Fusion Engineering and Design 87 (2012) 1519–1532

Contents lists available at SciVerse ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Global computational models for analysis of electromagnetic transients to support ITER tokamak design and optimization

V. Amoskov[a], D. Arslanova[a], A. Belov[a], V. Belyakov[a], T. Belyakova[a], E. Gapionok[a], N. Krylova[a], V. Kukhtin[a], E. Lamzin[a], N. Maximenkova[a], I. Mazul[a], V. Rozov[b], S. Sytchevsky[a,*]

[a] *D.V. Efremov Scientific Research Institute, 196641 St.-Petersburg, Russia*
[b] *ITER Organization, CS 90 046, 13067 St. Paul-Lez-Durance Cedex, France*

ARTICLE INFO

Article history:
Received 19 November 2011
Received in revised form
12 December 2011
Accepted 19 December 2011
Available online 20 July 2012

Keywords:
ITER
Simulation
Magnetic field
Electromagnetic transients
Differential approach
Integral approach
Eddy current
EM load
Finite element
Magnetic shell

ABSTRACT

The International thermonuclear experimental reactor (ITER) concept implies a variety of operating modes, design complexity and demand for high reliability. A point of the major concern is the transient electromagnetic (EM) effects. Complex electromagnetic behaviour due to strong inductive coupling, the presence of numerous field sources, and a range of plasma burn scenarios requires careful predictive simulations. Different mathematical models applicable for the design and optimization studies are reviewed. Practical experience in developing detailed global models to investigate eddy currents, EM forces and other EM loads is summarized. Two numerical techniques implemented in the dedicated computer codes are compared, and the validity of relevant models is discussed.

1. Introduction

Electromagnetic transients in tokamaks are one of the major challenges in their design. All design stages of the ITER project involve careful electromagnetic studies [1–3].

A pulsed operation [3] causes the appearance of large electromagnetic loads and thermal loss, that imposes significant limitations on the reactor design. This necessitates development of detailed computational models to investigate anticipated eddy currents, mechanical (ponderomotive) forces and heat loads deposited on conducting components. The study will be even more complicated in case of a pronounced surface effect of eddy currents.

In tokamaks, it is mandatory to take into account the inductive coupling between the main components. This demands for building a global model, at least for checking computations and a predictive analysis, and significantly limits the electromagnetic analysis, based on local models. Particularly, for the ITER blanket system, a series of intensive benchmark studies [4,5] with different codes were launched in order to validate global 3D models for EM analyses. Obtained by the domestic parties to an international project positive results [6] allowed going to the specific calculations that have demonstrated the coincidence of the data [7].

Reasoning from the machine sizes [1,9] and characteristic time constants of the EM transients [8], the ITER field can be modelled using the quasi-stationary approach [9,10].

The objectives of the study conducted were to compare two approaches, one based on the magnetic shells and other using 3D finite elements to the development of global computer models for ITER. The algorithms specific for tokamaks, in particular for ITER, are discussed that summarizes authors' eighteen-year experience in electromagnetic and optimization studies.

A general approach to modelling a transient EM process in conducting structures is well known and has been justified by a number of analytical solutions [9–15]. A system of the Maxwell equations is formulated in terms of the field vector **B** and electric field strength vector **E** (for simplification, a non-ferromagnetic conductor is assumed). The system is complemented with the constitutive equation to relate the electric field strength **E** and current density $\boldsymbol{\delta}$ as $\mathbf{E} = \rho\boldsymbol{\delta}$ for an isotropic medium defined by a scalar

* Corresponding author.
E-mail addresses: sytch@sintez.niiefa.spb.su, sytch@niiefa.sintez.spb.su (S. Sytchevsky).

0920-3796/$ – see front matter
doi:10.1016/j.fusengdes.2011.12.015

resistivity ρ. In a general case, a nonlinear tensor function is applied. Also, the known boundary conditions [10] are added to this system of equations for the **B** and **E** components on the conductor-vacuum boundary. The functions defining an extraneous transport current distribution are assumed known. Adding the boundary conditions of infinity, symmetry and initial conditions, we obtain a complete system of equations applicable for specific problems.

It is known that about 86% of the current generated by harmonic oscillations with frequency ω in a non-ferromagnetic conductor with resistivity $\boldsymbol{\rho_0}$ will be concentrated in a skin layer [9,10] with the depth defined as

$$2\Delta_0 = \sqrt{\frac{8\rho_0}{\mu_0\omega}} \quad (\mu_0 = 4\pi \cdot 10^{-7}\,\text{H/m})$$

At characteristic frequency 10^4 Hz, the skin layer for a copper conductor has a depth of 1.4 mm.

Let the characteristic time interval for a pulse field with the impulse front Δt be equal to one fourth of the oscillation period $T = 4 \times \Delta t$. For a nonmagnetic steel with a conductivity 10 times less than that of copper a skin layer depth $2\Delta_0$ varies in the range 8.9–28.2 mm at the frequency $\{\boldsymbol{\omega_1} = 2\pi/(4 \times 0.1\,\text{ms}) = 1.5 \times 10^4\,\text{s}^{-1}$, $\boldsymbol{\omega_2} = 2\pi/(4 \times 1.0\,\text{ms}) = 1.5 \times 10^3\,\text{s}^{-1}\}$.

This solution is obtained for an infinite half-space uniform conductor.

Assuming a steel conductor to be of a 60 mm thickness wall, as for the ITER vacuum vessel shells, we can evaluate the characteristic time interval as $\Delta t = \pi/(2\boldsymbol{\omega}) = 4.5$ ms at the skin layer depth of 60 mm. If the field varies in time exponentially with the time constant τ_0, the frequency ω can by substituted by the inverse value $1/\tau_0$ [1].Compared with the above estimates for a semi-infinite space or an infinite layer, a finite size of the conductors reduces the time scale of the field penetration. Therefore, as a rule, the analysis should be based on numerical simulation.

Account for the operating temperature of the ITER conducting structures (for the cooling of the conductor) can lead to an additional increase of the skin effects. For accurate analysis, a coupled problem should be solved for the total temperature distribution and local loads due to the eddy current.

Analytical solutions almost never provide the required accuracy for simulation of the EM transients in tokamaks [1,2]. This has inspired the development of a variety of simulation approaches: from simplified [1] or 2D [16–18] methods to 3D methods in the integral or differential formulation [19]. Nevertheless, analytical solutions allow qualitative description of the field penetration mechanism, efficient assessment of the space and time limitations for computational models and selection of a discretization step on the FE mesh.

A significant number of the ITER conducting structures may be described with the use of thin-walled elements with the characteristic thickness much smaller than other their dimensions. For the qualitative description a set of analytical solutions are applied [9] for the magnetic field penetration through conducting sheets. For the first time the field penetration was analytically described through solving a thermo diffusion problem [10] for an infinite conducting layer (flat sheet) with a thickness d at the boundary conditions $B(0,t) = B_1(t)$, $B(d,t) = B_2(t)$ and the initial condition $B(x,0) = f(x)$. The field was assumed uniform. The axis X was directed inward the layer normally to its surface. The origin of coordinates was located on the surface. The simplest solution has a form

$$f(x) = B_0 \sin\left(\frac{\pi x}{d}\right), \quad B_1 = B_2 = 0 \Rightarrow B(x,t) = B_0 \sin\left(\frac{\pi x}{d}\right) \exp\left(-\frac{\pi^2 \rho_0 t}{\mu_0 d^2}\right)$$

subject to zeroed boundary conditions. In this case the field decay occurs without a spatial re-distribution. The characteristic decay time for the first harmonic $\boldsymbol{\tau_0}$ is derived as

$$\tau_0 = \frac{\mu_0 d^2}{\pi^2 \rho_0}$$

This relation corresponds to the asymptotic decay for any initial field distribution assuming zero external field. Higher harmonics tend to decay more rapidly. If the layer thickness is 60 mm, as is an example above, the decay time is:

$$\tau_0 = \frac{\mu_0 \times 36 \times 10^{-4}}{p2 \times 6 \times 10^{-7}} = 0.8\,\text{ms}.$$

It should be noted that for a constant field applied periodically or a pulsed field with a cyclic frequency ω [9,13], the analytical solutions for the field penetration in an infinite flat layer are typically presented in terms of the characteristic decay time τ_0 and characteristic thickness Δ_0. For this case a uniform field distribution is considered assuming the size of the field penetration area is much smaller than the characteristic dimension R_0 of a region of a variable external field. These solutions can be applied to confirm the validity of computational models or select a discretization level for FE meshing.

The penetrating field behaviour can be investigated using solutions for the field generated by current filaments (round turn, parallel conductors with counter currents, or thin flat loop) located in a plane parallel to a layer with the boundaries $x = 0$, $x = -d$. One can obtain an asymptotic decay of a tangential field $B_F(-d,t)$ [8] outward a layer as $t \to \infty$.

If the field penetration in the layer is much smaller than its thickness as well as the characteristic dimensions of a magnet system, the solution for a thin current loop located in the plane $x = h$ can be found via expansion of a small parameter $(\rho_0 t/\mu_0 d^2)$ and reduced to the principal term.

The tangential field beyond the layer at $t \to 0$ is expressed in terms of the field derivative $\partial \mathbf{b}_F(0)/\partial h$ calculated on the surface $x = 0$ for the loop with a unit current. For the instantaneous current jump from 0 to i_0

$$B_F(-d,t) = -8\frac{\partial \mathbf{b}_F(0)}{\partial h} i_0 \left(\frac{\rho_0 t}{\mu_0 d^2}\right)^{3/2} \frac{d}{\sqrt{\pi}} \exp\left(\frac{-\mu_0 d^2}{4\rho_0 t}\right)^2,$$

for the linear current increase $i = k_i t$;

$$B_F(-d,t) = -32\frac{\partial \mathbf{b}_F(0)}{\partial h} k_i t \left(\frac{\rho_0 t}{\mu_0 d^2}\right)^{5/2} \frac{d}{\sqrt{\pi}} \exp\left(\frac{-\mu_0 d^2}{4\rho_0 t}\right)^2.$$

In this case the characteristic decay time is determined by the relation

$$\frac{1}{\tau_a} = \frac{4\rho_0}{\mu_0 d^2}.$$

In concordance with [9], the field penetration through an infinite flat sheet can be considered. The sheet thickness is assumed much smaller than the characteristic dimension R_0 of the region with a variable external field. So, this assumption makes it possible to determine the current density through a single component δ_F parallel to the layer surface F. The normal field components are continuous at the boundary $B_{x1} = B_{x2}$, the tangent field components are determined by the condition $[\mathbf{n}_2, (\mathbf{B}_2 - \mathbf{B}_1)] = \mu_0 \int_0^d \delta_F\, dx = \mu_0 J_F$ (the square brackets are for a vector product).

Assuming instant appearance of an external field in the region 1 in front of the sheet, EM transients will be described in 3 stages.

The first stage occurs at $t \ll \tau_1 = \mu_0 d^2/\rho_0$. At this time the current is concentrated in a layer $\Delta < d$. The field beyond the sheet in the region 2 is much lower than in region 1. The field in the region 1