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THE EFFECT OF AN ELECTROMAGNETIC SHIELDING ON THE FORCES ACTING AMONG THE CONDUCTORS OF THREE-PHASE LINES

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Abstract: When designing rotating electrical machines, transformer, and other electrical equipment for high power, it is necessary to resist the forces between the conductors carrying heavy currents. The paper deals with the magnetic shielding, which can reduce these forces. It presents a mathematical model of the magnetic field in the area of three parallel conductors of three-phase supply. Based on the numerical solution the Lorentz force per unit length of conductors has been determined. The calculation of eddy current losses in the shielding jacket has been performed. The computational algorithm is illustrated with numerical examples. The general rules for a reliable design of shielding have been developed.

Key words: electromagnetic force, shielding, circuit of heavy current electrical engineering, three-phase electrical equipment.

1. Introduction

The construction of high-performance electrical machines and other heavy electrical equipment must satisfy the condition that the conductors carrying high currents are mechanically resistant. This requirement must especially be satisfied in equipments where short-circuit currents can occur. Examples of highly mechanically stressed parts are fronts of the stator windings of turbine generators, outlets of large rotating machines or power transformers, inlets of arc furnaces, buses in electric substations, etc. When designing the fixing elements for the mechanically exposed conductors, two circumstances have to be respected: the conductors must be securely fastened to prevent their permanent deformation, and, at the same time, they must have access to cooling, which protects them against thermal damage.

The magnitude of the forces acting among the conductors is closely related to the magnetic field induced by the currents in them. The distribution of magnetic field in a certain domain near the conductors can be affected by suitable shielding elements. Generally, a *passive shielding* (the domain is protected from magnetic field by a magnetically conductive shell), or *active shielding* (time-varying magnetic smog is suppressed by a secondary magnetic field generated by eddy currents; these are induced by a magnetic field in an electrically conductive shielding shell), are used. The active shielding systems are accompanied by the production of Joule eddy current losses in the conductive material of the shell. The passive and active shieldings can be combined. In this article, we test the hypothesis that *the forces acting on conductors in various heavy-current components can significantly be reduced by a suitable active shielding*. The confirmation of this hypothesis may make the work of the designers of numerous power engineering devices much easier.

2. Statement of the problem

Consider a three-phase line, consisting of three parallel conductors X, Y, Z. Each of the three conductors is made of copper round-strand rope (so that the skin effect in the conductors can be neglected) and carries current of a symmetrical three-phase system. We determine the time dependencies of force $\boldsymbol{f}_X(t)$ acting on the conductor X and force $\boldsymbol{f}_Y(t)$ acting on the conductor Y. Due to the symmetry, the force acting on the conductor Z is similar to the force $\boldsymbol{f}_X(t)$, but it is time-shifted against the force acting on the conductor X. As we want to specify only the maximum values of forces, for the above reason we will not deal with the force acting on the conductor Z. Calculation of the forces $\boldsymbol{f}_X(t)$ and $\boldsymbol{f}_Y(t)$ will be carried out for the following arrangements:

- The line is unshielded (Fig. 1, a).
- The line is partially shielded by a conductive plate (Fig. 1, b), which is made of: a) copper, b) aluminium, c) iron.
- The line is fully shielded with a shell (Fig. 1, c) made of: a) copper, b) aluminium, c) iron.

We shall investigate the magnetic field around the conductor, forces $\boldsymbol{f}_X(t)$, $\boldsymbol{f}_Y(t)$ as functions of time and Joule losses in the shielding material. In paragraph 3, we shall formulate the mathematical model and in paragraph 4, we shall indicate its numerical implementation. The content of paragraph 5 is an illustrative example with a discussion of the results, and general conclusions are summarized in paragraph 6.

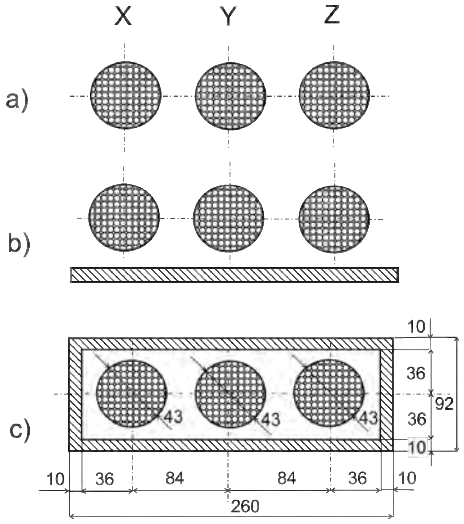

Fig. 1. Arrangement of conductors of lines: a – unshielded case; b – shielding with a plate; c – shielding with a shell.

3. Mathematical model

At first, we write equations for the distribution of the magnetic field in all definition subareas. For the magnetic vector potential $\boldsymbol{A}(t)$ in the non-linear conductive environment, the equation reads (see, e.g., [2], [3]):

$$\text{curl}\left(\frac{1}{\mu}\text{curl}\,\boldsymbol{A}\right) = -\gamma\frac{\partial \boldsymbol{A}}{\partial t} + \boldsymbol{J}, \qquad (1)$$

where μ is the magnetic permeability and $\boldsymbol{J}$ denotes the field current density.

As $\boldsymbol{J} = \mathbf{z}_0 J_z(t)$ and, thus, $\boldsymbol{A} = \mathbf{z}_0 A_z(x,y,t)$, then

- for the conductors X, Y, Z we get

$$\frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2} = \mu_0 J_z, \qquad (2)$$

- for the shielding element made of non-ferromagnetic material we obtain

$$\frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2} = \gamma\mu_0\frac{\partial A_z}{\partial t}, \qquad (3)$$

- for the shielding element made of non-linear ferromagnetic material we have

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A_z}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A_z}{\partial y}\right) = \gamma\frac{\partial A_z}{\partial t}. \qquad (4)$$

- Finally, for the surrounding air environment we can write

$$\frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2} = 0. \qquad (5)$$

The Lorentz force acting on the conductor carrying current of density $\boldsymbol{J}$ in a magnetic field $\boldsymbol{B}$ is

$$f = \int_V (J \times B)\, dV\,. \qquad (6)$$

The force acting on 1 meter of the conductor X has the following components

$$f_{\mathrm{X}x} = -J_z\int_S B_y \mathrm{d}S, \quad f_{\mathrm{X}y} = -J_z\int_S B_x \mathrm{d}S. \qquad (7)$$

Similarly, we can determine the force components $f_{\mathrm{Y}x}, f_{\mathrm{Y}y}$ acting on the conductor Y.

The volumetric Joule losses in the shielding element can be expressed in the form

$$w_{\mathrm{J}}(x,y,t) = \frac{J^2_{\mathrm{eddy},z}}{\gamma}, \qquad (8)$$

where γ is the electric conductivity and the density of eddy currents in shielding is

$$J_{\mathrm{eddy},z} = \gamma\mu\frac{\partial A_z}{\partial t}. \qquad (9)$$

Here, for non-ferromagnetic shielding $\mu = \mu_0$.

The mean value of the volumetric Joule losses in time is given by the formula

$$w_{\mathrm{J,mean}} = \frac{1}{T_{\mathrm{p}} V}\int_0^{T_{\mathrm{p}}}\int_V w_{\mathrm{J}}(x,y,t)\,\mathrm{d}V\,\mathrm{d}t \qquad (10)$$

where $x, y \in V$ and $t \in T_{\mathrm{p}}$, T_{p} denote the length of one period.

4. Computational model

The numerical solution of the mathematical model was performed by FEM, using QuickField 5.0 [4]. For both linear and non-linear shielding elements, the module Transient Electromagnetics was used. The convergence of the numerical solution for different values of discretization parameters $\delta_{\min}$, $\delta_{\max}$ (lengths of the sides of particular elements) and for different values of the time step Δt was examined in the calculation. It was shown that the accuracy of the calculated forces acting on the conductors X and Y is, above all, influenced by the values of $\delta_{\min}$ used for the discretization of cross-sections of the conductors (Fig. 1), while the discretization of the subfield formed by ambient air practically does not affect the accuracy of the solution. Further, it is shown that the effect of discretization Δt is negligible in comparison with the influence of geometric discretization $\delta_{\min}$. Apparently, this is associated with the existence of second derivatives with respect to the geometric variables and with the first derivatives with respect to time in the differential equations solved. The results suggested that for values $\delta_{\min} = 6.25 \cdot 10^{-4}$ m, $\delta_{\max} = 1.25 \cdot 10^{-2}$ m and Δt = 1.10^{-4} s, the maximum forces acting on the conductors X and Y can be computed with an accuracy reaching three significant digits.

For illustration of the results, the magnetic field lines $A(x, y, t)$ = const. are shown for these arrangements of the conductors:

- line is unshielded (Fig. 2),
- line is shielded with copper board (Fig. 3),
- line is shielded with iron shell (Fig. 4).

For Figs. 2, 3 and 4 the value of $t / T_{\mathrm{p}} = 4.75$, the scale being 0.0001 Wb/m.

The comparison of Fig. 2, Fig. 3 and Fig. 4 shows that the magnetic field around the conductor with the iron shielding is much stronger (the field lines are at the same value of "scale" denser), and when shielded by the copper board, the magnetic field is weaker than in the case of the unshielded line. Therefore, it can be expected that in the case of the copper shielding board, the forces among the conductors are reduced, and, on the contrary, in the case of the iron shielding shell the forces will dramatically increase. This will be more precisely expressed in the discussion of the results of the following illustrative example.

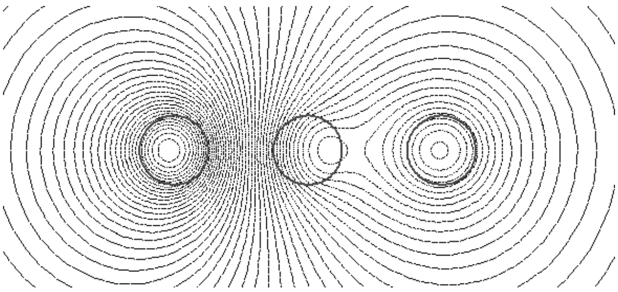

Fig. 2. Magnetic field for unshielded case.

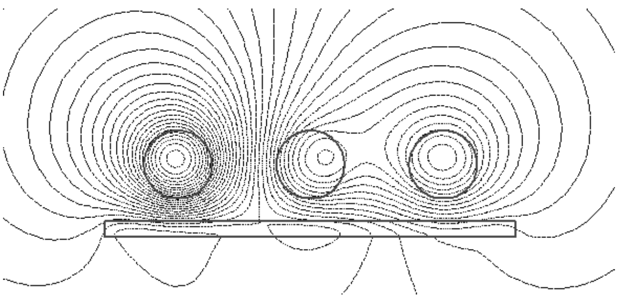

Fig. 3. Magnetic field for shielding with copper board.

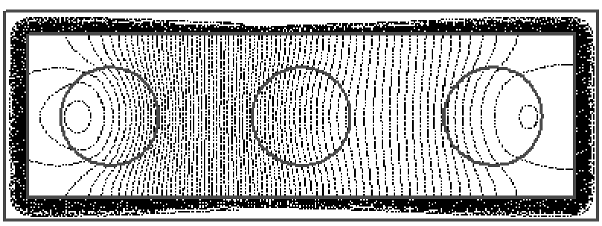

Fig. 4. Magnetic field for shielding with iron shell.

5. Illustrative example

Several calculations were performed for the considered configurations of shielding and for various shielding materials. We present the results of the calculation of forces among the conductors when the conductors X, Y, Z, arranged according to Fig 1 are realized by ropes with currents of a symmetrical three-phase system with an amplitude $I_{\mathrm{X}} = I_{\mathrm{Y}} = I_{\mathrm{Z}} = 7.187.10^3$ A, which corresponds to the current density amplitude $J_z = 4.95 \cdot 10^6$ Am^{-2} and frequency f = 50 Hz.

Table 1

Values of *x*-components of the forces acting on the conductors X **and** Y

configuration	$f_{\mathrm{X}x}$ [N/m]	[%]	$f_{\mathrm{Y}x}$ [N/m]	[%]
unshielded:	90	100	100	100
board of cooper	**45**	**50**	**55**	**55**
shell of iron	**35**	**39**	**40**	**40**
board of iron	105	117	120	120
shell of iron	400	444	390	390

The results are presented for the fifth period of the current T_{p}, i.e., for $4 \le t / T_{\mathrm{p}} \le 5$. The material of shielding is, in turn, copper $(\gamma = 5.7 \cdot 10^7 \text{ Sm}^{-1}, \mu_{\mathrm{r}} = 1)$, aluminium $(\gamma = 3.4 \cdot 10^7 \text{ Sm}^{-1}, \mu_{\mathrm{r}} = 1)$, and iron ($\gamma = 1.5 \cdot 10^6 \text{Sm}^{-1}$, whose $B(H)$ dependence is depicted in Fig. 5).

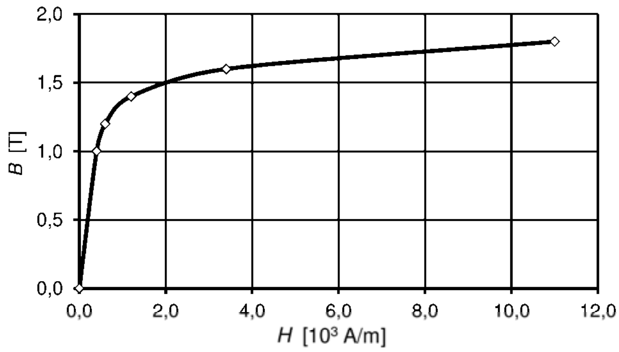

Fig. 5. The magnetization curve of ferrous shielding material.

The forces acting on the conductors X, Y and Z vary periodically with the frequency 2*f*. For example, the force acting on the conductor X is $\mathbf{f}_{\mathrm{X}}(t) = \mathbf{x}_0 f_{\mathrm{X}x}(t) + \mathbf{y}_0 f_{\mathrm{X}y}(t)$. Figs. 6–9 present the waveforms of the *x* and *y*-components while shielding is made of copper, and Figs. 10–13 present the corresponding curves when shielding is of iron. In these drawings, the maximum values of the forces are shown and, for greater clarity, also listed in Tab. 1.

The maximum value of the *x*-component acting on the conductor X is $f_{\mathrm{X}x} = \max\left|f_{\mathrm{X}x}(t)\right|$. The force components acting on unshielded conductors X and Y are taken as 100 %. Table 1 implies that while shielded, the *x*-component of force

- **decreases** with copper board; on the conductor X to 50% and on the conductor Y to 55 % ,
- **decreases** with copper shell; on the conductor X to 39% and on the conductor Y to 40 %, while
- **increases** with iron board; on the conductor X to 117% and on the conductor Y to 120 %,
- **increases** with iron shell; on the conductor X to 444% and on the conductor Y to 390 %.

Table 2

Time-space mean values of eddy current losses in the shielding material

	$w_{J,mean}$ [W/m^3]	
shielding material	board	shell
cooper	$1.593 \cdot 10^5$	$7.163 \cdot 10^4$
aluminium	$2.351 \cdot 10^5$	$1.027 \cdot 10^5$
iron	$4.566 \cdot 10^4$	$4.185 \cdot 10^5$

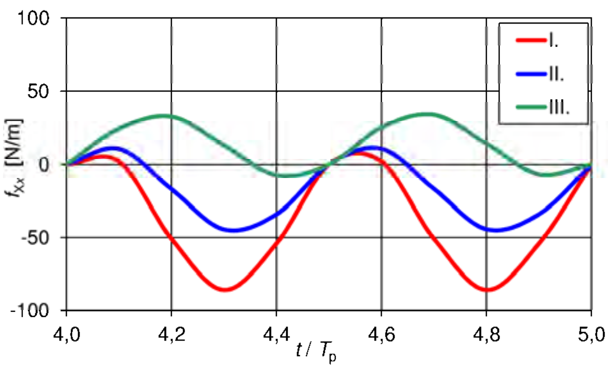

Fig. 6. Time dependencies of components f_{Xx} (I… unshielded case, II… shielding with a cooper board, III… shielding with a cooper shell).

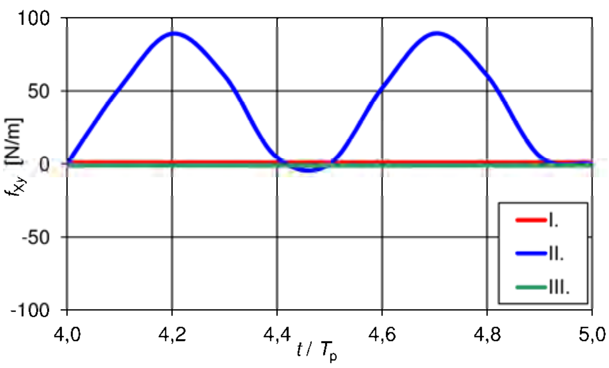

Fig. 7. Time dependencies of components f_{Xy} (I… unshielded case, II… shielding with a cooper board, III… shielding with a cooper shell).

Shielding with the board is asymmetric, which causes generation of a *y*-component of the force. If the board is made

- of copper, the *y*-component acting on the conductor X f_{Xy} = 90 N and on the Y conductor f_{Yy} = 60 N,
- of iron, both of these components increase: f_{Xy} = 95N and f_{Yy} = 90 N.

Table 2 gives the time-space mean Joule losses that are produced in the shielding material.

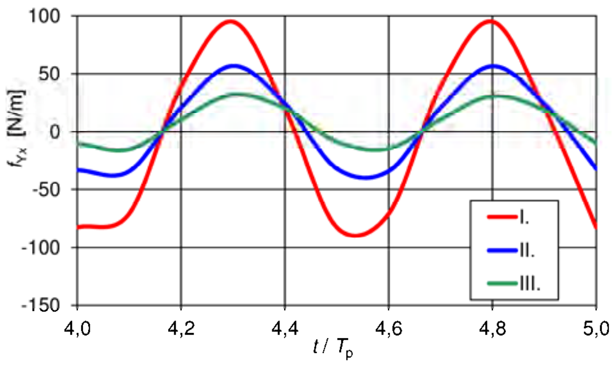

Fig. 8. Time dependencies of components f_{Yx} (I… unshielded case, II… shielding with a cooper board, III… shielding with a cooper shell).

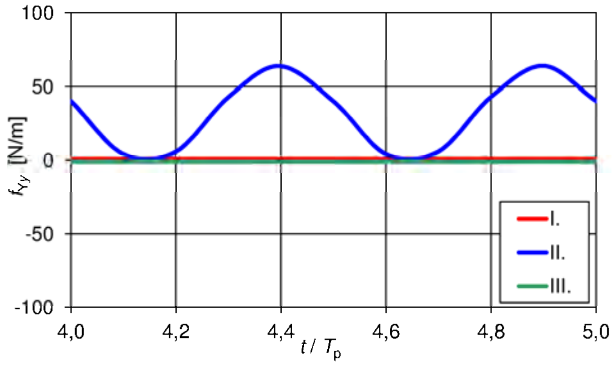

Fig. 9. Time dependencies of components f_{Yy} (I… unshielded case, II… shielding with a cooper board, III… shielding with a cooper shell).

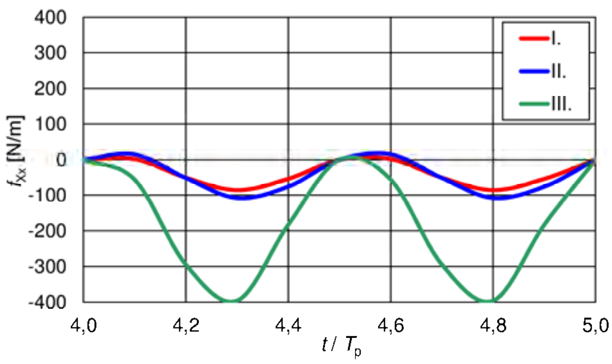

Fig. 10. Time dependencies of components f_{Xx} (I… unshielded case, II… shielding with an iron board, III… shielding with an iron shell).

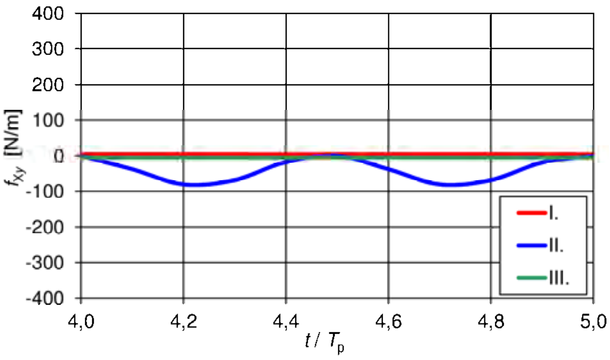

Fig. 11. Time dependencies of components f_{Xy} (I… unshielded case, II… shielding with an iron board, III… shielding with an iron shell).

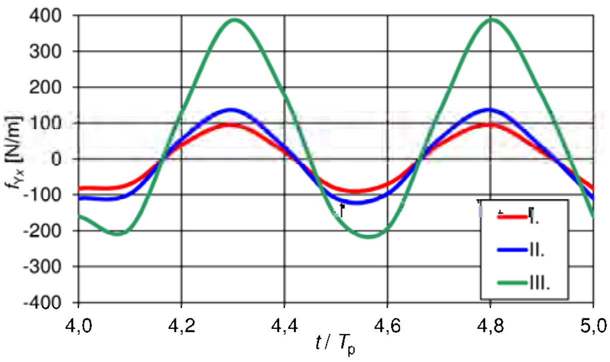

Fig. 12. Time dependencies of components f_{Yx} (I… unshielded case, II… shielding with an iron board, III… shielding with an iron shell).

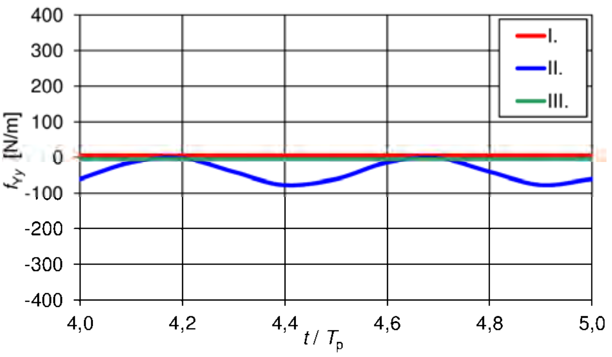

Fig. 13. Time dependencies of components f_{Yy} (I… unshielded case, II… shielding with an iron board, III… shielding with an iron shell).

6. Conclusion

The presented work shows that shielding of conductors X, Y, Z of a three phase line can considerably influence the forces acting among the conductors. The reduction of the forces occurs if the shielding is made of a highly conductive *non-ferromagnetic* material, while if the shielding is made of iron, the forces among conductors will increase significantly. If the shielding is asymmetric (in our case the shielding with a board), the *y*-component of force occurs. When designing a shielding for a power device, it has to be reckoned with the fact that the shielding is accompanied by the generation of the Joule losses in its elements. The specific design of the shielding must then be supplemented with calculating the temperature rise.

The shielding effect depends on a number of different parameters, mainly geometric dimensions, properties of the shielding material, effects of the surrounding structure, etc. The project of shielding should be treated as a multiparametric optimization coupled electromagnetic-thermal problem.

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ВПЛИВ ЕЛЕКТРОМАГНІТНОГО ЕКРАНУВАННЯ НА СИЛИ ВЗАЄМОДІЇ МІЖ ПРОВІДНИКАМИ ТРИФАЗНИХ ЛІНІЙ

Даніель Маєр, Богуш Ульріх, Петр Кропік

Під час проектування обертових електричних машин, трансформаторів та іншого електрообладнання високої потужності необхідно враховувати сили взаємодії між проводами зі струмами з великим чинним значенням. Розглянуто магнетне екранування, яке може зменшити ці сили. Викладено математичну модель магнетного поля в області трьох паралельних провідників трифазного живлення. На підставі числового розв’язання знайдено силу Лоренца, що діє на одиницю довжини провідників. Проведено розрахунок втрат на вихрові струми в захисному екрані. Обчислювальний алгоритм ілюструється числовими прикладами. Запропоновано загальні рекомендації для конструювання надійного екранування.

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