ANSYS (R) Macros for 3D DC Machines
Kearfott Guidance & Navigation Corp.

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Seminar Overview

- The objective of the seminar is to present modeling/analyses methodology for 3D simulations of permanent magnet machines

- The seminar is comprised of three parts
  - Overview/review of 2D analyses
    - Options that are readily available in 2D and not in 3D
  - Overview of the three formulations for the 3D magnetics in ANSYS
    - Nodal based scalar potential
    - Nodal based magnetic vector potential
    - Edge based element
  - Analysis of 3D DC permanent magnet machines

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**

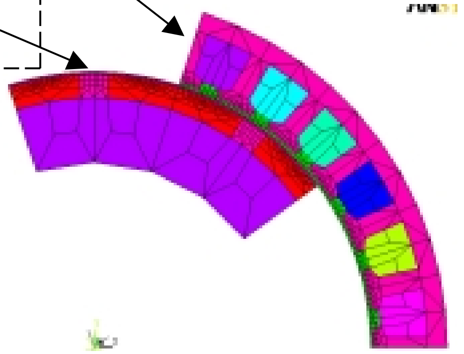
- For example <WIND_2D> executes the macro that generates the winding information using b_wndsc.mac.

```
*abbr,wind_2d,b_wndsc,0,0,0,0,0,0,0,0,1
```

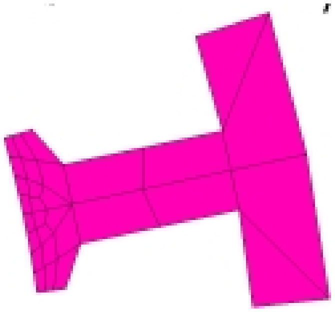
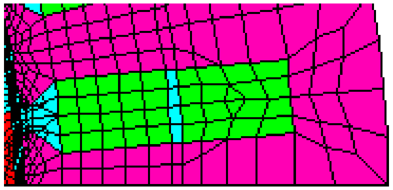
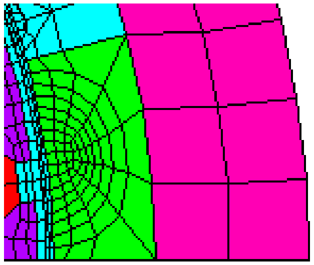
Overall process of generating the model, solving, post processing

- 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

These are incorporated in B_MACH2D

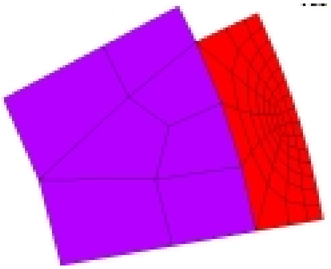


Laminate options for the stator

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.

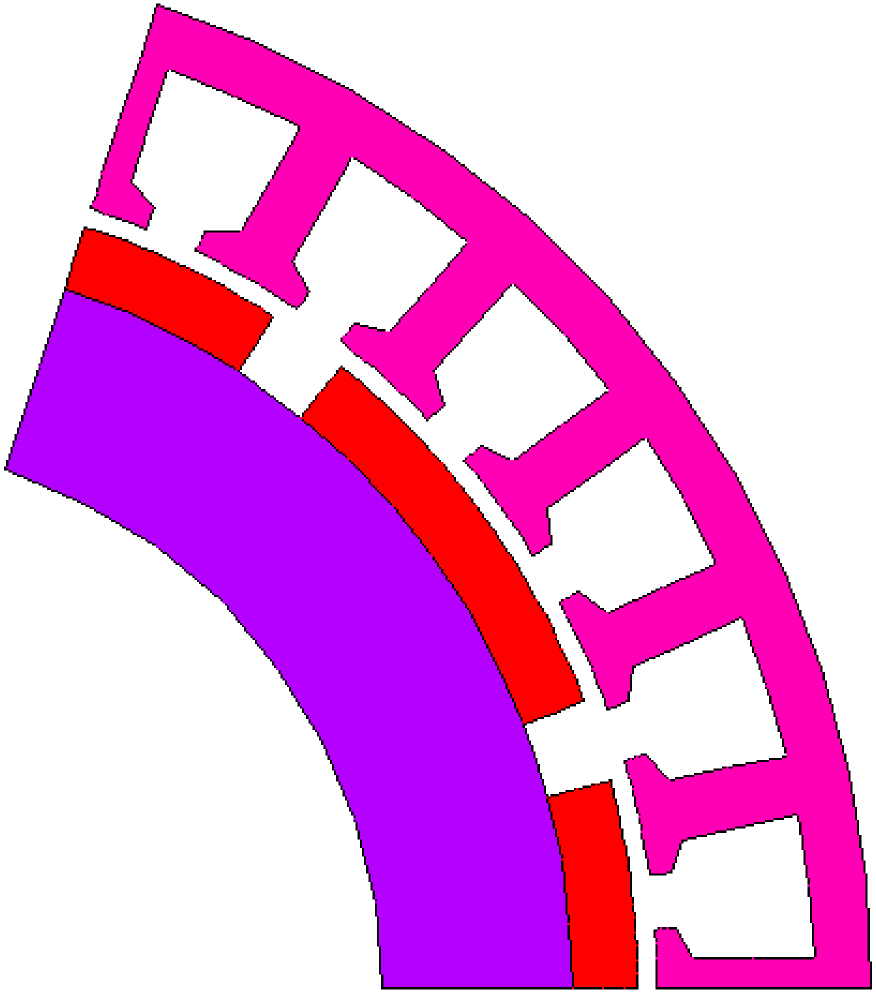
Laminate option for the rotor

Laminate		**Help**	**Plot file**
Permanent magnet-surface mount		<PMROTOR_H>	pm_rotor.doc

Example of a periodic model for a 10 pole BDC machine

- Permanent magnets are parallel magnetized

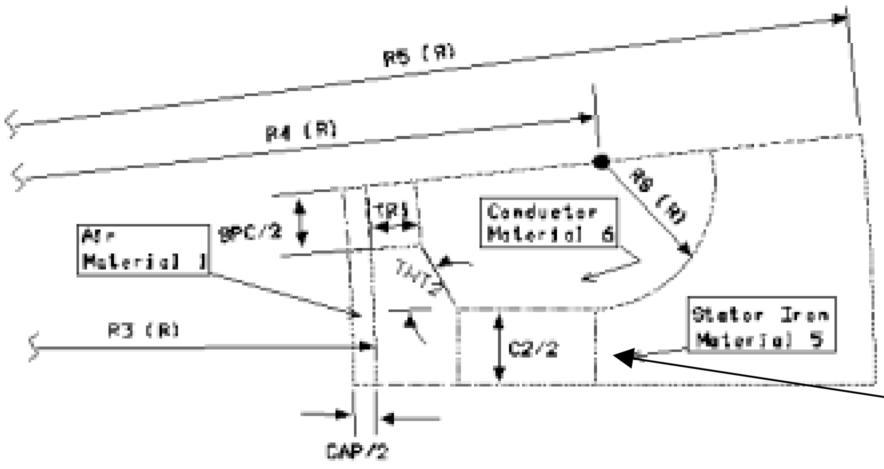
- Three phase winding
- Only 2 poles are to be modeled.



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.

Definition of the Stator Geometry Parameters



Tooth shank has a uniform width

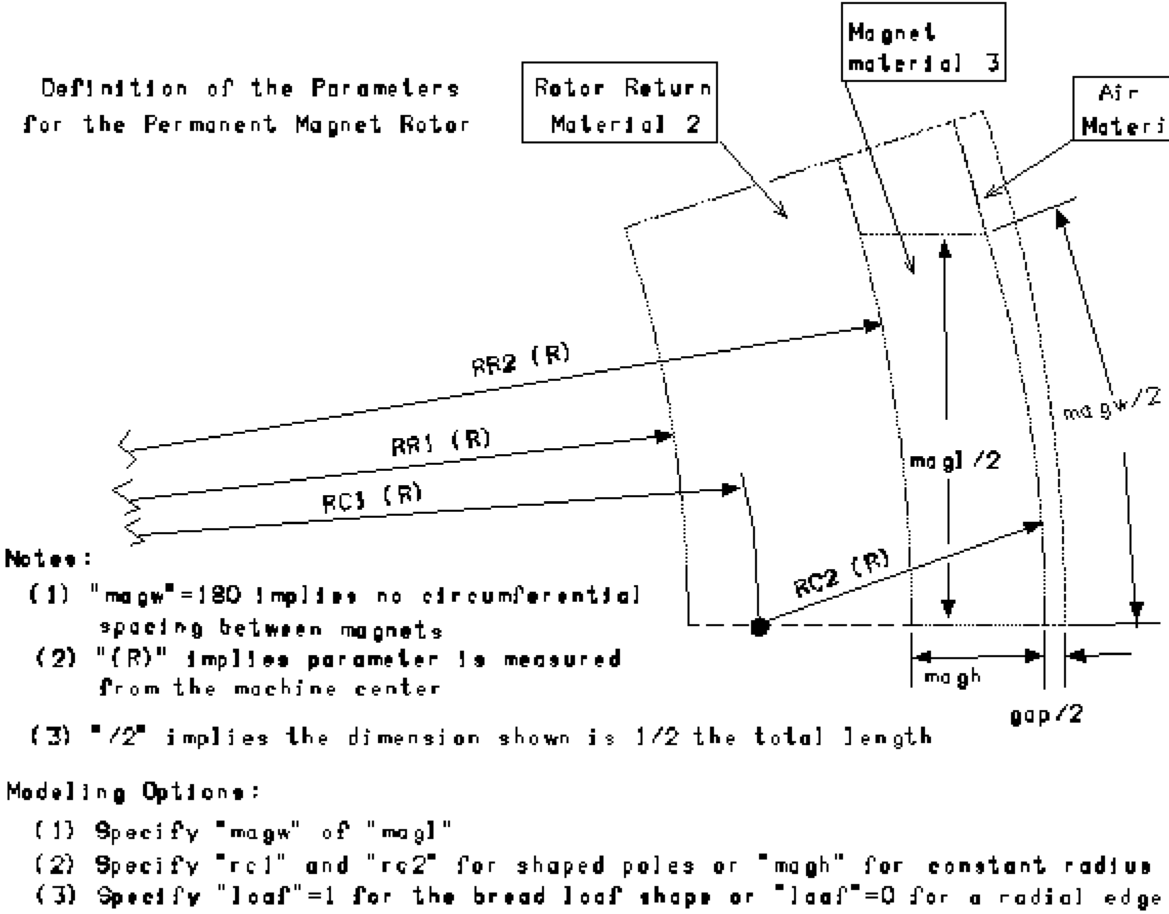
Notes:

(1) "(R)" implies the parameter is measured from the machine center

(2) "/2" implies the dimension shown is 1/2 the total length

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



Notes:

(1) "magw"=180 implies no circumferential spacing between magnets

(2) "(R)" implies parameter is measured from the machine center

(3) "/2" implies the dimension shown is 1/2 the total length

Modeling Options:

(1) Specify "magw" of "magl"

(2) Specify "rc1" and "rc2" for shaped poles or "magh" for constant radius

(3) Specify "loaf"=1 for the bread loaf shape or "loaf"=0 for a radial edge

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

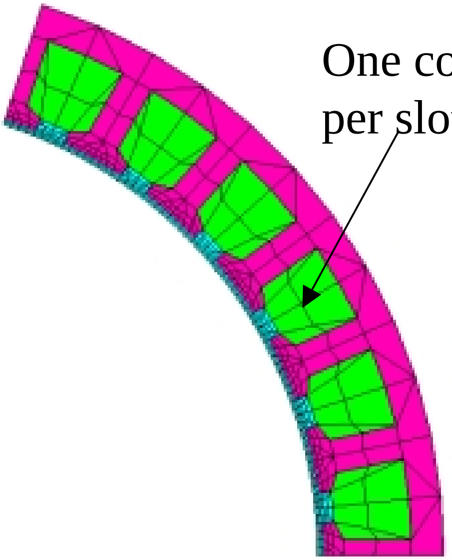
– rotor	component group for nodes/elements…
– stator	component group for nodes/elements
– s_coil	elements for stator coil
– r_iron	elements for magnet/iron in rotor; used for torque calculation

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
  - inductance Henries

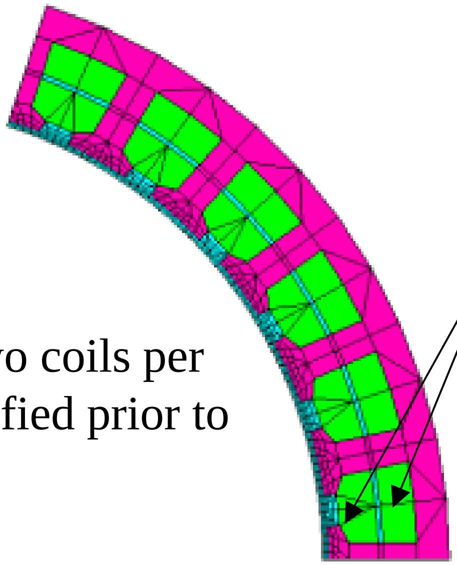
Model details and parameter definition

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)



One coil per slot

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



Two coils per slot

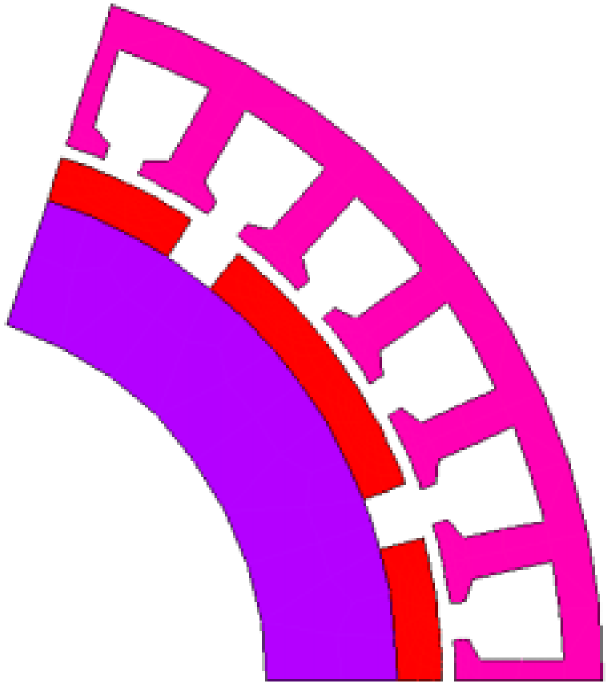
Modeling parameters-continued

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
```

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

ENTER Enter Parameter File Name -> _arg1 =

'mach2'

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

This can also loaded by using the command line as

/input,mach2,des

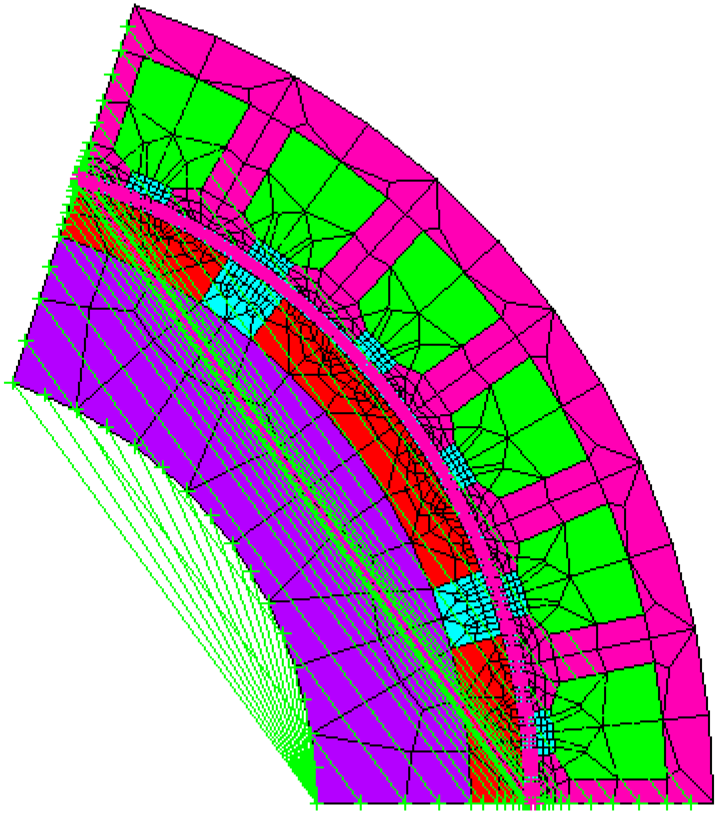
Notes that the single quotes are not needed.

Model generation

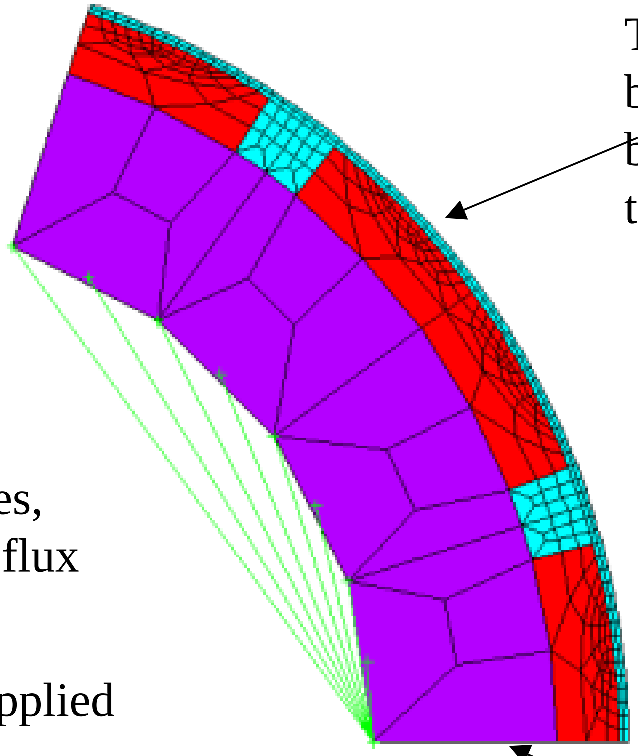
- The macro would be input into the command line as

```
b_mach2d,'mach2'
```

- 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



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.

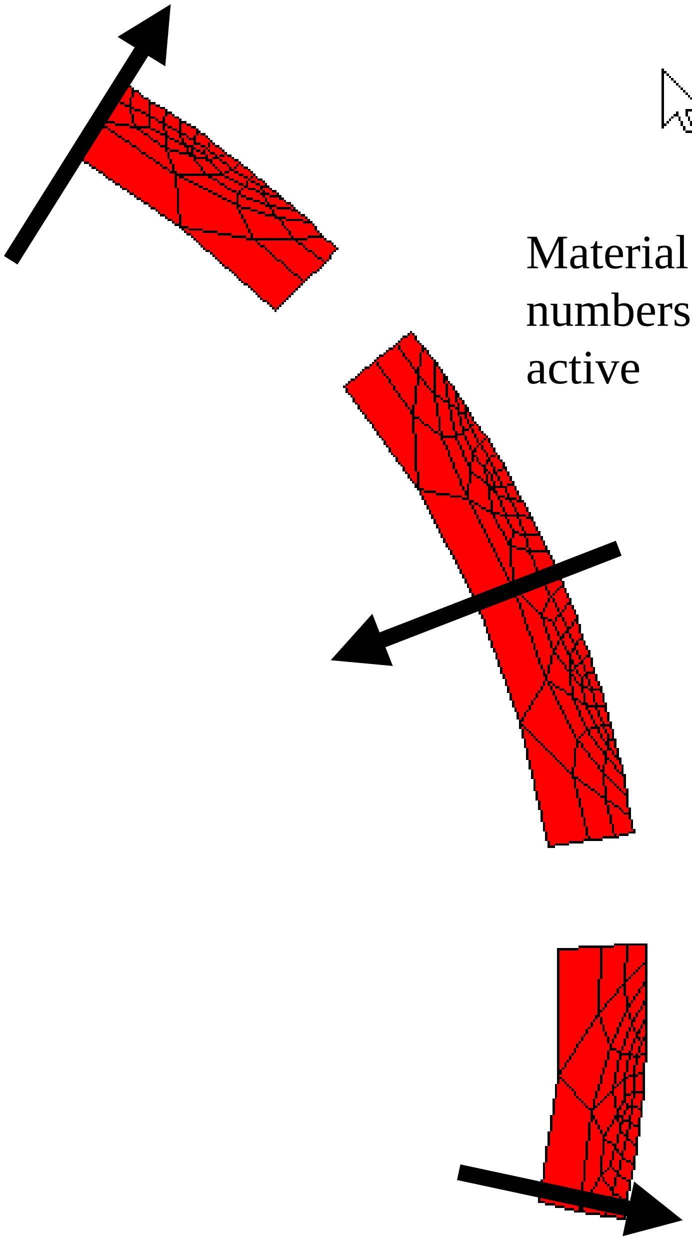
No AZ constraints are applied to the rotor.

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

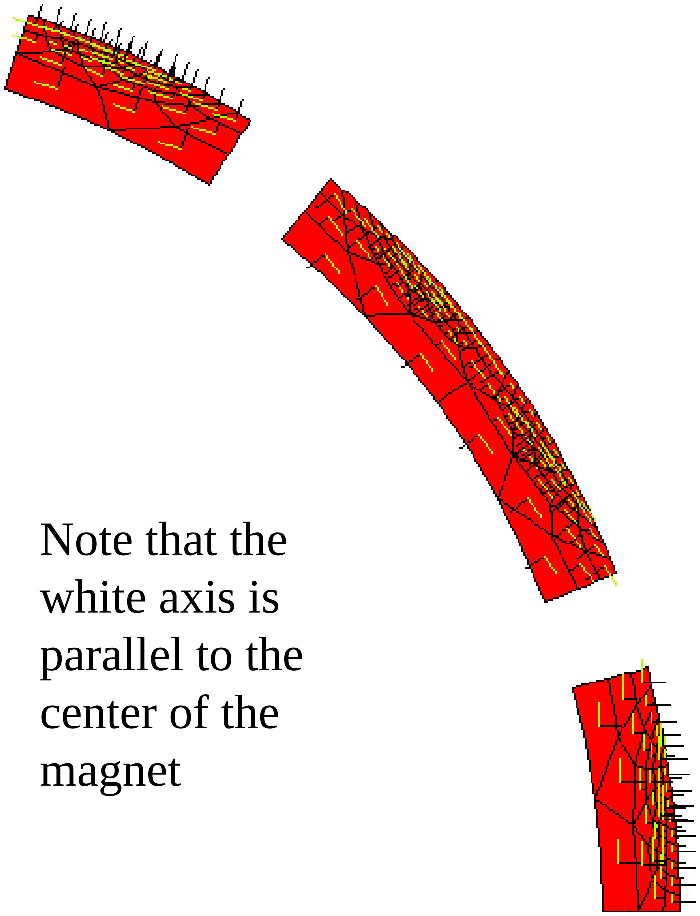
Utility> plot cntrls>symbol > element coordinate system

white axis: element X axis

green axis: element Y axis

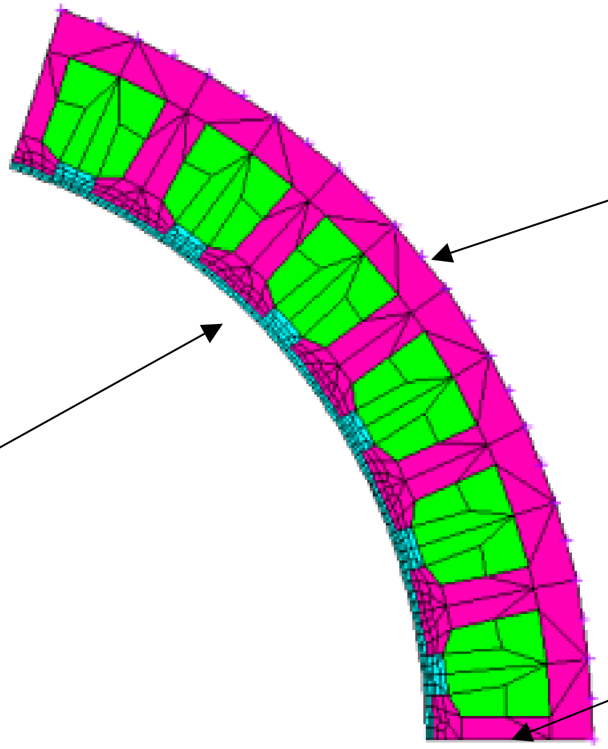
blue axis: element Z axis

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

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

Material properties - continued

The materials used in a model can consist of any combination of

- linear materials-isotropic, orthotropic
  - This requires the relative permeability MURX (iso)
- BH data
- permanent magnets
  - For parallel magnetization (MGXX)
  - Linear (MURX)

While the model has been constructed to use separate materials, no material properties have been input. The following definitions are required:

Material 1	free space for all air	(MURX = relative permeability = 1)
Material 2	rotor iron	(BH data for M54)
Material 3	rotor magnet	(MURX=1.06, MGXX=774000)
Material 5	stator iron	(BH data for M54)
Material 6	stator slotted region	(MURX=1)

Material Properties input

The most efficient method in terms of documentation and direct input is to use the command line.

Basic command to be entered into the command line or the parameter file is:

- MP,MURX,1,   1.0
- MP,MGXX,2,   774000
- MP,MURX,2,   1.06
- MP,MURX,3,   500
- MP,MURX,5,   500

Material ID   **Material Value**

MURX: linear permeability

MGXX: Hc for magnet

Permanent magnet material data

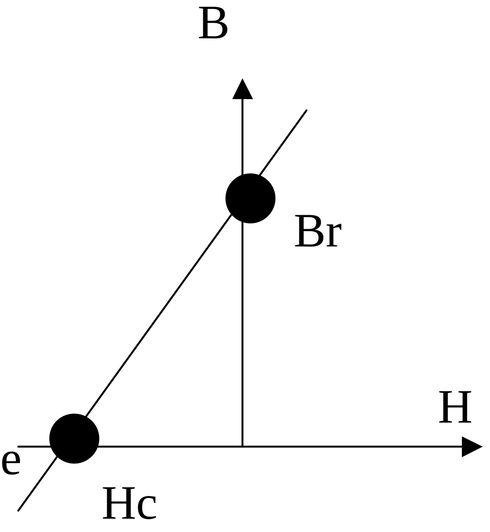
Permanent magnets require the Coercive force (Hc, A/m) and the permeability (not Br (T)).

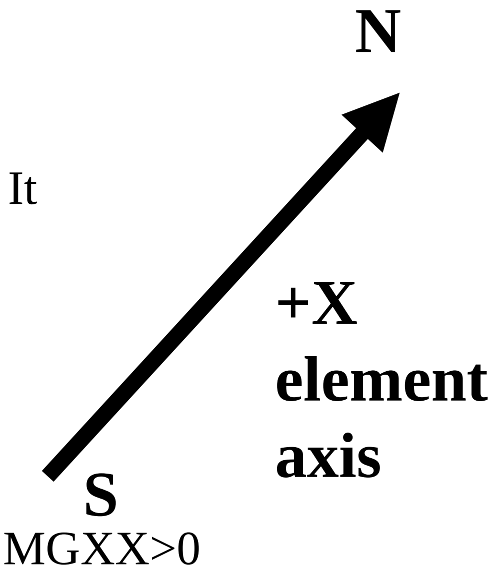
The permeability is usually considered to be isotropic. Most data sheets specify the Hc and Br. The permeability is then computed as Br/Hc/1.2566E-6. This value would be used in the MURX. Be sure to account for temperature effects when selecting the properties (This can significantly affect EMF calculations.)

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

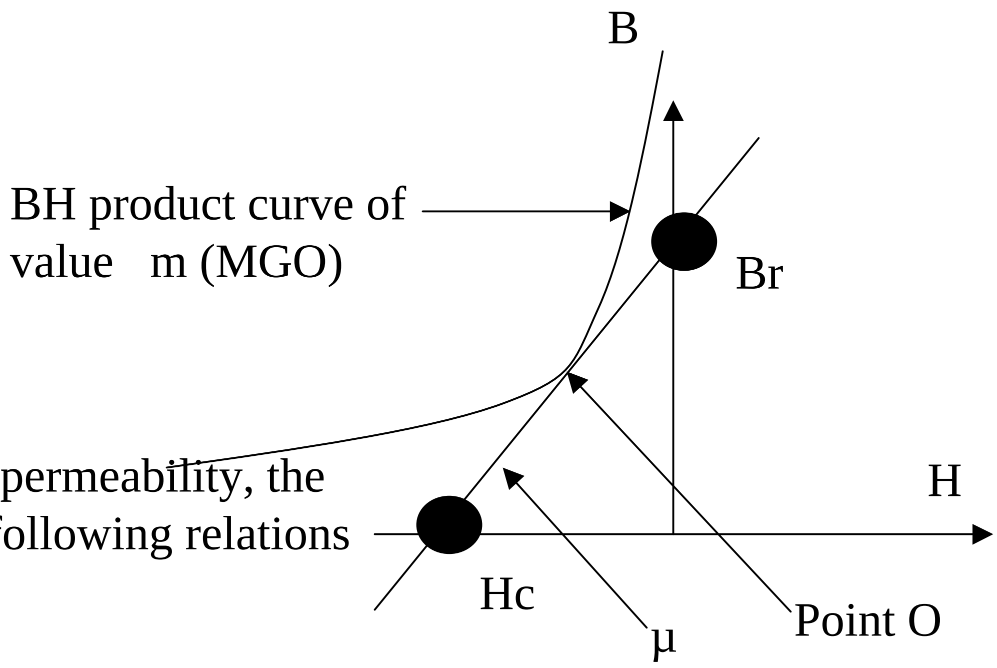
From the machine macros:

Parallel / radially magnetized: element axis
X is outbound-inbound
Y is circumferential





The BH product



For a given BH product and permeability, the Hc can be computed by the following relations

1) $B = \mu(H - Hc)$

2) $BH = -m$ (third quadrant)

3) $(dB/dHo) = \mu$ (relative permeability

Using these three expressions, $Hc = 2000*79.57\,(m\,\mu)^{1/2}$ (A/m)

This Hc value is used in the material properties input.

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

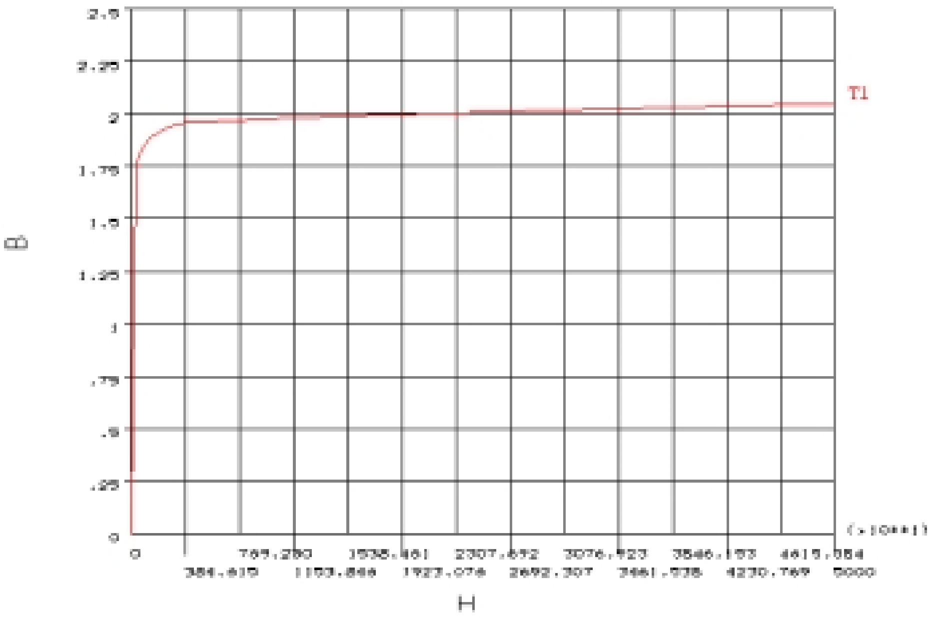
The M steels on the previous slide meet the following criteria:

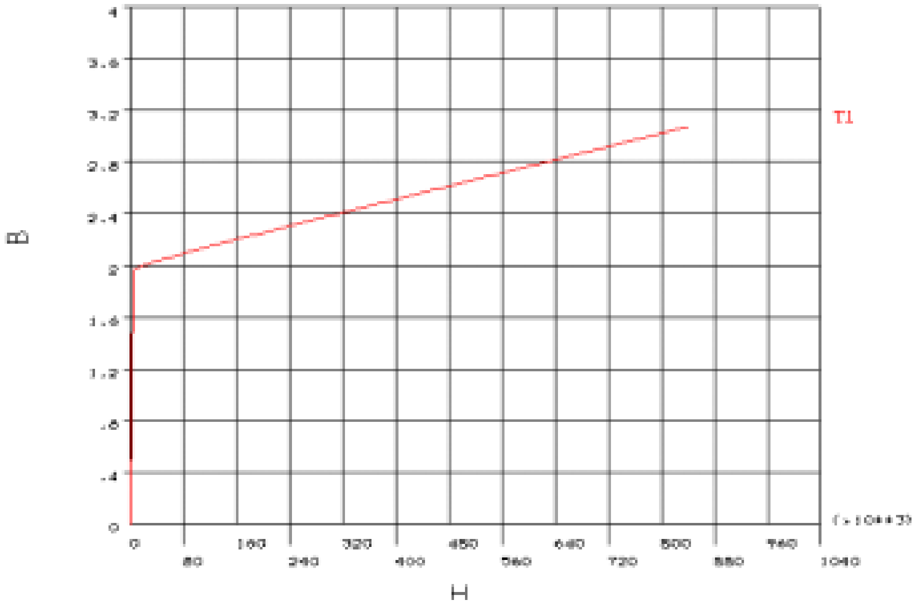
1) The curves are smooth through the knee of the curve

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

Deletes existing BH and linear data

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.

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

[/AXLAB] X-axis label

[/AXLAB] Y-axis label

[/GTHK] Thickness of axes: Single

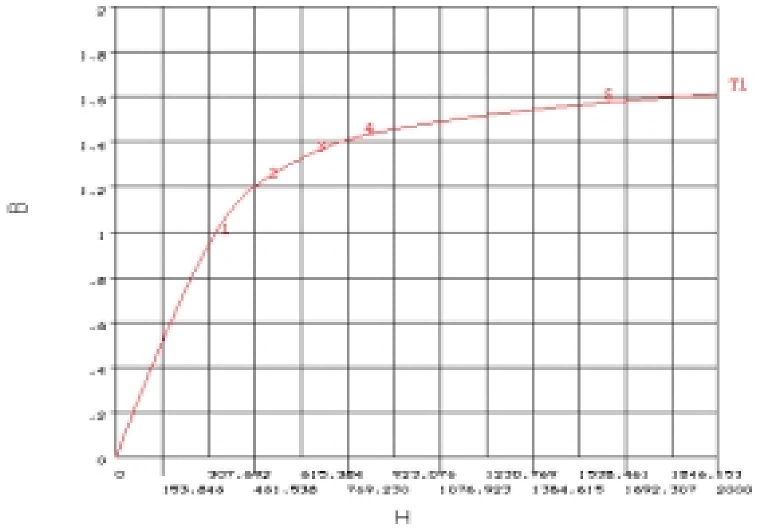
[/GRTYP] Number of Y-axes: Single Y-axis

[/XRANGE] X-axis range

○ Auto calculated

● Specified range

XMIN,XMAX Specified X range: 0 2000



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”

Model checking

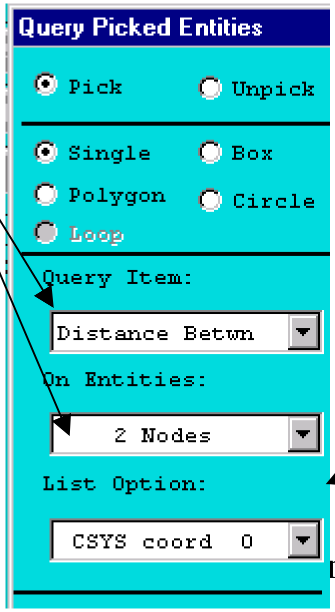
At this point the model could be solved to determine the cogging torque. Before any solutions are computed , it is recommend to check the model targeted to be simulated.

Checking the dimensions.

This can be accomplished by using the distance function. As an example check the thickness of the stator tooth (C2).

To compute a distance between two nodes
Utility>list>picked entities+

and select



Query Picked Entities

● Pick ○ Unpick

● Single ○ Box

○ Polygon ○ Circle

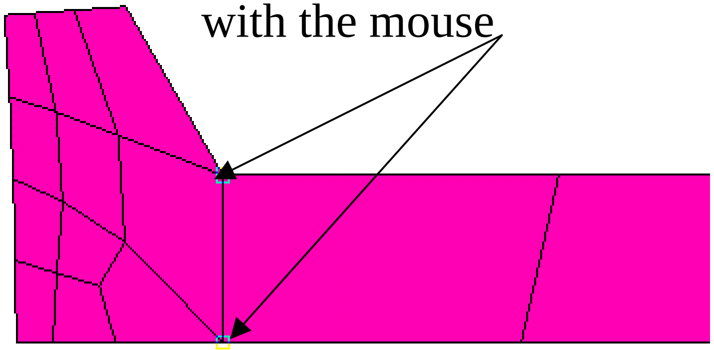
○ Loop

Query Item: Distance Betwn

On Entities: 2 Nodes

List Option: CSYS coord 0

Then select two nodes with the mouse



Once the two nods are selected, then select OK in this box. The distance in SI units will be displayed.

Specification of the winding

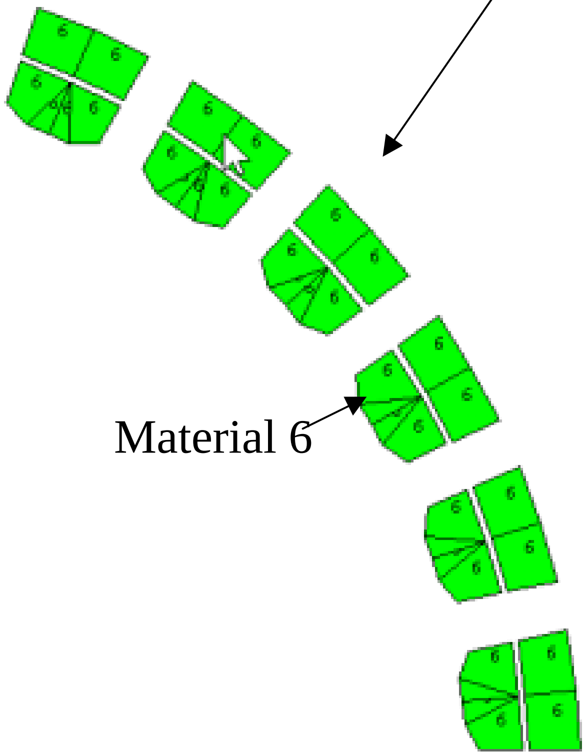
- For the DC application, currents (Amp-turns) must be applied to the stator.
- Even for a single analysis the process of applying the currents can be a tedious process leading to potential errors. This process can be multiplied by:
    - full machine model requiring >60 slots
    - polyphase machines
    - 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.

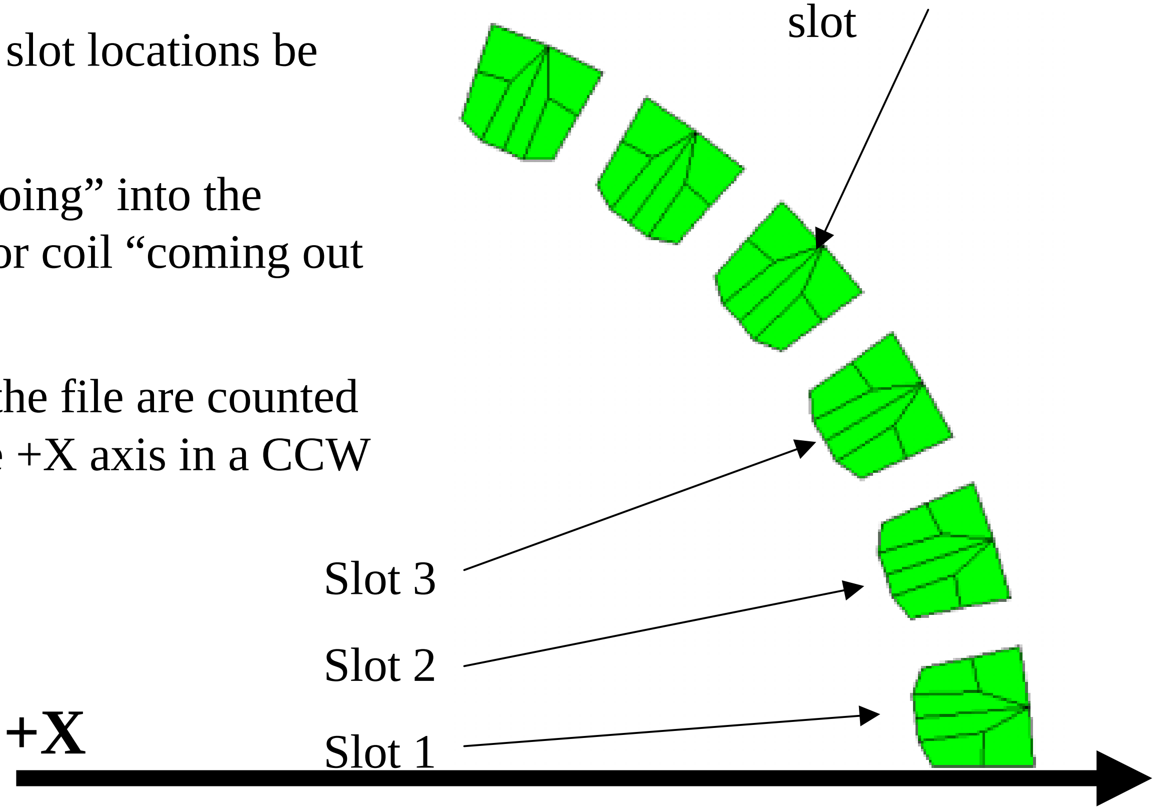


To get the coil below, enter NCONS=2 at the command line and use <STATOR>

Material 6

Winding file specification

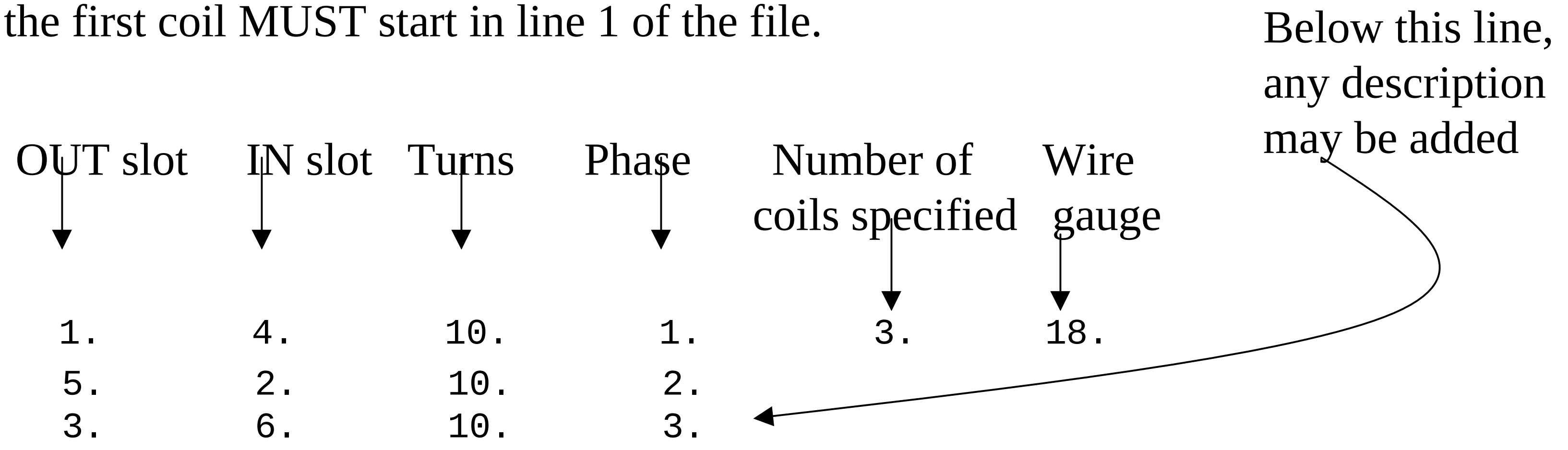
- The file requires that 2 slot locations be specified for a coil.
- One slot for the coil "going" into the laminate, and one slot for coil "coming out of the laminate"
- The slots specified in the file are counted from the slot nearest the +X axis in a CCW direction.



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.

  1234567890123456789012345678901234567890123456789012345678901234567890
       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.

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, cosine, flat
- To access these forms, the following parameter is used.

CURRFORM=‘sine’ (for the sine)
CURRFORM=‘cos’ (for the COsine)
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

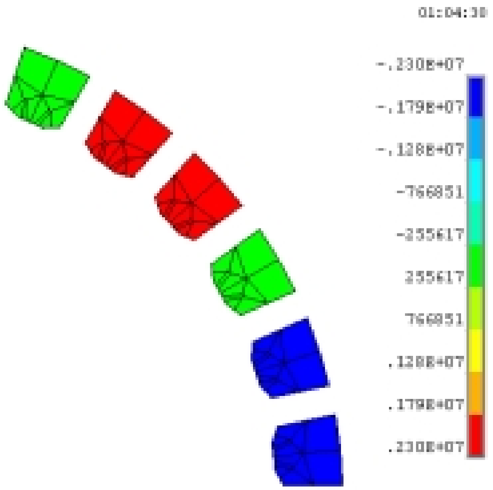
The default forms can be displayed by <PLT_FORM> once the parameter CURRFORM has been specified

Rotate / Applying a current and Solving

1) Move the rotor by 12 degrees using <ROTATE> and entering 12.

2) 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 to permit a balanced machine). Specifying currform=‘sine’ and with <LOAD> using -60° and 10 A (peak) for the first and second prompts.

```
_____CURRENTS APPLIED TO THE COIL______
Name of winding file:______ mach2acb.
Current form:_____________ sine.
Electrical angle:__________ -60.
Peak Current (A):__________ 10.
____Phase__ Phase_Factor__
       1.       -0.8660
       2.        0.0000
       3.        0.8660
__________________________
```

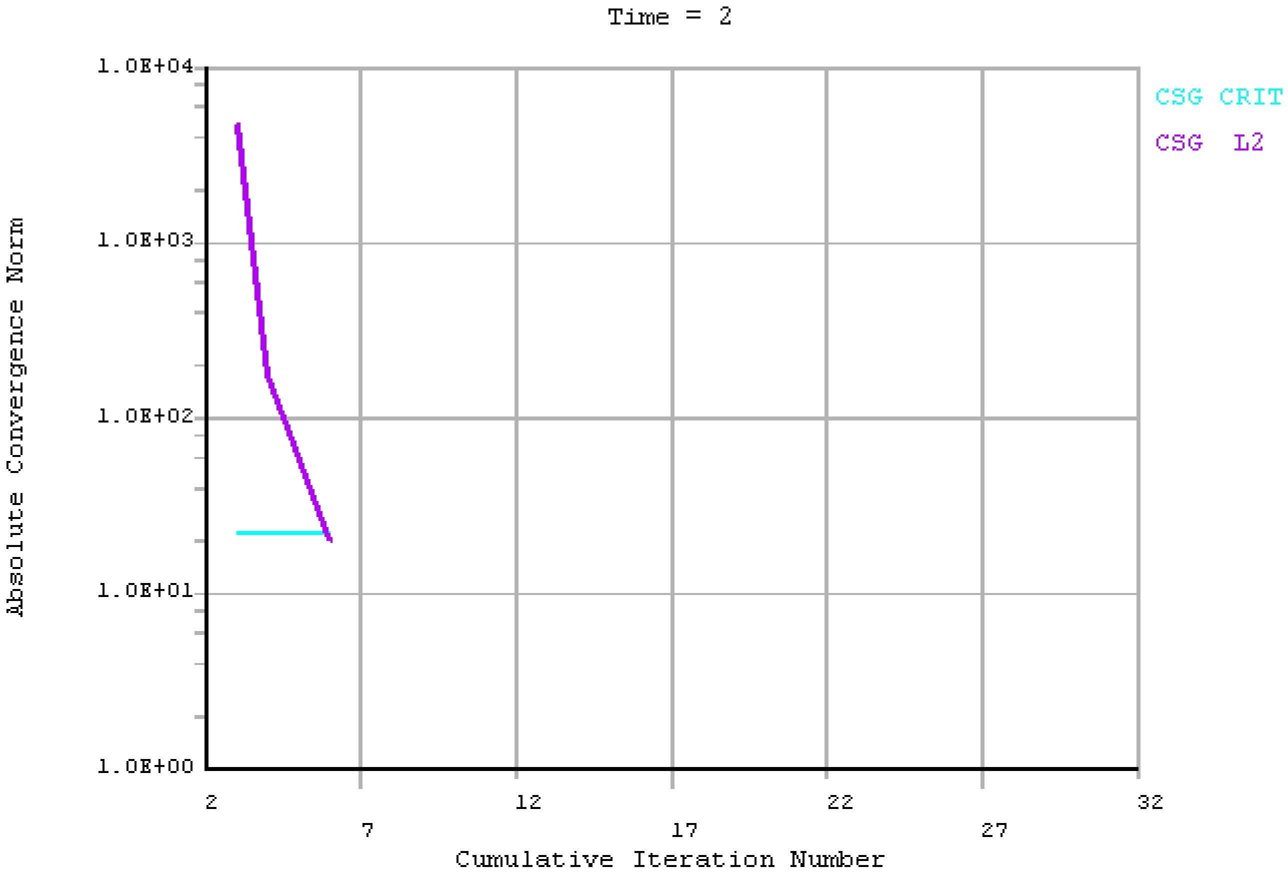


3) To solve, use <SOLUTION>

Element plot with the current density displayed

Nonlinear solution

Since the parameter file has BH data specified for the rotor/stator iron, a nonlinear solution was performed

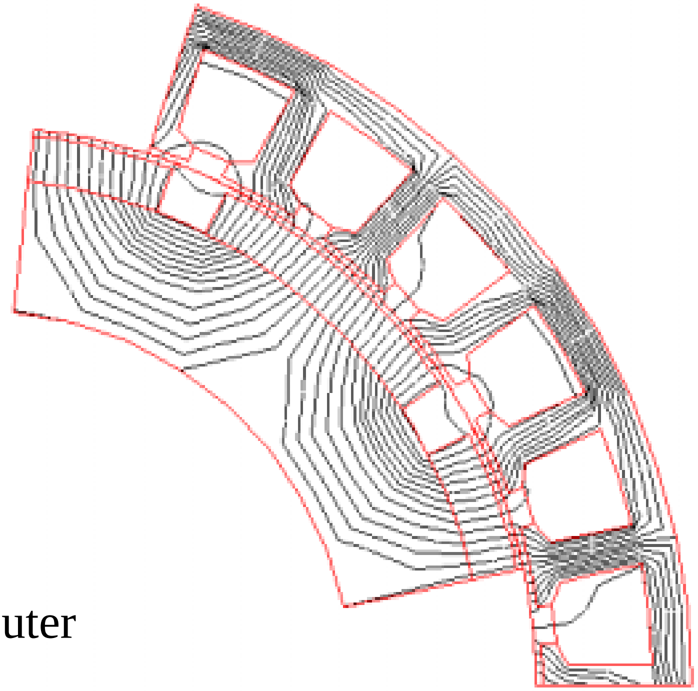


Flux line plots

Enter the postprocessor and use

<FLUXLINE>

This can be used with ZOOM

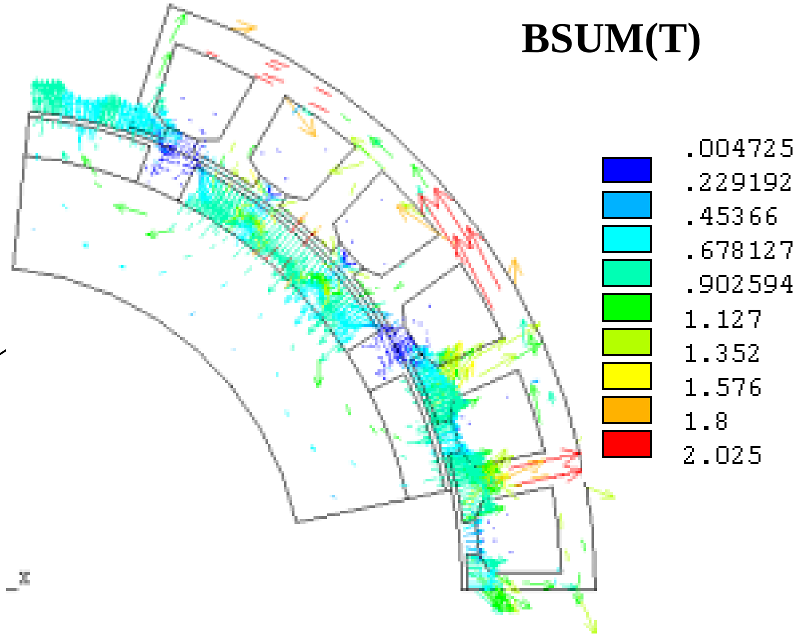


- The flux line plot yields an overall view of the field
  - confirm flux parallel condition at the inner and outer radii
  - confirm continuity at the lateral edges
  - confirm continuity across the CE’s
  - identify potential mesh refinement
  - confirm magnetization direction
  - inspect overall leakage
  - 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

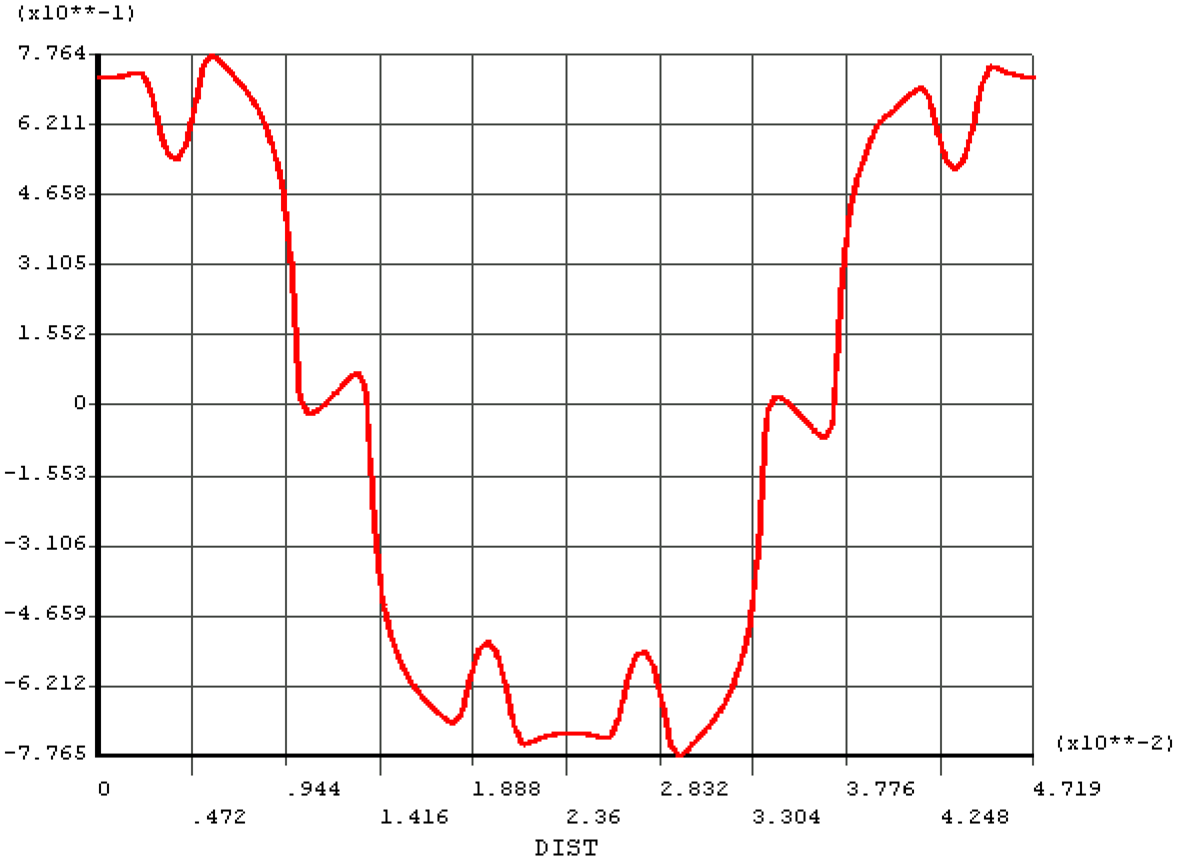
The torque is calculated by <MACHTORQ> and three methods are used to compute the torque. The torque is based on the stack thickness and the full 360° model. Good agreement indicates the adequacy of the finite element mesh The stack length is a parameter-it’s units are those of the other parameters.

```
________________TORQUE CALCULATION_____________________
Stack length:_______ 2.25.
Torque-virtual work (n-m):__________________________ 2.84386384.
Torque-Maxwell Stress (n-m):________________________ 2.78936506.
Torque-Maxwell Stress Line integration (n-m):_______ 2.84165941.
```

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

B Radial 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)



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>

For complex windings this is important to check to ensure that the winding is balanced.

```
_______SUMMARY OF FLUX LINKAGE FOR THE COILS____________
 Winding file:__________________ mach2acb.
 Stack length:__________________ 2.25.
 Periodic factor:_______________ 5.
 ___COIL___Turns_____Flux linkage_______Phase____
 ______________________Weber-t___________________
      1.     10.      -0.003403           1.
      2.     10.      -0.002635           3.
      3.     10.       0.006437           2.
 ____Phase_______Total Flux Linkage_______
        1.            -0.00340
        2.             0.00644
        3.            -0.00264
 The flux linkages reported are for the periodic section modeled.  The
  total flux linkages for each phase would be factored by the periodic
  factor.
```

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: **This is important to evaluate before proceeding to a 3D analysis**. Due to the nature of 3D this quantity is requires significantly more effort to calculate than for the 2D application.

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 (RPM)
6) The confirmation to continue

Multiple solutions using a constant current-continued

Before performing these analyses, make the entire model active and delete all the current densities using >loads>delete>excitation>on elements> pick all

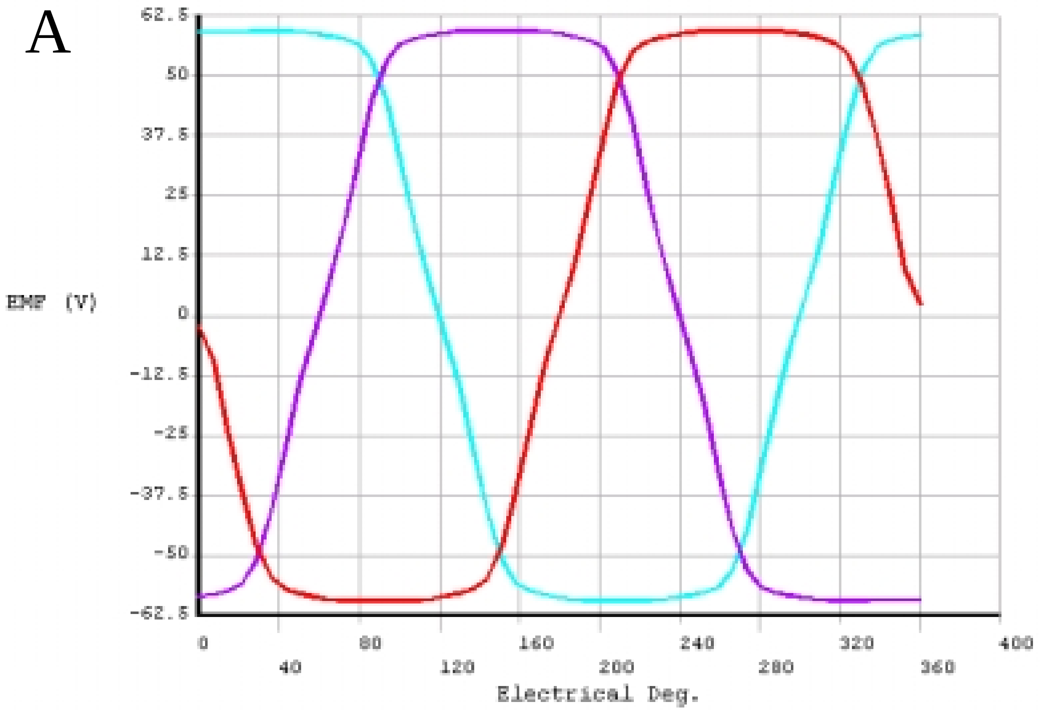
<ROT_CONS> for solutions from 0 to 36° at 4° increments (mechanical).

Prompt 1: 0 (this is a periodic model, the lower rotor edge will be moved to +X axis)
Prompt 2: 36 (ending ***mechanical angle***, 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.

Summary for the multiple solutions with constant current

A printed summary is contained in “mname”.sum. The plot below contains all phases. This plot was generated by <EMF_ANG>



For cogging torque, the angle increments must be smaller to define a reasonable smooth curve. It is important to confirm the balanced phases as well as the expected peak value

Location of Rotor

With the ability to arbitrarily move the rotor, it is necessary to be able to identify the current location of the rotor. This is accomplished using <ROT_ANG> which displays the current position of the rotor (measured +CCW from +X axis).

For a periodic model, the input to <ROTATE> is a the actual position of the rotor.

For a full 360 degree model, the input to <ROTATE> is the angle increment (+CCW) that the rotor is to be rotated.

```
__________Current Location of Rotor____________
Current Rotor marker node:________________ 414.
Current Rotor Location (CCW, +X axis):____ 0.
For a full model and to return rotor to the starting position, use
 ROTATE and enter the value shown above with the opposite sign.  For a
 periodic model, enter 0.
```

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.

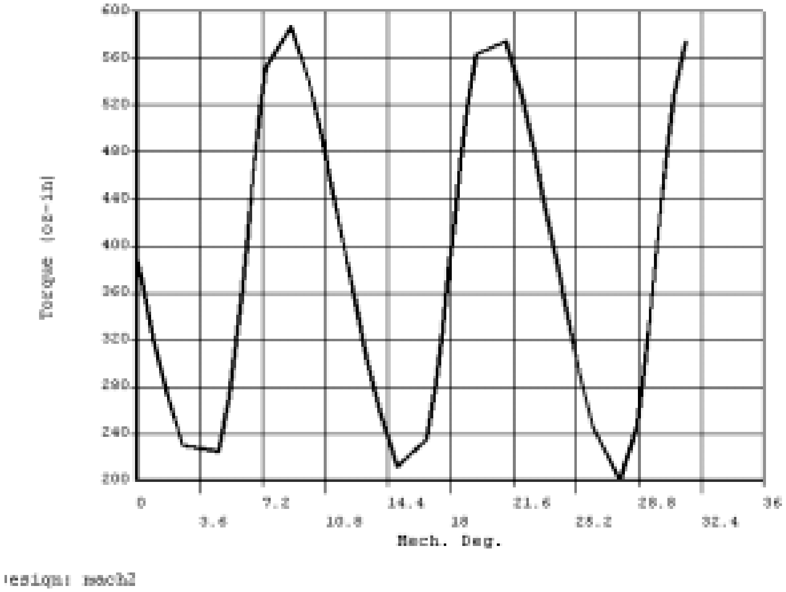
The input for <ROT_CURR> is

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 -120   (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.

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):_________________________ 36.
Increment Mech.  Angle (D):______________________ 4.
Starting Electrical Angle (D):__________________ -120.
Location of Zero Elec.  Ang.(+CCW,+X axis):______ 0.
Peak current (A):_______________________________ 10.
Rotation of the Rotor:__________________________ CCW.
MIN torque (oz-in):_____________________________ 204.62312.
MAX torque (oz-in):_____________________________ 588.329862.
Peak - Peak torque (oz-in):____________________ 383.706742.
Average torque (oz-in):_________________________ 394.
Number of solutions:____________________________ 10.
Maximum B magnitude:____________________________ 3.2440452.
Method to compute torque:_____ Virtual Work.
Time for all solutions (CPU):___________________ 79.1638184.
__________SUMMARY OF ANGLES/Torque_________________
___________I___________Mechanical_____Torque________
________________________ANGLE (D)_____(Oz-in)_______
            1.             0.00        390.6
            2.             4.00        204.8
            3.             8.00        587.8
            4.            12.00        389.8
            5.            16.00        204.6
            6.            20.00        588.3
            7.            24.00        391.5
            8.            28.00        205.0
            9.            32.00        588.0
           10.            36.00        390.6
```



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.
```

Summary

This has been a review of the 2D application.

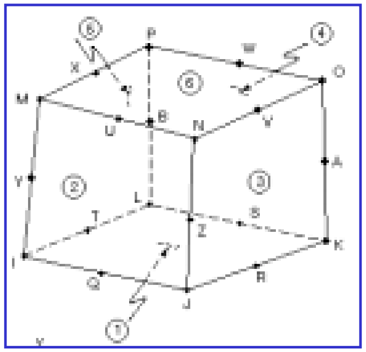
There are a number of advantages for performing a 2D analysis

- checking material properties for convergence
- checking the feasibility of a design
    - torque/cogg/EMF
- checking the level of saturation
- checking the balanced EMF

Overview of 3D magnetic analysis capability in ANSYS
Part II

Multiple element formulations are used to support the 3D simulations

- The element formulation affects virtually every aspect of the simulation
  - The implementation of the flux normal and flux parallel condition
    - the interpretation of the natural boundary condition
    - the interpretation of the use of the DOF constraint
  - The material sensitivity in convergence for problems with BH data
    - ν - B2 curve vs μ - H curve
  - The method to simulate the excitation (stranded coils)
  - The ability to include the iron region in the model
  - The use of iron-air interfaces in the model
  - Postprocessing
    - Flux calculation (the prelude to an EMF calculation)
    - “flux line” presentation

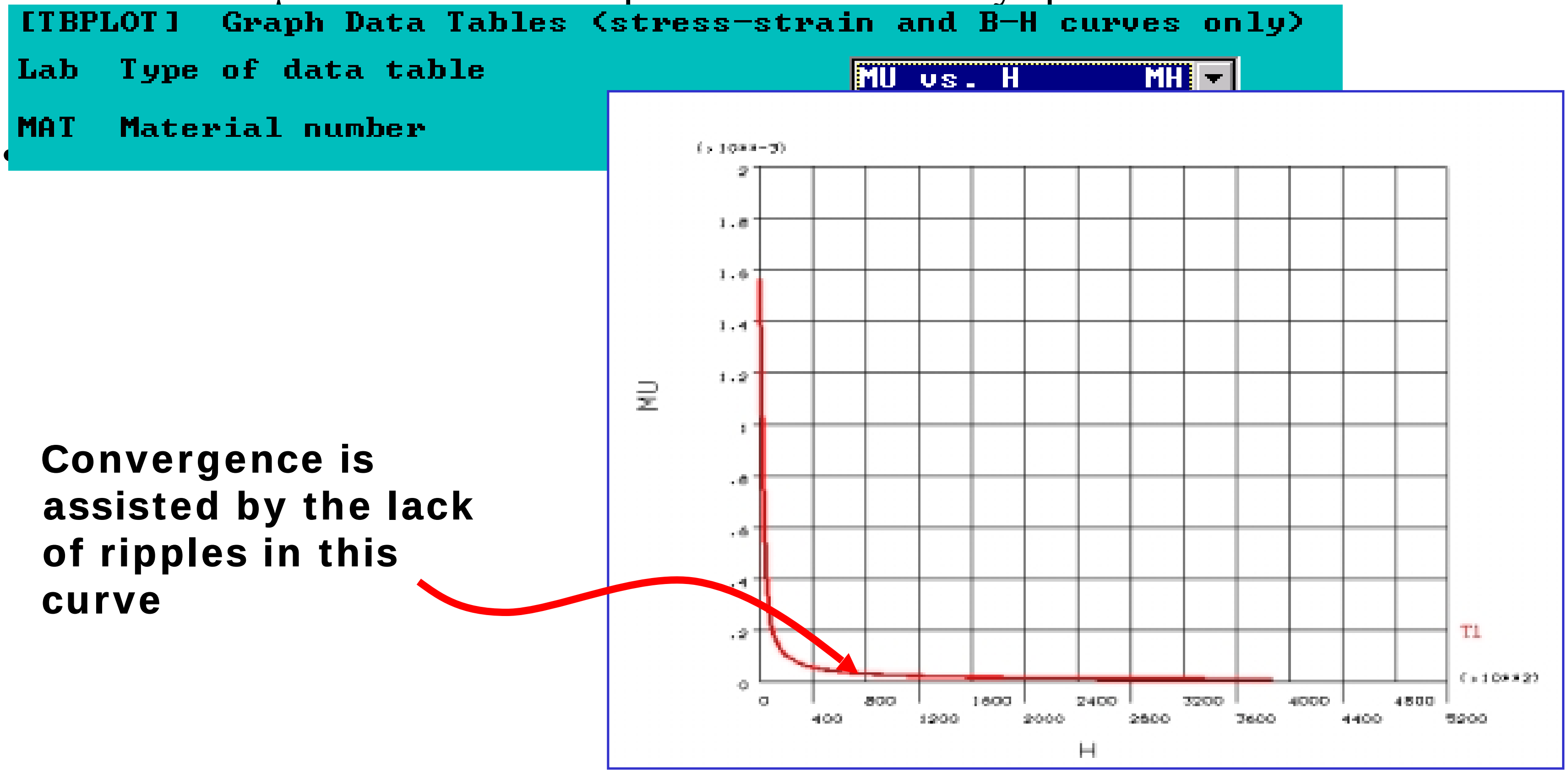


- Three element formulations are contained in the 3D simulation capabilities
  - Scalar potential formulation (static 1) [SOLID96]
    - reduced scalar potential (RSP) iron-air interfaces without coils
    - difference scalar potential (DSP) iron-air interfaces with single flux paths
    - general scalar potential (GSP) iron-air interfaces with multiple flux paths
  - Edge element formulation (static, AC, transient) [SOLID117]
    - can include arbitrary iron regions
    - periodic models must be full models-without coupling
  - Magnetic vector potential (MVP) formulation (static, AC, transient) [SOLID97]
    - without iron regions
  - The scalar can be used in AC & transient simulations, provided it is used with the MVP and the interface element INTER115

- Capabilities to perform 3D simulations include static, AC and transient, just as for the 2D simulations
- Default linear material properties are isotropic (specify MURX only)
- Material options for 3D also include orthotropic options for all three directions for MURn and RSVn (n=X,Y,Z)
  - A single BH curve can be used in any of the orthotropic directions and constant permeability can be used in the remaining direction
  - To use the BH curve in an orthotropic direction set the MURn to Zero (only required when specifying orthotropic properties)
- 3D Element library includes infinite boundary elements
- Complex combinations of physics regions are supported, just as for 2D simulations
  - Stranded vs massive conductors for AC
  - Voltage fed vs current fed
  - Complex iron regions

- Scalar potential formulation
  - Degree of freedom: MAG
  - Flux normal boundary condition:
    - The MAG dof must be constrained or coupled
  - Flux parallel boundary condition:
    - This is the natural boundary condition-no action is required. This condition applies to model edges in which constraints or coupling are not used. The menu contains a selection for the scalar & flux parallel condition-but it only references a note
  - Use of BH curves in the simulation
    - the μ-H curve must be examined for “smoothness”

The µ-H curve can be plotted from Utility>plot>data tables



[TBPLOT] Graph Data Tables (stress-strain and B-H curves only)

Lab Type of data table: MU vs. H MH

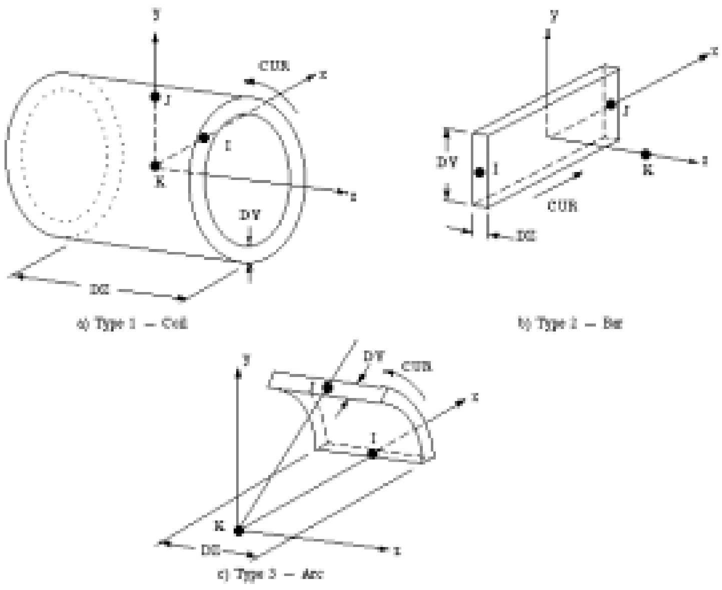
MAT Material number

Convergence is assisted by the lack of ripples in this curve

- The excitation for the scalar is based on Biot-Savart calculations using predefined coil shapes-sourc36. Therefore the finite element region for the coils or bars do not have to be modeled explicitly (as was the case for the 2D MVP)

Definition of the coil primitives from the help engine for the sourc36

Figure 4.36-1 SOURC36 Current Source Element



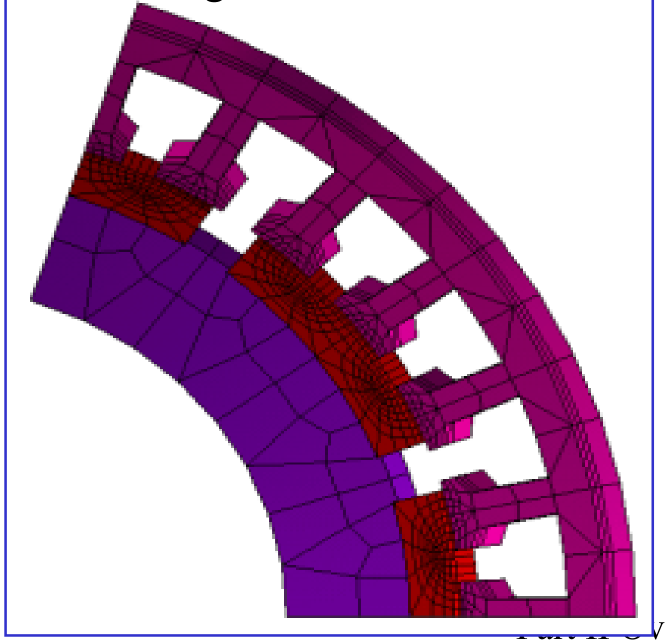
- The scalar formulation includes three types of scalar potentials, each particularly designed for models with certain physic regions.
- Reduced Scalar potential (RSP)-Can be used in models with:
  - iron regions and permanent magnets
  - Coils should not be used in conjunction with iron regions
  - Coils can be used in models without iron regions

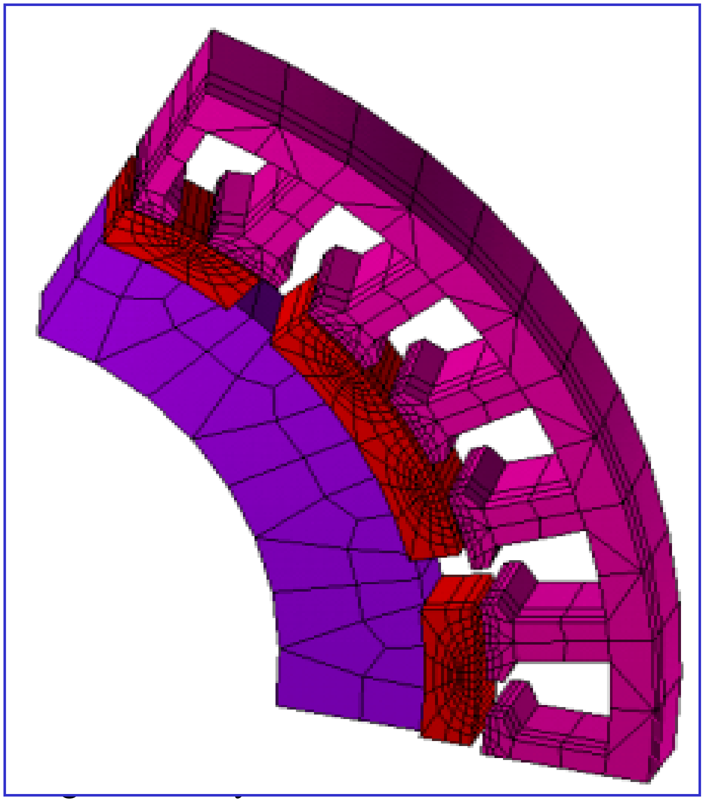
- Advantage of the RSP:
  - the simulation involves a single step solution
  - minimal computation with respect to the other scalar formulations

- Disadvantage of the RSP:
  - "numerical cancellation" prevents the RSP from being used in models with iron-air interfaces energized by sourc36's

- The RSP is suited to simulate a system which contains an iron air interface and permanent magnets-the analysis objective is to determine the cogg torque versus rotor angle

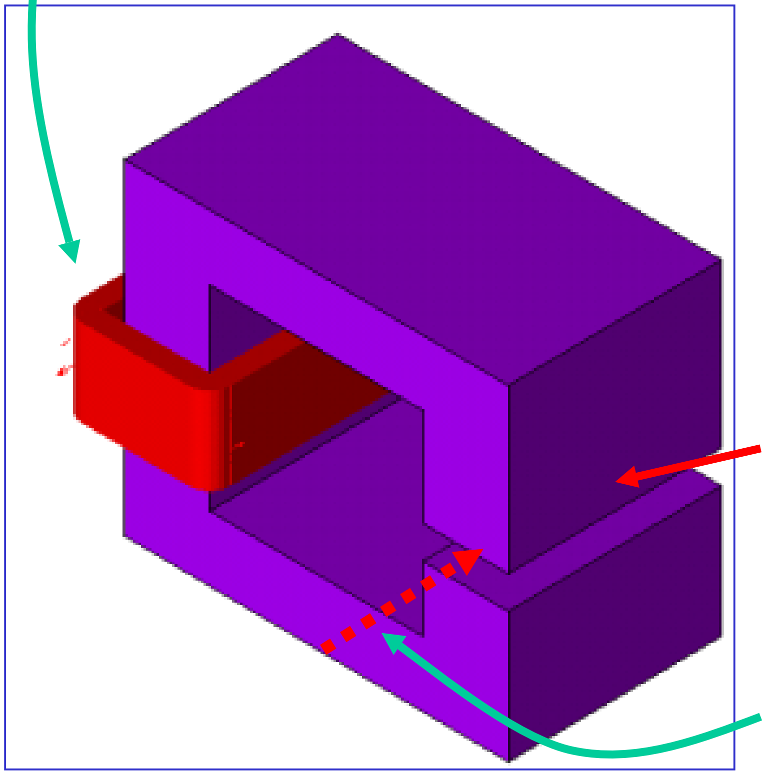
Two poles of a 10 pole machine for a stack with a 15 degree cone angle





- Difference Scalar potential (DSP)-Can be used in models with:
    - Coils can be used in conjunction with iron regions
    - Permanent magnets
    - Coils can be used in models without iron regions
    - Restriction: the model geometry must satisfy the condition of single connectivity.
        - This is tested by determining if the field in the iron approaches zero as the iron permeability approaches infinity. (actuators, machines with air gaps-see example on next slide)
    - Disadvantage:
        - The solution is a two step process

Example of a system in which the field becomes zero as the iron permeability becomes large



Coil to generate field to control particle motion

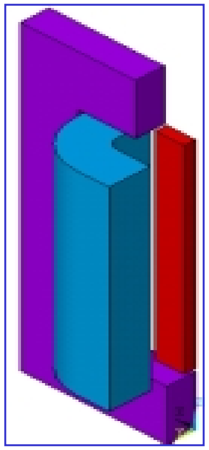
C-Shaped Magnet for linear accelerator

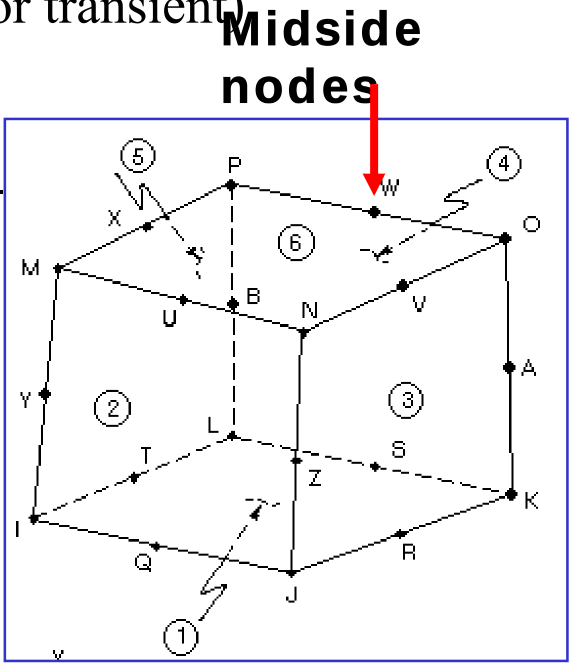
Air gap

Particle motion

- General Scalar potential (GSP)-Can be used in models with:
  - Sourc36 can be used in conjunction with iron regions
  - excitation by magnets
  - boundary conditions can include flux (Webers) specification
  - Sourc36 can be used in models without iron regions
  - Restriction: the model geometry must satisfy the condition of multiple connectivity.
    - This is tested by determining if the field in the iron does not approach zero as the iron permeability approaches infinity. (transformers, magnetizers, models with multiple flux paths- see example on next slide)
  - Disadvantage:
    - The solution is a three step process

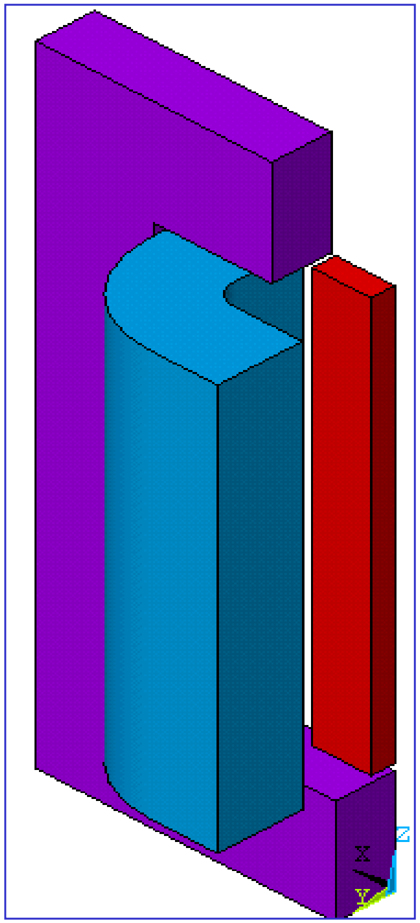
- The edge formulation represents an advance in the state of the art for simulation of complex iron regions in 3D models
  - Degree of freedom: AZ (VOLT for AC or transient)
  - Flux normal boundary condition:
    - This is the natural boundary condition-no action is required. This condition applies to model edges in which constraints or coupling are not used.



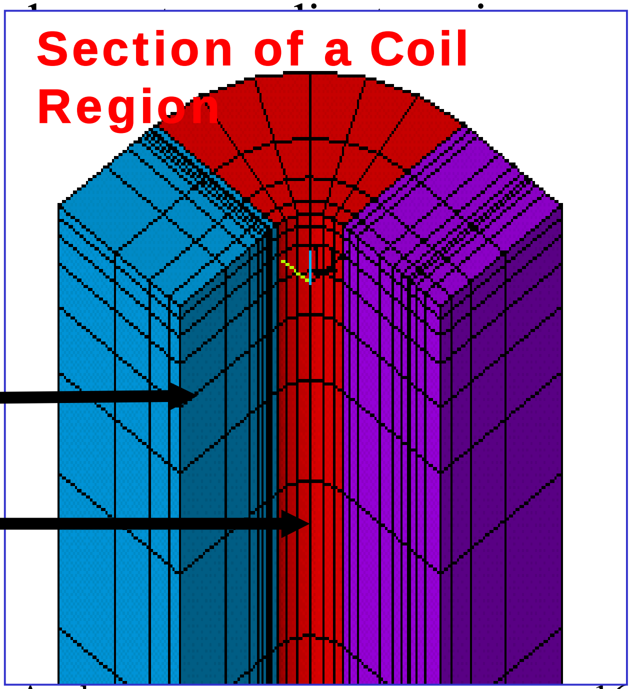


- Flux parallel boundary condition
  - The AZ dof must be constrained

- Use of BH curves in the simulation
  - The ν - B^2 curve must be examined for “smoothness”



- The excitation for the model using a coil region is similar to the 2D simulation: The coil region must be modeled with finite elements.
- The current density now has three components, JSX,JSY,JSZ
- These components are with respect to the
  - Arbitrary Cartesian coordinate system
  - Arbitrary cylindrical coordinate systems
  - Global coordinate systems (also)

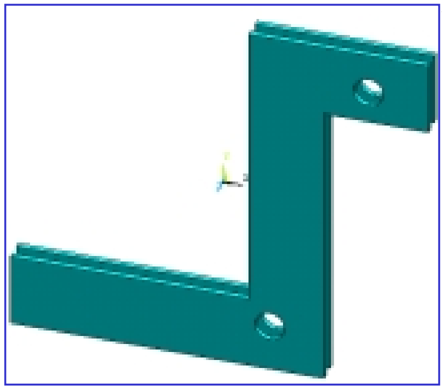


Section of a Coil Region

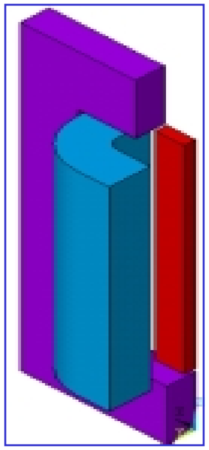
Global components are used for the straight sections

JSY is required for the corner (circumferential direction for a local cylindrical system)

- The 3D MVP formulation
  - Degree of freedoms: AX,AY, AZ (VOLT for AC or transient)
  - Flux normal boundary condition:
    - This is the natural boundary condition, but the component of A which is normal to the model boundary must be set to zero
      - X-Y plane, AZ must be constrained to zero
      - X-Z plane, AY must be constrained to zero
      - Y-Z plane, AX must be constrained to zero



- Flux parallel boundary condition
  - The components of A dof which are in the plane of the model boundary must be set to zero
    - X-Y plane, AX,AY must be constrained to zero
    - X-Z plane, AX,AZ must be constrained to zero
    - Y-Z plane, AY,AZ must be constrained to zero



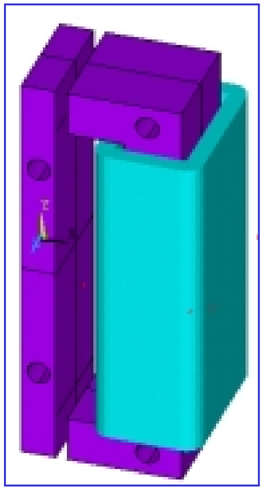
- Use of BH curves in the simulation
  - the ν - B^2 curve must be examined for “smoothness
- The excitation for the model using a coil region is similar to the edge formulation: The coil region must be modeled with finite elements.
- The current density now has three components, JSX,JSY,JSZ

- To assist in showing the 3D simulation capabilities, the following examples are shown below

3D keepered magnet

Static simulation

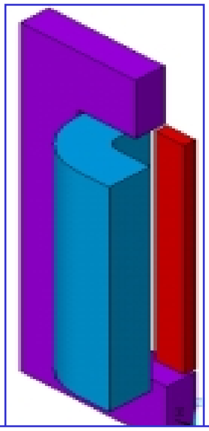
DSP formulation



3D actuator

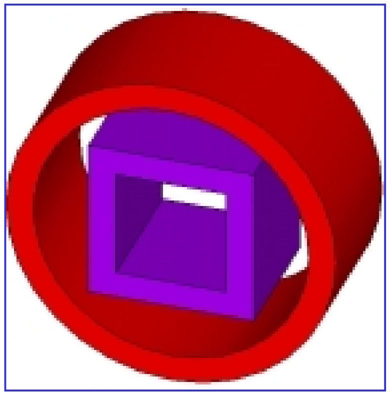
Static simulation

Edge formulation



3D bar inside a massive conductor AC simulation

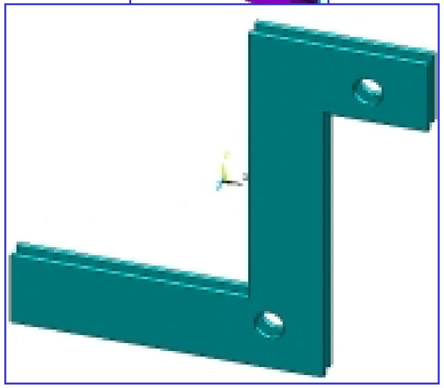
Edge formulation



3D bus bars

Static simulation

MVP formulation



PART III. Contents for the 3 D DC Machine Application

Overview of 3 D Simulations of Machines

- 3D simulations are performed for a variety of reason
  - uneven stack lengths for magnets & laminates
  - unsymmetric axial stacks
  - skewed stator stacks
  - Conical shaped stacks
  - end winding included in inductance/torque calculations

- 3D simulations usually demand larger models
  - Same level of meshing in the plane which is factored by the number of axial divisions
  - skewed stacks may require more axial divisions
  - Additional calculations are required due to finite element methodology
  - Some calculations are more efficiently performed for a 2D model

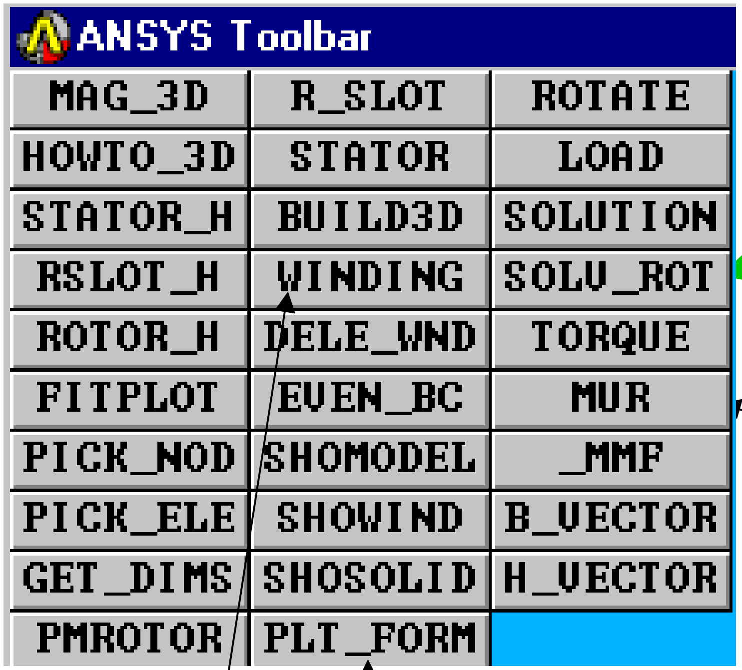
Overview of 3 D Simulations of Machines-cont'd

- If a preliminary design is being evaluated it is best to use a 2D simulation first.
  - misunderstanding of the winding diagrams
  - laminates not sized correctly-severe saturation

- In general a 2D simulation should proceed a 3D simulation
  - More iterations for the same amount of time

- For this reason the initial part of the 3D seminar was to review the 2D simulation of PM machines.

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

Single & Multiple solutions

Postprocessing

Model generation: <stator>,<r_slot>, <pmrotor><build3d>

Winding

Plot functions

Boundary conditions:

<even_bc>,<rotate>

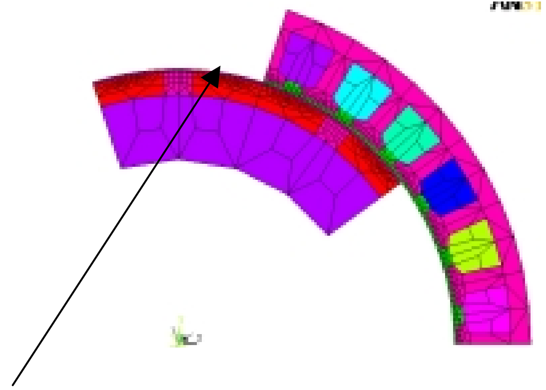
<load>

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_3D> under geometry generation
- Input the parameters into an ASCII file-or use the GUI to define the parameters
- Define the ASCII winding file (not required for no-load conditions)
- Construct the finite element model
  - If this is the first time the model is being constructed
  - Build the stator as a 2D model <STATOR>,<R_SLOT>
  - Build the rotor as a 2D model <PM_ROTOR>
    - It is easier to check a 2D model
    - It is more efficient to adjust a 2D model

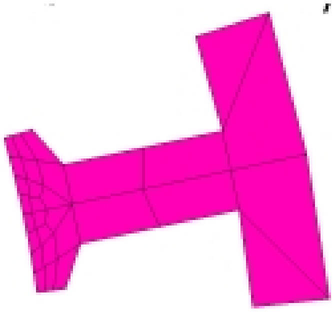
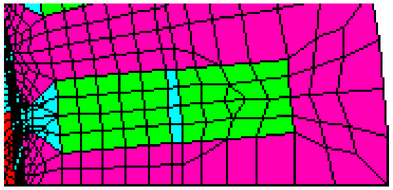
OR

Overall process - continued



- If the template has been checked and minor adjustments are being made
    - Build the 3D laminate model directly <BUILD3D>
        - clears the database, loads the new parameters
        - builds the 2d laminates
        - generates 3D model
        - applies periodicity if required
        - generates winding
        - applies constraint
- Connect the rotor to the stator with constraint equations <ROTATE>
- Apply the current <LOAD>
- Solve (linear or with BH data) <SOLUTION>
- Post process

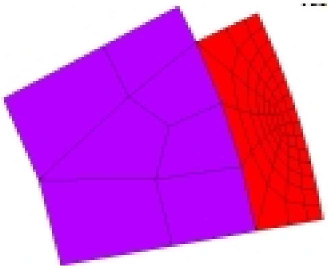
Laminate options for the stator

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

---

(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.

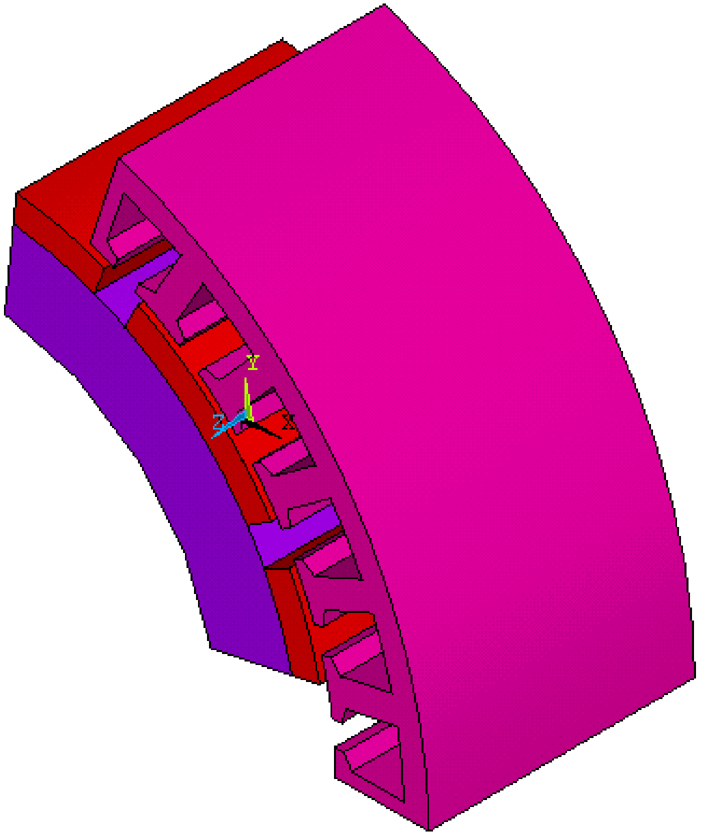
Laminate option for the rotor

Laminate		**Help**	**Plot file**
Permanent magnet-surface mount		<PMROTOR_H>	pm_rotor.doc
Import the rotor design		This is presented in the 2D notes	

Example of a periodic model for a 10 pole BDC machine

- Permanent magnets are parallel magnetized

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



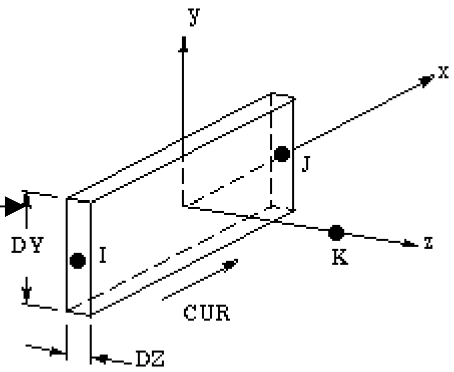
Basic modeling differences with the 2D methodology

In the 2D model, the current was applied by current densities and this became the load vector for the 2D MVP. For the 3D application, the current is applied using primitives from which the field due to the coil is computed using the Biot-Savart method.

The element used to construct the coil is the SOURC36. This element represent current flow, and it actually corresponds to the AMP-TURNS in the coil, not just AMPs

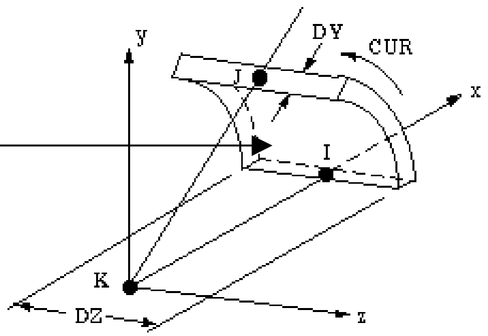
The section of the coil going into and out of the stack is represented by the bar.

This requires further parameter input



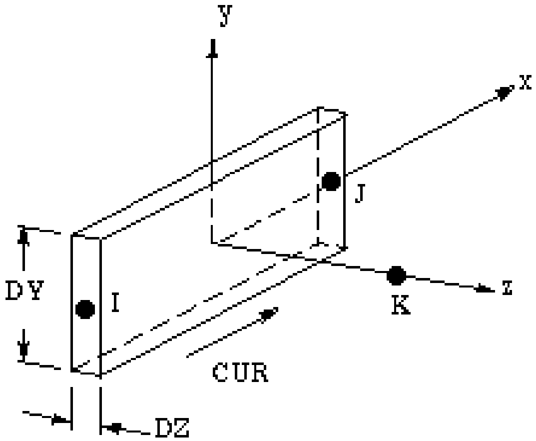
The section of the coil on the end face of the stack is represented by the arc.

These dimensions are computed from the winding file and the input for the straight section



c) Type 3 — Arc

Basic modeling differences with the 2D methodology-continued



These dimensions are input through the real constant set for the element. The current changes (AMP-TURNS) are performed by changing the real constant set.

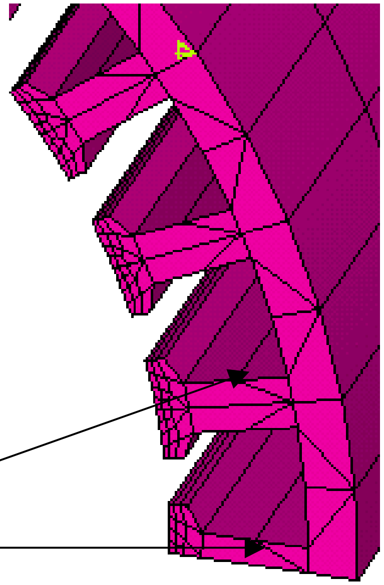
The <BUILD3D> or <WINDING> builds this data from the winding file and the additional size parameters (to be shown later)

The <LOAD> performs this function

The generation of these elements is performed with the direct element generation. These nodes usually have no connection with the elements for the laminate.

Since these are not finite element elements they can occupy the same location as the elements for the mesh

In fact the slots in the stator must still be meshed, else the edge of the laminate will be a flux parallel boundary condition

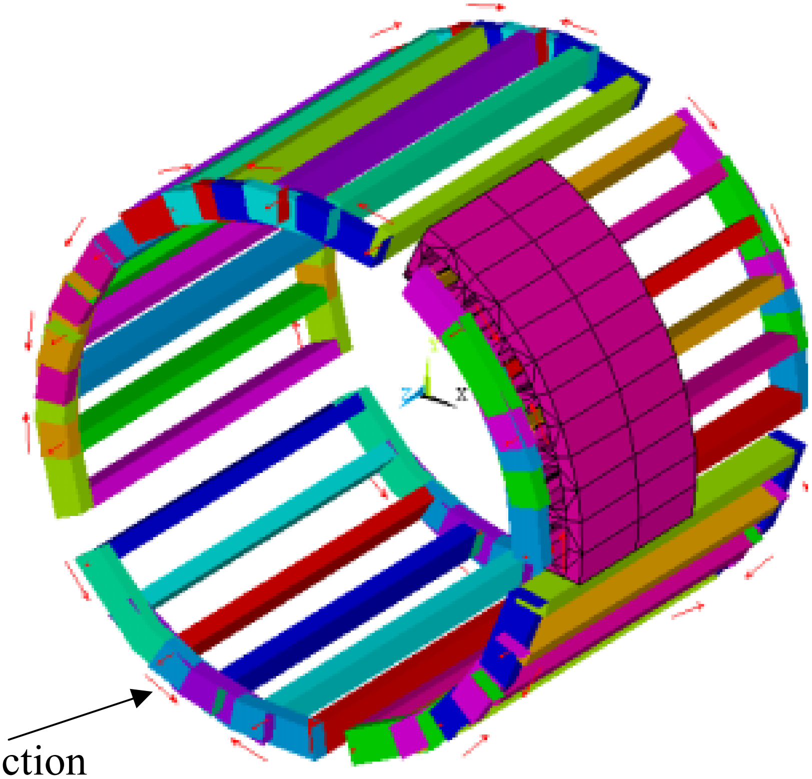


Basic modeling differences with the 2D methodology-continued

The definition for the winding file is the same for both the 2D and the 3D.

Note that in the 2D model, the winding file was only needed for the number of slots modeled in the stack

For 3D, even if the entire laminate is not being modeled, a significant portion of the winding must be modeled outside the modeled stack. This is due to the fact that the field due to a coil extends well outside the bore of the coil.



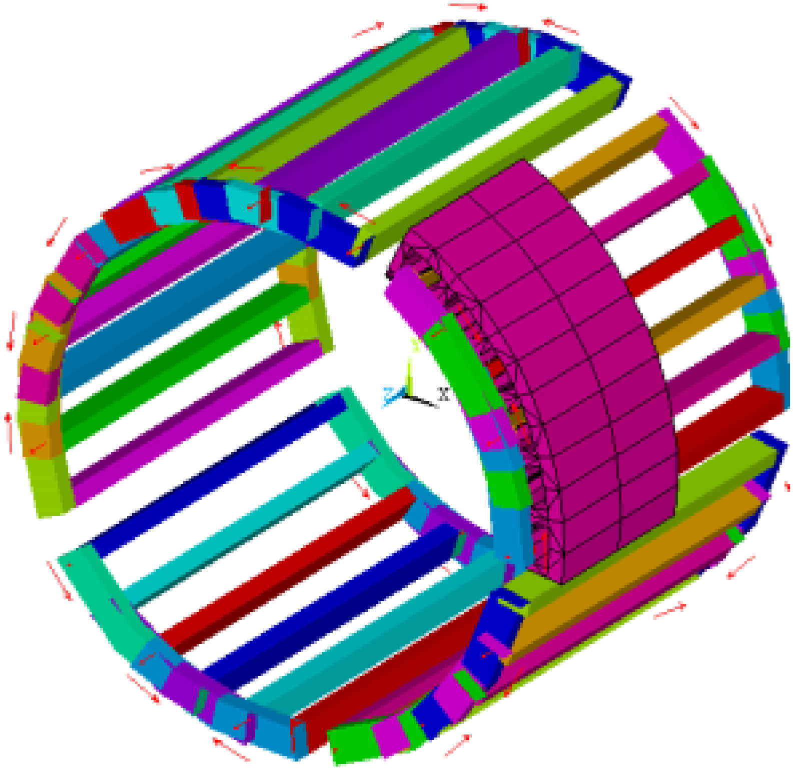
The arrows represent the direction of current at the time the winding is generated

(1/2)*(1/5) or
1/10th symmetry

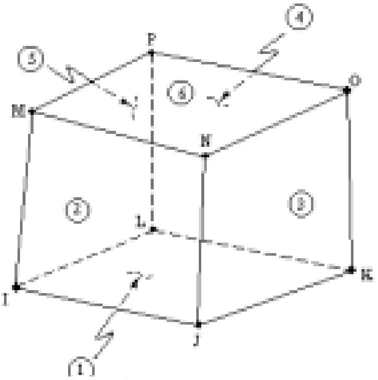
Basic modeling differences with the 2D methodology-continued

As will be shown later, it is not really necessary to model the entire winding for certain positions of the rotor.

These SOURC36 elements overlap the same region as the air elements in the slots. One of the advantages of this approach is that the coils can overlap each other, which is not the case with the 2D model, in which separate elements had to exist for separate coils in the same slot



Basic modeling differences with the 2D methodology-continued

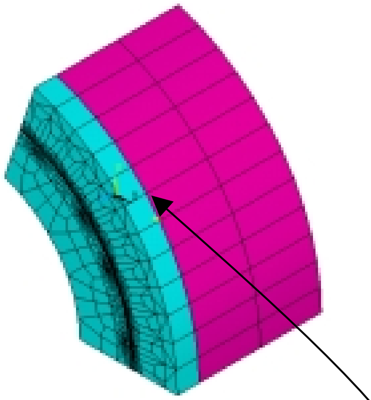


The solid portions of the finite element mesh is comprised of the 8 noded brick SOLID96

This uses the scalar formulation which represents H as Grad(Φ). This is a scalar potential.

Iron-air interface has special requirements during the solution

The degree of freedom in ANSYS is MAG



This affects the boundary condition

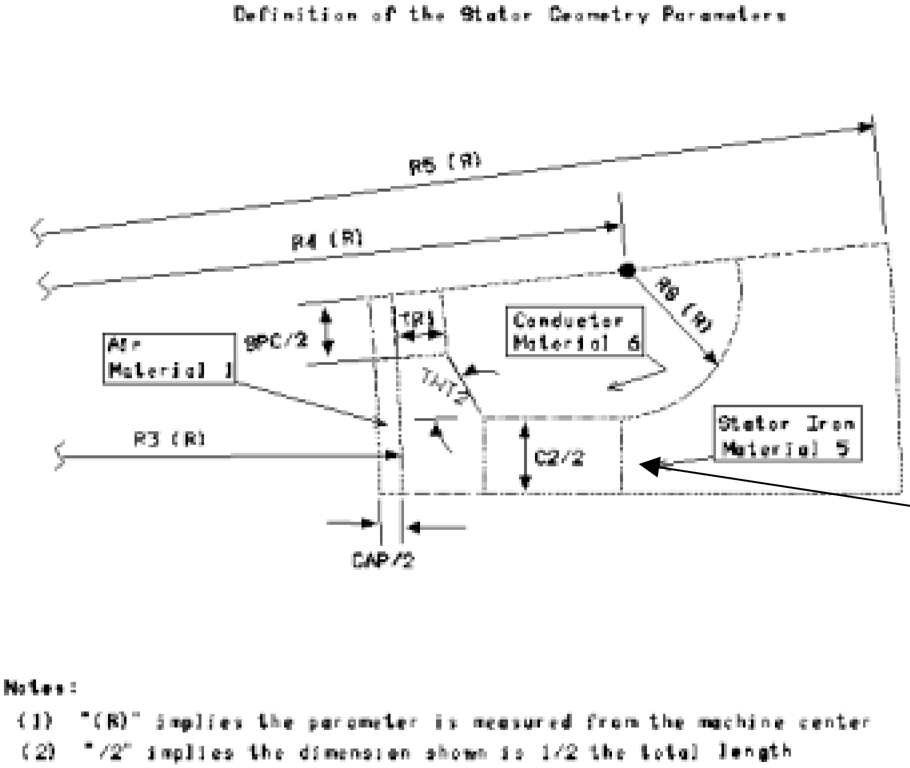
constrained on a surface: flux normal

free: flux parallel

In the case of the 2D model, the outer ring of nodes were constrained and the inner ring of nodes were coupled for the flux parallel condition. This also served as a means to "gauge" the problem. For the scalar, the flux parallel condition occurs naturally without any constraint. A single node in the model is constrained to "gauge" the problem.

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.



Definition of the Stator Geometry Parameters

Notes:

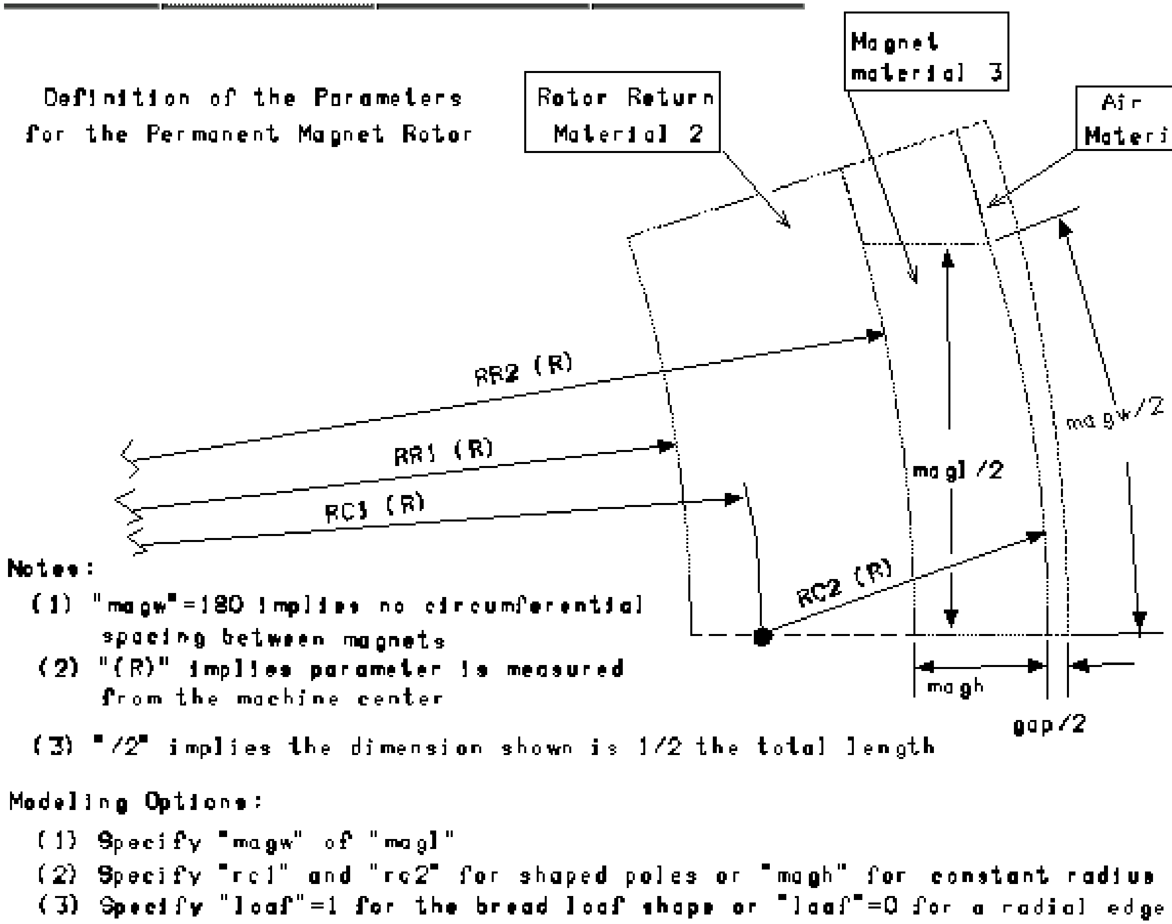
(1) "(R)" implies the parameter is measured from the machine center

(2) "/2" implies the dimension shown is 1/2 the total length

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



Definition of the Parameters for the Permanent Magnet Rotor

Notes:

(1) "magw"=180 implies no circumferential spacing between magnets

(2) "(R)" implies parameter is measured from the machine center

(3) "/2" implies the dimension shown is 1/2 the total length

Modeling Options:

(1) Specify "magw" of "magl"

(2) Specify "rc1" and "rc2" for shaped poles or "magh" for constant radius

(3) Specify "loaf"=1 for the bread loaf shape or "laaf"=0 for a radial edge

Additional parameters for the stator model

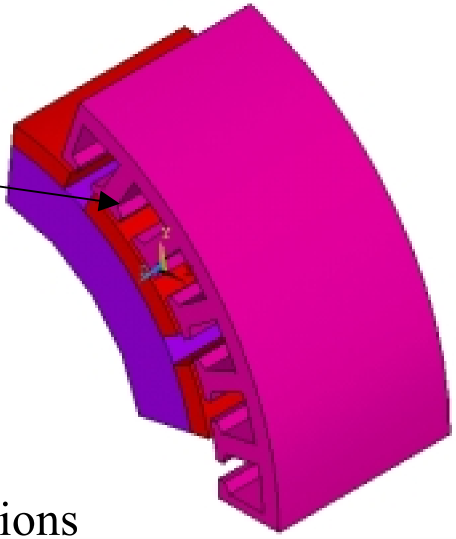
stat_id='slotsta' The stator model type identifier. (This prevents other model macros from using the data for the slotted stator.)

w_file = name of winding file (inclosed in single quotes). The file format is the same as for the 2D application = **'mach2f'**

currform='**sine'** the current varies as a sine

npole = number of poles contained in the complete machine =

nsp = number of stator teeth = **30**



nspgen= number of stator teeth to be generated = **6**

ggeom = the length conversion factor from the units of the parameters to meters (for English to MKS), =. **0254**

mname = **'mach2f'**

identification to be printed out in summaries/plots

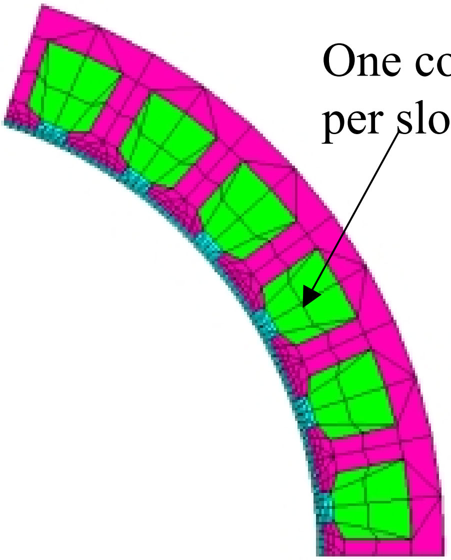
name of plot file (.f33)generated in the multiple solutions

<BUILD3D> saves the database to this name (.db)

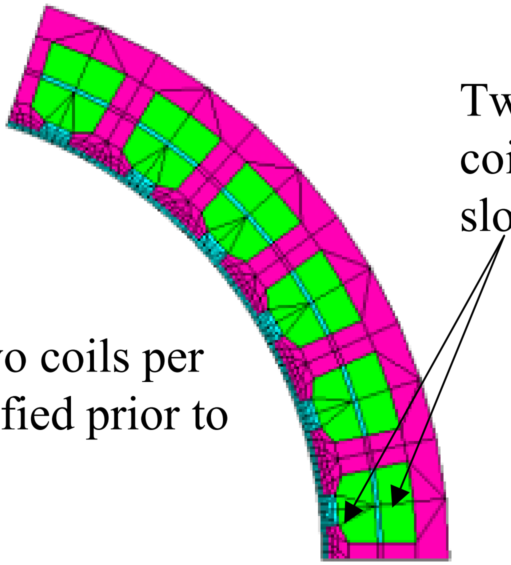
Additional parameters for the stator model-continued

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)



One coil per slot



Two coils per slot

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

In the case of the 3D application, the application of the current is different than for the 2D application, but the **NCONS=2** must still be used.

Additional parameters for the stator model-continued

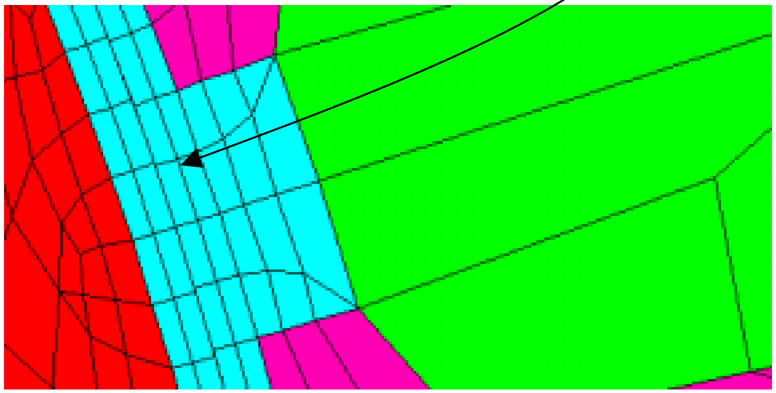
Mesh refinement level

most applications start with Level 2

STREF is for the stator (STREF=2) this controls:

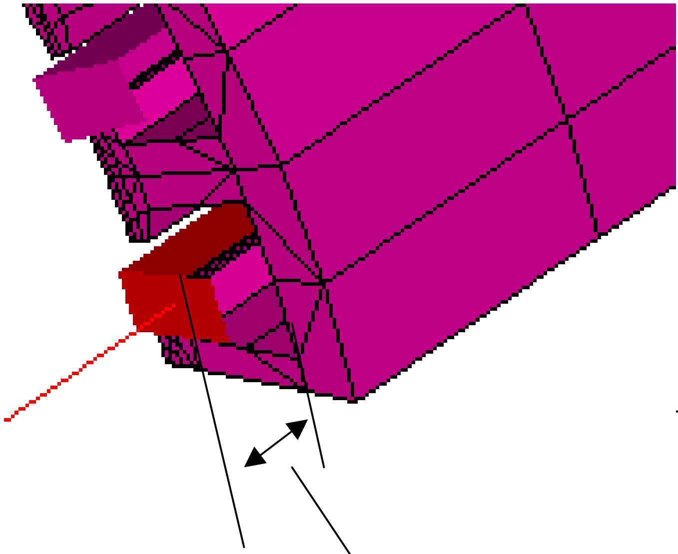
1) the number of layers of elements in the air gap on the stator side
2) the aspect ratio (increasing values forces aspect ratio to unity

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. The parameter S_MESH=1 allows the backiron to be coarsened (increasing values coarsens the backiron mesh)



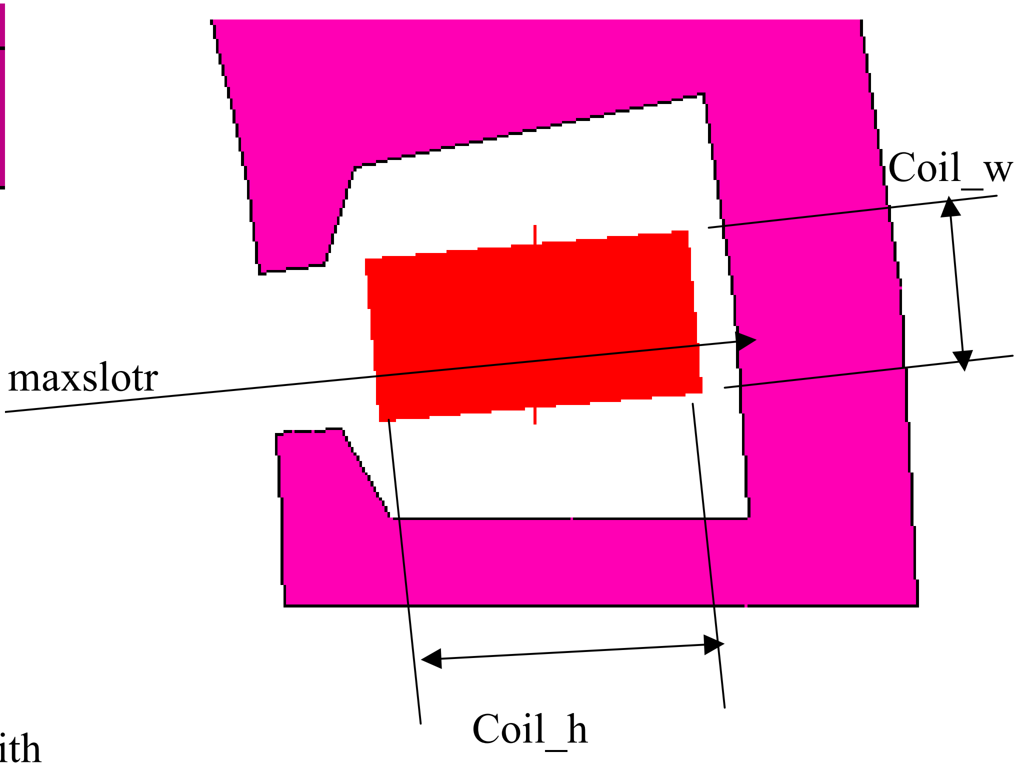
Additional parameters for the coil definition

coil_w = coil width
coil_h = coil height
maxslotr = maximum outer radius of the slot

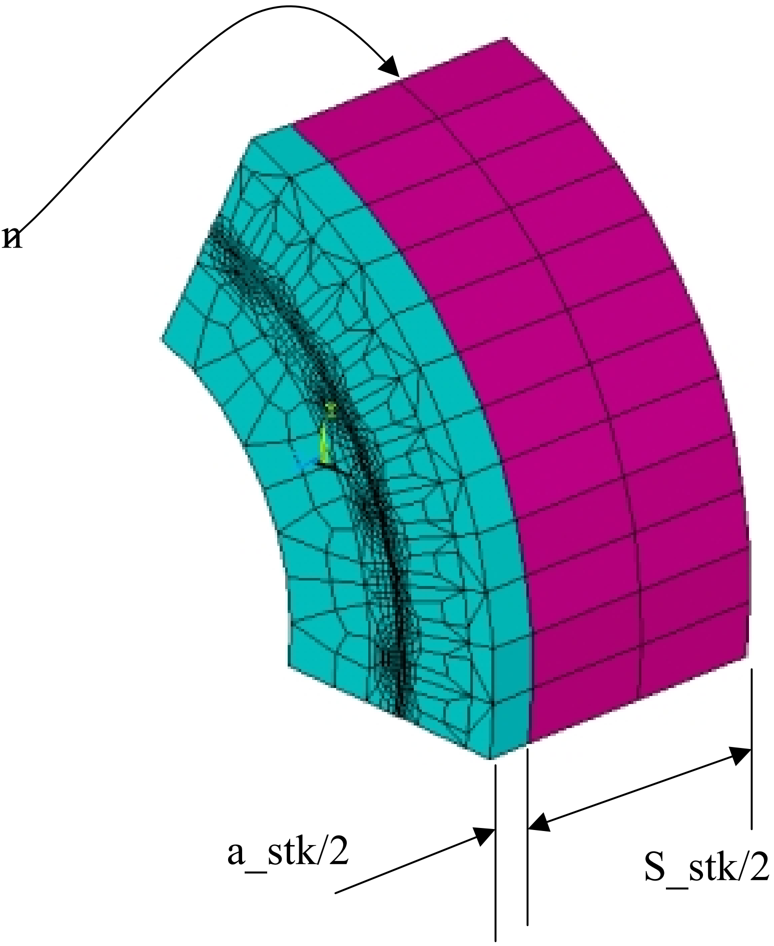


ax_clear = axial clearance of winding with the stack

It is important that that the coil, when centered does **not** come into contact with the iron



Additional parameters for the stator model-continued



s_stk = length of stator stack
n_div3d=axial number of divisions for the iron
a_stk   length of axial air outside the stack

For cases where the stator is not skewed, symmetry can be used in the modeling.

For modeling having a skewed stator, typically the entire axial length should be modeled

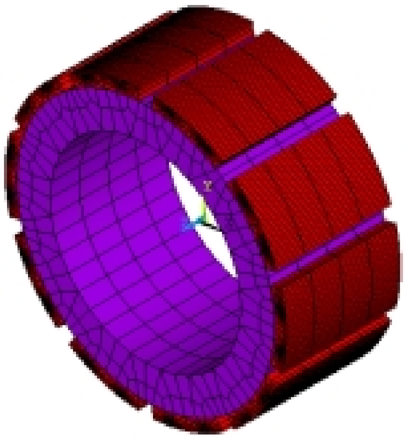
Additional parameters for the skewed stator model-continued

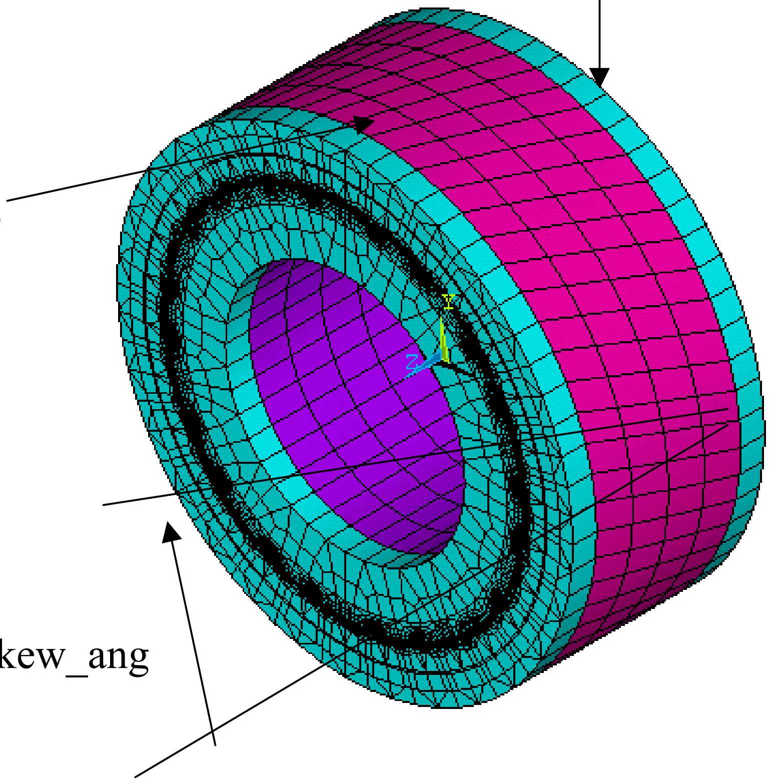
Two additional parameters are required to specified a skewed stator stack

skew_ang= skew angle for the stator (**degrees**)

skew_stk=‘stator’ (This indicates that the stator is to be skewed

Rotor is not skewed





The air outside the stack is not skewed

skew_ang

Parameters for the PM rotor

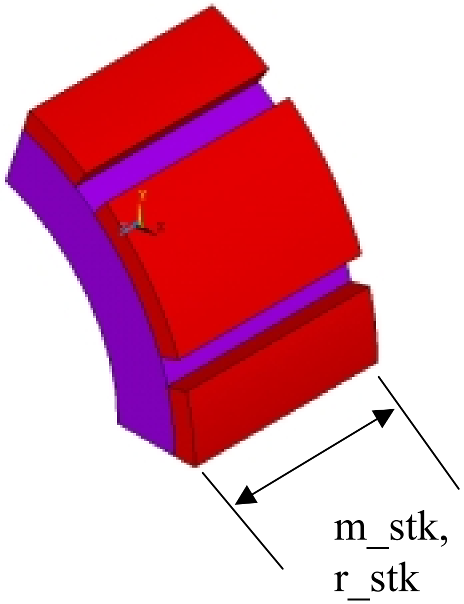
m_stk = length of magnet stack

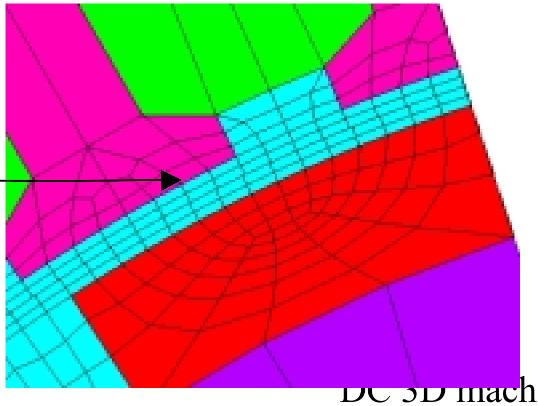
r_stk = length of rotor iron stack

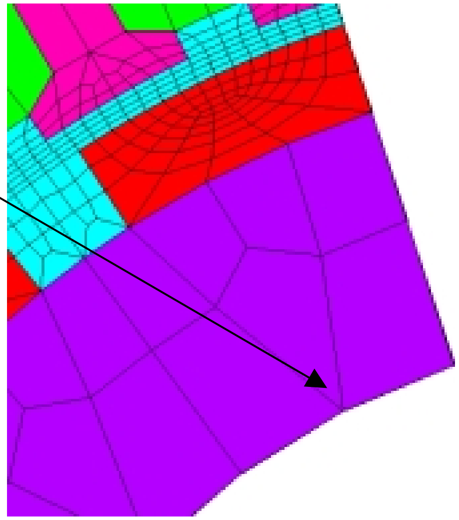
rref = level of mesh refinement for the rotor**=2**
(1 for least refinement, 5 for greatest refinement)

1) the number of layers of elements in the air gap on the stator side
2) the aspect ratio (increasing values forces aspect ratio to unity

r_mesh = additional coarsening of the mesh in rotor (increasing values from 1 to 5 coarsens the mesh in the backiron**)=1**







Material definitions / Components-same as those for the 2D application

- 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

(Once the complete model is built, it is recommended that the individual components be selected and viewed)

Parameter file for the example: mach2_3d.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_3d.des
!   3 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>    <pm_rotor>   permanent magnet       pm_rotor.mac
!
w_file='mach2f'    !  winding file name
rotor_id='pmrotor' !  rotor ID
stat_id='slotsta'  !  stator ID
mname='mach2_3d'   !  name of plot file (extention is .plt)
n_div3d=2          !  axial divisions
stkthk=2.25
r_stk=stkthk     !   rotor iron stack length
s_stk=stkthk     !   stator iron stack length
m_stk=stkthk     !   magnet stack length
a_stk=0  !       !   length of axial air outside the stack
npole=10         !   number of poles
```

Rotor data

```
!   rotor dimensions
rref=2          !   rotor mesh refinement
r_mesh=3        !   coarsens mesh in rotor backiron (increasing values coarsens)
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 dimensions
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
s_mesh=3         !   coarsening the mesh in the stator back iron ( increasing
                 !   values make it more coarse)
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
!    winding data
ax_clear=.1      !  axial clearance of winding with the stack
coil_w=.1        !  coil width
coil_h=.2        !  coil height
maxslotr=1.78    !  maximum outer radius of the slot
currform=‘sine’  !  Current form

ggeom=.0254      !   conversion factor from English to Metric for length
```

Model generation

- If the 2D laminates have not been generated before, it is straight forward to to generate them. This must be generated in the directory with the 2D macros.
  - Load the parameter file <get_dimn> and enter ‘mach2_3d’ in the pop up box, OK
  - use <pm_rotor> to build the rotor
  - use <stator> to build the stator
  - review the model

If a 2D solution had not been obtained before, this could be performed at this point by

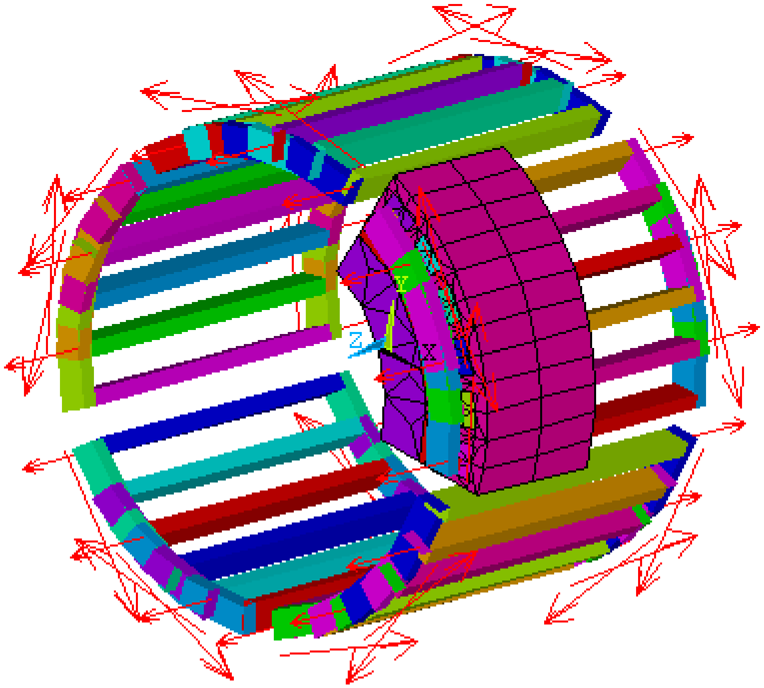
1) connect the model using <rotate>
2) build the winding <winding>
3) apply a current <load>
4) solve <solution>

Model generation - continued

- Once the 2 D model has been inspected, then the 3D model can be generated with <BUILD3D> using the 'mach2_3d' parameter file
  - clears the existing data base
  - loads the parameters from the input .des filename
  - builds the 2D laminates
  - extrudes the 2D models
  - builds the winding
  - applies periodicity , if necessary
  - applies nodal constraint
  - shifts the nodes of the model to form a "skewed" model

Model generation - continued

The full winding was generated because all the coils were specified in the winding file.



If the skew angle (skew_ang) is zero, only a half model is generated.

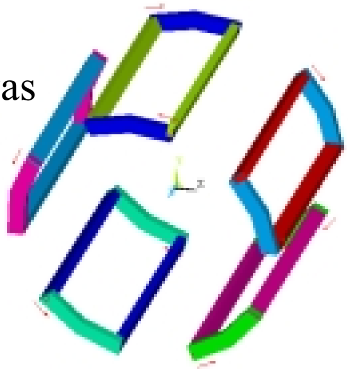
If a_stk is zero, no air is modeled in the axial face of the stack

At this point, the model needs to be connected and the currents needs to adjusted to reflect the input current form.

Summary of the winding generation

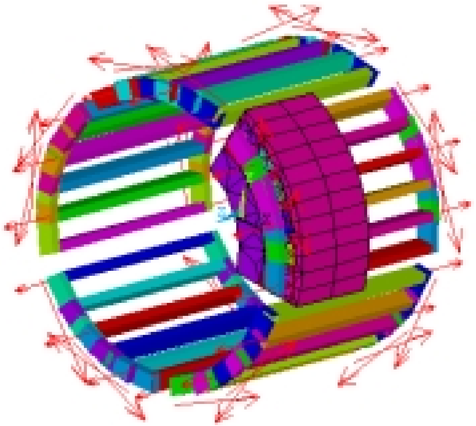
```
___________SUMMARY OF THE WINDING GENERATION___________

 Name of winding file:______________ mach2f .wnd.
 Name of coil element component:____ s_iron.
 Number of Phases:__________________ 3.
 Number of coils:___________________ 15.
 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.
```

The coil winding corresponding to Phase A was selected by utility>comp/assembly>select comp/assembly



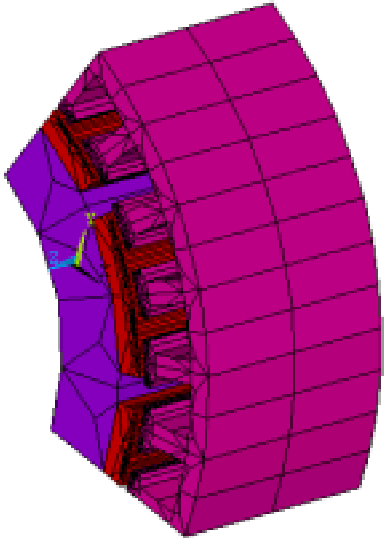
Use utility>plot>replot to display Phase A coils

Displaying the model



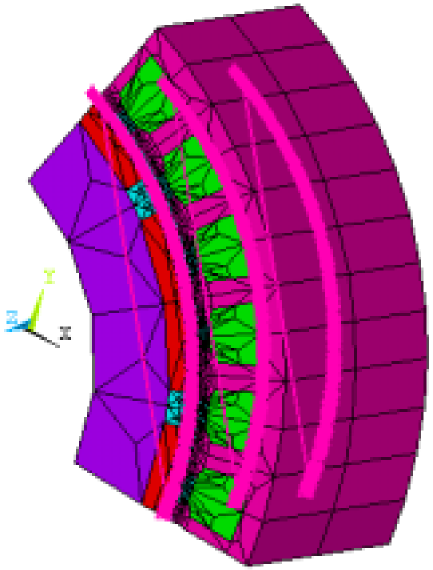
<SHOWIND> generates a plot of the winding and the stator iron

Color is based on the real set ID



<SHOMODEL> generates a plot of the rotor magnet and iron and the stator iron(air/slot regions are not shown)

Color is based on the real set ID



<SHOSOLID> generates a plot of all solid elements:

Color is based on the real set ID

Building the winding-if <BUILD3D> did not build it.

If the parameter file did not have the W_FILE parameter specified, or there was an error in the winding file to prevent it from being built, then it can be generated after the laminate model has been constructed

Prior to using this, the following data will be needed (as indicated in the parameter file input). Units correspond to the other parameter units.

Name of the winding file:	‘mach2f’
name of the element component for the iron of the stator	s_iron
axial clearance from the end of the stack to the inside of the coil bundle	ax_clear
coil width	coil_w
coil height	coil_h
angular location of Slot 1	180/nsp
maximum outer radius of the slot	maxslotr

Actual numbers can be entered into the pop-up box, or the parameters can be defined first and the parameter names can be input into the pop-up box

Measured +CCW from +X axis to start the numbering of the slots

Building the winding independently

When <WINDING> is executed the following prompts are displayed in the pop-up box.

Prompt displayed in the pop-up box	Input Response
Iron region element component	‘s_iron’
Winding axial clearance	ax_clear
Width of a single coil	coil_w
Height of single coil	coil_h
Angular location of first slot(CCW)	180/nsp
Maximum outer radius of slot	maxslotr

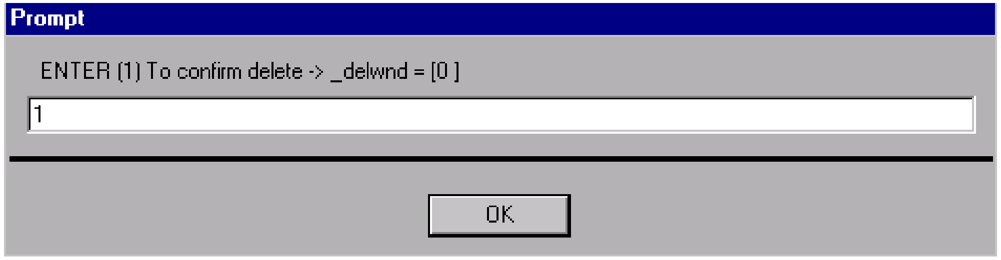
After this is input, checks are made, and then the winding will be constructed. The summary shown previously would be displayed again.

Deleting the winding

In some applications, a series of solutions is needed without any currents. The windings could be generated, and a zero current used.

This is not recommended (If these coils exist, certain calculations are still performed).

It is best to delete the windings using <DELE_WND>. If <DELE_WND> is used, the user is prompted to confirm by entering a 1



ENTER (1) To confirm delete -> _delwnd = [0]

1

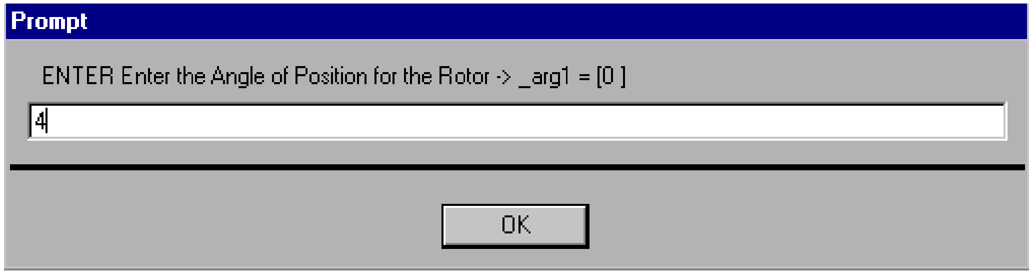
Once the winding is deleted, the stator iron is displayed.

If you are not sure if the winding has been deleted, then to determined if the windings are deleted use <SHOWIND> (If the winding is not displayed, there are no windings)

Connecting the rotor to the stator

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 this example use 4°



Prompt

ENTER Enter the Angle of Position for the Rotor -> _arg1 = [0]

4

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

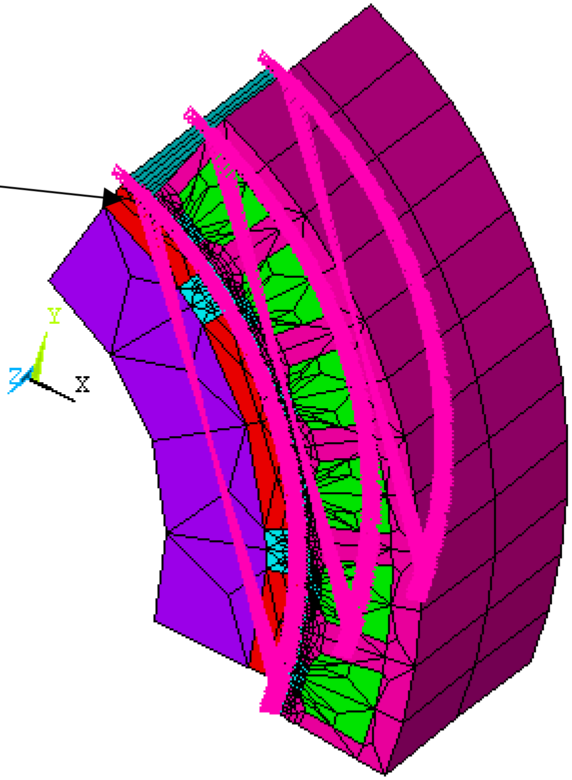
Rotor connected to the stator

```
>________________MOVEMENT OF THE ROTOR_________________<
OLD angle of the lower edge of the rotor:__________ 0.
NEW angle of lower edge of the rotor:______________ 4.
Number of nodes in rotor:__________________________ 327.
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.

Since the nodes for both rotor and stator are in the same Z plane for each layer, there are no CE’s mixing the nodes between different layers.

Applying the current to the winding.

Two items are required to apply current to the winding:

1) winding must have been generated

this was generated with the model using <BUILD3D> if the winding file was specified in the parameter file using the **w_file** parameter;

<SHOWIND> will display the winding which was generated.

2) a current form has been defined

two types of current forms are already present

currform=**'flat'**	specifies a constant current for a ll coils
currform=**'sine'**	specifies a 3 phase, balanced current (Ia+Ib+Ic=0)
currform=**'cos'**	specifies a 3 phase, balanced current (Ia+Ib+Ic=0)

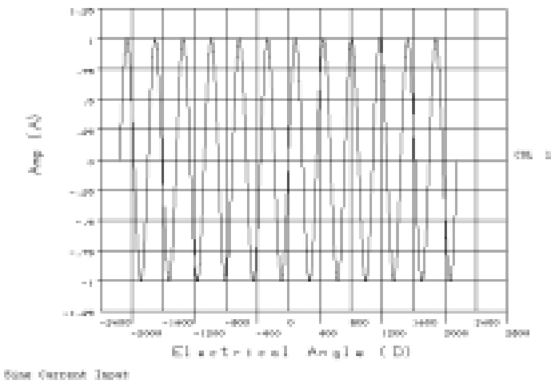
These can be specified in the parameter file, or input through by Utility>parameter>scalar parm. or by the command line. This must be performed before <LOAD> is used

Displaying the current form.

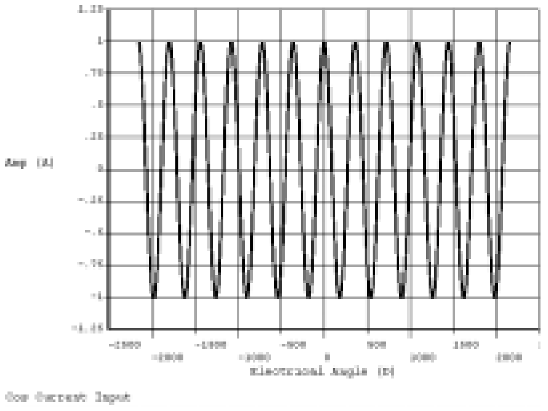
The current form should be verified prior to applying a current . This can be performed by <PLT_FORM>

Generating other functional forms was demonstrated in the 2D notes

Currform=‘sine’



Currform=‘cos’

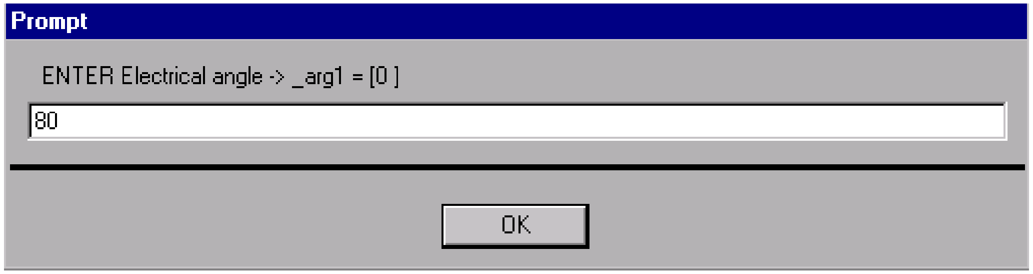


Applying the current to the winding

As an example of applying current to the stator, use 10A at 80 electrical degrees.

Use <LOAD>

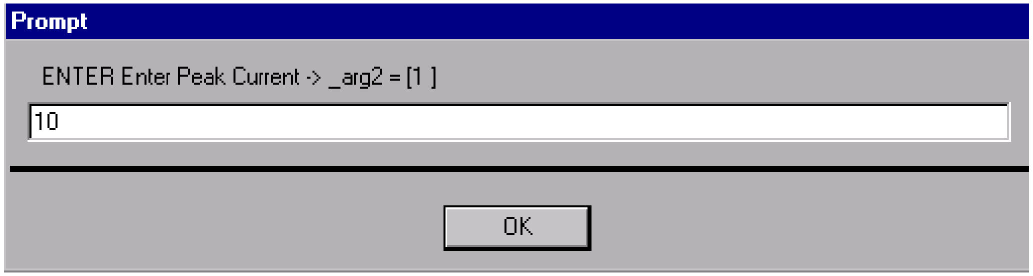
Specifying the 80°



ENTER Electrical angle -> _arg1 = [0]

80

Specifying the peak 10 Amps



ENTER Enter Peak Current -> _arg2 = [1]

10

Applying current to the winding

When this command is executed, the current winding file data is accessed. To determine the location of the coils.

The currform is used to determine the actual current

```
_____CURRENTS APPLIED TO THE COIL______
Name of winding file:______ mach2f
Current form:_____________ sine.
Electrical angle:__________ 80.
Peak Current (A):__________ 10.
____Phase__ Phase_Factor__
    1.        0.9848
    2.       -0.6428
    3.       -0.3420

__________________________
```

File extension is .wnd

If a current form is constructed, it is best to confirm that the sum of the currents is zero

Single Solution

To generate a single solution, use <SOLUTION>

This macro determines which solution strategy is to be used for the solution.

1) If there are no current sources (SOURC36) the Reduced Scalar Potential (RSP) is to be used. This is a single step process (It is understood that if BH data is present, iterations with in this single step is required.

2) If there are current sources, Difference Scalar Potential (DSP) is used. In this strategy, two steps are used.

Step 1: The magnetic field due to the coils is computed using the Biot-Savart calculation. The time to perform this calculation is based on the number of coils and the number of elements in the laminate model. This yields the solution in the air.

Step 2: Using the Step 1 field, the field in the iron is computed, taking into account the BH data for the iron

Solutions with BH data

As a part of the solution, force boundary conditions are applied to the rotor and the stator

If the iron has linear properties no iterations are required. If BH data is used, the monitor is displayed for the MAG degree of freedom and the out of balance load vector which is flux (Webers).

Poor Convergence:

If the BH data is poorly conditioned or the mesh is too coarse in the regions of saturation, the solution can converge slowly.

Actions:

1) check the BH data M-H curve (utility>plot>data tables>M-H). The M steels provided here have smooth MH curves. Other curves may not, and the data needs to be adjusted to result in a smooth M-H curve

2) If M steel has large permeabilities (MUR>10,000), the solution may need more iterations. If the iterations need to be increased, the solution can be obtained by:

```
mvpsol, , , , ,30
```

The default value is 25, and this value can be increased, as shown above. If the convergence monitors are showing wide oscillations, this will not resolve the issues The large oscillations could point to the need for a refined mesh

Poor Convergence-continued

3) If the convergence monitor is not showing wide oscillations, the convergence tolerance may be too restrictive. The default value for the solution is .001 this could be increased to .01 by

mvpsol, , , ,.01

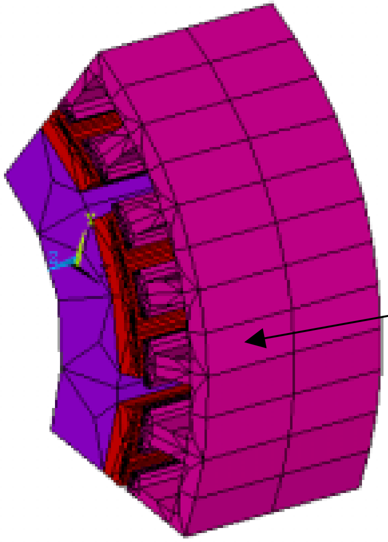
If this approach is used, it is recommended that a second solution be obtained with a reduced value (e.g., .008) and observe any difference in the torque. If the differences are small, this approach of reducing the tolerance would be acceptable.

4) Check the current input to ensure that the Amp-turn is not actually being inputted instead of just the amperage. If the value is too severe, the field saturation would also be severe resulting in more iterations.

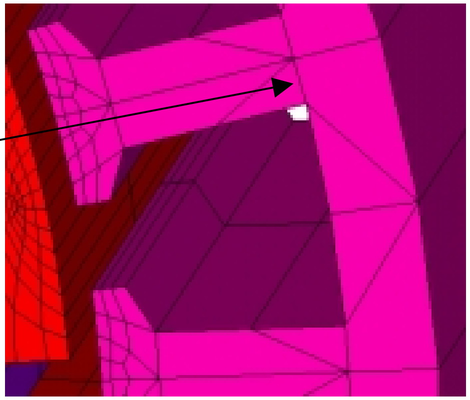
5) Check the magnet input to ensure that the correct value of Hc is being used. If it is to large, it would have the same effect as the excessive current application (Also confirm the units for the MGXX (Amps/meter not Oe, which differs by a factor of 250/p)

Poor Convergence-continued

6) Plot the MUR data (<MUR>) and determine if the elements are too coarse in the regions of saturation. If so, the mesh parameters can be adjusted, and the model can be regenerated.

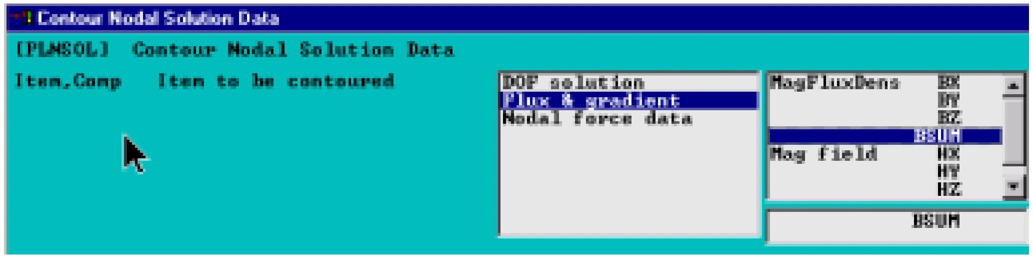


For certain applications, this mesh could be considered to be too coarse. The contribution of the reluctance to the finite element matrix is larger for larger elements. Since the field is changing direction in these elements, the opportunity for oscillations is increased since changes in the field in these elements would appear as large changes to the convergence monitor and could result in oscillations

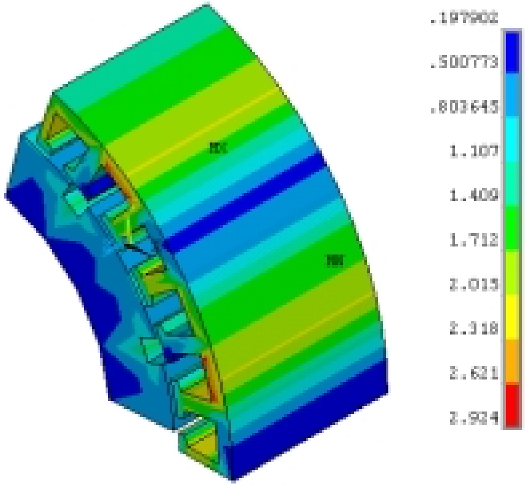


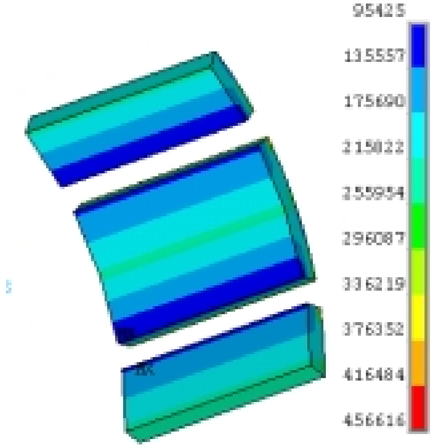
Plotting the nodal solution for BSUM

To plot BSUM (T) (or any component) use post proc>plot results>nodal solu>



BSUM(T)

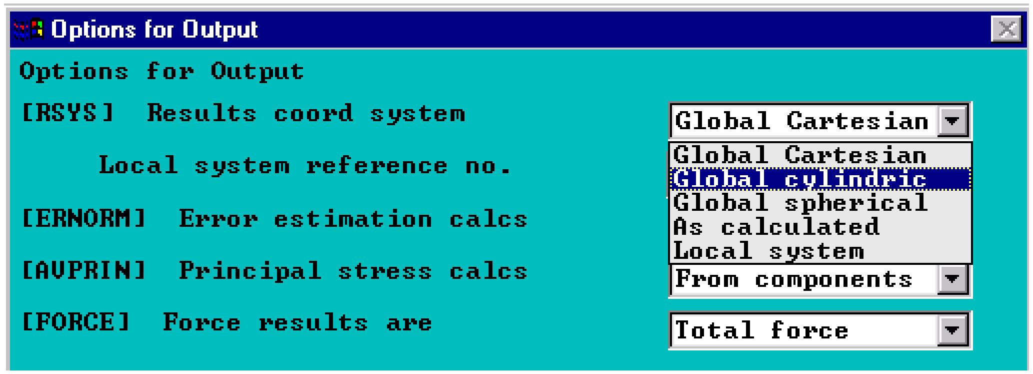




The plot of HSUM (Amp/m) for just the magnets, select just the magnet material (material 3) and then used post proc>plot results>nodal solu> (and select HSUM)

Plotting in the polar system

To alter the coordinate system for plotting components, use proc>options for outp



Options for Output

Options for Output

[RSYS] Results coord system: Global Cartesian

Local system reference no.

[ERNORM] Error estimation calcs

[AVPRIN] Principal stress calcs: From components

[FORCE] Force results are: Total force

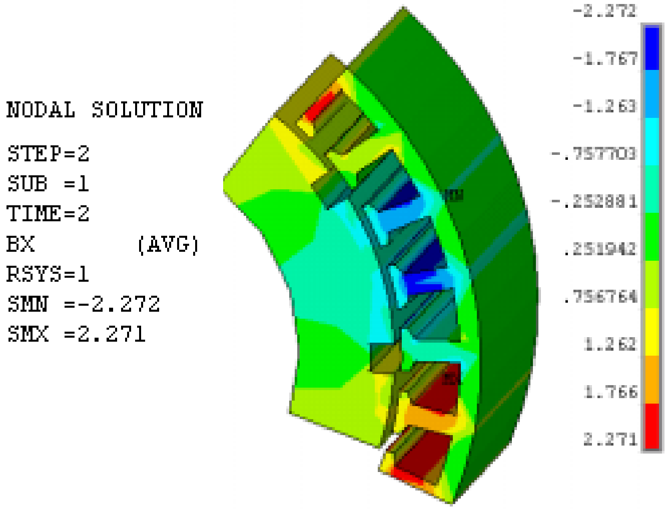
To plot the B radial use post Proc>nodal solu>

Contour Nodal Solution Data

[PLNSOL] Contour Nodal Solution Data

Item,Comp Item to be contoured: Flux & gradient, MagFluxDens BX

This indicates the coordinate system being used to interpret the component. Once this plot has been generated, to plot in the Cartesian system, return to options for outp box and reset



```
NODAL SOLUTION

STEP=2
SUB =1
TIME=2
BX         (AVG)
RSYS=1
SMN =-2.272
SMX =2.271
```

Post processing-torque

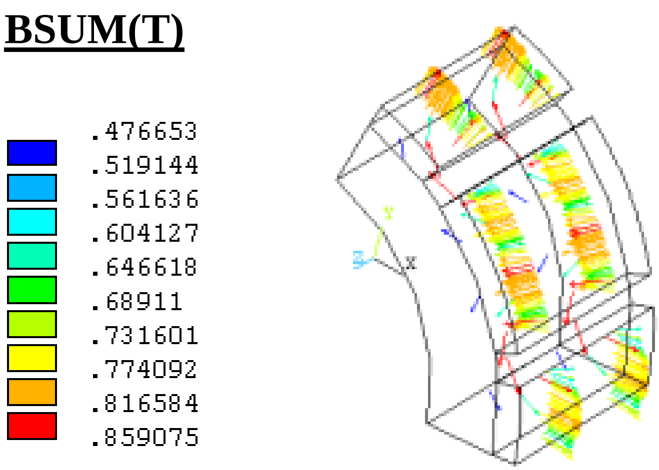
To compute the torque, use <TORQUE>

```
___________TORQUE FOR 3D MACHINES__________

Axial Symmetry factor:_________ 2.
Angular Symmetry factor:_______ 5.
Method to compute torque:______ Maxwell's stress tensor.
Torque on rotor(Nm):___________ -4.094 ( -580.9 oz-in).
________________________________________________
```

The torque value shown takes into account the symmetry both in the axial direction and the angular direction.

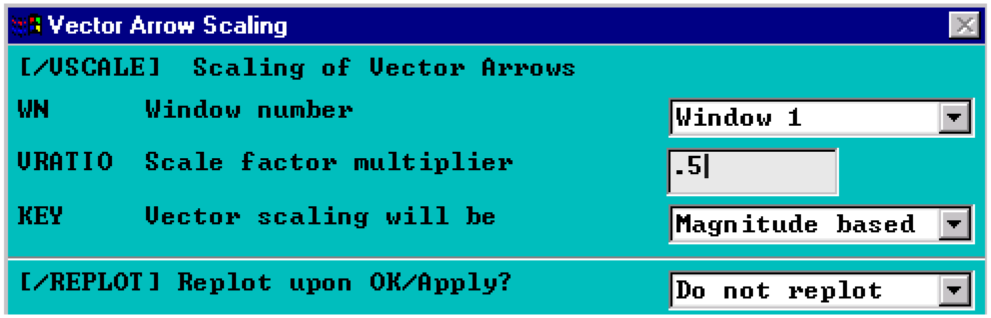
Vector plots

To display the B vector (T), use <B_VECTOR> or <H_VECTOR>


BSUM(T)

For this plot the rotor iron (material 2) and the magnet (material 3) were first selected before <B_VECTOR> was used

To set the length of the vector use, utility>pltcntrls>style>vector arrow scaling


Vector Arrow Scaling

[/VSCALE] Scaling of Vector Arrows

WN Window number: Window 1

VRATIO Scale factor multiplier: .5

KEY Vector scaling will be: Magnitude based

[/REPLOT] Replot upon OK/Apply?: Do not replot

Computing the MMF

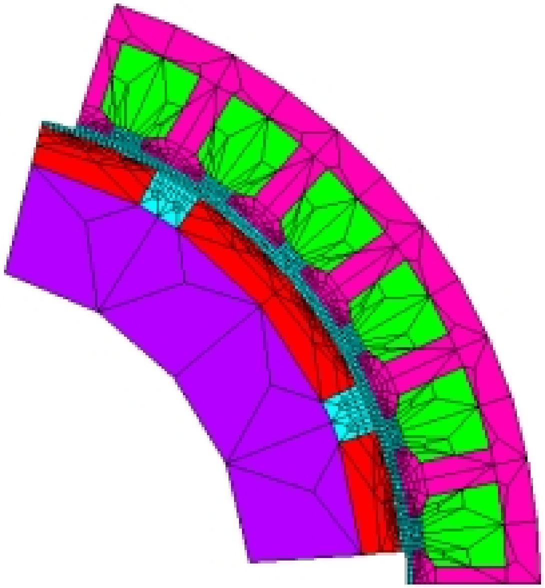
For models using BH data, this can be useful to assessing the effect of saturation as demonstrated in the 2D presentation.

The selection of the path in the 3D model is best accomplished by selecting a plane of nodes in which the MMF is to be calculated. Display the elements, and select the path as shown in the 2D presentation

Use <SHOSOLID> and obtain a side view (Front).

Reselect the nodes at the target plane, z=0.

To check that only nodes are in th
Z=0 plane, you could list the nod
out using utility>list>nodes



Even though the elements are active, only the nodes at Z=0 are active.

MMF evaluation

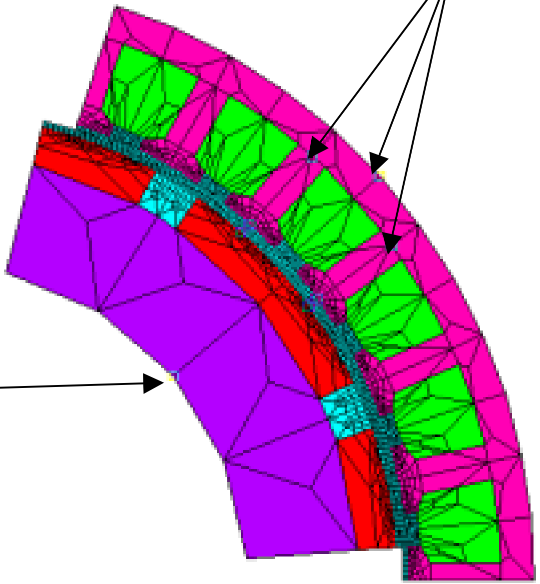
Use postproc>elec&mag>define path>nodes

When this is selected, use the mouse to select nodes in a closed path as described below.

Start and end with this node.

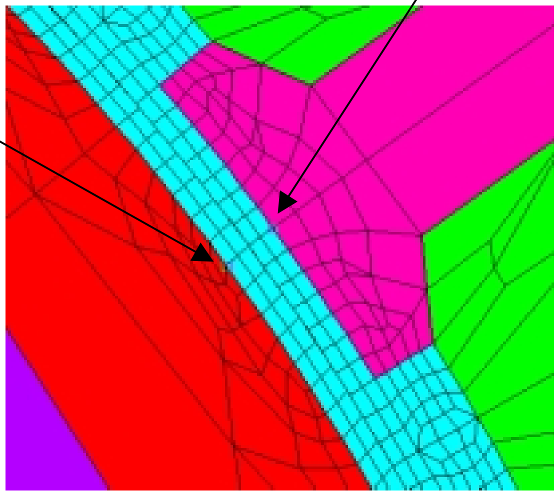
The first time it is selected, a small box will appear. The second time it is selected (to close the loop), the box will disappear.

2nd node is selected at the interface of the magnet and the air. Use the Zoom to get a better view of the interface for picking two nodes on either side of the air gap. After it is selected, use the Back Up and then continue picking the nodes on the path.



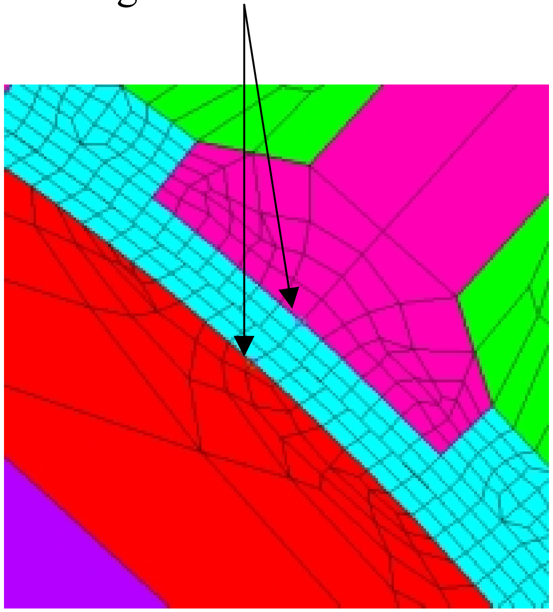
4th,5th,and 6th node in the iron

3rd node is selected at the interface of the stator iron and the air



MMF evaluation-cont'd

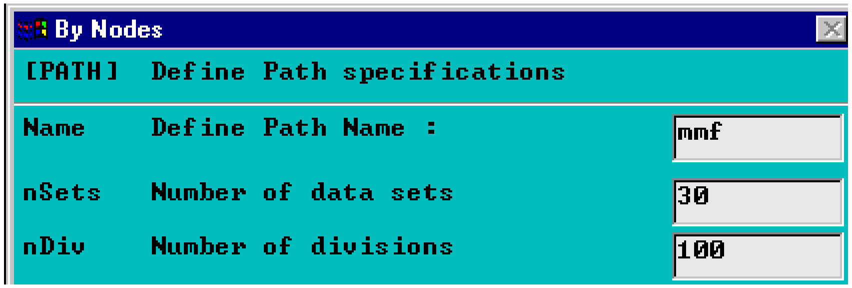
7th and 8th nodes are selected, at the interface of the stator iron and the air and at the magnet air interface



The last node selected is the first node of the path. The box will toggle off.

Once the last node has been selected, Select OK.

Once selected, this box will be displayed . The nDiv is the number of sampling points between the selected nodes.The true test of the appropriate value is to repeat the calculation using a larger value and observing that the MMF calculation changes insignificantly



[PATH] Define Path specifications

Name	Define Path Name :	mmf
nSets	Number of data sets	30
nDiv	Number of divisions	100

MMF evaluation continued

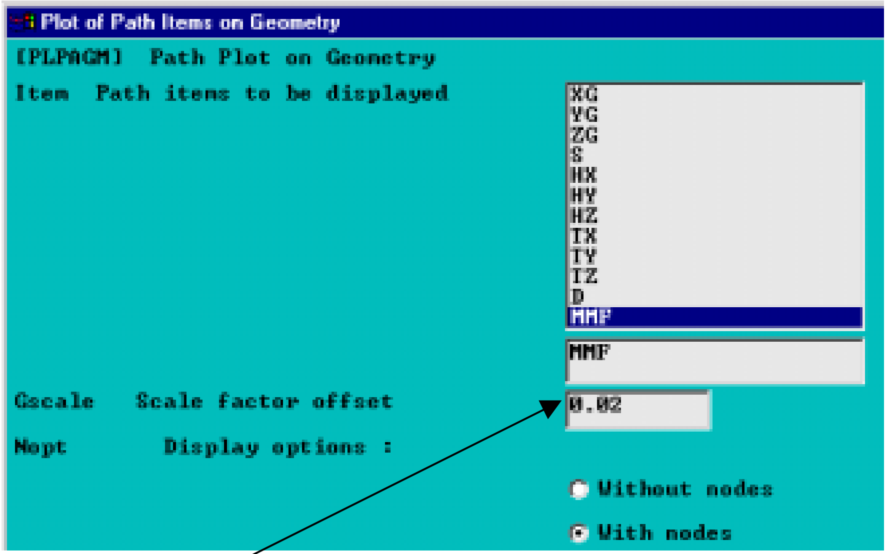
To compute the MMF use <_MMF> in the toolbar, since the MMF integral and H tangential are saved after the calculation

```
_______________ SUMMARY OF MMF CALCULATION___________________

MMF = -107.103551Ampere

NOTE:
Parameter defined for magnetomotive force : MMF.
Path Items for plotting:
"D" H tangential.
"MMF" MMF from path start to current position on path.
_________________________________________________________
```

MMF display on the geometry

Too display the MMF on the geometry, first select the no erase option in utility>plot ctrls>erase>erase between plot option

Then use post proc>path operations>-plot path item-On geometry



Plot of Path Items on Geometry

[PLPAGM] Path Plot on Geometry

Item Path items to be displayed

XG
YG
ZG
S
HX
HY
HZ
TX
TY
TZ
D
MMF

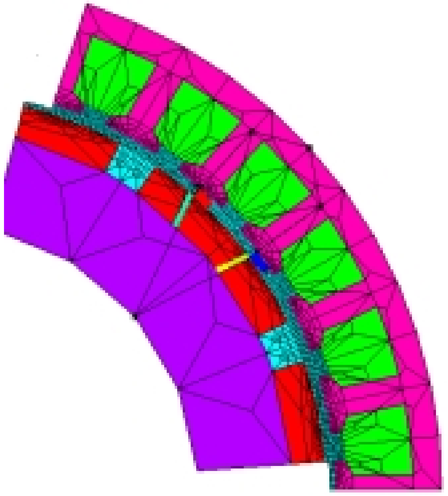
MMF

Gscale Scale factor offset 0.02

Nopt Display options :

○ Without nodes

● With nodes



This scales the value on the graph.

When this plot is complete reset the erase option (utility>plot ctrls>erase>erase between plot)

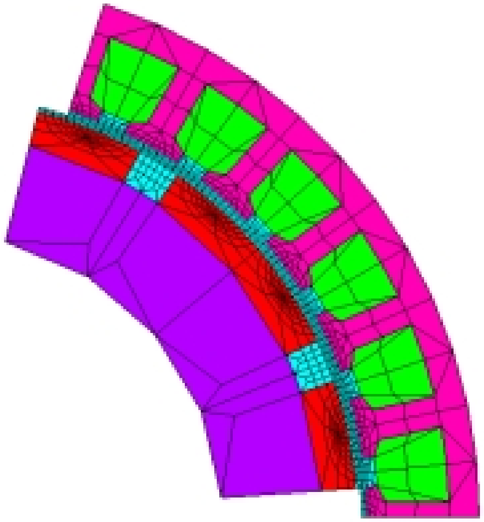
Optional comparison with the 2D model

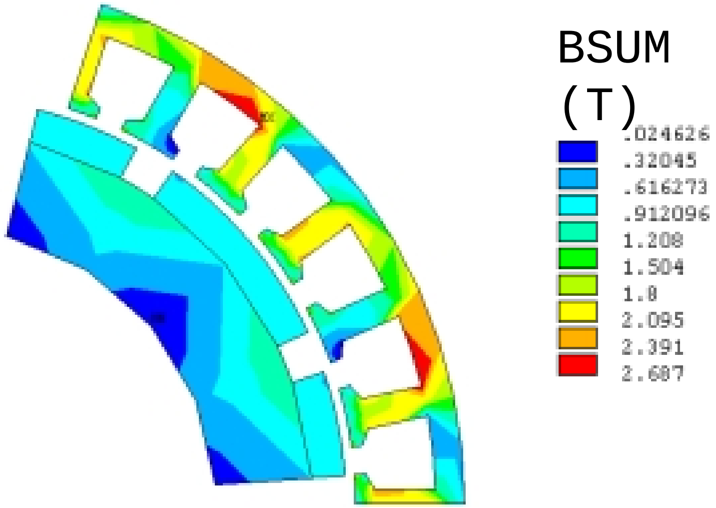
For comparison of the 3D with the 2D model is generated allow the parameter file mach2.des to contain the following changes:

f_mesh=3 for the backiron mesh
MURX of 500 for material 2 (rotor iron)
MURX of 500 for material 5 (stator iron)

To generate the model (using the Toolbar in the directory containing the 2D macros):

b_mach2d,'mach2'
<rotate>   (to 4°)
<load>   (at 80°, 10A)
<solution>
<mach_torq>
The Maxwells stress tensor results in a torque of 565 oz-in which is approximately 1% from the 2D Maxwells stress result





Comparison of the 2D model and the 3D model results and Possible Inferences

1) The element formulation between the two models is extremely different. The 2D employs the MVP while the 3D uses the scalar potential.

Condition	MVP	Scalar
flux parallel for outer surface	AZ is constrained	no constraints
flux parallel for inner surface	AZ is coupled	no coupling

Inference: The method of applying a single constraint on the 3D model stator side is appropriate.

2) Both models employ a periodic condition at the edge of the model. The degrees of freedom being coupled are different

	MVP	Scalar
DOF	AZ	MAG
Field variable	B	H

Inference: The periodic condition for the 3D appears to adequately represent the entire model.

Comparison of the 2D model and the 3D model results-continued

3) The 2D employs a current density applied to the coil region. The 3D model uses the Biot-Savart calculation to take into account the coil.

Inference: The use of Biot-Savart calculation adequately computes the field in the model due to the coil primitives

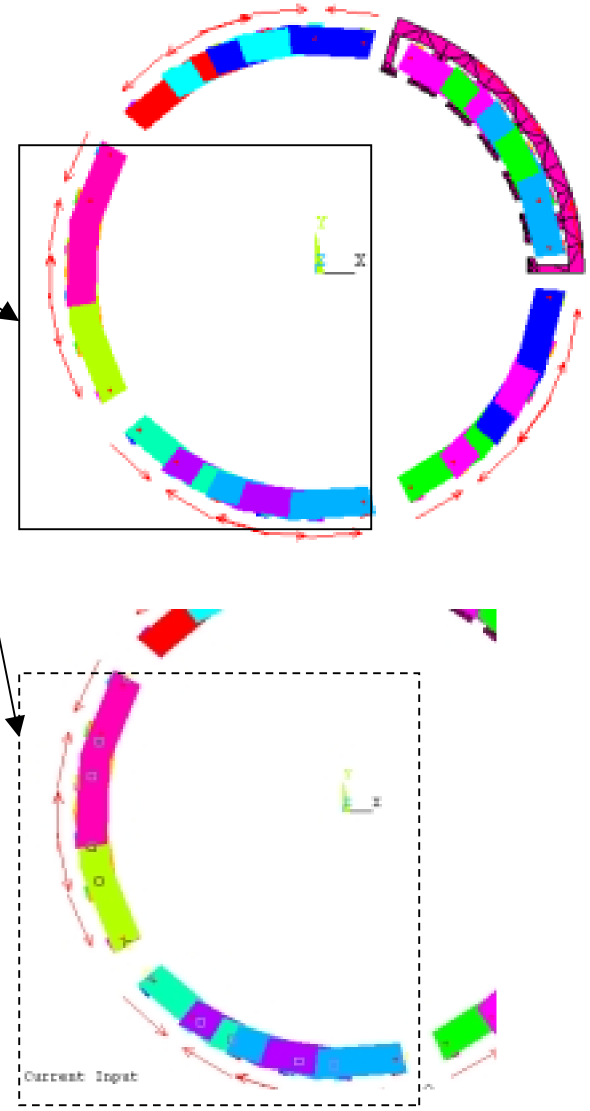
4) The 2D uses a single calculation to arrive at the solution for the AZ, from which the field is computed. The 3D uses a two step process to compute the field

Inference: Given the diversity of the two element formulations, the modeling methodology for the 3D yields acceptable results when compared to the 2D model

Effect of partial modeling of the winding.

The object is to remove this section of the winding and observe the effect on the torque. **First save the current model!**

1) Plot the winding <SHO_WIND> and select the front view
2) select the nodes using the box function and select the nodes as shown
3) select the elements attached to these node
4) delete the elements (preproc>delete>elements) PICKALL.
5) delete the nodes (preproc>delete>nodes) Use PICKALL
6) Use <SOLUTION>
7) Use <TORQUE>



The result is -580.6 oz-in which is effectively the same as the full winding. For this rotor position, the deleted coils are remote to the rotor. As the rotor is shifted, this may not be the case, which is the justification for modeling the entire winding

Effect of partial modeling of the winding-continued

Object is to determine the effect of just using the coils contained in the periodic section.

There are two approaches.

1) Delete the adjacent winding as before

2) Build the winding using mach2.wnd file which specifies the winding only in the periodic model.

Using 2) All the inputs are the same for the pop-up box except for the winding file (mach2.wnd)

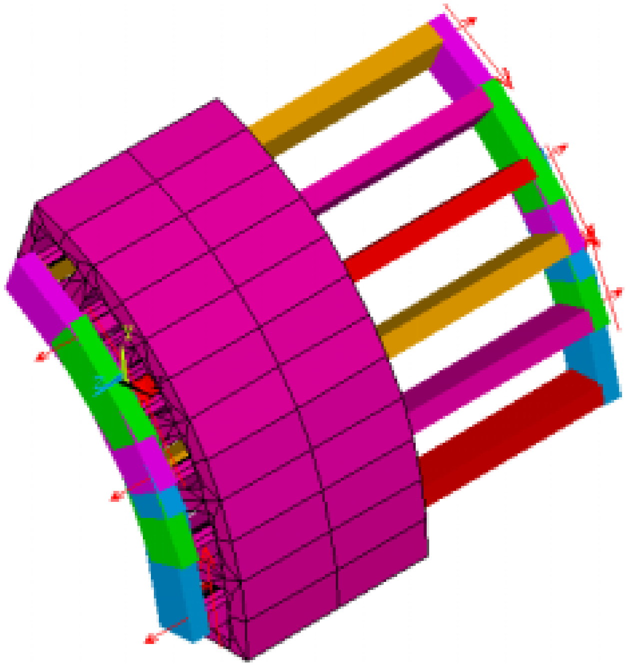
Prompt displayed in the pop-up box	**Input Response**
Winding file name	'mach2'
Iron region element component	's_iron'
Winding axial clearance	ax_clear
Width of a single coil	coil_w
Height of single coil	coil_h
Angular location of first slot(CCW)	180/nsp
Maximum outer radius of slot	maxslotr

Note that these parameters were previously defined <u>and they will need to be changed for a new machine</u>

Effect of partial modeling of the winding-continued

Once these prompts are answered, checks are performed and then the winding model is generated.

1) old elements are deleted
2) new elements are defined
3) new real constants are defined



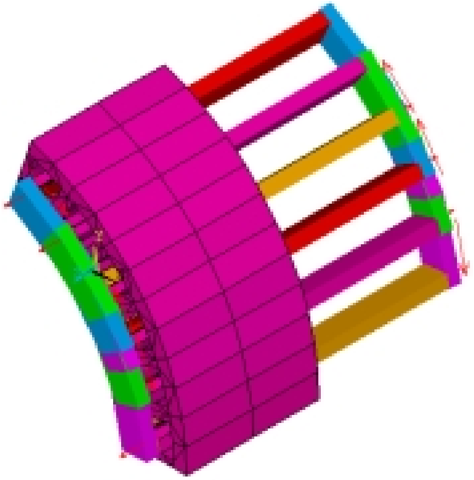
___________SUMMARY OF THE WINDING GENERATION___________
Name of winding file:______________ mach2 .wnd.
Name of coil element component:____ s_iron.
Number of Phases:__________________ 3.
Number of coils:___________________ 3.
Explanations for the Winding:
The coils associated with each phase are contained 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.

Effect of partial modeling of the winding-continued

Apply current to the coils for 80°, 10A using <LOAD> and inputting these values into the box

Solve using <SOLUTION>

Compute torque with <TORQUE>



Note that the torque has decreased by 5%.

```
___________TORQUE FOR 3D MACHINES__________

Axial Symmetry factor:_________ 2.
Angular Symmetry factor:_______ 5.
Method to compute torque:______ Maxwell's stress tensor.
Torque on rotor(Nm):___________ -3.8846 ( -551.2 oz-in).
________________________________________________
```

Summary of changing the model

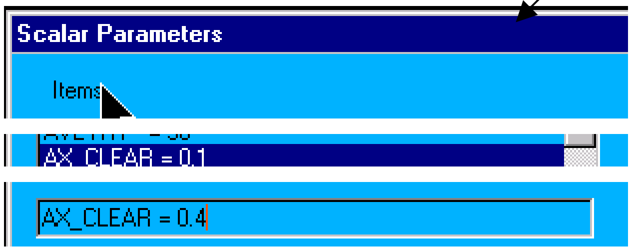
Situation:

The winding needs to be altered (turns, slots, bundle dimensions:ax_clear,coil_w,coil_h,maxslotr)

Steps:

Alter the winding file, and/or parameters to be changed. These parameters can be changed by:

1) at the command line (e.g., ax_clear=.4), or
2) by the GUI (utility>parameters>scalar parameters)
3) changing the parameter file, and using <GET_DIMS> and enter the file name in the pop-up box in single quotes (e.g., ‘mach2’)



AX_CLEAR = 0.1

AX_CLEAR = 0.4

Changing the winding coil-continued

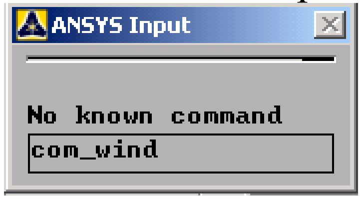
Use <WINDING> to generate the new winding

There are two methods to start the generation of the winding. If the data for the winding is stored as parameter data, then the macro COM_WIND can be used. It requires that the following parameters be altered before the macro is called.

Winding file name	w_file
Winding axial clearance	ax_clear
Width of a single coil	coil_w
Height of single coil	coil_h
Maximum outer radius of slot	maxslotr

This macro assumes that the stator has the winding and that the component name for the stator iron is ‘S_IRON’ and that the first slot in the stator is nearest +X axis , CCW. S

Since ax_clear was reset on the previous page. COM_WIND can be entered directly into the input window.



No known command

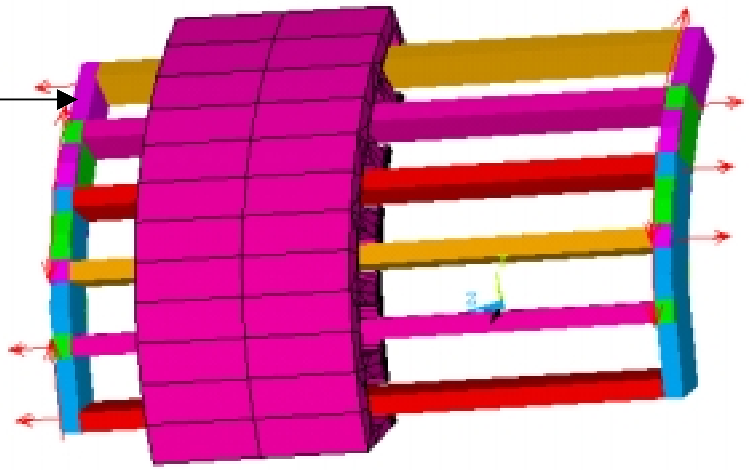
```
com_wind
```

Changing the winding coil-continued

```
___________SUMMARY OF THE WINDING GENERATION___________
Name of winding file:______________ mach2 .wnd.
Name of coil element component:____ s_iron.
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.
```

With this file only the winding common to the modeled stator has been generated.

Note that the end winding has been further extended beyond the end of the stack



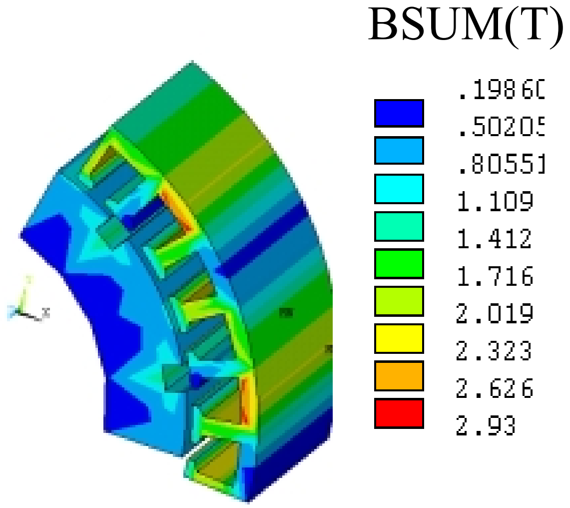
Changing the winding coil-continued

At this point, if the model has not been previously connected, use <ROTATE> In this case no actions have been taken to require the CEs to be regenerated. The CE symbols can be turned on and plotted to confirm.

To load the coils, use <LOAD> and input the electrical angle (80) and the peak amperage (10) . The model prepared for solution (<SOLUTION>)

Use <TORQUE>

```
___________TORQUE FOR 3D MACHINES__________
Axial Symmetry factor:_________ 2.
Angular Symmetry factor:_______ 5.
Method to compute torque:______ Maxwell's stress tensor.
Torque on rotor(Nm):___________ -3.9176 ( -555.9 oz-in).
```



Summary of changing the model-continued

Situation:

The stator/rotor needs to be altered:(see note)

Steps:

Alter the parameter file (.des file)
Use <BUILD3D> and input the new parameter file name (in single quotes)
Connect the rotor/stator with <ROTATE>
Apply current to the coils using <LOAD> and input the electrical angle and peak current

Note: If the stator/rotor has some significantly altered values it would be best to generate the 2D laminates first. When this has been checked, then using the <BUILD3D> would avoid unnecessary large number of errors.

Summary of changing the model-continued

Situation:

The periodic model for the design needs to be replace with a full model

Steps:

Alter the parameter file

- Set NSPGEN=NSP and NRPGEN=NRP
- Change the winding file name (W_FILE) to use a winding which specifies coils for all the slots

Use <BUILD3D> and input the new parameter file name

Connect the rotor/stator with <ROTATE>

Apply current to the coils using <LOAD> and input the electrical angle and peak current

Summary of changing the model-continued

Situation:
The material properties requires alteration.
Steps:
There are two approaches

1) Alter the parameter file to contain the new material properties
Use <GET_DIMS> and enter the new file name in single quotes (eg., ‘mach2’). If the model has already been connected and the load has been applied, no other actions are required. This allows the change to be documented.
- Change the material properties through the GUI or the command line

Since the nodes/elements or position or currents have not been changed, a solution can be obtained directly followed by post processing.

Multiple solutions

The single solution is useful for evaluating a particular design, but ultimately, the torque as a function of angle is needed. This can be generated by <SOLV_ROT>. This macro also generates a series of plots of the model. Position the model which would appear in the plots prior to starting this macro.

Prompt displayed in the pop-up box	**Definition**
Starting Mechanical Angle	The first solutions starts the rotor at this position, which is CCW from +X axis
Ending Mechanical Angle	The last solution positions the rotor at this angle
Incremental Mechanical Angle	The angle which the rotor is incremented starting with the solution at the starting mechanical angle
Stator force file name	Name of the file containing the forces on the stator. The extension is .dat. Defaults to ‘stator’

Multiple solutions-continued

Prompt displayed in the pop-up box	Definition
Rotor force file name	Name of the file containing the forces on the rotor. The extension is .dat. Defaults to ‘rotor’
Peak Amperage	This is the peak amperage (PK) applied to the current form(1)
Starting Electrical Angle.	If the PK > 0, this is needed to synchronize the electrical angle with the mechanical angle. If PK=0, this prompt is not shown
1 to continue OR 0 to Stop	If you do not want to stop the macro from starting, select OK

(1) This macro assumes that the current form has already been defined either using the CURRFORM parameter or by defining the table AMP_A (see the 2D notes)

Example use of the <SOLVE_ROT> for multiple solutions

Prompt displayed in the pop-up box	Value to be used
Starting Mechanical Angle position	0
Ending Mechanical Angle	36
Incremental Mechanical angle	4
Stator force file name	‘stator’
Rotor force file name forces on the rotor.	‘rotor’
Peak Amperage	10
Starting Electrical Angle.	60
1 to continue OR 0 to Stop	1

LOG files generated during the solutions

rotsols.log indicates which position is currently being solved

```
__RUNNING SUMMARY OF SOLUTIONS IN ROTSOLS.MAC____
 Starting Wall clock time:____________ 6.53416667.
 Cycle Number_________________________ 1.
 Current Wall Clock Time:______________ 6.55027778.
 Current mechanical angle of rotor:____ 0.
 Current torque by MXWF (oz-in):__________ 379.265744.
 * * * * * * * * * * * * * * * * * * * * * *
 Cycle Number_________________________ 2.
 Current Wall Clock Time:______________ 6.56972222.
 Current mechanical angle of rotor:____ 4.
 Current torque by MXWF (oz-in):__________ 187.303497.
```

This files gives an indication of the current torques. If the values appear to be incorrect, the solutions can be stopped. The Wall clock times are in Hours, and they should be approximately spaced.

LOG files generated during the solutions-continued

Ld_coil.log shows the current which was used for each iteration

```
Mechanical angle:__________ 0.
Electrical angle:__________ -120.

 LISTING OF THE DATA ON FILE ld_coil.sum
 _____CURRENTS APPLIED TO THE COIL______
 Name of winding file:______ mach2f.
 Current form:_____________ sine.
 Electrical angle:__________ -120.
 Peak Current (A):__________ 10.
 ____Phase__ Phase_Factor__
       1.      -0.8660
       2.       0.8660
       3.       0.0000
 __________________________

LIST REAL SETS       1 TO      87 BY       1

REAL CONSTANT SET      58  ITEMS   1 TO   6
   2.0000      -86.603      0.50800E-02  0.25400E-02   0.0000        0.0000
```

This file also contains the real constant sets used by the coils. If the torques are questionable, the currents and their synchronization to the mechanical angle should be reviewed

Solution controls

If the analyses need to be stopped, the parameter in the macro CHK_RUN.MAC can be altered to stop the solutions after the current solution is obtained.

```
/com,chk_run.mac
! This macro is called by rotsols.mac to to determine if the solutions may continue.
! If this parameter is set to 0, the macro will stop after the most recent solution.
!
!   proceed=1 => solution continues
!   proceed=0 => solution stops
proceed=1
```

Change this to 0   if the solutions are to be stopped

If this is used to stop the solutions, then it should be changed back before the next solution is started.

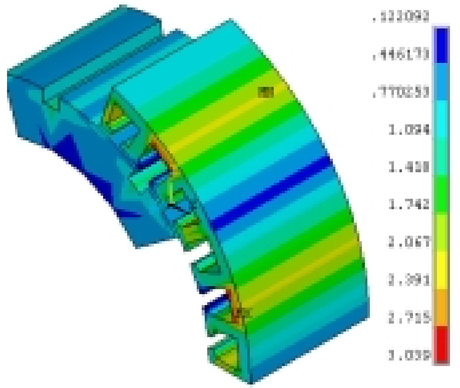
Solution summary

```
>____SUMMARY OF MAXIMUMS/RMS FOR THE SOLUTIONS__<
Starting Mechanical Angle (D)___________________ 0.
Ending Angle (D):_______________________________ 36.
Increment Angle (D):____________________________ 4.
Starting Electrical Angle (D)___________________ -120.
Current form____________________________________ sine.
Location of Zero Elec.Ang.(+CCW,+X axis):_______ 0.
Peak current for winding (A):___________________ 10.
File containing the STATOR forces:______________ stator .dat.
File containing the ROTOR forces:_______________ rotor .dat.
File containing the plots:______________________ mach2_3d .f33.
Rotation of the Rotor:__________________________ CCW.
MIN torque (oz-in):_____________________________ 187.303497.
MAX torque (oz-in):_____________________________ 580.526774.
Peak-Peak torque (oz-in):_______________________ 393.223277.
Average torque (oz-in):_________________________ 382.
Number of solutions:____________________________ 10.
Maximum B magnitude:____________________________ 3.03881641.
Method to compute torque:_____ Rotor-Maxwell stress.
Time for all solutions (CPU):___________________ 656.884537.
__________SUMMARY OF ANGLES/Torque__________________
___________I___________Mechanical_____Torque________
________________________ANGLE (D)_____(Oz-in)_______
            1.              0.00       379.3
            2.              4.00       187.3
            3.              8.00       580.5
            4.             12.00       379.3
            5.             16.00       187.3
            6.             20.00       580.5
            7.             24.00       379.3
            8.             28.00       187.3
            9.             32.00       580.5
           10.             36.00       379.3
____________________________________________________
```

Plots generated by the solutions

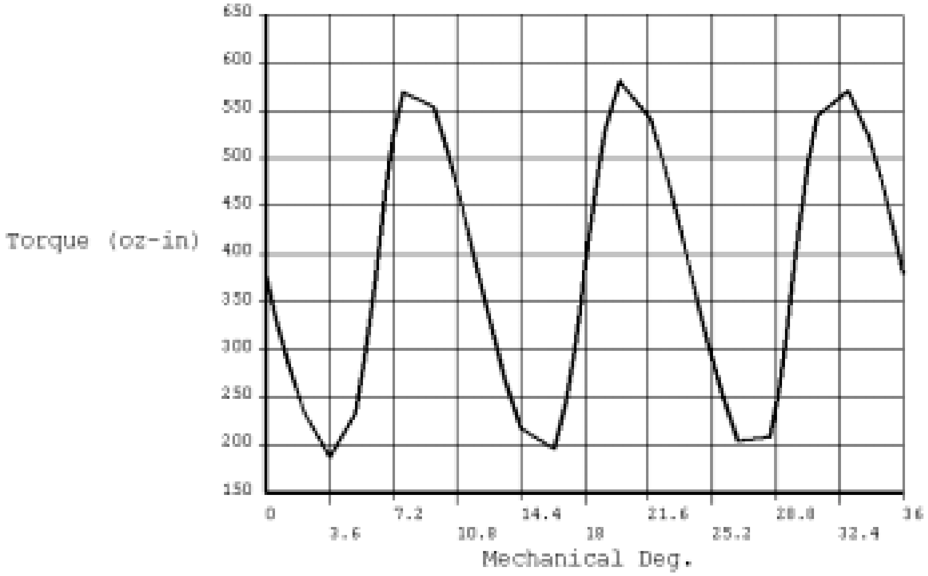
These plots can be shown by the Display utility. The torque plot is the last plot on the plot file

BSUM(T)



Design: mach2_3d / Mechanical Angle: 36

Each frame contains the current mechanical angle of the rotor



Torque versus mechanical angle

Cogging torque

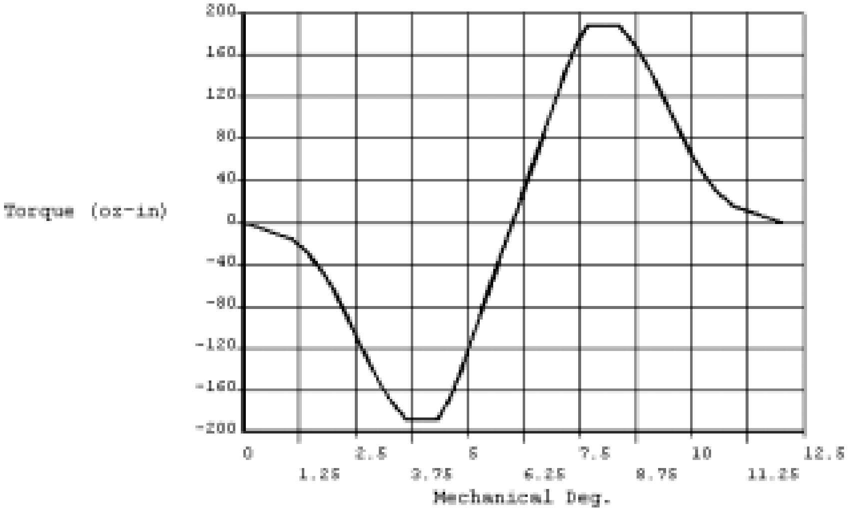
If the cogging torque is to be computed it is best to delete the winding first with <DELE_WND>. This would remove the Biot-Savart calculations. However, it would be most efficient to save the model first if you intend to use the model again with the currents and the winding. Use <SOLV_ROT>

Prompt displayed in the pop-up box	**Value to be used**
Starting Mechanical Angle position	0
Ending Mechanical Angle	36
Incremental Mechanical angle	4
Stator force file name	
Rotor force file name forces on the rotor.	
Peak Amperage	0
1 to continue OR 0 to Stop	1

Cogging torque-continued

```
>____SUMMARY OF MAXIMUMS/RMS FOR THE SOLUTIONS__<
 Starting Mechanical Angle (D)___________________ 0.
 Ending Angle (D):_______________________________ 12.
 Increment Angle (D):____________________________ 1.
 Note: The coils currents were not changed during these solutions.
 File containing the STATOR forces:______________ stator .dat.
 File containing the ROTOR forces:_______________ rotor .dat.
 File containing the plots:______________________ mach2_3d .f33.
 Rotation of the Rotor:__________________________ CCW.
 MIN torque (oz-in):_____________________________ -196.637252.
 MAX torque (oz-in):_____________________________ 196.637252.
 Peak-Peak torque (oz-in):_______________________ 393.274505.
 Average torque (oz-in):_________________________ 0.
 Number of solutions:____________________________ 13.
 Maximum B magnitude:____________________________ 3.03537217.
 Method to compute torque:_____ Rotor-Maxwell stress.
 Time for all solutions (CPU):___________________ 185.456665
 __________SUMMARY OF ANGLES/Torque__________________
 ___________I___________Mechanical_____Torque________
 ________________________ANGLE (D)_____(Oz-in)_______
             1.               0.00         0.0
             2.               1.00       -13.7
             3.               2.00       -64.6
             4.               3.00      -149.9
             5.               4.00      -196.6
             6.               5.00      -122.2
             7.               6.00         0.0
             8.               7.00       122.2
             9.               8.00       196.6
            10.               9.00       149.9
            11.              10.00        64.6
            12.              11.00        13.7
            13.              12.00         0.0
```

The individual plots are saved in the graphics file mach2_3d



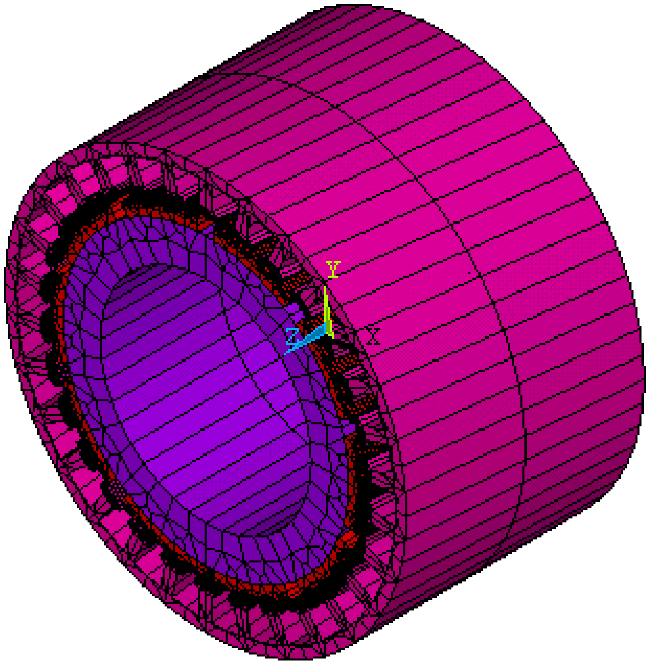
A skewed stator model

The parameter file mach2fsd.des is the same as the mach2_3d.des parameter file with the following exceptions for

skew_stk='stator'	the stator is the component to be skewed by "skew_ang"
skew_ang=6	the angle of skew(°) measured CCW
nspgen=nsp	the entire stator model is to be generated
nrpgen=nrp	the entire rotor model is to be generated

The model is constructed using <BUILD3D> using the parameter file 'mach2fsd' Since the model must correspond to the full length of the stack, no symmetry is used. This model did not have the winding constructed.

A skewed stator model-continued



The skewed stack has an additional consideration of the number of axial divisions.

This is because the stator elements are crossing over the rotor elements in the air gap. For demonstration purposes, only two axial divisions are used here.

The skewed stack is generated in the same manner as the straight stack. The last step is to shift the stator nodes in the circumferential direction.

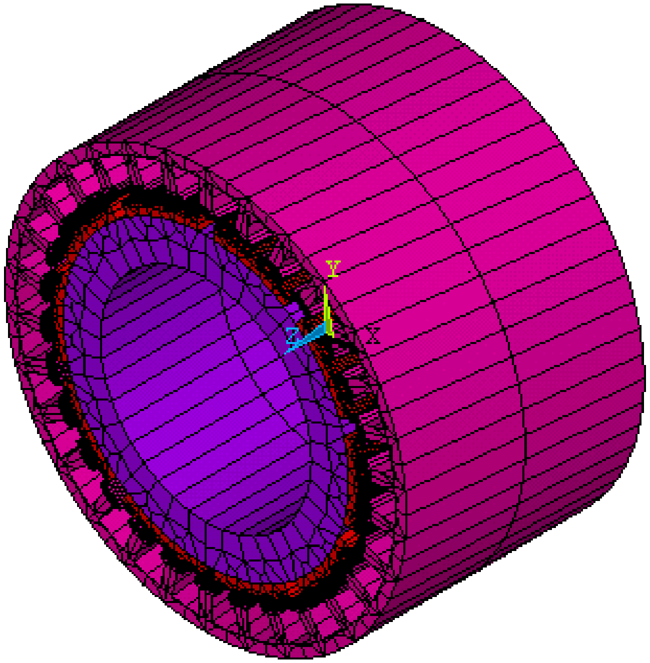
The nodes remain in the same Z plane. This allows the same method to connect the two models.

Full model rotor location

In dealing with full models it is not obvious about the identification of the location of the rotor. To obtain the current location of the rotor, use <ROT_ANG>.

The rotor marker node will change from model to model. The location is useful if the model has been moved and it is necessary to move to another location.

For full models, the angle in <ROTATE> is an increment when used from the toolbar. For periodic models, the angle in <ROTATE> is measured to the lower edge of the model.



```
Rotor marker node:_________ 65.
Rotor location:____________ 0 (CCW from +X axis).
```

Cogging torque calculation for the skewed stack.

Since the winding was not generated, there is no need to use DELE_WND.
To initiate the series of solutions, use <SOLV_ROT>

Prompt displayed in the pop-up box	**Value to be used**
Starting Mechanical Angle position	0
Ending Mechanical Angle	12
Incremental Mechanical angle	1
Stator force file name	
Rotor force file name forces on the rotor.	
Peak Amperage	0
1 to continue OR 0 to Stop	1

Cogg torque calculation for a 12° rotation using <SOLV_ROT>

```
>____SUMMARY OF MAXIMUMS/RMS FOR THE SOLUTIONS__<
 Starting Mechanical Angle (D)___________________ 0.
 Ending Angle (D):_______________________________ 12.
 Increment Angle (D):____________________________ 1.
 Note: The coils currents were not changed during these solutions.
 File containing the STATOR forces:______________ stator .dat.
 File containing the ROTOR forces:_______________ rotor .dat.
 File containing the plots:______________________ mach2s .f33.
 Rotation of the Rotor:__________________________ CCW.
 MIN torque (oz-in):_____________________________ -77.3036751.
 MAX torque (oz-in):_____________________________ 77.3036751.
 Peak-Peak torque (oz-in):_______________________ 154.60735.
 Average torque (oz-in):_________________________ 0.
 Number of solutions:____________________________ 13.
 Maximum B magnitude:____________________________ 3.00930517.
 Method to compute torque:_____ Rotor-Maxwell stress.
 Time for all solutions (CPU):___________________ 440.328125.
 __________SUMMARY OF ANGLES/Torque__________________
 ___________I___________Mechanical_____Torque________
 ________________________ANGLE (D)_____(Oz-in)_______
             1.              0.00        77.3
             2.              1.00        62.7
             3.              2.00        43.7
             4.              3.00         0.0
             5.              4.00       -43.7
             6.              5.00       -62.7
             7.              6.00       -77.3
             8.              7.00       -76.2
             9.              8.00       -32.3
            10.              9.00         0.0
            11.             10.00        32.3
            12.             11.00        76.2
            13.             12.00        77.3
 ____________________________________________________
```

Note that the torque ripple is 155 oz-in as compared to the 393 oz-in torque ripple for the straight stack machine.

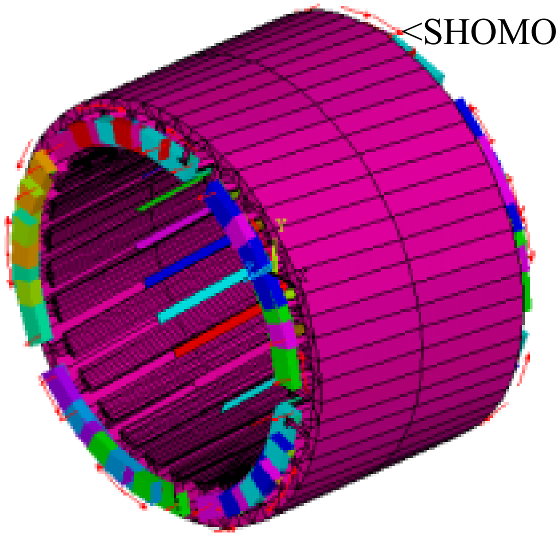
Skewed stator models-continued

If the winding is to be included in the model, it must be specified in the parameter file at the time the <BUILD3D> is started.

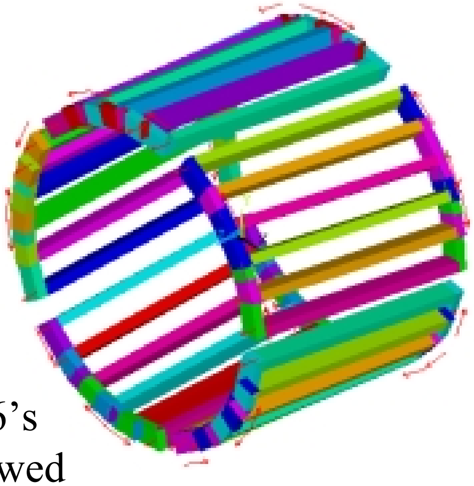
Since the model is a full model, the winding must also be a full winding for the machine. An example model with a skewed stator and a complete winding is mach2fsw.des (when <BUILD3D> is used, specify this file as the parameter file)

In this file   W_FILE='mach2f'

Once the model generation is complete, the <ROTATE> at 8° and <LOAD> -80° and 10A are required prior to start the <SOLUTION>

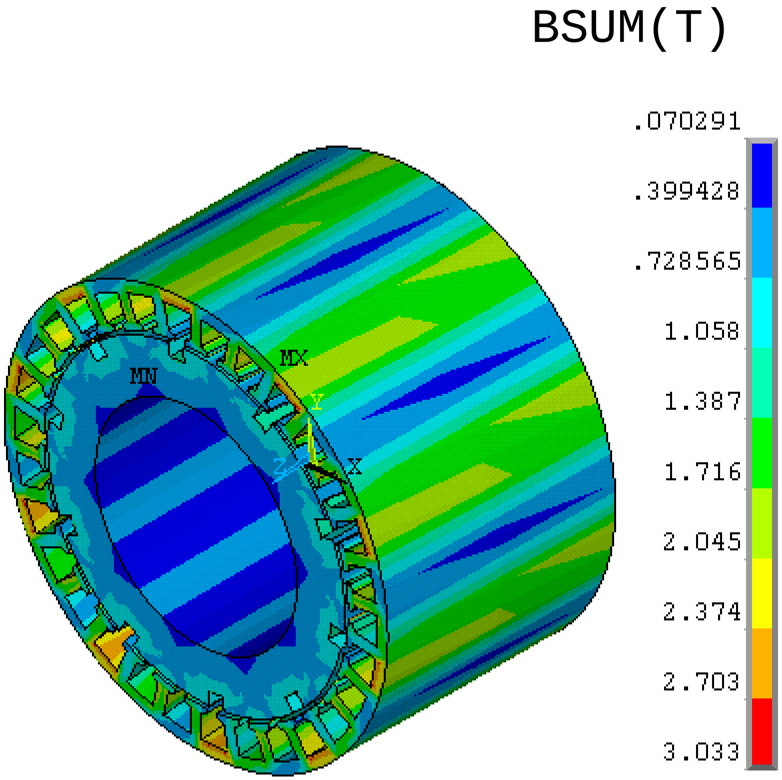


<SHOMOD>



The sourc36's are also skewed

Skewed Stator results



Note the effect of the B field in the skewed stator

Note the reduction in the from the torque from the straight stack

```
___________TORQUE FOR 3D MACHINES__________
Axial Symmetry factor:_________ 1.
Angular Symmetry factor:_______ 1.
Method to compute torque:______ Maxwell's stress tensor.
Torque on rotor(Nm):___________ 3.0274 ( 429.6 oz-in).
________________________________________________
```

Unequal Stack lengths – symmetrical design

Unequal lengths for the stacks can be specified in the parameter file.

The model is generated as the other models using extrusions. The extrusion lengths are based on the stack lengths. The elements are then modified to simulate the unequal lengths.

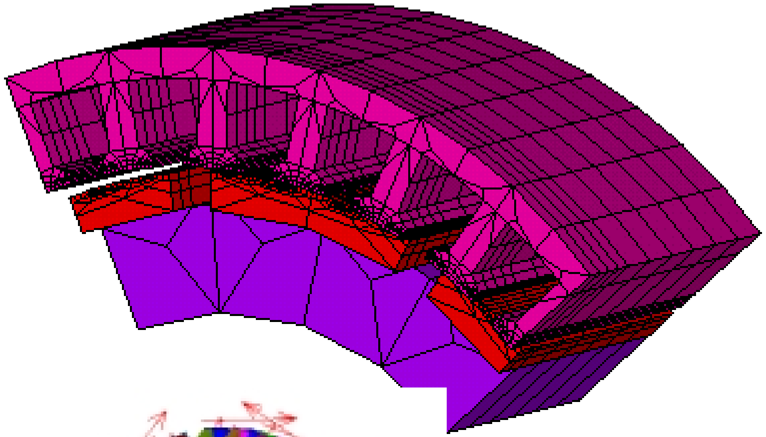
For a symmetrical design only half the model is required.

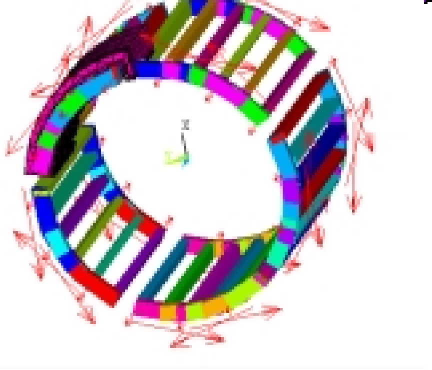
```
n_div3d=6     !   axial divisions
stkthk=2.25
r_stk=1.75    !   rotor iron stack length
s_stk=stkthk  !   stator iron stack length
m_stk=2       !   magnet stack length
a_stk=0.5     !   length of axial air outside the stack
```

These parameters are contained in machueq.des

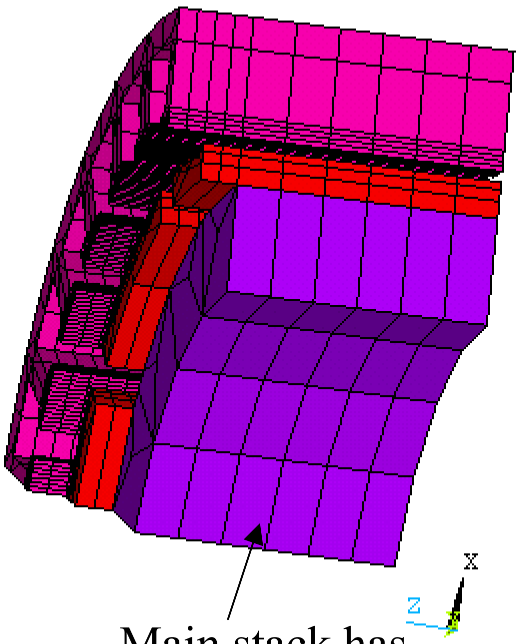
Unequal Stack lengths – symmetrical design - continued

The model is generated with <BMACH3D> using machueq.des With this methodology, designs with small differences in lengths should be avoided





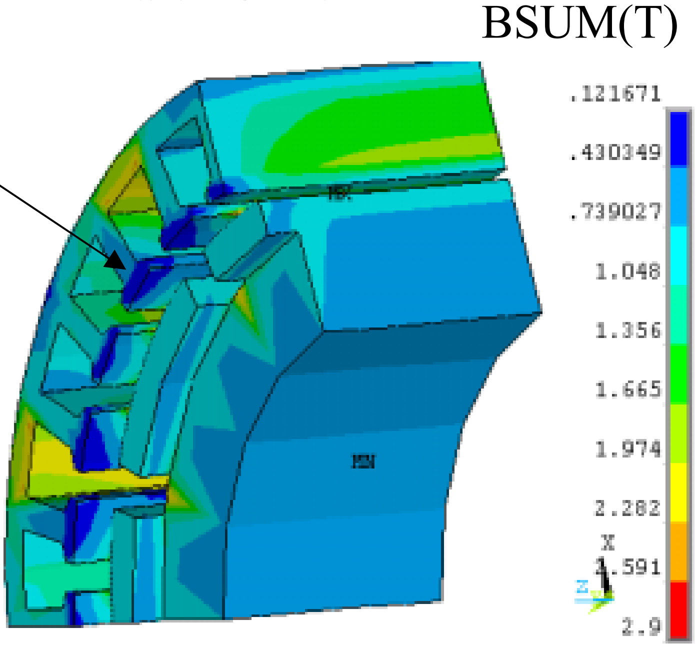
The full winding was used.



Main stack has n_div3d divisions

Unequal Stack lengths – symmetrical design - continued

To obtain a solution, use <ROTATE> at 0 and <LOAD> with current at –120 degrees and 10 A. Then generate a single solution with <SOLUTION>



Note the reduction in the field at the edge of the stator,and the 15% reduction in the torque. However, if a planar analysis had been used with the rotor stack thickness, the torque would have been 1.75/2.25*379=295 which is 12% less than the value shown below.

This requires a reasonable mesh divisions for the stator outside the rotor.

```
___________TORQUE FOR 3D MACHINES__________
Axial Symmetry factor:_________ 2.
Angular Symmetry factor:_______ 5.
Method to compute torque:______ Maxwell's stress tensor.
Torque on rotor(Nm):___________ 2.345 ( 332.8 oz-in).
________________________________________________
```

Rotor/magnet axial offset.

In the event the rotor/magnets are not at the axial center of the model, a full axial model is required. This option can be combined with unequal stack lengths.

The model is generated using the same parameters as for the unequal stack lengths.

The principle is demonstrated here using machueq.des

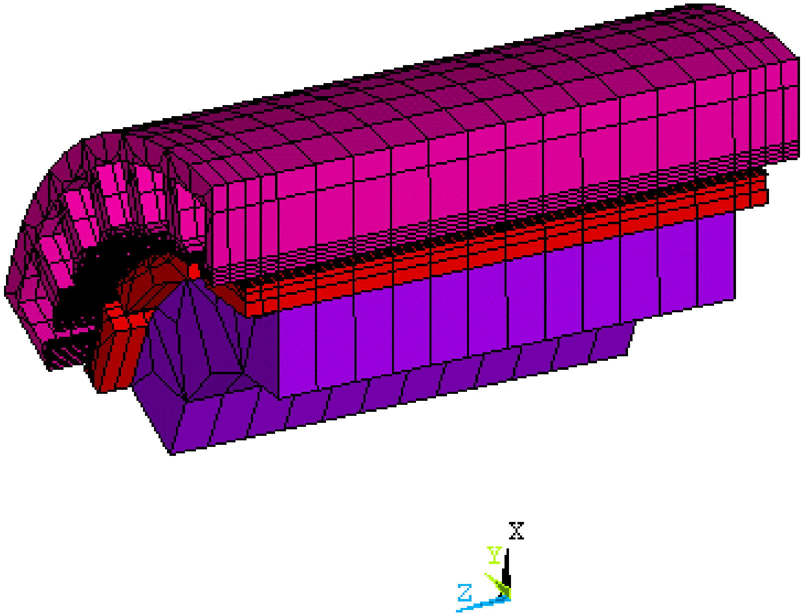
To generate the full axial model, set

Fullmod=1   in the parameter file.

Use the macro b_full3d,'machueq' to generate the full model.

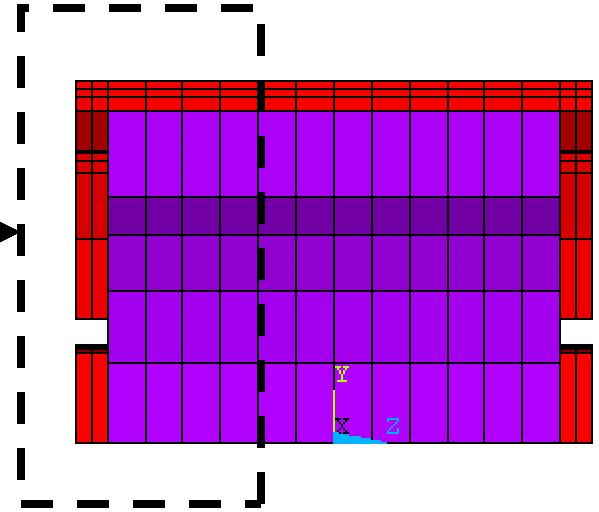
Rotor/magnet axial offset-continued

The full axial model is generated, as shown. The main part of the stack has 2* n_div3d divisions . The number of divisions are important since the physical edge of the rotor and magnets must be reasonably close to the modeled edge.



Rotor/magnet axial offset-continued

- To simulate the offset, select several layers of rotor and magnet elements from a side view. Use the BOX option for the element picker with the mouse.
- Then use the element modify command to change them to air: EMOD,ALL,MAT,1

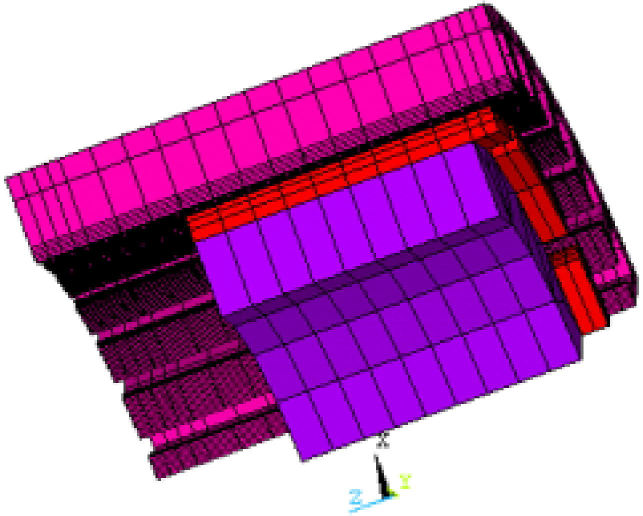


This preserves all the component definitions for the other macros.

Rotor/magnet axial offset-continued

If the edge is not in the precise location,

- Select the nodes at the edge of the rotor and magnet
- Use the NMOD command to reset the Z coordinate with NMOD,ALL,,,Z_NEW where Z_NEW is the target location for the new edge. The only concern is that some of the elements could be turned “inside-out”



For this case, for purpose of demonstration, the node coordinates are not changed.

Rotor/magnet axial offset-continued

To obtain a solution, use <ROTATE> at 0 and <LOAD> with current at –120 degrees and 10 A. Then generate a single solution with <SOLUTION>

The force is obtained by using
Force by components in
Elec&emag calc>-component force
And select R_IRON component and then
OK

```
SUMMARY OF FORCES BY VIRTUAL WORK
Load Step Number:       2.
Substep Number:         1.
Time:                0.2000E+01
Units of Force:        ( N )
Component        Force-X       Force-Y        Force-Z
   R_IRON     0.20248E+03   0.15608E+03    0.51860E-01
___________________________________________________
```

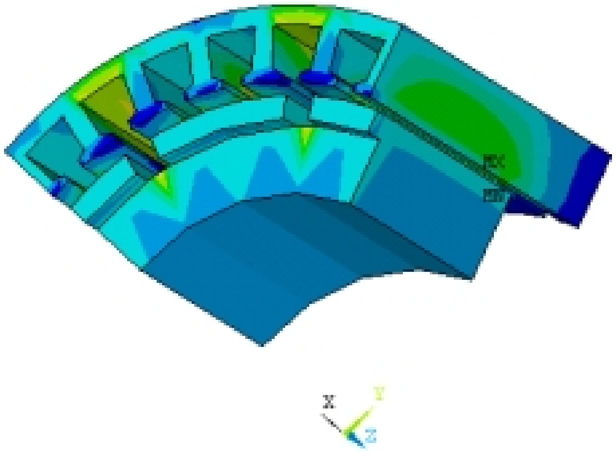
The torque is computed using <TORQUE>

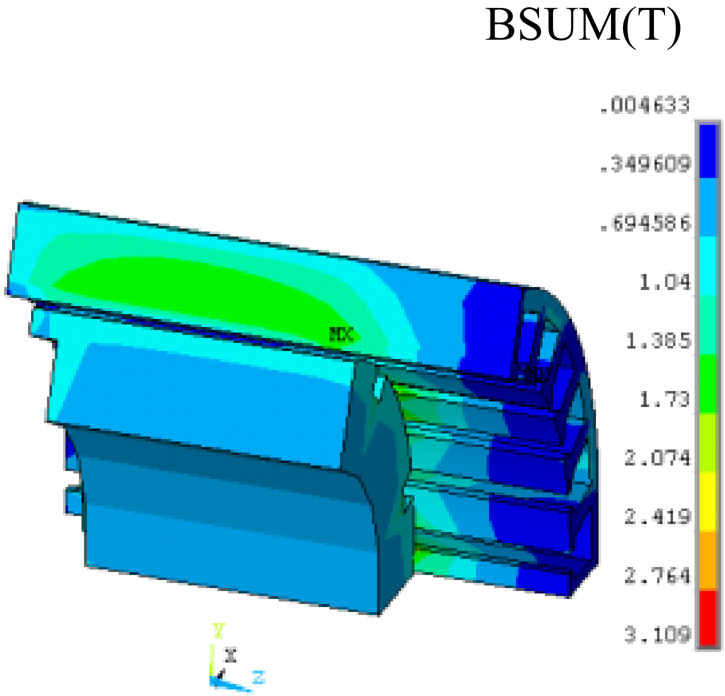
The value is consistent with the unequal stack since this model had less stack length.

```
___________TORQUE FOR 3D MACHINES__________
Axial Symmetry factor:_________ 1.
Angular Symmetry factor:_______ 5.
Method to compute torque:______ Maxwell's stress tensor.
Torque on rotor(Nm):___________ 1.6771 ( 238 oz-in).
________________________________________________
```

Rotor/magnet axial offset-continued

The stator shows a weak field in the additional length outside the overlap. The nonuniformity of the field in the axial direction is also shown.





Template requirements

If models are to be imported and it is intended to use the functionality of the toolbar , then the requirements are defined.

Material definitions

- 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)

Template requirements-continued

Components definition requirements

- All laminates use the following component names

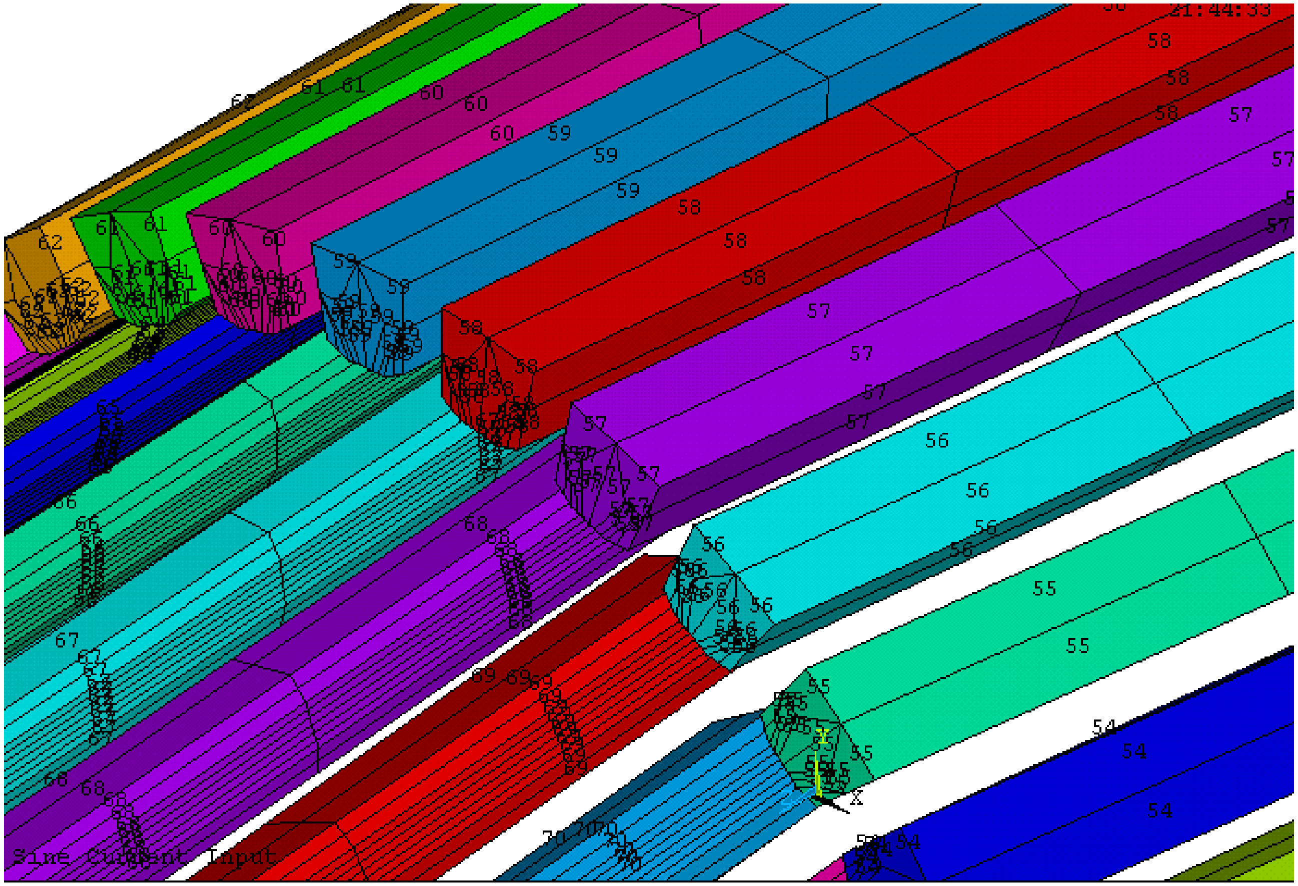
–rotor	component group for nodes/elements…
–stator	component group for nodes/elements
–s_coil	elements for stator coil
–r_iron	elements for magnet/iron in rotor; used for torque calculation

Real constant requirements

- Air gap on the stator side of the model : 6
- Air gap on the rotor side of the model : 5

Template requirements-continued

Each slot in the stator must have a unique real constant



Template requirements-continued

Certain parameters are required:

```
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
```

Winding data

```
w_file='mach2f'  !  winding file name
ax_clear=.1      !  axial clearance of winding with the stack
coil_w=.1        !  coil width
coil_h=.2        !  coil height
maxslotr=1.78    !  maximum outer radius of the slot
currform=‘sine’  !  Current form
```

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

Straight stack, skewed stator stacks with unequal lengths can be simulated

Appendix A

Macro list

for the 3D application

MACRO	DESCRIPTION	Calls
Aier_add	Demo macro for seminar	
B_mach3d	constructs an entire 3D model	Slotsta pmrotor mvrotor Rslotsta skew mach3d Pmach3d
B_wndsc	Constructs winding with CIRC124 from the winding file	G_area nowslt wire_gag wr_wnd
D_wnd	Deletes the winding	
copper	RSVX, MURX for copper	
Fmagbx	Applies force flags alows the summary file to be turned off	
G_parfil	Loads the parameter file from the toolbar	
Ld_coil	Applies current to a coil	
M14, m19, m2, m22, m27, m4, m43, m47, m50, m54, m6	M steels BH data	
Mabbr3d	Contains all the abbreviations for the toolbar	

Macro	Description	Calls
Mmf_	Computes MMF, retains path parameters	
mur	Computes the relative permeability	
mvpsol	Generates single static solution	
Mvrot3d	Rotates the rotor and connects to stator with CE. Updartes PM ccoordinate systems if present	Stitch6
Pmach3d	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	
Pl_force	Plots the nodal forces	
Sho_mod	Plots the brick model, coils or laminate	
skew	Skews the stack	
Rotsols	Solves multiple solution with a current form	Ld_coil tor_3d mvrot3d