ADVANCEMENTS IN PROGRAM ELTA FOR CALCULATION OF INDUCTION HEATING SYSTEMS

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ABSTRACT. This paper presents the advancements in program ELTA (program for Electro-Thermal Analysis). A coupled 1D program ELTA is a unique program for a preliminary study of the processes in a wide range of applications [1]. New version of ELTA can simulate two-dimensional distribution of power sources and temperature in rectangular cross-section of workpieces and more accurate temperature parameters than the previous version. Some examples illustrate the advantage of two-dimensional approach for calculation of temperature in the workpieces of square cross-section and relatively thick slabs. Program ELTA^{2Ø} is the further advancement of 1D program. This subject oriented program has been developed as continuation of program ELTA for two-dimensional calculation of temperature in cylindrical workpieces.

INTRODUCTION

New induction heating technologies require a detail analysis of electromagnetic, thermal and other processes previously than they will be introduced in industry. Computer simulation is the most effective method for solving for these problems. The authors have big practical experience of development and successful using ELTA programs.

Specific features of ELTA are its simplicity, easiness of use and reasonable accuracy for majority of practical applications. It can simulate cylindrical, plane-parallel and one-side systems for longitudinal and transversal heating of magnetic or non-magnetic, solid or hollow, even multi-layered loads with arbitrary properties and arbitrary initial temperatures of the layers. ELTA is based on a special 1D Finite Difference Method for solution of coupled Electromagnetic and Thermal problems in combination with analytical “Total Flux Method” to count for a finite length of the coil and workpiece in cylindrical and plane-parallel systems. This method gives good practical results in simulation of 2D systems of simple geometry and even 3D systems such as heating of relatively wide slabs in oval or rectangular inductors. However one-dimensional approach for internal problem does not provide accurate enough results for the workpieces of square cross-section and relatively thick slabs.

Having done a first step, researchers always want to know more, for example a temperature distribution in the cross-section of load. Role of computer simulation in induction heating technique and a strategy based on a hierarchical use of programs are described in [2]. What kind of program may be chosen? There are many commercial 2D and 3D programs. The researchers can choose one or another from them depending on tasks, their own preferences, price of the program, power of computer and other factors.

Knowing the main advantages of program ELTA users should like to have extended possibilities of this program. For this reason the authors added to a coupled 1D program

ELTA an internal block for calculation of temperature field in workpieces with rectangular cross-sections. A completely numerical program ELTA^{2Ø} for cylindrical systems.

MATHEMATICAL MODEL

New version of ELTA can calculate two-dimensional distribution of power sources and temperature in workpieces of square or rectangular cross-section. Non-linear differential equation for magnetic field $\dot{H}$ is [3]:

$$\frac{\partial}{\partial x}(\rho\frac{\partial \dot{H}}{\partial x})+\frac{\partial}{\partial y}(\rho\frac{\partial \dot{H}}{\partial y}) = j\omega\mu\mu_0\dot{H},$$

where ρ – electrical resistivity, ω – angular frequency, μ – permeability, *x, y* – coordinates of workpiece cross-section.

Non-linear differential equation for temperature *T* is described as:

$$C_v\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}(\lambda\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(\lambda\frac{\partial T}{\partial y})+w,$$

where C_v – volume specific heat, λ – thermal conductivity, $w=\rho\left(\frac{\partial \dot{H}}{\partial x}\frac{\partial \overset{*}{H}}{\partial x}+\frac{\partial \dot{H}}{\partial y}\frac{\partial \overset{*}{H}}{\partial y}\right)$ – power sources.

The internal part of electro-thermal problem is solved with account for planes of symmetry, i.e. only 1/4 part of workpiece is calculated.

ANALYSIS OF RESULTS

Series of calculations were performed to analyze a difference between the results of integral parameters of inductor and average temperature (see Table 1 and 2). Aluminum workpieces have length 60 cm and thickness×width *d*×*b*. Inductor power P_i =300 kW, frequency *f* = 400 and 200 Hz, duration of heating *t* = 40 s. Heat losses from surfaces were not taken into account.

The results of computer simulation show that integral parameters of inductor for one-dimensional and two-dimensional variant of calculation are approximately the same. The differences between the results of workpiece power, electrical efficiency and inductor impedance for square profile *d*×*b* = 8,12×8,12 cm^2 are 4 – 5 %.

Table 1. Comparison of 1D and 2D calculation for aluminum workpieces. *f* = 400 Hz.

Variant	*d*×*b*, cm^2	P_w, kW	η, %	cos φ	*Z*, mΩ	T_{aver}, °C	*Q'*, kW·hr/t
1D	8,12×8,12	168	55,97	0,283	18,74	370	175
2D		175	58,49	0,288	19,61	594	182
1D	6×11	165	54,98	0,291	19,99	458	171
2D		170	56,63	0,292	20,74	569	177
1D	3×22	167	55,53	0,309	29,75	593	173
2D		166	55,30	0,302	30,28	589	172
1D	1,5×44	166	55,41	0,293	55,92	623	173
2D		163	54,29	0,282	56,71	566	170
1D	1×66	122	40,92	0,223	80,62	500	127
2D		127	42,23	0,227	81,21	457	131

Table 2. Parameters of calculation for aluminum workpieces. f = 200 Hz.

Variant	$d \times b$, cm^2	P_w, kW	η, %	cos φ	Z, mΩ	T_{aver}, °C	Q', kW·hr/t
1D	6×11	162	53,87	0,358	11,26	460	168
2D		165	54,90	0,350	11,78	551	171

At the same time average temperature in the workpiece of square cross-section is sufficiently higher than for one-dimensional variant. In this case increment of average temperature during the heating increases 1,64 times. Applying 2D internal calculation, the best result of specific energy consumption is obtained too. This may be explained by the following reasons:

- 1D calculation expects that process of heating comes only from two sides of the workpiece;
- It is evident that heating sources from all four sides of workpiece must increase the average temperature for workpiece of square cross-section.

Average temperature for workpiece 6×11 cm^2 increases 1,25 – 1,21 times. At the same time average temperatures of thin aluminum workpieces calculated with 2D approach are lower than by using 1D ones due to lower temperature at the edges.

Distributions of temperature and heat source density for aluminum workpieces are shown in Figures 1, 2 and 3. The results of computer simulation show that distributions of power sources have distinctive type.

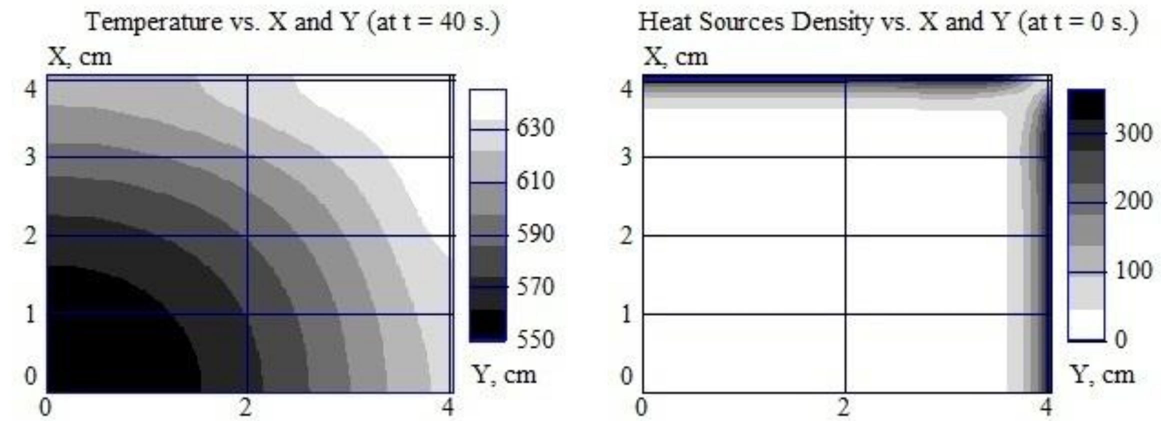

Figure 1. Color map of temperature and power density in the cross-section of workpiece 8,12×8,12 cm^2

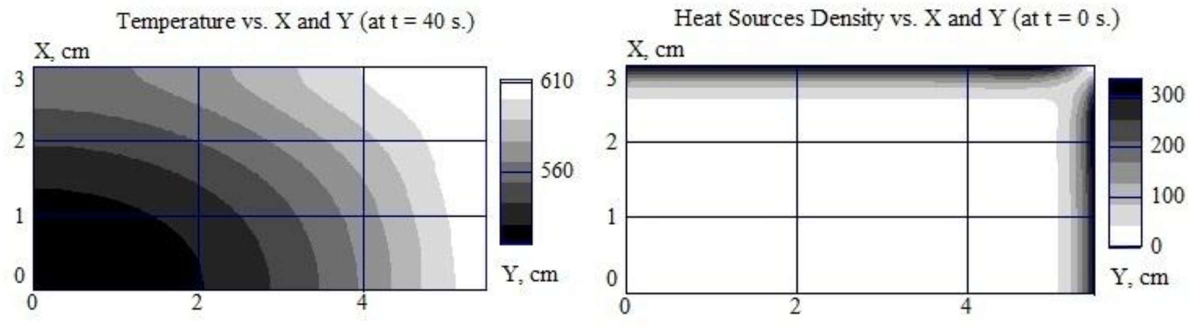

Figure 2. Color map of temperature and power density in the cross-section of workpiece 6×11 cm^2

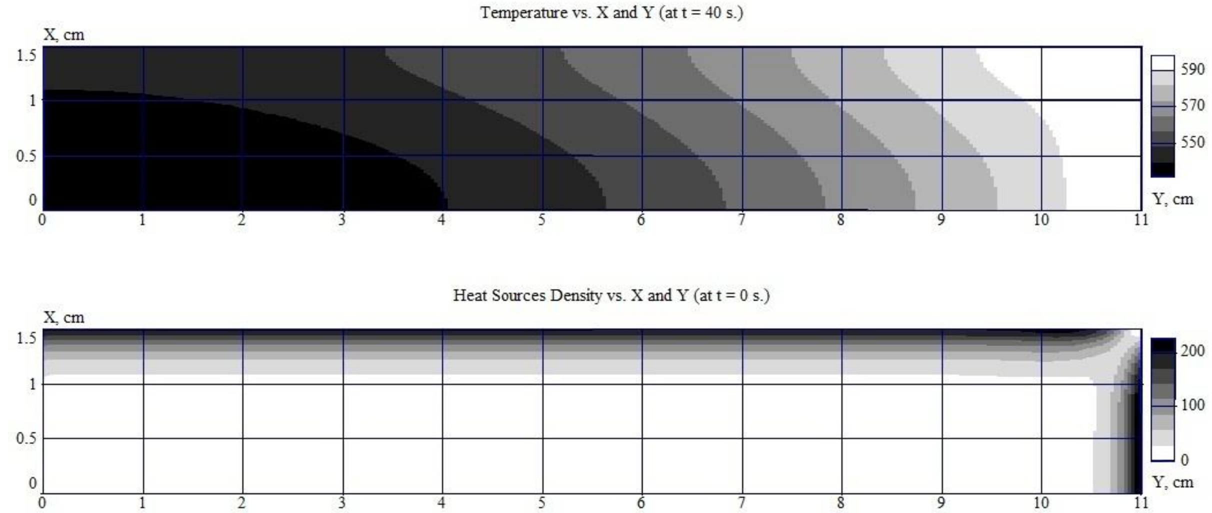

Figure 3. Color map of temperature and power density in the cross-section of workpiece 3×22 cm^2

2D MATHEMATICAL MODEL

Further advancement is development of two-dimensional program ELTA^{2Ø}. This subject oriented program simulates a wide range of electrothermal processes in cylindrical workpieces and may be simply and effectively used for many practical needs. ELTA^{2Ø} program provides a two dimensional simulation of electromagnetic and thermal fields in cylindrical induction heaters using both integral and differential numerical methods.

A sketch of 2D induction heating system is shown in Figure 4.

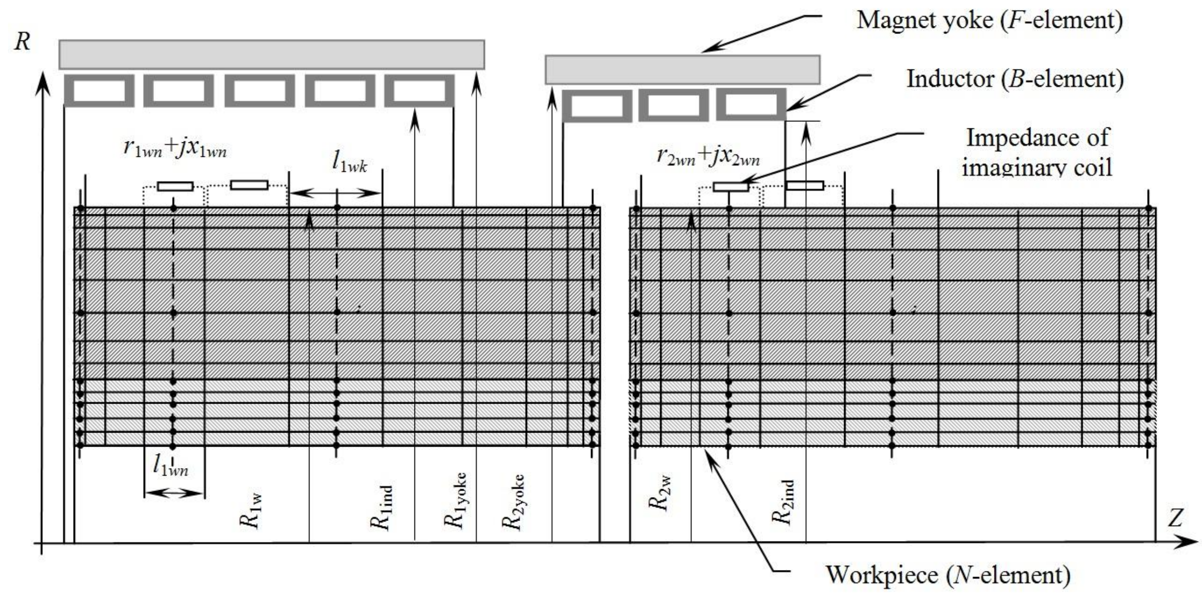

Figure 4. Sketch of calculated induction heating system

Method of Magnetization Forces is used for calculation of the inductor parameters in combination with one-dimensional differential numerical calculation of electromagnetic field inside the workpiece. Results of calculation of internal field are used in formulation of the impedance boundary conditions for solution of the external part of the problem. A system of equations describes voltage balance for each circuit with account of circuit resistance, self-and mutual inductances [3]:

$$\left.\begin{aligned} &Q \in B, && \dot{Z}_Q \dot{I}_Q + j\sum_P x_{QP}\dot{I}_P = \dot{U}_Q; \\ &Q \in N_k, && \dot{Z}_Q \dot{I}_Q + j\sum_P x_{QP}\dot{I}_P = 0; \\ &Q \in N_f, && \dot{I}_Q - \sum_P N_{QP} W_P \dot{I}_P = 0; \\ &Q \in F, && S_Q \dot{I}_Q - \sum_P N_{QP} W_P \dot{I}_P = 0 \end{aligned}\right\},$$

where Q, P – elements of system, $\dot{Z}_Q$ – impedance of coil, $\dot{I}$ – current, $\dot{U}$ – voltage, N_{QP} – coefficient of Magnetization Forces, $S_Q = \dfrac{\mu_Q}{1-\mu_Q}$.

Matrix form of equation is described as:

$$\begin{vmatrix} \dot{Z}_B & j(x_{Bk}) & j(x_{Bf}) & j(x_{BF}) \\ j(x_{kB}) & (\dot{Z}_{kk} + jx_{kk}) & j(x_{kf}) & j(x_{kF}) \\ (N_{fB}W_B) & (N_{fk}) & (N_{ff}) & (N_{fF}) \\ (N_{FB}W_{B1}) & (N_{Fk}) & (N_{Ff}) & ((N_{FF} - (S)) \end{vmatrix} \times \begin{vmatrix} \dot{I}_B \\ \dot{I}_k \\ \dot{I}_f \\ \dot{I}_F \end{vmatrix} = \begin{vmatrix} \dot{U}_B \\ 0 \\ 0 \\ 0 \end{vmatrix}.$$

Non-linear 1D differential equation for magnetic field and 2D differential equation for temperature are described as [3]:

$$\frac{1}{R}\frac{\partial}{\partial R}(\rho R \frac{\partial \dot{H}}{\partial R}) = -j\omega\mu\mu_0 \dot{H},$$

$$C_v \frac{\partial T}{\partial t} - \frac{1}{R}\frac{\partial T}{\partial R}(\lambda R \frac{\partial T}{\partial R}) - \frac{\partial T}{\partial Z}(\lambda \frac{\partial T}{\partial Z}) = w,$$

where R – radius, Z – axial coordinate, $w = \rho \left|\dfrac{\partial \dot{H}}{\partial R}\right|^2$ – power sources.

FEATURES OF ELTA^{2Ø} PROGRAM

The main features of this program are:

- ELTA^{2Ø} has "Model View", i.e. the system of geometrical visualization for main elements of technological line, that permits to control the preprocessing (see Figure 5). The **Main** menu contains the submenus **Inductors, Workpieces**, **Cooling Systems, Furnaces, Insulation Cover, Processing** and **Calculation**;
- ELTA^{2Ø} provides the great opportunities for visualization of output parameters in the form of graphs and tables, i.e. the advanced post processing. The **Results** menu contains the submenus **Window, Results, Report** and allows to select the organization of the result windows on the screen (see Figure 6);
- Program has very friendly user interface;

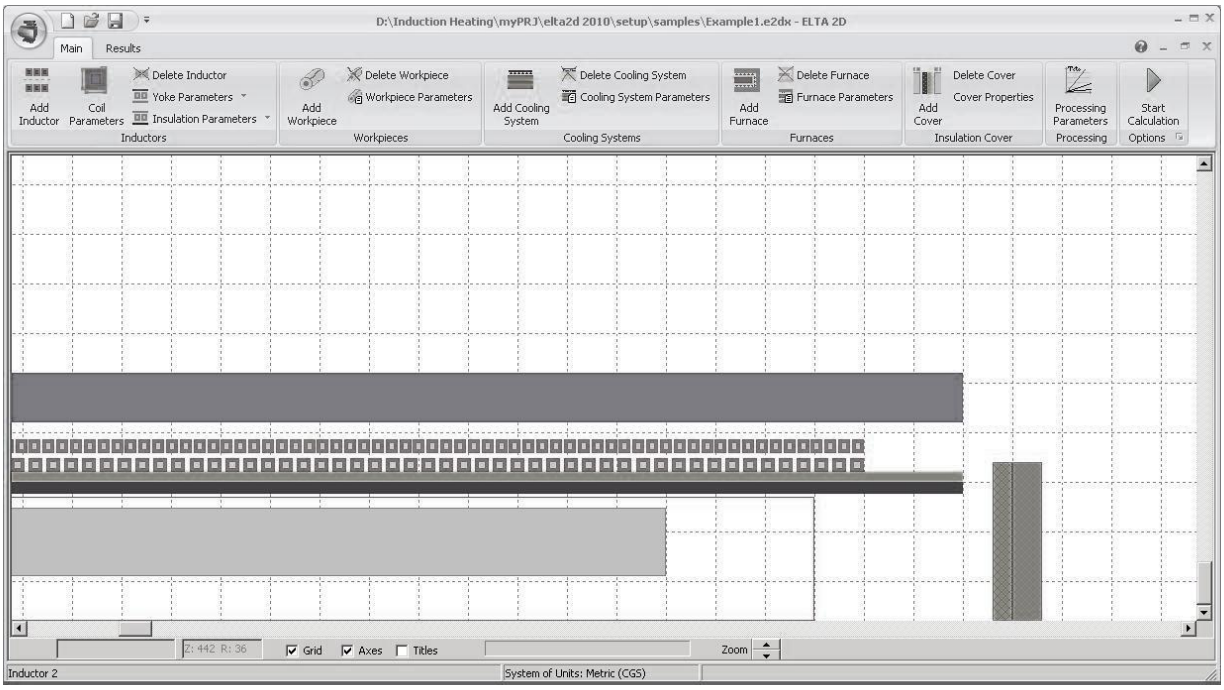

Figure 5. Model view and Main menu of ELTA$^{2\varnothing}$ program

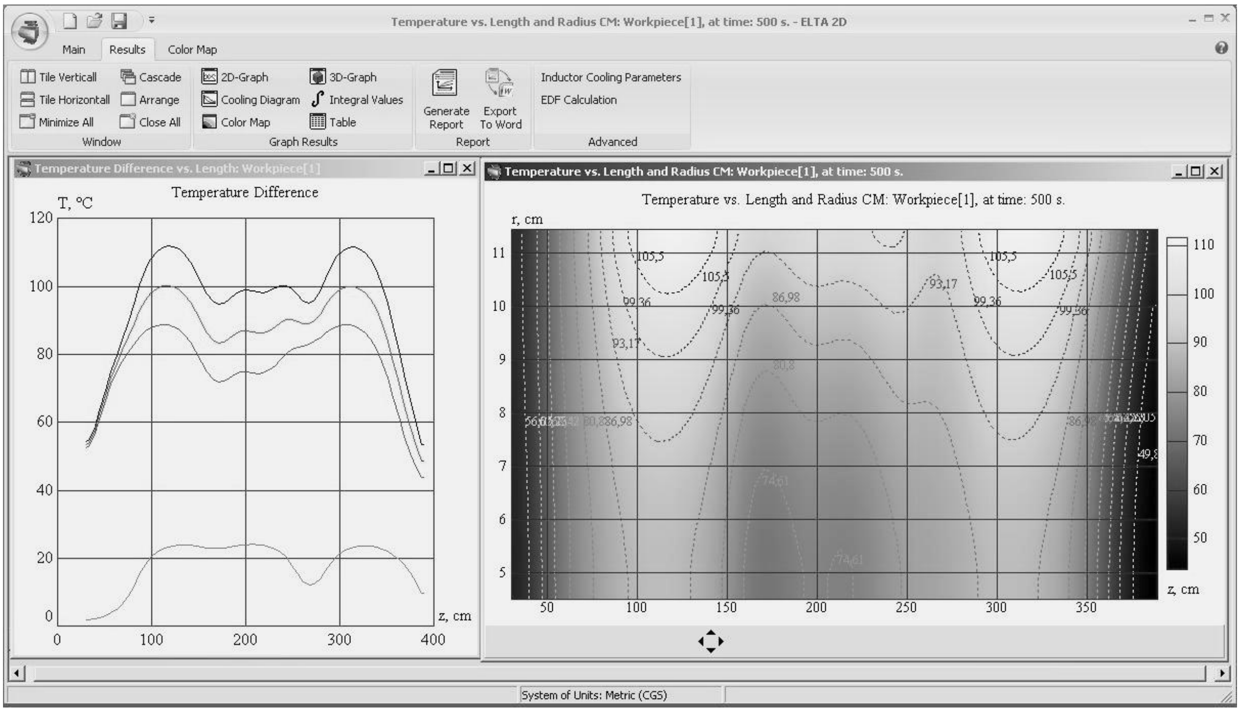

Figure 6. Menu Results of ELTA$^{2\varnothing}$ program

- ELTA$^{2\varnothing}$ is relatively simple program for understanding and realization; the boundary conditions in the problem of calculating the electrical and thermal parameters can be set automatically;
- Many typical technological heating lines with simultaneous, non-stationary semi-continuous and continuous processes can be simulated from start to stationary finish;

- $ELTA^{2Ø}$ can simulate the heating process with one, two or three layer induction coils;
- User may select from many variants of resonant circuits with different schemes of compensation: parallel; parallel with transformer; series; series with transformer; series-parallel; series-parallel with transformer; parallel-series; parallel-series with transformer, etc.;
- $ELTA^{2Ø}$ can take into account circuits with series connected induction coils and simultaneously multi frequency power sources for circuits;
- There is a special cooling diagram: applying the Time-Temperature Transformation curves (thermodynamics or kinetics ZTU-diagram) to this graph, the user can find the structural transformations in the cross-section of workpiece including the case depth and hardness;
- $ELTA^{2Ø}$ has a built-in report with report templates created by users and can export the results in a Word format.

CONCLUSIONS

The main advancements in program ELTA are two-dimensional calculation of temperature in cross-section of rectangular workpieces and temperature calculation in volume of cylindrical load. Series of calculations were performed to show the differences between the average temperatures in workpieces of square and rectangular cross-section by using one-dimensional and two-dimensional approaches.

The subject oriented program $ELTA^{2Ø}$ as continuation of ELTA program can simulate a wide range of electrothermal processes in cylindrical workpieces and may be simply and effectively used by students, scientists, industrial researchers and users of induction technology in multiple applications..

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