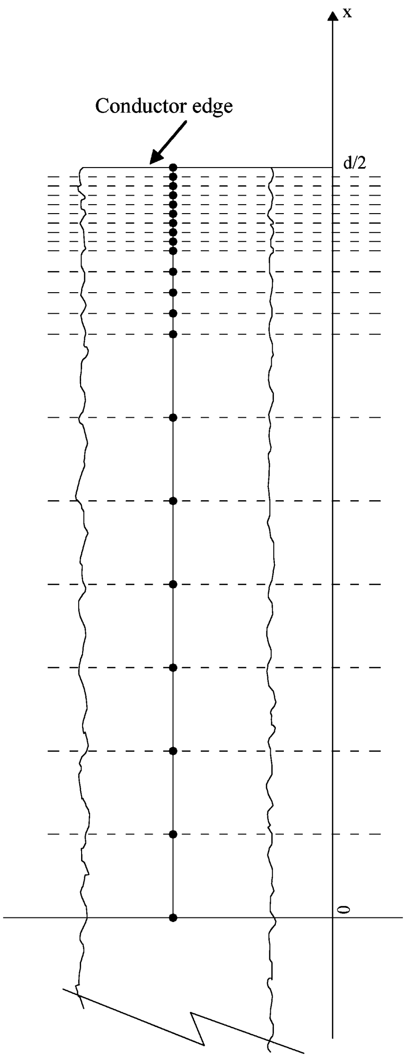

Fig. 6. Finite difference model: node positions.

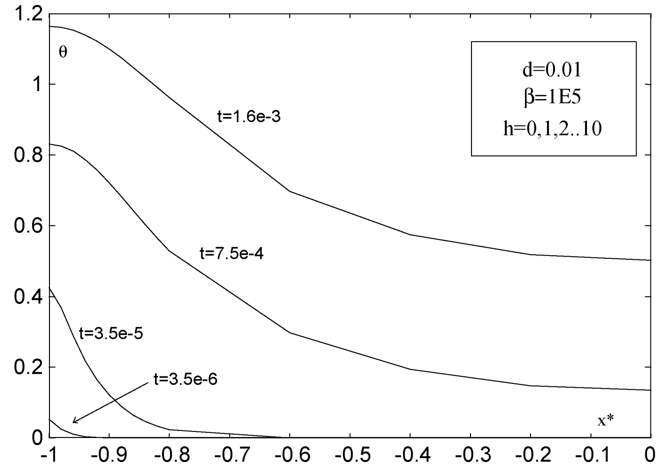

Fig. 7. Dimensionless temperature distributions for $\mathrm{d} = 0.01$ m, $\beta = 10^5\ \mathrm{s}^{-1}$.

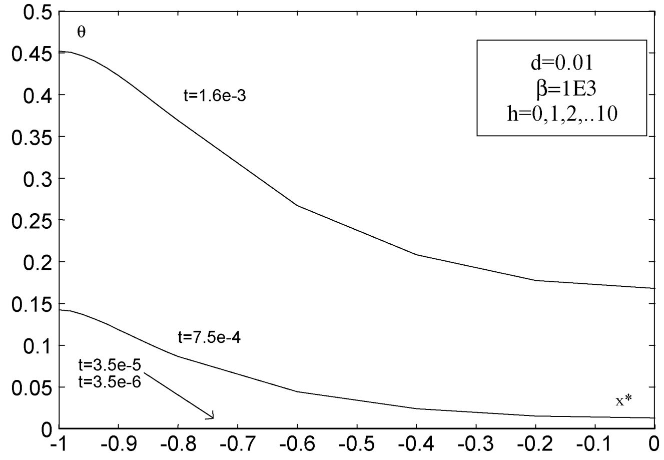

Fig. 8. Dimensionless temperature distributions for $\mathrm{d} = 0.01$ m, $\beta = 10^3\ \mathrm{s}^{-1}$.

(19) and (20). Thus, temperature evaluation may be achieved by taking into account only the heat source given by the steady terms of the electrical power distribution: these terms are obtained by the steady terms of the current density distribution. However, when current rise time is short enough (or, equivalently, β is very high), very high current values may locally and instantaneously occur. This fact instantaneously induces very high heat dissipation in small conductor areas; in particular, these phenomena occur very close to the conductor surface (skin effect). Thus, a quick temperature increase may sometimes occur in the high heat generation areas since the transient beginning. In order to establish the relation between temperature and current transient conditions, a numerical evaluation was carried out by implementing a FORTRAN-based finite difference numerical simulation. The slab was divided into unequally spaced slices; each slice is modeled by a node whose temperature is time dependent. Simulations were carried out for the half slab due to the slab symmetry. The total number of nodes is 21 (see Fig. 6 for the node configuration).

Heat flux dissipating toward the external environment was taken into account by introducing a constant heat-exchange rate. Heat-exchange rate values employed for simulations vary from 0–10 W/m^{2}K. However, it was demonstrated that the different heat-exchange rate values do not produce any meaningful differences in the temperature distribution. Simulation results are reported in Figs. 7–12; they are shown in terms of the following dimensionless temperature:

$$\theta = \frac{T - T_a}{\Delta T} \quad \text{where} \quad \Delta T = \frac{I_2^2}{4\sigma\lambda}. \tag{21}$$

I_2 is the amplitude of the current harmonic component per unit of length. Simulation results show that for $\mathrm{t} \leq 10^{-3}$ s (since the beginning of the current transient):

- the highest temperature values are found near the slab edge rather than inside the slab;
- the temperature quickly grows when the current rise time diminishes.

These temperature values are obtained for a current transient. If they were evaluated for steady-state current values, they would be higher than the simulated ones. However, the simulated temperature values are much higher than the ones that could be obtained by employing the same global current value with a uniform distribution, that is, neglecting the nonhomogeneous current density distribution due to the skin effect.

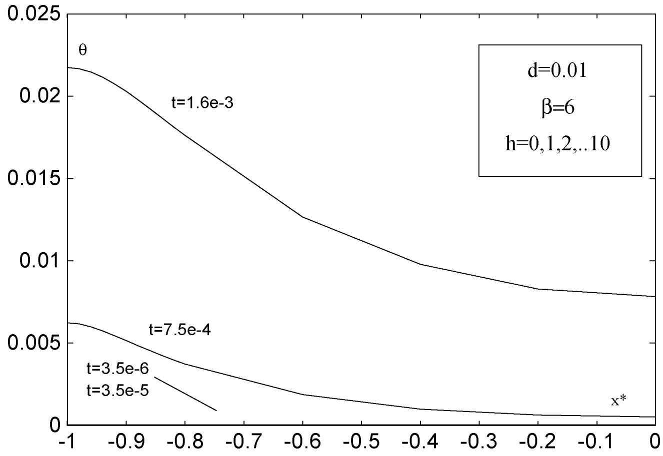

Fig. 9. Dimensionless temperature distributions for $\mathrm{d} = 0.01$ m, $\beta = 6\ \mathrm{s}^{-1}$.

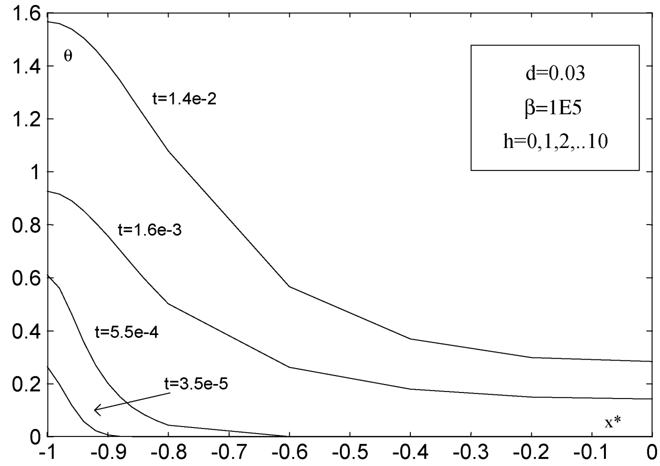

Fig. 10. Dimensionless temperature distributions for $\mathrm{d} = 0.03$ m, $\beta = 10^5\ \mathrm{s}^{-1}$.

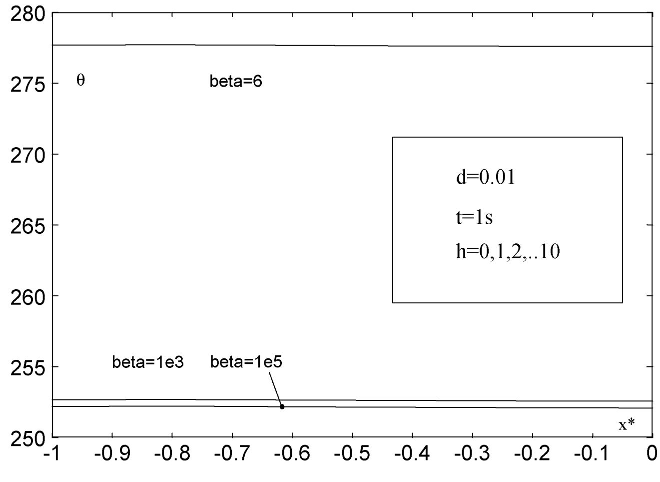

Fig. 11. Dimensionless temperature distributions for $\mathrm{d} = 0.01$ m, $\mathrm{t} = 1$ s.

IV. CONCLUSION

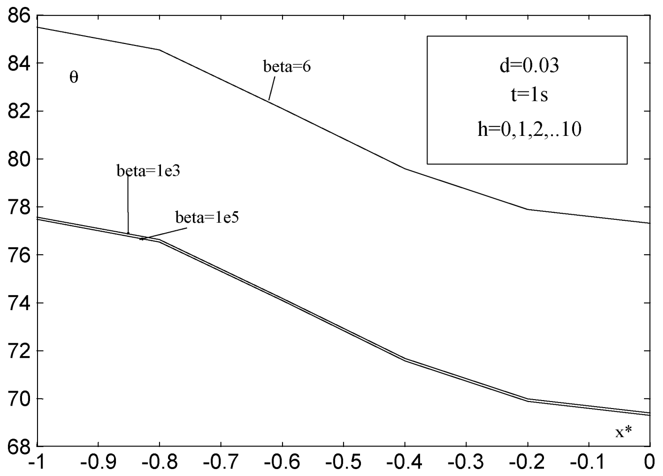

Fig. 12. Dimensionless temperature distributions for $\mathrm{d} = 0.03$ m, $\mathrm{t} = 1$ s.

A numerical method was employed to evaluate the temperature distribution inside rectangular conductors when fast current transients occur. The investigation demonstrates that current transient influences temperature distribution only when current rise time is short enough (shorter than 10^{-3} s) which is represented by the inverse value of an electrical circuit time constant. If the previous condition is verified, temperature may strongly rise near the conductor edge: maximum temperature value occurs at the same depth as the magnetic field one. Temperature distribution is insensitive to both conductor dimensions if the conductor is thicker than 0.01 m; furthermore, temperature distribution is insensitive to the heat-exchange rate when current transient elapsed time is shorter than 1 s. Short-circuit phenomena of conductor bars are generally characterized by current rise time which does not determine sudden temperature rise; in such cases, temperature may be found by employing only current regime rms value. In many applications, such as rail-guns or magnetic levitation, fast current transients may occur which last less than 1 s and are characterized by a rise time that is shorter than 0.1 s; in these cases, the transient current term must be taken into account to evaluate temperature distribution. In particular, high I_2 values (over $2 \cdot 10^5$ A) and low electrical conductivity metals (steel instead of copper) may induce a high temperature increase for short-current rise time (shorter than 10^{-4} s); for example, a steel-based rail gun may be characterized along the conductor edge by a maximum temperature increase that is higher than 300 K for a current rise time shorter than 10^{-4} s.

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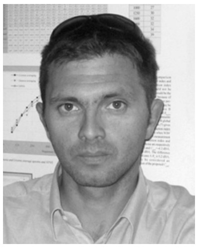

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