ANSYS (R) Macros for DC Machines

12/1/2000

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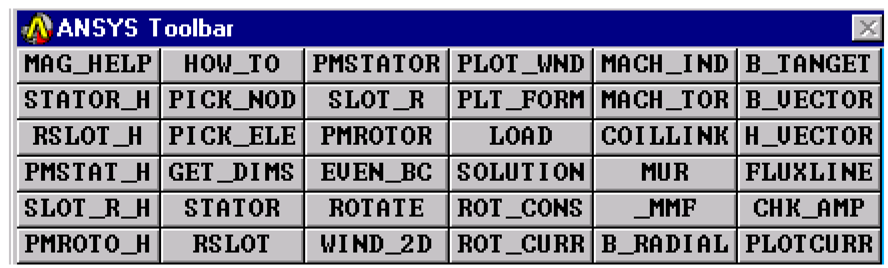
Contents for the DC Application

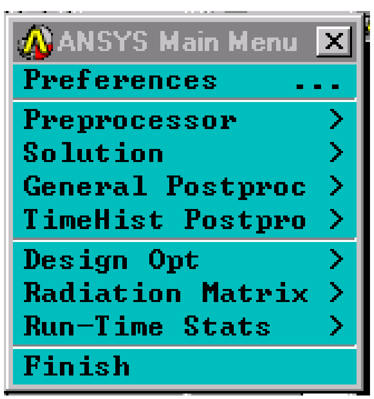
Overall menu layout

Utility menu for basic functionality for file handling, plotting entities, plot controls, parameter manipulations….

Command line to enter commands directly

The Toolbar which executes commands or macros



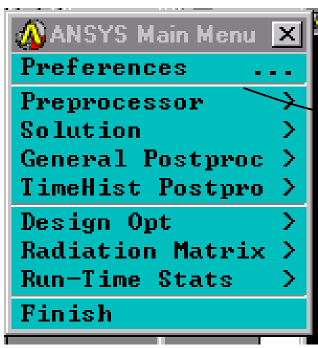


The ANSYS menu structure

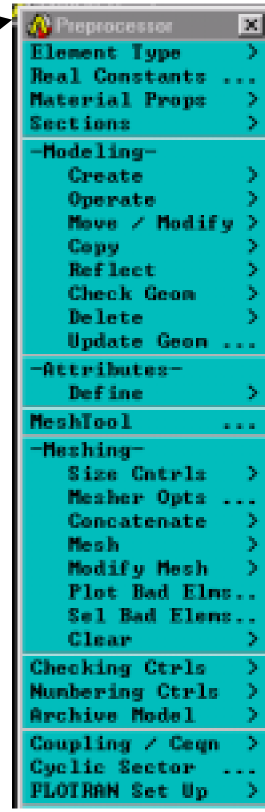
In this seminar the major focus is on the Toolbar which uses macros applicable to machine simulations.

Menu structure

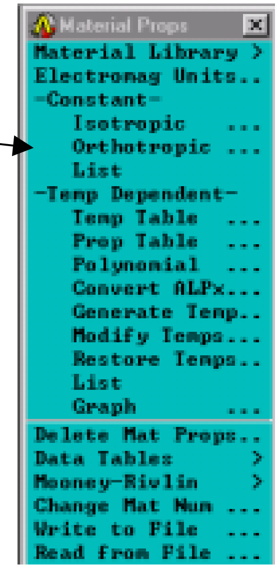
Main menu allows you to enter into individual modules which model, solve, Postprocess



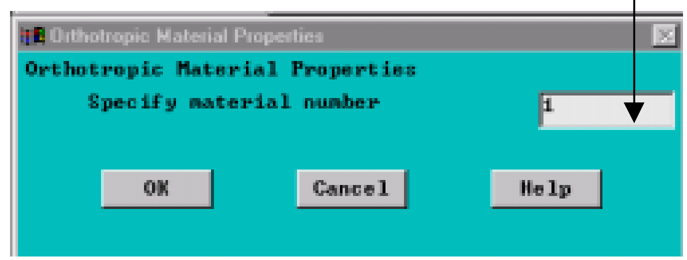
By selecting, for example the Processor, it displays options for the model generation



By selecting the material properties, options for the material modeling are displayed



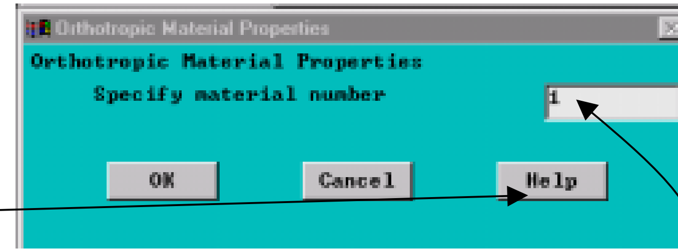
By selecting the orthotropic properties, it requests information for assigning a material number



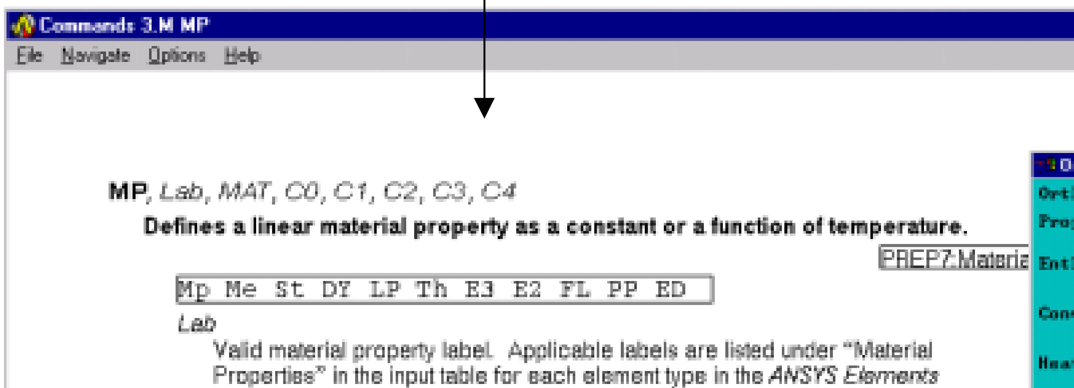
At this point, you can accept (OK), back out (Cancel) or request for Help

In the notes, a path for this would be specified as Preproc>material props>orthotropic

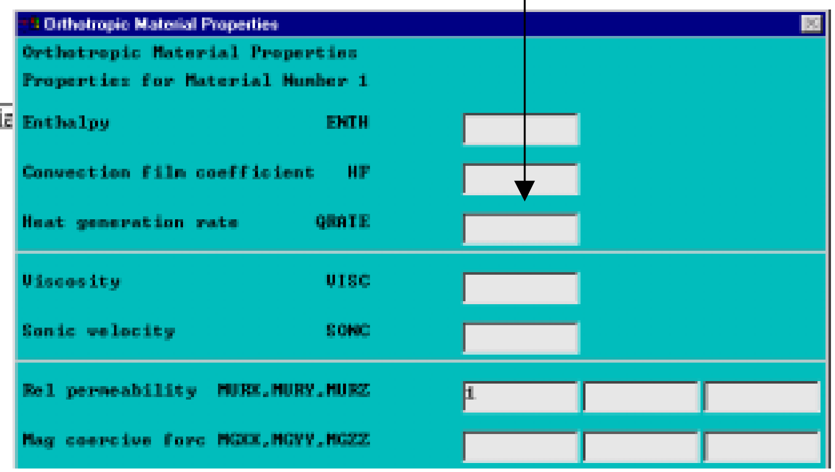
About the help engine



This help was generated by selecting Help in this panel



When the number is input and OK is selected, then the next panel is displayed to complete the material input.



This format described in detail how the command would be entered into the command window. "material number" in the window corresponds by name to MAT in the help display

At the bottom of each help, is the menu location

Menu Paths

Main Menu >Preprocessor >Loads >Other >Change Mat Props >Polynomial
Main Menu >Preprocessor >Material Props >Polynomial
Main Menu >Solution >Other >Change Mat Props >Polynomial

Once the data is input, for ANSYS to use the information, the OK must be selected.

Machine Toolbar - Combines model generation-winding & currents-solutions-studies-post processing and can be easily accessed through the Toolbar.

Defines all the Toolbar items

Description of the stator and rotor templates

Model generation: <stator>,<rslot>, <pmstator>,<slot_r> <pmrotor>

Boundary conditions (typical)

Postprocessing

Boundary conditions:

<even_bc>,<rotate>

Winding /currents

Single & Multiple solutions

More about the ToolBar

- Each ToolBar item is an abbreviation
  - It can execute a single command
  - It can execute a macro

- The <MAGHELP> gives a short explanation of each the ToolBar items
- To determine which macro is being called, it can be seen from the
  - Utility>Menu ctrls>edit toolbar
  - edit the macro **mabbr.mac**

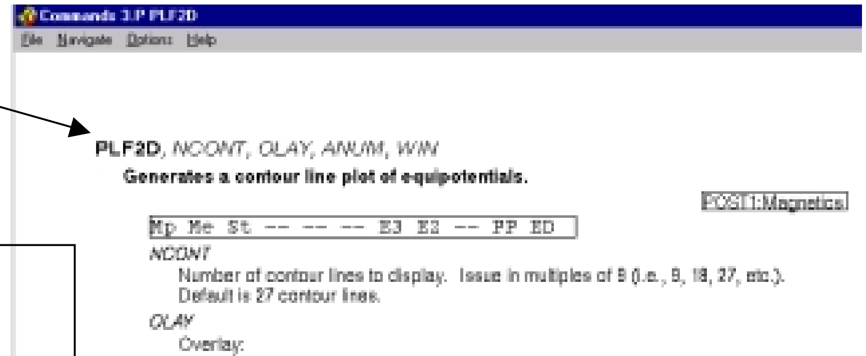
- For example <WIND_2D> executes the macro that generates the winding information using b_wndsc.mac.

*abbr,wind_2d,b_wndsc,0,0,0,0,0,0,0,0,1 ! generates the circuits for the
! windings

More information

If a command is used in the ToolBar, the ANSYS Help engine can provide more information.

<FLUXLINE> => *abbr,fluxline,plf2d

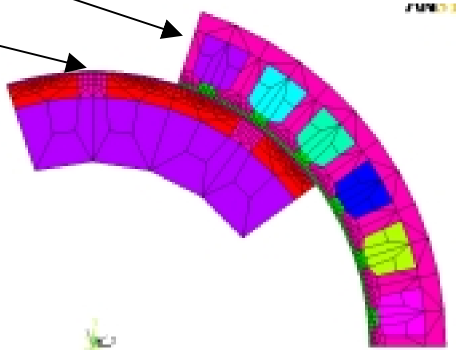



```
!  Generates the stator based on parameters
!  arg1 = 0  the winding is stops at the back of the tooth face
!       > 0  the winding occupies the entire slot
!  arg2 = mesh refinement, 1 is minimum number of elements, 5 is most
!         most refinement
!  arg3 = 0  use lower order element
!       > 0  use higher order element
!  arg4 = number of stator teeth to be generated
!       = 0 (default), no action, no additional teeth are generated
!       ne 0 Build arg4 number of teeth
!  arg5 = 0 coil elements use the lower order elements
!       = 1 coil elements use the higher order elements
!  arg6 = 0 coil loads will be specified by currents
!       = 1 coil load will be specified by voltages
!
!  arg7 = additional mesh control factor to control the elements at the
!         back of the magnet and the inner radius of the return path
!         Defaults to 1
```

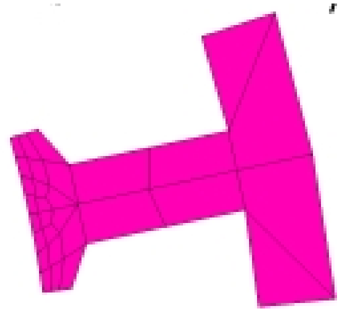
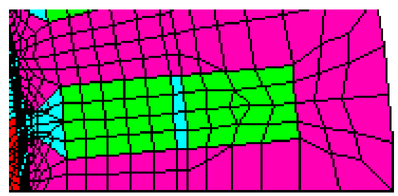
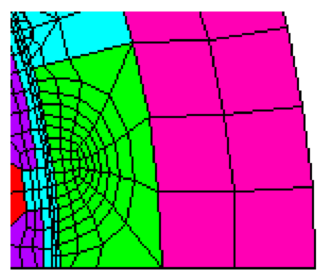
<STATOR> uses the macro slotsta.mac. The top of this macro describes the input by the user.

Overall process of generating the model, solving, post processing

- Identify the laminate models
  - this defines the files containing the parameter definitions. The available laminates are defined in <MAG_HELP> under geometry generation
- Input the parameters into a file-or use the GUI to define the parameters
- Define the winding file
- Build the stator
- Build the rotor
- Apply periodic conditions to the sides if a periodic model is used
- Connect the rotor to the stator with constraint equations
- Build the winding (current fed)
- Solve (linear or with BH data)
- Post process

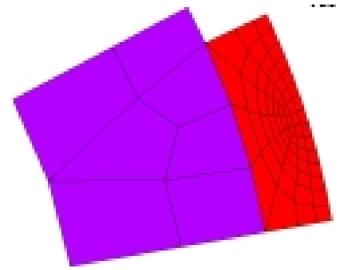


Laminate options for the stator

Laminate		ToolBar Help	Plot file(1)
Slotted stator-uniform tooth		<STATOR_H>	stator.doc
Slotted stator-uniform slot		<RSLOT_H>	rslotsta.doc
Permanent magnet stator		<PMSTAT_H>	pm_stat.doc

(1) These files are to be viewed using the DISPLAY Utility. See Appendix C for the use of the DISPLAY utility and the available templates.

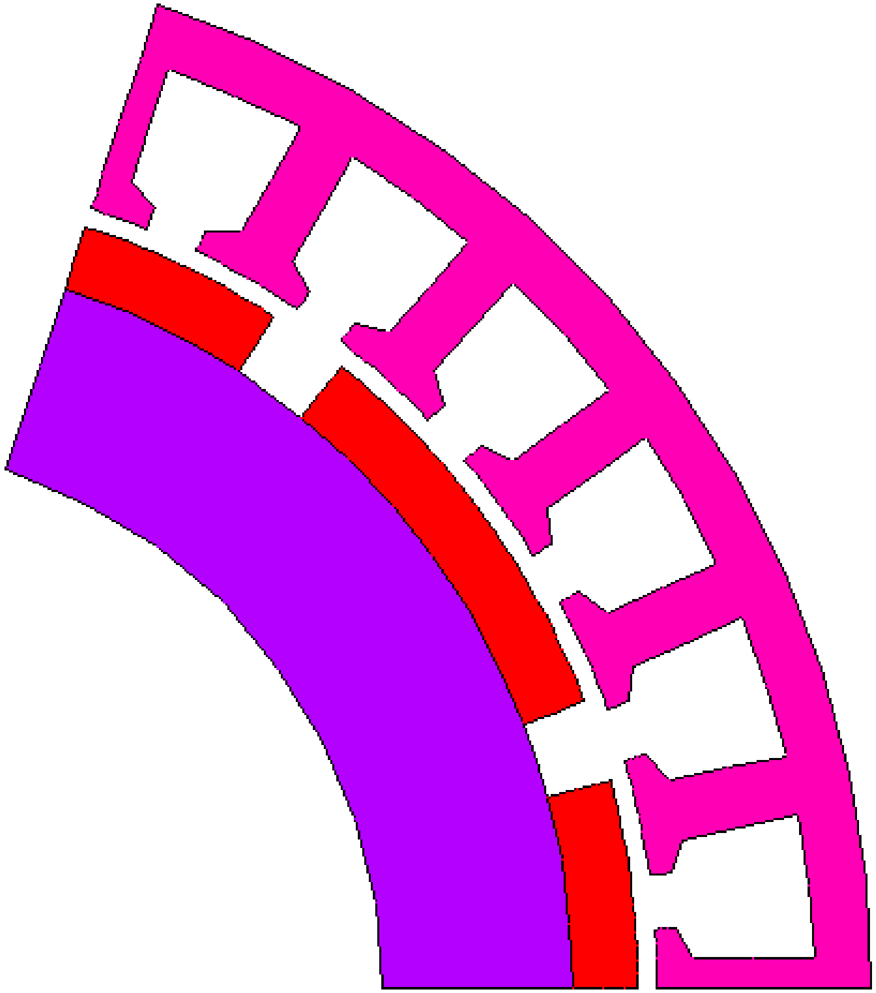
Laminate option for the rotor

Laminate		**Help**	**Plot file**
Permanent magnet-surface mount		<PMROTOR_H>	pm_rotor.doc
Import the rotor design		Contained in this seminar	

Example of a periodic model for a 10 pole BDC machine

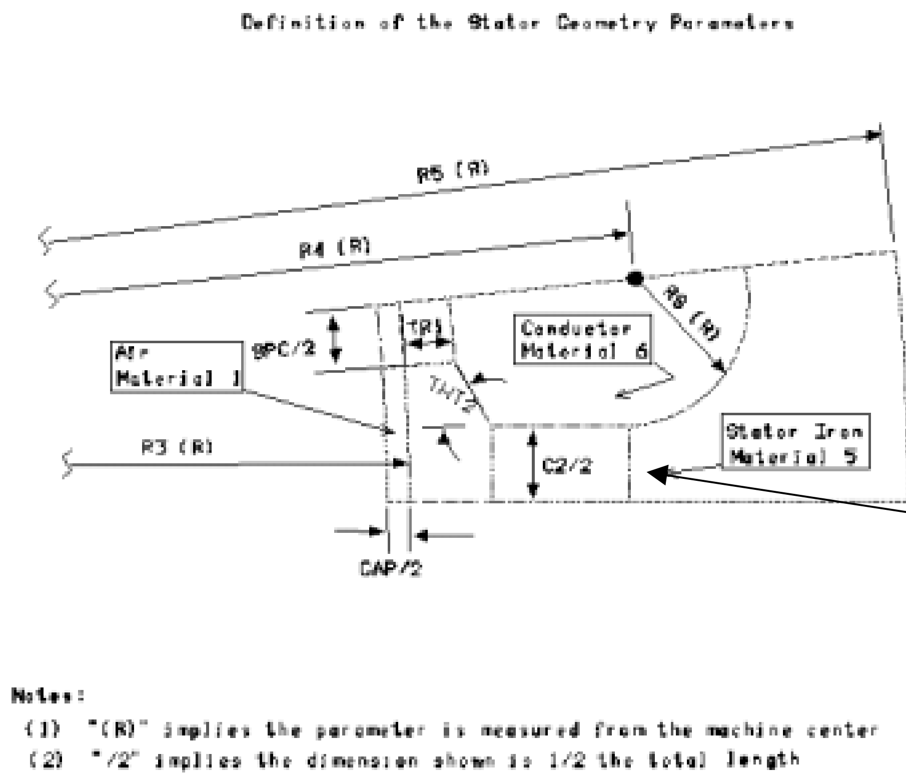
- Permanent magnets are parallel magnetized

- Three phase winding
- Only 2 poles are to be modeled.



Parameter Definition for the stator:

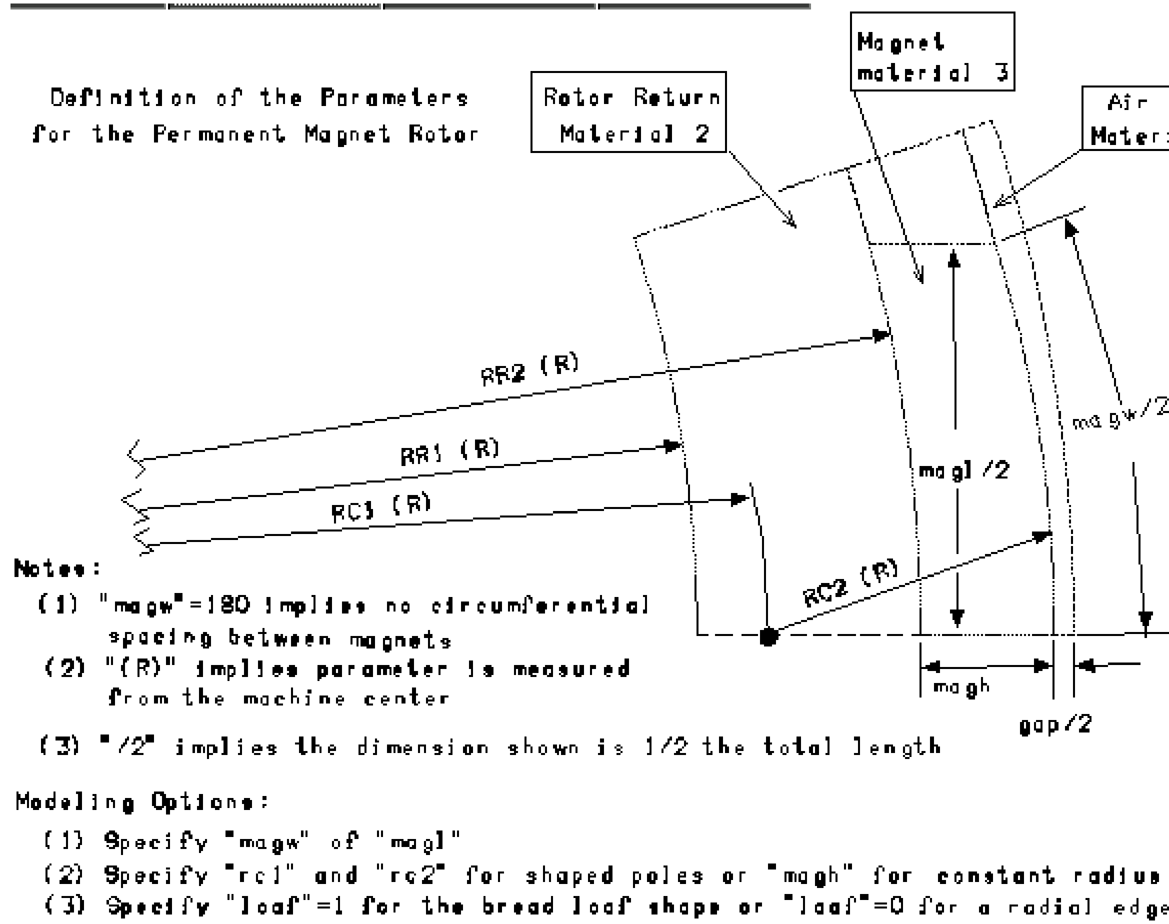
Information for the template for the stator-uniform tooth is available in <STATOR_H>. A diagram for the parameters is also available. The number of teeth is arbitrary. The model can consist of a two pole periodic model or a 360° model. The diagram shown below is a plot file that is displayed by the DISPLAY Utility. The name of the plot file is stator.doc which is in the display listing when <STATOR_H> is executed.



Tooth shank has a uniform width

Parameter Definition for the rotor:

Information for the template and the magnet shape options for the permanent magnet rotor is available in <PMROTO_H>. A diagram for the parameters is also available. The number of magnets is arbitrary; the magnets can be parallel or radially magnetized or tangentially magnetized



Material definitions / Components

- All laminates use the same material set identifications

– AIR	Material 1	Permeability (free space)
– rotor iron	Material 2	Permeability (BH data)
– permanent magnet	Material 3	Hc and Permeability (BH data)
– stator iron	Material 5	Permeability
– stator slots	Material 6	Permeability (free space)

- All laminates use the following component names

– rotor	component group for nodes/elements…
– stator	component group for nodes/elements
– s_coil	elements for stator coil
– r_iron	elements for magnet/iron in rotor; used for torque calculation

About the units:

- The input parameters can be in any units (inches,mm,cm…).
- A conversion factor (GGEOM) must be specified which converts the model from its input units to meters
- The model is built according to the parameters, then it is scaled into meters using GGEOM
- The material properties are to be in SI units
  - Hc: Amps/meter
  - flux density: Tesla
  - field intensity Amps/meter
- The output:
  - flux: Webers
  - flux density: Tesla
  - field intensity Amps/meter
  - torque N-m
  - force N

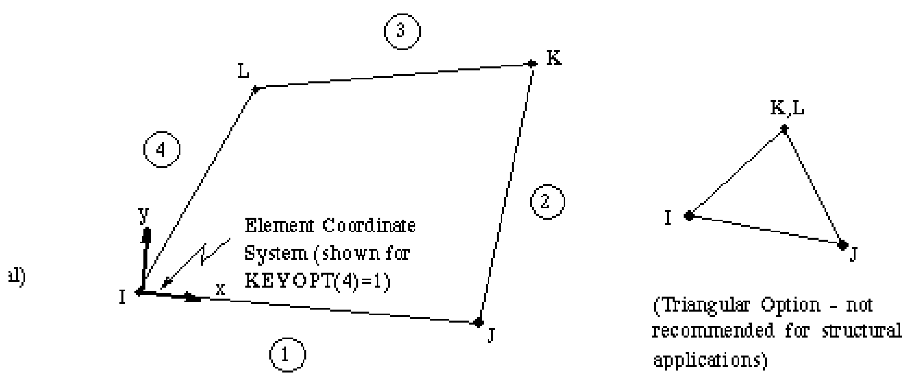
Some modeling details before the parameter file is constructed-selection of the element type

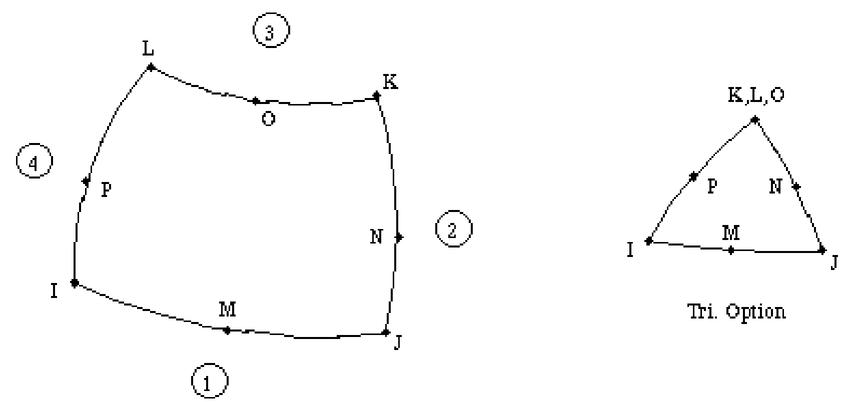
- Use of plane13 versus plane53
  - plane13 solves faster
  - most current loaded problems achieves accuracy with plane13
  - the 53 is considered to be more accurate
  - This is set by USE_53 in the parameter file

The plane13 is the four noded element, which allow the B to vary linearly over the four noded element

The plane53 is the eight noded element, which allow the B to vary quadratically over the eight noded element

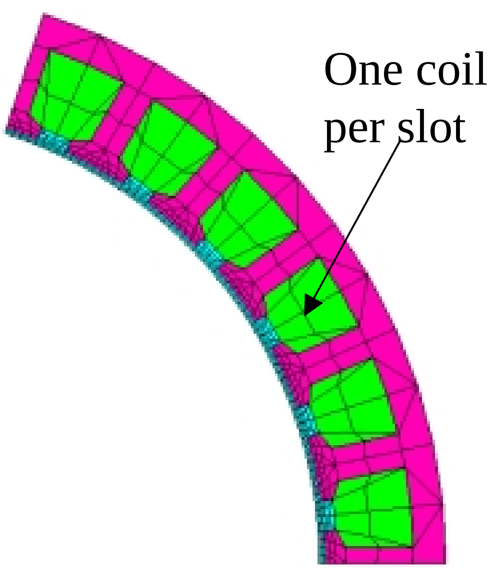
Figure 4.13-1 PLANE13 2-D Coupled-Field Solid



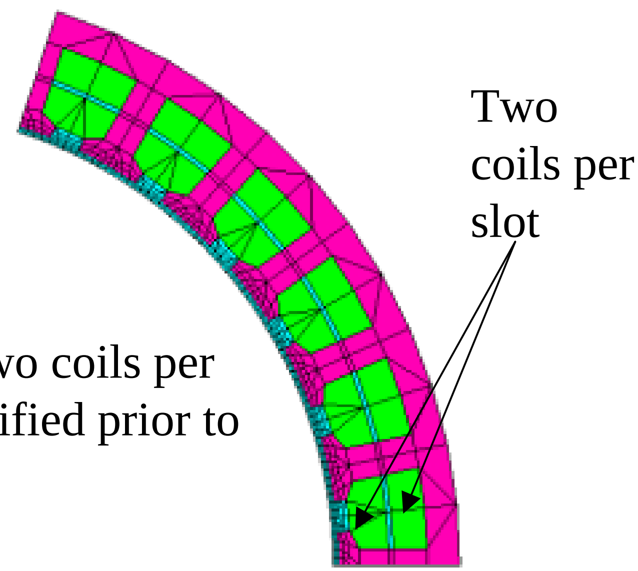


Model details and parameter definition

The number of coils cross sections can be in a single slot in the stator
This is set by NCONS in the parameter file (2 is maximum)



If the winding has two coils per slot, it must be identified prior to model generation



Modeling parameters-continued

Is this a periodic model or a full model?

  NRPGEN = number of complete magnets to be actually generated

  NSPGEN = number of stator teeth to be generated

Mesh refinement level

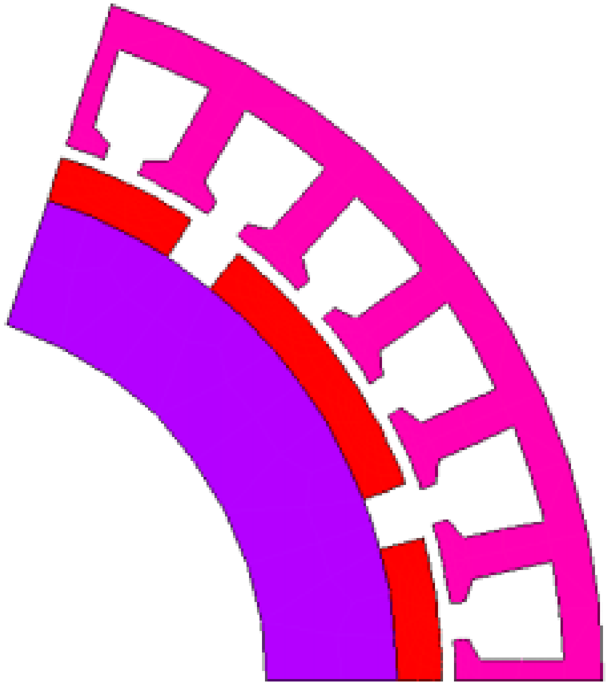
  most applications start with Level 2

    RREF is for the rotor (RREF=2)

    STREF is for the stator (STREF=2)

  for large number of stator teeth, the mesh at the air gap will be small, the backiron should perhaps be coarser to keep the number of elements to a minimal level

    should start with F_MESH=1



Six teeth are modeled, so NSPGEN=6

Two complete magnets are generated, so NRPGEN=2

Parameter file for the example: mach2.des: general data/rotor data/stator data/materials/current form. See the ToolBar help for the parameters. <STATOR_H> for the stator and <PMROTO_H> for the permanent magnet rotor

```
!   mach2.des
!   2 D model
!   Parameters for the 30 slot 10 pole PM machine
!   parameters are in inches!
!
! Component  Toolbar HELP  Toolbar to      Description               Macro
!                          Build Model
! stator:     <stator_h>   <stator>    slotted(uniform shank)    slotsta.mac
! rotor:      <rotor_h>    <b_rotor>   permanent magnet          pm_rotor.mac
!
!   General
w_file='mach2'    !  winding file to build the stator winding
f_mesh=2          !  increases the size of the elements in the iron, larger
                  !  values results in larger elements in the back iron
use_53=1          !  =0, uses plane13(4 noded quad),  =1, uses plane53(8 noded quad)
stkthk=2.25       !   stack length (in)

mname='mach2'     !   name of plot file (extention is .plt)
npole=10          !   number of poles
ggeom=.0254       !   conversion factor from English to Metric for length
```

Rotor data

```
!    rotor data
rotor_id='pmrotor'
rref=2             !  rotor mesh refinement
nrpgen=2           !   number of rotor poles to be generated for the model
nrp=10             !   number of rotor poles

rr1=1.00           !   inner radius of the rotor
rr2=1.35           !   outer radius of the rotor return path
magh=.12           !   magnet height
magw=150.          !   width of magnet (Electrical degrees)
gap=.035           !   rotor-stator air gap
```

Stator data

```
!   stator data
stat_id='slotsta'
ncons=1           !   number of phases in a single slot
nsp=30            !   number of stator slots in the complete machine
nspgen=6          !   number of stator poles to be generated for the model
stref=2           !   level of refinement in the stator
!                     used for argument in gnstator.mac

r3=rr2+magh+gap   !   inner radius of the stator tooth

spc=.1            !   spacing between the teeth
c2=.11            !   width of tooth shank (for uniform shank)
tr1=.04           !   length of the side of tooth
tht2=60.          !   angle of rear of tooth from side of shank

r4=r3+tr1+.25     !   inner radius of stator yoke
r5=1.90           !   outer radius of stator yoke
rs=.0             !   additional curvature for top of slot
```

Material data/ current form

To allow the parameter file to contain a complete set of data to define the model, the material data and current form can also be contained. These can also be entered through the GUI, which will be shown later.

Material number   Value

```
mp,murx,1,1          !  air                        Material 1
m54,2                !  rotor laminate             Material 2
mp,mgxx,3,774000     !  Hc  of magnet              Material 3
mp,murx,3,1.06       !  magnet                     Material 3
m54,5                !  stator laminate            Material 5
mp,murx,6,1          !  conductor (copper)         Material 6

/com,  Current form specification
currform='sine'   !  for sine input
```

BH data for M54 steel   m54, material number

These parameters can be stored in a separate file or loaded in the GUI. To load the data from a file such as mach2.des, use <GET_DIMS> and input 'mach2'. When <GET_DIMS> is selected the following prompt is displayed

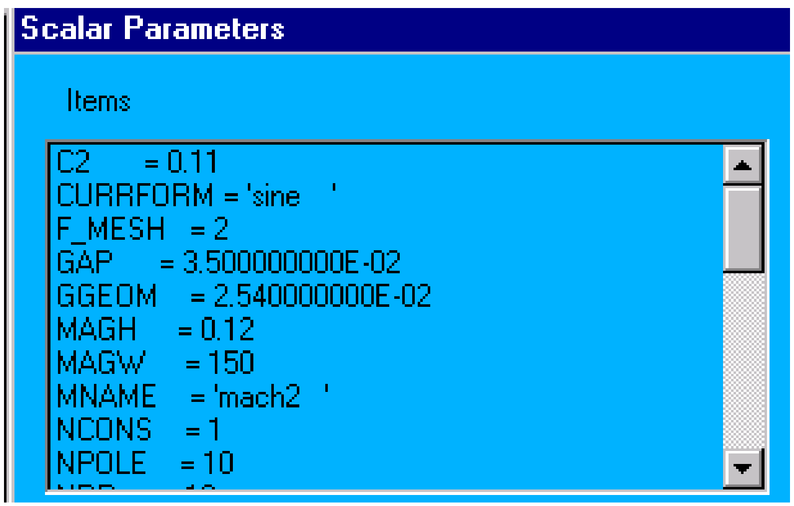
The name can be entered directly , which must be enclosed in single quotes indicating that it is character data.

Examining the parameter data

The parameters can be reviewed or altered by

Utility>parameters>scalar

An individual parameter can be selected and altered.



The parameters can be also be listed by entering *status at the command line.

NAME	VALUE	TYPE
C2	0.110000000	SCALAR
CURRFORM	sine	CHARACTER
F_MESH	2.00000000	SCALAR
GAP	3.500000000E-02	SCALAR
GGEOM	2.540000000E-02	SCALAR
MAGH	0.120000000	SCALAR
MAGW	150.000000	SCALAR
MNAME	mach2	CHARACTER
MUZ	1.256637061E-06	SCALAR
NCONS	1.00000000	SCALAR
NPOLE	10.0000000	SCALAR
NRP	10.0000000	SCALAR
NRPGEN	2.00000000	SCALAR
NSP	30.0000000	SCALAR
NSPGEN	6.00000000	SCALAR
PI	3.14159265	SCALAR
R3	1.50500000	SCALAR
R4	1.79500000	SCALAR
R5	1.90000000	SCALAR
ROTOR_ID	pmrotor	CHARACTER
RR1	1.00000000	SCALAR
NAME	VALUE	TYPE
RR2	1.35000000	SCALAR
RREF	2.00000000	SCALAR
RS	0.00000000	SCALAR
SPC	0.100000000	SCALAR
STAT_ID	slotsta	CHARACTER
STKTHK	2.25000000	SCALAR
STREF	2.00000000	SCALAR
THT2	60.0000000	SCALAR
TR1	4.000000000E-02	SCALAR
USE_53	1.00000000	SCALAR
W_FILE	mach2	CHARACTER

To build the rotor use <PMROTOR>

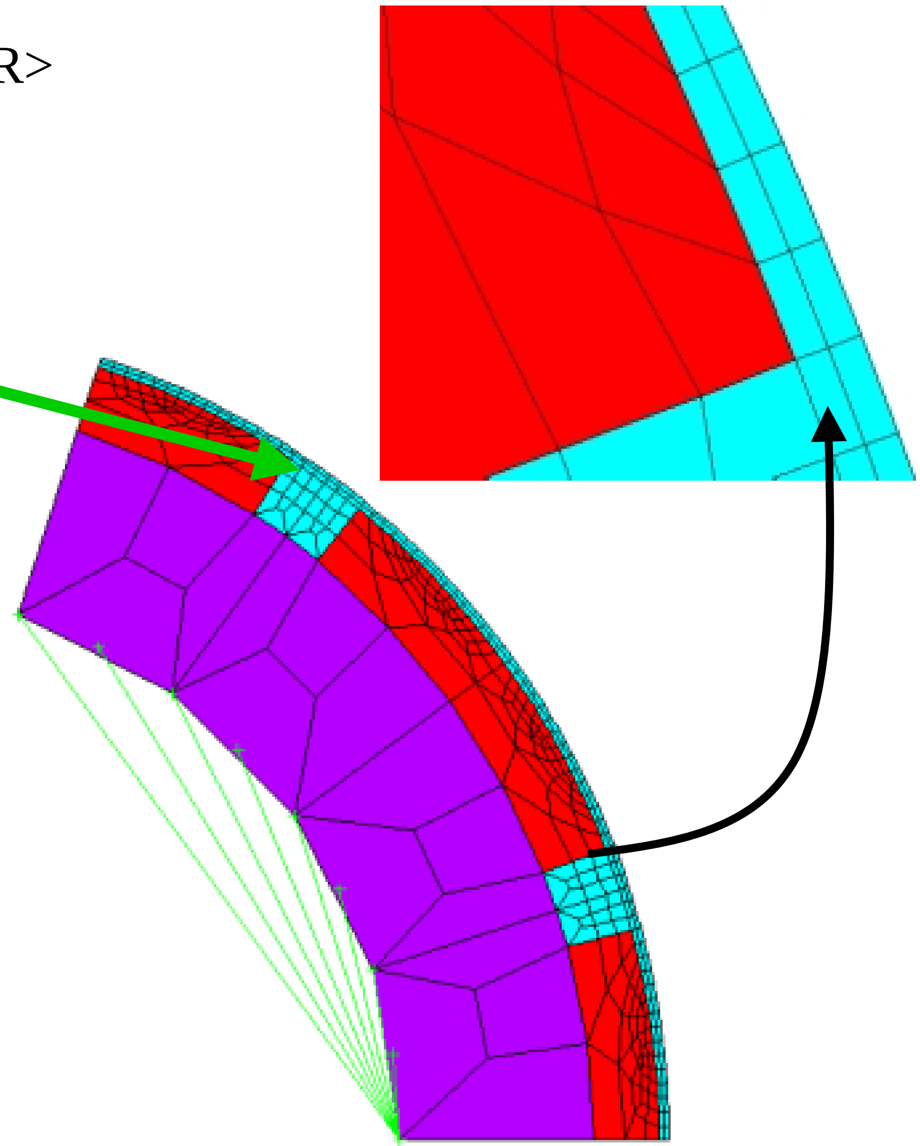
The rotor model is independent of the stator model

The rotor extends midway into the air gap

The rotor mesh is automatically refined in the air gap.

Mesh in the backiron can be refined by adjusting a single parameter F_MESH (see parameter file).

When the ToolBar is used, the abbreviation uses certain preset values. The abbreviations are contained in mabbr.mac and they can be seen from Utility>menu ctrls>edit toolbar



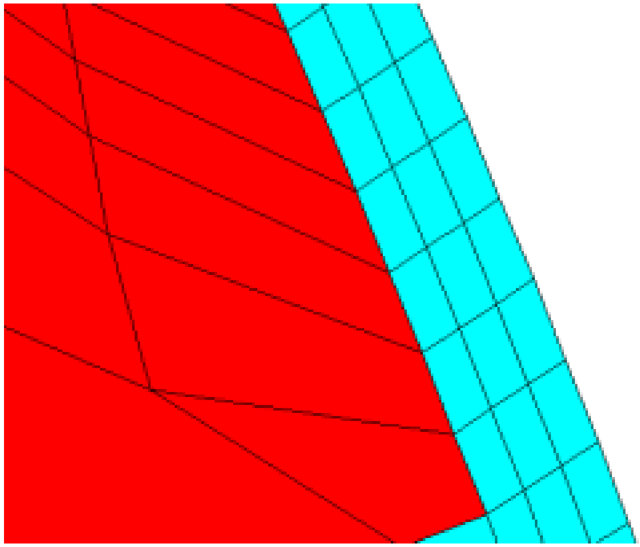
Mesh refinement in the air gap

The air gap in the rotor side can be refined by increasing RREF from 2 to a higher value up to 5. Larger values decrease the aspect ratio and increase the number of elements in the gap.

To observe this, enter rref=3 at the command line and rebuild the rotor using <PMROTOR>

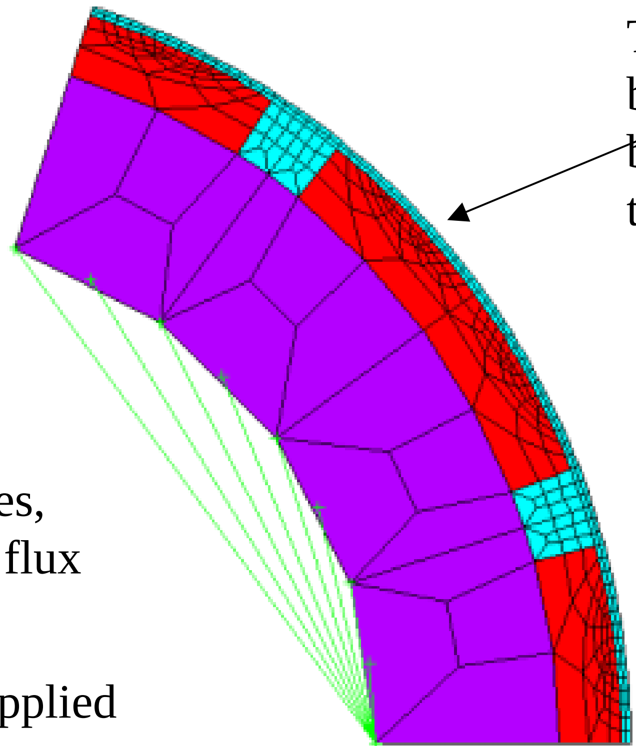
RREF	Number of elements in the rotor
2	364
3	1020

rref=2 is usually sufficient for a machine with currents



3 radial divisions

Boundary conditions for the rotor



The outer edge is a boundary, but it will be later connected to the stator using CEs

At the inner ring of nodes, CPs are used to enforce flux parallel condition.

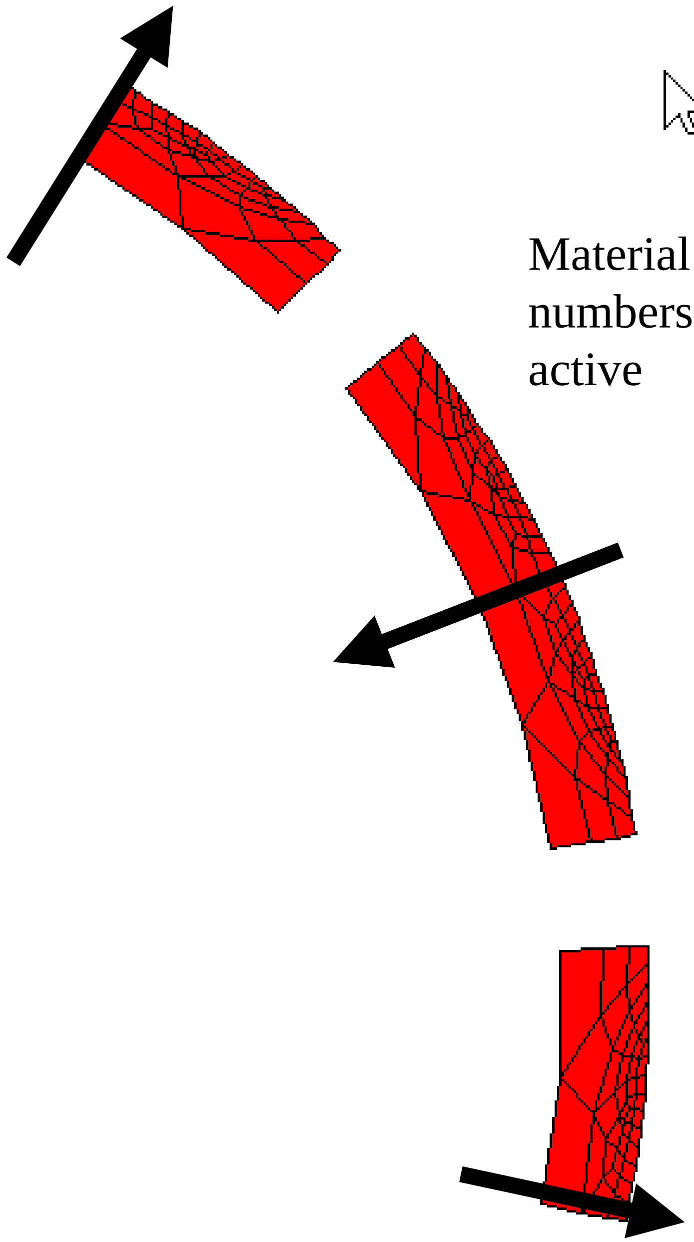
No AZ constraints are applied to the rotor.

The lateral edges are a boundary, but they will be later connected to the other side using CPs

About the PARALLEL magnet direction

This example uses parallel magnetization. For the periodic model, the following directions are used.

The alternating direction is defined by the different coordinate systems. Each half section of the magnet has a unique element coordinate system (ESYS) which corresponds to a unique local coordinate system. This requires only one magnet material (3) to be defined



Material numbers are active

Checking the magnet direction

To display the element directions, use

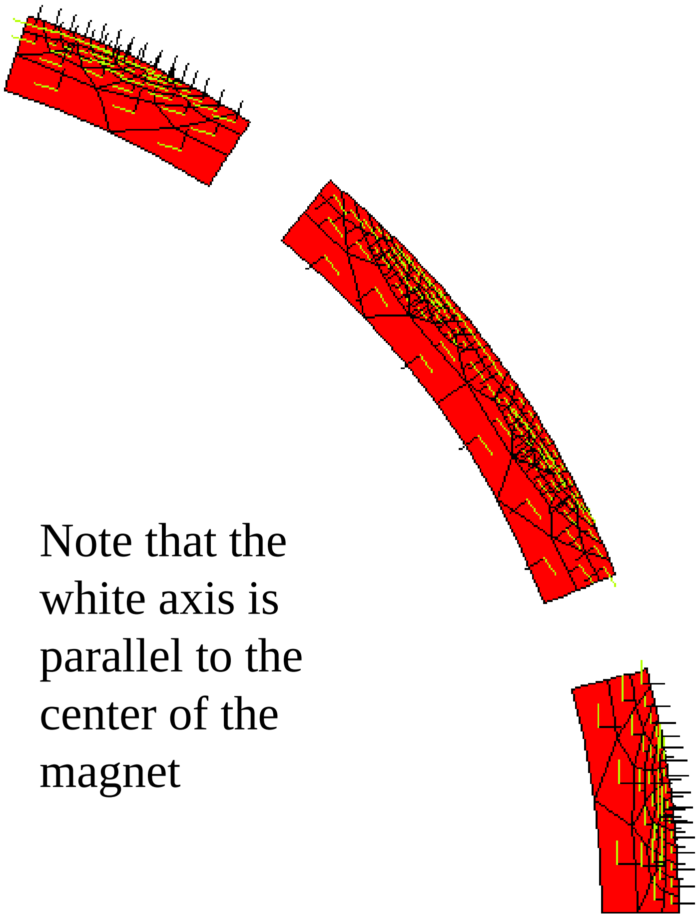
Utility> plot cntrls>symbol > element coordinate system

white axis: element X axis

green axis: element Y axis

blue axis: element Z axis

This indicates that the X axis is parallel to the magnet center, and therefore only MGXX is required. Once displayed turn this display option off.

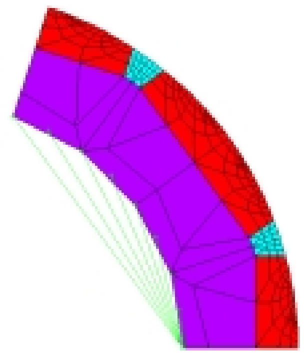


Note that the white axis is parallel to the center of the magnet

Other magnet shape options

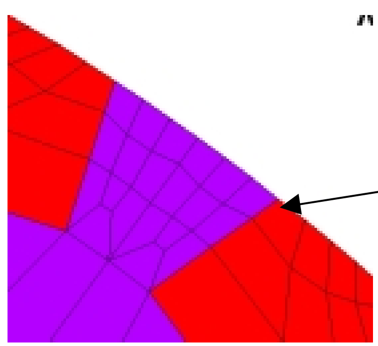
First, save the current model using Utility>file>save jobname.db so that it can be recalled later

Loaf option: enter loaf=1 at the command line and <PMROTOR>

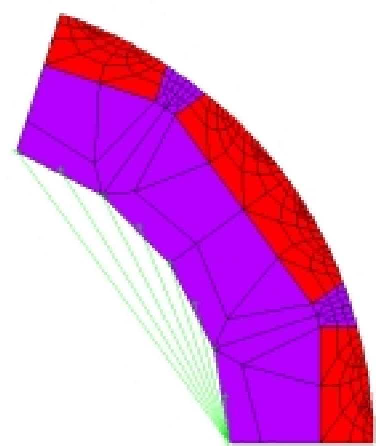


The sides of the magnet are parallel to the centerline of the magnet. The bottom is flat. The RR2 corresponds to the inner radius of the magnet at the edge of the magnet *If this option is used, RC1 and RC2 must be used to specify the height of the magnet not magh*

Embedded option+loaf option: enter embed=1 at the command line and <PMROTOR>

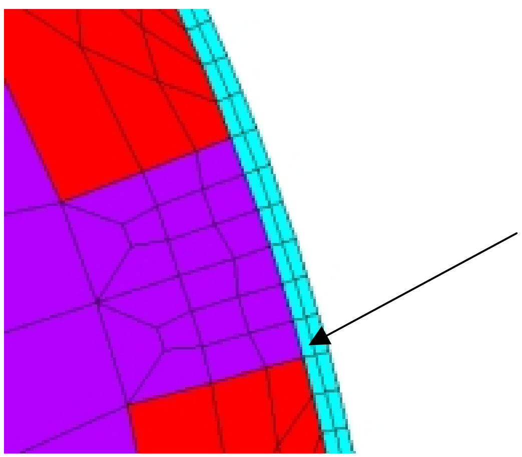


The space between the magnets is iron up to the top edge of the magnet.

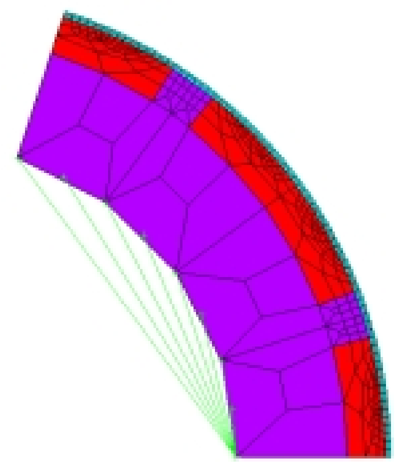


Magnet shape options-continued

Embedded option: enter loaf=0 (to turn off the loaf option) at the command line and <PMROTOR>



The space between the magnets is iron up to the top edge of the magnet.



Other magnet direction options

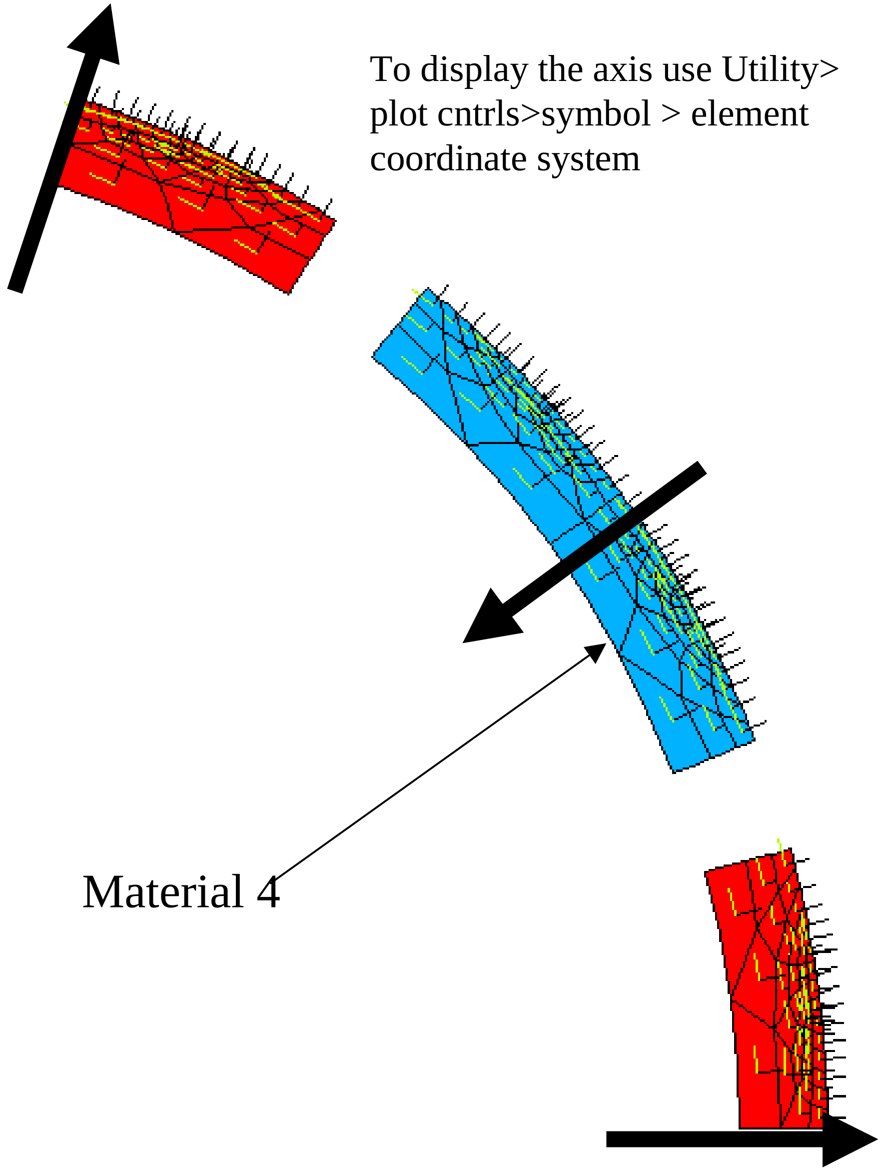
From the rotor help, the parameter RAD_MAG can be used to allow the magnet to be radially magnetized.

This would be accomplished by setting RAD_MAG=1 (set EMBED=0 to turn the embed option off) and rebuilding the rotor.

The rotor has the material numbers displayed and the element coordinate systems. Note that the arrows are radial. The center magnet has the inward direction. Since it is radial, the material number has to be changed. This is material 4 and its MGXX must be negative. There are no local coordinate systems needed.

<u>After this step, use Utility>file>resume and select file.db</u>

To display the axis use Utility> plot cntrls>symbol > element coordinate system



A set of independent parameters are defined for the slotted stator

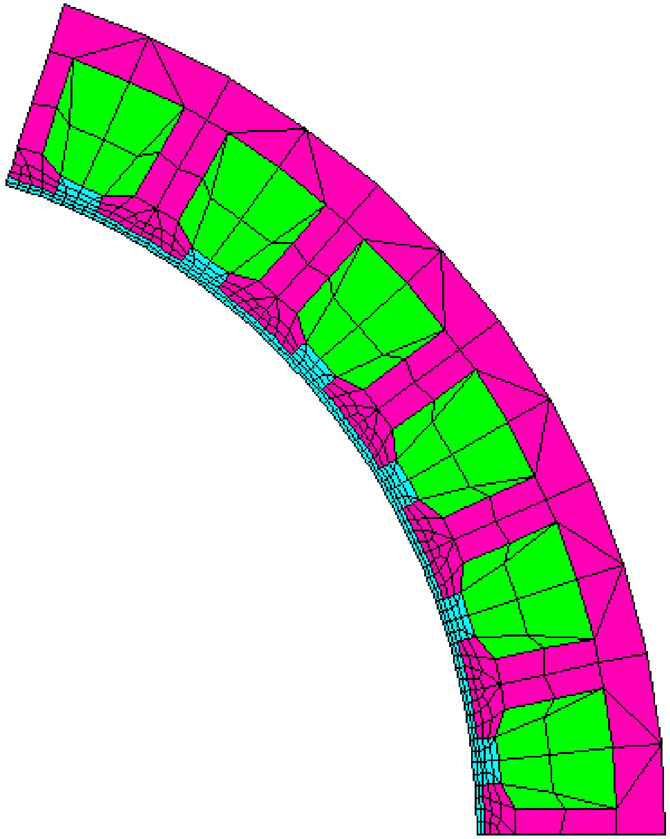
To build the slotted stator use <STATOR>

The stator model is independent of the rotor model

The stator extends midway into the air gap

The rotor mesh is automatically refined in the air gap.

Mesh can be refined by adjusting a single parameter (F_MESH).

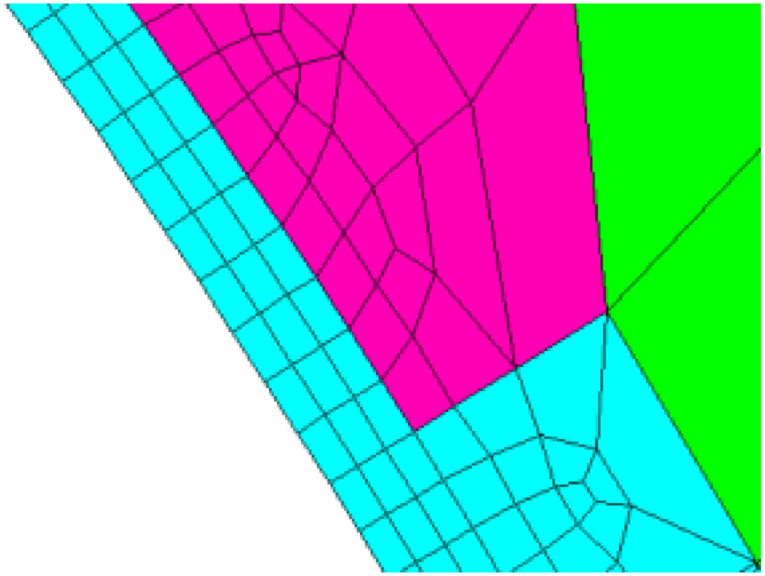


Mesh refinement in the air gap

The air gap in the rotor side can be refined by increasing STREF from 2 to a higher value up to 5. Larger values decrease the aspect ratio and increase the number of elements in the gap.

To observe this, enter stref=3 at the command line and rebuild the rotor using <STATOR>

RREF	Number of elements in the stator
2	432
3	1260



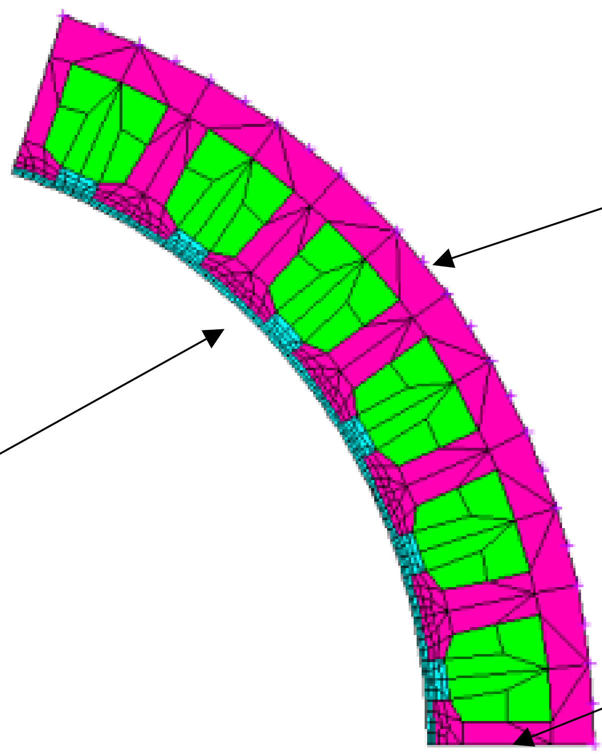
3 radial divisions

stref=2 is usually sufficient for a machine with currents

Stator boundary conditions

The currents could be considered as a boundary condition, but these are considered later.

The outer ring of nodes is automatically set to flux parallel by constraining AZ to zero

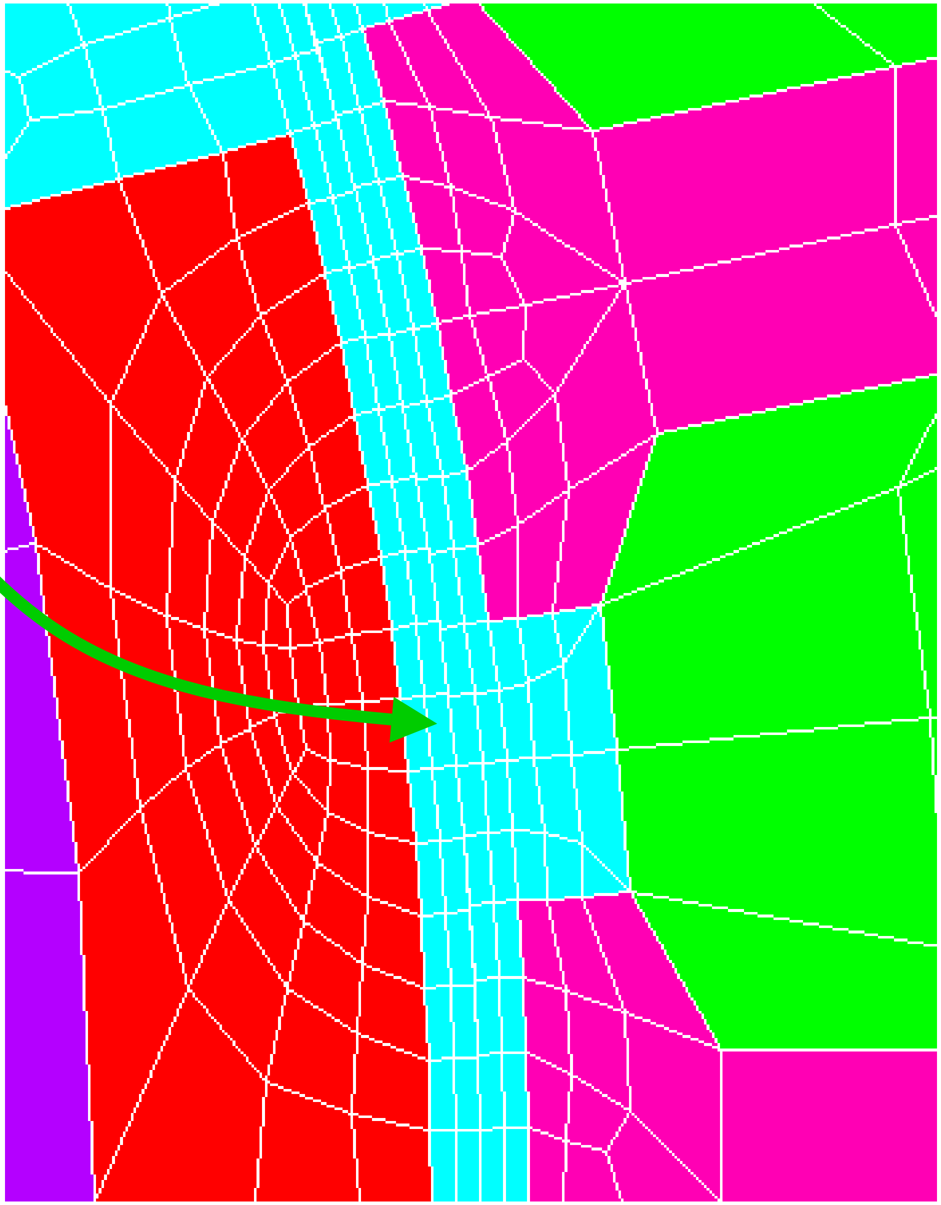


The inner edge is a boundary, but it will be later connected to the rotor using CEs

The lateral edges are a boundary, but they will be later connected to the other side using CPs

Coincident radial location for the models at the midgap radius, but not circumferentially

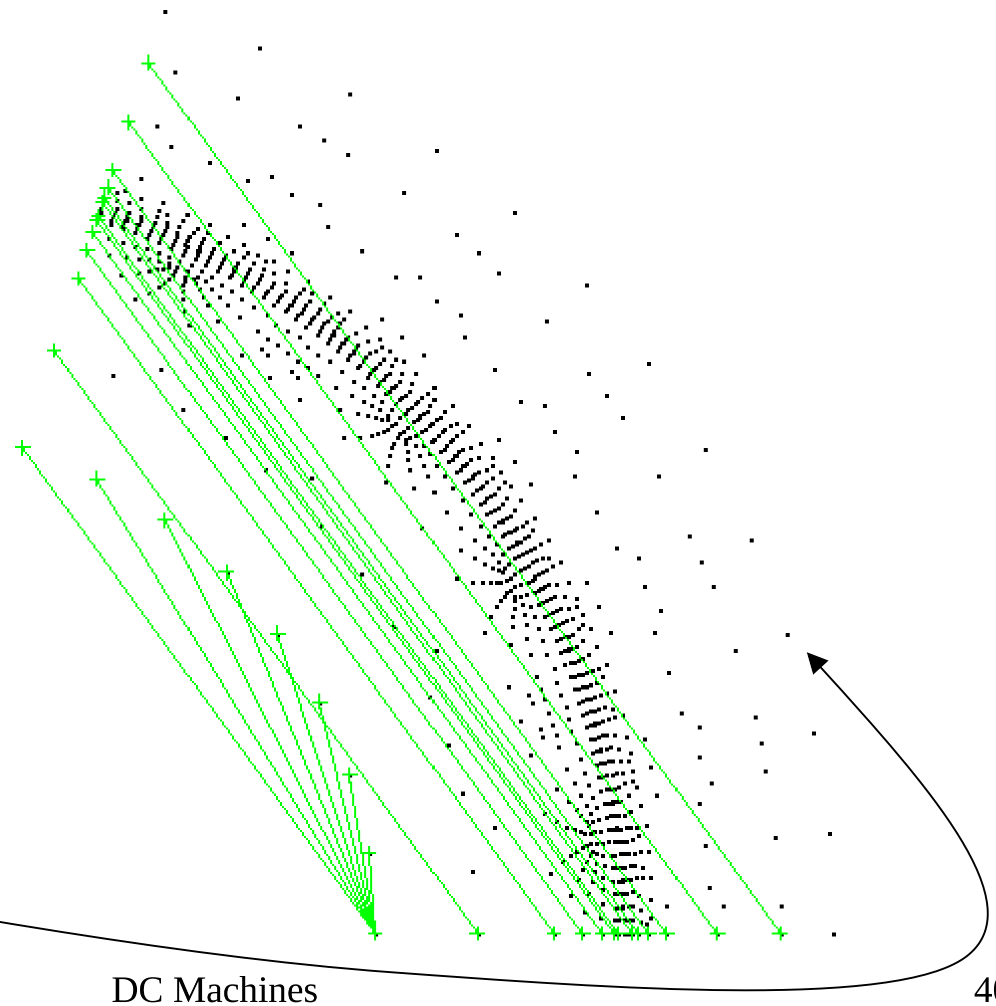
It is not required that the the mesh share nodes



Model error traps

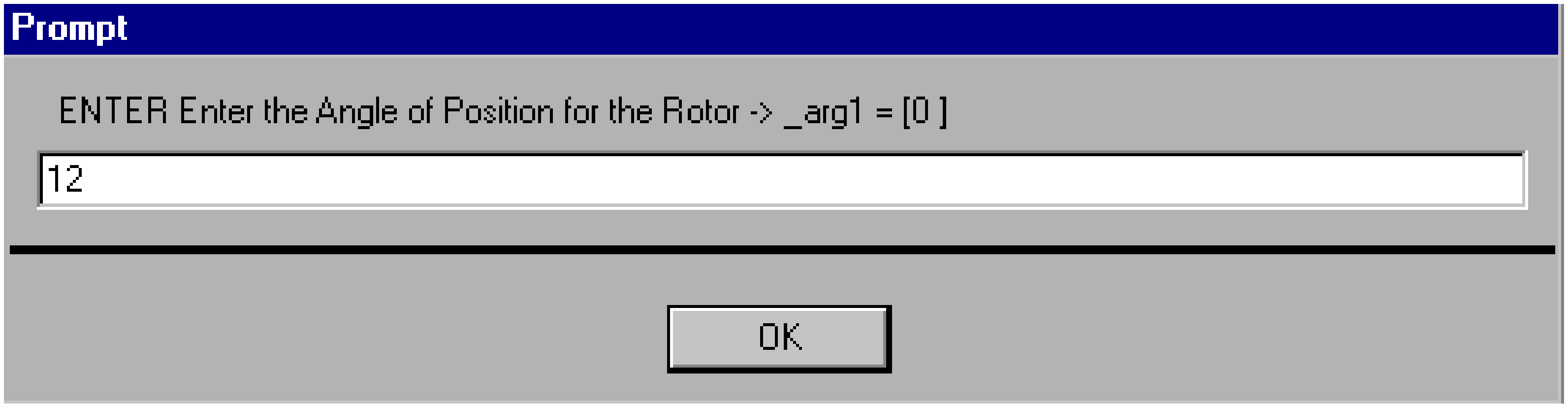
- There are a limited number of error traps built into the model macros
  - using the incorrect laminate type (the stator_id='slotsta' and you execute the pm_stat item)
  - the radii for the laminate are not in ascending order (the back iron radius is smaller than the inner tooth radius)
  - the GAP parameter was not specified
  - one of the laminate geometry parameters was not specified
- In the event an error is not displayed, and only a portion of the geometry is shown
  - the potential overlapping of the laminates due to error in the dimensions should be reviewed.
  - Compare the parameter file to the mach2.des file. This file (mach2.des) should not be changed-use it as a standard.

FIRST: This model requires periodic conditions to be applied to the sides of the model. Use <EVEN_BC>



CPs are generated for nodes at the same radius. Note that the outer ring of nodes are not used. These are constrained.

To connect the two models using CEs, and to rotate the rotor as required, use <ROTATE>. The angle is in degrees. Before using this macro, the CPs must be applied. If the CPs are not generated, this macro will not connect the rotor to the stator



For periodic models, the angle is measured from the +X axis in the CCW direction to the nearest edge of the rotor.

For full machines, the angle input is the angle increment that the rotor is to be rotated

The number in the brackets is the default value of 0. For a periodic model, the lower edge of the model is at the +X axis. For a full model, the rotor is not rotated

Rotor connected to the stator

After the rotor is rotated, and the two are connected, a summary is provided

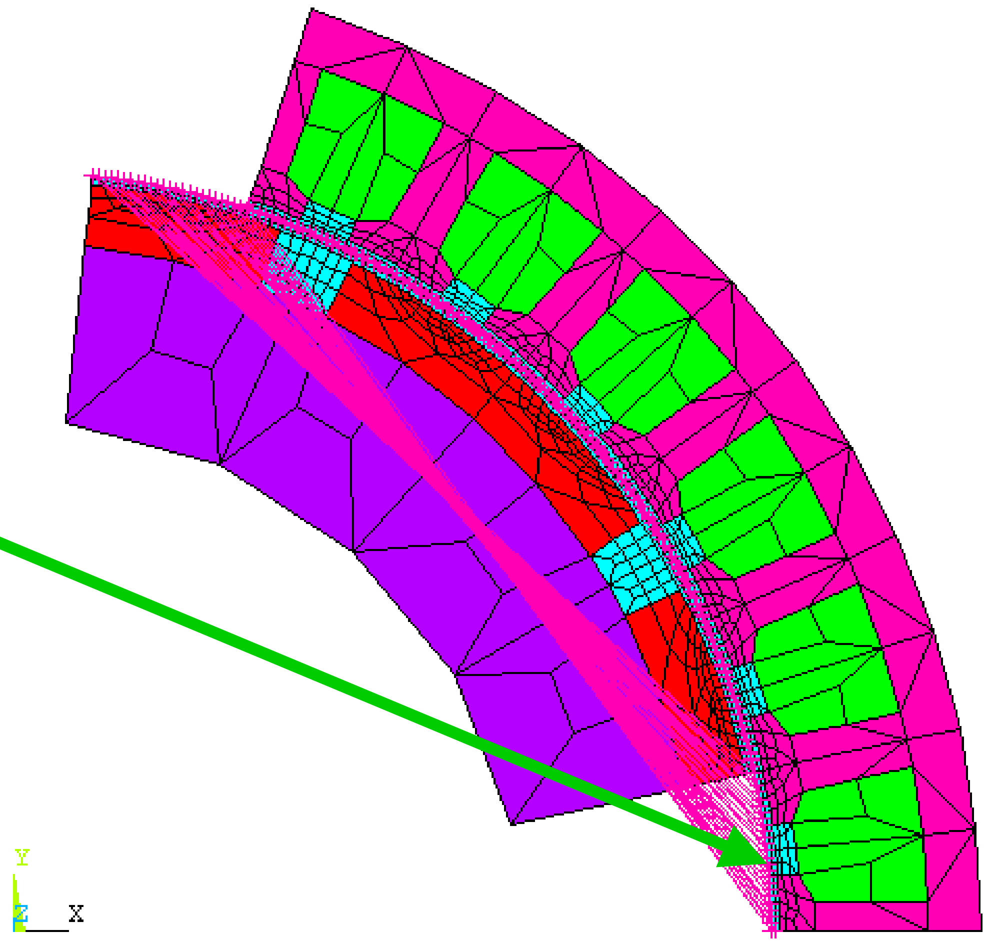
```
>________________MOVEMENT OF THE ROTOR_________________<
 OLD angle of the lower edge of the rotor:__________ 0.
 NEW angle of lower edge of the rotor:______________ 12.
 Number of nodes in rotor:__________________________ 145.
 Number of magnet coordinate systems moved:_________ 4.
 Was the Rotor "Stitched" to the Stator ?:__________ Yes.
 >______________________________________________________<
```

This indicates that the coordinate systems in the magnets were also rotated to maintain the same relative direction

This indicates that the CE's were generated

Rotor connected to the stator

The nodes outside the rotor-stator interface are appropriately connected



Checking magnet direction

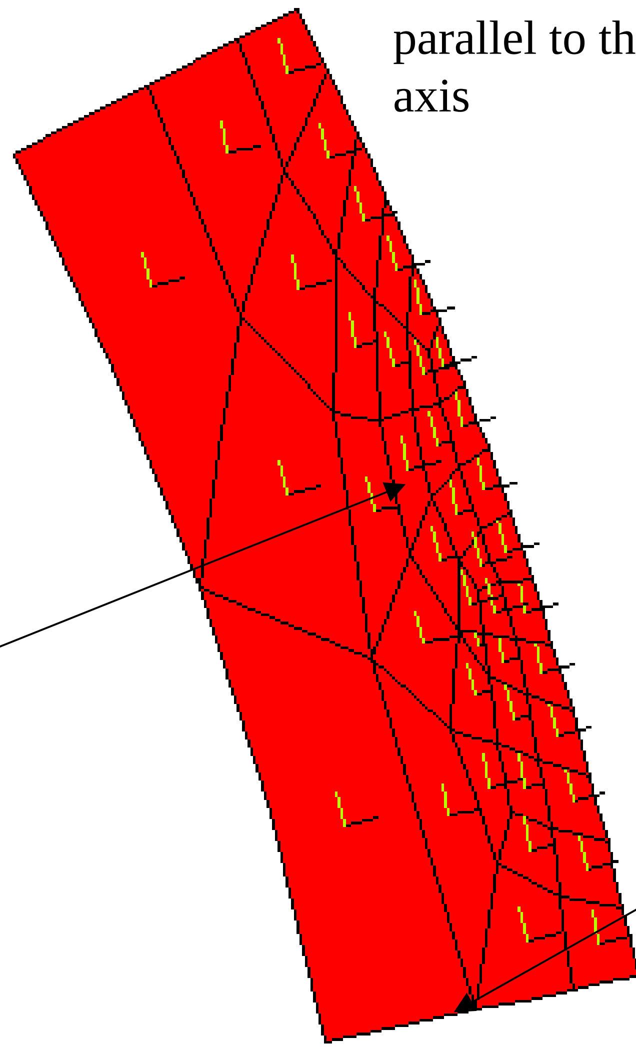
To display the element directions, use

Utility>plot cntrls>symbol > element coordinate system

white axis: element X axis

green axis: element Y axis

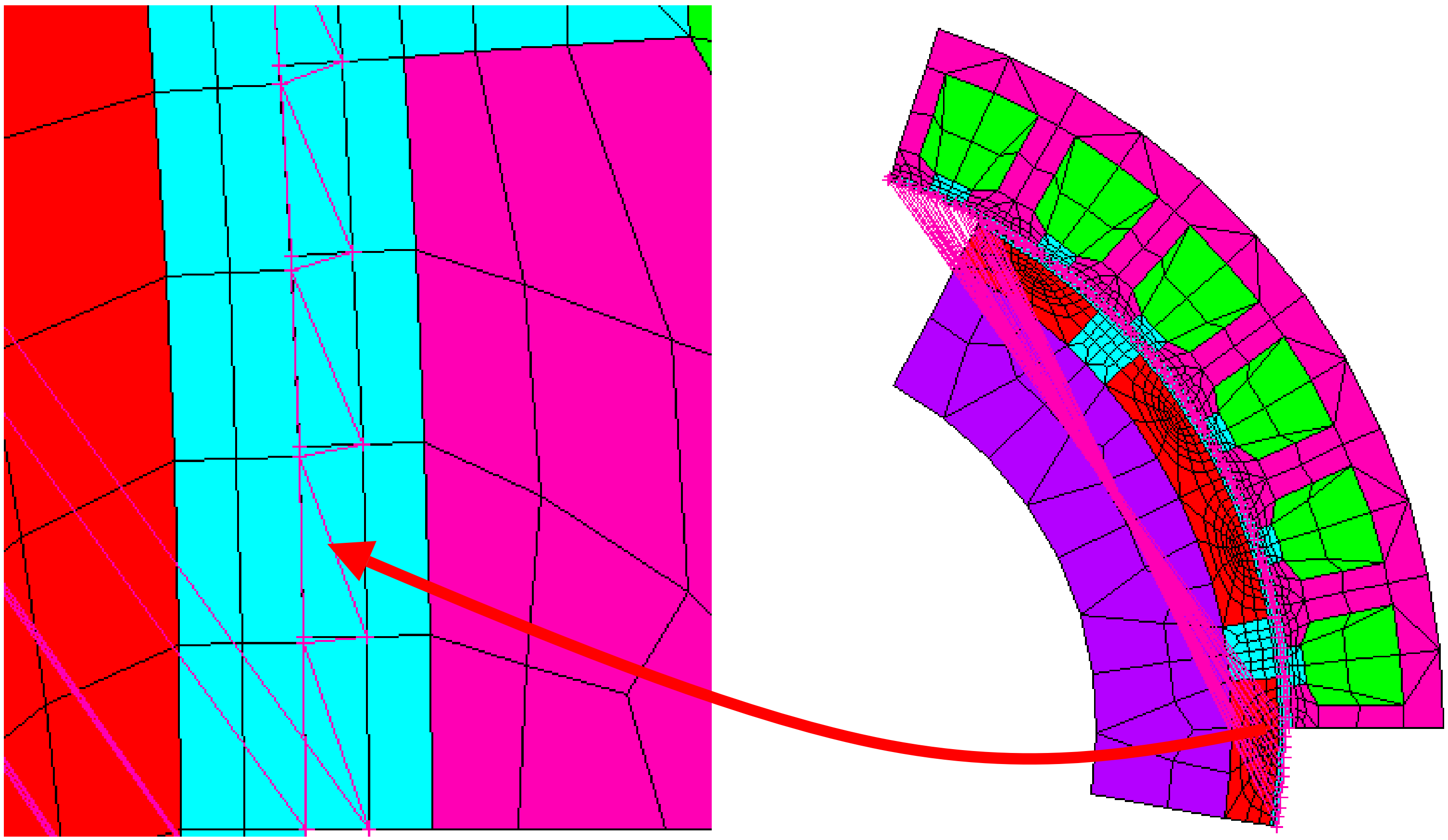
blue axis: element Z axis



Note that the white axis is still parallel to the center line of the axis

Center line of magnet

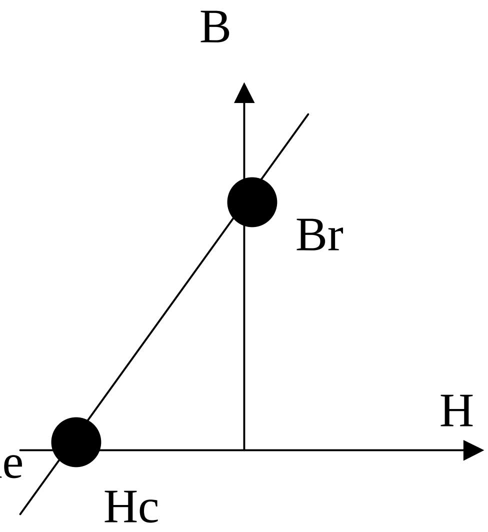
The rotor can be moved to arbitrary positions (CW or CCW)



Permanent magnet material data

Permanent magnets require the Coercive force (Hc, A/m) and the permeability (not Br (T)).

The permeability is usually considered to be isotropic. Most data sheets specify the Hc and Br. The permeability is then computed as Br/Hc/1.2566E-6. This value would be used in the MURX. Be sure to account for temperature effects when selecting the properties (This can significantly affect EMF calculations.)



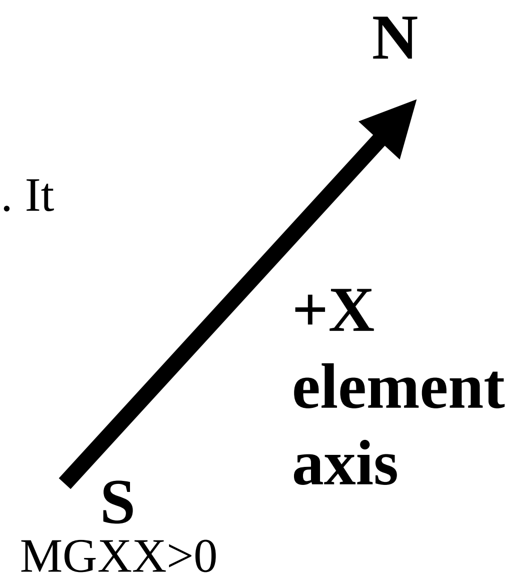
The Hc usually has only one component of the coercive force. It is interpreted in terms of the **element coordinate system (ESYS)**.

From the machine macros:

Parallel / radially magnetized: element axis

X is outbound-inbound

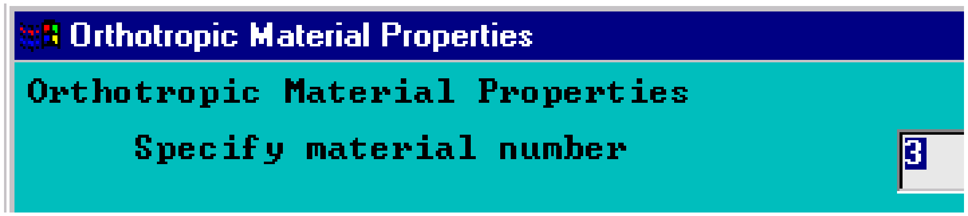
Y is circumferential



Magnet properties

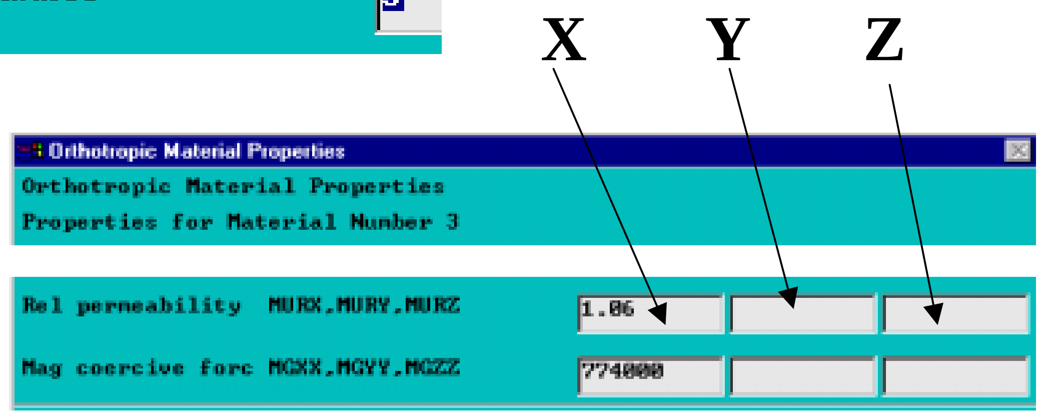
To insert magnet properties, use Preprocess>material props>orthrotropic…

and select 3 for the magnet from the machine macros



Select OK

The panel is displayed to input permeability (MURX) and the coercive force (MGXX). The other fields are for Y and Z. MURX is a relative permeability. Units for H are A/m (not Oe)



Select OK

Laminate data:
The materials can be altered in the preprocessor or in the solution module. To alter the rotor iron (material 2) or the stator iron (material 5) one of the following materials may be used.

M2	M4	M6	M14	M15
M19	M22	M27	M36	M43
M45	M47	M50	M54	

These are used by entering the preprocessor and entering at the command line

```
m14,2    !  for the rotor iron
m14,5    !  for the stator iron
```

BH data can also be entered for the magnets, material 3.

About the M steels

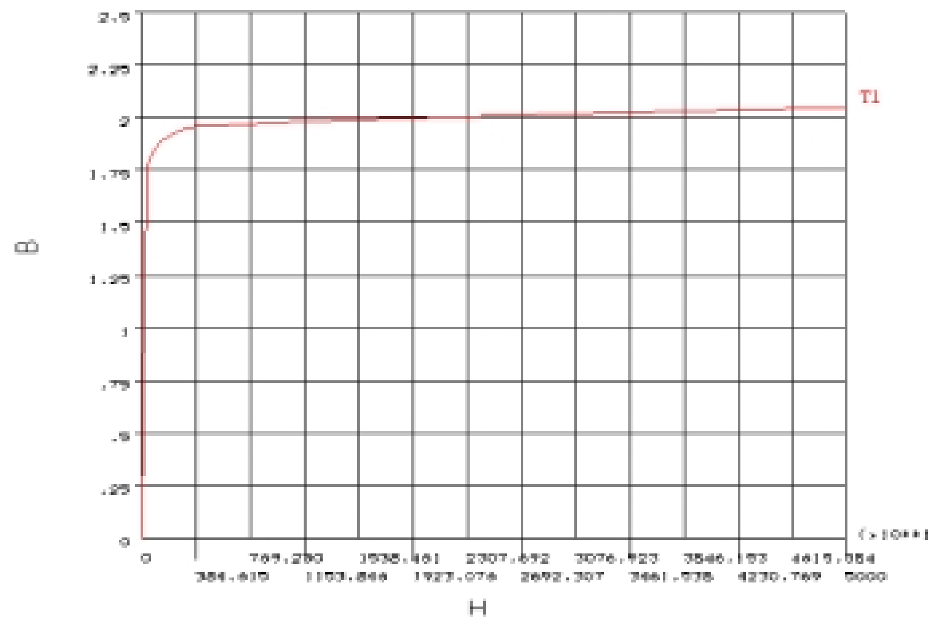
The M steels on the previous slide meet the following criteria:

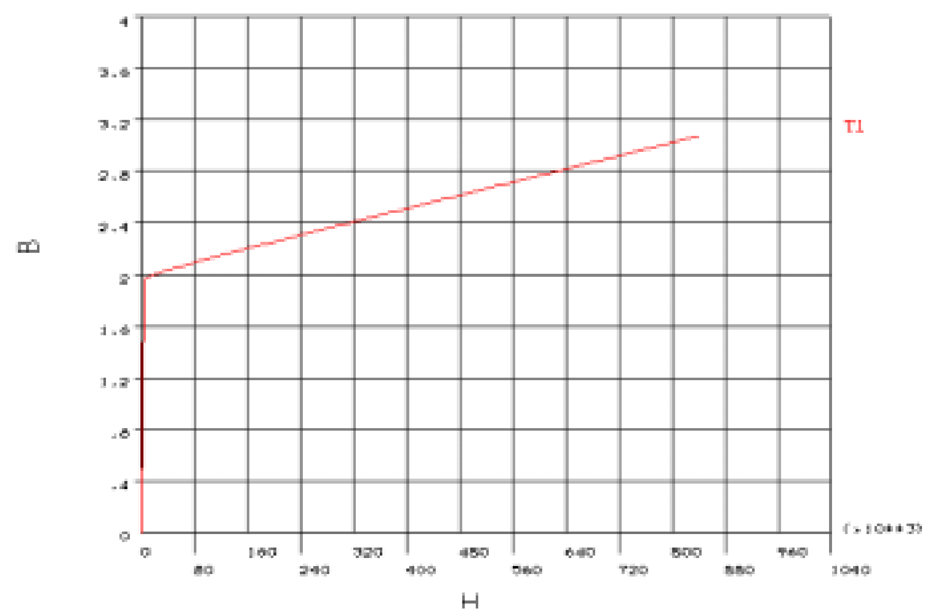
1) The curves are smooth through the knee of the curve

2) final slopes are free space

3) Final H > 500,000 A/m

It should be noted that some M steels have permeabilities >30,000. In these cases the initial load step may need more than 3 steps. The flux line plots should be inspected for reasonable flux lines in the iron





Inputting a new BH curve

To input a new curve, use an existing M material. (M50) to form m_ex.mac

```
/COM,ANSYS
/NOP
/COM,Internal UNITS set at file creation time = SI   (MKS)
/COM,M Steel
/COM,********* Typical B-H properties for demo purposes *********
TBDEL,ALL,arg1
MPDEL,ALL,arg1

TB,BH  ,arg1 ,   1,  30   !

TBPT,,   318.3      ,   .97
TBPT,,   477.5      , 1.22    ! 2
TBPT,,   636.6      , 1.34
TBPT,,   795.8      , 1.42    ! 4
TBPT,,   1592.      , 1.57
TBPT,,   3183.      , 1.69    ! 6
TBPT,,   4775.      , 1.75
TBPT,,   7958.      , 1.816
        ..
```

Comments (the /COM lines)

Deletes existing BH and linear data (TBDEL, MPDEL)

The maximum number of data points < 100

The first number is H, the second number is the corresponding B. The 0,0 point is not to be specified. The pairs are to be specified in ascending values of H and B.

Most laminate data is not extended to 100,000 A/m range. The data needs to extended to this level in a gradual fashion.

Extending the BH curve

1) The (μ_{tan}) for the last two pairs is (1.816-1.75) / (7958-4775)/ 1.2566e-6 = 16.5

2) Compute the additional data point using μ_{tan} = .5*16.5 = 8.25. Double the value of H or 2*7958 = 15,916. The New B = 8.25*(1.2566e-6)*7,958+1.816=1.9. The first additional pair is (15916, 1.9)

3) The next additional point is for H=2*15,916=31,832. The next permeability is .5*8.25=4.12, and corresponding new B=4.12*(1.2566E-6)*15,916+1.9=1.982 . The next additional pair is (31832,1.982)

4) The next additional point is for H=2*31,832=63,664. The next permeability is .5*4.12=2.06, and corresponding new B=2.06*(1.2566E-6)*31,382+1.982=2.06. The next additional pair is (63664,2.06)

5) The next additional point is for H=2*63,664=127,338. The next permeability is .5*2.06=1.03, and corresponding new B=1.03*(1.2566E-6)*63,664+2.06=2.142. The next additional pair is (127339,2.142)

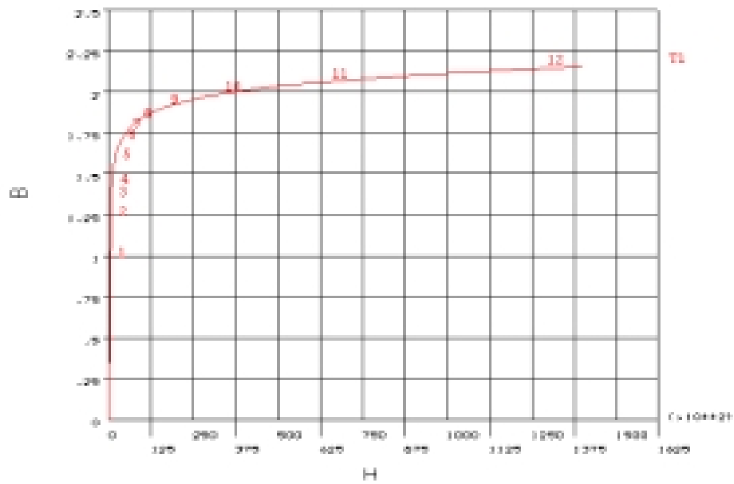
Adding new points to the BH data

The following lines would be added to the end of the existing file m_ex

```
tbpt,, 15916. , 1.9
tbpt,, 31832. , 1.982
tbpt,, 63664. , 2.06
tbpt,, 127338., 2.142
```

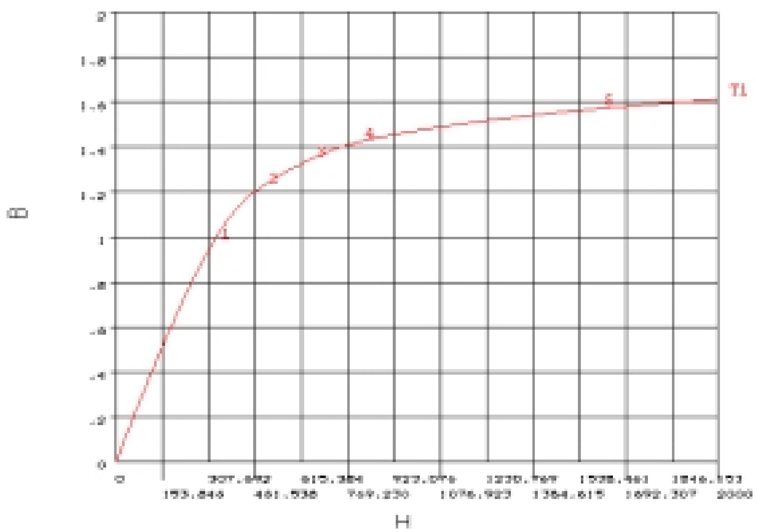
```
These form data points 9-12
```

To load the data enter m_ex,10. The plot is generated using Utility>plot>data tables [Mag field BH data] for material 10



Examination at the knee of the curve

When inputting a new curve, and the range is automatically selected, it is best to alter the range for H to observe the curve at low values of H. This is accomplished by Utility>plt ctrls>style>graphs>modify axes



Select the "Specified Range" and insert 0 and 2000. After selecting OK do a replot. The curve appears to be smooth. Once the plot has been examined, return to this panel and select the "Auto calculated option"

Plotting NB curve

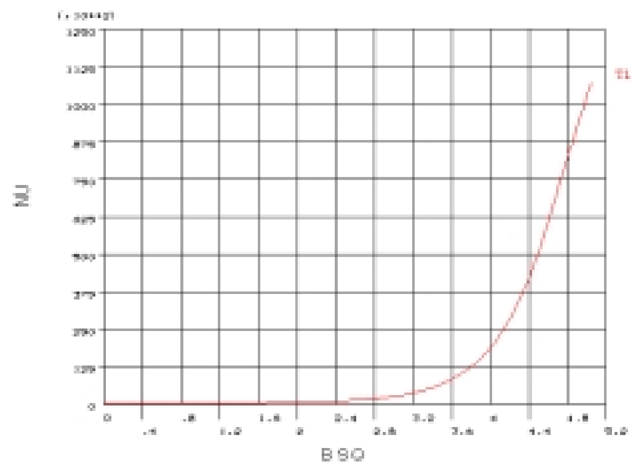
The N-B^2 curve should be plotted to ensure that the curve is monotonic. For nonlinear solutions, the Newton-Raphson method uses the derivative of the N-B^2 curve to determine the next increment in the degree of freedom. (N refers to NU which is 1/μ)

This is plotted by Utility>data table

Lab	Type of data table	NU vs. B**2 NB
MAT	Material number	10

Select OK

Note that the curve is monotonic and is smooth. This assists in the nonlinear solution process. If this has oscillations, some of the points on the curve should be adjusted. (1) remove the “kinks” in the curve (2) make the H spacing more even



Note that the BSQ scale is about 5 (T^2)

Specification of the winding

- For the DC application, currents (Amp-turns) must be applied to the stator.
- Even for a single analysis the process of applying the currents can be a tedious process leading to potential errors. This process can be multiplied by:
    - full machine model requiring >60 slots
    - polyphase machines
    - numerous solutions are required to determine machine torque versus angle
- Specification of the currents require two types of information
    - winding data of slot/turns for each coil
    - current form (amps versus electrical angle
- Since circuit elements are not required, the data for the winding and current form is stored for later usage.
- RSVX is not required. If RSVX is input, ANSYS assumes that the copper area is the cross sectional area of the slot, which is not physically correct.

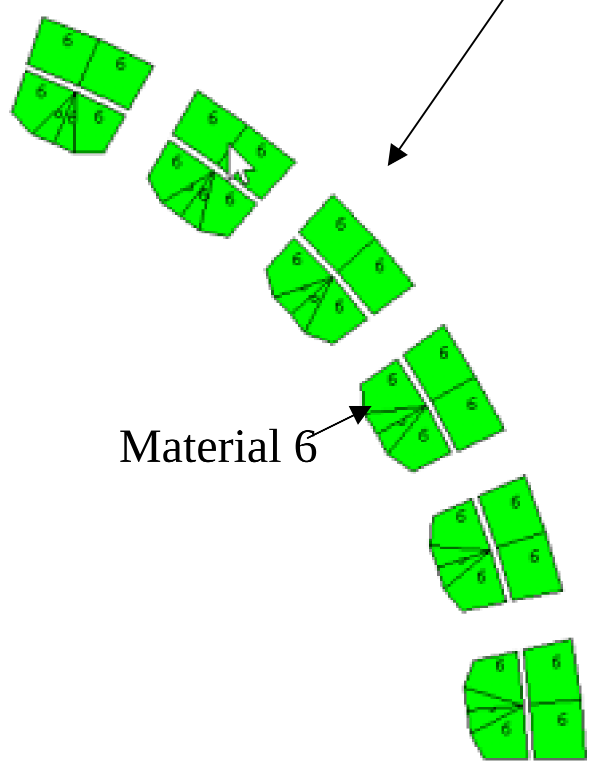
Specification of the winding -continued

- The winding data is specified in an ASCII file with fixed format. The file extension must be .wnd
- This file contains a single line for each coil
  - slot location for the coil going IN the laminate
  - slot location for the coil coming OUT of the laminate
  - number of turns for the coil
  - which phase the coil is associated with
  - wire gauge (used to compute the power loss (Watts) only)
- The wire gauge is optional-it is only used to compute a resistance to allow the power loss to be computed when the current is applied
- The winding file does have not a limit on the number of coils, and not all slots must have a coil.
- For periodic models, only the number coils for the periodic model need be specified.(for the 10 pole, of which 2 poles are modeled, only 3 coils are modeled, which require only 3 lines in the winding file
- For a full model, all the coils must be input

Multiple coils in a slot

- The maximum number of times that a slot number can be used is 2. This means that no more than two coil cross sections can be placed in a single slot.
- The maximum number of coil sections which can be placed in a slot MUST be specified in the NCONS parameter, which is the number of "phases" in a slot.
- When NCONS=2, the stator generation allows the slot region to be divided into two regions.
- This same geometry generation is also used for the AC application which requires the two coils not shared common nodes.
- All slots have the same material, Material 6
- If NCONS=2 is used, and the winding file only uses the slot one time, the coil would be in the back of the slot.

To get the coil below, enter NCONS=2 at the command line and use <STATOR>



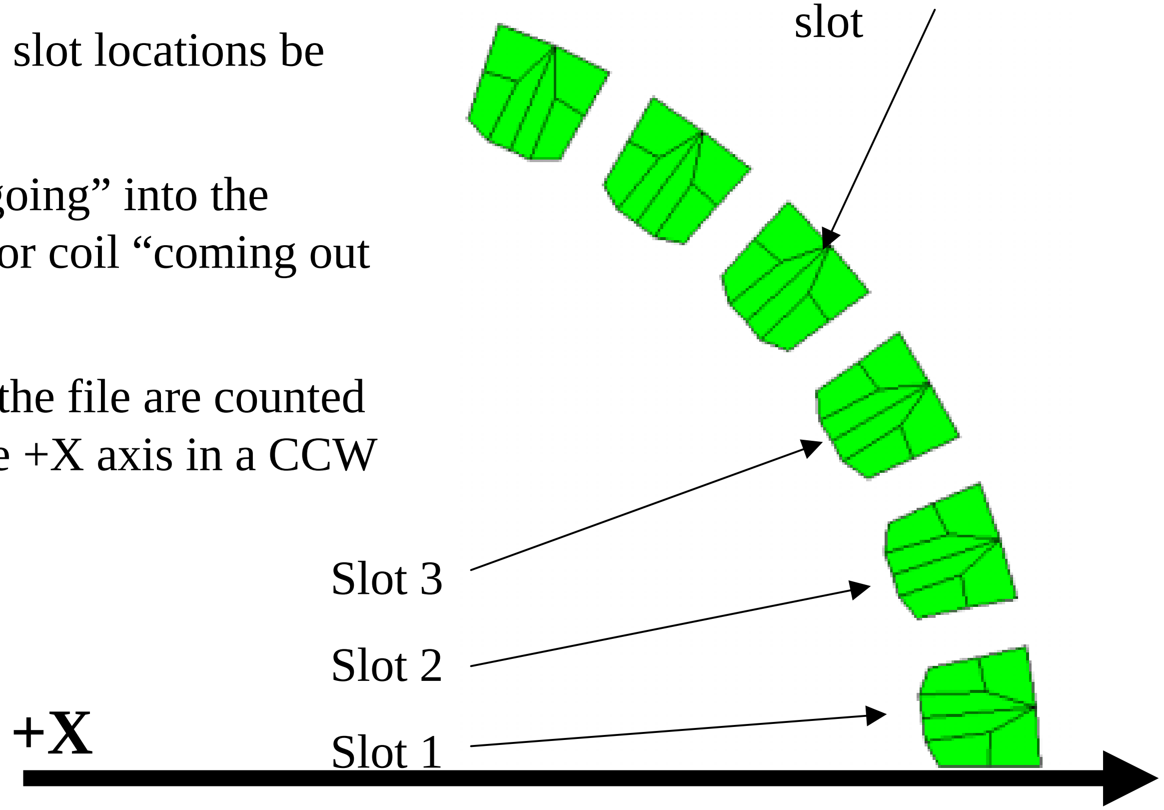
Winding file specification

•The file requires that 2 slot locations be specified for a coil.

•One slot for the coil “going” into the laminate, and one slot for coil “coming out of the laminate”

• The slots specified in the file are counted from the slot nearest the +X axis in a CCW direction.

Note that this model has only one coil per slot



Winding file specification for mach2.wnd

A separate line is specified for each coil and the specification for the first coil MUST start in line 1 of the file.

Below this line, any description may be added

OUT slot	IN slot	Turns	Phase	Number of coils specified	Wire gauge
1.	4.	10.	1.	3.	18.
5.	2.	10.	2.		
3.	6.	10.	3.		

```
 123456789012345678901234567890123456789012345678901234567890
          1         2         3         4         5         6
file:  mach2.wnd
```

```
columns    definition
1-10        out slot
11-20       in slot
21-30       number of turns
31-40       phase (1,2,3,,,)
41-50       number of lines in this file to be processed (first line only)
51-60       wire gauge (AWS)
```

Winding specification-continued

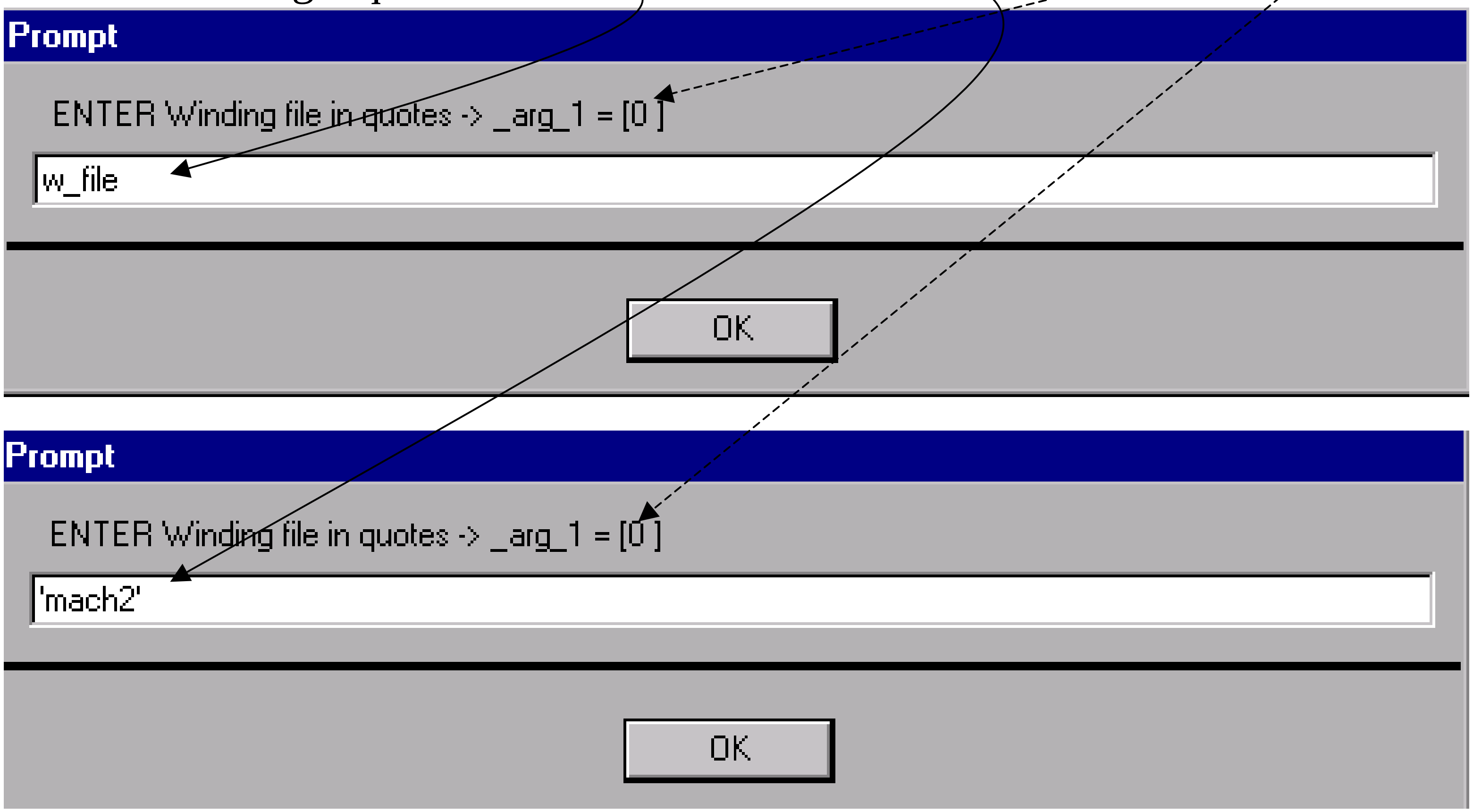
- The OUT slot at 0 degrees corresponds to a + current .
- The IN slot at 0 degrees corresponds to a - current
- The “Phase” is used to identify the current-phase relationship between the coils. It is assumed that the shift between phases is 360/Number of phases
- The actual specification of the current to be applied to the winding is performed using <LOAD>
- Since the winding file does not affect the geometry, the winding file can be arbitrarily changed (if NCONS is changed, the stator must be rebuilt prior to reusing <WIND_2D>).
- Any change in the winding file will require that the data storage for the winding be regenerated.

Winding data generation

The winding data is stored by <WIND_2D>. This displays a prompt for the name of the winding file (.wnd extension).

The name can be a parameter or can be input directly when it is enclosed in single quotes.

Default values (typical)



Winding data generation

A summary is provided, after the data is stored. This data is also stored with the data base.

mach2.sum

File

```
___________SUMMARY OF THE WINDING GENERATION___________

Name of winding file:______________ mach2 .wnd.
Name of coil element component:____ s_coil.
Number of Phases:__________________ 3.
Number of coils:___________________ 3.


Explanations for the Winding:
The coils associated with each phase are contained in a separate
 element component.  Phase 1 coils are contained in the component ph_a
 and Phase 2 in ph_b, etc.  All elements to apply Amp-turns are
 contained in the element component "winding".

In the generation of the winding, certain data was also stored for use
 during the solution phase to allow the currents to be applied to the
 winding.
```

This macro also generates a number of other element components C100n which should NOT be deleted, since they are used to apply the currents later on.

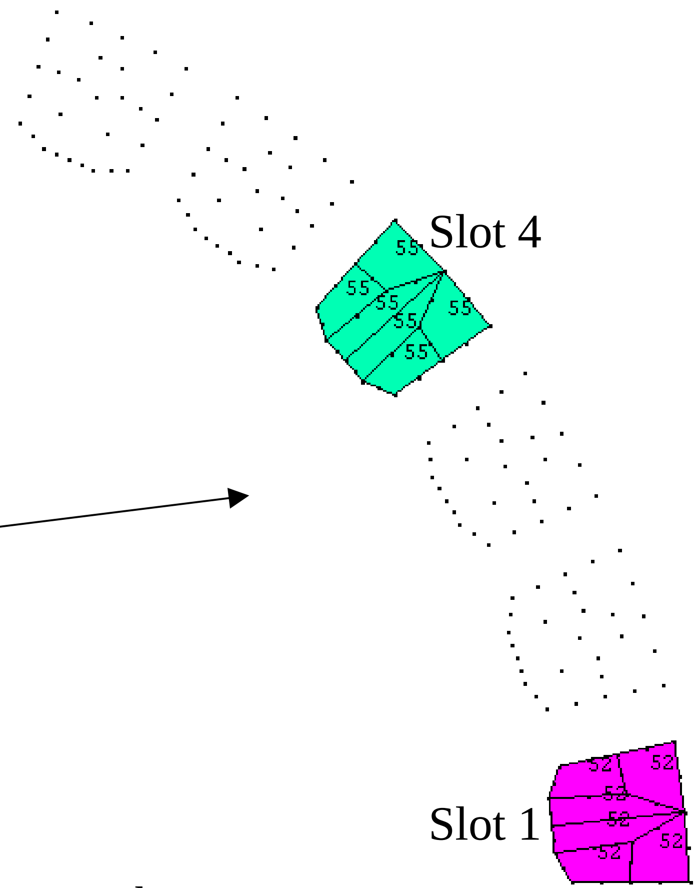
Element components for the phases

As indicated in the summary window, element components ph_a, ph_b, ph_c,,, are comprised of the cross sections corresponding to each phase.

Ph_a,ph_b,ph_c correspond to phase numbers 1 , 2 , 3 in the winding file respectively.

When the ph_a component is selected and the plotted the following plot is obtained.

To superimposed the nodes, the noerase option was used, and the nodes of the element component S_COIL were then plotted



Real set numbers are displayed

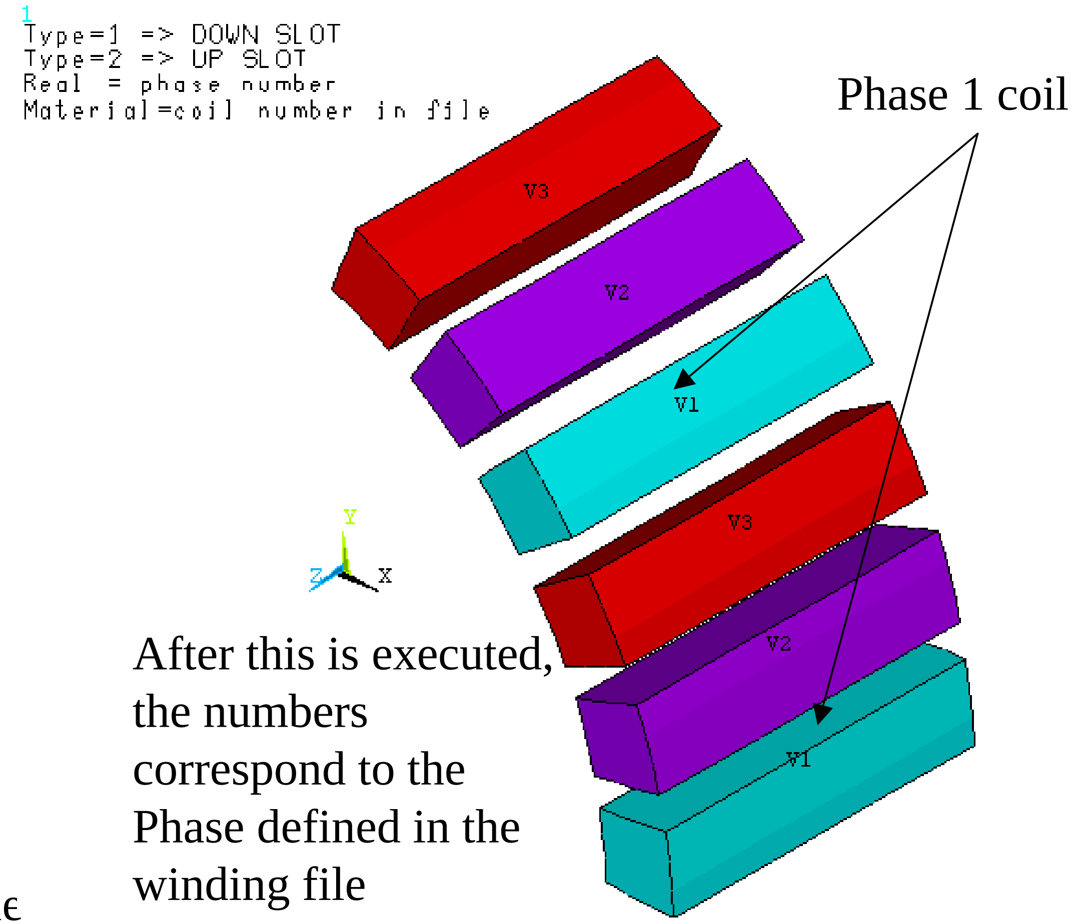
Displaying the winding

The winding can also be displayed using <PLOT_WND>

By default the entire winding can be displayed.

The coils are represented by volumes and the volumes are sized to fit the window of the slot.

The attributes can be made active which can display the phase, in/out direction, coil number for each coil in the file

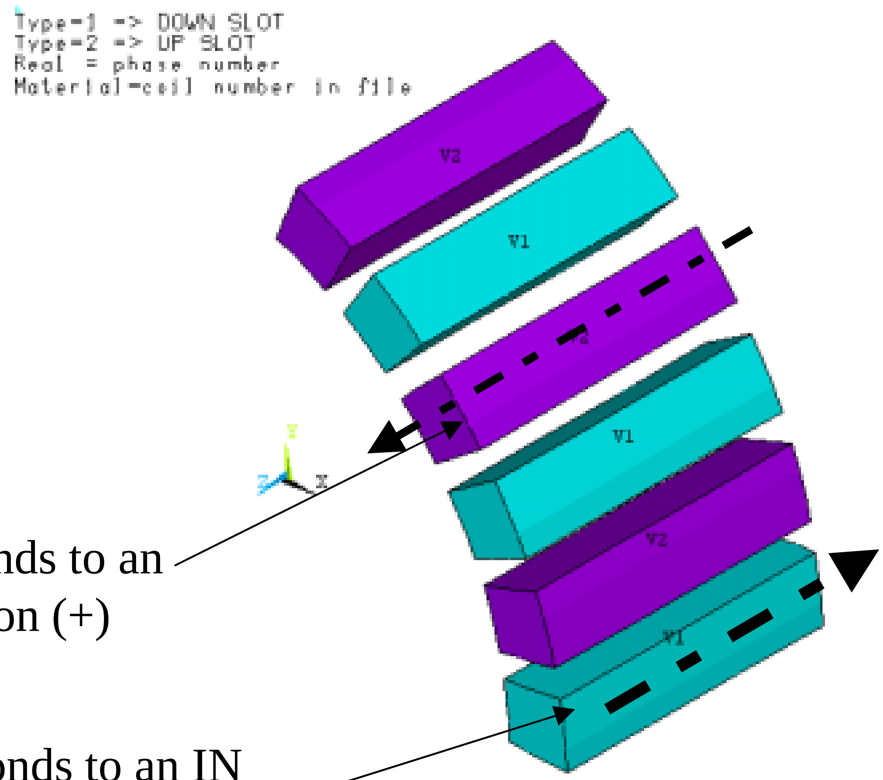


After this is executed, the numbers correspond to the Phase defined in the winding file

·

Displaying the winding-displaying IN/OUT direction for each coil

By making the TYPE active, the in/out direction specified in the file can be displayed

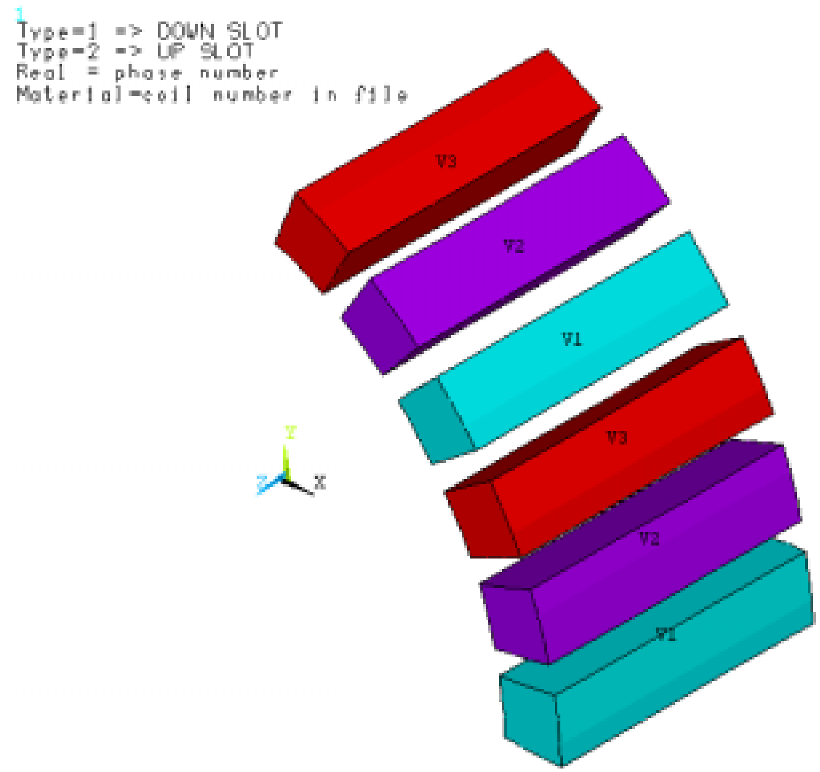


“2” corresponds to an OUT direction (+)

“1” corresponds to an IN direction (-)

Displaying the winding-displaying the coil number

The numbers shown in the volume correspond to the location of the coil specified in the winding file. The two volumes labeled as 2 correspond to the 2nd coil in the winding file



Displaying specified phases of the winding

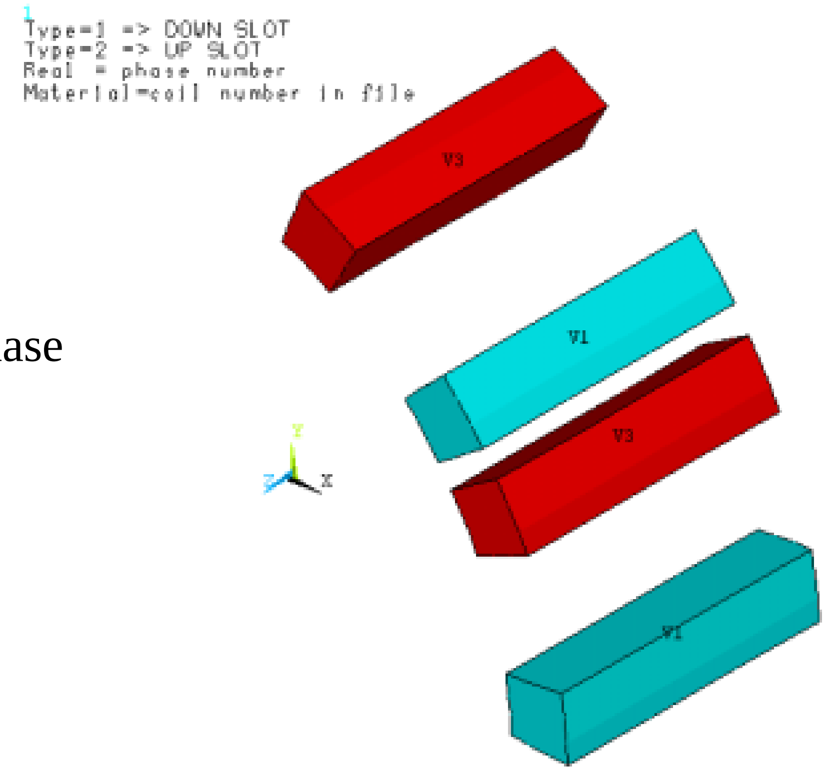
If only phases 1 and 3 were to be displayed, the command can be entered at the command line

pldcstr,1,3,2

Increment phase number (2)

Starting phase number (1)

Ending phase number (3)



Phases 1 and 3

Current form specification

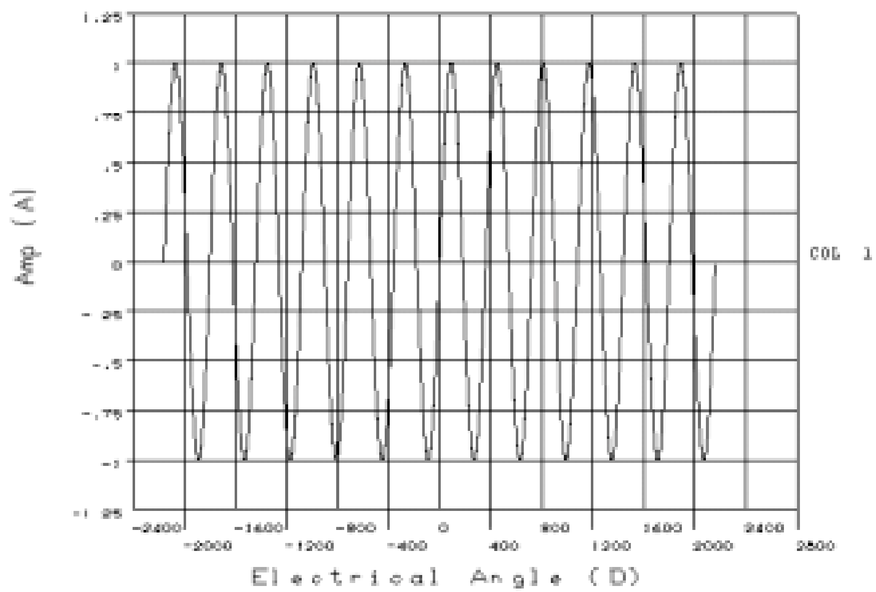
- The winding specification defined the coil locations and the turns.
- For any specific winding the current form could be varied. The current form is the basic shape of the current versus electrical angle
- This information can be used to solve for a specific electric angle at a specific rotor position or can be used to rotate the rotor and use the current form to provide a currents for the different rotor angle.
- Two predefined current forms are available:
  - sine
  - flat
- To access these forms, the following parameter is used.

  CURRFORM='sine' (for the sine)

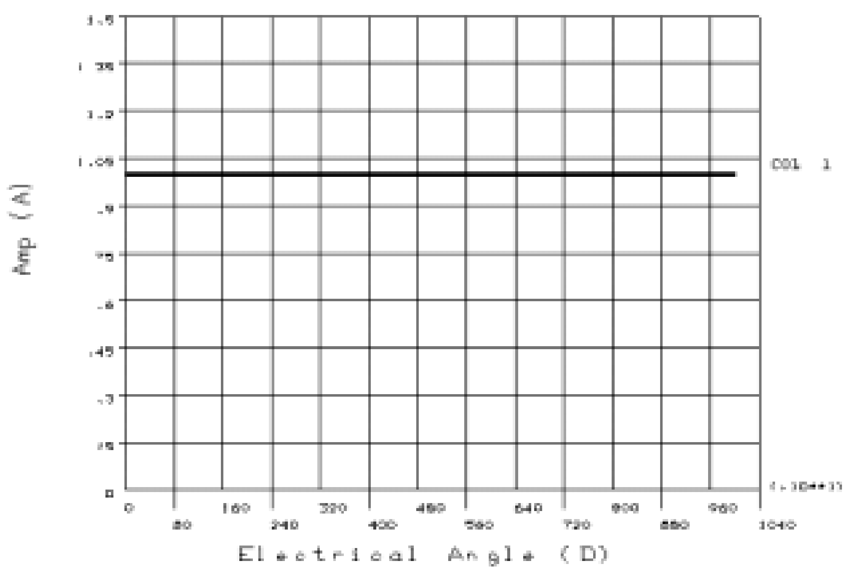
  CURRFORM='flat' (for constant current)
- This can be changed, with out having any affect on the model or the winding, but it must be specified prior to using the <LOAD> to apply the currents

Displaying the default current forms

The default forms can be displayed by <PLT_FORM> once the parameter CURRFORM has been specified



CURFORM='sine'



CURFORM='flat'

Definition of a new current form

•Other shapes can be defined by specifying the AMP_A table for 360 electrical degrees

•A square wave can be defined using the table amp_a (from 0 to 360 only)

the index is amp_a(I,0) which is the electrical angle
the value is amp_a(I,1) which is the factor

(*The 7 is the number of values*)

```
*set,amp_a
*dim,amp_a,table,7
amp_a(1,0)=0,.0001,119.99,120.001
amp_a(5,0)=239.99,240.01,359.99            !  angle
amp_a(1,1)= 0,  1,    1,     0,     0
amp_a(5,1)=-1, -1                          !  Form
```

Definition of a new current form-continued

- The index of the table must be extended to be sufficiently close to 360, but not 360, since it is to repeat

- If a new form is to be used, delete CURRFORM by entering

  CURRFORM=

  at the command line (or use the GUI Utility>parameter>scalar)

- Only one table is needed since the other phases are assumed to be offset by a constant phase shift.

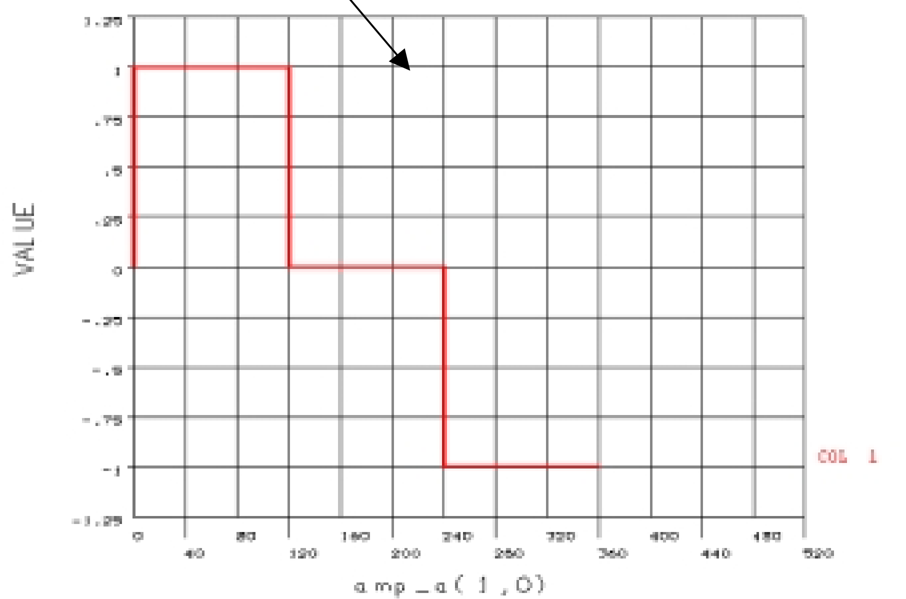
- The peak value in this table should be unity (1), since the total current applied is the value from this curve factored by input peak current to the <LOAD>

- The form should be defined to allow the phase currents to be balanced

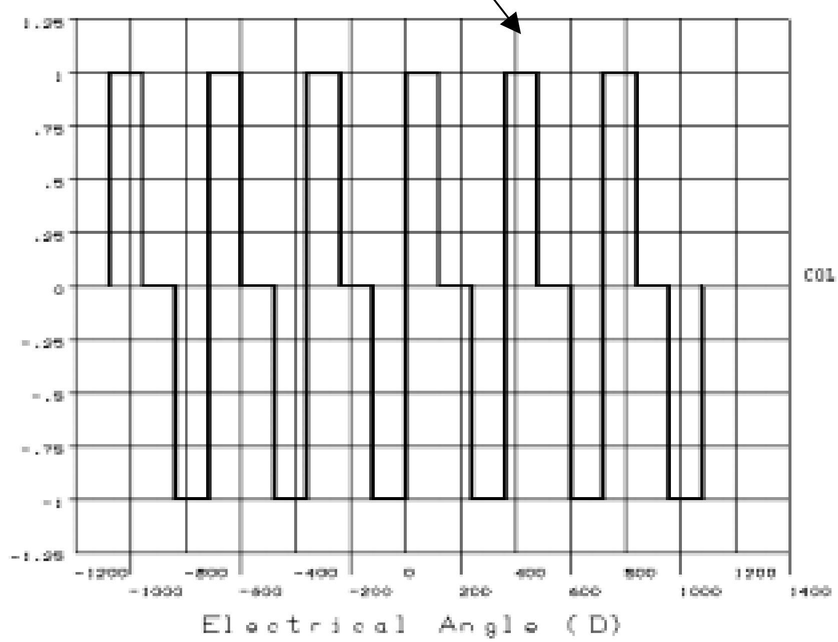
Displaying the new current form

*vplot,amp_a(1,0),amp_a(1,1)

can be used to show the form as defined

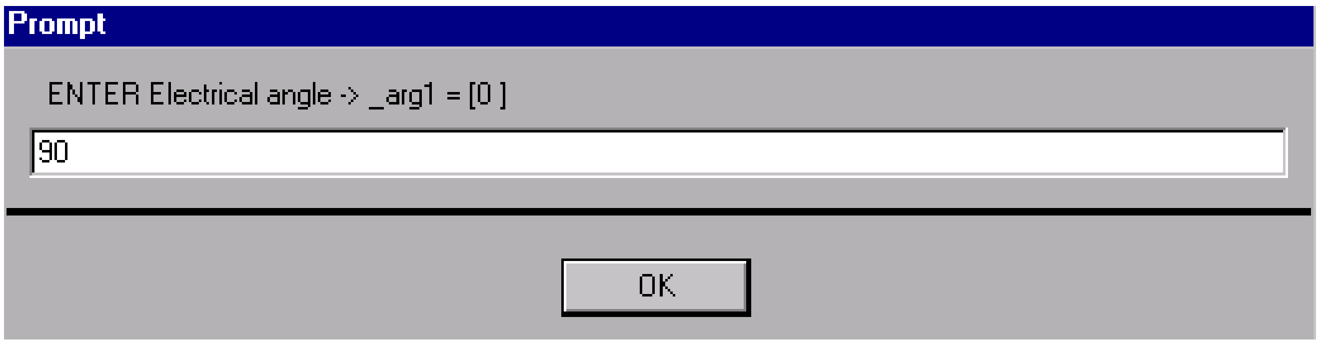


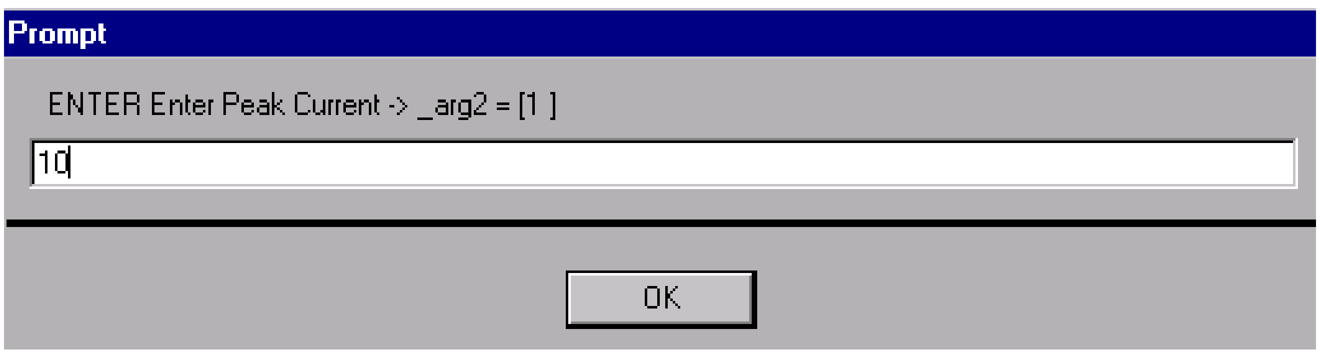
<PLT_FORM> can be used to show the form over a range



Applying a current

Once the form is specified, the current is applied by <LOAD> which requires the input of the electrical angle and the peak current. Multiple phases are assumed to be offset by360/(number of phases). Specifying currform=‘sine’ and with <LOAD> using 90° and 10 A (peak)

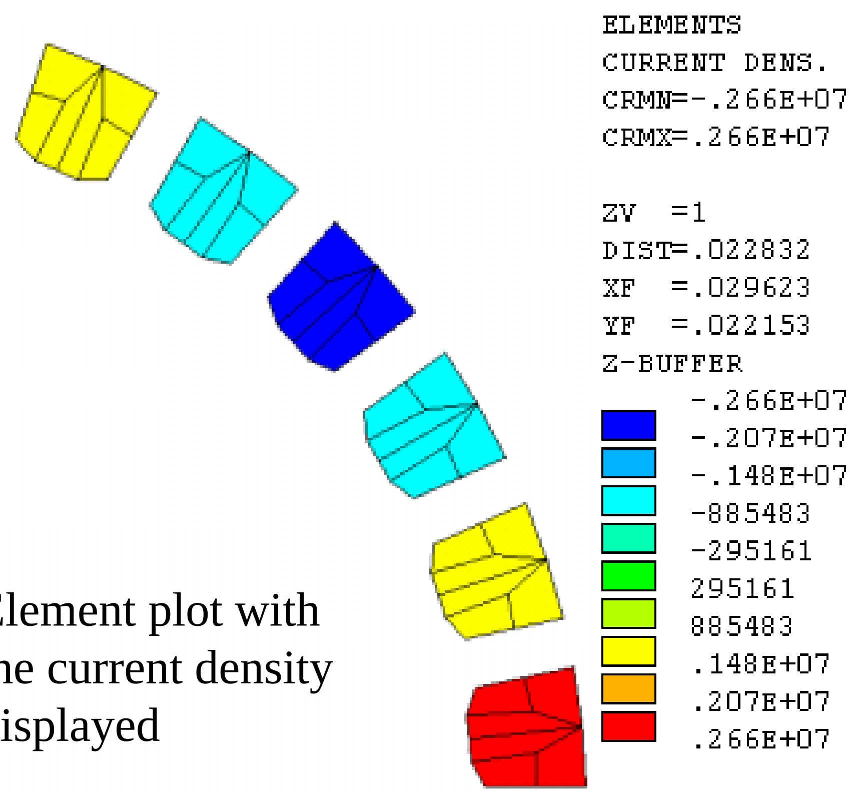




<LOAD> summary

The <LOAD> uses the current form (default or new), the data stored associated with the winding file, and the input from the two prompts to determine and to apply the current density (A/m^2) for each slot

```
_____CURRENTS APPLIED TO THE COIL______

Name of winding file:______ mach2.
Current form:_____________ sine.
Electrical angle:__________ 90.
Peak Current (A):__________ 10.

____Phase__ Phase_Factor__

       1.        1.0000
       2.       -0.5000
       3.       -0.5000
```



Element plot with the current density displayed

Load summary - continued

If the winding file contained the wire gauge input, the <LOAD> also computes the DC resistance and power loss for each coil as shown below.

```
The following coil resistances and RMS heat loads have been generated.
   The RMS heat loads are stored in joule_h.mac and can be used after
  the model have been converted to a thermal model.
 Wall time: 39.9347222 at time of heat generation input.

 ___Coil____Resistance(O)____RMS Heat(W)_______
      1.      0.0617            3.1
      2.      0.0617            3.1
      3.      0.0617            3.1
 Total heat generation (W):________ 9.3.
```

The wall time allows for traceability

Additionally, the heat generation input is contained in joule_h.mac

```
 /nopr !
 /com, Wall time: 39.9347222 at time of heat generation input.
 /com, Peak current: 10.
 Esel,all !
bfe,      492.,hgen,1,      40972.045
bfe,      493.,hgen,1,      40972.045
bfe,      494.,hgen,1,      40972.045
```

This input can be used directly in Preprocessor or Solution module once the model has been converted to a thermal model. To use this data, enter joule_h at the command line

Summary of conditions

- The macros apply the following conditions
- ROTOR
  - applies CPs at the inner radius for the flux parallel condition
- STATOR
  - applies the constraints to the outer radius for flux parallel condition
  - applies a force flag for the force/torque calculation
- <EVEN_BC>
  - applies the CPs to enforce the periodic condition (for full models this is not used)
- <WIND_2D>
  - builds the winding data-this does NOT apply any conditions
- <LOAD>
  - this applies the current to the winding using the winding data and the CURRFORM parameter (or a new form in the AMP_A array)
- <SOLUTION>
  - applies the force condition to the rotor

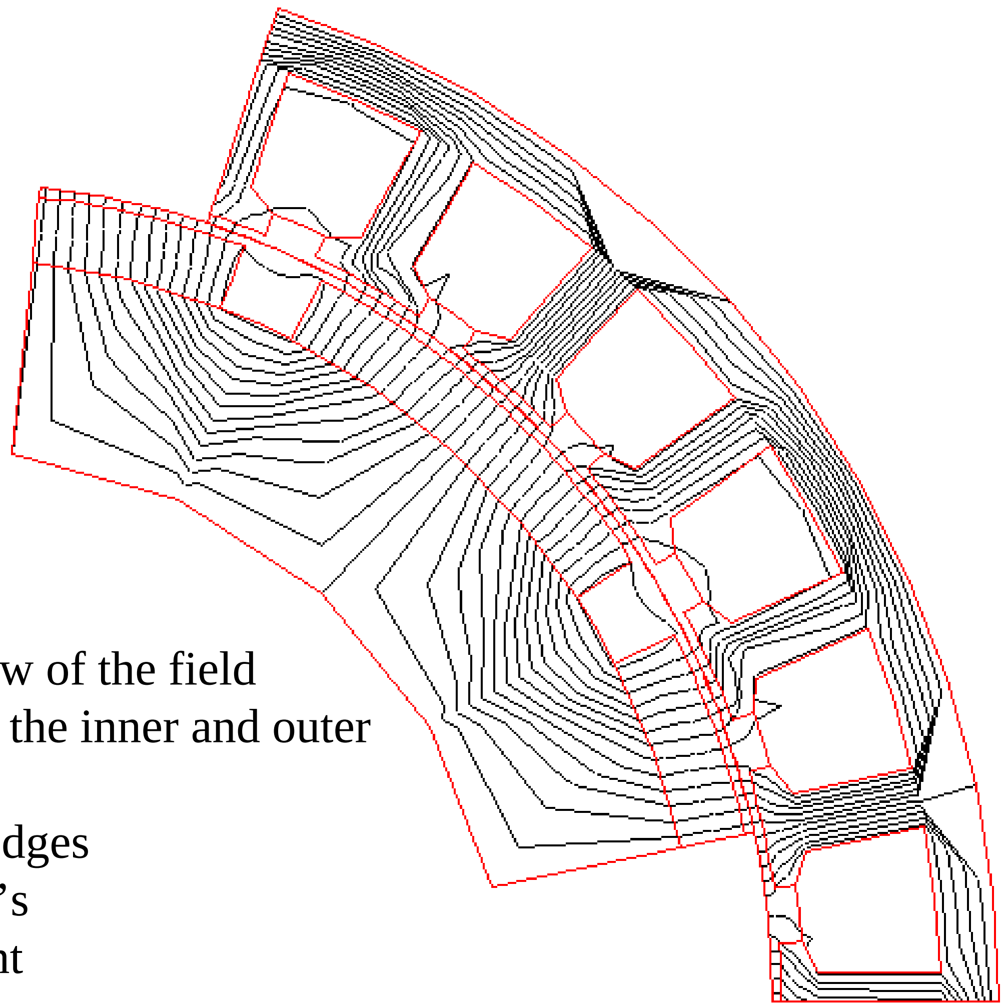
A single solution

- At this point:
  - the models are connected <ROTATE>
  - the winding data is stored <WIND_2D>
  - the current form has been specified CURRFORM='sine'
  - the current has been applied <LOAD>
- A single solution is obtained by <SOLUTION>
  - The default number of substeps for the first phase of the solution is 3

- If convergence is too slow, and if M steels are being used with large permeabilities, the number of substeps may need to be increased. This is accomplished by using the macro directly.

Mvpsol,,5

Flux line plot



Enter the postprocessor and use

<FLUXLINE>

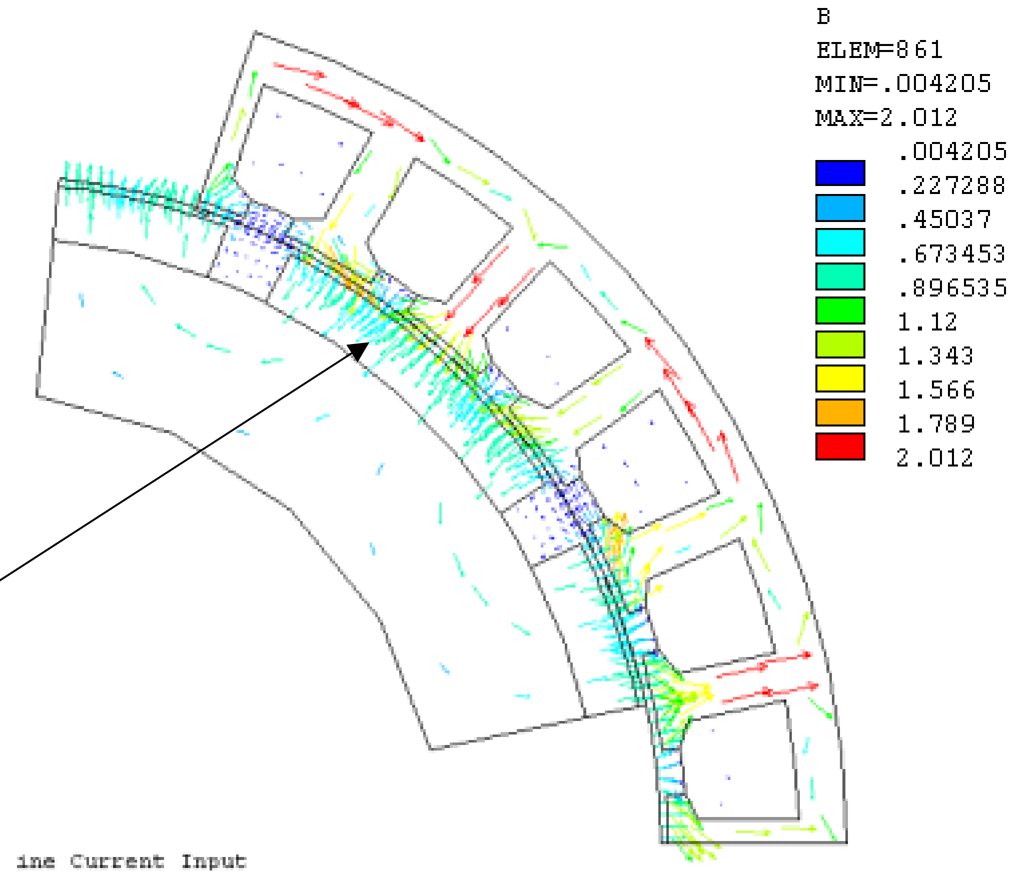
This can be used with ZOOM

- The flux line plot yields an overall view of the field
  - confirm flux parallel condition at the inner and outer radii
  - confirm continuity at the lateral edges
  - confirm continuity across the CE's
  - identify potential mesh refinement
  - confirm magnetization direction
  - inspect overall leakage
  - identify internal gaps in the model (flux normal)

Flux density (B) vector plot (T)

Additional plots for the vectors for the flux density (<B_VECTOR>) or field (<H_VECTOR> can be obtained . These vector plots are an enhancement over the standard vector plots in that the elements of different materials are outlined. These plots also work with the ZOOM

- The vector plots also yield an overall view of the field
  - confirm magnetization direction (in/out)
  - direction of the flux
  - identify regions of saturation



Note the 2nd quadrant behavior of the magnet

Torque calculation

The torque is calculated by <MACHTORQ> and three methods are used to compute the torque. The torque is based on the stack thickness and the full 360° model. Good agreement indicates the adequacy of the finite element mesh The stack length is a parameter-it's units are those of the other parameters.

```
________________TORQUE CALCULATION_____________________

 Stack length:_______ 2.25.
 Torque-virtual work (n-m):__________________________ -2.45476162.
 Torque-Maxwell Stress (n-m):________________________ -2.41471993.
 Torque-Maxwell Stress Line integration (n-m):_______ -2.45329854.
```

Note that the stack thickness is the value input as the STKTHK parameter

Computing the torque using the GUI

The torque can also be obtained from the GUI by Postproces>elec&mag calc>comp. Torque (and select CSTATOR component and Select OK)

Component	Torque
CSTATOR	0.86024E+01

By virtual work (N-m)

To convert this to the full model (the periodic model is 1/5th of the full model) for a 2.25 inch stack, factor the above number by

$$5*2.25*.0254*8.6 = 2.457 \text{ N-m}$$

Since the force flag was also applied to the rotor (R_IRON) the GUI can be used to obtain this torque. When using the GUI again, **deselect** CSTATOR and select R_IRON

Component	Torque
R_IRON	-0.85906E+01

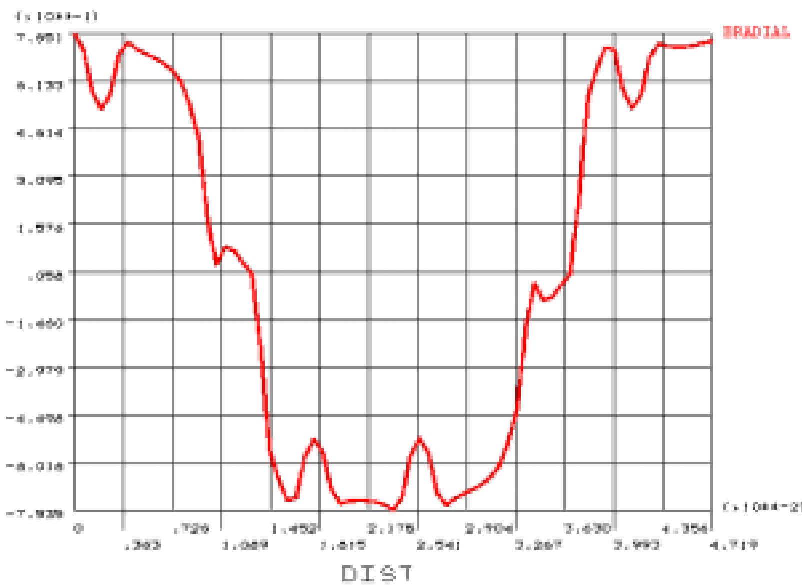
By virtual work (N-m)

Note that the rotor is opposite sign and is within .1% of the stator value

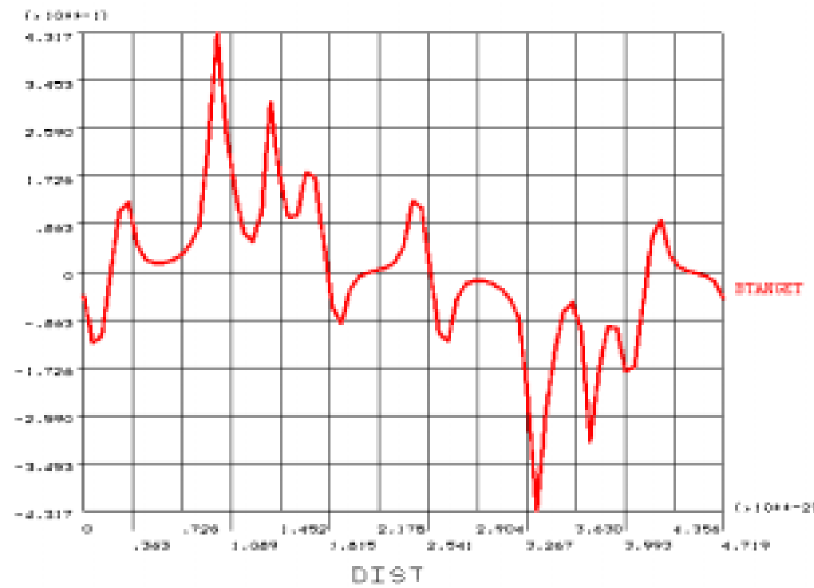
B-radial and B-tangential in the air gap

Once the torque has been computed, then then line graphs for the flux density at the torque calculation radius by using <B_RADIAL> and <B_TANGET> (after the torque is calculated)

B radial (T)



B tangential (T)

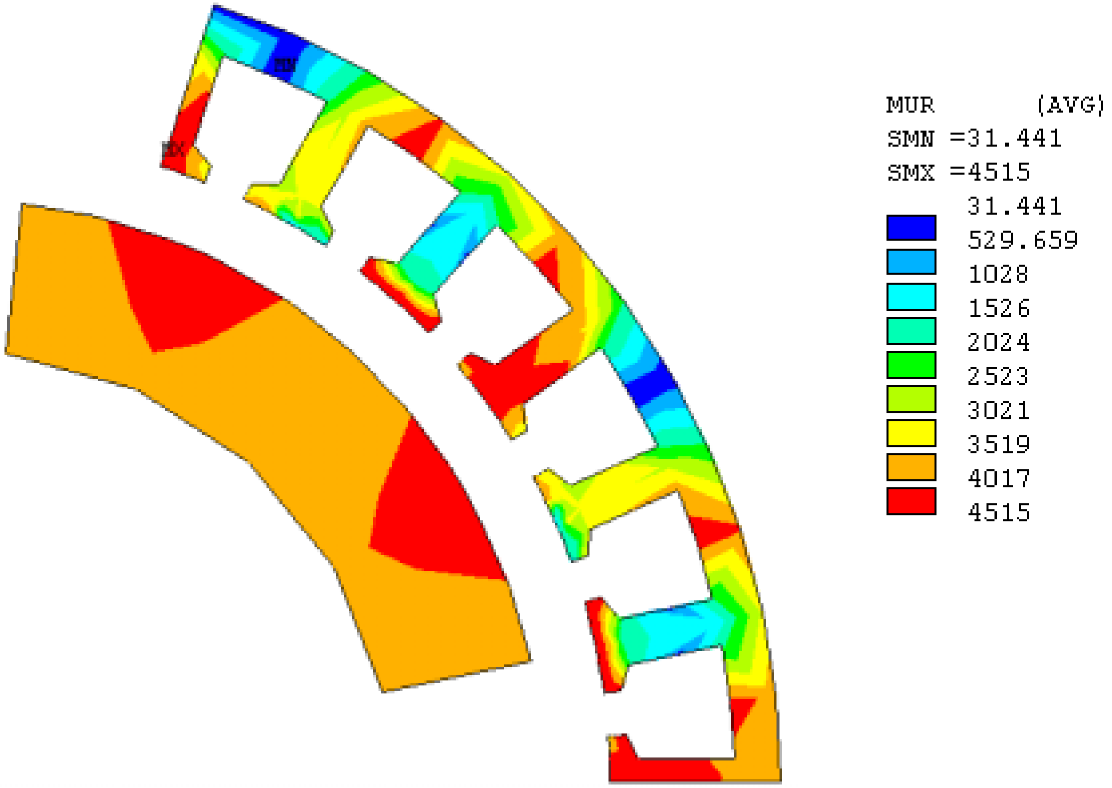


Relative permeability's

Prior to computing the relative permeability, it is recommended to select out materials 2 and 5

<MUR> computes the relative permeability (MUR) as an element item and then plots MUR

This identifies regions of saturation



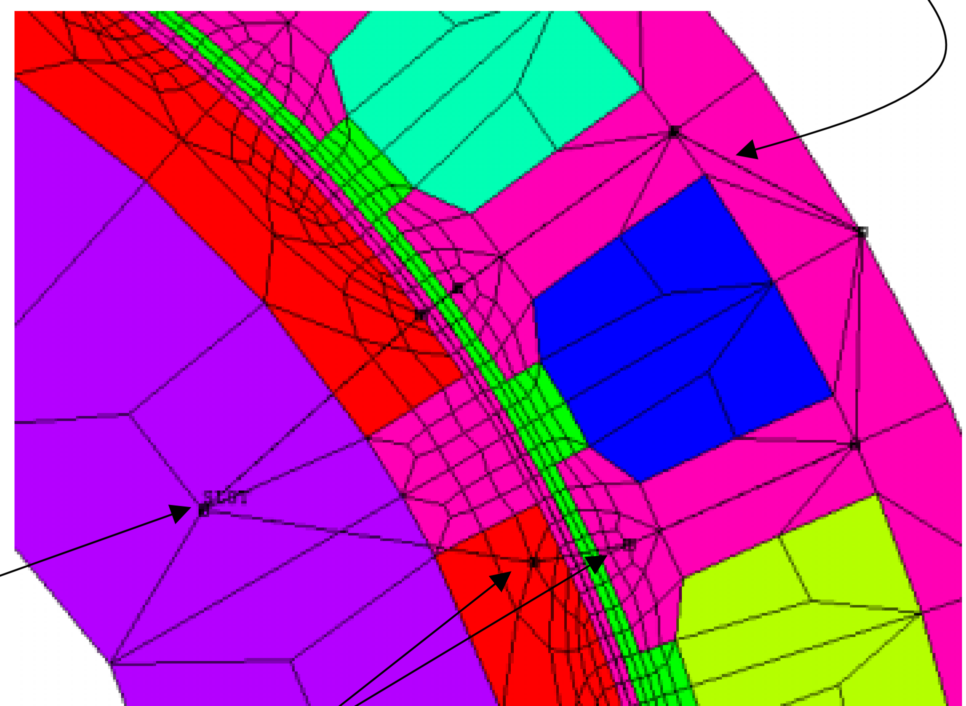
Computing the MMF in the iron

Form a path around the 3rd slot

The MMF can be used to obtain a more quantitative value of the effect of the saturation. MMF which is in the iron can be transferred to the air gap to increase the torque

Make the entire model active and use the GUI to define a path around one of the slots. The path definition is started using

Postprocess>Elec&mag..>define path>by nodes

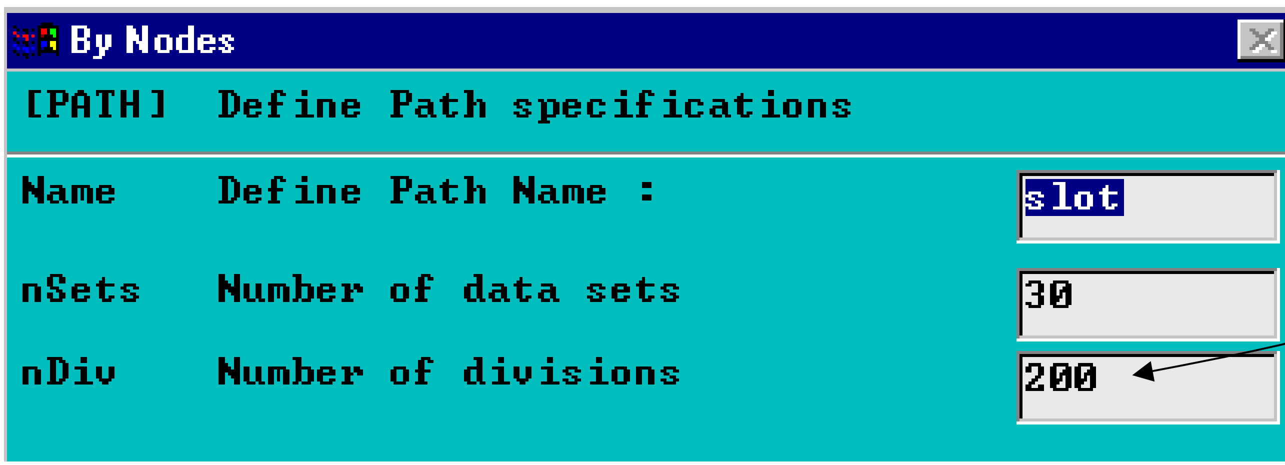


Starting node and ending node. When this node is first selected, the small box appears at the node. When it is picked as the last node, the box toggles off

Select nodes close to the air gap

Completing the path definition

Once the path is complete, additional data is required to identify the path as well as the number of sampling points to compute the MMF



Since large changes in the MMF is expected across the air gap, this number should be made large. Select OK

MMF-continued

To compute the MMF and to retain the H tangential and the MMF, it is best to use the macro MMF_ since it does not delete the path items. This is entered at the command line. (The results will vary depending on the path selected)

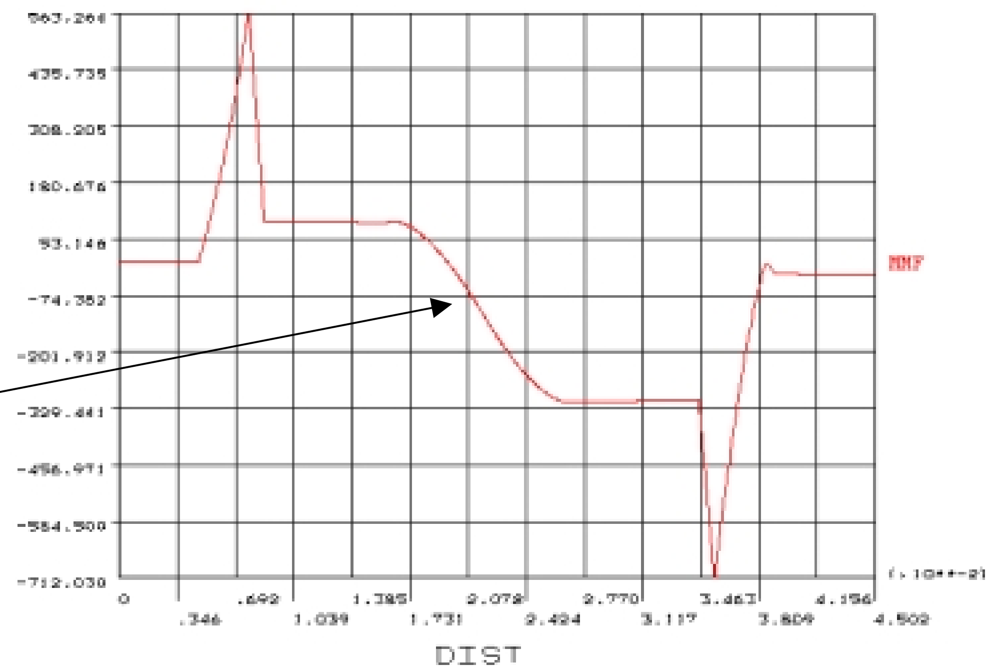
The MMF summary indicates that D (H-tangential) and MMF (the integral of H) along the path are stored as path items.

```
***** ANSYS MMF command macro results *****

** Note: MMF macro is only valid when the path is completely contained
 within a material.
If a path node exists at a material interface, select (ESEL) only
 desired material elements before calling the macro.

MMF = -27.102245 Ampere

Issue "status" to review calculated parameter "MMF”

The path item D stores the H tangential along the path.
The path item MMF stores the accumulated MMF along the path.
These items can be plotted as a line graph or superimposed on the
 geometry.
```

Plotting the MMF along the path

The MMF is plotted by Postprocess>plot results>-plot path item- > on graph

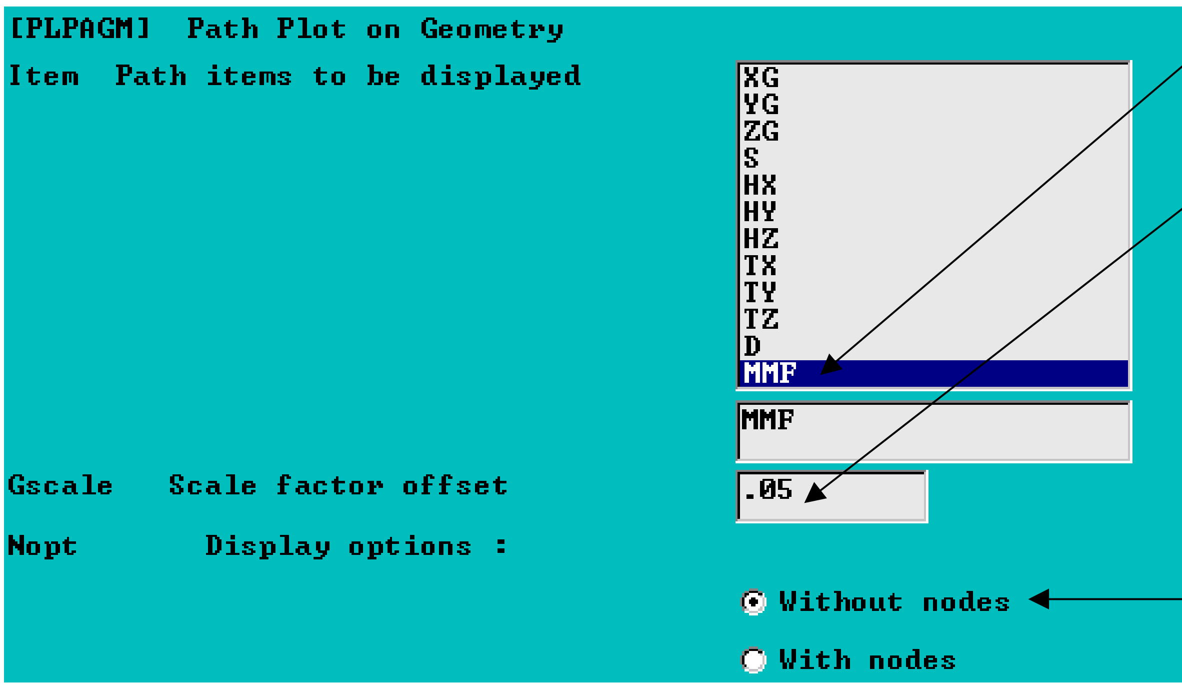
This appears to be a large change, but it is difficult to determine its location in the model



Plotting MMF on the model

The MMF can be plotted on the model by Postprocess>plot results>-plot path item- > on geometry.

Before executing this command, generate an element plot and then turn on the noerase option (/noerase in the command line would be sufficient)



Select the MMF

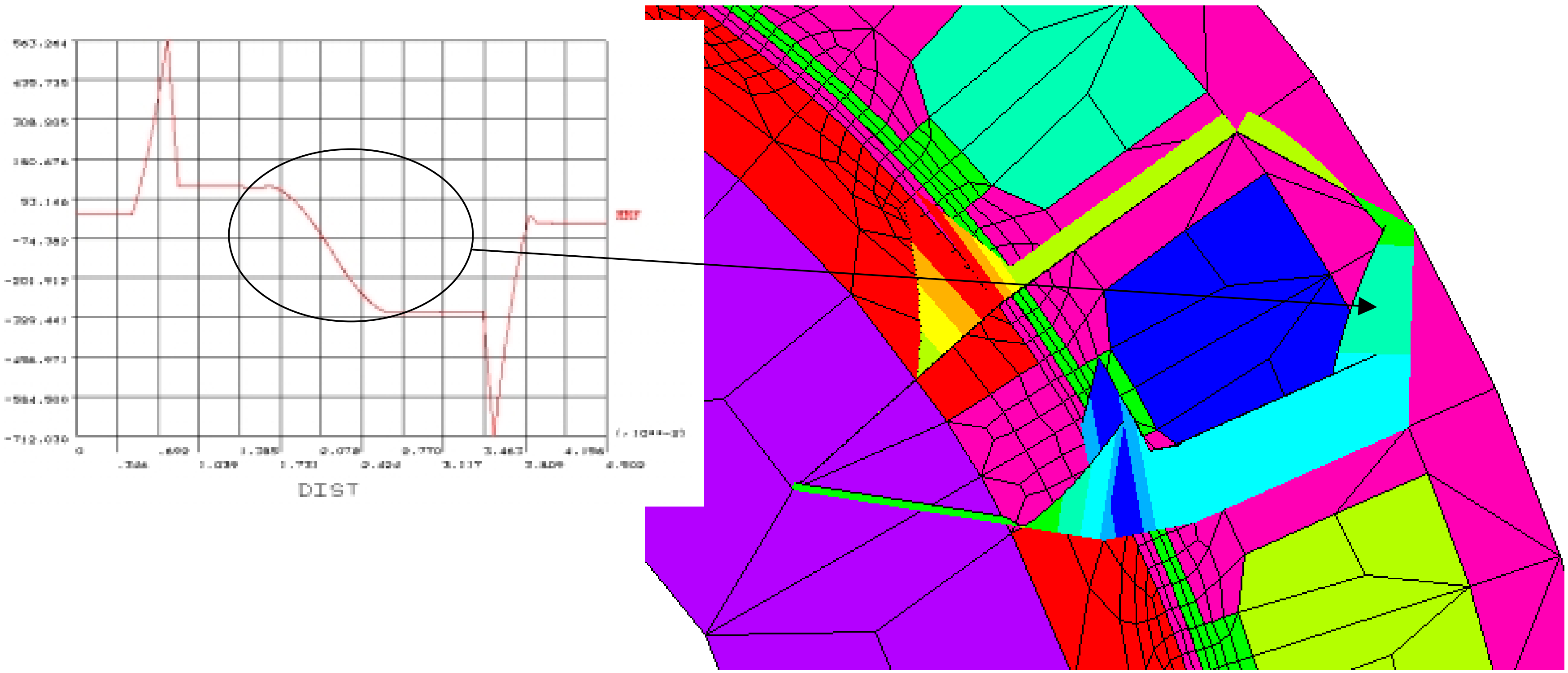
Input a small scale factor to avoid overplot

The element plot will show the relative relocation- use "without the node option"

Select OK

Plotting MMF on the model-continued

With the MMF on the element plot, the relative relocation of the MMF change due to the saturation can be determined.



Computing the flux linkage for the winding file

The flux linkage is the flux through the individual coils factored by the coil turns. The winding file is used to determine the location of the coils. It is assumed that the winding has been loaded. This macro is typically used for computing the open circuit EMF (no currents applied). This calculation is initiated by <COILLINK>

```
_______SUMMARY OF FLUX LINKAGE FOR THE COILS____________

Winding file:__________________ mach2.
Stack length:__________________ 2.25.
Periodic factor:_______________ 5.

___COIL___Turns_____Flux linkage_______Phase____
______________________Weber-t___________________

     1.     10.      -0.002620          1.
     2.     10.      -0.003279          2.
     3.     10.       0.006391          3.

____Phase_______Total Flux Linkage_______

       1.             -0.00262
       2.             -0.00328
       3.              0.00639
```

If the full model was analyzed, then there would be 15 coils, but still only three phases

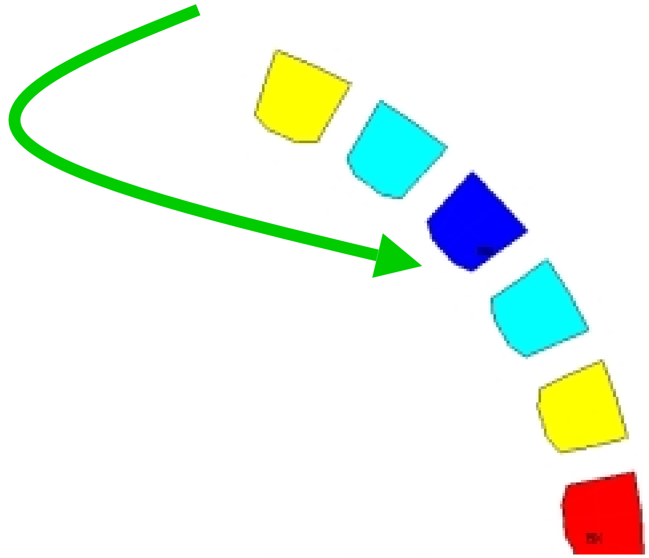
```
The flux linkages reported are for the periodic section modeled.  The
 total flux linkages for each phase would be factored by the periodic
 factor.
```

Checking the currents in the winding

The currents in the slot can be verified in the post processor by <CHK_AMP>. An element plot of the coil regions is displayed with the REAL set numbers also displayed. These numbers corresponds to the Real No. column shown below.

```
___SUMMARY OF CURRENTS IN THE SLOTS______
____ Slot____Real_____Current_______
_____No._____No.______(Amp-turns)___
       1.      52.         100.0
       2.      53.          50.0
       3.      54.         -50.0
       4.      55.        -100.0
       5.      56.         -50.0
       6.      57.          50.0
```

The current density in the slots can be displayed by <PLOTCURR>



Multiple solutions using a constant current

A study of the rotor rotation versus constant current or cogg torque or Open Circuit EMF can be obtained. The currents must first be set:

1) set the currents either using the <LOAD>
2) to determine the cogg torque or an Open Circuit EMF, select the entire model and delete the currents (bfedel,all,all)

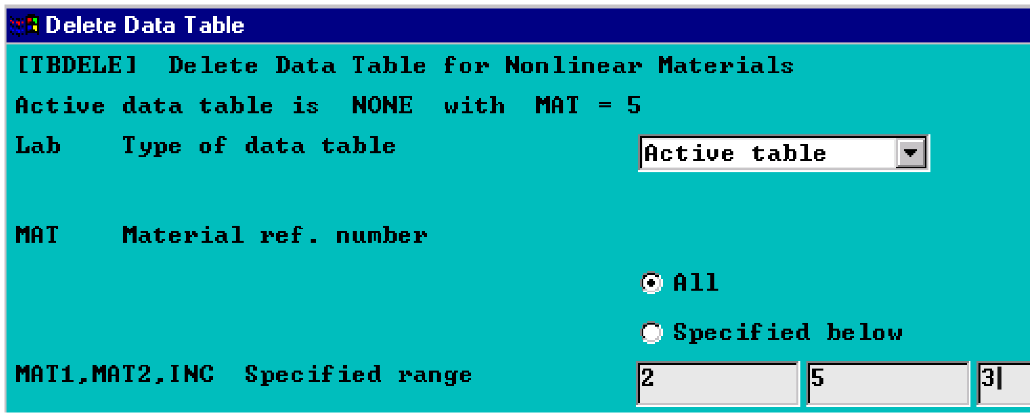
To initiate the solution, use <ROT_CONS>.
This item will prompt for the following data:
1) The starting mechanical angle (measured from +X axis) for the rotor
   (For a periodic model, the rotor is moved to this angle. For a full model, no initial movement is made. For full models, the rotor needs to be moved to the initial position, using <ROTATE>)
2) The ending mechanical angle
3) The increment in the mechanical angle
4) The name of the element component used for the torque computation (defaults to the rotor component "r_iron")
5) The rotor speed (Hz)
6) The confirmation to continue

Using the <ROT_CONS> for the current model

- For purposes of demonstrating this, delete the BH data

    tbdel,bh,all

    Preprocess>material props>data tables>delete



Then select OK

Define a linear permeability of 500 for materials 2 and 5

- Select all elements and delete all current densities

    bfedel, all,all

    Preproces>loads>delete>excitation>on elements

    (and pick all in the picker box)

Multiple solutions using a constant current-continued

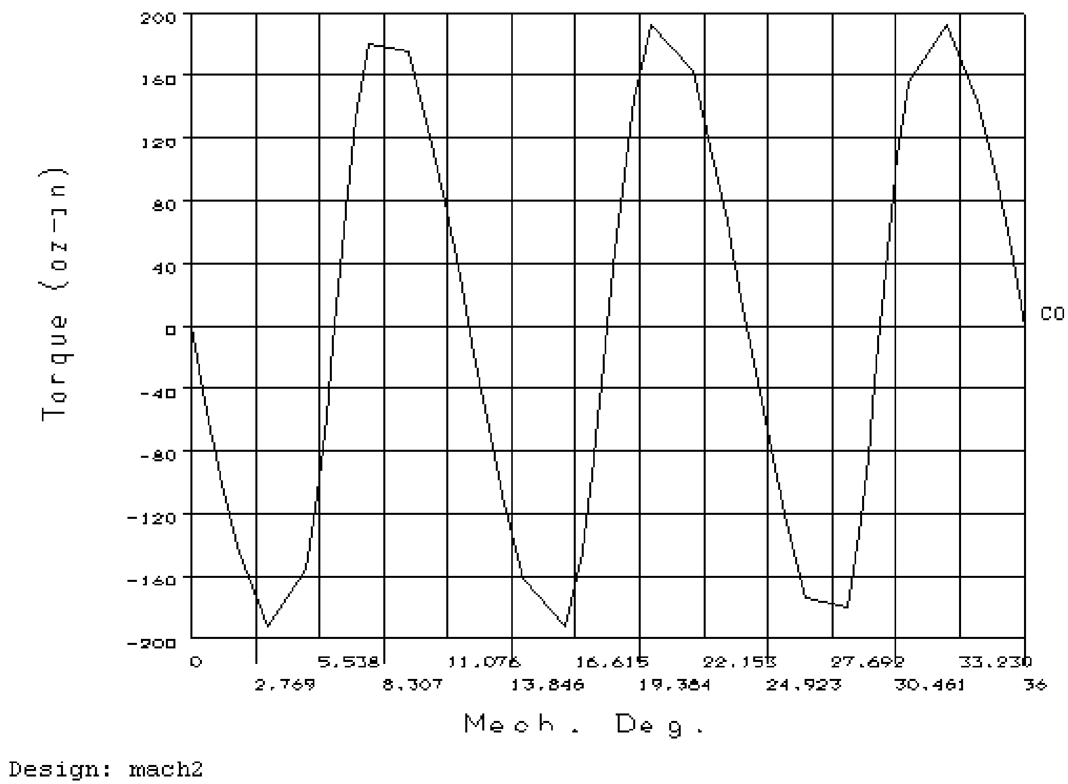
<ROT_CONS> for solutions from 0 to 36° at 4° increments (mechanical).

Prompt 1: 0 (this is a periodic model, the lower rotor edge will be moved to +X axis)
Prompt 2: 36 (ending ***<u>mechanical angle</u>***, degrees) (36*10/2=180° electrical)
Prompt 3: 4 (increment mechanical angle)
Prompt 4 CR (defaults)
Prompt 5 60 (the rotor speed, Hz) (needed to compute EMF)
Prompt 6 1 (entering 1; the solution continues. The default is 0 to stop)(A protective flag in the event an item is unintentionally executed)

This will produce 36/4 +1 or 10 solutions, starting from 0, ending at 36.

Multiple solutions using a constant current-results

The graphics results are stored in “mname”.f33 (mname was specified in the parameter file). At the end of the solution the torque versus mechanical angle is displayed. The .f33 file also contains by default, the plot of the flux density for each angle in the solution in addition to the torque curve



More increments would refine the curve

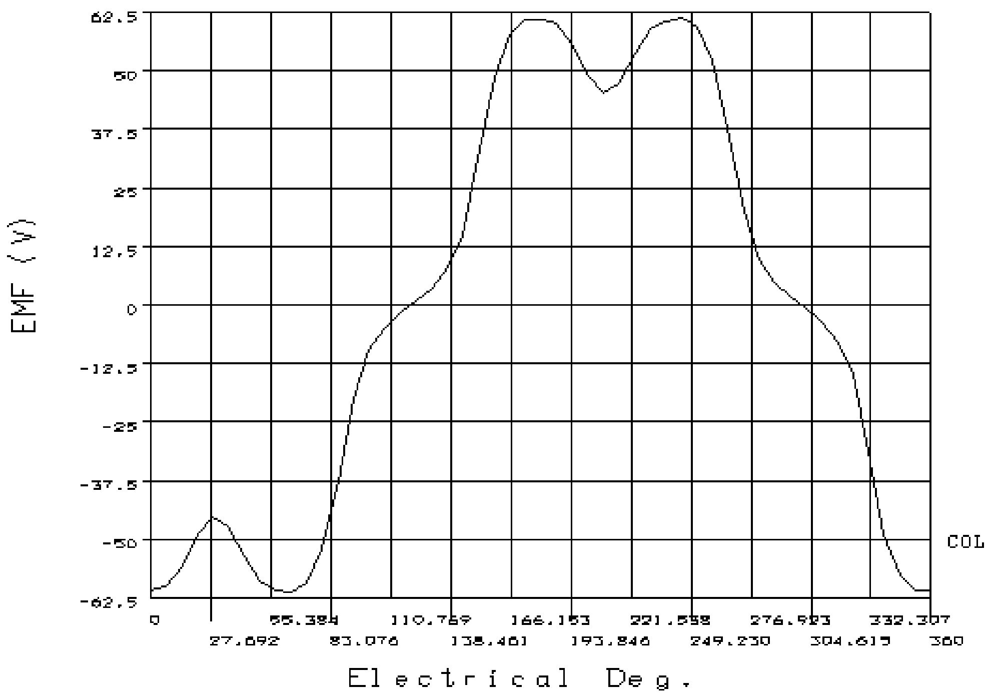
Summary for the multiple solutions with constant current

A printed summary is contained in “mname”.sum

```
>____SUMMARY OF MAXIMUMS/RMS FOR THE SOLUTIONS__<
 Starting Angle (D):_____________________________ 0.
 Ending Angle (D):_______________________________ 36.
 Increment Angle (D):____________________________ 4.
 Location of Zero Elec.  Ang.  (+CCW,+X axis):_____ 0.
 Rotation of the Rotor:__________________________ CCW.
 MIN torque (oz-in):_____________________________ -197.063489.
 MAX torque (oz-in):_____________________________ 197.063489.
 Peak - Peak torque (oz-in):____________________ 394.126978.
 Number of solutions:____________________________ 10.
 Maximum B magnitude:____________________________ 2.73368435.
 Method to compute torque:_____ Virtual Work.
 Time for all solutions (CPU):___________________ 45.5054336.

 __________SUMMARY OF ANGLES/Torque__________________
 ___________I___________Mechanical_____Torque________
 ________________________ANGLE (D)_____(Oz-in)_______
            1.               0.00     0.00000
            2.               4.00  -196.86864
            3.               8.00   196.74575
            4.              12.00    -0.52698
            5.              16.00  -197.06349
            6.              20.00   197.06349
            7.              24.00     0.52698
            8.              28.00  -196.74575
            9.              32.00   196.86864
           10.              36.00     0.00000
```

The EMF is also calculated. The results shown below were obtained by using .5 angle increment from 0 to 72 mechanical degrees. Since derivatives are being computed a finer step is required

If all currents were deleted prior to using <ROT_CONS>, this is considered to be the open circuit EMF



mach2 EMF for Phase A

This plot was obtained from the mach2.f33 where mach2 specified by MNAME parameter. This corresponds to the rotor frequency specified at the use of <ROT_CONS>. Only Phase A is plotted. This shape follows that of the Bradial plot

The Table for the calculated EMF.

```
__________SUMMARY OF EMF FOR THE SOLUTIONS___________
Starting Angle (D):_____________________________ 0.
Ending Angle (D):_______________________________ 72.
Increment Angle (D):____________________________ 0.5.
Location of Zero Elec.  Ang.  (+CCW,+X axis):_____ 0.
Rotor speed:____________________________________ 60 (Hz).
Rotation of the Rotor:__________________________ CCW.
MIN EMF (V):_____________________________ -61.2477796.
MAX EMF (V):_____________________________  61.2477796.
Peak - Peak EMF(V):_____________________ 122.495559.
Number of solutions:____________________________ 145.
Time for all solutions (CPU):___________________ 2023.31939.
```

___________SUMMARY OF ANGLES/EMF___________________

I	Electical ANGLE (D)	EMF (V)
1.	0.00	-61.07821
2.	7.20	-60.00431
3.	14.40	-55.65664
4.	21.60	-48.97940
5.	28.80	-45.23026
6.	36.00	-47.36711
7.	43.20	-53.56332
.	.	.
.	.	.
40.	280.80	9.52822
41.	288.00	4.99299
42.	295.20	1.63691
43.	302.40	-0.88017
44.	309.60	-3.72699
45.	316.80	-7.90068
46.	324.00	-14.92158
47.	331.20	-31.19316
48.	338.40	-48.69019
49.	345.60	-57.71023
50.	352.80	-60.90536
51.	360.00	-60.92613

Multiple solution using a current form

The <ROT_CURR> can be used to step through the rotor motion and the specified current form. The resulting plots are contained in the file "mname".f33, where "mname" is a character parameter). The current form for this analysis is "sine" (as shown previously)

This item will prompt for the following data:

1) The starting mechanical angle (measured from +X axis) for the rotor
   (For a periodic model, the rotor is moved to this angle. For a full model, no initial movement is made. For full models, the rotor needs to be moved to the initial position, using <ROTATE>)
2) The ending mechanical angle
3) The increment in the mechanical angle
4) The starting electrical angle (in reference to the current form)
5) The peak current which will be applied to the turns and the current form
6) A confirmation to continue.

Multiple solutions using a current form

Since the currents will be reassigned, there is no need to delete the current densities.

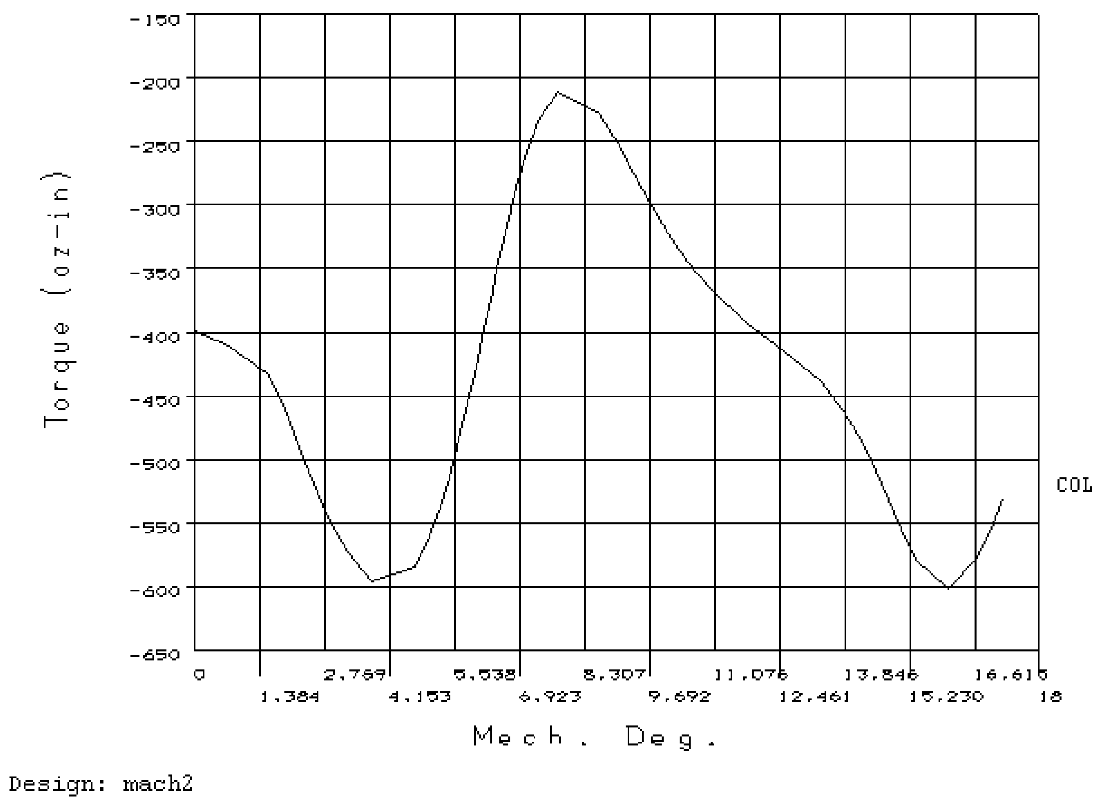
The input for <ROT_CURR> is

Prompt 1: 0 (this is a periodic model, the lower rotor edge will be moved to +X axis)
Prompt 2: 18 (ending mechanical angle)
Prompt 3: 2 (angle increment)
Prompt 4 60 (starting electrical angle to be used in the first solution)
Prompt 5: 10 (peak current Amps (not amp-turns))
Prompt 6 1 (entering 1; the solution continues. The default is 0 to stop)

This will produce 18/2 +1 or 10 solutions, starting from 0, ending at 18.

Multiple solutions using a current form-results

The graphics results are stored in "mname".f33 (mname was specified in the parameter file). At the end of the solution the torque versus mechanical angle is displayed. The .f33 file also contains by default, the plot of the flux density for each angle in the solution in addition to the torque curve



More increments would refine the curve

Summary for the multiple solutions with a current form

```
>____SUMMARY OF MAXIMUMS/RMS FOR THE SOLUTIONS__<
Starting Mech.  Angle (D):_______________________ 0.
Ending Mech.  Angle (D):_________________________ 18.
Increment Mech.  Angle (D):______________________ 2.
Starting Electrical Angle (D):__________________ 60.
Location of Zero Elec.  Ang.(+CCW,+X axis):______ 0.
Rotation of the Rotor:__________________________ CCW.
MIN torque (oz-in):_____________________________ -601.690258.
MAX torque (oz-in):_____________________________ -207.720118.
Peak - Peak torque (oz-in):____________________ 393.97014.
Average torque (oz-in):_________________________ -434.
Number of solutions:____________________________ 10.
Maximum B magnitude:____________________________ 2.81026869.
Method to compute torque:_____ Virtual Work.
Time for all solutions (CPU):___________________ 47.8287744.

__________SUMMARY OF ANGLES/Torque__________________
___________I___________Mechanical_____Torque________
________________________ANGLE (D)_____(Oz-in)_______
            1.              0.00  -398.73842
            2.              2.00  -469.39378
            3.              4.00  -601.42862
            4.              6.00  -424.78112
            5.              8.00  -207.72012
            6.             10.00  -316.62749
            7.             12.00  -399.28811
            8.             14.00  -470.99707
            9.             16.00  -601.69026
           10.             18.00  -424.75274

____________________________________________________
```

Inductance calculation for a current range

The inductance can computed for a range of currents using the incremental method built into ANSYS (R).

The model must be fully constructed, <EVEN_BC> must be applied for a periodic model and the <ROTATE> must be used prior to using this macro.

The winding need not be constructed, nor a solution obtained.

The coils are specified in the winding file and the rotor can be placed into an arbitrary position.

The <MACH_IND> prompts for the following:

1) The winding file name (must be enclosed in single quotes)
2) The electrical angle
2) Rotor position (measured from the +X axis for periodic models. For full models this is an increment from the current position_
3) Starting current (Amps)
4) Ending current (Amps)
6) The total number of solution (including the starting and the ending current)
7) The confirmation to continue

Inductance calculation for a current range-input

Using the linear properties for the existing model at a rotor position of 0 degrees

The following prompts will be displayed:

Prompt 1: ‘mach2’ (the name of the winding file used to generate the winding)

Prompt 2: 90 (electrical angle)

Prompt 3: 0 (rotor position- for a periodic model, it is measured from the +X axis. For a full model it is an increment)

Prompt 4: 10 starting current (Amps)

Prompt 5: 30 ending current (Amps)

Prompt 6: 3 total number of solutions

Prompt 7 1 (entering 1; the solution continues. The default is 0 to stop)

Inductance calculation for a current range-summary

For the linear model, all the inductances should be independent of the current range.

```
______________MATRIX SUMMARY CALCULATION____________________
Winding file:___________ mach2.
Electrical angle:_______ 90.
Rotor position:_________ 0 (CCW from +X axis).
Symmetry factor:_________ 5.
Stack length (inches):___ 2.25.

__Current_______________Inductance (mH) Matrix_______________
__(A)_______Laa______Lbb______Lcc______Lab______Lac______Lbc_

10.00       0.186    0.186    0.186   -0.034   -0.034   -0.034
20.00       0.186    0.186    0.186   -0.034   -0.034   -0.034
30.00       0.186    0.186    0.186   -0.034   -0.034   -0.034
____________________________________________________________
Total CPU time (Sec):   175.
```

How to change a parameter for the stator and resolve:

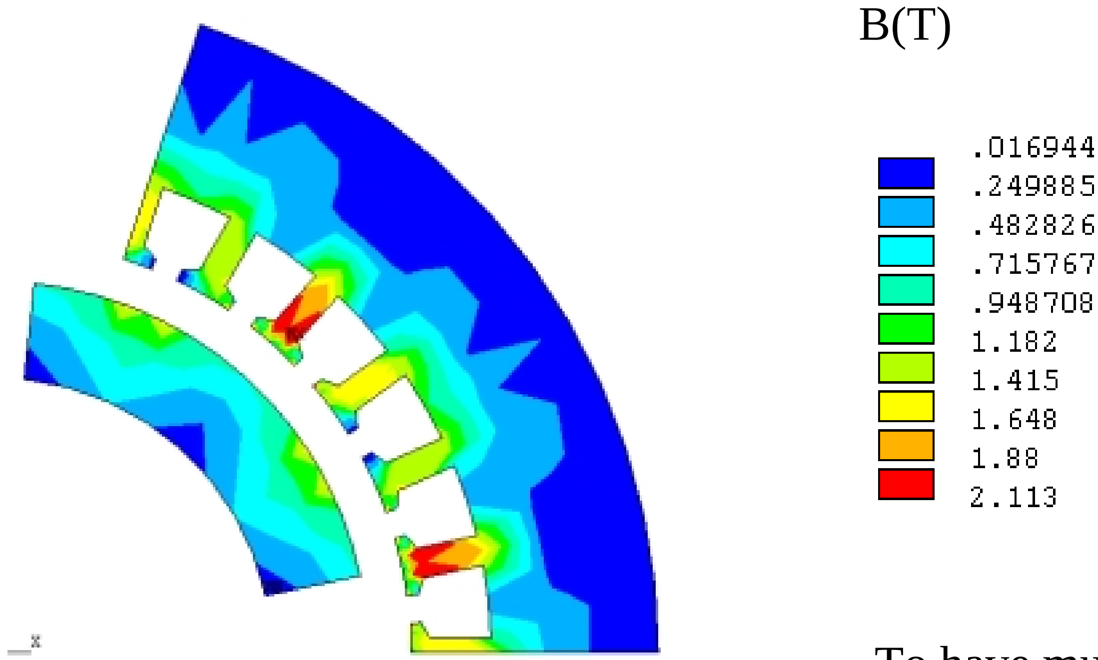
Using the previous model, to observe the effect of a new backiron radius for the stator, reset the parameter for the outer radius (**R5 say, R5=2.4**)
the following steps are necessary (after the parameter is changed). If you plan to use the existing stator model later on, save the model prior to changing the parameter (save,mach2,db)

• <STATOR>	to get the new stator
•<EVEN_BC>	to reapply the periodic conditions
•<ROTATE>	to reconnect the rotor to the stator
•<WIND_2D>	Since the stator was regenerated, the winding must be regenerated
•<LOAD>	Apply currents to the winding
•<SOLUTION>	Obtain a single solution

For the rotor replacement, the winding nor the current needs to be reapplied (I.e., the <WIND_2D> , <LOAD>.

Changing the stator model

Once the solution is obtained the processing can be performed as was shown for the original model



To have multiple solutions in a loop for different radii requires very little effort.

How to change a parameter for the rotor and resolve:

Using the previous model (resume,mach2,db) , to observe the effect of a new angle for the magnet, reset the parameter (MAGW**=170**)
the following steps are necessary (after the parameter is changed)

- <PM_ROTOR> to get the new rotor
- <EVEN_BC> to reapply the periodic conditions
- <ROTATE> to reconnect the rotor to the stator. (This must be used even if the rotor is not to be rotated-it must still be connected by the CE's) (use 12)

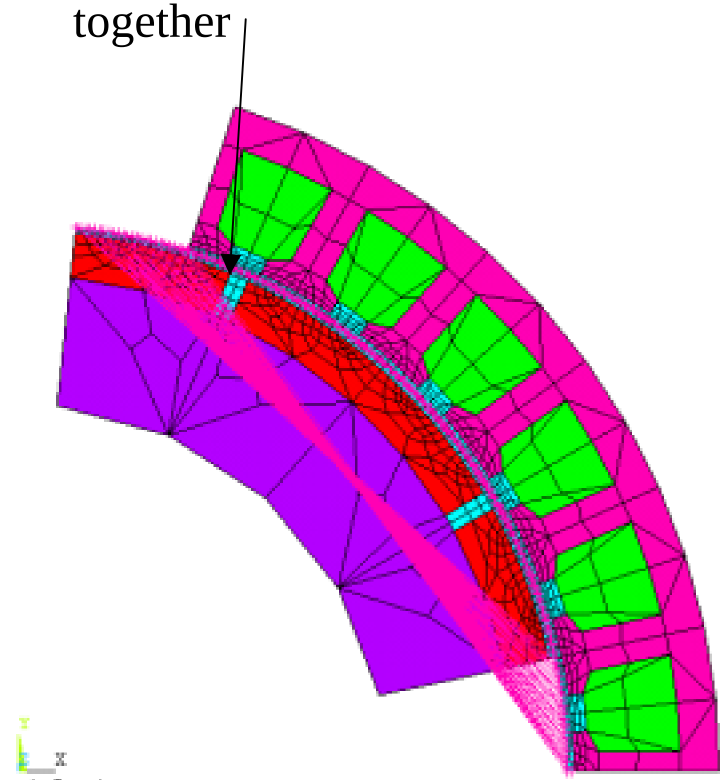
<LOAD> (optional-to change the currents) (use 90 degrees, 10 amps)

- <SOLUTION> Obtain a single solution

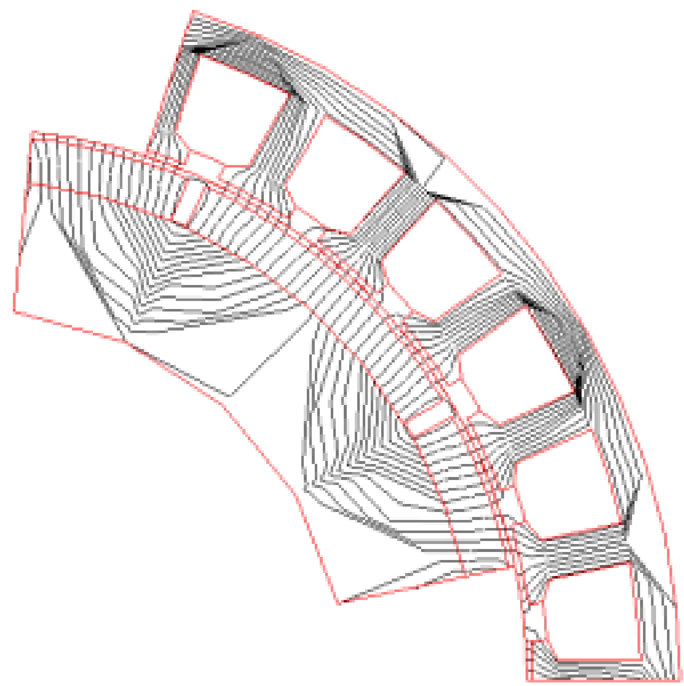
- If the <LOAD> was not used, the solution would use the currents which were previously defined for the stator.

How to change a parameter for the rotor and resolve-results

The magnets are closer together



Flux line plot-magnets are parallel



Combining the steps for a full model

If the entire model is to be rebuilt on frequent occasions, the steps used in the Toolbar can be placed into a single macro, which would take as its input, the name of the parameter file. This type of file is shown below.

```
out,b_mach2d,out
/com,b_mach2d.mac
!
!  builds the complete model-see steps below
!
!  arg1 = name of parameter file (*.des)
!  arg2 = 0, build the winding
!       NE 0, do not build the winding
!
/com,(1)  remove the existing model & check for error condition
/nerr,0,1e5
fini
/cle,all
_arg1=arg1
*get,_targ1,parm,_arg1,type
*if,_targ1,ne,3,then
  /out
  /nerr
  *msg,error
  Parameter file name was input correctly. It needs to be a character&
  parameter or enclosed in single quotes  as 'mach2'.  No action
  /out,b_mach2d,out,,append
  _error=1
*endif
*if,_error,eq,1,:end

/out
```

Combining the steps for a full model-continued

```
/com, (2) load the new parameter file
/inp,%arg1%,des                          !  the parameter file


/com, (3) Build the new rotor
pm_rotor,rref,use_53,nrpgen,use_53       !  build the permanent magnet rotor
/out,b_mach2d,out,,append


/com, (4) Build the new stator
slotsta,0,stref,use_53,nspgen,use_53     !  build the slotted stator
/out,b_mach2d,out,,append


/com, (6)  Apply the periodic conditions
permach,1                                !  applies periodic conditions to model sides
/out,b_mach2d,out,,append


/com, (7) Connect the two models
mvrotor,,1                               !  Moves and attaches the rotor/stator
/out,b_mach2d,out,,append


/com, (8)  Build the winding
*if,arg2,eq,0,then
 b_wndsc,w_file,'s_coil'                 !  builds the winding
*endif

abbr,,mabbr,mac                          !  Restores the ToolBar

:end
```

Combining the steps for a full model-continued

- The macro would be input into the command line as

  b_mach2d,’mach2’

- This would generate the entire model as before
- By changing the parameter file and the MNAME parameter a complete record of the design can be generated.
  - Winding file name, parameters, material properties
- The parameter MNAME is displayed in the title, and is the file name for some of the summaries
- The character names are limited to 8 characters

Importing a rotor laminate model from outside

- A finite element model for the rotor can be imported from outside the macros.
  - IGES file
  - finite element mesh (if so, it must include the air mesh in the gap)
- It is best to import the laminate rotor model first, then build the stator model (and winding)
- Model requirements for the rotor model
  - The Laminate model from a CAD package will not contain any areas associated with the air. The air must be be added to the laminate model. The imported rotor model can be periodic or a full model.
  - The outer radius of the rotor model must at a constant radius and must be extended to the mid radius of the air gap. This is the radius to which the stator model extends inward.
  - The magnets must be material 3
  - The iron must be material 2
  - The GAP parameter must be specified (anyway)

Importing a rotor laminate model from outside-continued

- The element type used in the stator must match the element type used in the rotor
  - if plane13's are used in the rotor, plane13 must be used in the stator (USE_53=0) in the parameter file
  - if plane53's are used in the rotor, plane53 must be used in the stator (USE_53=1) in the parameter file
- the rotor model must be meshed
- The individual magnets must not share common nodes with other magnets

- Once the rotor finite element model is complete, used MAG_CONV
  - this defines the local coordinate systems for the magnets (parallel)
  - modifies the element ESYS to use the local coordinate system to allow the magnets to alternate in and out

Importing a rotor laminate model from outside-continued

  - for radial magnetization, it alternates the materials of the magnet to be 3 and 4.
  - The user must define the Hc for material 4 to opposite in sign of material 3
  - modifies the elements outside the iron and magnets to material 1 and REAL 5
  - defines the ROTOR component group to be comprised of the elements and nodes forming the rotor
  - defines the element component R_IRON to be the magnet iron to allow the forces/torques to be computed
- If the inner edge is a model boundary, the nodes at the inner ring must be coupled in AZ to form a flux parallel condition
- Most likely, the model is not in meters, the model therefore needs to scaled. The stator will be scaled by the macro.

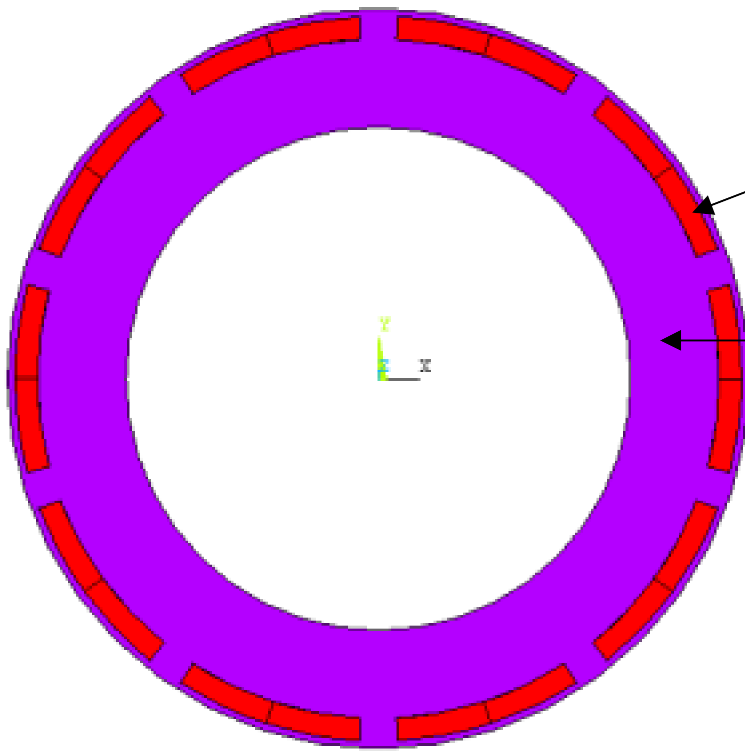
Example of a machine with an imported 10 pole rotor laminate

1) The model does not have any air modeled in the air gap.

2) No elements are attached

3) The parameter file mach2.des contains the stator for this rotor. The GAP is correct

4) This is a full model



Parallel magnets

laminate

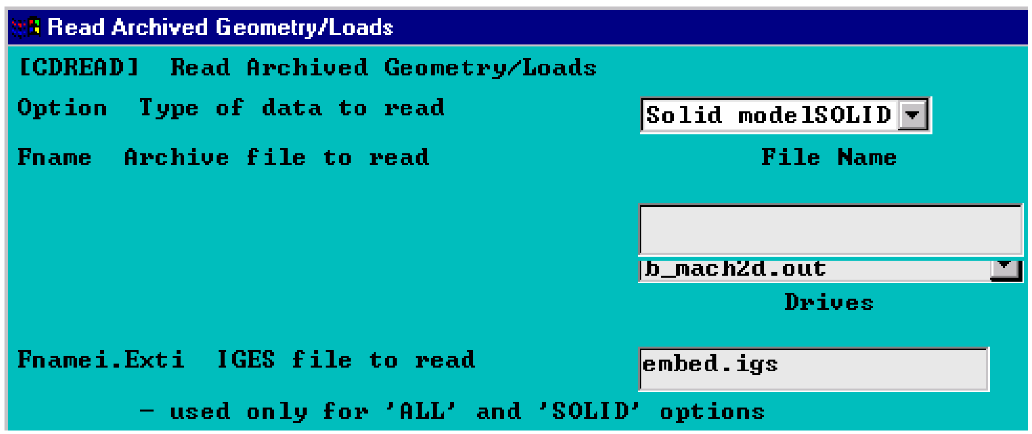
Outer radius correspond to rr2+magh. The center of the air gap corresponds to rbc=rr2+magh+gap/2

Loading the IGES file and the parameters

•Prior to loading the IGES:

clear the data base (Utility>clear & start)

• To load this IGES file use Preprocess> archive model>read and load the IGES file embed.igs



This loads the solid model only- no elements are attached.

Select OK

The parameters are loaded by /inp,mach2f,des

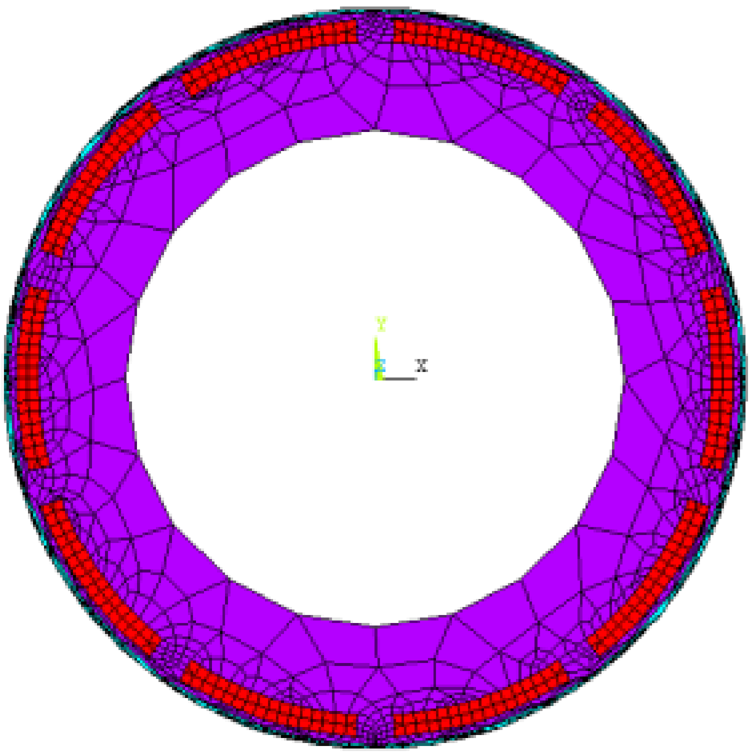
Adding the air outside the laminate (the steps below are contained in air_add.mac)

To control the mesh, it would be best to generate 4 areas with an inner radius of rr2+magh and an outer radius of rr2+magh+gap/2.

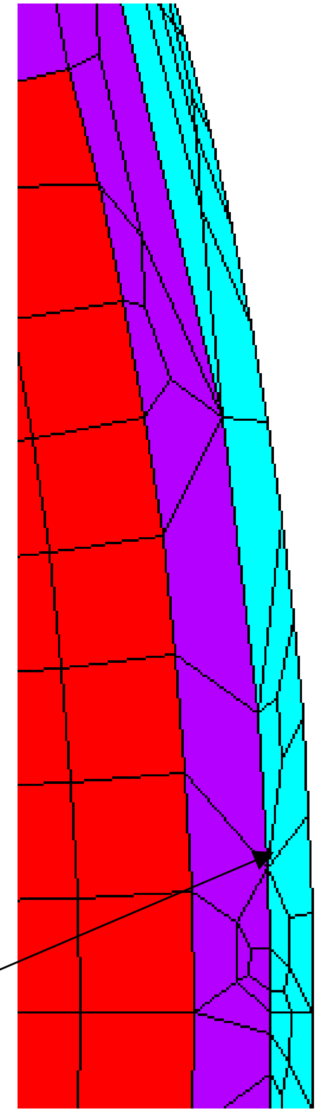
```
Pcircle,rr2+magh,rr2+magh+gap/2,0,90  !  Define the air gap
csys,1                                !  Make the cylindrical system active
agen,4,all,,,0,90                     !  Duplicate the areas around
asel,all                              !  Make all the areas active
aglue,all                             !  Connect the areas
asel             !This displays the picker box- Select out the rotor laminate
aatt,2,2,1       ! Set the attribute for the laminate
lesi,p           ! This displays the picker box-  Set one of the radial line
                 !   segments to 2 units
lsel,,loc,x,rbc  !  Select the outer line segments
lesi,all,,,20    !  Set the circumferential divisions for the air to 20
lsel,,loc,x,rr1  !  Select the inner line segments
lesi,all,,,1     !   Set to 1
```

Define the element type (type 1) for plane53 and mesh

The plane53 needs to be used, since the stator will be built with plane53 (use_53=1 in the parameter file)



More effort would be required to get a uniform mesh



Use the MAG-CONV macro

Enter mag_conv at the command line

It is recommended to check the element coordinate systems using

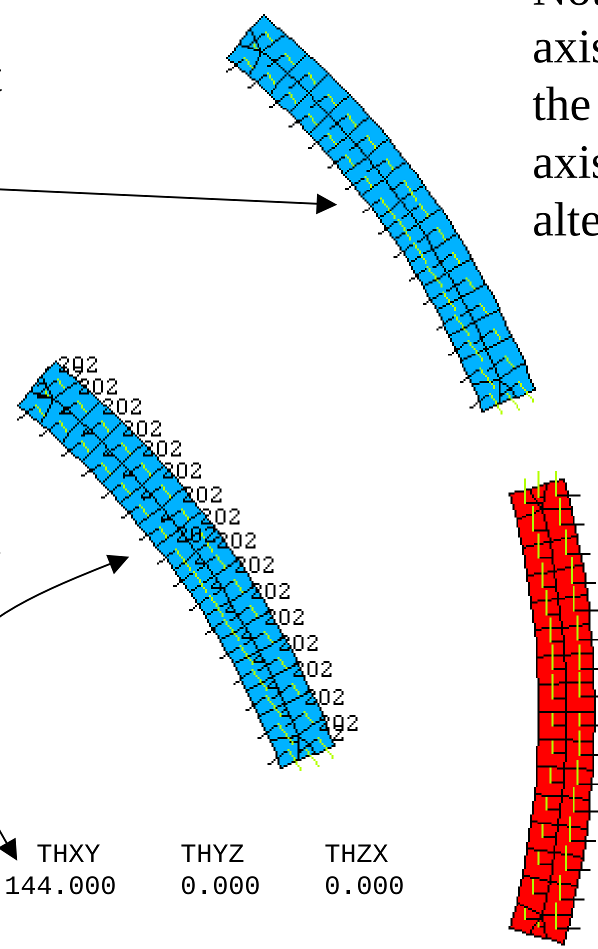
/psym,edir,1

The element coordinate system can be turned on using

/pnum,esys,1

This will identify the coordinate system which can be listed

cslis,202



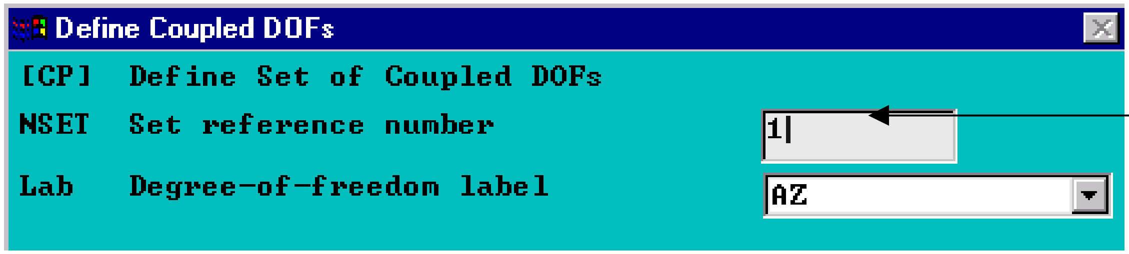
Note that white axis is parallel to the center of the axis and that they alternate

CSYS	TYPE	XC	YC	ZC	THXY	THYZ	THZX
202	0	0.0000	0.0000	0.0000	-144.000	0.000	0.000

Apply the CP at the inner ring of nodes

Select the inner ring of nodes (make the entire model active, select the exterior nodes and then reselect the inner ring of nodes)

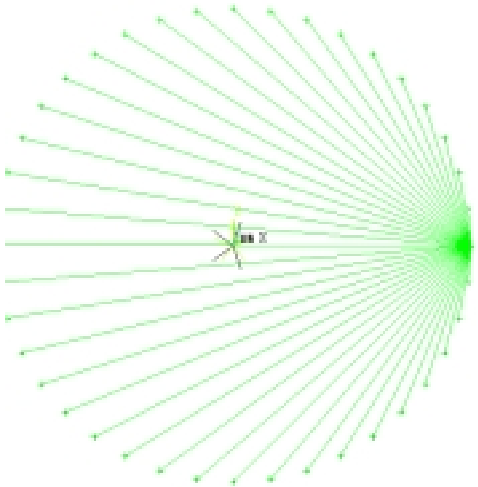
Use Preproces>coupling/ceqn>couple DOF



Enter 1 for the set number

Select OK

The green symbols correspond to the couple set. The lines originate from the master DOF of the set



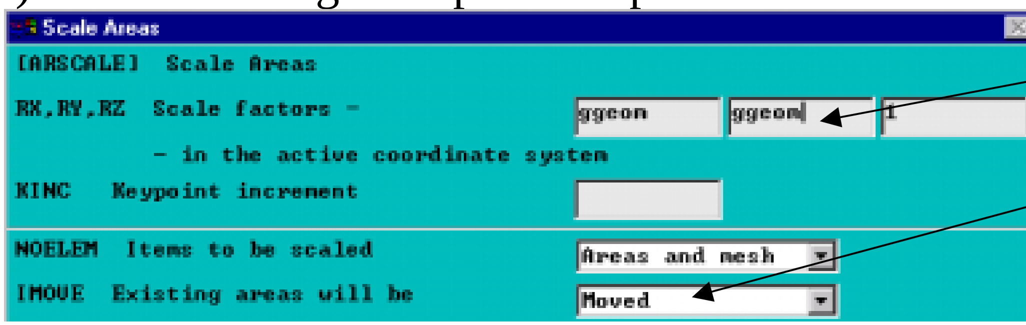
Scaling the rotor model to meters

The solid model can be scaled, but sometimes it is not accomplished if there are extraneous entities that cannot be scaled by the area scaling operation.

1) ensure that all entities are active

2) make the Cartesian system active (csys,0)

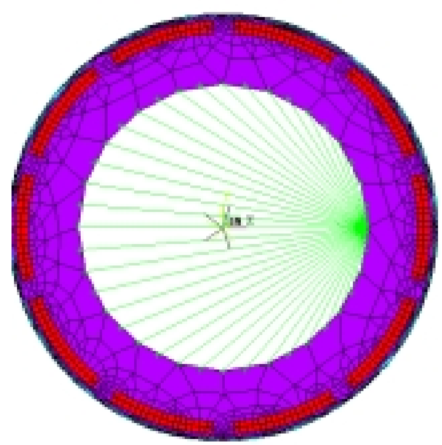
3) for area scaling: Preproces>operation>scale-areas



This parameter is in the parameter file

This forces the areas to be scaled not copied

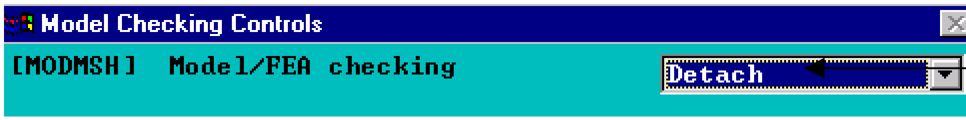
Select OK



The model plot will appear to be the same, since the scaling is uniform

Alternate method for scaling

If the area scaling cannot be accomplished, the mesh can be detached and then the nodes can be scaled. Make sure that **ONLY** the rotor model is active Preproces>checking ctrls>model checking



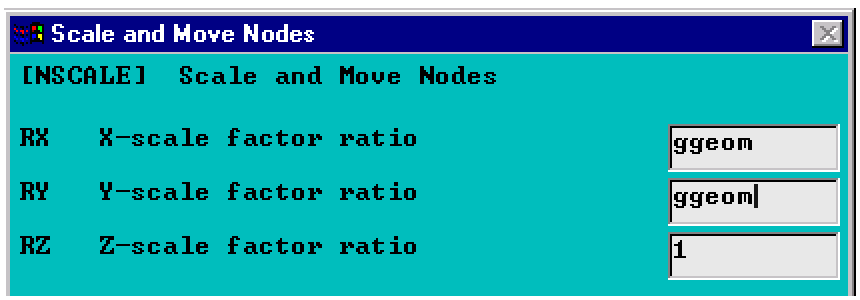
Select the Detach option

Select OK

Ensure that the Cartesian coordinate system is active (csys,0)

The scaling is accomplished by

Preproces>operate>scale-nodes-scale & copy



Obtained from the parameter file

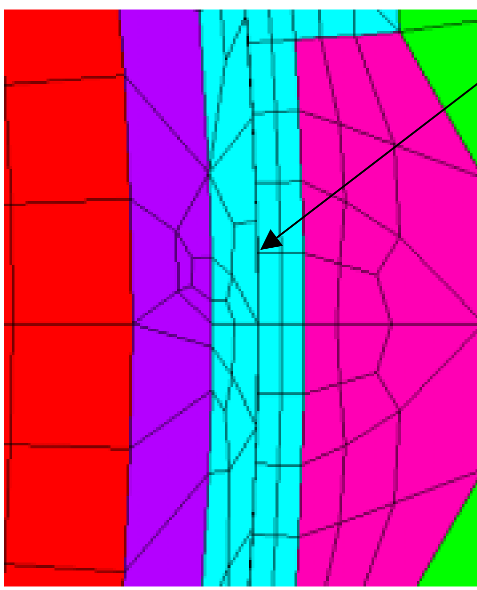
Select OK

Stator generation, steps leading to a solution

Use <STATOR> for the stator

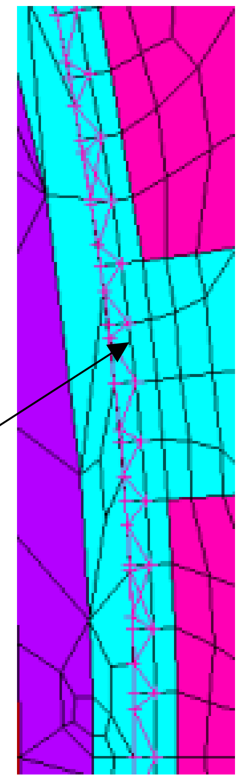
Use <WIND_2D> for the winding with ‘mach2f’ for the winding file.
This file contains the coils for all the slots

Use <ROTATE> to connect the model. Use 0 degrees
Use <LOAD> to apply the currents
(90 degrees with 10 Amps)
Use <SOLUTION> for a single solution



Nodal coordinates can be checked

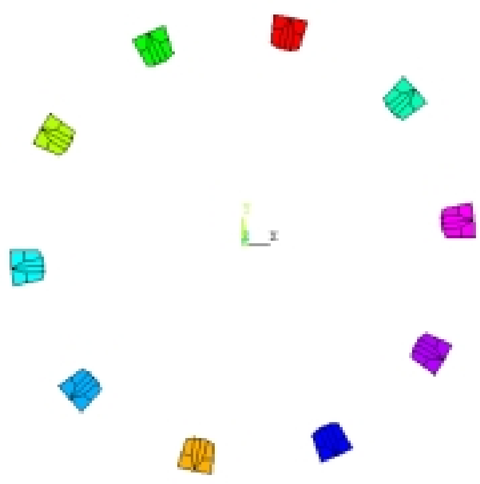
CE’s from <ROTATE> inspect for unused nodes



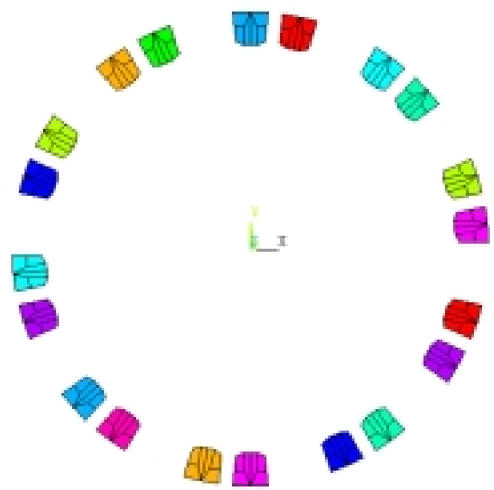
Checking the winding

With the winding being used for the entire machine, the potential for winding errors increase. The individual phase can be plotted by using the components generated by the macro.

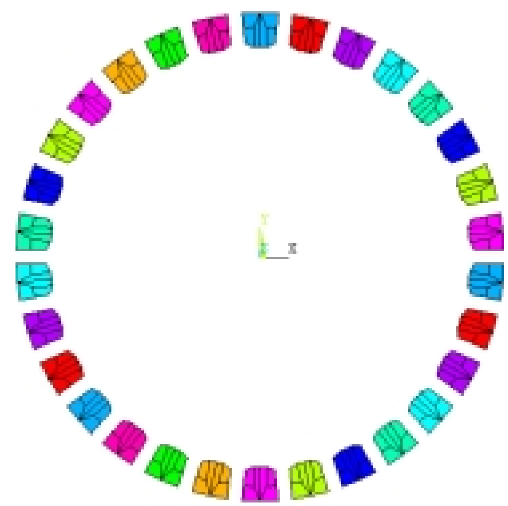
PH_A is for phase A, PH_B is for phase B PH_C is for phase C (as defined in the winding file). The select logic for components can be used to display individual phases. The real set numbers are displayed in the plots.



Phase A only



Phase A and Phase B



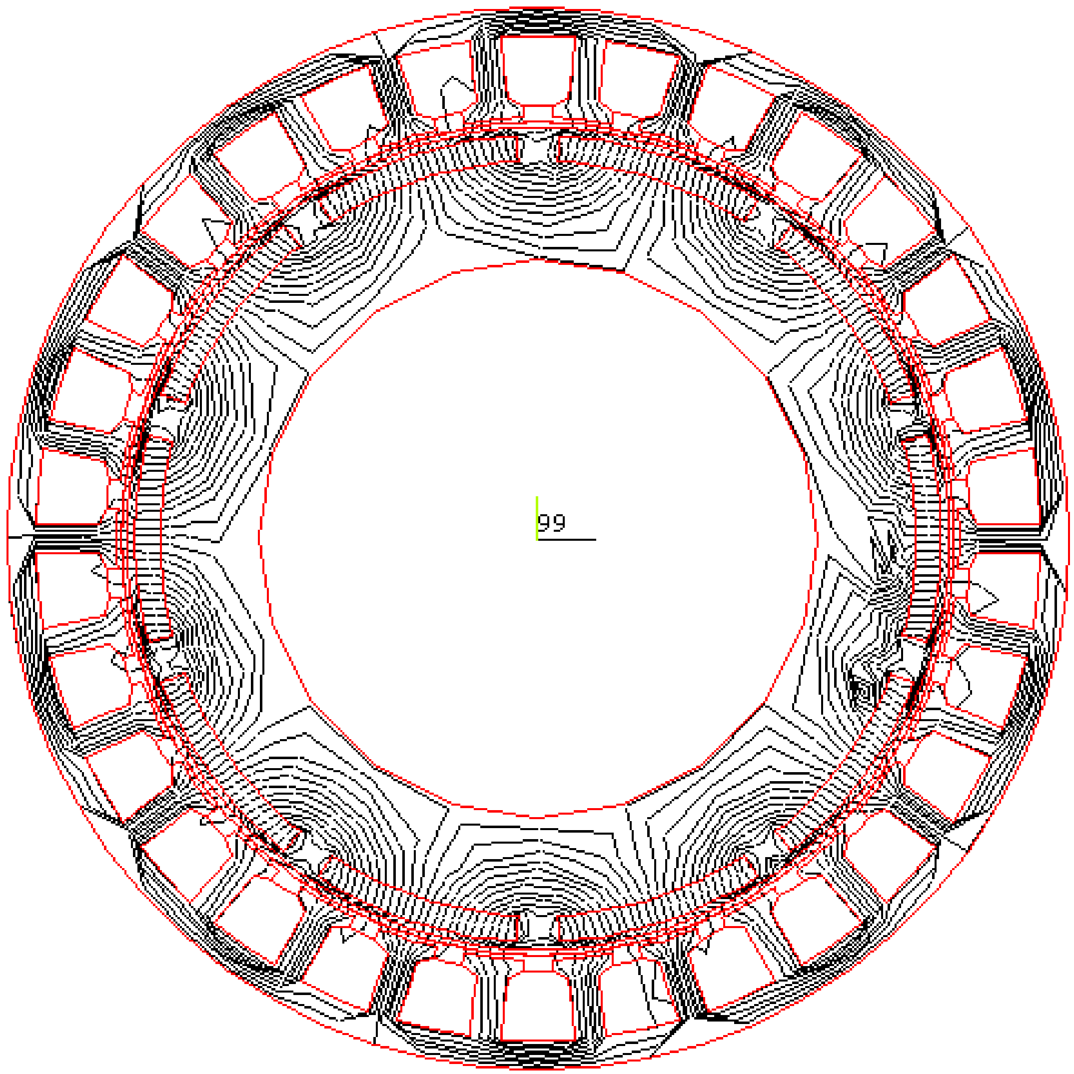
All Phases

Solution results for the entire model

Note:

Check the flux plots in the region of the magnets-parallel to the magnet center

Computing torque indicates that the mesh needs to be refined

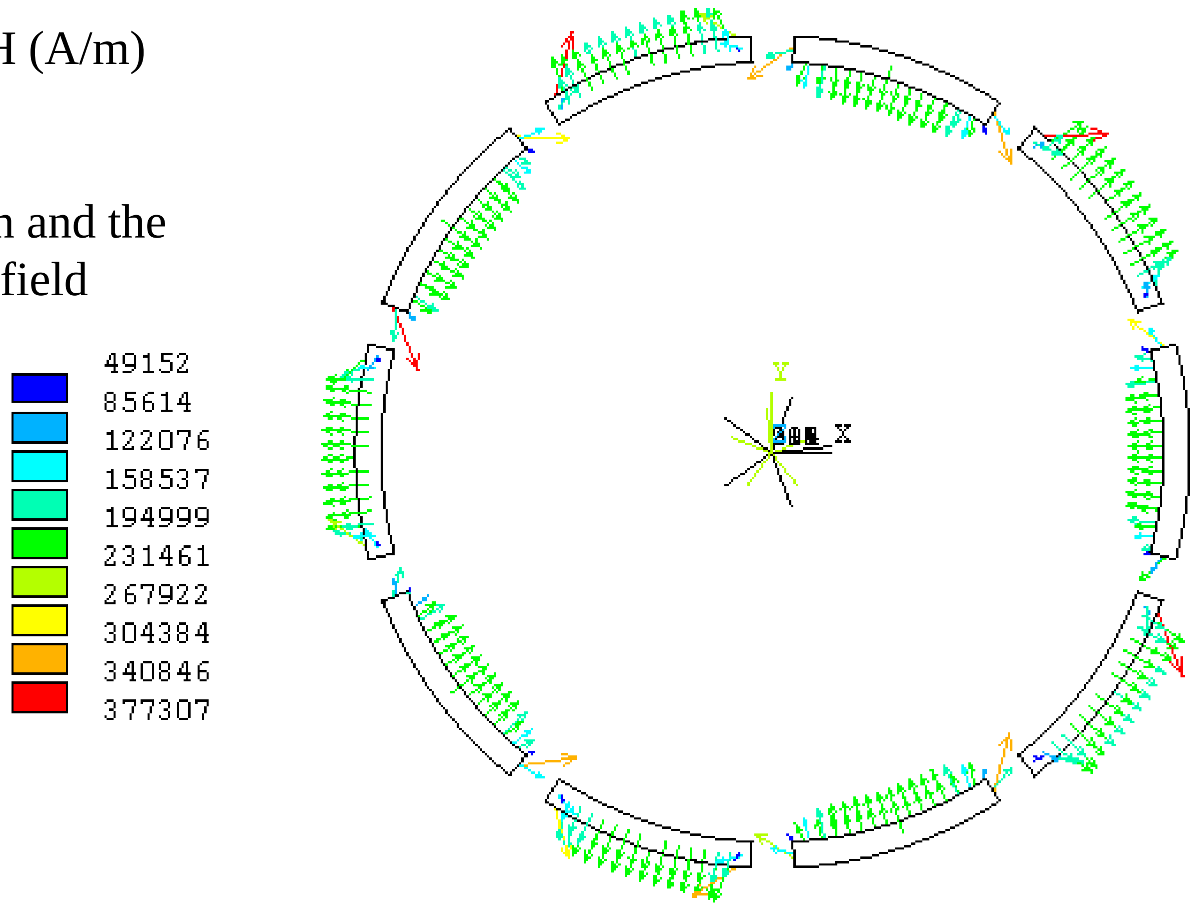


Checking the magnets

Select the magnets (material 3)

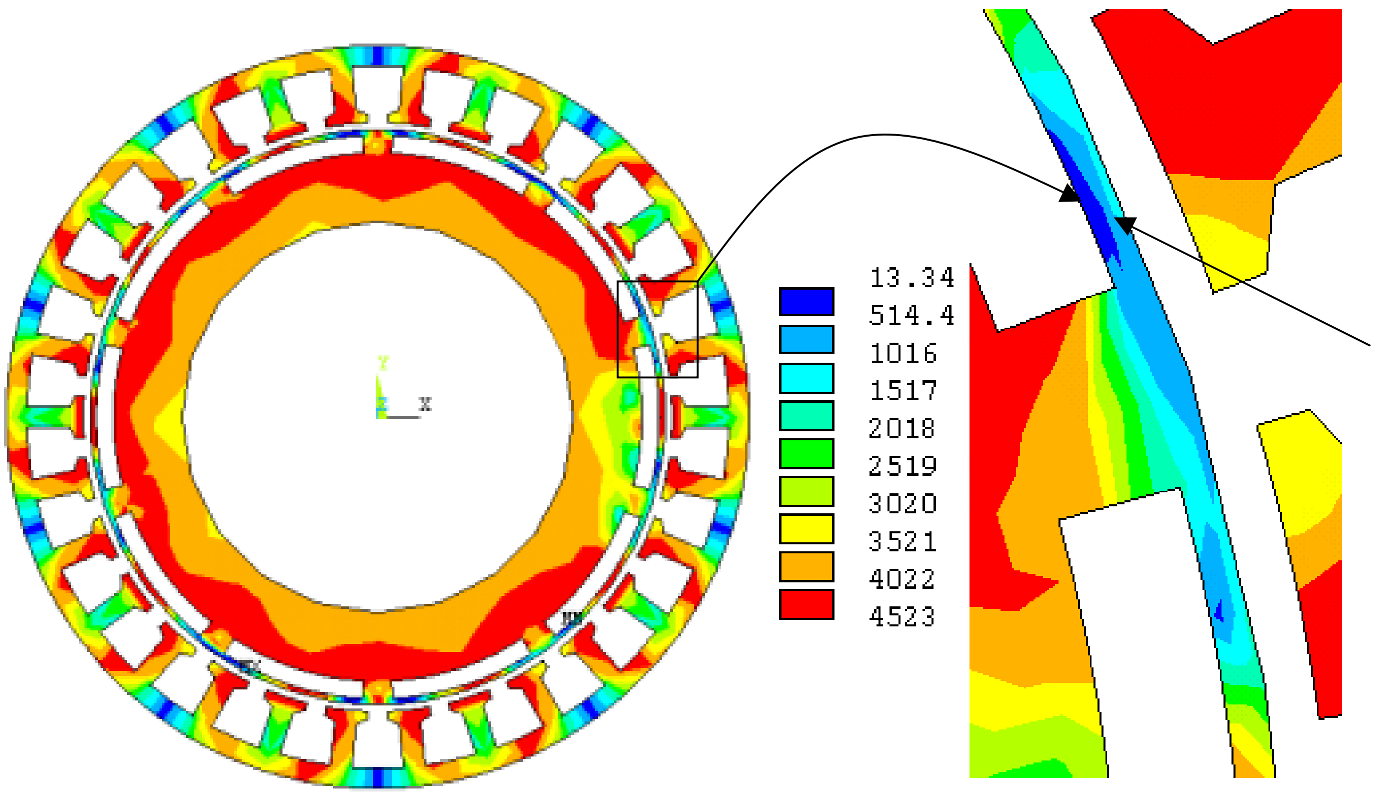
Use <H-VECTOR> to plot H (A/m)

Note the alternating direction and the repeating consistency of the field



Confirming the region of saturation

The MUR can be plotted using <MUR>



Note the level of saturation in this region

Checking the currents

The summary of the currents in the slots is obtained by <CHK-AMP>

These correspond to the slot numbers in the winding file, and are counted CCW from +X axis

These are the real set numbers of the elements in the slots

___SUMMARY OF CURRENTS IN THE SLOTS______<

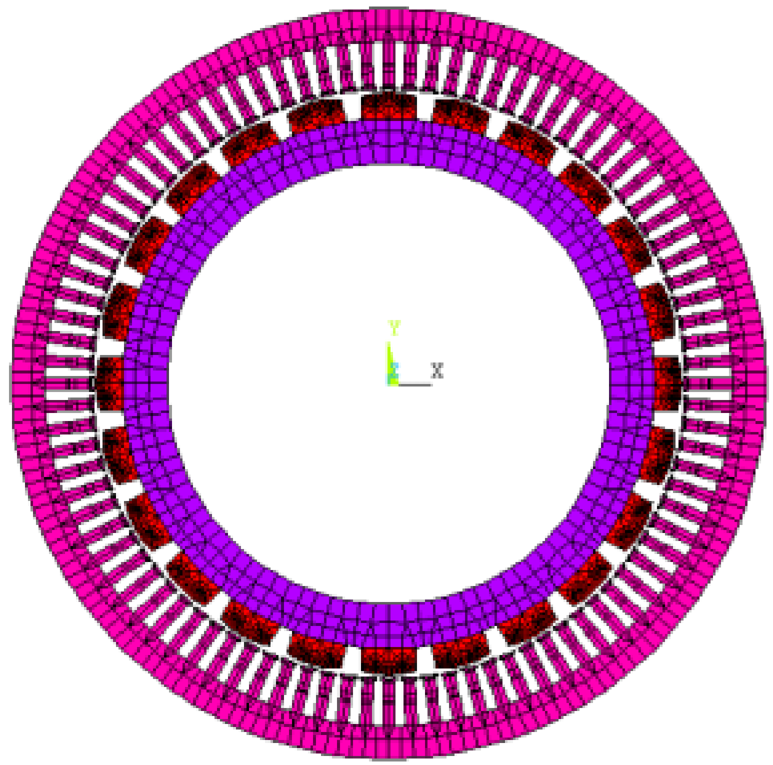
Slot No.	Real No.	Current (Amp-turns)
1.	52.	100.0
2.	53.	50.0
3.	54.	-50.0
4.	55.	-100.0
5.	56.	-50.0
6.	57.	50.0
7.	58.	100.0
8.	59.	50.0
9.	60.	-50.0
10.	61.	-100.0
11.	62.	-50.0
12.	63.	50.0
13.	64.	100.0
14.	65.	50.0
15.	66.	-50.0
16.	67.	-100.0
17.	68.	-50.0
18.	69.	50.0
19.	70.	100.0
20.	71.	50.0
21.	72.	-50.0
22.	73.	-100.0
23.	74.	-50.0
24.	75.	50.0
25.	76.	100.0
26.	77.	50.0
27.	78.	-50.0
28.	79.	-100.0
29.	80.	-50.0
30.	81.	50.0

The current density is retained in the element item JS.
Which can be plotted by <PLOTCURR>

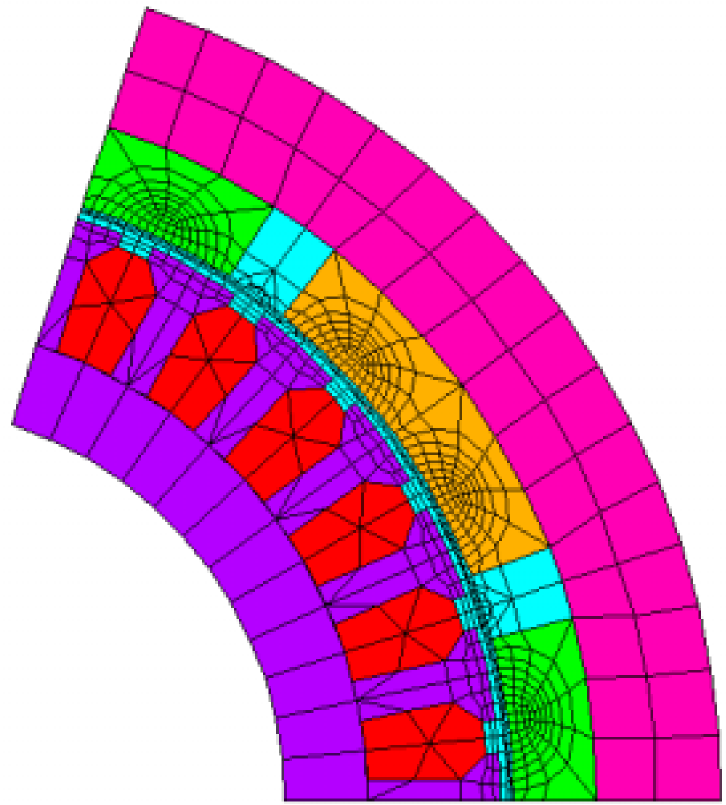
Other machines can be easily generated. Parameter file is Pm9224.des

Using <STATOR>, the full model of a 92 stator tooth stator can be constructed by altering the parameter file. <PM_ROTOR> was used for the rotor. Using an odd number of stator teeth is easily incorporated into a model.

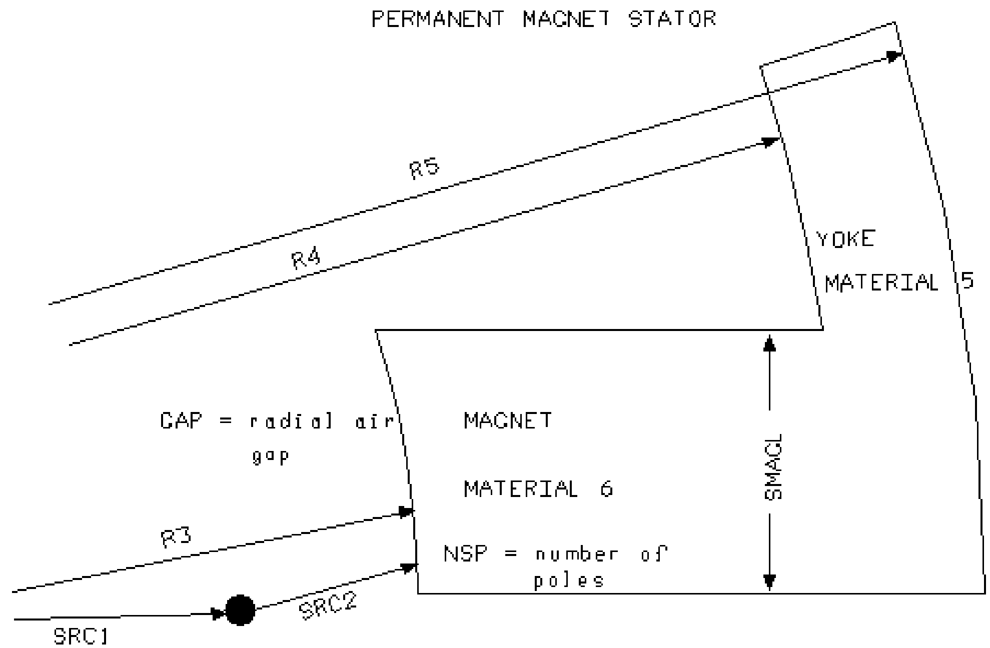
There is no dependency of the rotor design on the stator or vice versa



Example of permanent magnets on the stator (<PMSTATOR>) and a wound rotor (<SLOT_R>). Both components can be slotted. Parameter file is Pms1.des



Information for the template and the magnet shape options for the permanent magnet stator is available in <PMSTAT_H>. A diagram for the parameters is also available. The number of magnets is arbitrary)



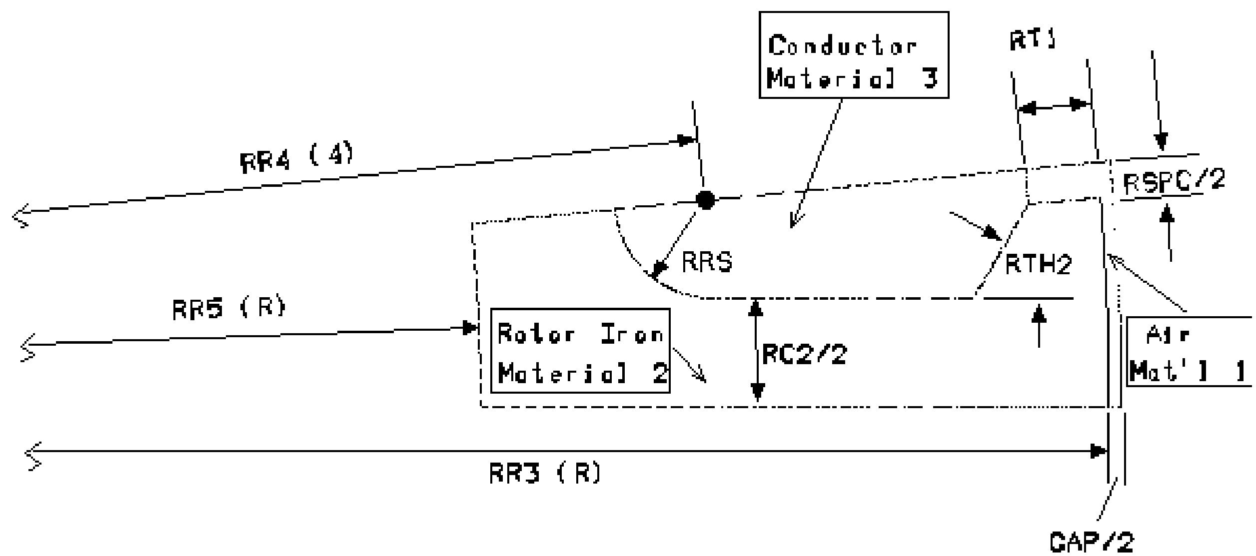
1) Dimensions R3,R4,R5,SRC1 are measured from the centerline

2) The width of the magnet may also defined by an electrical angle (180 implies magnets are touching).

3) The loaf option is obtained by SLOAF=1

Information for the template for the open slotted rotor is available in <SLOT_R_H>. A diagram for the parameters is also available. The number of rotor slots is arbitrary)

Definition of the Parameters for the Rotor
with a Uniform Shank

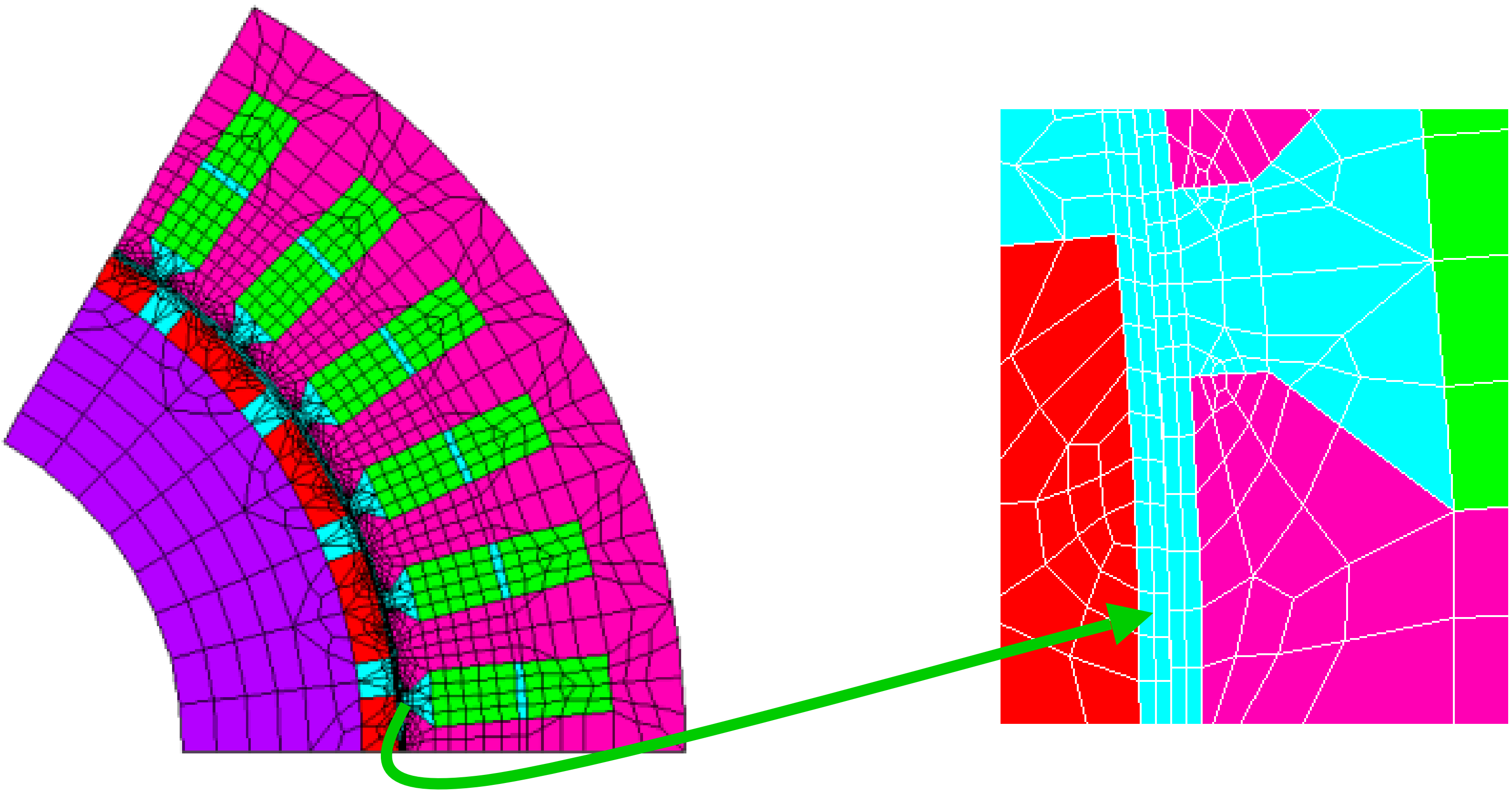


Notes:

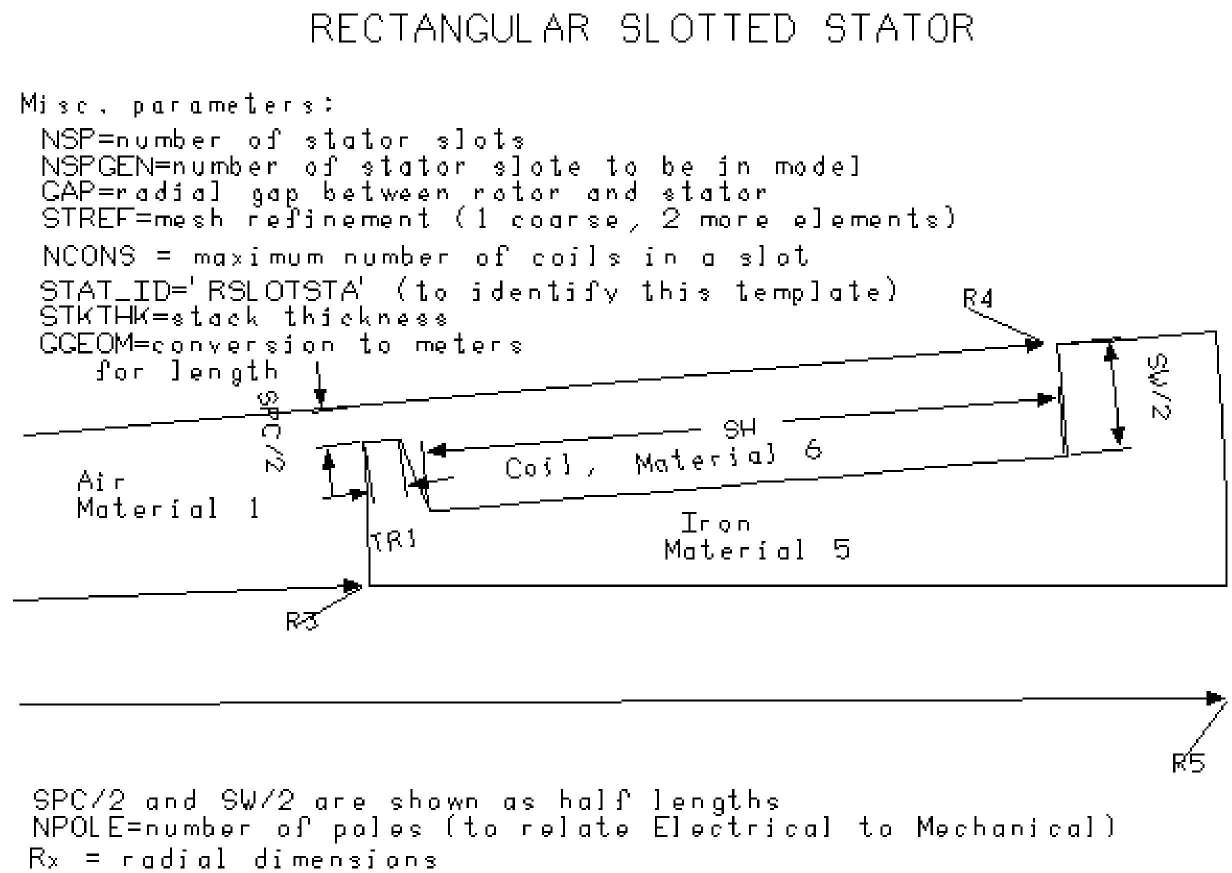
(1) The "(R)" implies that the dimension is measured from machine center

(2) The "/2" implies that only half of the dimension is show

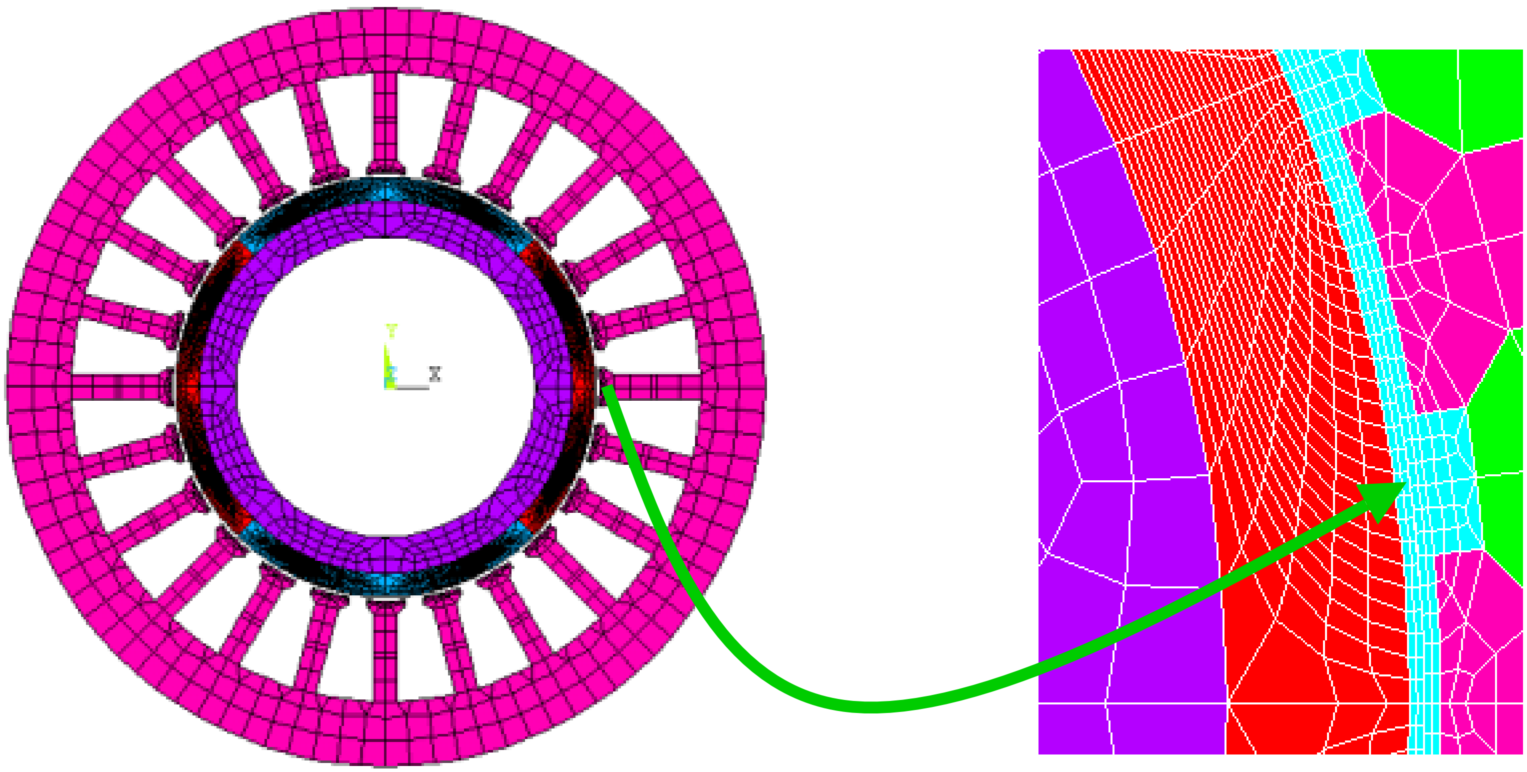
The stator can also use a rectangular slot. The stator can be interchanged with the rotor model, since they are independent. The change can occur without rebuilding the rotor model. Parameter file is Rect1.des



Information for the template of the rectangular slotted stator is available in <RSLOT_H>. A diagram for the parameters is also available. The number of stator slots is arbitrary)



The permanent magnets can extend 180° electrical and be radially magnetized. The modeler allows the air gap to be refined and the back iron to be less refined to allow the solutions to be more efficient. This is automatically accomplished with out user input. Parameter file is Radm1.des



Summary

The DC machine macros are an efficient method to resolve design issues and investigate sensitivities of design parameters.

The APDL in ANSYS allows for torque variation to be examined due to cogg or with current of an arbitrary form.

Examination of the magnet operation can be easily performed.

The modular design of the modeler allow for ease of incorporating new templates

Appendix A

Macro list

MACRO LIST

MACRO	DESCRIPTION	Calls
Aier_add	Demo macro for seminar	
B_mach2d	Example of constructing an entire model	Slotsta pmrotor mvrotor
B_wndsc, b2wndsc	Constructs winding with CIRC124 from the winding file	G_area nowslt wire_gag wr_wnd
Ckslot	Prints out summary of currents applied to the stator	
coillink	Computes the flux linkage for each coil based on the coils defined in the winding file	
copper	RSVX, MURX for copper	
embedd	Example embedded magnet	
Fmagbx	Applies force flags alows the summary file to be turned off	
G_area	Computes the area of the active elements	
G_parfil	Loads the parameter file from the toolbar	
Ld_coil	Applies current to a coil	
L_matrix	Modified version of lmatrix to compute the inductance matrix	
M14, m19, m2, m22, m27, m4, m43, m47, m50, m54, m6	M steels BH data	
mabbr	Contains all the abbreviations for the toolbar	
machtorq	Computes the torque by the Maxwell's stress tensor	Mtorqc2d

MACRO LIST

Macro	Description	Calls
Mag_conv	Makes modification to a rotor laminate which was imported	
Mmf_	Computes MMF, retains path parameters	
mur	Computes the relative permeability	
mvpsol	Generates single static solution	
mvrotor	Rotates the rotor and connects to stator with CE. Updartes PM ccoordinate systems if present	Stitch6
M_induc	Computes the inductance for a range of currents	S_ind l_matrix
permach	Generates CPs for periodic models	
Plt_form	Plots current form	
plvln	Generates vector plots with outlines for elements with different materials	
Pm_rotor	Generates the PM rotor	
Pm_stat	Generates the PM stator	
Put_amp	Applies current (A-t) for active elements	
Rotsol1	Solves multiple solution with constant current	Coillink mtorqc2d mvrotor
Rotsol2	Solves multiple solution with a current form	Ld_coil mtorqc2d mvrotor
slotrot	Generates the slotted rotor (open)	

Appendix B

Select Logic Review

The select logic allows the portions of the model to made active or in active.
ANSYS commands ***works*** only on the active elements.

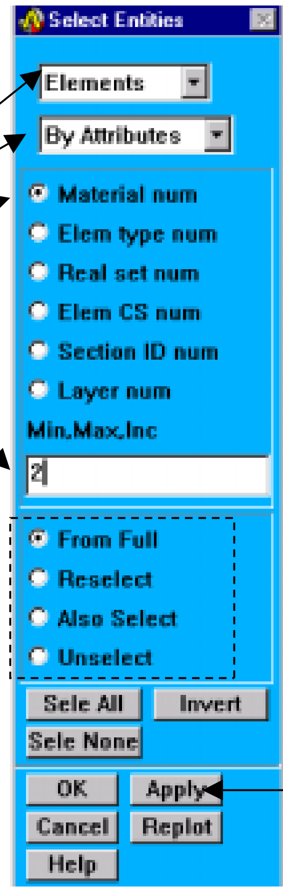
Using the rotor as an example.

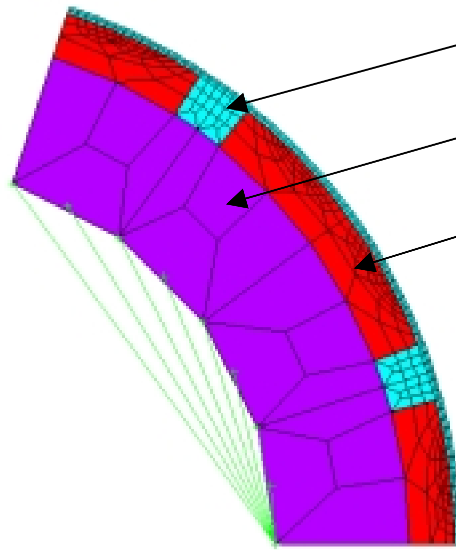
Select material 2 and plot

Utility>select entity

Make these selections

This determines what "Boolean" is to be used





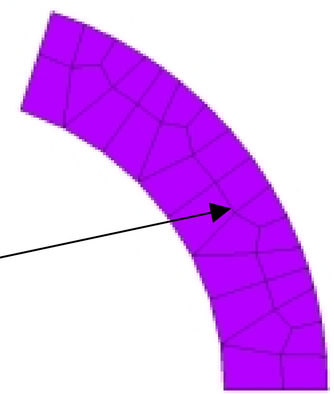
Material 1

Material 2

Material 3

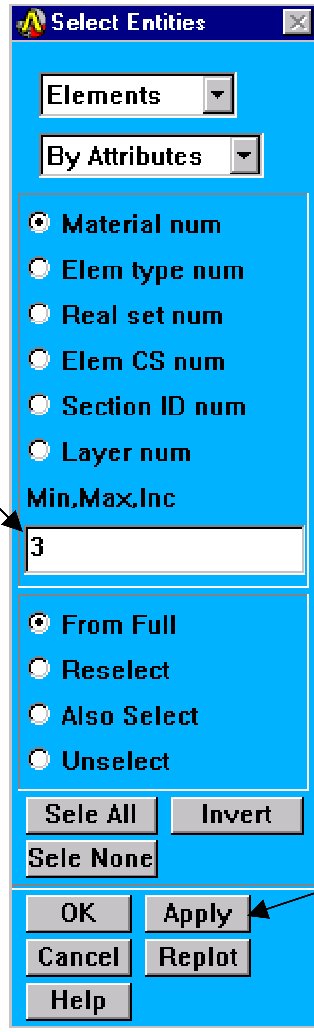
Select

Replot

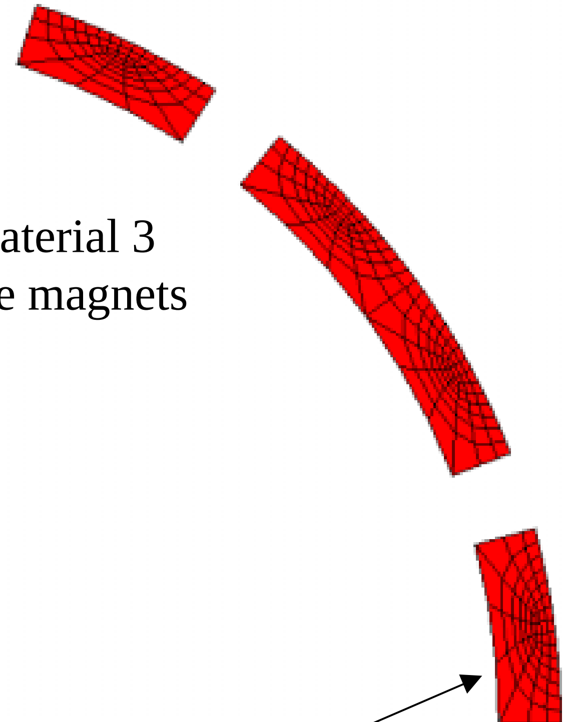


Select logic

Select the magnet elements which are material 3



Material 3
the magnets

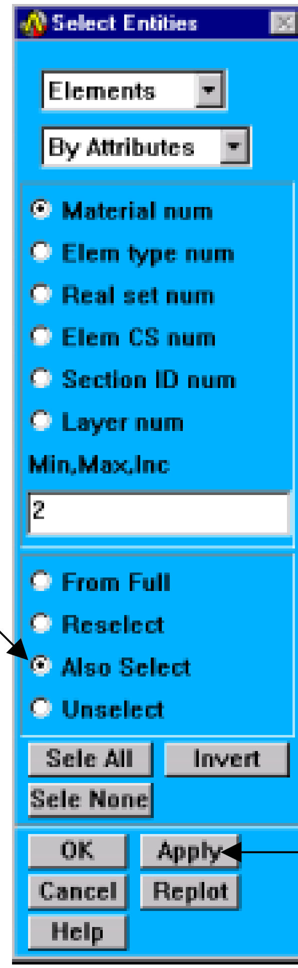


Select

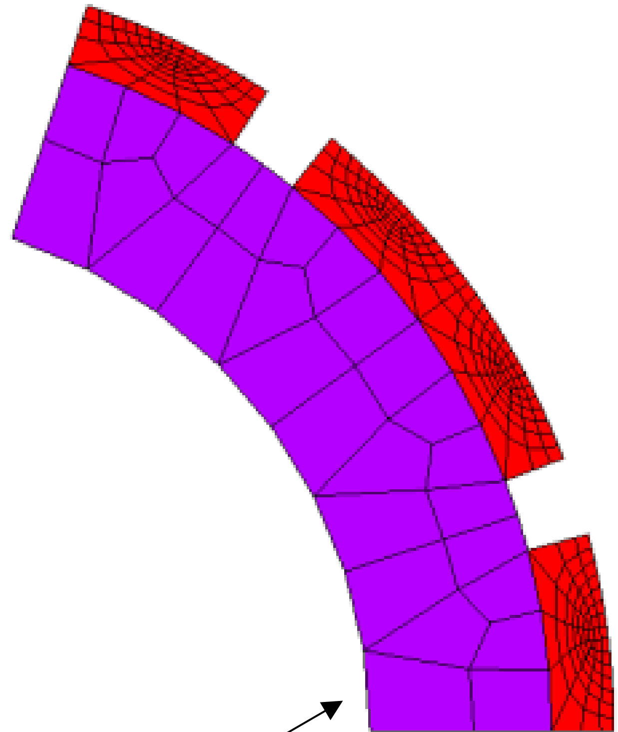
Replot

Select logic

To replot the iron use the “Also” select.



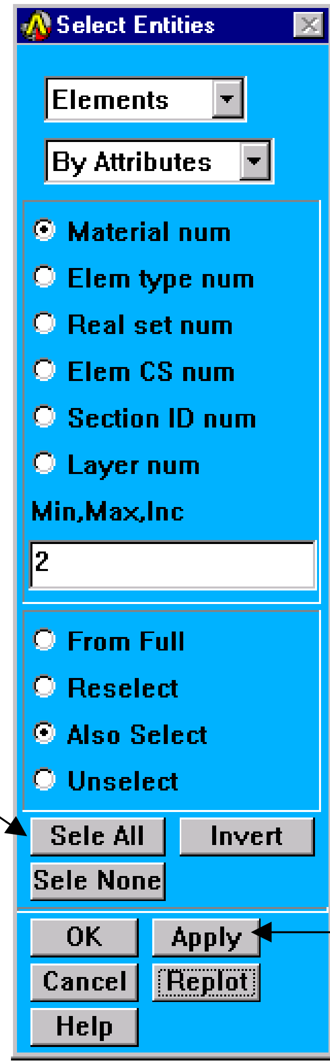
Apply
Replot



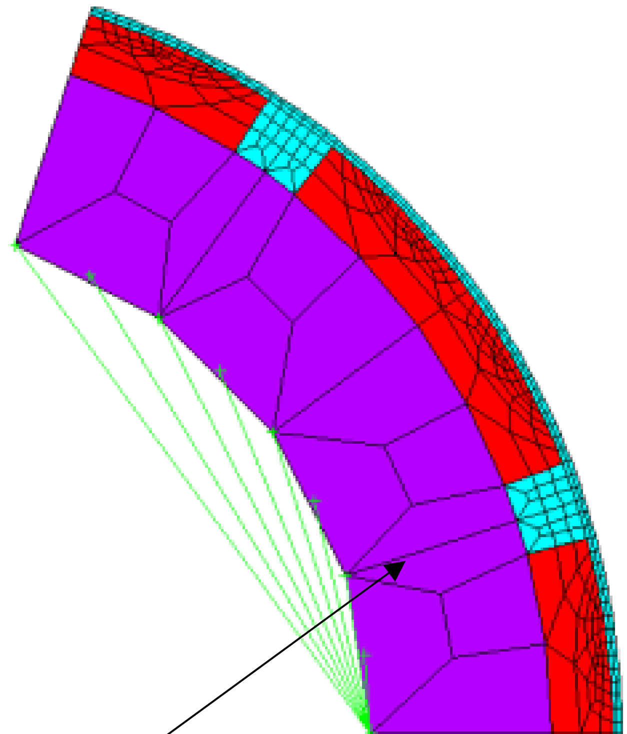
Select logic

To get the entire model active

Use Sele All



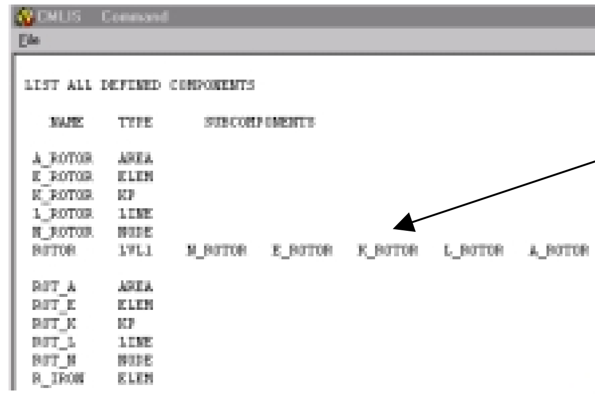
Select Replot



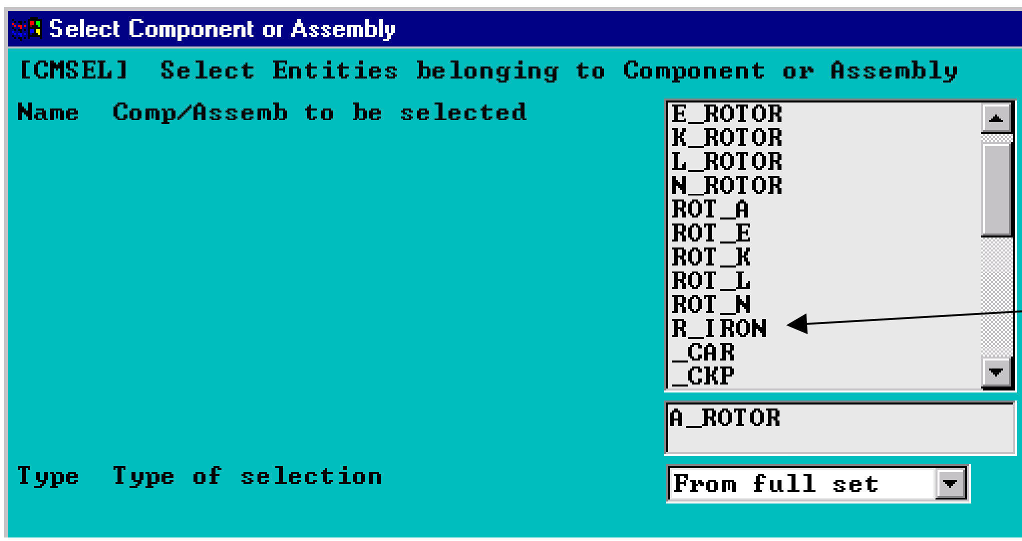
Use of Components for selection. A component is a set of entities. A list can be obtained by entering at the command line: cmlist

Select logic can be used to select component. To select R_IRON use

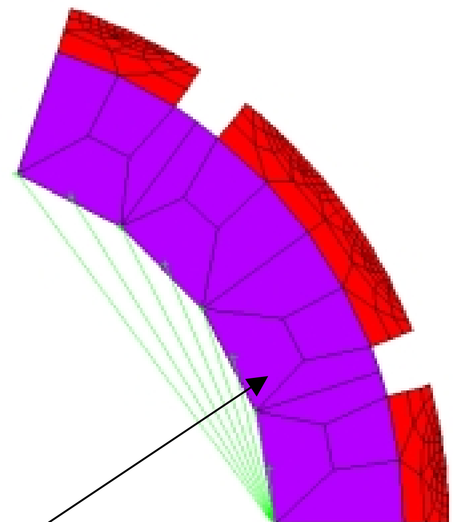
Utility>select>comp/assembly>select comp/assembly



A component group is comprised of other components



Select then OK

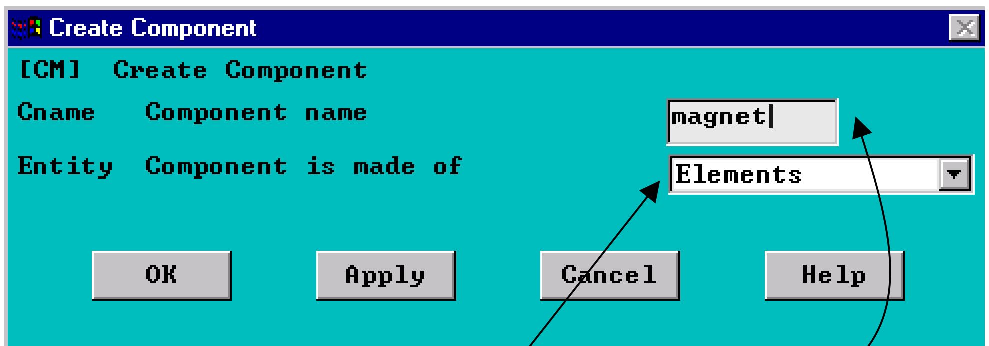


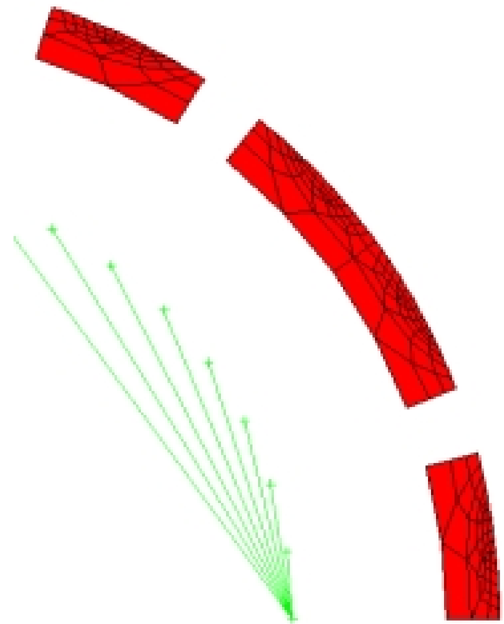
Use Utility>plot>replot

Defining a component for the magnets called "magnet"

Select material 3

Use Utility>comp/assembly>create comp





Select the entity "element" and enter the name and select OK

The "magnet" component will appear when selections are to be made.

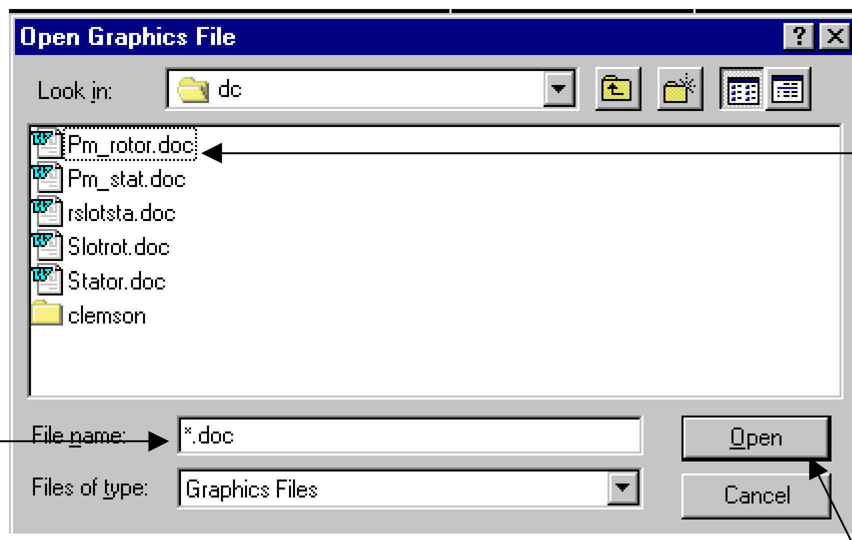
Appendix C

Display Utility and templates

Using the display utility

Execute the Display utility from the START>ANSYS>DISPLAY UTILITY

To open one of the display files for the parameter definitions, enter *.doc

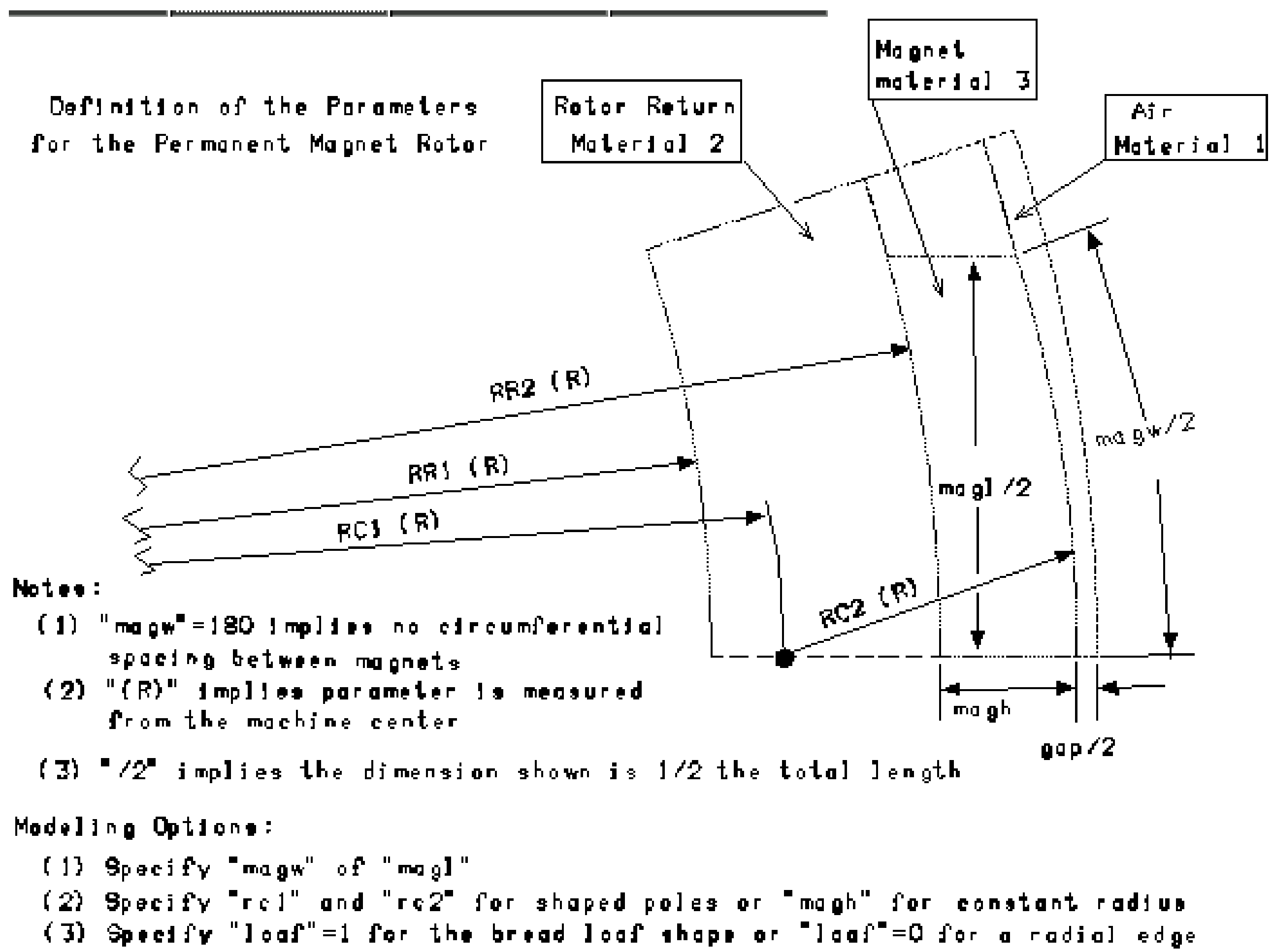


Select pm_rotor.doc for the permanent magnet rotor

Then select Open

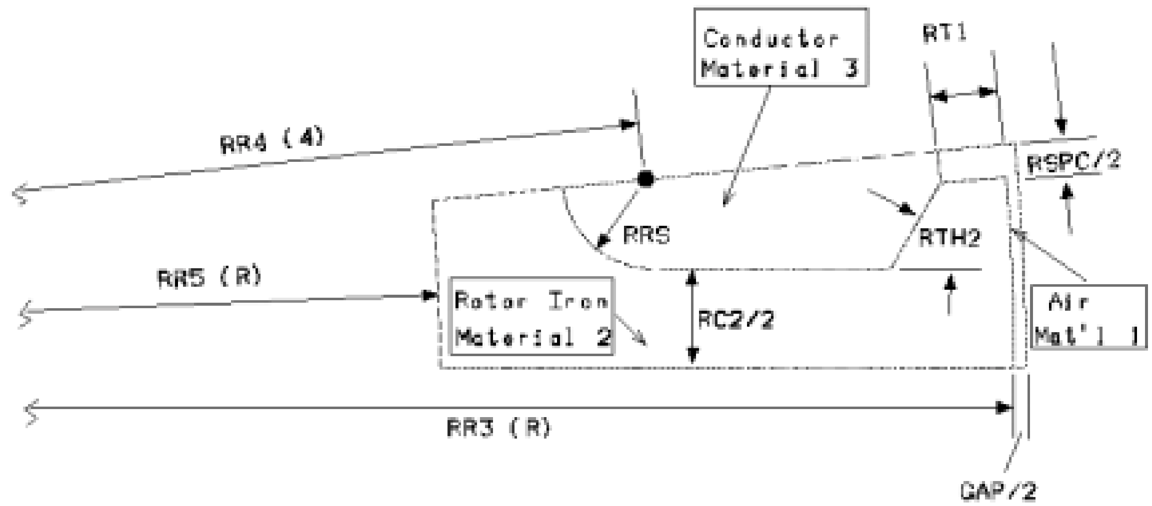
To display the next plot use "plot next"

Permanent Magnet Rotor : pm_rotor.doc



Slotted Rotor : slotrot.doc

Definition of the Parameters for the Rotor
with a Uniform Shank

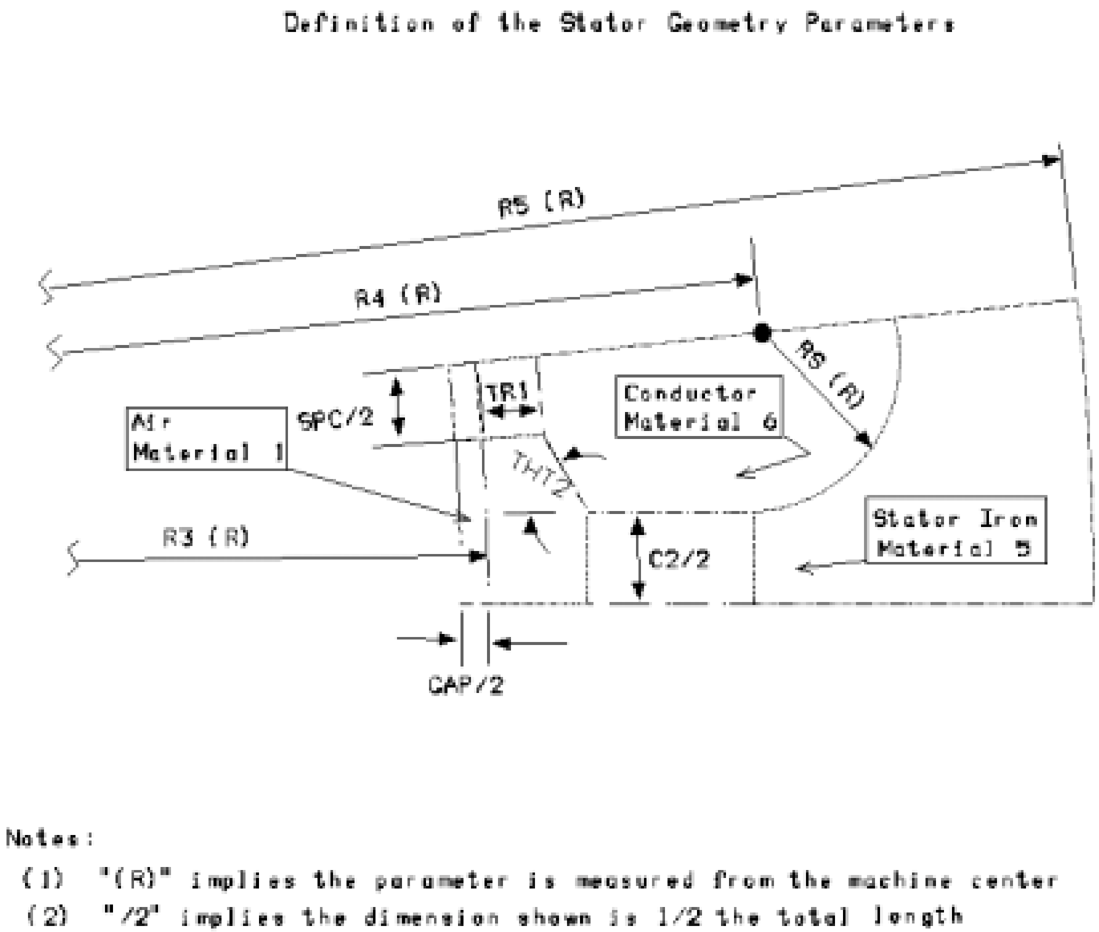


Notes:

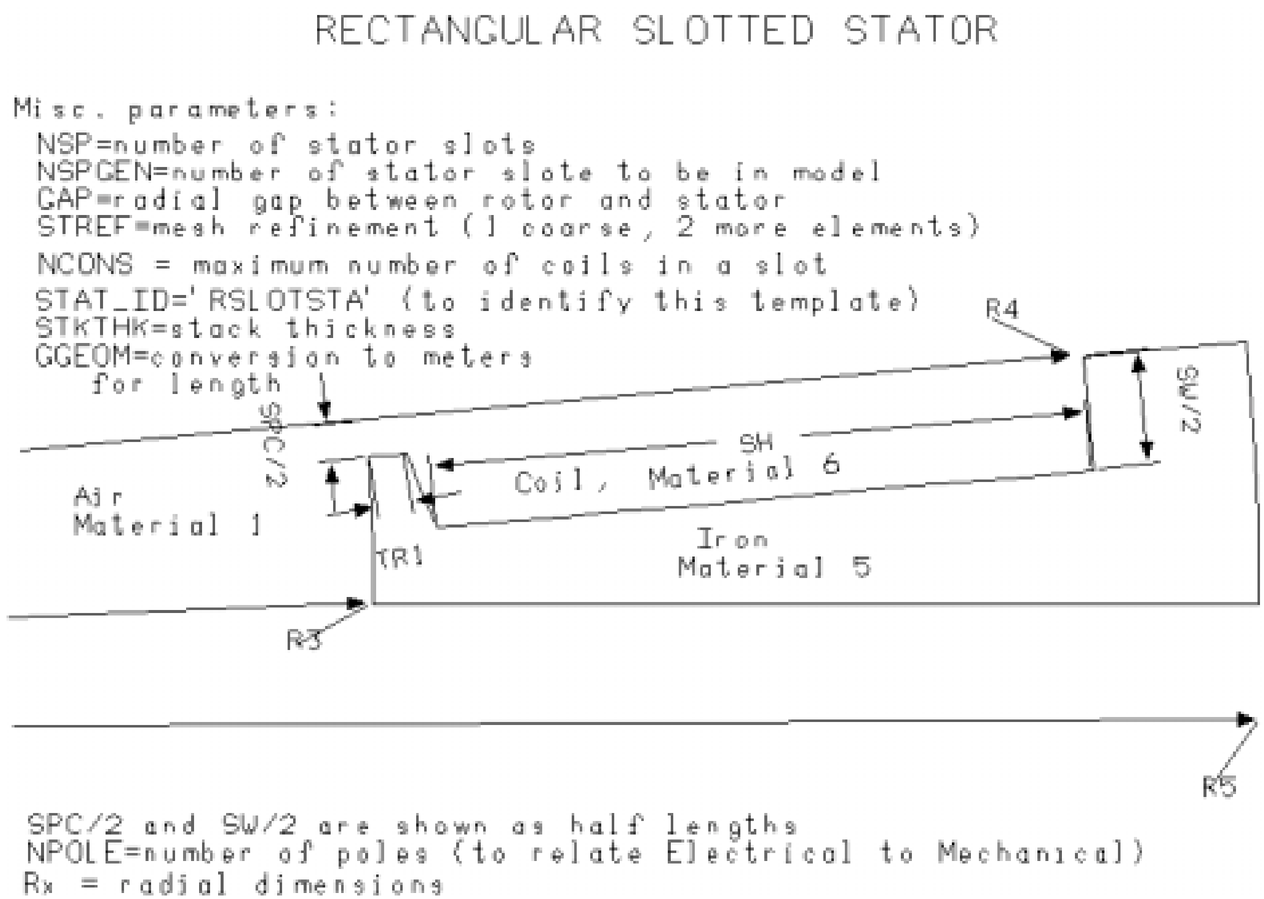
(1) The "(R)" implies that the dimension is measured from machine center

(2) The "/2" implies that only half of the dimension is show

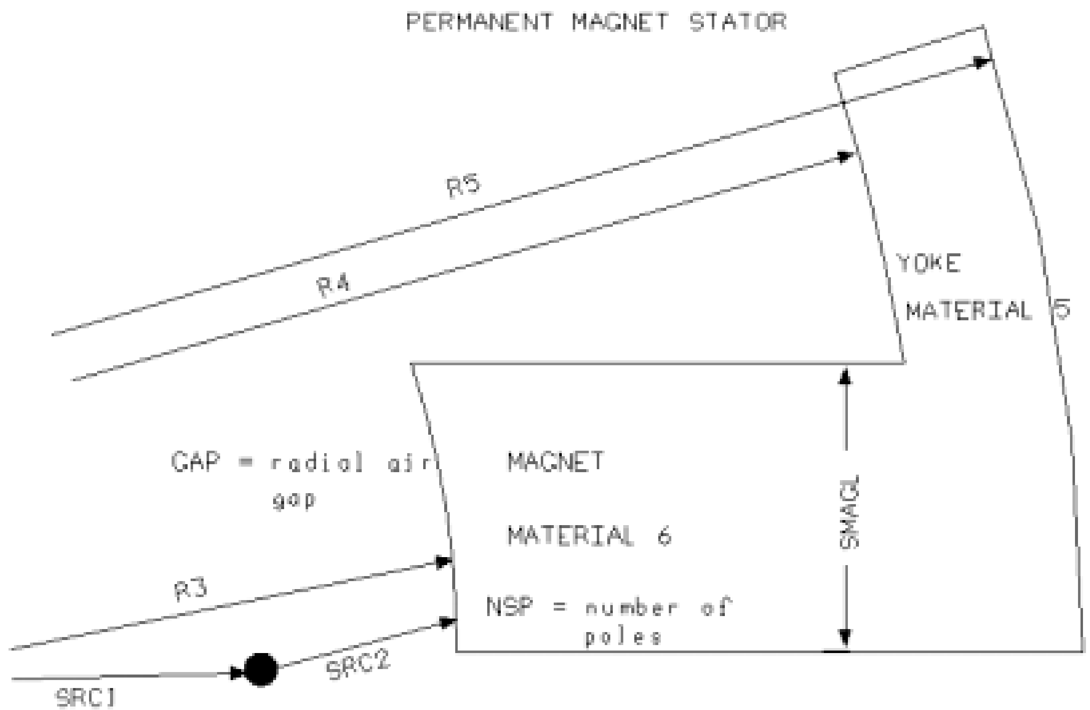
Slotted Rotor : slotrot.doc



Slotted Stator-uniform slot : rslotsta.doc



Permanent magnet in the stator : pm_stat.doc



1) Dimensions R3,R4,R5,SRC1 are measured from the centerline
2) The width of the magnet may also defined by an electrical angle (180 implies magnets are touching).
3) The loaf option is obtained by SLOAF=1

Appendix D
Listing of Help Files for the Templates