COMSOL MULTIPHYSICS

AC/DC MODULE

REFERENCE GUIDE

VERSION 3.4

COMSOL

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AC/DC Module Reference Guide

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Introduction

The AC/DC Module 3.4 is an optional package that extends the COMSOL Multiphysics™ modeling environment with customized user interfaces and functionality optimized for the analysis of electromagnetic effects, components, and systems. Like all modules in the COMSOL family, it provides a library of prewritten ready-to-run models that make it quicker and easier to analyze discipline-specific problems.

This particular module solves problems in the general areas of electrostatic fields, magnetostatic fields, and quasi-static fields. The application modes included here are fully multiphysics enabled, making it possible to couple them to any other physics application mode in COMSOL Multiphysics or the other modules. For example, to find the heat distribution in a motor you would first find the current in the coils using one of the quasi-static application modes in this module, and then couple it to a heat equation in the main COMSOL Multiphysics package or the Heat Transfer Module.

The underlying equations for electromagnetics are automatically available in all of the application modes—a feature unique to COMSOL Multiphysics. This also makes nonstandard modeling easily accessible.

The documentation set for the AC/DC Module consists of two printed books, the *AC/DC Module User's Guide* and the *AC/DC Module Model Library*, and this *AC/DC Module Reference Guide*. All three books are available in PDF and HTML versions from the COMSOL Help Desk. This book contains reference information such as application mode implementation details, information about command-line programming, and details about the command-line functions that are specific to the AC/DC Module (for example, functions for electromagnetic force computations and import of SPICE netlists).

Typographical Conventions

All COMSOL manuals use a set of consistent typographical conventions that should make it easy for you to follow the discussion, realize what you can expect to see on the screen, and know which data you must enter into various data-entry fields. In particular, you should be aware of these conventions:

- A **boldface** font of the shown size and style indicates that the given word(s) appear exactly that way on the COMSOL graphical user interface (for toolbar buttons in the corresponding tooltip). For instance, we often refer to the **Model Navigator**, which is the window that appears when you start a new modeling session in COMSOL; the corresponding window on the screen has the title **Model Navigator**. As another example, the instructions might say to click the **Multiphysics** button, and the boldface font indicates that you can expect to see a button with that exact label on the COMSOL user interface.
- The names of other items on the graphical user interface that do not have direct labels contain a leading uppercase letter. For instance, we often refer to the Draw toolbar; this vertical bar containing many icons appears on the left side of the user interface during geometry modeling. However, nowhere on the screen will you see the term "Draw" referring to this toolbar (if it were on the screen, we would print it in this manual as the **Draw** menu).
- The symbol **>** indicates a menu item or an item in a folder in the **Model Navigator**. For example, **Physics>Equation System>Subdomain Settings** is equivalent to: On the **Physics** menu, point to **Equation System** and then click **Subdomain Settings**. **COMSOL Multiphysics>Heat Transfer>Conduction** means: Open the **COMSOL Multiphysics** folder, open the **Heat Transfer** folder, and select **Conduction**.

- A `Code` (monospace) font indicates keyboard entries in the user interface. You might see an instruction such as "Type `1.25` in the **Current density** edit field." The monospace font also indicates COMSOL Script codes.
- An *italic* font indicates the introduction of important terminology. Expect to find an explanation in the same paragraph or in the Glossary. The names of books in the COMSOL documentation set also appear using an italic font.

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The Application Modes

The Application Mode Variables

The application modes in the AC/DC Module define a large set of variables. The purpose of this reference chapter is to list all the variables that each application mode define. Other information, like the theoretical background for the application mode, can be found in the chapter "The Application Modes" on page 127 of the *AC/DC Module User's Guide*.

The *application mode variables* listed in the following sections are all available in postprocessing and when formulating the equations. You can use any function of these variables when postprocessing the result of the analysis. It is also possible to use these variables in the expressions for the physical properties in the equations.

The application mode variable tables are organized as follows:

- The **Name** column lists the names of the variables that you can use in the expressions in the equations or for postprocessing. The indices *i* and *j* (using an italic font) in the variable names can mean any of the spatial coordinates. For example, E*i* means either Ex, Ey, Ez in 3D when the spatial coordinates are x, y, and z. In 2D axisymmetry E*i* stands for either Er or Ez. The variable names of vector and tensor components are constructed using the names of the spatial coordinates. For example, if you use x1, y1, and z1 as the spatial coordinate names, the variables for the vector components of the electric field are Ex1, Ey1, and Ez1.

  In a COMSOL Multiphysics model, the variable names get an underscore plus the application mode name appended to the names listed in the tables. For example, the default name of the Electrostatics application mode is emes. With this name the variable for the x component of the electric field is Ex_emes.
- The **Type** column indicates if the variable is defined on subdomains (S), boundaries (B), edges (E), or points (P). The column indicates the top level where the variables is defined. Many variables that are available on subdomains also exist on boundaries, edges, and points, but take the average value of the values in the subdomains around the boundary, edge, or point in question.
- The **Analysis** column specifies for which type of analysis the variable is defined. The available analysis types are, for example, static, transient, harmonic, and eigenfrequency. The available analysis types are application-mode dependent. Some variables are defined differently depending on the analysis type, and others are only available for some analysis types.

- The **Constitutive Relation** column indicates the constitutive relation for which the variable definition applies. The abbreviations used are defined in the table below.

ABBREVIATION	CONSTITUTIVE RELATION
epsr	$\mathbf{D} = \varepsilon_0\varepsilon_r\mathbf{E}$
P	$\mathbf{D} = \varepsilon_0\mathbf{E} + \mathbf{P}$
Dr	$\mathbf{D} = \varepsilon_0\varepsilon_r\mathbf{E} + \mathbf{D}_r$
mur	$\mathbf{B} = \mu_0\mu_r\mathbf{H}$
M	$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$
Br	$\mathbf{B} = \mu_0\mu_r\mathbf{H} + \mathbf{B}_r$

- The **Material Parameters** column appears in the tables for the electromagnetic waves application modes. It indicates if the refractive index n or the relative permeability ε_r, the conductivity σ, and the relative permeability μ_r are used as material parameters in the expression for the variable.
- The **Description** column gives a description of the variables.
- The **Expression** column gives the expression of the variables in terms of other physical quantities. In these expressions, the subscripts i and j of vector and tensor components stand for one of the spatial coordinates. For example, E_i is either E_x, E_y, or E_z. When two equal subscripts appear in an expression this implies a summation. For example $\sigma_{ij}E_j = \sigma_{ix}E_x + \sigma_{iy}E_y + \sigma_{iz}E_z$.

Common Variables

There are a couple of variables that the application modes share. These variables are listed in the tables below. In some cases, the variables only exist when a certain boundary condition or application mode property has been selected.

See page 6 for a description of the notation used in the tables.

APPLICATION SCALAR VARIABLES

There are no common scalar variables, see the corresponding section for application modes.

APPLICATION SUBDOMAIN VARIABLES

The common subdomain variables are given the table below.

TABLE 2-1: COMMON APPLICATION MODE SUBDOMAIN VARIABLES

NAME	DIMENSION	DESCRIPTION	EXPRESSION
d	2D	thickness	d
dr_guess		default guess for width in radial direction of infinite element domain	Δ_r
R0_guess		default guess for inner radius of infinite element domain	R_0
S*i*		infinite element x_i coordinate	s_i
S0*i*_guess		default guess for inner x_i coordinate of infinite element domain	S_{0i}
Sd*i*_guess		default guess for width along x_i coordinate of infinite element domain	Δ_i
dVol		Volume integration contribution	dV

APPLICATION BOUNDARY VARIABLES

The common boundary variables are given the table below.

TABLE 2-2: COMMON APPLICATION MODE BOUNDARY VARIABLES

NAME	DESCRIPTION	EXPRESSION
dbnd	boundary thickness	d_{bnd}
dVolbnd	Area integration contribution	dA

Electrostatic Fields

A number of variables and physical quantities are available for postprocessing and for use in equations and boundary conditions. They are all given in the following tables.

See page 6 for a description of the notation used in these tables. The "up" and "down" subscripts indicate that the variable should be evaluated on the geometrical up or down side of the boundary.

Conductive Media DC Application Mode

The fundamental fields that can be derived from the electric potential are available for postprocessing and for use in equations and boundary conditions.

APPLICATION MODE SUBDOMAIN VARIABLES

The subdomain variables for Conductive Media DC are given the table below.

TABLE 2-3: APPLICATION MODE SUBDOMAIN VARIABLES, CONDUCTIVE MEDIA DC

NAME	DESCRIPTION	EXPRESSION
V	electric potential	V
sigma	electric conductivity	σ
sigma*ij*	electric conductivity, $x_i x_j$ component	σ_{ij}
Qj	current source	Q_j
d	thickness	d
Je*i*	external current density, x_i component	J_i^e
normJe	external current density, norm	$\sqrt{\mathbf{J}^e \cdot \mathbf{J}^e}$
Ji*i*	potential current density, x_i component	$\sigma_{ij} E_j$
normJi	potential current density, norm	$\sqrt{\mathbf{J}^i \cdot \mathbf{J}^i}$
J*i*	total current density, x_i component	$J_i^e + J_i^i$
normJ	total current density, norm	$\sqrt{\mathbf{J} \cdot \mathbf{J}}$
E*i*	electric field, x_i component	$-\frac{\partial V}{\partial x_i}$

TABLE 2-3: APPLICATION MODE SUBDOMAIN VARIABLES, CONDUCTIVE MEDIA DC

NAME	DESCRIPTION	EXPRESSION
normE	electric field, norm	$\sqrt{\mathbf{E} \cdot \mathbf{E}}$
Q	resistive heating	$\mathbf{J} \cdot \mathbf{E}$

APPLICATION BOUNDARY VARIABLES

The boundary variables for Conductive Media DC are given in the table below.

TABLE 2-4: APPLICATION MODE BOUNDARY VARIABLES, CONDUCTIVE MEDIA DC

NAME	DESCRIPTION	EXPRESSION
tE*i*	tangential electric field, x_i component	$-\mathbf{t}_i \cdot \nabla_t V$
normtE	tangential electric field, norm	$\sqrt{t\mathbf{E} \cdot t\mathbf{E}}$
nJ	current density outflow	$\mathbf{n} \cdot \mathbf{J}$
nJs	source current density	$\mathbf{n}_{\mathrm{up}} \cdot (\mathbf{J}_{\mathrm{down}} - \mathbf{J}_{\mathrm{up}})$
Js*i*	surface current density, x_i component	$d\sigma t E_i$
normJs	surface current density, norm	$\sqrt{\mathbf{J}_s \cdot \mathbf{J}_s}$
sigmabnd	electric conductivity on boundary	σ_{bnd}
Qs	surface resistive heating	$\mathbf{J}_s \cdot t\mathbf{E}$
Qjl	line current source	Q_{jl}
Qj0	point current source	Q_{j0}

APPLICATION POINT VARIABLES

The point variable for the Conductive Media DC application mode appears in the following table.

TABLE 2-5: APPLICATION MODE POINT VARIABLES, CONDUCTIVE MEDIA DC

NAME	TYPE	DESCRIPTION	EXPRESSION
Qj0	P	Point current source	Q_{j0}

Shell, Conductive Media DC Application Mode

For application mode variables see the section “Conductive Media DC Application Mode” on page 9.

The fundamental fields that can be derived from the electric potential are available for postprocessing and for use in equations and boundary conditions.

APPLICATION MODE SCALAR VARIABLES

The application-specific scalar variable in this mode is given in the following table.

TABLE 2-6: APPLICATION MODE SCALAR VARIABLES, ELECTROSTATICS,

NAME	DESCRIPTION	EXPRESSION
epsilon0	permittivity of vacuum	ε_0

APPLICATION MODE SUBDOMAIN VARIABLES

The subdomain variables for Electrostatics are given the table below.

TABLE 2-7: APPLICATION MODE SUBDOMAIN VARIABLES, ELECTROSTATICS,

NAME	CONSTITUTIVE RELATION	DESCRIPTION	EXPRESSION
V		electric potential	V
epsilonr	epsr, Dr	relative permittivity	ε_r
epsilonr	P	relative permittivity	1
epsilonr*ij*	epsr, Dr	relative permittivity, x_ix_j component	ε_{rij}
epsilonr*ij*	P	relative permittivity, x_ix_j component	1
epsilon		permittivity	$\varepsilon_0\varepsilon_r$
epsilon*ij*		permittivity, x_ix_j component	$\varepsilon_0\varepsilon_{rij}$
P*i*	P	electric polarization, x_i component	P_i
P*i*	epsr, Dr	electric polarization, x_i component	$D_i - \varepsilon_0 E_i$
normP		electric polarization, norm	$\sqrt{\mathbf{P}\cdot\mathbf{P}}$
Dr*i*	epsr	remanent displacement, x_i component	0
Dr*i*	P	remanent displacement, x_i component	P_i
Dr*i*	Dr	remanent displacement, x_i component	D_{ri}
normDr		remanent displacement, norm	$\sqrt{\mathbf{D}_\mathrm{r}\cdot\mathbf{D}_\mathrm{r}}$
rho		space charge density	ρ

TABLE 2-7: APPLICATION MODE SUBDOMAIN VARIABLES, ELECTROSTATICS,

NAME	CONSTITUTIVE RELATION	DESCRIPTION	EXPRESSION
E*i*		electric field, x_i component	$-\frac{\partial V}{\partial x_i}$
normE		electric field, norm	$\sqrt{\mathbf{E}\cdot\mathbf{E}}$
D*i*	epsr	electric displacement, x_i component	$\varepsilon_0\varepsilon_{rij}E_j$
D*i*	P	electric displacement, x_i component	$\varepsilon_0 E_i + P_i$
D*i*	Dr	electric displacement, x_i component	$\varepsilon_0\varepsilon_{rij}E_j + D_{ri}$
normD		electric displacement, norm	$\sqrt{\mathbf{D}\cdot\mathbf{D}}$
We		electric energy density	$\frac{\mathbf{E}\cdot\mathbf{D}}{2}$

APPLICATION BOUNDARY VARIABLES

The boundary variables for Electrostatics are given in the table below.

TABLE 2-8: APPLICATION MODE BOUNDARY VARIABLES, ELECTROSTATICS,

NAME	DESCRIPTION	EXPRESSION
nD	surface charge density	$\mathbf{n}_{\mathrm{up}}\cdot(\mathbf{D}_{\mathrm{down}} - \mathbf{D}_{\mathrm{up}})$
epsilonbnd	relative permittivity on boundary	$\varepsilon_{\mathrm{bnd}}$
unT*i*	Maxwell surface stress tensor, x_i component, up side of boundary	$-\frac{1}{2}(\mathbf{E}_{\mathrm{up}}\cdot\mathbf{D}_{\mathrm{up}})n_{i\mathrm{down}} + (\mathbf{n}_{\mathrm{down}}\cdot\mathbf{D}_{\mathrm{up}})E_{i\mathrm{up}}$
dnT*i*	Maxwell surface stress tensor, x_i component, down side of boundary	$-\frac{1}{2}(\mathbf{E}_{\mathrm{down}}\cdot\mathbf{D}_{\mathrm{down}})n_{i\mathrm{up}} + (\mathbf{n}_{\mathrm{up}}\cdot\mathbf{D}_{\mathrm{down}})E_{i\mathrm{down}}$
unTE*i*	electric Maxwell surface stress tensor, x_i component, up side of boundary	$-\frac{1}{2}(\mathbf{E}_{\mathrm{up}}\cdot\mathbf{D}_{\mathrm{up}})n_{i\mathrm{down}} + (\mathbf{n}_{\mathrm{down}}\cdot\mathbf{D}_{\mathrm{up}})E_{i\mathrm{up}}$
dnTE*i*	electric Maxwell surface stress tensor, x_i component, down side of boundary	$-\frac{1}{2}(\mathbf{E}_{\mathrm{down}}\cdot\mathbf{D}_{\mathrm{down}})n_{i\mathrm{up}} + (\mathbf{n}_{\mathrm{up}}\cdot\mathbf{D}_{\mathrm{down}})E_{i\mathrm{down}}$

APPLICATION EDGE VARIABLES

The edge variable for Electrostatics appears in the following table:

TABLE 2-9: APPLICATION MODE EDGE VARIABLES, ELECTROSTATICS,

NAME	DESCRIPTION	EXPRESSION
Ql	line charge density	Q_1

APPLICATION POINT VARIABLES

The point variable for Electrostatics appears in the following table:

TABLE 2-10: APPLICATION MODE POINT VARIABLES, ELECTROSTATICS,

NAME	DESCRIPTION	EXPRESSION
Q0	charge	Q_0

Electrostatics, Generalized Application Mode

The fundamental fields that can be derived from the electric potential are available for postprocessing and for use in equations and boundary conditions.

APPLICATION MODE SCALAR VARIABLES

The application-specific variables in this mode are given in the following table.

TABLE 2-11: APPLICATION MODE SCALAR VARIABLES, ELECTROSTATICS, GENERALIZED

NAME	DESCRIPTION	EXPRESSION
epsilon0	permittivity of vacuum	ε_0
mu0	permeability of vacuum	μ_0
T	time constant	T

APPLICATION MODE SUBDOMAIN VARIABLES

The subdomain variables for Electrostatics, Generalized are given the table below.

TABLE 2-12: APPLICATION MODE SUBDOMAIN VARIABLES, ELECTROSTATICS, GENERALIZED

NAME	CONST. REL.	DESCRIPTION	EXPRESSION
V		electric potential	V
epsilon0		permittivity of vacuum	ε_0
mu0		permeability of vacuum	μ_0
T		time constant	T
sigma		electric conductivity	σ
sigma`ij`		electric conductivity, x_ix_j component	σ_{ij}

TABLE 2-12: APPLICATION MODE SUBDOMAIN VARIABLES, ELECTROSTATICS, GENERALIZED

NAME	CONST. REL.	DESCRIPTION	EXPRESSION
epsilonr	epsr, Dr	relative permittivity	ε_r
epsilonr	P	relative permittivity	1
epsilonr*ij*	epsr, Dr	relative permittivity, $x_i x_j$ component	$\varepsilon_{\mathrm{r}ij}$
epsilonr*ij*	P	relative permittivity, $x_i x_j$ component	1
epsilon		permittivity	$\varepsilon_0\varepsilon_\mathrm{r}$
epsilon*ij*		permittivity, $x_i x_j$ component	$\varepsilon_0\varepsilon_{\mathrm{r}ij}$
Je*i*		external current density, x_i component	J_i^e
normJe		external current density, norm	$\sqrt{\mathbf{J}^e\cdot\mathbf{J}^e}$
Ji*i*		potential current density, x_i component	$\sigma_{ij}E_j$
normJi		potential current density, norm	$\sqrt{\mathbf{J}^i\cdot\mathbf{J}^i}$
J*i*		total current density, x_i component	$J_i^e + J_i^i$
normJ		total current density, norm	$\sqrt{\mathbf{J}\cdot\mathbf{J}}$
P*i*	P	electric polarization, x_i component	P_i
P*i*	epsr, Dr	electric polarization, x_i component	$D_i - \varepsilon_0 E_i$
normP		electric polarization, norm	$\sqrt{\mathbf{P}\cdot\mathbf{P}}$
Dr*i*	epsr	remanent displacement, x_i component	0
Dr*i*	P	remanent displacement, x_i component	P_i
Dr*i*	Dr	remanent displacement, x_i component	$D_{\mathrm{r}i}$
normDr		remanent displacement, norm	$\sqrt{\mathbf{D}_\mathrm{r}\cdot\mathbf{D}_\mathrm{r}}$
rho0		space charge density	ρ_0
E*i*		electric field, x_i component	$-\frac{\partial V}{\partial x_i}$
normE		electric field, norm	$\sqrt{\mathbf{E}\cdot\mathbf{E}}$
D*i*	epsr	electric displacement, x_i component	$\varepsilon_0\varepsilon_{\mathrm{r}ij}E_j$
D*i*	P	electric displacement, x_i component	$\varepsilon_0 E_i + P_i$

TABLE 2-12: APPLICATION MODE SUBDOMAIN VARIABLES, ELECTROSTATICS, GENERALIZED

NAME	CONST. REL.	DESCRIPTION	EXPRESSION
D*i*	Dr	electric displacement, x_i component	$\varepsilon_0\varepsilon_{rij}E_j + D_{ri}$
normD		electric displacement, norm	$\sqrt{\mathbf{D}\cdot\mathbf{D}}$
We		electric energy density	$\frac{\mathbf{E}\cdot\mathbf{D}}{2}$
Q		resistive heating	$\mathbf{J}\cdot\mathbf{E}$

APPLICATION MODE BOUNDARY VARIABLES

The boundary variables for Electrostatics, Generalized are given the table below.

TABLE 2-13: APPLICATION MODE BOUNDARY VARIABLES, ELECTROSTATICS, GENERALIZED

NAME	DESCRIPTION	EXPRESSION
nD	surface charge density	$\mathbf{n}_{\mathrm{up}}\cdot(\mathbf{D}_{\mathrm{down}} - \mathbf{D}_{\mathrm{up}})$
nJ	current density outflow	$\mathbf{n}\cdot\mathbf{J}$

APPLICATION MODE EDGE VARIABLES

The edge variables for Electrostatics, Generalized are given the table below.

TABLE 2-14: APPLICATION MODE EDGE VARIABLES, ELECTROSTATICS, GENERALIZED

NAME	DESCRIPTION	EXPRESSION
Ql	line charge density	Q_{l}
Qjl	line current source	$Q_{j\mathrm{l}}$

APPLICATION MODE POINT VARIABLES

The point variables for Electrostatics, Generalized are given the table below.

TABLE 2-15: APPLICATION MODE POINT VARIABLES, ELECTROSTATICS, GENERALIZED

NAME	DESCRIPTION	EXPRESSION
Q0	charge	Q_0
Qj0	point current source	Q_{j0}

Magnetostatic and Quasi-Static Fields

3D and 2D Quasi-Statics Application Modes

APPLICATION MODE VARIABLES

The fundamental fields that can be derived from the electric potential are available for postprocessing and for use in equations and boundary conditions.

In the expressions containing the electric potential, set this potential to zero if it is not a dependent variable.

See page 6 for a description of the notation used in this table.

APPLICATION MODE SCALAR VARIABLES

The application-specific variables in this mode are given in the following table.

TABLE 2-16: APPLICATION MODE SCALAR VARIABLES, 2D AND 3D QUASI-STATICS

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
nu	harmonic	frequency	ν
omega	harmonic	angular frequency	$2\pi\nu$
epsilon0		permittivity of vacuum	ε_0
mu0		permeability of vacuum	μ_0
psi0	gauge fixing on	scaling for gauge fixing variable	ψ_0

APPLICATION MODE SUBDOMAIN VARIABLES

The subdomain variables for 2D and 3D Quasi-Statics are given the table below.

TABLE 2-17: APPLICATION MODE SUBDOMAIN VARIABLES, 2D AND 3D QUASI-STATICS

NAME	DIMENSION	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
V	2D, 3D			electric potential	V
A*i*	2D, 3D			magnetic potential, x_i component	$\mathbf{A}_i$
curlA*i*	3D, 2D			curl of magnetic potential, x_i component	$(\nabla\times\mathbf{A})_i$

TABLE 2-17: APPLICATION MODE SUBDOMAIN VARIABLES, 2D AND 3D QUASI-STATICS

NAME	DIMENSION	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
mur	2D, 3D		mur, Br	relative permeability	μ_r
mur	2D, 3D		M	relative permeability	1
mur*ij*	3D		mur, Br	relative permeability, x_ix_j component	μ_{rij}
mur*ij*	3D		M	relative permeability, x_ix_j component	1
mu	2D, 3D			permeability	$\mu_0\mu_r$
mu*ij*	3D			permeability, x_ix_j component	$\mu_0\mu_{rij}$
epsilonr	2D, 3D	harmonic	epsr, Dr	relative permittivity	ε_r
epsilonr	2D, 3D	harmonic	P	relative permittivity	1
epsilonr*ij*	2D, 3D	harmonic	epsr, Dr	relative permittivity, x_ix_j component	ε_{rij}
epsilonr*ij*	2D, 3D	harmonic	P	relative permittivity, x_ix_j component	1
epsilon	2D, 3D	harmonic		permittivity	$\varepsilon_0\varepsilon_r$
epsilon*ij*	2D, 3D	harmonic		permittivity, x_ix_j component	$\varepsilon_0\varepsilon_{rij}$
sigma	2D, 3D	transient, harmonic, static, electric potential		electric conductivity	σ
sigma*ij*	2D, 3D	transient, harmonic, static, electric potential		electric conductivity, x_ix_j component	σ_{ij}
delta	2D, 3D	harmonic		skin depth	$\dfrac{1}{\omega\sqrt{\frac{1}{2}\mu\varepsilon\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right)}}$

TABLE 2-17: APPLICATION MODE SUBDOMAIN VARIABLES, 2D AND 3D QUASI-STATICS

NAME	DIMENSION	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
P*i*	2D, 3D	harmonic	P	electric polarization, x_i component	$P_i e^{j\text{phase}}$
P*i*	2D, 3D	harmonic	epsr, Dr	electric polarization, x_i component	$D_i - \varepsilon_0 E_i$
normP	2D, 3D	harmonic		polarization, norm	$\sqrt{\mathbf{P} \cdot \mathbf{P}^*}$
Dr*i*	2D, 3D	harmonic	epsr	remanent displacement, x_i component	0
Dr*i*	2D, 3D	harmonic	P	remanent displacement, x_i component	P_i
Dr*i*	2D, 3D	harmonic	Dr	remanent displacement, x_i component	$D_{ri} e^{j\text{phase}}$
normDr	2D, 3D	harmonic		remanent displacement, norm	$\sqrt{\mathbf{D}_r \cdot \mathbf{D}_r^*}$
M*i*	3D	static, transient	M	magnetization, x_i component	M_i
M*i*	3D	harmonic	M	magnetization, x_i component	$M_i e^{j\text{phase}}$
M*i*	3D		mur, Br	magnetization, x_i component	$B_i/\mu_0 - H_i$
normM	3D			magnetization, norm	$\sqrt{\mathbf{M} \cdot \mathbf{M}^*}$
M*i*	2D	static, transient	M	magnetization, x_i out of plane component	M_i
M*i*	2D	harmonic	M	magnetization, x_i out of plane component	$M_i e^{j\text{phase}}$
M*i*	2D		mur, Br	magnetization, x_i out of plane component	$B_i/\mu_0 - H_i$

TABLE 2-17: APPLICATION MODE SUBDOMAIN VARIABLES, 2D AND 3D QUASI-STATICS

NAME	DIMENSION	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
normM	2D			magnetization, norm	$\lvert M_i \rvert$
Br*i*	3D		mur	remanent flux density, x_i component	0
Br*i*	3D		M	remanent flux density, x_i component	$\mu_0 M_i$
Br*i*	3D	static, transient	Br	remanent flux density, x_i component	$B_{\mathrm{r}i}$
Br*i*	3D	harmonic	Br	remanent flux density, x_i component	$B_{\mathrm{r}i} e^{j\,\mathrm{phase}}$
normBr	3D			remanent flux density, norm	$\sqrt{\mathbf{B}_\mathrm{r} \cdot \mathbf{B}_\mathrm{r}^*}$
Br*i*	3D		M	remanent flux density, x_i out of plane component	$\mu_0 M_i$
Br*i*	3D	static, transient	Br	remanent flux density, x_i out of plane component	$B_{\mathrm{r}i}$
Br*i*	3D	harmonic	Br	remanent flux density, x_i out of plane component	$B_{\mathrm{r}i} e^{j\,\mathrm{phase}}$
normBr	2D			remanent flux density, norm	$\lvert B_\mathrm{r} \rvert$
Je*i*	3D, 2D	static, transient		external current density, x_i component	J_i^e
Je*i*	3D, 2D	harmonic		external current density, x_i component	$J_i^e e^{j\,\mathrm{phase}}$
normJe	3D, 2D			external current density, norm	$\sqrt{\mathbf{J}^e \cdot \mathbf{J}^{e\,*}}$
v*i*	3D, 2D	electric potential		velocity, x_i component	v_i

TABLE 2-17: APPLICATION MODE SUBDOMAIN VARIABLES, 2D AND 3D QUASI-STATICS

NAME	DIMENSION	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
normv	3D, 2D	electric potential		velocity, norm	$\sqrt{\mathbf{v}\cdot\mathbf{v}}$
Ei	3D, 2D	harmonic		electric field, x_i component	$-j\omega A_i-\frac{\partial V}{\partial x_i}$
Ei	3D, 2D	transient		electric field, x_i component	$-\frac{\partial A_i}{\partial t}$
Ei	3D, 2D	static, electric potential		electric field, x_i component	$-\frac{\partial V}{\partial x_i}$
normE	3D, 2D			electric field, norm	$\sqrt{\mathbf{E}\cdot\mathbf{E}^*}$
Di	3D, 2D	harmonic	epsr	electric displacement, x_i component	$\varepsilon_0\varepsilon_{\mathrm{r}ij}E_j$
Di	3D, 2D	harmonic	P	electric displacement, x_i component	$\varepsilon_0 E_i+P_i$
Di	3D, 2D	harmonic	Dr	electric displacement, x_i component	$\varepsilon_0\varepsilon_{\mathrm{r}ij}E_j+D_{\mathrm{r}i}$
normD	3D, 2D	harmonic		electric displacement, norm	$\sqrt{\mathbf{D}\cdot\mathbf{D}^*}$
Bi	3D			magnetic flux density, x_i component	$(\nabla\times\mathbf{A})_i$
normB	3D			magnetic flux density, norm	$\sqrt{\mathbf{B}\cdot\mathbf{B}^*}$
Bi	2D			magnetic flux density, x_i out of plane component	$(\nabla\times\mathbf{A})_i$
normB	2D			magnetic flux density, norm	$\lvert B_i\rvert$
Hi	3D		mur	magnetic field, x_i component	$\mu_{\mathrm{r}ij}^{-1}B_j/\mu_0$
Hi	3D		M	magnetic field, x_i component	B_i/μ_0-M_i

TABLE 2-17: APPLICATION MODE SUBDOMAIN VARIABLES, 2D AND 3D QUASI-STATICS

NAME	DIMENSION	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
H*i*	3D		Br	magnetic field, x_i component	$\mu_{rij}^{-1}(B_j - B_{rj})/\mu_0$
normH	3D			magnetic field, norm	$\sqrt{\mathbf{H} \cdot \mathbf{H}^*}$
H*i*	2D		mur	magnetic field, x_i out of plane component	$\mu_r^{-1}B_i/\mu_0$
H*i*	2D		M	magnetic field, x_i out of plane component	$B_i/\mu_0 - M_i$
H*i*	2D		Br	magnetic field, x_i out of plane component	$\mu_r^{-1}(B_i - B_{ri})/\mu_0$
normH	2D			magnetic field, norm, x_i out of plane component	$\lvert H_i \rvert$
Ji*i*	3D, 2D	harmonic		induced current density, x_i component	$-j\omega\sigma_{ij}A_j$
normJi	3D, 2D	harmonic		induced current density, norm	$\sqrt{\mathbf{J}^i \cdot \mathbf{J}^{i*}}$
Ji*i*	3D, 2D	transient		induced current density, x_i component	$\sigma_{ij}E_j$
normJi	3D, 2D	transient		induced current density, norm	$\sqrt{\mathbf{J}^i \cdot \mathbf{J}^i}$
Jd*i*	3D, 2D	harmonic		displacement current density, x_i component	$j\omega D_i$
normJd	3D, 2D	harmonic		displacement current density, norm	$\sqrt{\mathbf{J}^d \cdot \mathbf{J}^{d*}}$
Jp*i*	3D, 2D	electric potential		potential current density, x_i component	$-\sigma_{ij}\frac{\partial V}{\partial x_j}$
normJp	3D, 2D	electric potential		potential current density, norm	$\sqrt{\mathbf{J}^p \cdot \mathbf{J}^{p*}}$

TABLE 2-17: APPLICATION MODE SUBDOMAIN VARIABLES, 2D AND 3D QUASI-STATICS

NAME	DIMENSION	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
Jv*i*	3D, 2D	electric potential		velocity current density, x_i component	$\sigma_{ij}(\mathbf{v}\times\mathbf{B})_j$
normJv	3D, 2D	electric potential		velocity current density, norm	$\sqrt{\mathbf{J}^v\cdot\mathbf{J}^{v*}}$
J*i*	3D, 2D	static, electric potential		total current density, x_i component	$J_i^e+J_i^v+J_i^p$
J*i*	3D, 2D	static		total current density, x_i component	J_i^e
J*i*	3D, 2D	transient		total current density, x_i component	$J_i^e+J_i^i$
J*i*	3D, 2D	harmonic, electric potential		total current density, x_i component	$J_i^e+J_i^v+J_i^p+J_i^i+J_i^d$
J*i*	3D, 2D	harmonic		total current density, x_i component	$J_i^e+J_i^i+J_i^d$
normJ	3D, 2D			total current density, norm	$\sqrt{\mathbf{J}\cdot\mathbf{J}^*}$
Ev*i*	3D, 2D	electric potential		Lorentz electric field, x_i component	$(\mathbf{v}\times\mathbf{B})_i$
normEv	3D, 2D	electric potential		Lorentz electric field, norm	$\sqrt{\mathbf{E}_v\cdot\mathbf{E}_v{}^*}$
Gf*i*	3D, 2D	static, harmonic		gauge fixed field, x_i component	$\mathbf{A}$
Gf*i*	3D, 2D	transient		gauge fixed field, x_i component	$\sigma\mathbf{A}$
Weav	3D, 2D	harmonic		time average electric energy density	$\mathrm{Re}\left(\frac{\mathbf{D}\cdot\mathbf{E}^*}{4}\right)$
Wm	3D, 2D	static		magnetic energy density	$\frac{\mathbf{H}\cdot\mathbf{B}}{2}$

TABLE 2-17: APPLICATION MODE SUBDOMAIN VARIABLES, 2D AND 3D QUASI-STATICS

NAME	DIMENSION	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
Wmav	3D, 2D	harmonic		time average magnetic energy density	$\frac{1}{4}\mathrm{Re}(\mathbf{H}\cdot\mathbf{B}^*)$
Wav	3D, 2D	harmonic		time average total energy density	$W_\mathrm{e}^\mathrm{av}+W_\mathrm{m}^\mathrm{av}$
Q	3D, 2D	static, electric potential		resistive heating	$\mathbf{J}\cdot(\mathbf{E}+\mathbf{v}\times\mathbf{B}+\sigma^{-1}\mathbf{J}^e)$
Q	3D, 2D	transient		resistive heating	$\mathbf{J}\cdot(\mathbf{E}+\sigma^{-1}\mathbf{J}^e)$
Qav	3D, 2D	harmonic, electric potential		time average resistive heating	$\frac{1}{2}\mathrm{Re}(\mathbf{J}\cdot(\mathbf{E}^*+\mathbf{v}\times\mathbf{B}^*+\sigma^{-1}\mathbf{J}^{e*}))$
Qav	3D, 2D	harmonic		time average resistive heating	$\frac{1}{2}\mathrm{Re}(\mathbf{J}\cdot(\mathbf{E}^*+\sigma^{-1}\mathbf{J}^{e*}))$
Po`i`	3D, 2D	static, electric potential		power flow, x_i component	$(\mathbf{E}\times\mathbf{H})_i$
normPo	3D, 2D	static, electric potential		power flow, norm	$\sqrt{\mathbf{S}\cdot\mathbf{S}^*}$
Po`i`av	3D, 2D	harmonic		time average power flow, x_i component	$\frac{1}{2}\mathrm{Re}(\mathbf{E}\times\mathbf{H}^*)_i$
normPoav	3D, 2D	harmonic		time average power flow, norm	$\sqrt{\mathbf{S}^\mathrm{av}\cdot\mathbf{S}^{\mathrm{av}*}}$

APPLICATION MODE BOUNDARY VARIABLES

The boundary variables for 2D and 3D Quasi-Statics are given the table below.

TABLE 2-18: APPLICATION MODE BOUNDARY VARIABLES, 2D AND 3D QUASI-STATICS

NAME	DIMENSION	ANALYSIS	DESCRIPTION	EXPRESSION
Js`i`	3D, 2D		surface current density, x_i component	$\mathbf{n}_\mathrm{up}\times(\mathbf{H}_\mathrm{down}-\mathbf{H}_\mathrm{up})$
normJs	3D, 2D		surface current density, norm	$\sqrt{\mathbf{J}_s\cdot\mathbf{J}_s^*}$
nJ	3D, 2D	electric potential	normal current density	$\mathbf{n}\cdot\mathbf{J}$
nJs	3D, 2D	electric potential	source current density	$\mathbf{n}_\mathrm{up}\cdot(\mathbf{J}_\mathrm{down}-\mathbf{J}_\mathrm{up})$

TABLE 2-18: APPLICATION MODE BOUNDARY VARIABLES, 2D AND 3D QUASI-STATICS

NAME	DIMENSION	ANALYSIS	DESCRIPTION	EXPRESSION
sigmabnd	3D, 2D	static, harmonic	conductivity on boundaries	σ_{bnd}
epsilonrbnd	3D, 2D	harmonic	permittivity on boundaries	$\varepsilon_{\mathrm{rbnd}}$
murbnd	3D, 2D	harmonic	permeability on boundaries	μ_{rbnd}
tE*i*	3D, 2D	electric potential	tangential electric field, x_i component	$-\mathbf{t}_i \cdot \nabla_t V$
normtE	3D, 2D	electric potential	tangential electric field, norm	$\sqrt{t\mathbf{E} \cdot t\mathbf{E}^*}$
tD*i*	3D, 2D	electric potential	tangential electric displacement, x_i component	tE_i
normtD	3D, 2D	electric potential	tangential electric displacement, norm	$\sqrt{t\mathbf{D} \cdot t\mathbf{D}^*}$
Qs	3D, 2D	transient	surface resistive heating	$\mathbf{J}_{\mathrm{s}} \cdot \mathbf{E}$
Qsav	3D, 2D	harmonic	time average surface resistive heating	$\frac{1}{2}\mathrm{Re}(\mathbf{J}_s \cdot \mathbf{E}^*)$
nPo	3D, 2D	static, electric potential	power outflow	$\mathbf{n} \cdot \mathbf{S}$
nPoav	3D, 2D	harmonic	time average power outflow	$\mathbf{n} \cdot \mathbf{S}^{\mathrm{av}}$
deltabnd	3D, 2D	harmonic, impedance cond.	skin depth	$\dfrac{1}{\omega\sqrt{\frac{1}{2}\mu\varepsilon\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right)}}$
unT*i*	3D,	static, transient	Maxwell surface stress tensor, x_i component, up side of boundary	$-\frac{1}{2}(\mathbf{H}_{\mathrm{up}} \cdot \mathbf{B}_{\mathrm{up}})n_{i\mathrm{down}} + (\mathbf{n}_{\mathrm{down}} \cdot \mathbf{H}_{\mathrm{up}})B_{i\mathrm{up}}$
dnT*i*	3D	static, transient	Maxwell surface stress tensor, x_i component, down side of boundary	$-\frac{1}{2}(\mathbf{H}_{\mathrm{down}} \cdot \mathbf{B}_{\mathrm{down}})n_{i\mathrm{up}} + (\mathbf{n}_{\mathrm{up}} \cdot \mathbf{H}_{\mathrm{down}})B_{i\mathrm{down}}$

TABLE 2-18: APPLICATION MODE BOUNDARY VARIABLES, 2D AND 3D QUASI-STATICS

NAME	DIMENSION	ANALYSIS	DESCRIPTION	EXPRESSION
unT*i*av	3D	harmonic	Maxwell surface stress tensor, x_i component, up side of boundary	$-\frac{1}{4}\mathrm{Re}(\mathbf{H}_{\mathrm{up}}\cdot\mathbf{B}^*_{\mathrm{up}})n_{i\mathrm{down}} + \frac{1}{2}\mathrm{Re}((\mathbf{n}_{\mathrm{down}}\cdot\mathbf{H}_{\mathrm{up}})B^*_{i\mathrm{up}})$
dnT*i*av	3D	harmonic	Maxwell surface stress tensor, x_i component, down side of boundary	$-\frac{1}{4}\mathrm{Re}(\mathbf{H}_{\mathrm{down}}\cdot\mathbf{B}^*_{\mathrm{down}})n_{i\mathrm{up}} + \frac{1}{2}\mathrm{Re}((\mathbf{n}_{\mathrm{up}}\cdot\mathbf{H}_{\mathrm{down}})B^*_{i\mathrm{down}})$
unT*i*	2D	static, transient	Maxwell surface stress tensor, x_i out of plane component, up side of boundary	$-\frac{1}{2}H_{i\mathrm{up}}B_{i\mathrm{up}}n_{i\mathrm{down}}$
dnT*i*	2D	static, transient	Maxwell surface stress tensor, x_i out of plane component, down side of boundary	$-\frac{1}{2}H_{i\mathrm{down}}B_{i\mathrm{down}}n_{i\mathrm{up}}$
unT*i*av	2D	harmonic	Maxwell surface stress tensor, x_i out of plane component, up side of boundary	$-\frac{1}{4}\mathrm{Re}(H_{i\mathrm{up}}\cdot B_{i\mathrm{up}})n_{i\mathrm{down}}$
dnT*i*av	2D	harmonic	Maxwell surface stress tensor, x_i out of plane component, down side of boundary	$-\frac{1}{4}\mathrm{Re}(H_{i\mathrm{down}}\cdot B_{i\mathrm{down}})n_{i\mathrm{up}}$

The Electric Currents Application Mode

The fundamental fields that can be derived from the electric potential are available for postprocessing and for use in equations and boundary conditions.

See page 6 for a description of the notation used in this table.

APPLICATION MODE SCALAR VARIABLES

The application-specific variables in this mode are given in the following table.

TABLE 2-19: APPLICATION MODE SCALAR VARIABLES, ELECTRIC CURRENTS

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
nu	harmonic	Frequency	ν
omega	harmonic	Angular frequency	$2\pi\nu$
epsilon0		Permittivity of vacuum	ε_0
mu0		Permeability of vacuum	μ_0

APPLICATION MODE SUBDOMAIN VARIABLES

The subdomain variables for Electric Currents are given the table below.

TABLE 2-20: APPLICATION MODE SUBDOMAIN VARIABLES, ELECTRIC CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
V			Electric potential	V
epsilonr		epsr, Dr	relative permittivity	ε_r
epsilonr		P	relative permittivity	1
epsilonr*ij*		epsr, Dr	relative permittivity, x_ix_j component	ε_{rij}
epsilonr*ij*		P	relative permittivity, x_ix_j component	1
epsilon			permittivity	$\varepsilon_0\varepsilon_r$
epsilon*ij*			permittivity, x_ix_j component	$\varepsilon_0\varepsilon_{rij}$
sigma			electric conductivity	σ
sigma*ij*			electric conductivity, x_ix_j component	σ_{ij}
P*i*	harmonic	P	electric polarization, x_i component	$P_ie^{j\text{phase}}$

TABLE 2-20: APPLICATION MODE SUBDOMAIN VARIABLES, ELECTRIC CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
P*i*	transient	P	electric polarization, x_i component	P_i
P*i*		epsr, Dr	electric polarization, x_i component	$D_i - \varepsilon_0 E_i$
normP			polarization, norm	$\sqrt{\mathbf{P}\cdot\mathbf{P}^*}$
Dr*i*		epsr	remanent displacement, x_i component	0
Dr*i*		P	remanent displacement, x_i component	P_i
Dr*i*	harmonic	Dr	remanent displacement, x_i component	$D_{\mathrm{r}i}e^{j\mathrm{phase}}$
Dr*i*	transient	Dr	remanent displacement, x_i component	$D_{\mathrm{r}i}$
normDr			remanent displacement, norm	$\sqrt{\mathbf{D}_\mathrm{r}\cdot\mathbf{D}_\mathrm{r}^*}$
Je*i*	harmonic		external current density, x_i component	$J_i^e e^{j\mathrm{phase}}$
Je*i*	transient		external current density, x_i component	J_i^e
normJe			external current density, norm	$\sqrt{\mathbf{J}^e\cdot\mathbf{J}^{e*}}$
E*i*			electric field	$-\frac{\partial V}{\partial x_i}$
normE			electric field, norm	$\sqrt{\mathbf{E}\cdot\mathbf{E}^*}$

TABLE 2-20: APPLICATION MODE SUBDOMAIN VARIABLES, ELECTRIC CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
D*i*		epsr	electric displacement, x_i component	$\varepsilon_0\varepsilon_{\mathrm{r}ij}E_j$
D*i*		P	electric displacement, x_i component	$\varepsilon_0 E_i + P_i$
D*i*		Dr	electric displacement, x_i component	$\varepsilon_0\varepsilon_{\mathrm{r}ij}E_j + D_{\mathrm{r}i}$
normD			electric displacement, norm	$\sqrt{\mathbf{D}\cdot\mathbf{D}^*}$
Jd*i*	harmonic		displacement current density, x_i component	$j\omega D_i$
Jd*i*	transient		displacement current density, x_i component	$\frac{\partial D_i}{\partial t}$
normJd			displacement current density, norm	$\sqrt{\mathbf{J}^d\cdot\mathbf{J}^{d*}}$
Jp*i*			potential current density, x_i component	$-\sigma_{ij}\frac{\partial V}{\partial x_j}$
normJp			potential current density, norm	$\sqrt{\mathbf{J}^p\cdot\mathbf{J}^{p*}}$
J*i*			total current density, x_i component	$J_i^e + J_i^d + J_i^p$
normJ			total current density, norm	$\sqrt{\mathbf{J}\cdot\mathbf{J}^*}$
Weav	harmonic		time average electric energy density	$\frac{1}{4}\mathrm{Re}(\mathbf{D}\cdot\mathbf{E}^*)$
We	transient		electric energy density	$\frac{1}{2}(\mathbf{D}\cdot\mathbf{E}^*)$

TABLE 2-20: APPLICATION MODE SUBDOMAIN VARIABLES, ELECTRIC CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
Qav	harmonic		time average resistive heating	$\frac{1}{2}\mathrm{Re}(\mathbf{J}\cdot(\mathbf{E}^* + \sigma^{-1}\mathbf{J}^{e*}))$
Q	transient		resistive heating	$\mathbf{J}\cdot(\mathbf{E}^* + \sigma^{-1}\mathbf{J}^{e*})$

APPLICATION MODE BOUNDARY VARIABLES

The boundary variables for Electric Currents are given the table below.

TABLE 2-21: APPLICATION MODE BOUNDARY VARIABLES, ELECTRIC CURRENTS

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
tE*i*		tangential electric field, x_i component	$-\mathbf{t}_i \cdot \nabla_t V$
normtE	harmonic	tangential electric field, norm	$\sqrt{t\mathbf{E}\cdot t\mathbf{E}^*}$
normtE	transient	tangential electric field, norm	$\sqrt{t\mathbf{E}\cdot t\mathbf{E}}$
tD*i*		tangential electric displacement, x_i component	$\varepsilon t E_i$
normtD	harmonic	tangential electric displacement, norm	$\sqrt{t\mathbf{D}\cdot t\mathbf{D}^*}$
normtD	transient	tangential electric displacement, norm	$\sqrt{t\mathbf{D}\cdot t\mathbf{D}}$
sigmabnd		electric conductivity on boundary	σ_{bnd}
epsilonrbnd		relative permittivity on boundary	$\varepsilon_{\mathrm{rbnd}}$
Js*i*	harmonic, shielding cond.	surface current density, x_i component	$d(\sigma t E_i + j\omega t D_i)$
Js*i*	transient, shielding cond.	surface current density, x_i component	$d\left(\sigma t E_i + \frac{\partial t D_i}{\partial t}\right)$

TABLE 2-21: APPLICATION MODE BOUNDARY VARIABLES, ELECTRIC CURRENTS

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
Qsav	harmonic, shielding cond.	time average surface resistive heating	$\frac{1}{2}\mathrm{Re}(\mathbf{J}_s \cdot \mathbf{E}^*)$
Qs	transient, shielding cond.	surface resistive heating	$\mathbf{J}_s \cdot \mathbf{E}$
nJ		normal current density	$\mathbf{n} \cdot \mathbf{J}$
nJs		Source current density	$\mathbf{n}_{\mathrm{up}} \cdot (\mathbf{J}_{\mathrm{down}} - \mathbf{J}_{\mathrm{up}})$

Perpendicular Induction Currents, Vector Potential Application Mode

The fundamental fields that can be derived from the electric potential are available for postprocessing and for use in equations and boundary conditions.

At the edges of the modeled structure, the magnetic potential, electric field and tangential magnetic field can be used for postprocessing. The energy flow in the normal direction is also available.

See page 6 for a description of the notation used in this table.

APPLICATION MODE SCALAR VARIABLES

The application-specific variables in this mode are given in the following table.

TABLE 2-22: APPLICATION MODE SCALAR VARIABLES, PERPENDICULAR CURRENTS

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
nu	harmonic	frequency	ν
omega	harmonic	angular frequency	$2\pi\nu$
epsilon0		permittivity of vacuum	ε_0
mu0		permeability of vacuum	μ_0

APPLICATION MODE SUBDOMAIN VARIABLES

The subdomain variables for Perpendicular Currents are given the table below.

TABLE 2-23: APPLICATION MODE SUBDOMAIN VARIABLES, PERPENDICULAR CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
Az			magnetic potential, z component	A_z
curlA`i`			curl of magnetic potential, x_i component	$(\nabla\times\mathbf{A})_i$
mur		mur, Br	relative permeability	μ_r
mur		M	relative permeability	$\mathbf{1}$
mur`ij`		mur, Br	relative permeability, x_ix_j component	μ_{rij}
mur`ij`		M	relative permeability, x_ix_j component	1
mu			permeability	$\mu_0\mu_r$
mu`ij`			permeability, x_ix_j component	$\mu_0\mu_{rij}$
epsilonr	harmonic	epsr, Dr	relative permittivity	ε_r
epsilonr	harmonic	P	relative permittivity	1
epsilon	harmonic		permittivity	$\varepsilon_0\varepsilon_r$
sigma			electric conductivity	σ
delta	harmonic		skin depth	$\dfrac{1}{\omega\sqrt{\frac{1}{2}\mu\varepsilon\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right)}}$
deltaV	static, transient		potential difference	ΔV
deltaV	harmonic		potential difference	$\Delta V e^{j\text{phase}}$

TABLE 2-23: APPLICATION MODE SUBDOMAIN VARIABLES, PERPENDICULAR CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
L			length	L
Pz	harmonic	P	electric polarization, z component	$P_z e^{j\mathrm{phase}}$
Pz	harmonic	epsr, Dr	electric polarization, z component	$D_z - \varepsilon_0 E_z$
Drz	harmonic	epsr	remanent displacement, z component	0
Drz	harmonic	P	remanent displacement, z component	P_z
Drz	harmonic	Dr	remanent displacement, z component	$D^{\mathrm{r}}{}_z e^{j\mathrm{phase}}$
M*i*	static, transient	M	magnetization, x_i component	M_i
M*i*	harmonic	M	magnetization, x_i component	$M_i e^{j\mathrm{phase}}$
M*i*		mur, Br	magnetization, x_i component	$B_i/\mu_0 - H_i$
normM			magnetization, norm	$\sqrt{\mathbf{M} \cdot \mathbf{M}^*}$
Br*i*		mur	remanent flux density, x_i component	0
Br*i*		M	remanent flux density, x_i component	$\mu_0 M_i$
Br*i*	static, transient	Br	remanent flux density, x_i component	$B_{\mathrm{r}i}$
Br*i*	harmonic	Br	remanent flux density, x_i component	$B_{\mathrm{r}i} e^{j\mathrm{phase}}$

TABLE 2-23: APPLICATION MODE SUBDOMAIN VARIABLES, PERPENDICULAR CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
normBr			remanent flux density, norm	$\sqrt{\mathbf{B}_\mathrm{r} \cdot \mathbf{B}_\mathrm{r}^*}$
Jez	static, transient		external current density, z component	J_z^e
Jez	harmonic		external current density, z component	$J_z^e e^{j\mathrm{phase}}$
v*i*			velocity, x_i component	v_i
normv			velocity, norm	$\sqrt{\mathbf{v} \cdot \mathbf{v}}$
Ez	transient		electric field, z component	$-\frac{\partial A_z}{\partial t}$
Ez	harmonic		electric field, z component	$-j\omega A_z$
normE	transient, harmonic		electric field, norm	$\lvert E_z \rvert$
Dz	harmonic	epsr	electric displacement, z component	$\varepsilon_0\varepsilon_\mathrm{r}E_z$
Dz	harmonic	P	electric displacement, z component	$\varepsilon_0 E_z + P_z$
Dz	harmonic	Dr	electric displacement, z component	$\varepsilon_0\varepsilon_\mathrm{r}E_z + D_{\mathrm{r}z}$
normD	harmonic		electric displacement, norm	$\lvert D_z \rvert$
Bx			magnetic flux density, x component	$\frac{\partial A_z}{\partial y}$
By			magnetic flux density, y component	$-\frac{\partial A_z}{\partial x}$

TABLE 2-23: APPLICATION MODE SUBDOMAIN VARIABLES, PERPENDICULAR CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
normB			magnetic flux density, norm	$\sqrt{\mathbf{B}\cdot\mathbf{B}^*}$
Hi		mur	magnetic field, x_i component	$\mu_{rij}^{-1}B_j/\mu_0$
Hi		M	magnetic field, x_i component	$B_i/\mu_0 - M_i$
Hi		Br	magnetic field, x_i component	$\mu_{rij}^{-1}(B_j - B_{rj})/\mu_0$
normH			magnetic field, norm	$\sqrt{\mathbf{H}\cdot\mathbf{H}^*}$
Jpz			potential current, z component	$\sigma\Delta V/L$
Jiz	transient, harmonic		induced current density, z component	σE_z
Jdz	harmonic		displacement current density, z component	$j\omega D_z$
Jvz			velocity current density, z component	$\sigma(v_x B_y - v_y B_x)$
Jz	static		total current density, z component	$J_z^e + J_z^v + J_z^p$
Jz	transient		total current density, z component	$J_z^e + J_z^v + J_z^p + J_z^i$
Jz	harmonic		total current density, z component	$J_z^e + J_z^v + J_z^p + J_z^i + J_z^d$
normJ			total current density, norm	$\|J_z\|$
Evz	harmonic		Lorentz electric field, z component	$(v_x B_y - v_y B_x)$
normEv	transient, harmonic		Lorentz electric field, norm	$\|E_{vz}\|$

TABLE 2-23: APPLICATION MODE SUBDOMAIN VARIABLES, PERPENDICULAR CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
Wm	static, transient		magnetic energy density	$\frac{\mathbf{H}\cdot\mathbf{B}}{2}$
Weav	harmonic		time average electric energy density	$\frac{1}{4}\mathrm{Re}(E_z D_z^*)$
Wmav	harmonic		time average magnetic energy density	$\frac{1}{4}\mathrm{Re}(\mathbf{H}\cdot\mathbf{B}^*)$
Wav	harmonic		time average total energy density	$W_\mathrm{e}^\mathrm{av} + W_\mathrm{m}^\mathrm{av}$
Q	static		resistive heating	$J_z\left(v_x B_y - v_y B_x + \frac{\Delta V}{L} + \sigma^{-1} J_z^e\right)$
Q	transient		resistive heating	$J_z\left(E_z + v_x B_y - v_y B_x + \frac{\Delta V}{L} + \sigma^{-1} J_z^e\right)$
Qav	harmonic		time average resistive heating	$\frac{1}{2}\mathrm{Re}\left(J_z\left(E_z^* + v_x B_y^* - v_y B_x^* + \frac{\Delta V^*}{L} + \sigma^{-1} J_z^{e*}\right)\right)$
Pox	transient		power flow, x component	$-E_z H_y$
Poy	transient		power flow, y component	$E_z H_x$
normPo	transient		power flow, norm	$\sqrt{\mathbf{S}\cdot\mathbf{S}^*}$
Poxav	harmonic		time average power flow, x component	$-\frac{1}{2}\mathrm{Re}(E_z H_y^*)$
Poyav	harmonic		time average power flow, y component	$\frac{1}{2}\mathrm{Re}(E_z H_x^*)$
normPoav	harmonic		time average power flow, norm	$\sqrt{\mathbf{S}^\mathrm{av}\cdot\mathbf{S}^{\mathrm{av}*}}$

APPLICATION MODE BOUNDARY VARIABLES

The boundary variables for Perpendicular Currents are given the table below.

TABLE 2-24: APPLICATION MODE BOUNDARY VARIABLES, PERPENDICULAR CURRENTS

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
Jsz		surface current density, z component	$n_{x\mathrm{up}}(H_{y\mathrm{down}}-H_{y\mathrm{up}})-n_{y\mathrm{up}}(H_{x\mathrm{down}}-H_{x\mathrm{up}})$
murbnd		relative permeability on boundary	μ_{rbnd}
sigmabnd	harmonic	conductivity on boundary	$\varepsilon_{\mathrm{rbnd}}$
epsilonrbnd	harmonic	relative permittivity on boundary	σ_{bnd}
Qs	transient	surface resistive heating	$\mathbf{J}_{\mathrm{s}}\cdot\mathbf{E}$
Qsav	harmonic	time average surface resistive heating	$\frac{1}{2}\mathrm{Re}(\mathbf{J}_s\cdot\mathbf{E}^*)$
nPo	transient	power outflow	$\mathbf{n}\cdot\mathbf{S}$
nPoav	harmonic	time average power outflow	$\mathbf{n}\cdot\mathbf{S}^{\mathrm{av}}$
unT`i`	static, transient	Maxwell surface stress tensor, x_i component, up side of boundary	$-\frac{1}{2}(\mathbf{H}_{\mathrm{up}}\cdot\mathbf{B}_{\mathrm{up}})n_{i\mathrm{down}}+(\mathbf{n}_{\mathrm{down}}\cdot\mathbf{H}_{\mathrm{up}})B_{i\mathrm{up}}$
dnT`i`	static, transient	Maxwell surface stress tensor, x_i component, down side of boundary	$-\frac{1}{2}(\mathbf{H}_{\mathrm{down}}\cdot\mathbf{B}_{\mathrm{down}})n_{i\mathrm{up}}+(\mathbf{n}_{\mathrm{up}}\cdot\mathbf{H}_{\mathrm{down}})B_{i\mathrm{down}}$
unT`i`av	harmonic	Maxwell surface stress tensor, x_i component, up side of boundary	$-\frac{1}{4}\mathrm{Re}(\mathbf{H}_{\mathrm{up}}\cdot\mathbf{B}^*_{\mathrm{up}})n_{i\mathrm{down}}+\frac{1}{2}\mathrm{Re}((\mathbf{n}_{\mathrm{down}}\cdot\mathbf{H}_{\mathrm{up}})B^*_{i\mathrm{up}})$
dnT`i`av	harmonic	Maxwell surface stress tensor, x_i component, down side of boundary	$-\frac{1}{4}\mathrm{Re}(\mathbf{H}_{\mathrm{down}}\cdot\mathbf{B}^*_{\mathrm{down}})n_{i\mathrm{up}}+\frac{1}{2}\mathrm{Re}((\mathbf{n}_{\mathrm{up}}\cdot\mathbf{H}_{\mathrm{down}})B^*_{i\mathrm{down}})$

Azimuthal Induction Currents, Vector Potential Application Mode

The fundamental fields that can be derived from the electric potential are available for postprocessing and for use in equations and boundary conditions.

At the edges of the modeled structure, the magnetic potential, electric field and tangential magnetic field can be used for postprocessing. The energy flow in the normal direction is also available.

See page 6 for a description of the notation used in this table.

APPLICATION MODE SCALAR VARIABLES

The application-specific variables in this mode are given in the following table.

TABLE 2-25: APPLICATION MODE SCALAR VARIABLES, AZIMUTHAL CURRENTS

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
nu	harmonic	frequency	ν
omega	harmonic	angular frequency	$2\pi\nu$
epsilon0		permittivity of vacuum	ε_0
mu0		permeability of vacuum	μ_0

APPLICATION MODE SUBDOMAIN VARIABLES

The subdomain variables for Azimuthal Currents are given the table below.

TABLE 2-26: APPLICATION MODE SUBDOMAIN VARIABLES, AZIMUTHAL CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
Aphidr			magnetic potential divided by r	u
Aphi			magnetic potential, φ component	ru
Aphir			magnetic potential, r derivative of φ component	$r\frac{\partial u}{\partial r} + u$

TABLE 2-26: APPLICATION MODE SUBDOMAIN VARIABLES, AZIMUTHAL CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
Aphiz			magnetic potential, z derivative of φ component	$r\frac{\partial u}{\partial z}$
Aphit	transient		magnetic potential, time derivative of φ component	$r\frac{\partial u}{\partial t}$
curlAi			curl of magnetic potential, x_i component	$(\nabla\times\mathbf{A})_i$
mur		mur, Br	relative permeability	μ_r
mur		M	relative permeability	1
murij		mur, Br	relative permeability, x_ix_j component	$\mu_{\mathrm{r}ij}$
murij		M	relative permeability, x_ix_j component	1
mu			permeability	$\mu_0\mu_\mathrm{r}$
muij			permeability, x_ix_j component	$\mu_0\mu_{\mathrm{r}ij}$
epsilonr	harmonic	epsr, Dr	relative permittivity	ε_r
epsilonr	harmonic	P	relative permittivity	1
epsilon	harmonic		permittivity	$\varepsilon_0\varepsilon_\mathrm{r}$
sigma			electric conductivity	σ
delta	harmonic		skin depth	$\frac{1}{\omega\sqrt{\frac{1}{2}\mu\varepsilon\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right)}}$
Vloop	static, transient		loop potential	V_loop

TABLE 2-26: APPLICATION MODE SUBDOMAIN VARIABLES, AZIMUTHAL CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
Vloop	harmonic		loop potential	$V_{\mathrm{loop}}e^{j\mathrm{phase}}$
Pphi	harmonic	P	electric polarization, φ component	$P_{\varphi}e^{j\mathrm{phase}}$
Pphi	harmonic	epsr, Dr	electric polarization, φ component	$D_{\varphi}-\varepsilon_0 E_{\varphi}$
Drphi	harmonic	epsr	remanent displacement, φ component	0
Drphi	harmonic	P	remanent displacement, φ component	P_{φ}
Drphi	harmonic	Dr	remanent displacement, φ component	$D_{r\varphi}e^{j\mathrm{phase}}$
M*i*	static, transient	M	magnetization, x_i component	M_i
M*i*	harmonic	M	magnetization, x_i component	$M_i e^{j\mathrm{phase}}$
M*i*		mur, Br	magnetization, x_i component	$B_i/\mu_0 - H_i$
normM			magnetization, norm	$\sqrt{\mathbf{M}\cdot\mathbf{M}^*}$
Br*i*		mur	remanent flux density, x_i component	0
Br*i*		M	remanent flux density, x_i component	$\mu_0 M_i$
Br*i*	static, transient	Br	remanent flux density, x_i component	$B_{\mathrm{r}i}$
Br*i*	harmonic	Br	remanent flux density, x_i component	$B_{\mathrm{r}i}e^{j\mathrm{phase}}$

TABLE 2-26: APPLICATION MODE SUBDOMAIN VARIABLES, AZIMUTHAL CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
normBr			remanent flux density, norm	$\sqrt{\mathbf{B}_\mathrm{r} \cdot \mathbf{B}_\mathrm{r}^*}$
Jephi	static, transient		external current density, φ component	J_φ^e
Jephi	harmonic		external current density, φ component	$J_\varphi^e e^{j\mathrm{phase}}$
v*i*			velocity, x_i component	v_i
normv			velocity, norm	$\sqrt{\mathbf{v} \cdot \mathbf{v}}$
Ephi	transient		electric field, φ component	$-\frac{\partial A_\varphi}{\partial t}$
Ephi	harmonic		electric field, φ component	$-j\omega A_\varphi$
normE	transient, harmonic		electric field, norm	$\lvert E_\varphi \rvert$
Dphi	harmonic	epsr	electric displacement, φ component	$\varepsilon_0 \varepsilon_\mathrm{r} E_\varphi$
Dphi	harmonic	P	electric displacement, φ component	$\varepsilon_0 E_\varphi + P_\varphi$
Dphi	harmonic	Dr	electric displacement, φ component	$\varepsilon_0 \varepsilon_\mathrm{r} E_\varphi + D_{\mathrm{r}\varphi}$
normD	harmonic		electric displacement, norm	$\lvert D_\varphi \rvert$
Br			magnetic flux density, r component	$-\frac{\partial A_\varphi}{\partial z}$
Bz			magnetic flux density, z component	$u + \frac{\partial A_\varphi}{\partial r}$

TABLE 2-26: APPLICATION MODE SUBDOMAIN VARIABLES, AZIMUTHAL CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
normB			magnetic flux density, norm	$\sqrt{\mathbf{B}\cdot\mathbf{B}^*}$
H*i*		mur	magnetic field, x_i component	$\mu_{rij}^{-1}B_j/\mu_0$
H*i*		M	magnetic field, x_i component	$B_i/\mu_0 - M_i$
H*i*		Br	magnetic field, x_i component	$\mu_{rij}^{-1}(B_j - B_{rj})/\mu_0$
normH			magnetic field, norm	$\sqrt{\mathbf{H}\cdot\mathbf{H}^*}$
Jpphi			loop current, φ component	$\sigma V_{\mathrm{loop}}/2\pi r$
Jiphi	transient, harmonic		induced current density, φ component	σE_φ
Jdphi	harmonic		displacement current density, φ component	$j\omega D_\varphi$
Jvphi			velocity current density, φ component	$\sigma(v_z B_r - v_r B_z)$
Jphi	static		total current density, φ component	$J_\varphi^e + J_\varphi^v + J_\varphi^p$
Jphi	transient		total current density, φ component	$J_\varphi^e + J_\varphi^v + J_\varphi^p + J_\varphi^i$
Jphi	harmonic		total current density, φ component	$J_\varphi^e + J_\varphi^v + J_\varphi^p + J_\varphi^i + J_\varphi^d$
normJ			total current density, norm	$\lvert J_\varphi \rvert$
Wm	static, transient		magnetic energy density	$\frac{\mathbf{H}\cdot\mathbf{B}}{2}$
Weav	harmonic		time average electric energy density	$\frac{1}{4}\mathrm{Re}(E_\varphi D_\varphi^*)$

TABLE 2-26: APPLICATION MODE SUBDOMAIN VARIABLES, AZIMUTHAL CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
Wmav	harmonic		time average magnetic energy density	$\frac{1}{4}\mathrm{Re}(\mathbf{H}\cdot\mathbf{B}^*)$
Wav	harmonic		time average total energy density	$W_e^{\mathrm{av}} + W_m^{\mathrm{av}}$
Q	static		resistive heating	$J_\varphi\left(v_r B_z - v_z B_r + \frac{V_{\mathrm{loop}}}{2\pi r} + \sigma^{-1}J_\varphi^e\right)$
Q	transient		resistive heating	$J_\varphi\left(E_\varphi + v_r B_z - v_z B_r + \frac{V_{\mathrm{loop}}}{2\pi r} + \sigma^{-1}J_\varphi^e\right)$
Qav	harmonic		time average resistive heating	$\frac{1}{2}\mathrm{Re}\left(J_\varphi\left(E_\varphi^* + v_r B_z^* - v_z B_r^* + \frac{V_{\mathrm{loop}}^*}{2\pi r} + \sigma^{-1}J_\varphi^{e*}\right)\right)$
Por	transient		power flow, r component	$E_\varphi H_z$
Poz	transient		power flow, z component	$-E_\varphi H_r$
normPo	transient		power flow, norm	$\sqrt{\mathbf{S}\cdot\mathbf{S}^*}$
Porav	harmonic		time average power flow, r component	$-\frac{1}{2}\mathrm{Re}(E_\varphi H_z^*)$
Pozav	harmonic		time average power flow, z component	$\frac{1}{2}\mathrm{Re}(E_\varphi H_z^*)$
normPoav	harmonic		time average power flow, norm	$\sqrt{\mathbf{S}^{\mathrm{av}}\cdot\mathbf{S}^{\mathrm{av}*}}$

APPLICATION MODE BOUNDARY VARIABLES

The boundary variables for Azimuthal Currents are given the table below.

TABLE 2-27: APPLICATION MODE BOUNDARY VARIABLES, AZIMUTHAL CURRENTS

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
Jsphi		surface current density, φ component	$n_{z\mathrm{up}}(H_{r\mathrm{down}} - H_{r\mathrm{up}}) - n_{r\mathrm{up}}(H_{z\mathrm{down}} - H_{z\mathrm{up}})$
murbnd		relative permeability on boundary	μ_{rbnd}
sigmabnd	harmonic	conductivity on boundary	$\varepsilon_{\mathrm{rbnd}}$
epsilonrbnd	harmonic	relative permittivity on boundary	σ_{bnd}
Qs	transient	surface resistive heating	$\mathbf{J}_{\mathrm{s}} \cdot \mathbf{E}$
Qsav	harmonic	time average surface resistive heating	$\frac{1}{2}\mathrm{Re}(\mathbf{J}_s \cdot \mathbf{E}^*)$
nPo	transient	power outflow	$\mathbf{n} \cdot \mathbf{S}$
nPoav	harmonic	time average power outflow	$\mathbf{n} \cdot \mathbf{S}^{\mathrm{av}}$
unT*i*	static, transient	Maxwell surface stress tensor, x_i component, up side of boundary	$-\frac{1}{2}(\mathbf{H}_{\mathrm{up}} \cdot \mathbf{B}_{\mathrm{up}})n_{i\mathrm{down}} + (\mathbf{n}_{\mathrm{down}} \cdot \mathbf{H}_{\mathrm{up}})B_{i\mathrm{up}}$
dnT*i*	static, transient	Maxwell surface stress tensor, x_i component, down side of boundary	$-\frac{1}{2}(\mathbf{H}_{\mathrm{down}} \cdot \mathbf{B}_{\mathrm{down}})n_{i\mathrm{up}} + (\mathbf{n}_{\mathrm{up}} \cdot \mathbf{H}_{\mathrm{down}})B_{i\mathrm{down}}$
unT*i*av	harmonic	Maxwell surface stress tensor, x_i component, up side of boundary	$-\frac{1}{4}\mathrm{Re}(\mathbf{H}_{\mathrm{up}} \cdot \mathbf{B}^*_{\mathrm{up}})n_{i\mathrm{down}} + \frac{1}{2}\mathrm{Re}((\mathbf{n}_{\mathrm{down}} \cdot \mathbf{H}_{\mathrm{up}})B^*_{i\mathrm{up}})$
dnT*i*av	harmonic	Maxwell surface stress tensor, x_i component, down side of boundary	$-\frac{1}{4}\mathrm{Re}(\mathbf{H}_{\mathrm{down}} \cdot \mathbf{B}^*_{\mathrm{down}})n_{i\mathrm{up}} + \frac{1}{2}\mathrm{Re}((\mathbf{n}_{\mathrm{up}} \cdot \mathbf{H}_{\mathrm{down}})B^*_{i\mathrm{down}})$

In-Plane Induction Currents, Magnetic Field Application Mode

All the nonzero components of the fundamental electromagnetic field quantities can be used in visualization and postprocessing of the results and when defining the equations and boundary conditions. Both magnetic and electric energy and resistive heating can be computed, as well as the two components of the Poynting vector. At the boundaries, the magnetic field, the transversal electric field and the normal energy are available.

See page 6 for a description of the notation used in this table.

APPLICATION MODE SCALAR VARIABLES

The application-specific variables in this mode are given in the following table.

TABLE 2-28: APPLICATION MODE SCALAR VARIABLES, IN-PLANE CURRENTS

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
nu	harmonic	frequency	ν
omega	harmonic	angular frequency	$2\pi\nu$
epsilon0		permittivity of vacuum	ε_0
mu0		permeability of vacuum	μ_0

APPLICATION MODE SUBDOMAIN VARIABLES

The subdomain variables for In-Plane Currents are given the table below.

TABLE 2-29: APPLICATION MODE SUBDOMAIN VARIABLES, IN-PLANE CURRENTS

NAME	ANALYSIS	CONST REL.	DESCRIPTION	EXPRESSION
Hz			magnetic field, z component	H_z
normH			magnetic field, norm	$\|H_z\|$
nu	harmonic		frequency	ν
omega	harmonic		angular frequency	$2\pi\nu$
d			thickness	d
epsilon0			permittivity of vacuum	ε_0
mu0			permeability of vacuum	μ_0

TABLE 2-29: APPLICATION MODE SUBDOMAIN VARIABLES, IN-PLANE CURRENTS

NAME	ANALYSIS	CONST REL.	DESCRIPTION	EXPRESSION
mur		mur, Br	relative permeability	μ_r
mur		M	relative permeability	1
mu			permeability	$\mu_0\mu_r$
epsilonr	harmonic	epsr, Dr	relative permittivity	ε_r
epsilonr	harmonic	P	relative permittivity	1
epsilonr`ij`	harmonic	epsr, Dr	relative permittivity, x_ix_j component	ε_{rij}
epsilonr`ij`	harmonic	P	relative permittivity, x_ix_j component	1
epsilon	harmonic		permittivity	$\varepsilon_0\varepsilon_r$
epsilon`ij`	harmonic		permittivity, x_ix_j component	$\varepsilon_0\varepsilon_{rij}$
sigma			electric conductivity	σ
sigma`ij`			electric conductivity, x_ix_j component	σ_{ij}
P`i`	harmonic	P	external polarization, x_i component	$P_ie^{j\mathrm{phase}}$
P`i`	harmonic	epsr, Dr	electric polarization, x_i component	$D_i - \varepsilon_0 E_i$
normP	harmonic		electric polarization, norm	$\sqrt{\mathbf{P}\cdot\mathbf{P}^*}$
Dr`i`	harmonic	epsr	remanent displacement, x_i component	0

TABLE 2-29: APPLICATION MODE SUBDOMAIN VARIABLES, IN-PLANE CURRENTS

NAME	ANALYSIS	CONST REL.	DESCRIPTION	EXPRESSION
Dr*i*	harmonic	P	remanent displacement, x_i component	P_i
Dr*i*	harmonic	Dr	remanent displacement, x_i component	$D_{ri}e^{j\mathrm{phase}}$
normDr	harmonic		remanent displacement, norm	$\sqrt{\mathbf{D}_\mathrm{r} \cdot \mathbf{D}_\mathrm{r}^*}$
Mz	static, transient	M	magnetization, z component	M_z
Mz	harmonic	M	magnetization, z component	$M_z e^{j\mathrm{phase}}$
Mz		mur, Br	magnetization, z component	$B_z/\mu_0 - H_z$
Brz		mur	remanent flux density, z component	0
Brz		M	remanent flux density, z component	$\mu_0 M_z$
Brz	static, transient	Br	remanent flux density, z component	B_{rz}
Brz	harmonic	Br	remanent flux density, z component	$B_{rz}e^{j\mathrm{phase}}$
Je*i*	static, transient		external current density, x_i component	J_i^e
Je*i*	harmonic		external current density, x_i component	$J_i^e e^{j\mathrm{phase}}$
normJe			external current density, norm	$\sqrt{\mathbf{J}_i^e \cdot \mathbf{J}_i^{e*}}$
v*i*			velocity, x_i component	v_i

TABLE 2-29: APPLICATION MODE SUBDOMAIN VARIABLES, IN-PLANE CURRENTS

NAME	ANALYSIS	CONST REL.	DESCRIPTION	EXPRESSION
normv			velocity, norm	$\sqrt{\mathbf{v} \cdot \mathbf{v}}$
Bz		mur	magnetic flux density, z component	$\mu_0\mu_r H_z$
Bz		M	magnetic flux density, z component	$\mu_0(H_z + M_z)$
Bz		Br	magnetic flux density, z component	$\mu_0\mu_r H_z + B_{rz}$
normB			magnetic flux density, norm	$\lvert B_z \rvert$
Ex	static, transient		electric field, x component	$\sigma_{xi}^{-1}(J_i - J_i^e) - v_y B_z$
Ex	harmonic		electric field, x component	$\sigma_{cxi}^{-1}(J_i - J_i^e - j\omega D_{ri} + (\sigma_{iy}v_x - \sigma_{ix}v_y)B_z)$
Ey	static, transient		electric field, y component	$\sigma_{yi}^{-1}(J_i - J_i^e) + v_x B_z$
Ey	harmonic		electric field, y component	$\sigma_{cyi}^{-1}(J_i - J_i^e - j\omega D_{ri} + (\sigma_{iy}v_x - \sigma_{ix}v_y)B_z)$
normE			electric field, norm	$\sqrt{\mathbf{E} \cdot \mathbf{E}^*}$
D*i*	harmonic	epsr	electric displacement, x_i component	$\varepsilon_0\varepsilon_{rij}E_j$
D*i*	harmonic	P	electric displacement, x_i component	$\varepsilon_0 E_i + P_i$
D*i*	harmonic	Dr	electric displacement, x_i component	$\varepsilon_0\varepsilon_{rij}E_j + D_{ri}$
normD	harmonic		electric displacement, norm	$\sqrt{\mathbf{D} \cdot \mathbf{D}^*}$
Ji*i*			induced current density, x_i component	$\sigma_{ij}E_j$

TABLE 2-29: APPLICATION MODE SUBDOMAIN VARIABLES, IN-PLANE CURRENTS

NAME	ANALYSIS	CONST REL.	DESCRIPTION	EXPRESSION
normJi			induced current density, norm	$\sqrt{\mathbf{J}^i \cdot \mathbf{J}^{i*}}$
Jvx			velocity current density, x component	$\sigma_{xx} v_y B_z - \sigma_{xy} v_x B_z$
Jvy			velocity current density, y component	$\sigma_{yx} v_y B_z - \sigma_{yy} v_x B_z$
normJv			velocity current density, norm	$\sqrt{\mathbf{J}^v \cdot \mathbf{J}^{v*}}$
Jd*i*	harmonic		displacement current density, x_i component	$j\omega D_i$
normJd	harmonic		displacement current density, norm	$\sqrt{\mathbf{J}^d \cdot \mathbf{J}^{d*}}$
Jx			total current density, x component	$\frac{\partial H_z}{\partial y}$
Jy			total current density, y component	$-\frac{\partial H_z}{\partial y}$
normJ			total current density, norm	$\sqrt{\mathbf{J} \cdot \mathbf{J}^*}$
Wm	static, transient		magnetic energy density	$\frac{H_z B_z}{2}$
Wmav	harmonic		time average magnetic energy density	$\frac{1}{4}\mathrm{Re}(H_z B_z^*)$
Weav	harmonic		time average electric energy density	$\frac{1}{4}\mathrm{Re}(\mathbf{E} \cdot \mathbf{D}^*)$
Wav	harmonic		time average total energy density	$W_e^{\mathrm{av}} + W_m^{\mathrm{av}}$
Q	static, transient		resistive heating	$\mathbf{J} \cdot (\mathbf{E} + \sigma^{-1}\mathbf{J}^e) + J_x v_y B_z - J_y v_x B_z$

TABLE 2-29: APPLICATION MODE SUBDOMAIN VARIABLES, IN-PLANE CURRENTS

NAME	ANALYSIS	CONST REL.	DESCRIPTION	EXPRESSION
Qav	harmonic		time average resistive heating	$\frac{1}{2}\mathrm{Re}(\mathbf{J}\cdot(\mathbf{E}^* + \sigma^{-1}\mathbf{J}^{e*}) + J_x v_y B_z^* - J_y v_x B_z^*)$
Pox	static, transient		power flow, x component	$E_y H_z$
Poy	static, transient		power flow, y component	$-E_x H_z$
normPo	static, transient		power flow, norm	$\sqrt{\mathbf{S}\cdot\mathbf{S}^*}$
Poxav	harmonic		time average power flow, x component	$\frac{1}{2}\mathrm{Re}(E_y H_z^*)$
Poyav	harmonic		time average power flow, y component	$-\frac{1}{2}\mathrm{Re}(E_x H_z^*)$
normPoav	harmonic		time average power flow, norm	$\sqrt{\mathbf{S}^{\mathrm{av}}\cdot\mathbf{S}^{\mathrm{av}*}}$

APPLICATION MODE BOUNDARY VARIABLES

The boundary variables for In-Plane Currents are given the table below.

TABLE 2-30: APPLICATION MODE BOUNDARY VARIABLES, IN-PLANE CURRENTS

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
nPo	static, transient	power outflow	$\mathbf{n}\cdot\mathbf{S}$
nPoav	harmonic	time average power outflow	$\mathbf{n}\cdot\mathbf{S}^{\mathrm{av}}$

Meridional Induction Currents, Magnetic Field Application Mode

The magnetic field is available for postprocessing and for use in equations and boundary conditions at both subdomains and boundaries. At boundaries, you can also work with the tangential electric field and the normal component of the Poynting vector. Energy expressions and resistive heating are available in subdomains beside the standard electromagnetic field densities.

See page 6 for a description of the notation used in this table.

APPLICATION MODE SCALAR VARIABLES

The application-specific variables in this mode are given in the following table.

TABLE 2-31: APPLICATION MODE SCALAR VARIABLES, MERIDIONAL CURRENTS

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
nu	harmonic	frequency	ν
omega	harmonic	angular frequency	$2\pi\nu$
epsilon0		permittivity of vacuum	ε_0
mu0		permeability of vacuum	μ_0

APPLICATION MODE SUBDOMAIN VARIABLES

The subdomain variables for Meridional Currents are given the table below.

TABLE 2-32: APPLICATION MODE SUBDOMAIN VARIABLES, MERIDIONAL CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
Hphidr			magnetic field divided by r	u
Hphi			magnetic field, φ component	ru
normH			magnetic field, norm	$\lvert H_\varphi \rvert$
Hphir			magnetic field, r derivative of φ component	$r\frac{\partial u}{\partial r} + u$
Hphiz			magnetic field, z derivative of φ component	$r\frac{\partial u}{\partial z}$
Hphit	transient		magnetic field, time derivative of φ component	$r\frac{\partial u}{\partial t}$
mur		mur, Br	relative permeability	μ_r
mur		M	relative permeability	1
mu			permeability	$\mu_0\mu_r$
epsilonr	harmonic	epsr, Dr	relative permittivity	ε_r

TABLE 2-32: APPLICATION MODE SUBDOMAIN VARIABLES, MERIDIONAL CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
epsilonr	harmonic	P	relative permittivity	1
epsilonr`ij`	harmonic	epsr, Dr	relative permittivity, $x_i x_j$ component	ε_{rij}
epsilonr`ij`	harmonic	P	relative permittivity, $x_i x_j$ component	1
epsilon	harmonic		permittivity	$\varepsilon_0 \varepsilon_r$
epsilon`ij`	harmonic		permittivity, $x_i x_j$ component	$\varepsilon_0 \varepsilon_{rij}$
sigma			electric conductivity	σ
sigma`ij`			electric conductivity, $x_i x_j$ component	σ_{ij}
P`i`	harmonic	P	external polarization, x_i component	$P_i e^{j\mathrm{phase}}$
P`i`	harmonic	epsr, Dr	electric polarization, x_i component	$D_i - \varepsilon_0 E_i$
normP	harmonic		electric polarization, norm	$\sqrt{\mathbf{P} \cdot \mathbf{P}^*}$
Dr`i`	harmonic	epsr	remanent displacement, x_i component	0
Dr`i`	harmonic	P	remanent displacement, x_i component	P_i
Dr`i`	harmonic	Dr	remanent displacement, x_i component	$D_{ri} e^{j\mathrm{phase}}$
normDr	harmonic		remanent displacement, norm	$\sqrt{\mathbf{D}_\mathrm{r} \cdot \mathbf{D}_\mathrm{r}^*}$

TABLE 2-32: APPLICATION MODE SUBDOMAIN VARIABLES, MERIDIONAL CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
Mphi	static, transient	M	magnetization, φ component	M_φ
Mphi	harmonic	M	magnetization, φ component	$M_\varphi e^{j\mathrm{phase}}$
Mphi		mur, Br	magnetization, φ component	$B_\varphi/\mu_0 - H_\varphi$
Brphi		mur	remanent flux density, φ component	0
Brphi		M	remanent flux density, φ component	$\mu_0 M_\varphi$
Brphi	static, transient	Br	remanent flux density, φ component	$B_{\mathrm{r}\varphi}$
Brphi	harmonic	Br	remanent flux density, φ component	$B_{\mathrm{r}\varphi}e^{j\mathrm{phase}}$
Je*i*	static, transient		external current density, x_i component	J_i^e
Je*i*	harmonic		external current density, x_i component	$J_i^e e^{j\mathrm{phase}}$
normJe			external current density, norm	$\sqrt{\mathbf{J}_i^e \cdot \mathbf{J}_i^{e*}}$
v*i*			velocity, x_i component	v_i
normv			velocity, norm	$\sqrt{\mathbf{v} \cdot \mathbf{v}}$
Bphi		mur	magnetic flux density, φ component	$\mu_0\mu_r H_\varphi$
Bphi		M	magnetic flux density, φ component	$\mu_0(H_\varphi + M_\varphi)$

TABLE 2-32: APPLICATION MODE SUBDOMAIN VARIABLES, MERIDIONAL CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
Bphi		Br	magnetic flux density, φ component	$\mu_0\mu_r H_\varphi + B_{r\varphi}$
normB			magnetic flux density, norm	$\lvert B_\varphi \rvert$
Er	static, transient		electric field, r component	$\sigma_{ri}^{-1}(J_i - J_i^e) + v_z B_\varphi$
Er	harmonic		electric field, r component	$\sigma_{cri}^{-1}(J_i - J_i^e - j\omega D_{ri} + (\sigma_{ir}v_z - \sigma_{iz}v_r)B_\varphi)$
Ez	static, transient		electric field, z component	$\sigma_{zi}^{-1}(J_i - J_i^e) - v_r B_\varphi$
Ez	harmonic		electric field, z component	$\sigma_{czi}^{-1}(J_i - J_i^e - j\omega D_{ri} + (\sigma_{ir}v_z - \sigma_{iz}v_z)B_\varphi)$
normE			electric field, norm	$\sqrt{\mathbf{E} \cdot \mathbf{E}^*}$
D`i`	harmonic	epsr	electric displacement, x_i component	$\varepsilon_0\varepsilon_{rij}E_j$
D`i`	harmonic	P	electric displacement, x_i component	$\varepsilon_0 E_i + P_i$
D`i`	harmonic	Dr	electric displacement, x_i component	$\varepsilon_0\varepsilon_{rij}E_j + D_{ri}$
normD	harmonic		electric displacement, norm	$\sqrt{\mathbf{D} \cdot \mathbf{D}^*}$
Ji`i`			induced current density, x_i component	$\sigma_{ij}E_j$
normJi			induced current density, norm	$\sqrt{\mathbf{J}^i \cdot \mathbf{J}^{i*}}$
Jvr			velocity current density, r component	$\sigma_{rz}v_r B_\varphi - \sigma_{rr}v_z B_\varphi$
Jvz			velocity current density, z component	$\sigma_{zz}v_r B_\varphi - \sigma_{zr}v_z B_\varphi$

TABLE 2-32: APPLICATION MODE SUBDOMAIN VARIABLES, MERIDIONAL CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
normJv			velocity current density, norm	$\sqrt{\mathbf{J}^v \cdot \mathbf{J}^{v*}}$
Jdi	harmonic		displacement current density, x_i component	$j\omega D_i$
normJd	harmonic		displacement current density, norm	$\sqrt{\mathbf{J}^d \cdot \mathbf{J}^{d*}}$
Jr			total current density, r component	$-\frac{\partial H_\varphi}{\partial z}$
Jz			total current density, z component	$u + \frac{\partial H_\varphi}{\partial r}$
normJ			total current density, norm	$\sqrt{\mathbf{J} \cdot \mathbf{J}^*}$
Wm	static, transient		magnetic energy density	$\frac{H_\varphi B_\varphi}{2}$
Wmav	harmonic		time average magnetic energy density	$\frac{1}{4}\mathrm{Re}(H_\varphi B_\varphi^*)$
Weav	harmonic		time average electric energy density	$\frac{1}{4}\mathrm{Re}(\mathbf{E} \cdot \mathbf{D}^*)$
Wav	harmonic		time average total energy density	$W_e^{\mathrm{av}} + W_m^{\mathrm{av}}$
Q	static, transient		resistive heating	$\mathbf{J} \cdot (\mathbf{E} + \sigma^{-1}\mathbf{J}^e) + J_z v_r B_\varphi - J_r v_z B_\varphi$
Qav	harmonic		time average resistive heating	$\frac{1}{2}\mathrm{Re}(\mathbf{J} \cdot (\mathbf{E}^* + \sigma^{-1}\mathbf{J}^{e*}) + J_z v_r B_\varphi^* - J_r v_z B_\varphi^*)$
Por	static, transient		power flow, r component	$-E_z H_\varphi$
Poz	static, transient		power flow, z component	$E_r H_\varphi$
normPo	static, transient		power flow, norm	$\sqrt{\mathbf{S} \cdot \mathbf{S}^*}$

TABLE 2-32: APPLICATION MODE SUBDOMAIN VARIABLES, MERIDIONAL CURRENTS

NAME	ANALYSIS	CONST. REL.	DESCRIPTION	EXPRESSION
Porav	harmonic		time average power flow, r component	$-\frac{1}{2}\mathrm{Re}(E_z H_\varphi^*)$
Pozav	harmonic		time average power flow, z component	$\frac{1}{2}\mathrm{Re}(E_r H_\varphi^*)$
normPoav	harmonic		time average power flow, norm	$\sqrt{\mathbf{S}^{\mathrm{av}} \cdot \mathbf{S}^{\mathrm{av}*}}$

APPLICATION MODE BOUNDARY VARIABLES

The boundary variables for Meridional Currents are given the table below.

TABLE 2-33: APPLICATION MODE BOUNDARY VARIABLES, MERIDIONAL CURRENTS

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
nPo	static, transient	power outflow	$\mathbf{n}\cdot\mathbf{S}$
nPoav	harmonic	time average power outflow	$\mathbf{n}\cdot\mathbf{S}^{\mathrm{av}}$

Magnetostatics, No Currents Application Mode

The fundamental fields that can be derived from the electric potential are available for postprocessing and for use in equations and boundary conditions.

See page 6 for a description of the notation used in this table.

APPLICATION MODE SCALAR VARIABLES

The application-specific variables in this mode are given in the following table.

TABLE 2-34: APPLICATION MODE SCALAR VARIABLES, MAGNETOSTATICS, NO CURRENTS

NAME	DESCRIPTION	EXPRESSION
mu0	permeability of vacuum	μ_0

APPLICATION MODE SUBDOMAIN VARIABLES

The subdomain variables for Magnetostatics, No Currents are given the table below.

TABLE 2-35: APPLICATION MODE SUBDOMAIN VARIABLES, MAGNETOSTATICS, NO CURRENTS

NAME	CONST. REL.	DESCRIPTION	EXPRESSION
Vm		magnetic potential	V_m
mur	mur, Br	relative permeability	μ_r
mur	M	relative permeability	1
mur*ij*	mur, Br	relative permeability, x_ix_j component	μ_{rij}
mur*ij*	M	relative permeability	1
mu		permeability	$\mu_0\mu_r$
mu*ij*		permeability, x_ix_j component	$\mu_0\mu_{rij}$
M*i*	M	magnetization, x_i component	M_i
M*i*	mur, Br	magnetization, x_i component	$B_i/\mu_0 - H_i$
normM		magnetization, norm	$\sqrt{\mathbf{M}\cdot\mathbf{M}^*}$
Br*i*	mur	remanent flux density, x_i component	0
Br*i*	M	remanent flux density, x_i component	$\mu_0 M_i$
Br*i*	Br	remanent flux density, x_i component	B_{ri}
normBr		remanent flux density, norm	$\sqrt{\mathbf{B}_r\cdot\mathbf{B}_r^*}$
H*i*		magnetic field, x_i component	$-\frac{\partial V_m}{\partial x_i}$
normH		magnetic field, norm	$\sqrt{\mathbf{H}\cdot\mathbf{H}^*}$
B*i*	mur	magnetic flux density, x_i component	$\mu_0\mu_{rij}H_j$
B*i*	M	magnetic flux density, x_i component	$\mu_0(H_i + M_i)$
B*i*	Br	magnetic flux density, x_i component	$\mu_0\mu_{rij}H_j + B_{ri}$

TABLE 2-35: APPLICATION MODE SUBDOMAIN VARIABLES, MAGNETOSTATICS, NO CURRENTS

NAME	CONST. REL.	DESCRIPTION	EXPRESSION
normB		magnetic flux density, norm	$\sqrt{\mathbf{B}\cdot\mathbf{B}^*}$
Wm		magnetic energy density	$\dfrac{\mathbf{H}\cdot\mathbf{B}}{2}$

APPLICATION MODE BOUNDARY VARIABLES

The boundary variables for Magnetostatics, No Currents are given the table below.

TABLE 2-36: APPLICATION MODE BOUNDARY VARIABLES, MAGNETOSTATICS, NO CURRENTS

NAME	DESCRIPTION	EXPRESSION
`tH`*i*	tangential magnetic field, x_i component	$-\mathbf{t}_i\cdot\nabla_t V_m$
`normtH`	tangential magnetic field, norm	$\sqrt{\mathbf{H}_t\cdot\mathbf{H}_t^*}$
`nB`	normal magnetic flux density	$\mathbf{n}\cdot\mathbf{B}$
`unT`*i*	Maxwell surface stress tensor, x_i component, up side of boundary	$-\frac{1}{2}(\mathbf{H}_{\mathrm{up}}\cdot\mathbf{B}_{\mathrm{up}})n_{i\mathrm{down}} + (\mathbf{n}_{\mathrm{down}}\cdot\mathbf{H}_{\mathrm{up}})B_{i\mathrm{up}}$
`dnT`*i*	Maxwell surface stress tensor, x_i component, down side of boundary	$-\frac{1}{2}(\mathbf{H}_{\mathrm{down}}\cdot\mathbf{B}_{\mathrm{down}})n_{i\mathrm{up}} + (\mathbf{n}_{\mathrm{up}}\cdot\mathbf{H}_{\mathrm{down}})B_{i\mathrm{down}}$

3

Programming Reference

The Programming Language

Earlier in this documentation, the examples use the COMSOL Multiphysics graphical user interface for solving problems with the AC/DC Module. Although this user interface provides a convenient environment for modeling many problems, it can sometimes be useful to work with a programming tool.

For details on specific functions, see the *Command Reference*.

A summary of the application structure, and how application objects are used for a convenient transformation of application mode data to PDE and boundary coefficients, is presented in the following section. Thereafter the same problem as solved in "An Example—Eddy Currents" on page 21 is built using the programming language.

The Application Structure

The process of performing a simulation using the application modes available through the AC/DC Module includes the correct setup of the application structure. The application structure contains the necessary information for the model setup in several fields. This section describes the application structure in the context of the AC/DC Module. See also the section "Application Structures" on page 56 in the *COMSOL Multiphysics Scripting Guide*. Most fields have corresponding entries in the FEM structure, described in the section "Specifying a Model" on page 9 in the *COMSOL Multiphysics Scripting Guide*. The following table gives an overview of the fields in the application structure.

FIELD	DESCRIPTION
`appl.mode`	Application mode class
`appl.dim`	Cell array of dependent variable names
`appl.sdim`	Cell array of spatial coordinates
`appl.border`	Assembly on interior boundaries; turn on/off assembly on interior boundaries
`appl.name`	Application mode name
`appl.var`	Cell array or structure with application-specific scalar variables.
`appl.assign`	Assigned variable names

FIELD	DESCRIPTION
`appl.assignsuffix`	Suffix to append to all application mode variable names
`appl.equ`	Structure containing domain properties
`appl.bnd`	Structure containing boundary conditions
`appl.edg`	Structure containing edge conditions
`appl.pnt`	Structure containing point conditions
`appl.prop`	Application mode specific properties

Most of these fields have default values and need not be specified when solving a problem using the programming language. The function `multiphysics` is used to transform the application structure data to the FEM structure to generate the complete set of equations. See the corresponding entry in the *Command Reference* for details.

The application mode specific names of the fields in the structures in the table above can be found in the chapter "Application Mode Programming Reference" on page 77.

APPLICATION MODE CLASS

The application modes are specified via a corresponding class name.

To specify the class, write the name of the class as a string, for example,

```
appl.mode.class='PerpendicularCurrents';
```

which specifies that the Perpendicular Currents application mode will be used.

Some application modes, for example the Conductive Media DC and Electrostatics application modes, can be used both for Cartesian and axisymmetric problems. The default is to use Cartesian coordinates. To specify an axisymmetric problem, use

```
appl.mode.type = 'axi';
```

DEPENDENT VARIABLES

The `dim` field in the application structure states the names of the dependent variables, and hence gives the dimension of the corresponding PDE system. If the `dim` field is missing, the corresponding standard names of the electromagnetic field quantities solved for are used. Note that in some axisymmetric modes, there is a variable transformation in the equations solved. In those modes, the default name of the dependent variable name has `dr` added to the name of the electromagnetic quantity, since the dependent variable is divided by r.

The default name of the dependent variable in the Perpendicular currents quasi-statics application mode is `'Az'`.

You can set a new name of the dependent variable by typing

```
appl.dim = {'A'};
```

SPATIAL COORDINATES

The names of the spatial coordinates are given in `fem.sdim`. However, `fem.sdim` only gives the names of the spatial coordinates of the geometry: one variable in 1D, two variables in 2D, and three variables in 3D. To specify all three spatial coordinates, use `appl.sdim`. The additional spatial coordinates are used when giving names to vector component variables.

For example, in 2D Cartesian coordinates

```
fem.sdim = {'x1' 'y1'};
appl.sdim = {'x1' 'y1' 'z1'};
```

defines the spatial coordinates x_1, y_1, z_1.

In cylindrical coordinates

```
fem.sdim = {'r' 'z'};
appl.sdim = {'r' 'phi' 'z'};
```

defines the spatial coordinates r, φ , z.

The coordinates defined both in `fem.sdim` and `appl.sdim` should match.

APPLICATION NAME

This field is used for giving the application a name. If no name is specified, a default name is used.

```
appl.name = 'magnet';
```

APPLICATION MODE PROPERTIES

Some application modes define properties to, for example, specify which type of analysis to perform or which dependent variables to use. These are specified in the `appl.prop` structure. For example, the Perpendicular Currents application mode defines the field `appl.prop.analysis`, which specifies if a static, transient, or time-harmonic analysis should be performed. For instance,

```
appl.prop.analysis = 'harmonic';
```

indicates time-harmonic analysis.

The default element type used for domains and boundaries can be specified in the `appl.prop.elemdefault` field. For example, you can write

```
appl.prop.elemdefault='Lag1';
```

to obtain linear Lagrange elements.

APPLICATION SCALAR VARIABLES

For scalar variables that are valid in the whole model, such as permittivity and permeability of vacuum and angular frequency, the values can be specified in the `appl.var` field. Note that only predefined variable names can be used in this field.

For the Perpendicular Currents application mode, the variables can be set as

```
appl.var.epsilon0 = 1;
appl.var.mu0 = 1;
appl.var.nu = 100;
```

The `appl.var` field can also be specified as a cell array,

```
appl.var = {'epsilon0', 1, 'mu0', 1, 'nu', 100};
```

The default values in the Perpendicular Currents application mode in the harmonic formulation are

```
appl.var.epsilon0 = 8.854187817e-12;
appl.var.mu0 = 4*pi*1e-7;
appl.var.nu = 50;
```

ASSIGNED VARIABLE NAMES

To avoid duplication of variable names, the `appl.assign` field can be used to state the relation between the assigned name of a variable that you can use in postprocessing and in the PDE and boundary coefficients, and the default name that is used in the COMSOL Multiphysics and AC/DC Module algorithms. This field is hence only necessary when you solve a multiphysics problem where variable name conflicts may arise.

If you want to use the variable name `w` for the intrinsic variable `omega` in the Perpendicular currents quasi-statics mode, all you have to enter is

```
appl.assign.omega = 'w';
```

This can also be specified as a cell array,

```
appl.assign = {'omega' 'w’};
```

The odd entries in the `assign` field state the default application scalar variable names or the postprocessing variable names. These are listed in the subsection “Application

Mode Variables" for each application mode in "The Application Mode Formulations" on page 128. The even entries in `appl.assign` are the variable names that you want to use for the physical entities when modeling.

There is also a field `appl.assignsuffix`, which can be used to add a suffix to the name of all application mode variables. Variables appearing in `appl.assign` will take the given assigned name, while the others will get the suffix added to their names.

DOMAIN PROPERTIES

The application structure field `appl.equ` is used for specifying electromagnetic properties that will be transformed into PDE coefficients. For example the Perpendicular Currents application mode defines the fields

```
appl.equ.sigma
appl.equ.mur
appl.equ.epsilonr
appl.equ.v
appl.equ.Jez
appl.equ.M
appl.equ.Br
appl.equ.Pz
appl.equ.Drz
appl.equ.deltaV
appl.equ.L
appl.equ.magconstrel
appl.equ.elconstrel
```

Now consider an example with two materials. To use other values than the default for the physical properties, enter them as follows.

Scalars such as `sigma` are given as a cell array with the values,

```
appl.equ.sigma={'5.9e7' '0'};
```

Vectors such as `M` are given as a nested cell array with the vector components as elements in the inner cell array,

```
appl.equ.M={{'0' '0'} {'0' '500'}};
```

In the 3D case, the vector has three components,

```
appl.equ.M={{'0' '0' '0'} {'0' '500' '0'}};
```

Tensors or matrix variables are given as cell arrays with the tensor components,

```
appl.equ.mur={{'1' '2'; '3' '4'} {'5' '6' '7' '8'}};
```

This example shows two ways of writing a 2x2 tensor. The first tensor is written row by row with a semicolon separating the rows,

$$\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}$$

while the second tensor is written column by column,

$$\begin{bmatrix} 5 & 7 \\ 6 & 8 \end{bmatrix}$$

There are a number of short-hand ways of writing a tensor. In 2D `{'1' '2'}` is a diagonal tensor

$$\begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix}$$

`{'1' '2' '3'}` is a symmetric tensor

$$\begin{bmatrix} 1 & 2 \\ 2 & 3 \end{bmatrix}$$

and `{'1' '2' '3' '4'}` is the full tensor

$$\begin{bmatrix} 1 & 3 \\ 2 & 4 \end{bmatrix}$$

Similarly in 3D `{'1' '2' '3'}` is a diagonal tensor

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 3 \end{bmatrix}$$

`{'1' '2' '3' '4' '5' '6'}` is a symmetric tensor

$$\begin{bmatrix} 1 & 2 & 4 \\ 2 & 3 & 5 \\ 4 & 5 & 6 \end{bmatrix}$$

and `{'1' '2' '3' '4' '5' '6' '7' '8' '9'}` is the full tensor

$$\begin{bmatrix} 1 & 4 & 7 \\ 2 & 5 & 8 \\ 3 & 6 & 9 \end{bmatrix}$$

Constitutive Relations

In the static and quasi-static application modes three different constitutive relations between both the **D** and **E** fields and the **B** and **H** fields can be used. To specify which ones to use, use the fields `appl.equ.elconstrel` and `appl.equ.magconstrel`. Their values are listed in the table below.

CONSTITUTIVE RELATION	VARIABLE	VALUE
$\mathbf{D} = \varepsilon_0\varepsilon_r\mathbf{E}$	`elconstrel`	`epsr`
$\mathbf{D} = \varepsilon_0\mathbf{E} + \mathbf{P}$	`elconstrel`	`P`
$\mathbf{D} = \varepsilon_0\varepsilon_r\mathbf{E} + \mathbf{D}_r$	`elconstrel`	`Dr`
$\mathbf{B} = \mu_0\mu_r\mathbf{H}$	`magconstrel`	`mur`
$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$	`magconstrel`	`M`
$\mathbf{B} = \mu_0\mu_r\mathbf{H} + \mathbf{B}_r$	`magconstrel`	`Br`
$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$	`magconstrel`	`fH`
$\mathbf{B} = \mu_0\mu_r\mathbf{H} + \mathbf{B}_r$	`magconstrel`	`aniso_fH`

Refractive Index and Relative Permittivity

In the wave application modes, the material data can be given either by the refractive index or the three properties relative permittivity, relative permeability and conductivity. To specify which of the two to use, use the field `appl.equ.matparams`. It takes the value `n` for refractive index and the value `epsr` for the other three properties. For example,

```
appl.equ.matparams = {'n' 'epsr'};
appl.equ.n = {'1.2' '1'};
appl.equ.epsilonr = {'1' '2'};
appl.equ.sigma = {'0' '1e4'};
appl.equ.mur = {'1' '1.1'};
```

specifies the refractive index $n = 1.2$ for the first domain and $\varepsilon_r = 2$, $\sigma = 10^4$ S/m, and $\mu_r = 1.1$ for the second one.

BOUNDARY CONDITIONS

The boundary conditions for the simulation is given in the `appl.bnd` field. First you have to select which type of boundary condition you want at each boundary. This is done using the field `appl.bnd.type`. Then some boundary conditions requires certain boundary variables to be set, unless the default value is sufficient. Note that not all types of boundary conditions require a boundary variable.

For example, the boundary variables defined by the Perpendicular Currents application mode are

```
appl.bnd.J0
appl.bnd.Jn
appl.bnd.H0
appl.bnd.Js0z
appl.bnd.A0z
appl.bnd.eta
appl.bnd.Esz
appl.bnd.sigmabnd
appl.bnd.murbnd
appl.bnd.murtensorbnd
appl.bnd.mutype
appl.bnd.epsilonrbnd
appl.bnd.type
```

The variables are specified using the same form for scalars, vectors, and tensors as above for the subdomain variables.

DOMAIN GROUPS

Often you have a model with several subdomains having the same physical properties and many boundaries where you want to apply the same boundary condition. To simplify the notation, the index vectors in the fields `equ.ind` and `bnd.ind` are used. Consider this example:

```
appl.equ.sigma = {'5.9e7' '0'};
appl.equ.ind = [1 2 1 1 1];
```

Here you have five subdomains. Subdomain 2 is nonconducting, whereas the other four subdomains have the electric conductivity $5.9 \cdot 10^7$ S/m.

Here is another example where three different boundary conditions are applied to six boundaries:

```
appl.bnd.type = {'tH0' 'H' 'A'};
appl.bnd.A0z = {[] [] '100'};
appl.bnd.H0 = {[] {'10' '5'} []};
appl.bnd.ind = [1 2 2 2 3 3];
```

This specifies the magnetic field at boundaries 2, 3, and 4, the magnetic potential at boundaries 5 and 6 and electric insulation at boundary 1. Note that the electric insulation condition does not need any boundary variable to be defined and that we have set the variables to an empty vector where the value is ignored.

There is an alternative syntax for the index vector using a cell array of numeric vectors instead of a single numeric vector as in the examples above. In this case the numeric vectors in the cell array list the domains having the same settings. For example,

```
appl.equ.ind = {[1 3 4 5] 2};
```

is equivalent to

```
appl.equ.ind = [1 2 1 1 1];
```

and

```
appl.bnd.ind = {1 [2 3 4] [5 6]};
```

is equivalent to

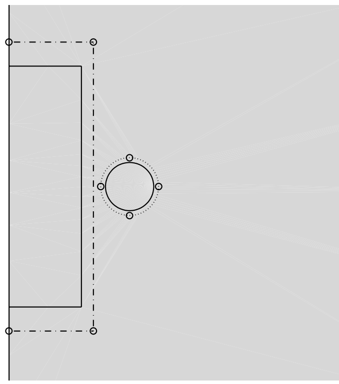
```
appl.bnd.ind = [1 2 2 2 3 3];
```

Eddy Currents in the Programming Language

Next, reproduce the model describing eddy currents in a cylinder in the programming language by creating an application structure and an FEM structure. The application structure contains the physical properties stated above, and the FEM structure contains the geometry, the mesh, and finally the solution vector.

This section extends the example by doing some postprocessing that is not included in the modeling procedure using the graphical user interface. For this purpose, add lines around the cylinder and a circle around the coil as shown in the figure below. These curves do not represent physical boundaries, but you can use them for evaluating a line integral of the magnetic field, in order to calculate the current flowing inside the curve from the integral form of Ampère's law,

$$\oint_C \mathbf{H} \cdot d\mathbf{l} = I$$



PREPROCESSING

Start by clearing the FEM and application structures to avoid accidental use of old data.

```
clear fem appl
```

Give the space dimensions of the problem.

```
fem.sdim={'r' 'z'};
```

Then define the variables to be used in the solution process. When programming it is easy to parameterize a model using workspace variables. If several physical quantities in the model depend on one variable, you can define this variable as a workspace variable.

In this model the current flowing through the coil is `I0`, and the radius of the coil is `rad`. To define these variables and give them a value, just enter

```
I0=1e3;
rad=0.01;
```

You can now define the FEM structure constants that you want to use when defining the domain properties and boundary conditions.

```
fem.const.sigCoil=3.7e7;
fem.const.sigCyl=3.7e7;
fem.const.J0=I0/(pi*rad^2);
fem.const.Js0=I0/(2*pi*rad);
```

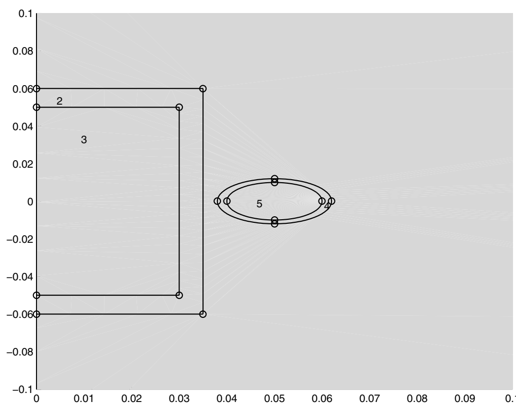
The geometry data is stored in the geom field of the FEM structure. For more details on how to create geometries, see “Geometry Modeling and CAD Tools” on page 23 in the *COMSOL Multiphysics User’s Guide*.

```
c1=circ2(0.05,0,rad);
r1=rect2(0,0.2,-0.25,0.25);
r2=rect2(0,0.03,-0.05,0.05);
r3=rect2(0,0.035,-0.06,0.06);
c5=circ2(0.05,0,0.012);

fem.geom=geomcomp({c1 r1 r2 c2 c3 c4 c5});
```

To verify that the geometry is correct, and to find the domain numbers of the subdomains, enter the commands

```
geomplot(fem,'sublabels','on');
axis([0 0.1 -0.1 0.1]);
```



Similarly you can find the domain numbers of the boundaries by entering the command

```
geomplot(fem,'edgelabels','on');
```

SKIN EFFECT MODELING

It is now time to create the application structure. This is the part where you put the physics into the code. First, define the application mode to be used. Use the Azimuthal currents application mode, just as when modeling in the graphical user interface. The name of that class is AzimuthalCurrents.

```
appl.mode.class='AzimuthalCurrents';
```

To indicate that the problem is axisymmetric, use the `type` field of the application mode.

```
appl.mode.type='axi';
```

The Azimuthal Currents application can handle static, transient, and time-harmonic problems. To specify that a time-harmonic analysis should be performed, set the analysis property.

```
appl.prop.analysis='harmonic';
```

Static analysis is the default that COMSOL Multiphysics would use if you do not specify the analysis property.

The frequency of the source in this model is 100 Hz. Enter the following to use a correct value of the application scalar variable `nu`, the frequency.

```
appl.var.nu=100;
```

Set the symmetry condition at the symmetry axis, and magnetic insulation on all the other boundaries. At the interior boundaries no boundary condition is invoked. Note that the field `appl.bnd.ind` specifies the condition to be used at each boundary. The following means that the first boundary condition applies to boundaries 1, 3, 5, 7, and 9, whereas the second condition is employed at boundaries 2, 11, and 14. The command `zeros(1,22)` creates a vector with 22 zeros, and the next two lines modify some of the elements in the vector.

```
appl.bnd.type={'ax' 'A0'};
appl.bnd.ind=zeros(1,22);
appl.bnd.ind([1 3 5 7 9])=1;
appl.bnd.ind([2 11 14])=2;
```

In the field `appl.bnd.type`, `ax` stands for the axial symmetry boundary condition, and `A0` for the electric insulation boundary condition, which fixes A_φ to zero at the boundary. See page 100 for a complete list of the available boundary conditions.

Apply the current in the coil by using the variable `J0`. Specify the electric conductivity in the coil and cylinder too, but use the default values for the dielectric and magnetic properties. The field `appl.equ.ind` specifies that the first value applies to subdomains 1, 2, and 4, the second value to subdomain 3 and the last value to subdomain 5.

```
appl.equ.sigma={'0' 'sigCyl' 'sigCoil'};
appl.equ.Jephi={'0' '0' 'J0'};
appl.equ.ind=[1 1 2 1 3];
```

Generate the corresponding fields in the FEM structure by calling the function `multiphysics`.

```
fem.appl=appl;
fem=multiphysics(fem);
```

Initialize the mesh by invoking the function `meshinit` and then create the extended mesh by invoking `meshextend`. For more details on creating meshes see the entries of the functions `meshinit`, `meshrefine` and `meshextend` in the *Command Reference*.

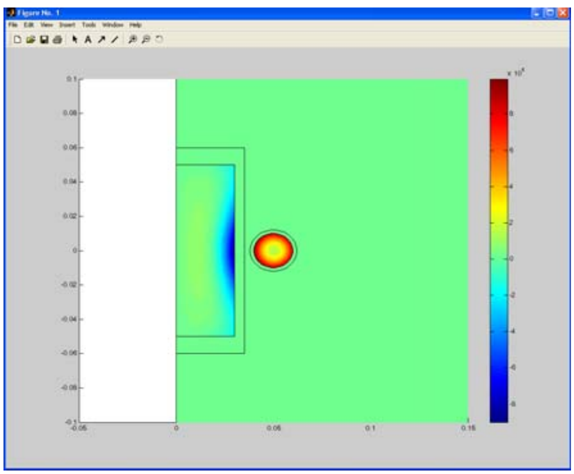
```
fem.mesh=meshinit(fem);
fem.xmesh=meshextend(fem);
```

Use the adaptive solver for solving this problem. Set the number of adaptive refinements to 2.

```
fem=adaption(fem,...
    'ngen',2,'report','on');
```

Visualize the result as a surface plot.

```
postplot(fem,'tridata','Jphi','tribar','on')
axis([-0.05 0.15 -0.1 0.1]);
```



SURFACE CURRENTS MODELING

This problem can also be modeled using surface currents, as described on page 21 in the *AC/DC User's Guide*. You simply set the electric conductivity in the coil to zero, and specify boundary conditions on the interior boundaries surrounding the coil.

The conductivity in the coil is modified by entering

```
fem.const.sigCoil=0;
```

The new boundary conditions are invoked by entering the following. To enable the conditions at interior boundaries, the `appl.border` field is used.

```
appl.bnd.type={'ax' 'A0' 'Js'};
appl.bnd.Js0phi={[] [] 'Js0'};
appl.bnd.ind([17 18 20 21])=3;
appl.border='on';
```

You must also remove the source on the subdomain representing the coil

```
appl.equ.Jephi={'0' '0' '0'};
```

The new PDE system can be generated when the `fem.appl` field is updated.

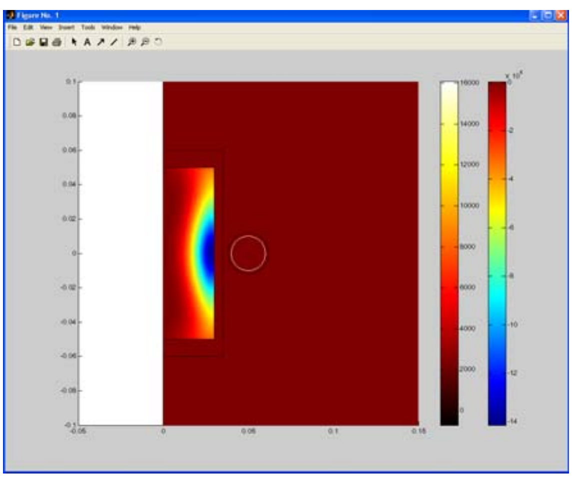
```
fem.appl=appl;
fem=multiphysics(fem);
fem.xmesh=meshextend(fem);
```

The adaptively refined mesh can be used for solving this problem too. Simply call the linear solver.

```
fem.sol=femlin(fem);
```

A similar plot as before, but without any current density in the coil domain can be obtained. To see the surface currents, use a line plot.

```
postplot(fem,'tridata','Jphi','tribar','on',...
  'lindata','Jsphi','linmap','hot')
axis([-0.05 0.15 -0.1 0.1]);
```



POSTPROCESSING

There are functions for both evaluation and integration available in COMSOL Multiphysics. In the AC/DC Module there are some special functions for computing forces and torques.

To compute the total current in the coil and cylinder, respectively, you can use the integration function `postint`. Additionally, an interpolation function, `postinterp`, is available. `postinterp` allows you to transform your solution from one mesh to another.

You can now obtain the total currents in both domains using either surface integrals or line integrals. The induced current in the cylinder is obtained by integrating over the domain representing the cylinder

```
Iind0=postint(fem,'Jphi','dl',3)
```

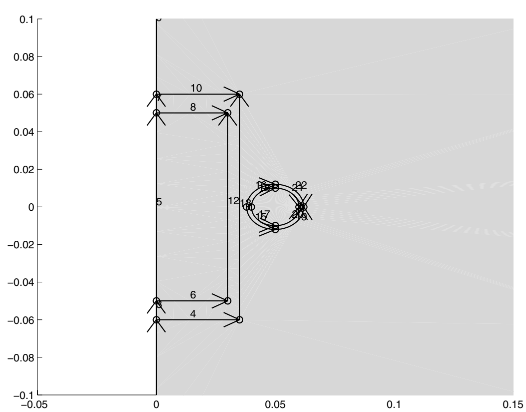
which gives the result

```
Iind0 =

-967.54 - 47.00i
```

Using line integrals over the two line meshes, it is possible to obtain the total currents in the coil and cylinder, respectively. For the integration, use the components `tr` and `tz` of the tangential vector. To find out in which direction the tangential vector is pointing along the boundaries, enter the commands

```
geomplot(fem,'edgelabels','on','edgearrows','on')
axis([-0.05 0.15 -0.1 0.1]);
```



A line integral around the cylinder is evaluated by entering

```
Iind=postint(fem,'tr*Hr+tz*Hz','dl',[3 5 7 10],'edim',1)...
  -postint(fem,'tr*Hr+tz*Hz','dl',[4 13],'edim',1);
```

Similarly, compute the line integral around the coil by entering

```
I=postint(fem,'tr*Hr+tz*Hz','dl',[16 22],'edim',1)...
  -postint(fem,'tr*Hr+tz*Hz','dl',[15 19],'edim',1);
```

The results are

```
Iind =

-965.06 - 46.19i

I =

999.11 - 0.04i
```

For more examples of postprocessing functionality, see the chapter "Postprocessing and Visualization" in the *COMSOL Multiphysics User's Guide*.

PARAMETRIC STUDY

You can also make a simple parametric study. Leaving the total current unchanged in the coil but altering the radius of the coil is one example of such a study. This invokes parameterization of both the geometry and the equation system.

In this study, use a geometry without the additional nonphysical interior boundaries. You therefore first have to regenerate the PDE system. Do this by modifying the FEM and application structures created earlier:

```
fem.geom=geomcomp({c1 r1 r2});
appl.bnd.ind=[1 2 1 0 1 0 2 0 2 3 3 3 3];
appl.equ.ind=1:3;
fem.appl=appl;
fem=multiphysics(fem);
```

Then enter the following commands to perform the parametric study.

```
dQ=zeros(1,0);
for rad=0.005:0.001:0.015
  % Set Js0
  fem.const.Js0=I0/(2*pi*rad);

  % Generate geometry
  c1=circ2(0.05,0,rad);
  fem.geom=geomcomp({c1 r1 r2});

  % Generate mesh
```

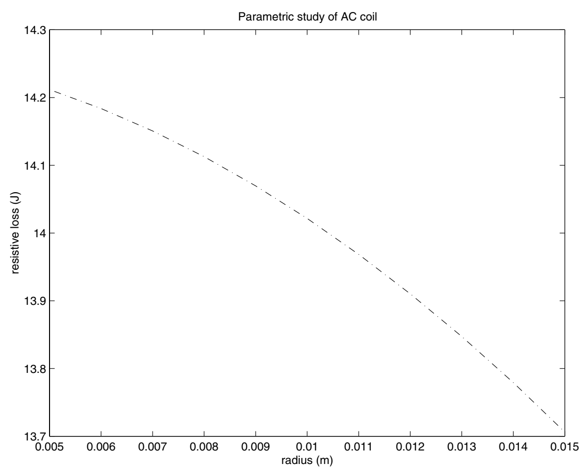
```
    fem.mesh=meshinit(fem);
    fem.mesh=meshrefine(fem);
    fem.xmesh=meshextend(fem);

    % Solve problem
    fem.sol=femlin(fem);

    % Compute resistive loss
    Q=postint(fem,'Qav','dl',2);
    dQ=[dQ Q];
  end
```

The following commands create a plot of the results:

```
  plot([0.005:0.001:0.015],dQ,'-.');
  title('Parametric study of AC coil')
  xlabel('radius (m)')
  ylabel('resistive loss (J)')
```



MULTIPHYSICS MODELING

The inductive heating generated in the cylinder increases the temperature there. This affects the electric conductivity of the copper, so that the generated heat is a function of both the temperature and the electromagnetic fields. This means that when modeling this phenomenon, you must solve the heat transfer simulation together with the electromagnetic field simulation to take the nonlinear effects into account.

For details on how to do this, see "Inductive Heating of a Copper Cylinder" on page 16 in the *AC/DC Module Model Library.*

Application Mode Programming Reference

This reference chapter tabulates the application mode dependent fields of the application structure. For each application mode these are the following sections:

- *Dependent variables*, which gives the variables in `appl.dim`. In the COMSOL Multiphysics graphical user interface (GUI) you find these variables in the **Dependent variables** edit field in the Model Navigator.
- *Application mode class and name*, which specifies the values to use in `appl.mode` and gives the default value of `appl.name`. In the GUI, `appl.name` appears in the **Application mode name** edit field in the Model Navigator.
- *Scalar variables*, which specifies the variables in `appl.var`. The corresponding GUI dialog box is the **Application Scalar Variables** dialog box.
- *Properties*, which specifies all fields in `appl.prop`, for example which type of analysis to perform or which elements to use. In the GUI you find the properties in the **Application Mode Properties** dialog box.
- *Subdomain/Boundary/Edge/Point Variables*, which specifies the variables available in `appl.equ`, `appl.bnd`, `appl.edg`, `appl.pnt`. The GUI dialog boxes corresponding to these fields are the **Subdomain Settings**, **Boundary Settings**, **Edge Settings**, and **Point Settings** dialog boxes, respectively.
- *Boundary Conditions*, which specifies which type of boundary conditions are available and which boundary variables are significant for each boundary condition. In the user interface, the boundary condition types correspond to the items in the **Boundary condition** list in the **Boundary Settings** dialog box.

See also the chapter “The Programming Language” on page 60 for a general discussion of the various fields in the application structure.

Conductive Media DC

DEPENDENT VARIABLES

FIELD	DEFAULT	DESCRIPTION
`appl.dim`	`{'V'}`	Electric potential

APPLICATION MODE CLASS AND NAME

FIELD	VALUE	DEFAULT
`appl.mode.class`	`EmConductiveMediaDC`	
`appl.name`		`emdc`

PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.prop.elemdefault`	`Lag1 | Lag2 | Lag3 | Lag4 | Lag5`	`Lag2`	Default element type. Lagrange elements of order 1 to 5.
`appl.prop.weakconstr`	`off | ideal | non-ideal`	`off`	The type of weak constraints to use.

SUBDOMAIN VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.equ.sigma`	expression or cell array of expressions	`5.99e7`	Electric conductivity
`appl.equ.sigrel`	`sigma | res0`	`sigma`	Use expression for conductivity or resistivity
`appl.equ.Qj`	expression	`0`	Current source
`appl.equ.Je`	cell array of expressions	`0`	External current density
`appl.equ.res0`	expression	`1.72e-8`	Resistivity at reference temperature
`appl.equ.T`	expression	`0`	Temperature
`appl.equ.T0`	expression	`0`	Reference temperature
`appl.equ.alpha`	expression	`0`	Temperature coefficient

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.equ.d`	expression	1	Thickness (2D only)
`appl.equ.Stype`	String	`none`	Infinite element type
`appl.equ.Sd`	cell array of expressions		Width of infinite element region
`appl.equ.S0`	cell array of expressions		Inner coordinate for infinite element region
`appl.equ.R0`	expression		Inner radius for infinite element region
`appl.equ.srcpnt`	cell array of expressions	`0 0 0`	Center point for infinite elements
`appl.equ.srcaxis`	cell array of expressions	`0 0 1`	Center axis for infinite elements
`appl.equ.coord0n`	cell array of strings	`0 0 0`	Stretched in direction
`appl.equ.r0n`	string	`0`	Stretched in r-direction
`appl.equ.user`	cell array of expressions		User-defined coordinates

BOUNDARY VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.bnd.J0`	cell array of expression	0	Current density
`appl.bnd.Jn`	expression	0	Normal current density
`appl.bnd.V0`	expression	0	Electric potential
`appl.bnd.sigmabnd`	expression	0	Electric conductivity
`appl.bnd.dbnd`	expression	1	Thickness
`appl.bnd.Vref`	expression	0	Reference potential
`appl.bnd.I0`	expression	0	Source current
`appl.bnd.inport`	string	0	Use as inport?
`appl.bnd.portnr`	string	1	Port number
`appl.bnd.type`	string	`V0 | cont`	The type of boundary condition
`appl.bnd.pertype`	string	`sym`	The type of periodic boundary condition
`appl.bnd.chsrcdst`	string	0	Change source and destination

`appl.bnd.type` takes the default value `V0` on exterior boundaries and `cont` on interior boundaries.

BOUNDARY CONDITIONS

DESCRIPTION	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Current flow	`J`	`J0`	Current density
Inward current flow	`nJ`	`Jn`	Normal current density

Distributed resistance	`ss`	`sigmabnd`
		`dbnd`
		`Vref`
			Conductivity
			Thickness
			Reference potential

Electric insulation	`nJ0`		
Current source	`dnJ`	`Jn`	Normal current density
Continuity	`cont`		

DESCRIPTION	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Electric potential	V	V0	Electric potential
Ground	V0		
Electric shielding	sh	sigmabnd d	Conductivity Thickness
Floating potential	fp	I0	Source current
Port	port	portnr inport	Port number Use as inport?
Axial symmetry	ax		
Periodic boundary	periodic	pertype chsrcdst	Type Change src/dst
Circuit terminal	term		

The **Type** column indicates the possible values for `appl.bnd.type`.

EDGE VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.edg.type`	`V0 | Qj0`	`Qj0`	The type of point condition
`appl.edg.Qlj`	expression	0	Line current source
`appl.edg.V0`	expression	0	Electric potential

POINT VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.pnt.type`	`V0 | Qj0`	`Qj0`	The type of point condition
`appl.pnt.V0`	expression	0	Electric potential
`appl.pnt.Qj0`	expression	0	Point current source

Shell, Conductive Media DC

DEPENDENT VARIABLES

FIELD	DEFAULT	DESCRIPTION
`appl.dim`	`{'V'}`	Electric potential

APPLICATION MODE CLASS AND NAME

FIELD	VALUE	DEFAULT
`appl.mode.class`	`CondMediaShell`	
`appl.name`		`emdcsh`

PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.prop.elemdefault`	`Lag1 | Lag2 | Lag3 | Lag4 | Lag5`	`Lag2`	Default element type. Lagrange elements of order 1 to 5.
`appl.prop.weakconstr`	`off | ideal | non-ideal`	`off`	The type of weak constraints to use.

BOUNDARY VARIABLES

See subdomain variables of Conductive Media DC

EDGE VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.edg.Jn`	expression	0	Normal current density
`appl.edg.V0`	expression	0	Electric potential
`appl.edg.sigmabnd`	expression	0	Electric conductivity
`appl.edg.dedg`	expression	1	Thickness

EDGE CONDITIONS

DESCRIPTION	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Inward current flow	`nJ`	`Jn`	Normal current density
Electric insulation/ Continuity	`nJ0`		
Electric potential	`V`	`V0`	Electric potential
Ground	`V0`		
Electric shielding	`sh`	`sigmabnd` `d`	Conductivity Thickness

POINT VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.pnt.type`	`V0 | Qj0`	`Qj0`	The type of point condition
`appl.pnt.V0`	expression	0	Electric potential
`appl.pnt.Qj0`	expression	0	Point current source

Electrostatics

DEPENDENT VARIABLES

FIELD	DEFAULT	DESCRIPTION
`appl.dim`	`{'V'}`	Electric potential

APPLICATION MODE CLASS AND NAME

FIELD	VALUE	DEFAULT
`appl.mode.class`	`EmElectrostatics`	
`appl.name`		`emes`

SCALAR VARIABLES

FIELD	DEFAULT	DESCRIPTION
`appl.var.epsilon0`	`8.854187817e-12`	Permittivity of vacuum

PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.prop.elemdefault`	`Lag1 | Lag2 | Lag3 | Lag4 | Lag5`	`Lag2`	Default element type. Lagrange elements of order 1 to 5.
`appl.prop.weakconstr`	`off | ideal | non-ideal`	`off`	The type of weak constraints to use.

SUBDOMAIN VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.equ.epsilonr`	expression | cell array of expressions	1	Relative permittivity
`appl.equ.rho`	expression	0	Space charge density
`appl.equ.P`	cell array of expressions	0	Electric polarization
`appl.equ.Dr`	cell array of expressions	0	Remanent displacement
`appl.equ.elconstrel`	`epsr | P | Dr`	`epsr`	Constitutive relation

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.equ.maxwell`	cell array of expressions		Force variables
`appl.equ.nTsrcpnt`	cell array of expressions	`0 0 0`	Center point for torque
`appl.equ.nTsrcaxis`	cell array of expressions	`0 0 1`	Center axis for torque
`appl.equ.Stype`	String	`none`	Infinite element type
`appl.equ.Sd`	cell array of expressions		Width of infinite element region
`appl.equ.S0`	cell array of expressions		Inner coordinate for infinite element region
`appl.equ.R0`	expression		Inner radius for infinite element region
`appl.equ.srcpnt`	cell array of expressions	`0 0 0`	Center point for infinite elements
`appl.equ.srcaxis`	cell array of expressions	`0 0 1`	Center axis for infinite elements
`appl.equ.coordOn`	cell array of strings	`0 0 0`	Stretched in direction
`appl.equ.rOn`	string	`0`	Stretched in r-direction
`appl.equ.user`	cell array of expressions		User defined coordinates

BOUNDARY VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.bnd.D0`	cell array of expressions	0	Electric displacement
`appl.bnd.rhos`	expression	0	Surface charge density
`appl.bnd.V0`	expression	0	Electric potential
`appl.bnd.d`	expression	0	Thickness
`appl.bnd.Q0`	expression	0	Total charge
`appl.bnd.inport`	string	`0 | 1`	Use as inport?
`appl.bnd.portnr`	string	1	Port number
`appl.bnd.type`	string	`V0 | cont`	The type of boundary condition
Periodic boundary	`periodic`	`pertype` `chsrcdst`	Type Change src/dst

`appl.bnd.type` takes the default value `V0` on exterior boundaries and `cont` on interior boundaries.

BOUNDARY CONDITIONS

DESCRIPTION	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Electric displacement	D	D0	Electric displacement
Surface charge	r	rhos	Surface charge density
Zero charge/ Symmetry	nD0		
Continuity	cont		
Electric potential	V	V0	Electric potential
Ground	V0		
Electric shielding	sh	rhos d	Surface charge density Thickness
Floating potential	fp	Q0	Total charge
Port	port	portnr inport	Port number Use as inport?
Axial symmetry	ax		
Periodic boundary	periodic	pertype chsrcdst	Type Change src/dst

The **Type** column indicates the possible values for `appl.bnd.type`.

EDGE VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.edg.type	V | Q	Q	The type of point condition
appl.edg.Ql	expression	0	Line charge
appl.edg.V0	expression	0	Electric potential

POINT VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.pnt.type	V | Q	Q	The type of point condition
appl.pnt.V0	expression	0	Electric potential
appl.pnt.Q0	expression	0	Point charge

Electrostatics, Generalized

DEPENDENT VARIABLES

FIELD	DEFAULT	DESCRIPTION
`appl.dim`	`{'V'}`	Electric potential

APPLICATION MODE CLASS AND NAME

FIELD	VALUE	DEFAULT
`appl.mode.class`	`ElectrostaticsGeneralized`	
`appl.name`		`emqv`

SCALAR VARIABLES

FIELD	DEFAULT	DESCRIPTION
`appl.var.epsilon0`	`8.854187817e-12`	Permittivity of vacuum
`appl.var.mu0`	`4*pi*1e-7`	Permeability of vacuum
`appl.var.T`	`1e-17`	Time constant

PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.prop.elemdefault`	`Lag1 | Lag2 | Lag3 | Lag4 | Lag5`	`Lag2`	Default element type. Lagrange elements of order 1 to 5.
`appl.prop.weakconstr`	`off | ideal | non-ideal`	`off`	The type of weak constraints to use.

SUBDOMAIN VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.equ.sigma`	expression | cell array of expressions	0	Electric conductivity, isotropic
`appl.equ.epsilonr`	expression | cell array of expressions	1	Relative permittivity, isotropic
`appl.equ.rho0`	expression	0	Space charge density
`appl.equ.Je`	cell array of expressions	0	External current density

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.equ.P	cell array of expressions	0	Electric polarization
appl.equ.Dr	cell array of expressions	0	Remanent displacement
appl.equ.elconstrel	epsr | P | Dr	epsr	Constitutive relation

BOUNDARY VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.bnd.J0	cell array of expression	0	Current density
appl.bnd.Jn	expression	0	Normal current density
appl.bnd.D0	cell array of expressions	0	Electric displacement
appl.bnd.rhos	expression	0	Surface charge density
appl.bnd.q	expression	0	Conductance to ground
appl.bnd.g0	expression	0	Normal flow
appl.bnd.V0	expression	0	Electric potential
appl.bnd.sigmabnd	expression	0	Electric conductivity
appl.bnd.d	expression	1	Thickness
appl.bnd.Vref	expression	0	Reference potential
appl.bnd.type	string	V0 | cont	The type of boundary condition

appl.bnd.type takes the default value V0 on exterior boundaries and cont on interior boundaries.

BOUNDARY CONDITIONS

DESCRIPTION	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Current flow	J	J0	Current density
Inward current flow	nJ	Jn	Normal current density

DESCRIPTION	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION

Distributed resistance	`ss`	`sigmabnd`
		`d`
		`Vref`
			Conductivity
			Thickness
			Reference potential

Electric displacement	`D`	`D0`	Electric displacement
Surface charge	`r`	`rhos`	Surface charge density

General flow	`n`	`q`
		
		`g0`
			Conductance to ground
			Normal flow

Electric insulation	`n0`		
Current source	`dnJ`	`Jn`	Normal current density

General source	`dn`	`q`
		
		`g0`
			Conductance to ground
			Normal flow

Continuity	`cont`		
Electric potential	`V`	`V0`	Electric potential
Ground	`V0`		
Axial symmetry	`ax`		

The **Type** column indicates the possible values for `appl.bnd.type`.

EDGE VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.edg.Ql`	expression	0	Line charge
`appl.edg.Qlj`	expression	0	Line current source

POINT VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.pnt.type`	V | Q	Q	The type of point condition
`appl.pnt.V0`	expression	0	Electric potential
`appl.pnt.Q0`	expression	0	Point charge
`appl.pnt.Qj0`	expression	0	Point current source

3D and 2D Quasi-Statics

DEPENDENT VARIABLES

FIELD	DEFAULT	DESCRIPTION
`appl.dim`	`{'V','Ax','Ay','Az','psi'}`	Electric and magnetic potential and gauge fixing variable. `Az` is not available in 2D. For axisymmetric models the default magnetic potential variables are `Ar` and `Az`.

All dependent variables have to be specified including those that are not in use, for example when using only the magnetic potential in magnetostatics or quasi-statics.

APPLICATION MODE CLASS AND NAME

FIELD	VALUE	DEFAULT
appl.mode.class	QuasiStatics	
appl.name		emqa | emqav | emqvw | emqap

In 3D the default value for `appl.name` is `emqa` for magnetostatics, `emqav` for quasi-statics, and `emqvw` for quasi-statics with small currents. In 2D the default value for `appl.name` is `emqvw` for small currents and `emqap` otherwise.

SCALAR VARIABLES

FIELD	DEFAULT	DESCRIPTION
appl.var.epsilon0	8.854187817e-12	Permittivity of vacuum
appl.var.mu0	4*pi*1e-7	Permeability of vacuum
appl.var.nu	50	Frequency
appl.var.psi0	psi0_guess	Gauge variable scaling

PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.prop.analysis	static | harmonic | smallcurr | transsmallcurr	harmonic	Analysis type, magnetostatic, quasi-static, or quasi-static with small currents
appl.prop.potential	VA | A	VA	Which potential to use as dependent variables, only the magnetic potential or both.
appl.prop.biasapplmode	none | string	none	Use selected application mode as bias

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.prop.gaugefix	on | off | auto	auto	Only in 3D. Specifies if gauge fixing should be added.
appl.prop.elemdefault	Vec1 | Vec2 | Vec3 | Vec1_lag1 | Vec2_lag2 | Vec3_lag3 | Lag1 | Lag2 | Lag3 | Lag4 | Lag5	Vec1 | Vec2 | Vec1_lag1 | Vec2_lag2 | Lag2	Default element type.

SUBDOMAIN VARIABLES

FIELD	DIMENSION	VALUE	DEFAULT	DESCRIPTION
appl.equ.sigma	3D, 2D	expression | cell array of expressions	0	Electric conductivity, isotropic
appl.equ.mur	3D, 2D	expression	1	Relative permeability, isotropic
appl.equ.epsilonr	3D, 2D	expression	1	Relative permittivity, isotropic
appl.equ.v	3D, 2D	cell array of expressions	0	Velocity
appl.equ.Je	3D, 2D	cell array of expressions	0	External current density
appl.equ.M	3D	cell array of expressions	0	Magnetization
appl.equ.Mz	2D	expression	0	Magnetization
appl.equ.Mphi	2D axi	expression	0	Magnetization
appl.equ.Br	3D	cell array of expressions	0	Remanent flux density
appl.equ.Brz	2D	expression	0	Remanent flux density
appl.equ.Brphi	2D axi	expression	0	Remanent flux density
appl.equ.P	3D, 2D	cell array of expressions	0	Electric polarization
appl.equ.Dr	3D, 2D	cell array of expressions	0	Remanent displacement

FIELD	DIMENSION	VALUE	DEFAULT	DESCRIPTION
`appl.equ.magconstrel`	3D, 2D	`mur	M	Br	fH	aniso_fH`	`mur`	Magnetic constitutive relation
`appl.equ.elconstrel`	3D, 2D	`epsr	P	Dr`	`epsr`	Electric constitutive relation
`appl.equ.normfH`	3D, 2D	expression		Nonlinear expression for normH
`appl.equ.fH`	3D, 2D	cell array of expressions		Nonlinear expression for H
`appl.equ.maxwell`	3D, 2D	cell array of expressions		Force variables
`appl.equ.Stype`	3D, 2D	String	`none`	Infinite element type
`appl.equ.Sd`	3D, 2D	cell array of expressions		Width of infinite element region
`appl.equ.S0`	3D, 2D	cell array of expressions		Inner coordinate for infinite element region
`appl.equ.R0`	3D, 2D	expression		Inner radius for infinite element region
`appl.equ.srcpnt`	3D, 2D	cell array of expressions	`0 0 0`	Center point for infinite elements
`appl.equ.srcaxis`	3D	cell array of expressions	`0 0 1`	Center axis for infinite elements
`appl.equ.coordOn`	3D, 2D	cell array of strings	`0 0 0`	Stretched in direction
`appl.equ.rOn`	3D, 2D	string	`0`	Stretched in r-direction
`appl.equ.user`	3D, 2D	cell array of expressions		User-defined coordinates

BOUNDARY VARIABLES

FIELD	DIMENSION	VALUE	DEFAULT	DESCRIPTION
`appl.bnd.J0`	3D, 2D	cell array of expression	0	Current density
`appl.bnd.Jn`	3D, 2D	expression	0	Normal current density
`appl.bnd.H0`	3D	cell array of expressions	0	Magnetic field
`appl.bnd.H0z`	2D	expression	0	Magnetic field
`appl.bnd.H0phi`	2D axi	expression	0	Magnetic field

FIELD	DIMENSION	VALUE	DEFAULT	DESCRIPTION
`appl.bnd.Js0`	3D, 2D	cell array of expressions	0	Surface current density
`appl.bnd.A0`	3D, 2D	cell array of expressions	0	Magnetic potential
`appl.bnd.V0`	3D, 2D	expression	0	Electric potential
`appl.bnd.d`	3D, 2D	expression	1	Thickness
`appl.bnd.Vref`	3D, 2D	expression	0	Reference potential
`appl.bnd.eta`	3D, 2D	expression	1	Surface impedance
`appl.bnd.Es`	3D, 2D	cell array of expressions	0	Surface electric field
`appl.bnd.sigmabnd`	3D, 2D	expression | cell array of expressions	0	Electric conductivity, isotropic
`appl.bnd.murbnd`	3D, 2D	expression | cell array of expressions	1	Relative permeability, isotropic
`appl.bnd.epsilonrbnd`	3D, 2D	expression | cell array of expressions	1	Relative permittivity, isotropic
`appl.bnd.I0`	3D, 2D	`expression`	0	Source current
`appl.bnd.eltype`	3D, 2D	string	`V0 | cont`	The type of boundary condition for the electric field
`appl.bnd.magtype`	3D, 2D	string	`A0 | cont`	The type of boundary condition for the magnetic field
Periodic boundary	`3D, 2D`	`periodic`	`pertype` `chsrcdst`	Type Change src/dst

`appl.bnd.eltype` takes the default value `V0` on exterior boundaries and `cont` on interior boundaries. `appl.bnd.magtype` takes the default value `A0` on exterior boundaries and `cont` on interior boundaries.

BOUNDARY CONDITIONS FOR THE ELECTRIC FIELD

DESCRIPTION	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Current flow	`J`	`J0`	Current density
Inward current flow	`nJ`	`Jn`	Normal current density

Distributed resistance	`ss`	`sigmabnd`
		`sigmatensorbnd`
		`sigmatype`
		`epsilonrbnd`
		`epsrtensorbnd`
		`epstype`
		`d`
		`Vref`
			Conductivity
			Relative permittivity (only for time-harmonic problems)
			Thickness
			Reference potential

Electric insulation	`nJ0`		
Current source	`dnJ`	`Jn`	Normal current density
Continuity	`cont`		
Electric potential	`V`	`V0`	Electric potential
Ground	`V0`		

Electric Shielding	`sh`	`sigmabnd`
		`epsilonrbnd`
		`d`
			Conductivity
			Relative permittivity
			Thickness

Floating potential	`fp`	`I0`	Source current
Axisymmetry	`ax`		Only in 2D axisymmetry
Periodic boundary	`periodic`	`pertype` `chsrcdst`	Type Change src/dst

The **Type** column indicates the possible values for `appl.bnd.eltype`.

BOUNDARY CONDITIONS FOR THE MAGNETIC FIELD

DESCRIPTION	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Magnetic field	`H`	`H0`	Magnetic field
Surface current	`Js`	`Js0`	Surface current density
Electric insulation	`tH0`		
Continuity	`cont`		
Magnetic potential	`A`	`A0`	Magnetic potential
Magnetic insulation	`A0`		

Impedance boundary condition	`IM`	`Es`
		`sigmabnd`
		`epsilonrbnd`
		`murbnd`
			Surface electric field
			Conductivity
			Relative permittivity
			Relative permeability

Transition boundary condition	`sIM`	`Es` `eta`	Surface electric field Surface impedance
Axisymmetry boundary condition	`ax`		Only in 2D axisymmetry
Periodic boundary	`periodic`	`pertype` `chsrcdst`	Type Change src/dst

The **Type** column indicates the possible values for `appl.bnd.magtype`.

EDGE VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.edg.I0`	expression	0	Current, only available in 3D

POINT VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.edg.V0`	expression	0	Electric potential

Perpendicular and Azimuthal Currents

DEPENDENT VARIABLES

Variables for Perpendicular Currents.

FIELD	DEFAULT	DESCRIPTION
`appl.dim`	`{'Az'}`	Magnetic potential, z component

Variables for Azimuthal Currents.

FIELD	DEFAULT	DESCRIPTION
`appl.dim`	`{'Aphidr'}`	Magnetic potential, φ component divided by r

APPLICATION MODE CLASS AND NAME

Class and name for Perpendicular Currents.

FIELD	VALUE	DEFAULT
`appl.mode.class`	`PerpendicularCurrents`	
`appl.name`		`emqa`

Class and name for Azimuthal Currents.

FIELD	VALUE	DEFAULT
`appl.mode.class`	`AzimuthalCurrents`	
`appl.name`		`emqa`

SCALAR VARIABLES

FIELD	DEFAULT	DESCRIPTION
`appl.var.epsilon0`	`8.854187817e-12`	Permittivity of vacuum
`appl.var.mu0`	`4*pi*1e-7`	Permeability of vacuum
`appl.var.nu`	`50`	Frequency

PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.prop.analysis	static | transient | harmonic	static	Analysis type, magnetostatic, transient quasi-static, or time-harmonic quasi-static
appl.prop.biasapplmode	none | string	none	Use specified application mode as bias
appl.prop.elemdefault	Lag1 | Lag2 | Lag3 | Lag4 | Lag5	Lag2	Default element type. Lagrange elements of order 1 to 5.
appl.prop.weakconstr	off | ideal | non-ideal	off	The type of weak constraints to use.

SUBDOMAIN VARIABLES

FIELD	APPL. MODE	VALUE	DEFAULT	DESCRIPTION
appl.equ.sigma		expression	0	Electric conductivity
appl.equ.mur		expression | cell array of expressions	1	Relative permeability
appl.equ.epsilonr		expression	1	Relative permittivity
appl.equ.v		cell array of expressions	0	Velocity
appl.equ.Jez	Perpendicular	expression	0	External current density
appl.equ.Jephi	Azimuthal	expression	0	External current density
appl.equ.M		cell array of expressions	0	Magnetization
appl.equ.Br		cell array of expressions	0	Remanent flux density
appl.equ.Pz	Perpendicular	expression	0	Electric polarization
appl.equ.Pphi	Azimuthal	expression	0	Electric polarization
appl.equ.Drz	Perpendicular	expression	0	Remanent displacement
appl.equ.Drphi	Azimuthal	expression	0	Remanent displacement

FIELD	APPL. MODE	VALUE	DEFAULT	DESCRIPTION
appl.equ.deltaV	Perpendicular	expression	0	Potential difference
appl.equ.L	Perpendicular	expression	1	Length
appl.equ.Vloop	Azimuthal	expression	0	Loop potential
appl.equ.magconstrel		mur | M | Br | fH | aniso_fH	mur	Magnetic constitutive relation
appl.equ.elconstrel		epsr | P | Dr	epsr	Electric constitutive relation
appl.equ.maxwell		cell array of expressions		Force variables
appl.equ.normfH		expression		Nonlinear expression for normH
appl.equ.fH		cell array of expressions		Nonlinear expression for H
appl.equ.Stype		String	none	Infinite element type
appl.equ.Sd		cell array of expressions		Width of infinite element region
appl.equ.S0		cell array of expressions		Inner coordinate for infinite element region
appl.equ.R0		expression		Inner radius for infinte element region
appl.equ.srcpnt		cell array of expressions	0 0 0	Center point for infinite elements
appl.equ.coordOn		cell array of strings	0 0 0	Stretched in direction
appl.equ.rOn		string	0	Stretched in r-direction
appl.equ.user		cell array of expressions		User-defined coordinates

BOUNDARY VARIABLES

FIELD	APPL., MODE	VALUE	DEFAULT	DESCRIPTION
appl.bnd.J0		cell array of expression	0	Current density
appl.bnd.Jn		expression	0	Normal current density
appl.bnd.H0		cell array of expressions	0	Magnetic field

FIELD	APPL., MODE	VALUE	DEFAULT	DESCRIPTION
appl.bnd.Js0z	Perpendicular	expression	0	Surface current density
appl.bnd.Js0phi	Azimuthal	expression	0	Surface current density
appl.bnd.A0z	Perpendicular	expression	0	Magnetic potential
appl.bnd.A0phi	Azimuthal	expression	0	Magnetic potential
appl.bnd.eta		expression	1	Surface impedance
appl.bnd.Esz	Perpendicular	expression	0	Surface electric field
appl.bnd.Esphi	Azimuthal	expression	0	Surface electric field
appl.bnd.sigmabnd		expression	0	Electric conductivity
appl.bnd.murbnd		expression	1	Relative permeability, isotropic
appl.bnd.murtensorbnd		cell array of expressions	1	Relative permeability, anisotropic
appl.bnd.mutype		iso | aniso	iso	Indicates if the permeability is isotropic or anisotropic
appl.bnd.epsilonrbnd		expression	1	Relative permittivity, isotropic
appl.bnd.type		string	A0 | cont	The type of boundary condition
appl.bnd.pertype	Perpendicular	sym | antisym	sym	Type of periodic boundary
appl.bnd.chsrcdst	Perpendicular	0 | 1	0	Change source and destination
appl.bnd.index	Perpendicular	string	0	Index for sector symmetry
appl.bnd.nsect	Perpendicular	Integer	2	Number of sectors

`appl.bnd.type` takes the default value `A0` on exterior boundaries and `cont` on interior boundaries.

BOUNDARY CONDITIONS

DESCRIPTION	APPL. MODE	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Magnetic field		H	H0	Magnetic field
Surface current	Perpendicular	Js	Js0z	Surface current density

DESCRIPTION	APPL. MODE	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Surface current	Azimuthal	Js	Js0phi	Surface current density
Electric insulation		tH0		
Continuity		cont		
Magnetic potential	Perpendicular	A	A0z	Magnetic potential
Magnetic potential	Azimuthal	A	A0phi	Magnetic potential
Magnetic insulation		A0		
Impedance boundary condition		IM	Es sigmabnd epsilonrbnd murbnd murtensorbnd mutype	Surface electric field Conductivity Relative permittivity Relative permeability
Transition boundary condition		sIM	Es eta	Surface electric field Surface impedance
Axial symmetry	Azimuthal	ax		
Periodic boundary	Perpendicual	periodic	pertype chsrcdst	Type Change src/dst
Sector symmetry	Perpendicular	sector	nsect index	Number of sectors Group index
Sector antisymmetry	Perpendicular	antisector	nsect index	Number of sectors Group index

The **Type** column indicates the possible values for `appl.bnd.type`.

POINT VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.pnt.I0`	expression	0	Current

In-Plane and Meridional Currents, Magnetic Field

DEPENDENT VARIABLES

Variables for In-Plane Currents, Magnetic Field.

FIELD	DEFAULT	DESCRIPTION
`appl.dim`	`{'Hz'}`	Magnetic field, z component

Variables for Meridional Currents, Magnetic Field.

FIELD	DEFAULT	DESCRIPTION
`appl.dim`	`{'Hphidr'}`	Magnetic field, φ component divided by r

APPLICATION MODE CLASS AND NAME

Class and name for In-Plane Currents.

FIELD	VALUE	DEFAULT
`appl.mode.class`	`InPlaneCurrents`	
`appl.name`		`emqh`

Class and name for Meridional Currents.

FIELD	VALUE	DEFAULT
`appl.mode.class`	`MeridionalCurrents`	
`appl.name`		`emqh`

SCALAR VARIABLES

FIELD	DEFAULT	DESCRIPTION
`appl.var.epsilon0`	`8.854187817e-12`	Permittivity of vacuum
`appl.var.mu0`	`4*pi*1e-7`	Permeability of vacuum
`appl.var.nu`	`50`	Frequency

PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.prop.analysis`	`static | transient | harmonic`	`static`	Analysis type, magnetostatic, transient quasi-static, or time-harmonic quasi-static
`appl.prop.elemdefault`	`Lag1 | Lag2 | Lag3 | Lag4 | Lag5`	`Lag2`	Default element type. Lagrange elements of order 1 to 5.
`appl.prop.weakconstr`	`off | ideal | non-ideal`	`off`	The type of weak constraints to use.

SUBDOMAIN VARIABLES

The names of `Mz`, `Mphi`, `Brz`, and `Brphi` depend on the name of the spatial coordinate `z` or `phi`. If another name is used for the spatial coordinate, the variable names change accordingly.

FIELD	APPL. MODE	VALUE	DEFAULT	DESCRIPTION
`appl.equ.sigma`		expression | cell array of expressions	`5.99e7`	Electric conductivity
`appl.equ.mur`		expression | cell array of expressions	1	Relative permeability
`appl.equ.epsilonr`		expression | cell array of expressions	1	Relative permittivity
`appl.equ.v`		cell array of expressions	0	Velocity
`appl.equ.Je`		cell array of expressions	0	External current density
`appl.equ.Mz`	In-Plane	expression	0	Magnetization
`appl.equ.Mphi`	Meridional	expression	0	Magnetization
`appl.equ.Brz`	In-Plane	expression	0	Remanent flux density
`appl.equ.Brphi`	Meridional	expression	0	Remanent flux density
`appl.equ.P`		cell array of expressions	0	Electric polarization
`appl.equ.Dr`		cell array of expressions	0	Remanent displacement

FIELD	APPL. MODE	VALUE	DEFAULT	DESCRIPTION
`appl.equ.magconstrel`		`mur | M | Br`	`mur`	Magnetic constitutive relation
`appl.equ.elconstrel`		`epsr | P | Dr`	`epsr`	Electric constitutive relation

BOUNDARY VARIABLES

FIELD	APPL. MODE	VALUE	DEFAULT	DESCRIPTION
`appl.bnd.H0z`	In-Plane	expression	0	Magnetic field
`appl.bnd.H0phi`	Meridional	expression	0	Magnetic field
`appl.bnd.E0`		cell array of expressions	0	Electric field
`appl.bnd.sigmabnd`		expression | cell array of expressions	0	Electric conductivity
`appl.bnd.murbnd`		expression | cell array of expressions	1	Relative permeability
`appl.bnd.epsilonrbnd`		expression | cell array of expressions	1	Relative permittivity
`appl.bnd.type`		string	`H0 | cont`	The type of boundary condition

`appl.bnd.type` takes the default value `H0` on exterior boundaries and `cont` on interior boundaries.

BOUNDARY CONDITIONS

DESCRIPTION	APPL. MODE	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Induced electric field		`E`	`E0`	Electric field
Lorentz electric field		`Ev`	`E0`	Electric field
Total electric field		`Etot`	`E0`	Electric field
Magnetic insulation		`tE0`		
Continuity		`cont`		
Magnetic field	In-Plane	`H`	`H0z`	Magnetic field

DESCRIPTION	APPL. MODE	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Magnetic field	Meridional	`H`	`H0phi`	Magnetic field
Electric insulation		`H0`		

Impedance boundary condition		`IM`	`sigmabnd`
			`sigmatensorbnd`
			`sigmatype`
			`murbnd`
			`epsilonrbnd`
			`epsrtensorbnd`
			`esptype`
				Conductivity
				
				Relative permeability
				
				Relative permittivity

Axial symmetry	Meridional	`ax`		

The **Type** column indicates the possible values for `appl.bnd.type`.

DEPENDENT VARIABLES

FIELD	DEFAULT	DESCRIPTION
`appl.dim`	`{'Vm'}`	Magnetic potential

APPLICATION MODE CLASS AND NAME

FIELD	VALUE	DEFAULT
`appl.mode.class`	`MagnetostaticsNoCurrents`	
`appl.name`		`emnc`

SCALAR VARIABLES

FIELD	DEFAULT	DESCRIPTION
`appl.var.mu0`	`4*pi*1e-7`	Permeability of vacuum

PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.prop.elemdefault`	`Lag1 | Lag2 | Lag3 | Lag4 | Lag5`	`Lag2`	Default element type. Lagrange elements of order 1 to 5.
`appl.prop.weakconstr`	`off | ideal | non-ideal`	`off`	The type of weak constraints to use.

SUBDOMAIN VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.equ.mur`	expression | cell array of expressions	1	Relative permeability
`appl.equ.M`	cell array of expressions	0	Magnetization
`appl.equ.Br`	cell array of expressions	0	Remanent flux density
`appl.equ.magconstrel`	`mur | M | Br | fB | anis_fB`	`mur`	Magnetic constitutive relation
`normfB`	expression		Nonlinear relation for normB

FIELD	VALUE	DEFAULT	DESCRIPTION
`fB`	cell array of expressions		Nonlinear relation for B
`appl.equ.maxwell`	cell array of expressions		Force variables
`appl.equ.Stype`	String	`none`	Infinite element type
`appl.equ.Sd`	cell array of expressions		Width of infinite element region
`appl.equ.S0`	cell array of expressions		Inner coordinate for infinite element region
`appl.equ.R0`	expression		Inner radius for infinte element region
`appl.equ.srcpnt`	cell array of expressions	`0 0 0`	Center point for infinite elements
`appl.equ.srcaxis`	cell array of expressions	`0 0 1`	Center axis for infinite elements
`appl.equ.coordOn`	cell array of strings	`0 0 0`	Stretched in direction
`appl.equ.rOn`	string	`0`	Stretched in r-direction
`appl.equ.user`	cell array of expressions		User defined coordinates

BOUNDARY VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.bnd.B0`	cell array of expressions	0	Magnetic flux density
`appl.bnd.Bn`	expression	0	Normal flux density
`appl.bnd.Vm0`	expression	0	Magnetic potential
`appl.bnd.murext`	expression	1	Relative permeability
`appl.bnd.d`	expression	0	Thickness
`appl.bnd.type`	string	`B0 | cont`	The type of boundary condition
`appl.bnd.pertype`	sym | antisym	`sym`	The type of periodic boundary condition
`appl.bnd.chsrcdst`	0 | 1	0	Change source and destination

`appl.bnd.type` takes the default value `B0` on exterior boundaries and `cont` on interior boundaries.

BOUNDARY CONDITIONS

DESCRIPTION	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Magnetic flux density	`B`	`B0`	Magnetic flux density
Inward flux density	`nB`	`Bn`	Normal flux density
Magnetic insulation	`nB0`		
Continuity	`cont`		
Magnetic potential	`Vm`	`Vm0`	Magnetic potential
Zero potential	`Vm0`		
Magnetic shielding	`ms`	`murext` `d`	Relative permeability Thickness
Periodic boundary	`periodic`	`pertype` `chsrcdst`	Type Change src/dst

The **Type** column indicates the possible values for `appl.bnd.type`.

POINT VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
`appl.bnd.fixpot`	`0 | 1`	0	Fix potential at this point
`appl.bnd.Vm0`	expression	0	Magnetic potential

4

Function Reference

Summary of Commands

Commands Grouped by Function

Force Computation

FUNCTION	PURPOSE
`cemforce`	Compute the total force on an object by the principle of virtual displacement.
`cemtorque`	Compute the total torque on an object by the principle of virtual displacement.

Lumped Parameter Computation

FUNCTION	PURPOSE
`rlcmatrix`	Compute the full lumped parameter matrix using the port boundary conditions defined in the model.

File Exchange

FUNCTION	PURPOSE
`spiceimport`	Import a SPICE netlist as system of ODEs

Purpose Compute the total force on an object by the principle of virtual displacement.

Syntax

```
F = cemforce(fem,W,...)
```

Description `F = cemforce(fem,W,...)` computes forces on subdomains by the principle of virtual displacement. `W` is the expression for the energy.

Valid property/value pairs for the `cemforce` function are given in the following table.

TABLE 4-1: VALID PROPERTY/VALUE PAIRS

PROPERTY NAME	PROPERTY VALUE	DEFAULT	DESCRIPTION
`Const`	cell array of pairs		List of constants and values
`Cont`	`off` | `on` | `internal`	`off`	Make output continuous
`Context`	`local` | `main`	`local`	Evaluation context
`Contorder`	positive integer	2	Order of smoothing polynomial for use with `Cont`
`Delta`	scalar	`1e-8`	Displacement
`Dl`	integer vector	all domains	Domain list
`Solnum`	integer	1	Solution number
`Geomnum`	positive integer	1	Geometry number
`Intorder`	positive integer	`2*fem.sshape` or 4	Integration order
`T`	scalar		Time for evaluation
`U`	FEM solution	`fem.sol.u`	Solution for evaluation

`Dl` is a vector of integers that states the subdomains for which the force is computed.

`Delta` is the displacement that the subdomains in `Dl` are moved in the force computation. The default values of `delta` is `1e-8*pmax`, where `pmax` is the maximum absolute value of all the points in the mesh.

For more information on properties, see `posteval` and `postint`.

Cationary Note that for axisymmetric models, the expression of the energy should be multiplied by `2*pi*r` to obtain the correct forces, since the integration should be carried out on the 3D domain. This means that `W` is typically the expression `'2*pi*r*Wav'`. In these cases, the virtual displacement in the radial direction makes no sense, since a movement in the meridional plane corresponds to an expansion of the whole structure, rather than a displacement. The value obtained for the radial force is therefore always false. Due to the symmetry, the correct value is always zero.

Example Compute the force between two current-carrying conductors surrounded by air.

```
clear fem
fem.geom=rect2(0,1,0,1)+circ2(0.3,0.5,0.1)+circ2(0.7,0.5,0.1);
fem.sdim={'x' 'y'};
fem.mesh=meshinit(fem);
fem.appl.mode='PerpendicularCurrents';
fem.appl.prop.elemdefault='Lag1';
fem.appl.equ.Jez={'0' '1' '-1'};
fem=multiphysics(fem);
fem.xmesh=meshextend(fem);
fem.sol=femlin(fem);
F=cemforce(fem,'Wm','delta',1e-7,'dl',2)
```

Cautionary The function only supports linear Lagrange elements. The results when using other elements are not reliable.

See Also `posteval`, `postint` (in the *COMSOL Multiphysics Reference Guide*)

Purpose Compute the total torque on an object by the principle of virtual displacement. This function is only available for 2D models.

Syntax `F = cemtorque(fem,W...)`

Description `F = cemtorque(fem,W,...)` computes torque on subdomains by the principle of virtual displacement. `W` is the expression for the energy.

Table 4-2 contains the valid property/value pairs for the `cemtorque` function.

TABLE 4-2: VALID PROPERTY/VALUE PAIRS

PROPERTY NAME	PROPERTY VALUE	DEFAULT	DESCRIPTION
`Const`	cell array of pairs		List of constants and values
`Cont`	`off | on | internal`	`off`	Make output continuous
`Context`	`local|main`	`local`	Evaluation context
`Contorder`	positive integer	2	Order of smoothing polynomial for use with `Cont`
`Delta`	scalar	`1e-8`	Displacement
`Dl`	integer vector	all domains	Domain list
`Mid`	vector	`[0 0]`	Torque axis
`Solnum`	integer	1	Solution number
`Geomnum`	positive integer	1	Geometry number
`Intorder`	positive integer	`2*fem.sshape` or 4	Integration order
`T`	scalar		Time for evaluation
`U`	FEM solution	`fem.sol.u`	Solution for evaluation

`Dl` is a vector of integers that states the subdomains for which the torque is computed.

`Delta` is the displacement angle for the rotation of the subdomains in `Dl` in the torque computation.

`Mid` specifies the torque axis, and hence the point about which the subdomains are rotated.

For more information on properties, see `posteval` and `postint`.

Cautionary The function only supports linear Lagrange elements. The results when using other elements are not reliable.

See Also `cemforce`, `posteval`, `postint`

Purpose

Compute the full lumped parameter matrix using the port boundary conditions defined in the model.

Syntax

```
X = rlcmatrix(fem,out,...)
```

Description

`X = rlcmatrix(fem,out,...)` computes the multiconductor lumped parameter matrix `out` from the model stored in the `fem` structure.

By default, `rlcmatrix` searches for all port boundary conditions and goes through them all. The lumped parameter matrix `out` can either be one of the following strings: `'Y'` for the admittance matrix, `'Z'` for the impedance matrix, and `'C'` for the capacitance matrix. Which it is depends on the application mode and property (fixed voltage, fixed current, and fixed current density) that is used for the analysis.

The Y-parameter matrix, for instance, is defined by:

```
I1 = Y11*V1 + Y12*V2 + ... + Y1N*VN
I2 = Y21*V1 + Y22*V2 + ... + Y2N*VN
...
IN = YN1*V1 + YN2*V2 + ... + YNN*VN
```

where `Vi` is the complex voltage on conductor port i, `Ij` is the current into conductor j, and `Yij` is the admittance between port i and j corresponding to `X(i,j)` in the output from `rlcmatrix`.

If the model in `fem` has N ports, `rlcmatrix` computes a N-by-N lumped parameter matrix `X`. A parametric sweep results in a N-by-N-by-M matrix, where M is the number of parameters returned by the solver.

Property value pairs to `rlcmatrix` are passed on as solver parameters to the solver.

Cautionary

This script does not work for the energy method extraction of the lumped parameters.

See Also

`femsolver`, `posteval`, `postint` (in the *COMSOL Multiphysics Reference Guide*)

Purpose

Import an electric circuit from a netlist in the SPICE format.

Syntax

`fem = spiceimport(filename,...)`

Description

`fem = spiceimport(filename,...)` reads the netlist `filename` and return an `ode` structure representing the circuit in the file.

Table 4-2 contains the valid property/value pairs for the `spiceimport` function.

TABLE 4-3: VALID PROPERTY/VALUE PAIRS

PROPERTY NAME	PROPERTY VALUE	DEFAULT	DESCRIPTION
`Fem`	FEM structure		Model to add circuit to
`ac`	`off | on`	`off`	Time harmonic analysis
`Suffix`	`string`	`cir`	Suffix for circuit variables

If the `fem` argument is not supplied `spiceimport` will just add the `ode` to a new `fem` structure, only containing a point geometry.

More details about the SPICE import can be found under section “SPICE Circuit Import” on page 70 of the *AC/DC Module User’s Guide*.

Cautionary

The script is mainly intended for small and simplified circuits coupled to a finite element model.

The SPICE import does not support small-signal models of any semiconductor device models. In a time-harmonic simulation you can only connect sources and passive devices.

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