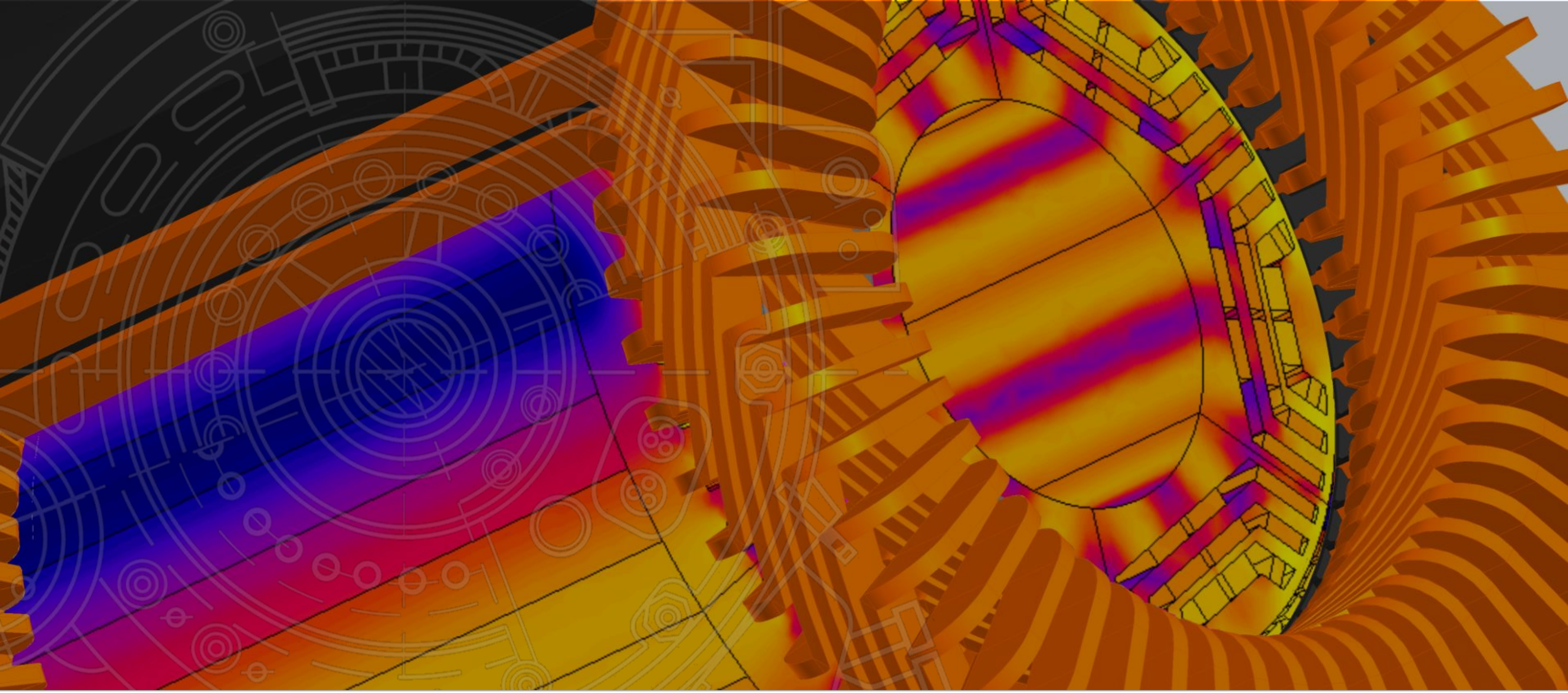

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INSET PMSM MAGNETO-THERMAL MODELING AND ANALYSIS

Flux 2D : Multiphysics Application Example

OUTLINE

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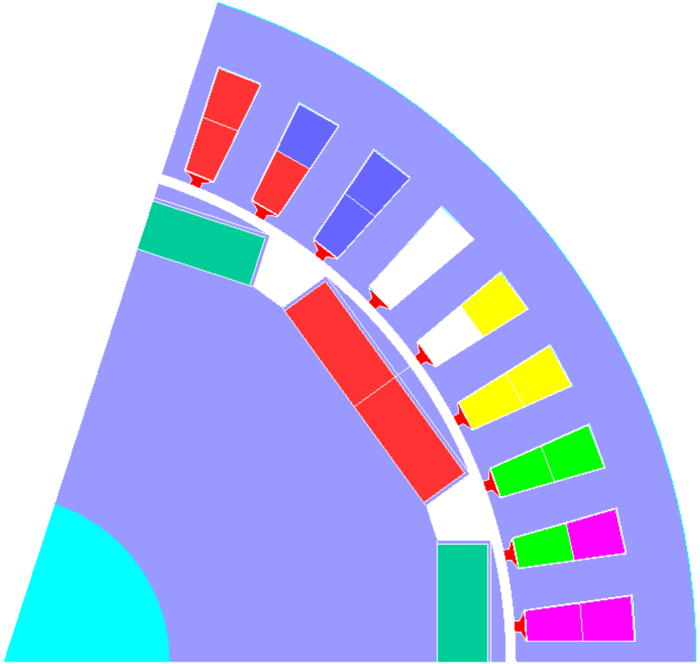
1. INTRODUCTION

1. Introduction

Modeling objectives

- **Performance study of an inset magnet PMSM**
    - Transient magnetic analysis
    - Steady-state thermal analysis
- **Comparison with measurement results**
    - Temperatures in critical points
    - Phase voltages and currents
    - Magnetic torque
    - Power balance and losses



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1. Introduction

About the machine: IKERMAQ

- **Permanent Magnet Synchronous Machine**
- **Sensor positioning in prototype**
  - Thermocouples in coil, magnets, and housing
  - Test coils to evaluate magnetic flux in teeth and yoke
- **Inset geometry**
  - Magnets are embedded in rotor but very close to the air gap

Parameter	IkerMAQ
Power	75 kW
Speed	1080 rpm
Torque	700 Nm
EMF (phase)	293 V_{rms}
Current (phase)	87 A_{rms}
External stator radius	0.188 m
Effective length	0.31 m
Pole pairs number	5
Slots number	45
Internal stator radius	0.139 m
Airgap	2.5 mm

1. Introduction

Operating point of the machine

- Operating point selected according to the test-bench
- Operating in generator mode
- **Mechanical input**: external driven machine
- **Electric output**: passive RL load

External driven machine

Passive RL load

Parameter	Value	Units
Speed	1080	rpm
Torque	452	Nm
R load	2.28	Ω
L load	3.165	mH

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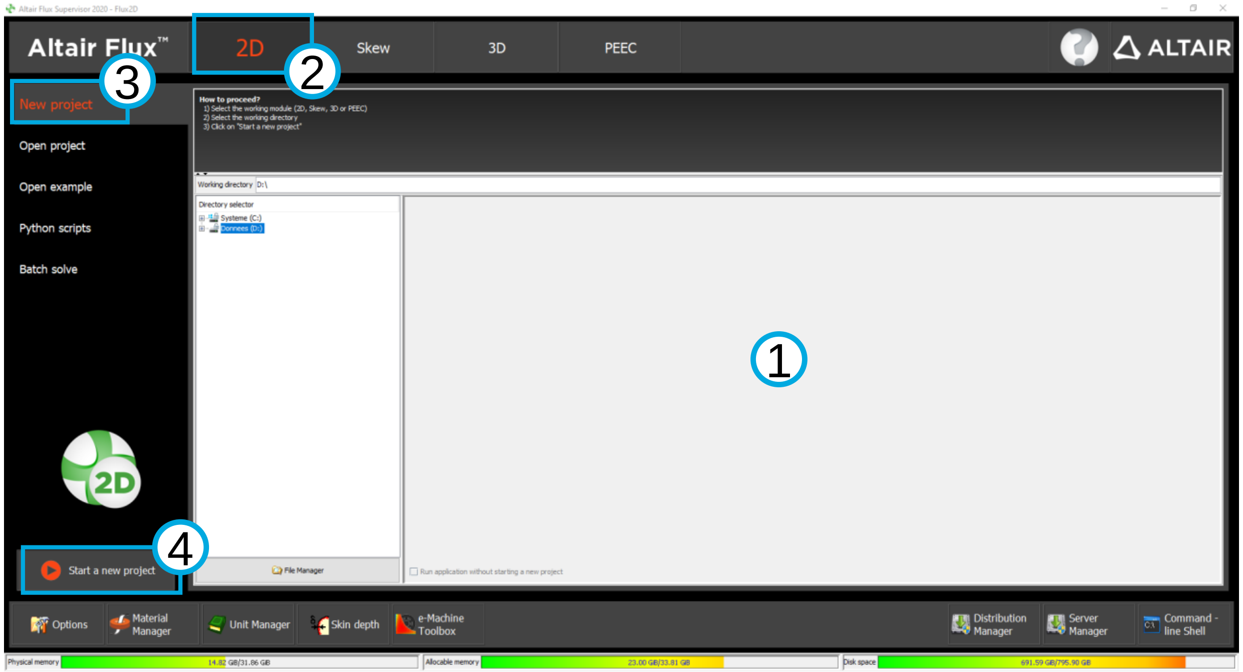
1. Introduction

Start a new project in Flux 2D

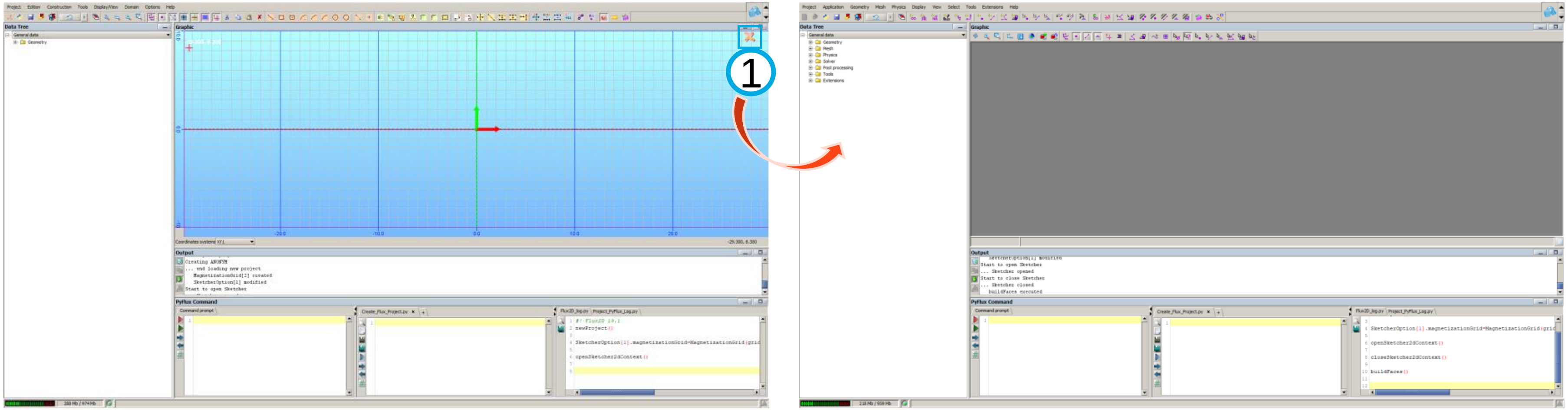


Step	Action
1	Open Flux supervisor
2	Select the [2D] simulation context
3	Click on [New project]
4	Click on [Start a new project]

1. Introduction

Start a new project in Flux 2D

Step	Action
1	Click on the icon to close the Flux Sketch context



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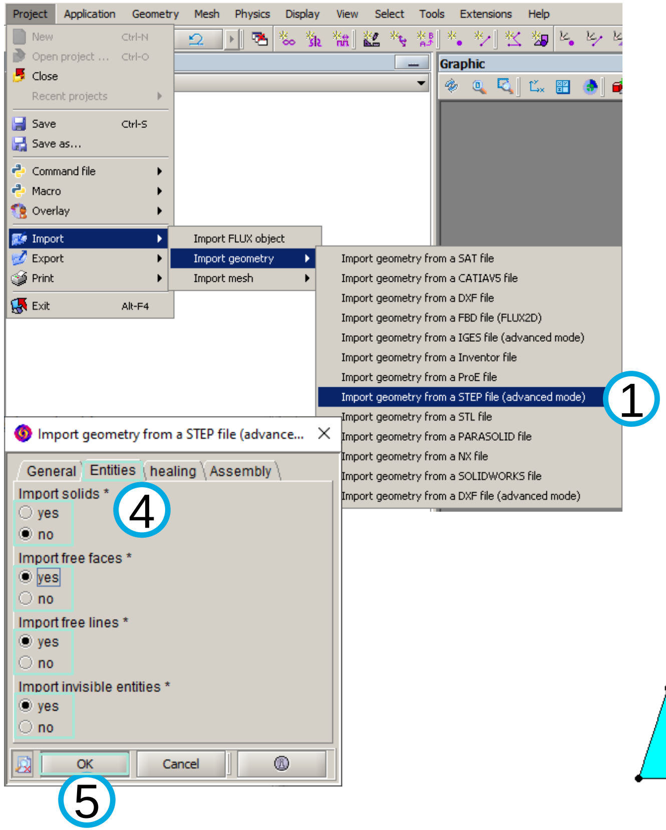
2. MAGNETIC ANALYSIS

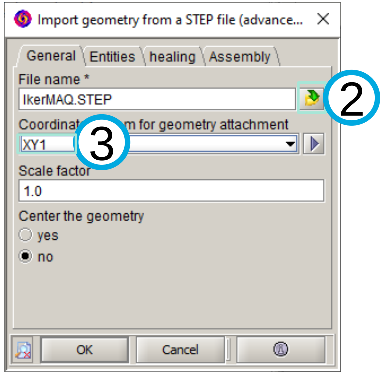
2.1 GEOMETRY AND MESHING

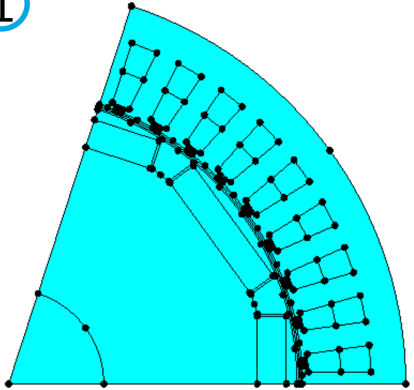
2.1 Magnetic Analysis: Geometry and meshing

2.1.1 Import the geometry

Step	Action
1	Import the IkerMAQ motor geometry by clicking on [Project] –[Import] – [Import geometry] – [Import geometry from a STEP file (advanced mode)]
2	Click on the icon , and locate the file “IkerMAQ.STEP”
3	Select “XY1” as the coordinate system
4	Click on [Entities] tab, import the faces, lines, and invisible entities, and DO NOT import the solids
5	Click on [OK]







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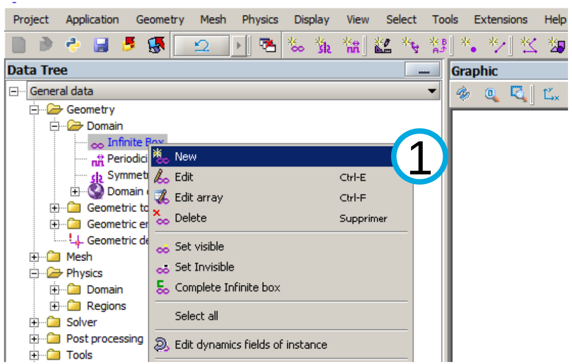
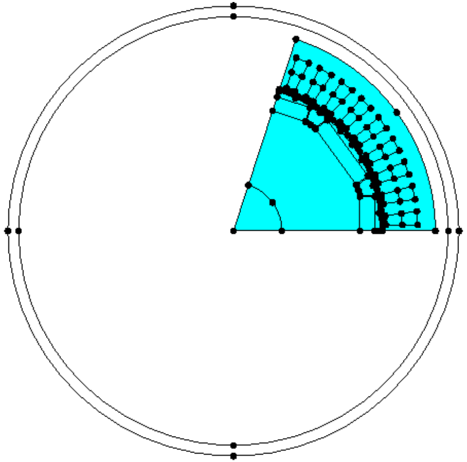
2.1 Magnetic Analysis: Geometry and meshing

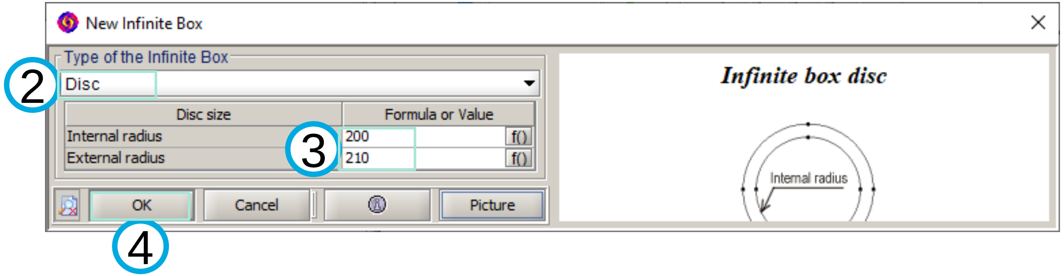
2.1.2 Create the infinite box

- Create a new Infinite box

Step	Action
1	Right click on the **Data Tree** [Geometry] – [Domain] – [Infinite box], and click on [New]
2	Select “Disc” as the type
3	Enter the size information
4	Click on [OK]







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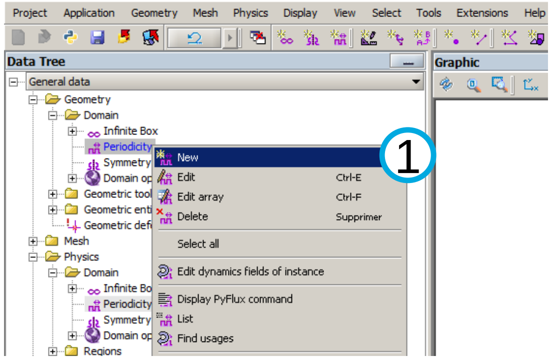
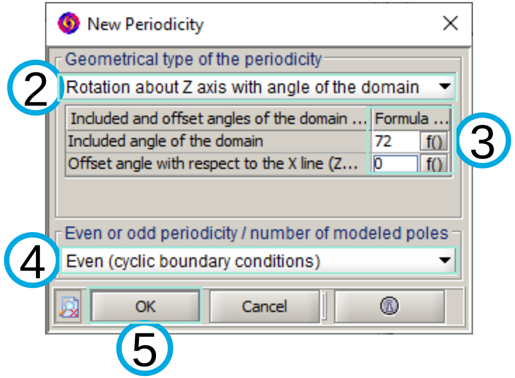
2.1 Magnetic Analysis: Geometry and meshing

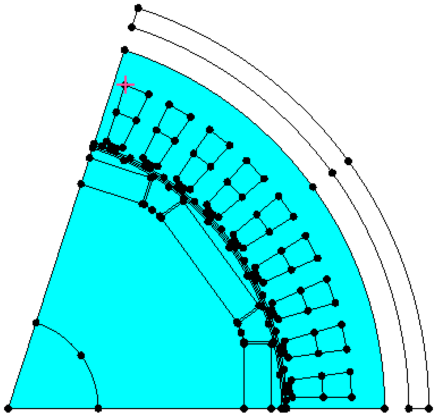
2.1.2 Create the infinite box

- Define the Periodicity

Step	Action
1	Right click on the **Data Tree** [Geometry] – [Domain] – [Periodicity], and click on [New]
2	Select "Rotation about Z axis with angle of the domain"
3	Enter the periodicity parameters
4	Select "Even (cyclic boundary conditions)"
5	Click on [OK]





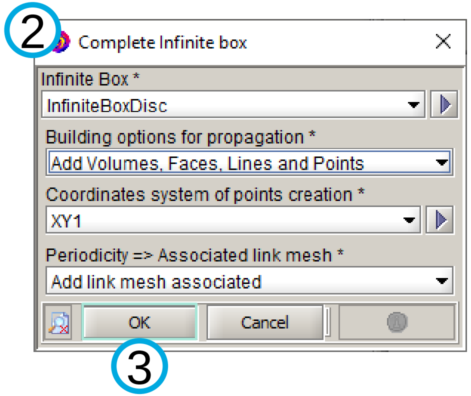


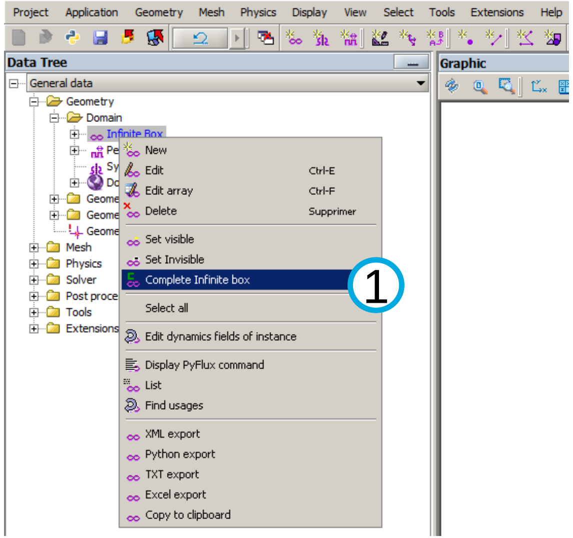
2.1 Magnetic Analysis: Geometry and meshing

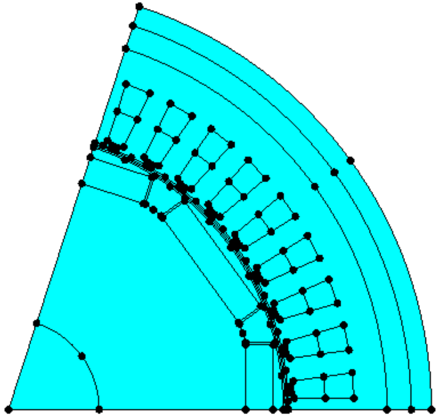
2.1.2 Create the infinite box

- Complete the Infinite box

Step	Action
1	Right click on the **Data Tree** [Geometry] – [Domain] - [Infinite box], and click on [Complete Infinite box]
2	Verify the setting parameters
3	Click on [OK]







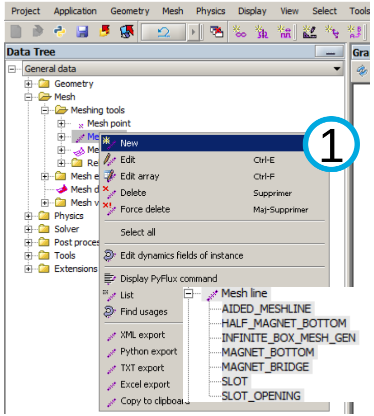
2.1 Magnetic Analysis: Geometry and meshing

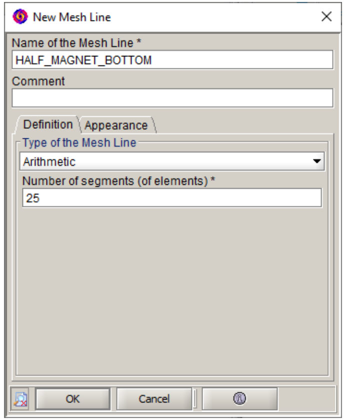
2.1.3 Mesh generation process

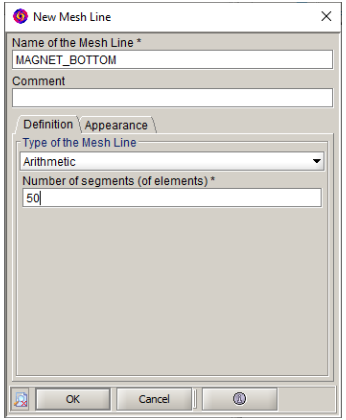
- Create Mesh lines

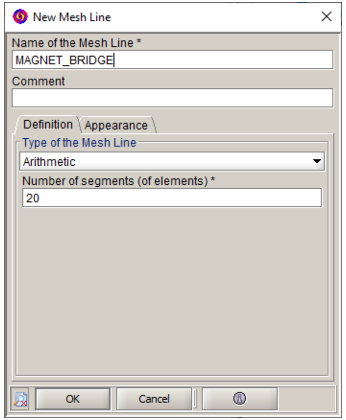
Step	Action
1	Right click on the **Data Tree** [Mesh] – [Meshing tools] - [Mesh line], and click on [New]
2	Create the following five Mesh lines

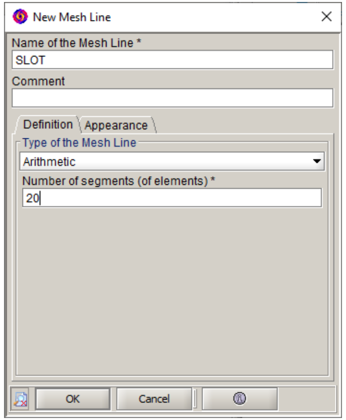
Name	Type	Number of segments
HALF_MAGNET_BOTTOM	Arithmetic	25
MAGNET_BOTTOM	Arithmetic	50
MAGNET_BRIDGE	Arithmetic	20
SLOT	Arithmetic	20
SLOT_OPENING	Arithmetic	5

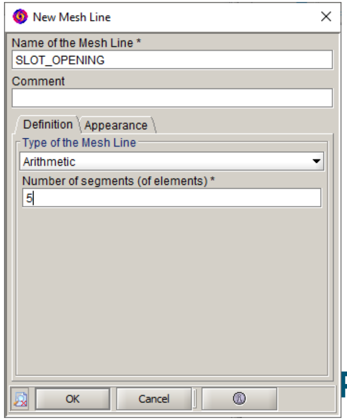








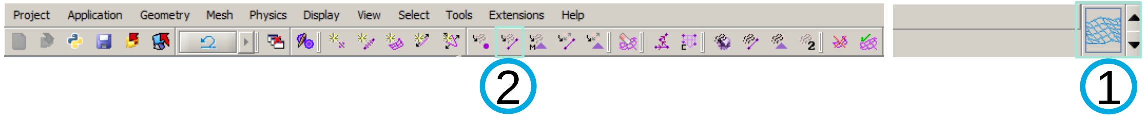




2.1 Magnetic Analysis: Geometry and meshing

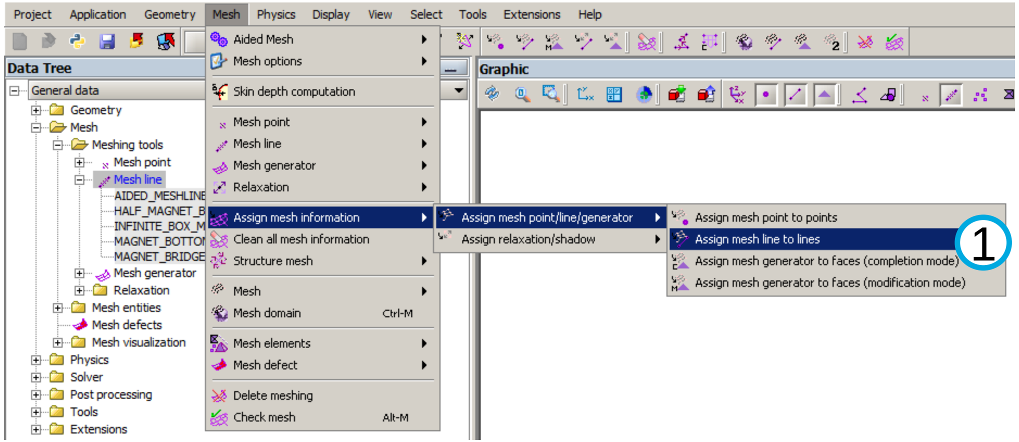
2.1.3 Mesh generation process

- Assign Mesh lines to Lines



Method 1	Action
1	Click on the icon to change to Mesh toolbar
2	Click on the icon to assign Mesh line to Lines

Method 2	Action
1	Click on [Mesh] – [Assign mesh information] – [Assign mesh point/line/generator] – [Assign mesh line to lines]



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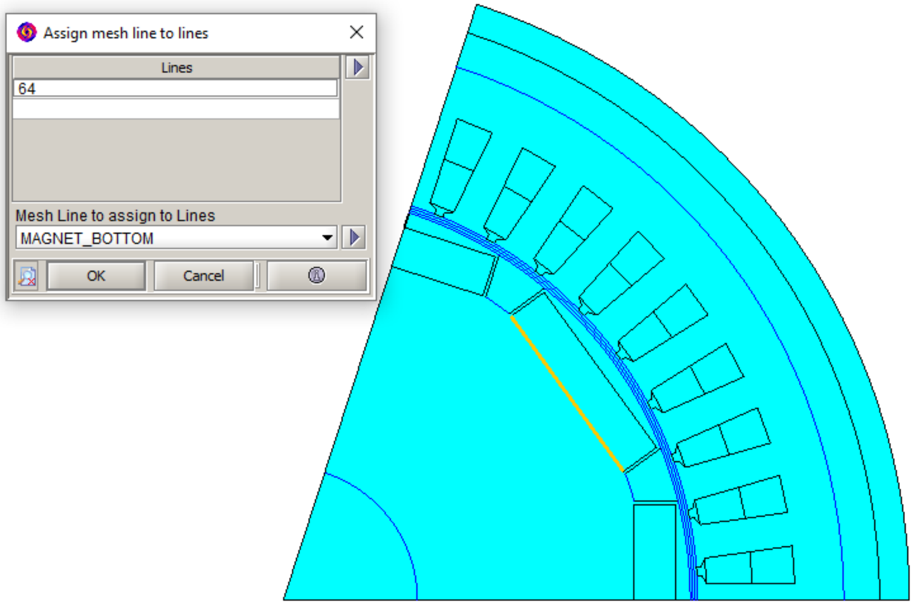
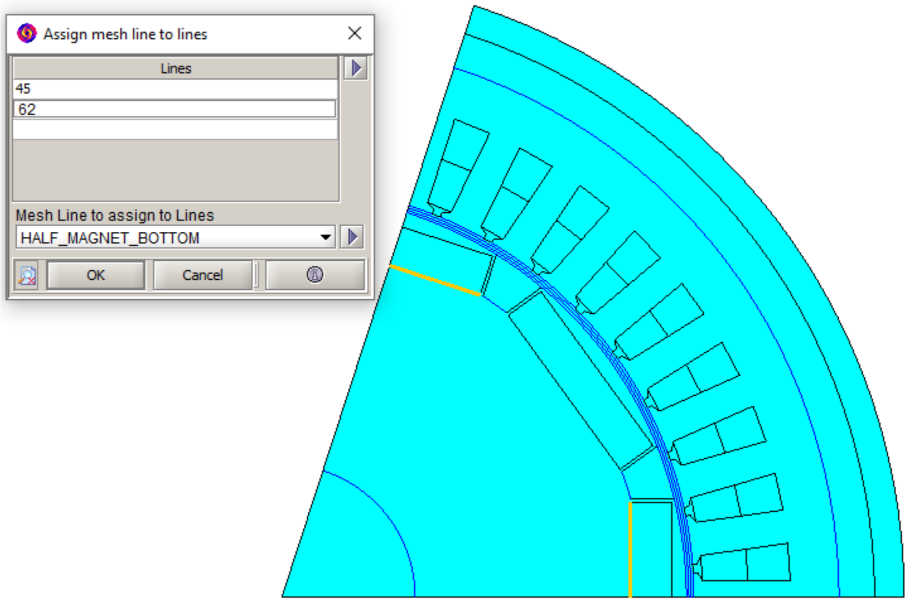
2.1 Magnetic Analysis: Geometry and meshing

2.1.3 Mesh generation process

- Assign Mesh lines to Lines
- MAGNET_BOTTOM and HALF_MAGNET_BOTTOM

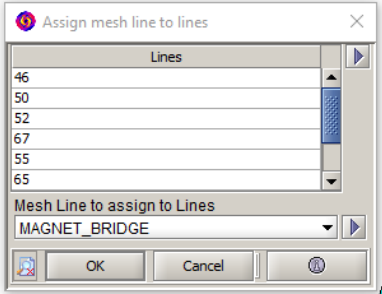


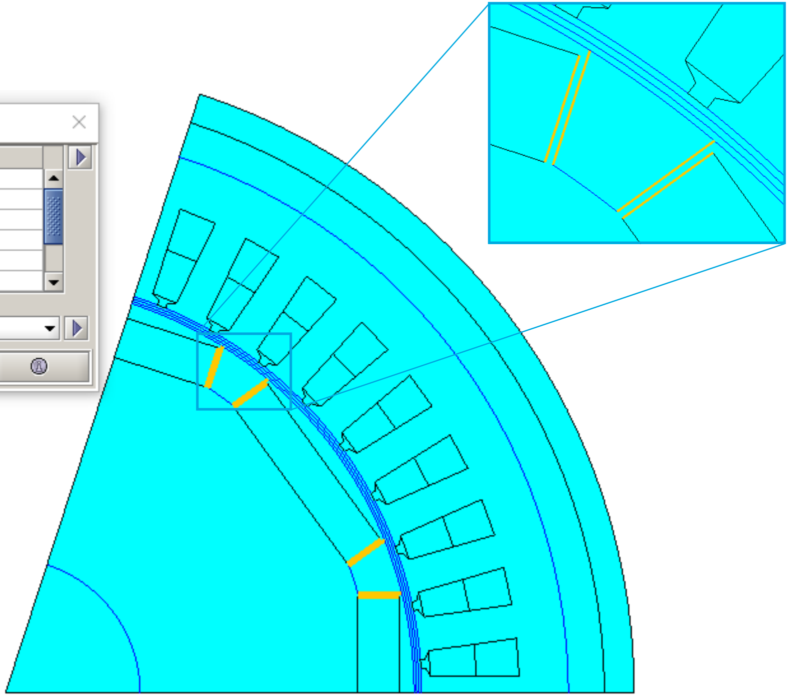


2.1 Magnetic Analysis: Geometry and meshing

2.1.3 Mesh generation process

- Assign Mesh lines to Lines
- MAGNET_BRIDGE

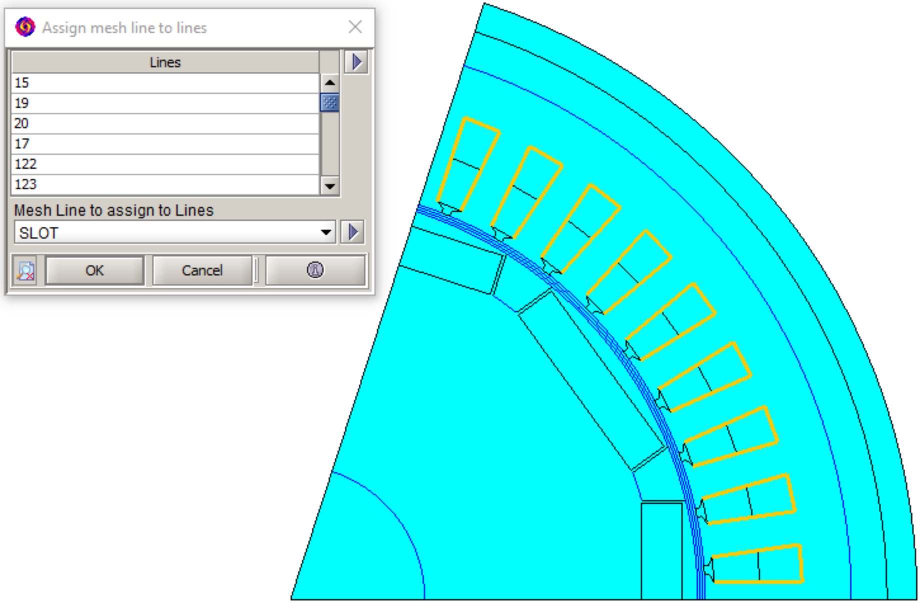


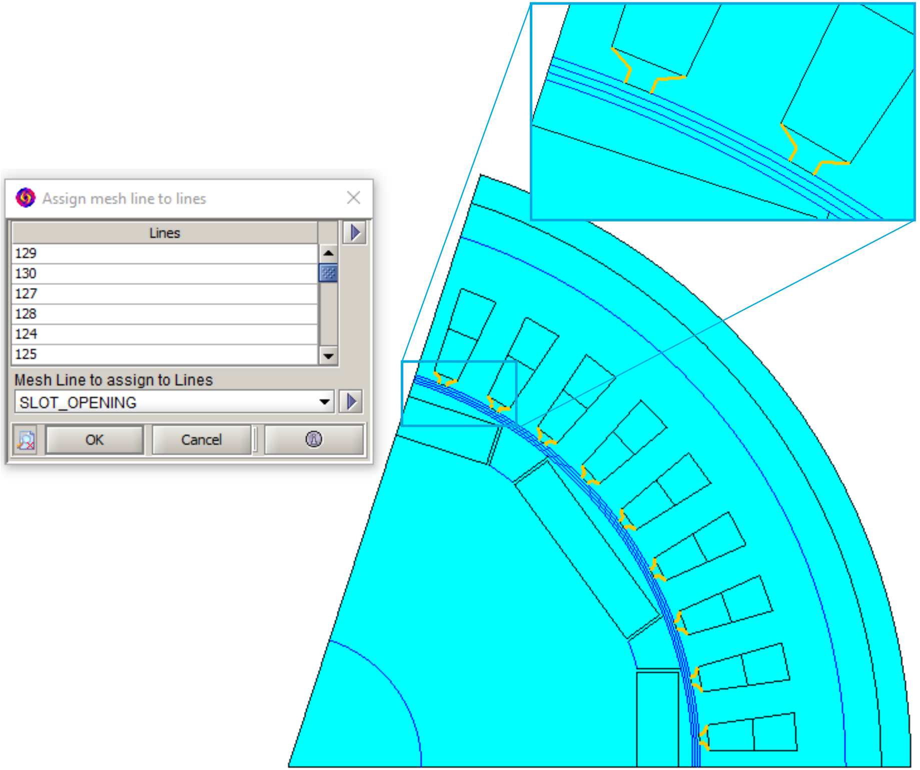


2.1 Magnetic Analysis: Geometry and meshing

2.1.3 Mesh generation process

- Assign Mesh lines to Lines
- SLOT and SOLT_OPENING





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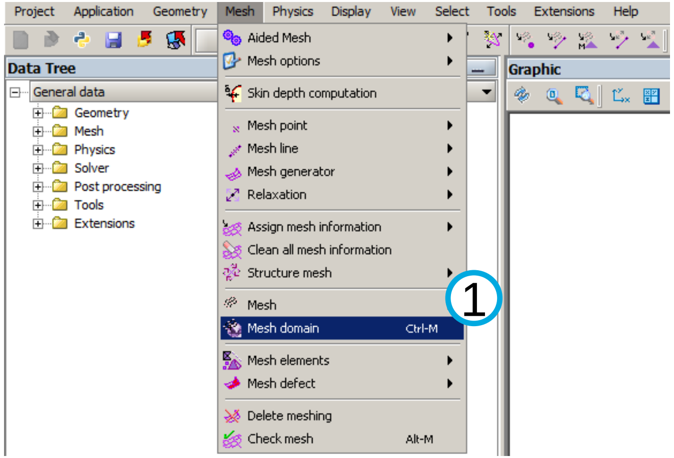
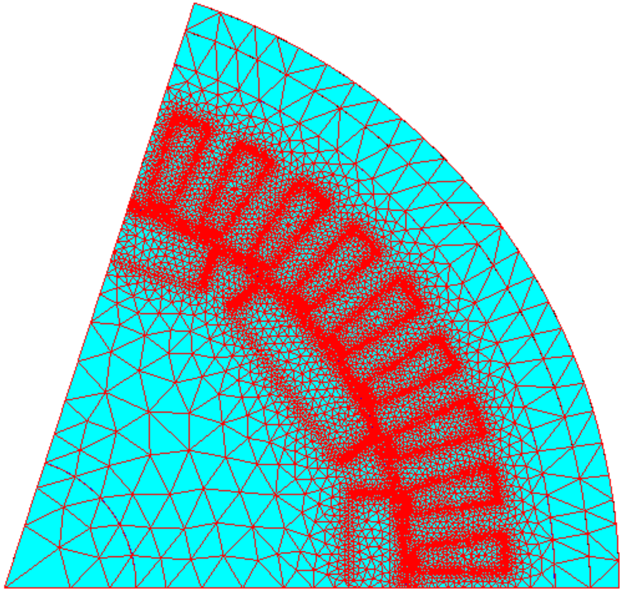
2.1 Magnetic Analysis: Geometry and meshing

2.1.3 Mesh generation process

- Mesh domain

Step	Action
1	Click on [Mesh] – [Mesh domain]



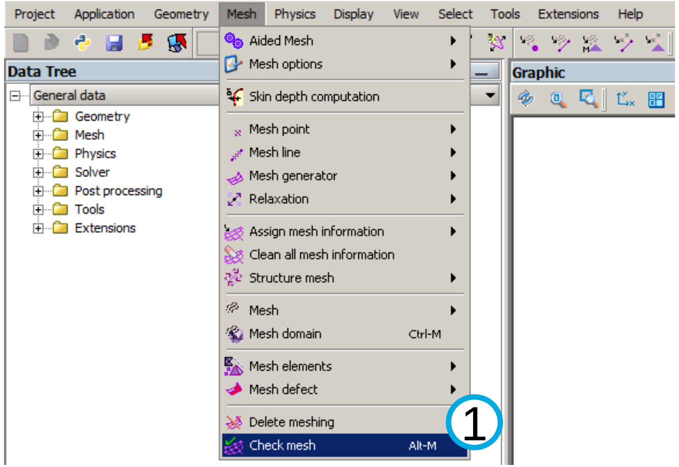


2.1 Magnetic Analysis: Geometry and meshing

2.1.3 Mesh generation process

- Check the mesh

Step	Action
1	Click on [Mesh] – [Check mesh]




```
Surface elements :
   Number of elements not evaluated     : 0  %
   Number of excellent quality elements : 98.97  %
   Number of good quality elements      : 0.95  %
   Number of average quality elements   : 0.08  %
   Number of poor quality elements      : 0  %

Number of nodes : 30579
Number of line elements : 2514
Number of surface elements : 15238
Mesh order : 2nd order
```

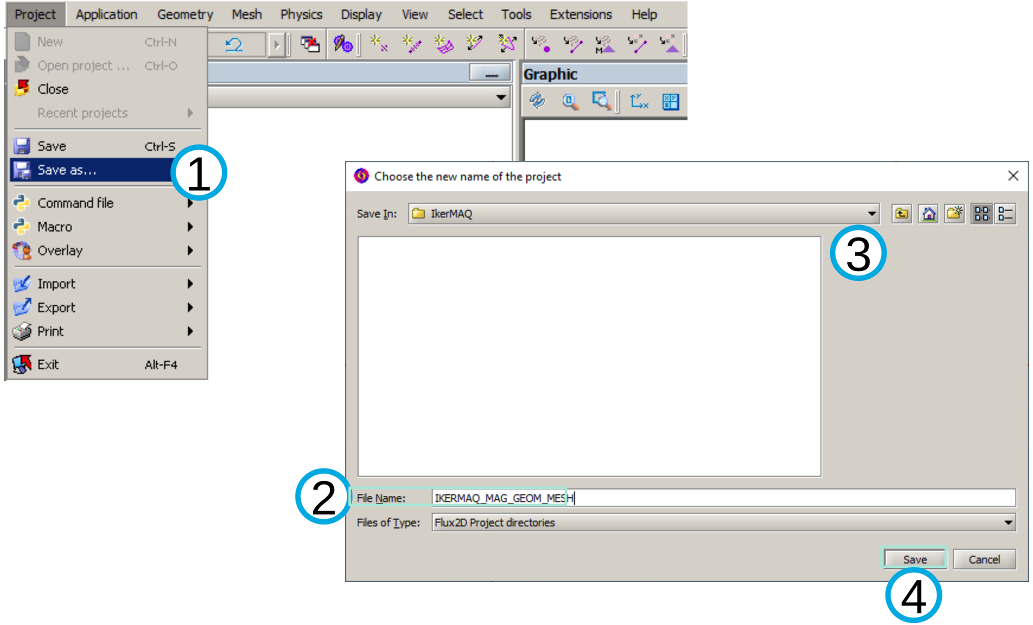
Tips: exact number of elements may depend on Flux version

2.1 Magnetic Analysis: Geometry and meshing

2.1.4 Save the project

- Project name: IKERMAQ_MAG_GEOM_MESH.FLU

Step	Action
1	Click on [Project] – [Save as]
2	Define the project name as “IKERMAQ_GEOM_MESH.FLU”
3	Verify the location
4	Click on [OK]



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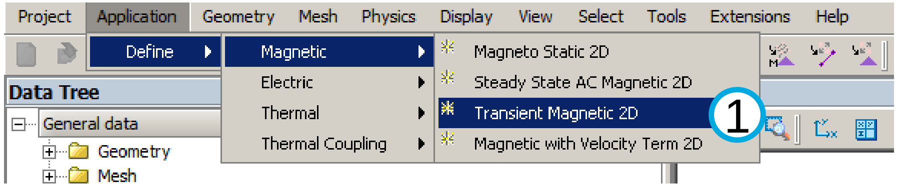
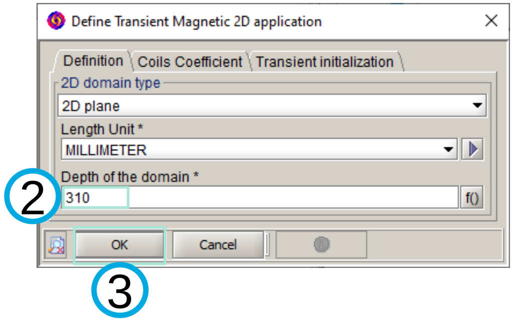
2.2 PHYSICAL DESCRIPTION PROCESS

2.2 Magnetic Analysis: Physical description process

2.2.1 Define the simulation application

Step	Action
1	Click on [Application] – [Define] – [Magnetic] – [Transient Magnetic 2D]
2	In the [Definition] tab, define "310" as the depth of the domain
3	Click on [OK]





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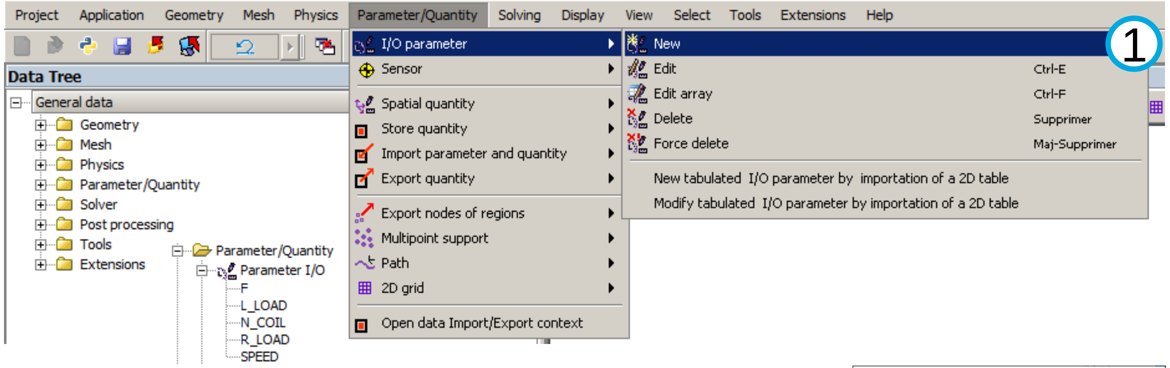
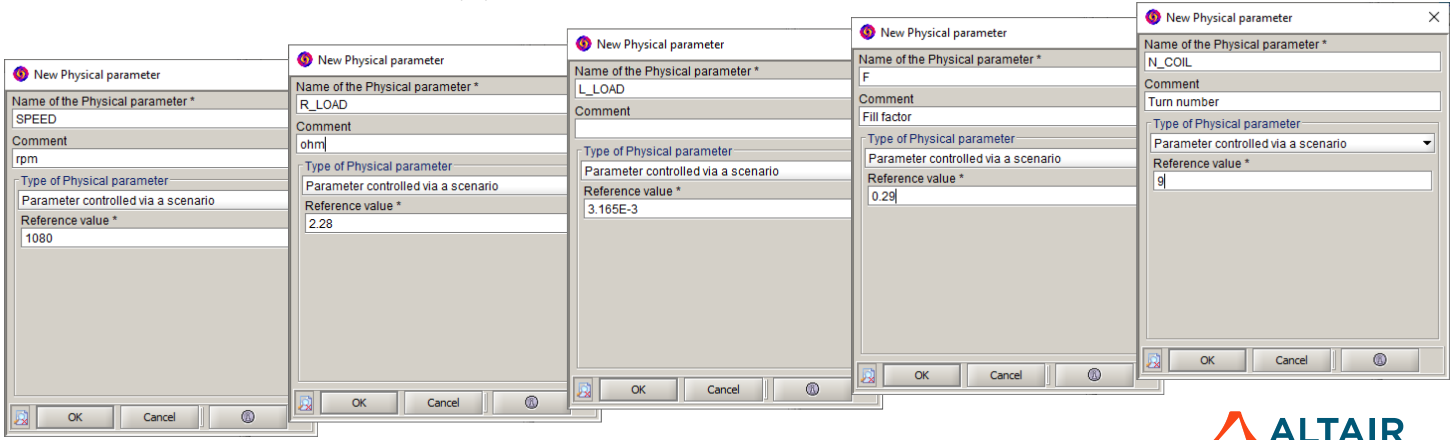
2.2 Magnetic Analysis: Physical description process

2.2.2 Create I/O parameters

Step	Action
1	Click on [Parameter/Quantity] – [I/O Parameter] – [New]
2	Create the following five "Physical parameters"



Name	Reference value
SPEED	1080
R_LOAD	2.28
L_LOAD	3.165E-3
F	0.29
N_COIL	9



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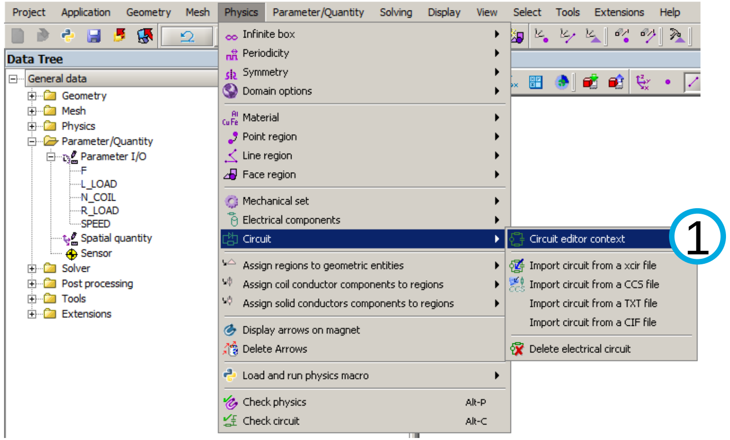
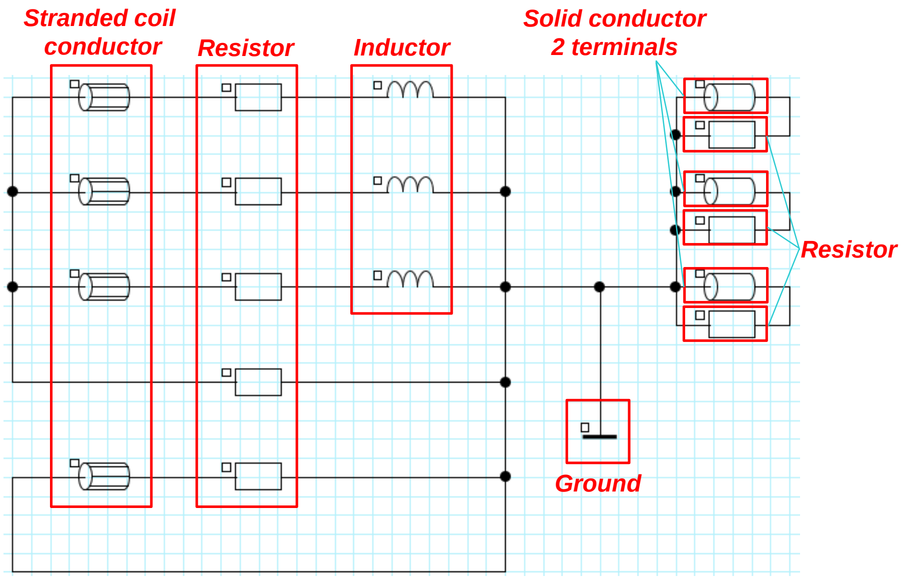
2.2 Magnetic Analysis: Physical description process

2.2.3 Define the coupling circuit

- Create the coupling circuit

Step	Action
1	Click on [Physics] – [Circuit] – [New]
2	Create the following coupling circuit



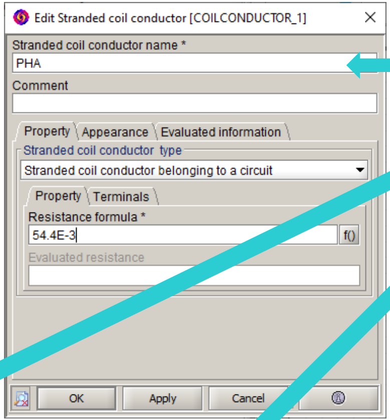


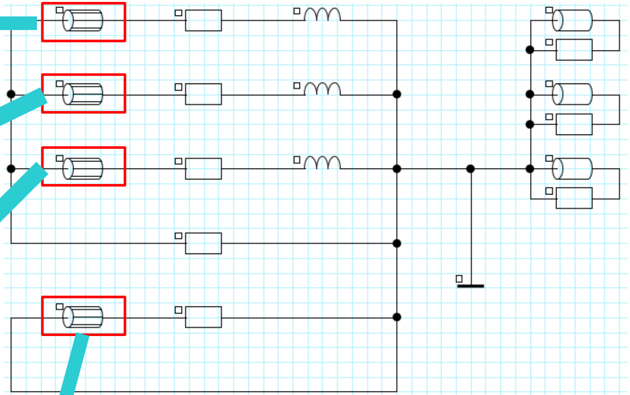
2.2 Magnetic Analysis: Physical description process

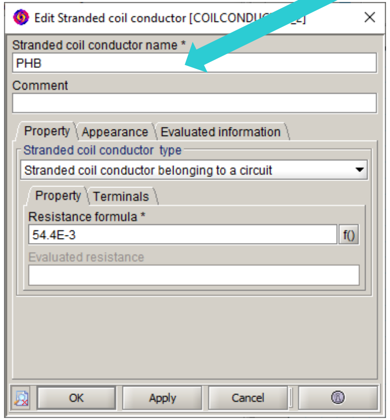
2.2.3 Define the coupling circuit

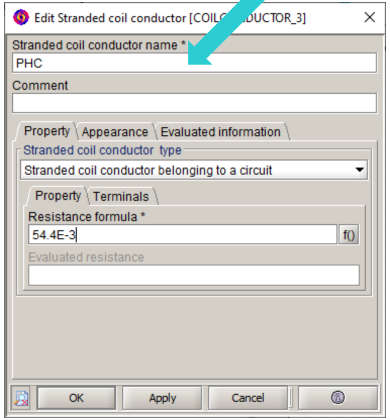
- Define component parameters

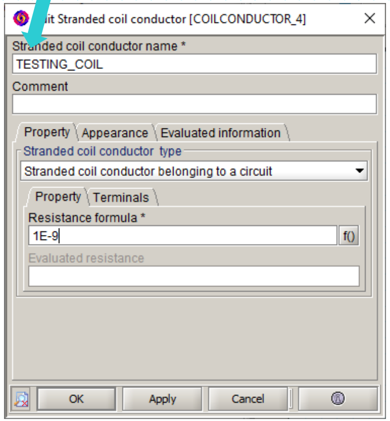
Step	Action
1	Double click respectively on the four Stranded coil conductors
2	Enter the name and the resistance value for each Stranded coil conductor









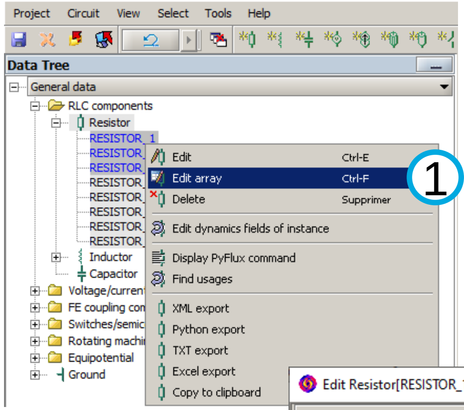


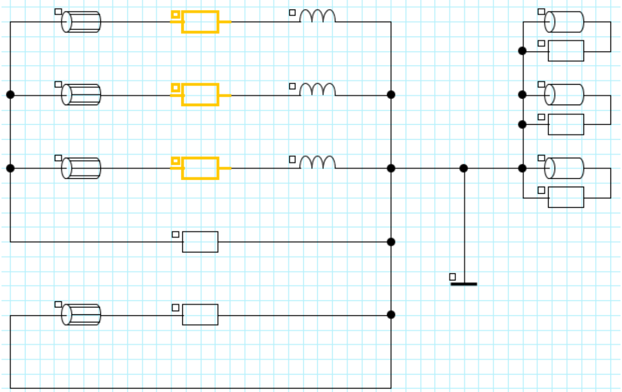
2.2 Magnetic Analysis: Physical description process

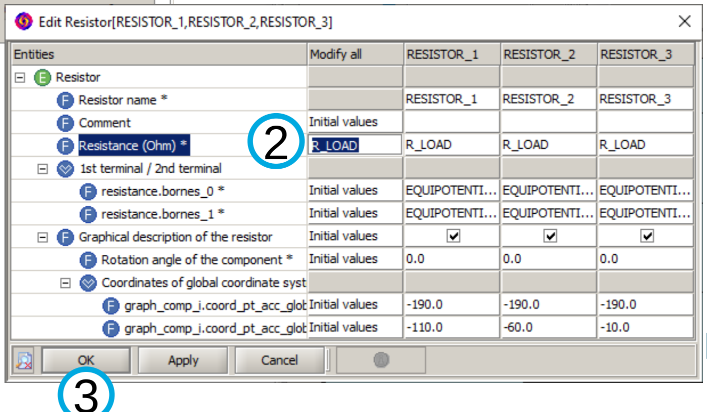
2.2.3 Define the coupling circuit

- Define component parameters

Step	Action
1	Select the three load resistors from the **Data Tree** [RLC components] – [Resistor], right click and click [Edit array]
2	Modify all the Resistance value by the parameter “R_LOAD”
3	Click on [OK]





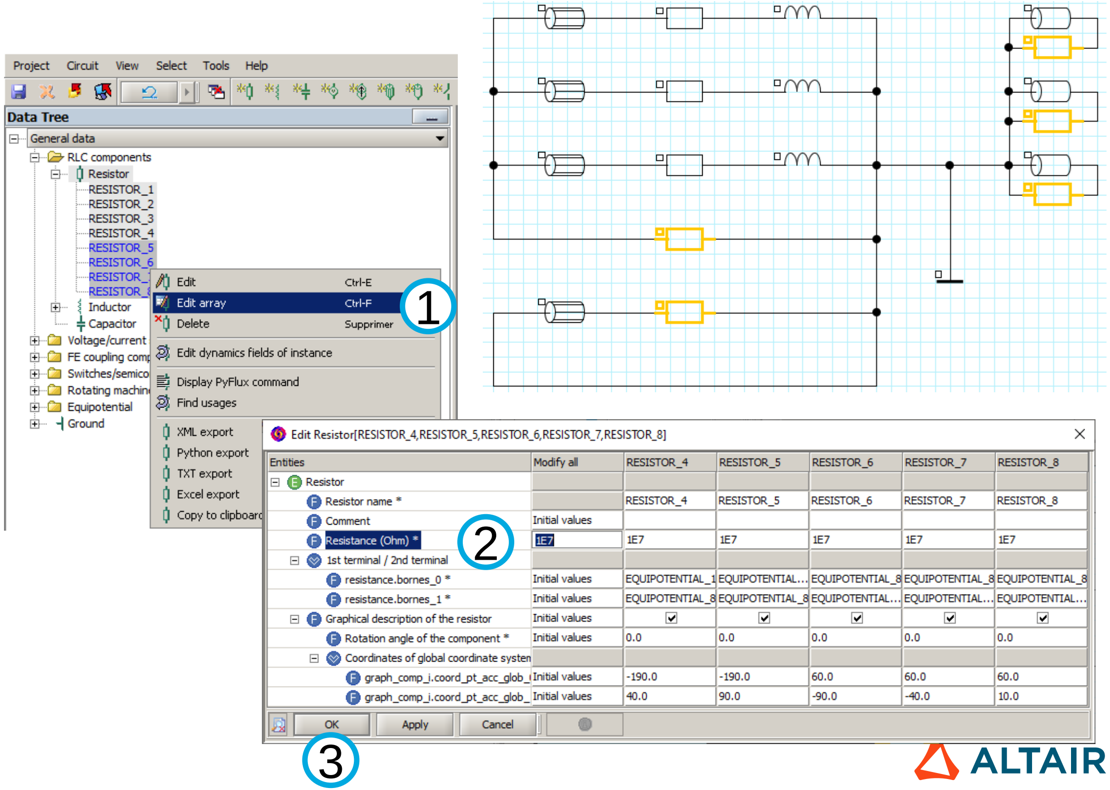


2.2 Magnetic Analysis: Physical description process

2.2.3 Define the coupling circuit

- Define component parameters

Step	Action
1	Select the other resistors from the **Data Tree** [RLC components] – [Resistor], right click and click [Edit array]
2	Modify all the Resistance value by “1E7”
3	Click on [OK]



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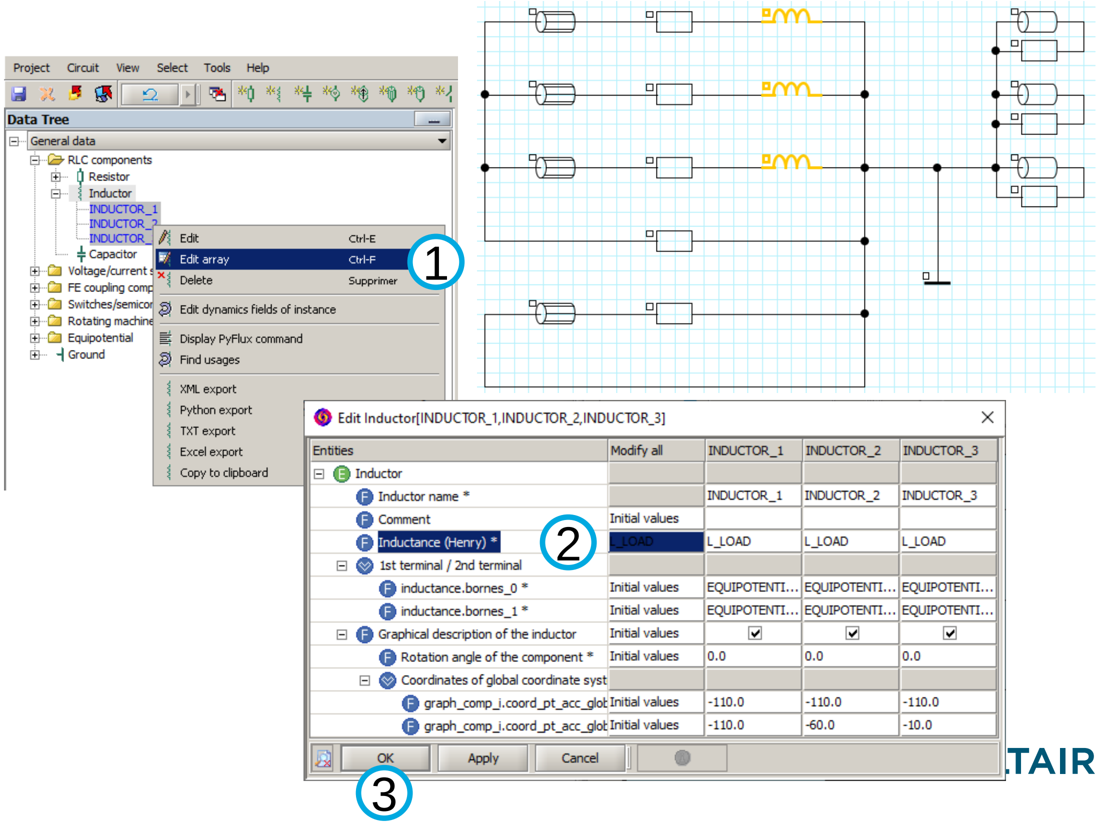
2.2 Magnetic Analysis: Physical description process

2.2.3 Define the coupling circuit

- Define component parameters

Step	Action
1	Select the three load inductors from the **Data Tree** [RLC components] – [Inductor], right click and click [Edit array]
2	Modify all the Inductance value by parameter “L_LOAD”
3	Click on [OK]



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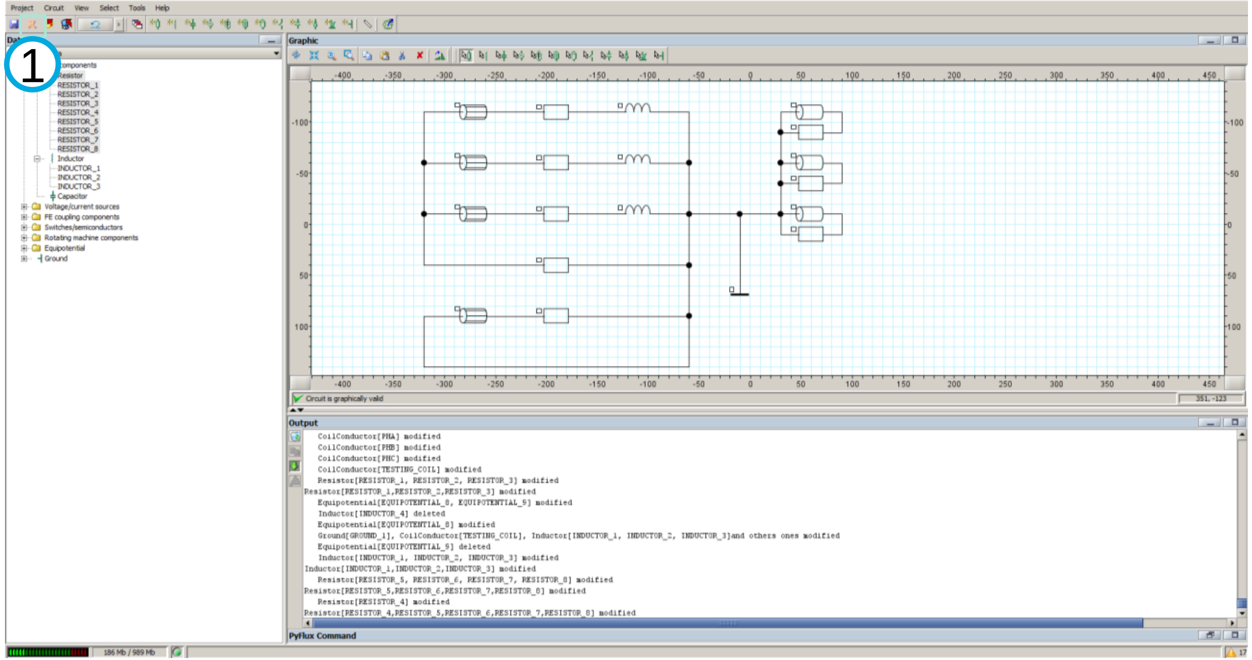
2.2 Magnetic Analysis: Physical description process

2.2.3 Define the coupling circuit

- Close the Circuit editor context

Step	Action
1	Click on the icon to close the Circuit editor context



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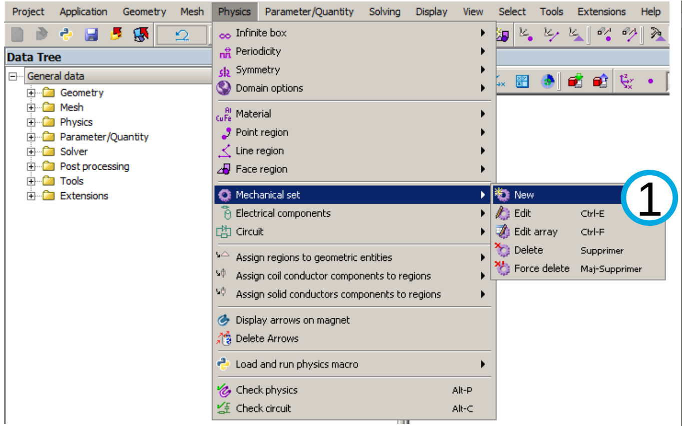
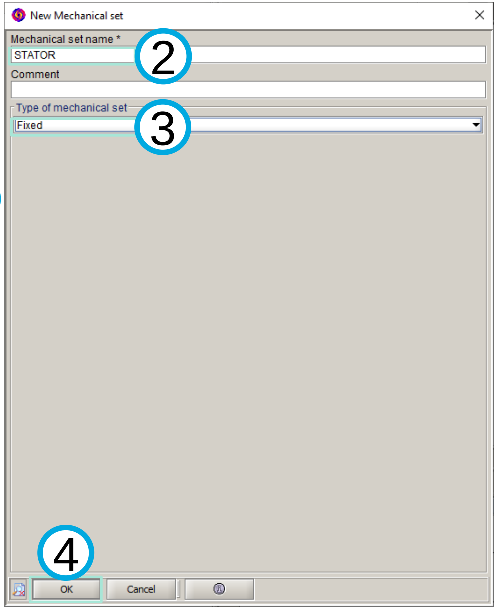
2.2 Magnetic Analysis: Physical description process

2.2.4 Create mechanical sets

- Fixed Mechanical set: STATOR

Step	Action
1	Click on [Physics] – [Mechanical set] – [New]
2	Define the name as "STATOR"
3	Select the type "Fixed"
4	Click on [OK]





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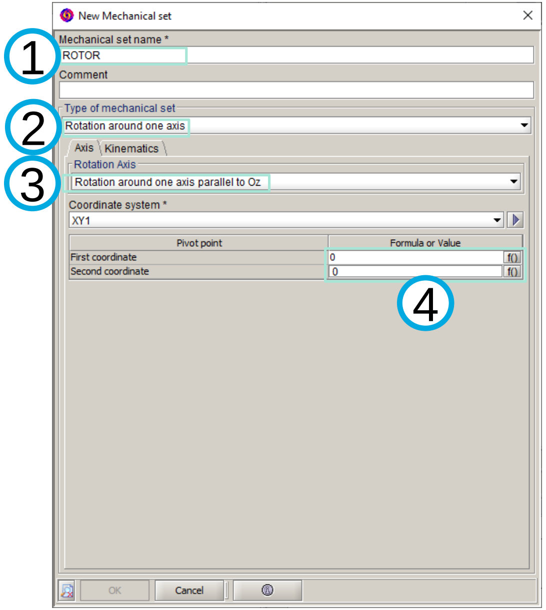
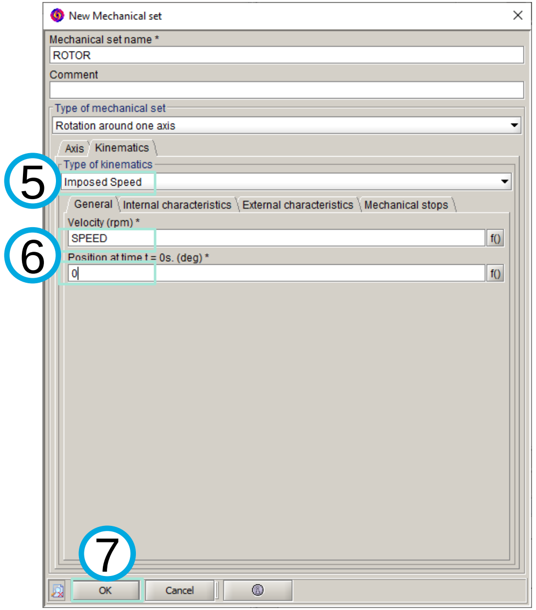
2.2 Magnetic Analysis: Physical description process

2.2.4 Create mechanical sets

- Rotation Mechanical set: ROTOR

Step	Action
1	Create the second mechanical set, define the name as “ROTOR”
2	Select the type as “Rotation around one axis”
3	Select the axis as “Rotation around one axis parallel to Oz”
4	Define the pivot point as (0, 0)
5	In [Kinematics] tab, select the type as “Imposed Speed”
6	Define the parameter “SPEED” as the velocity, initial position as 0.
7	Click on [OK]



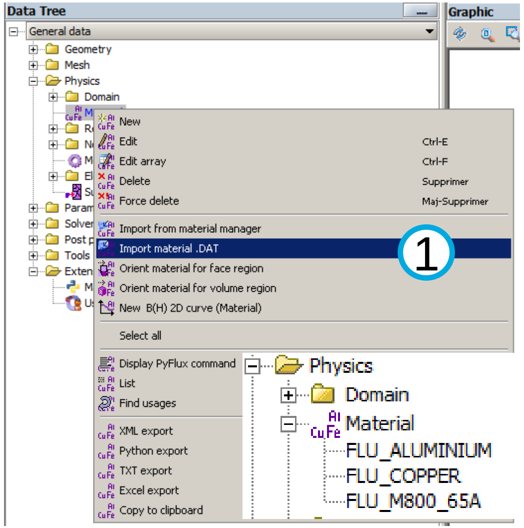


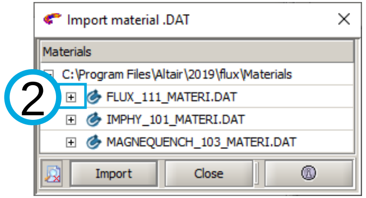
2.2 Magnetic Analysis: Physical description process

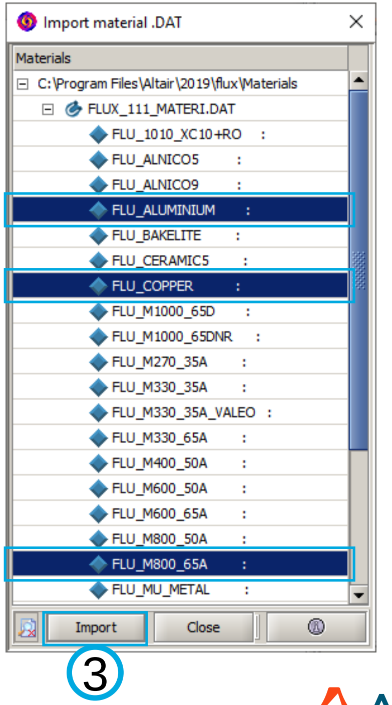
2.2.5 Define materials for the motor

- Import material (.DAT file)

Step	Action
1	Right click on the **Data Tree** [Physics] – [Material], click on [Import material .DAT]
2	Click on the [+] to release the material list “FLUX_111_MATERI.DAT”
3	Press on [Ctrl], multi-select “FLU_ALUMINIUM”, “FLU_COPPER”, and “FLU_M800_65A”, click on [Import]





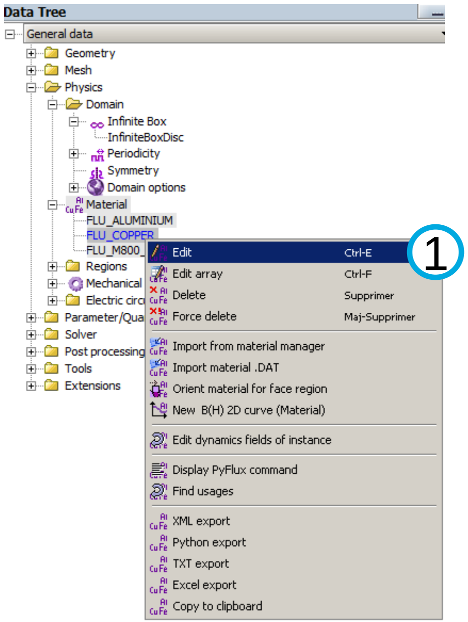


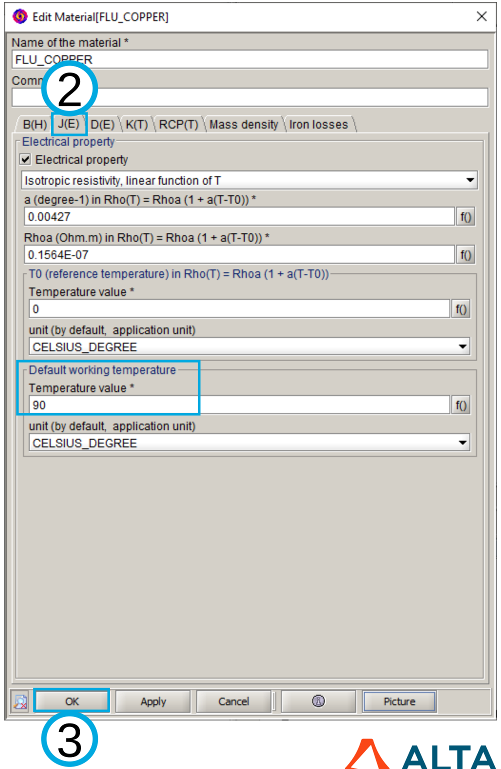
2.2 Magnetic Analysis: Physical description process

2.2.5 Define materials for the motor

- Modify material properties

Step	Action
1	Right click on the **Data Tree** [Physics] – [Material] – [FLU_COPPER], and click on [Edit]
2	Modify the Default working temperature value in the [J(E)] tab
3	Click on [OK]





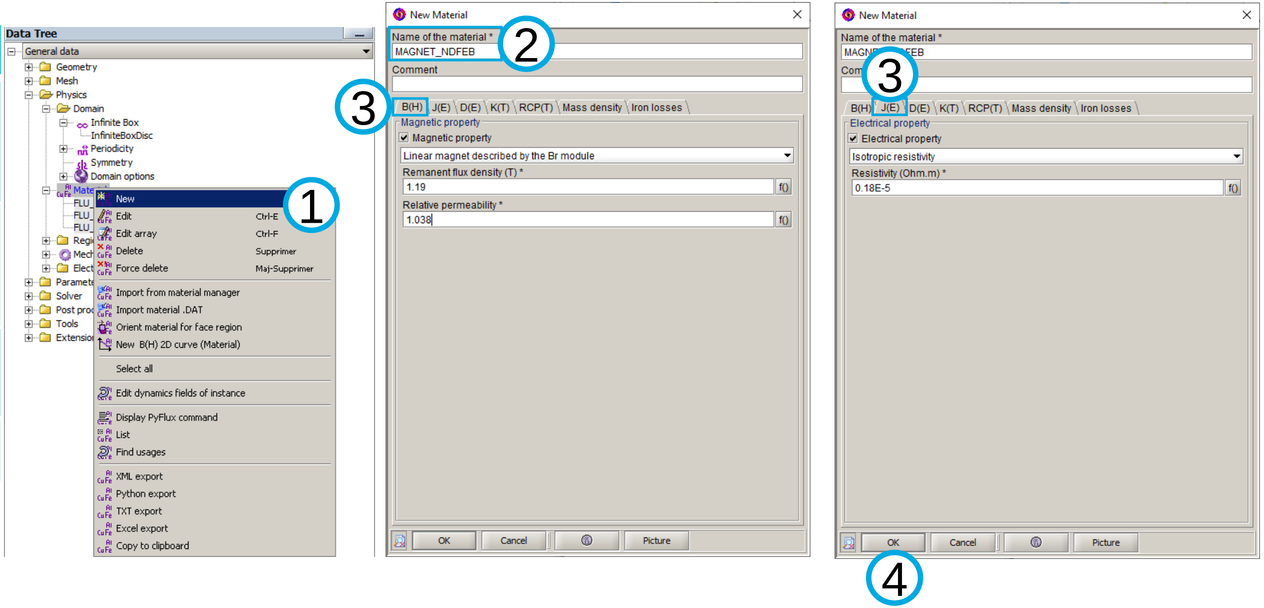
ALTAIR

2.2 Magnetic Analysis: Physical description process

2.2.5 Define materials for the motor

- Create the magnet material

Step	Action
1	Right click on the Data Tree [Physics] – [Material], and click on [New]
2	Define the name of the material as “MAGNET_NDFEB”
3	Enter the material properties in the B(H) and the J(E) tab
4	Click on [OK]



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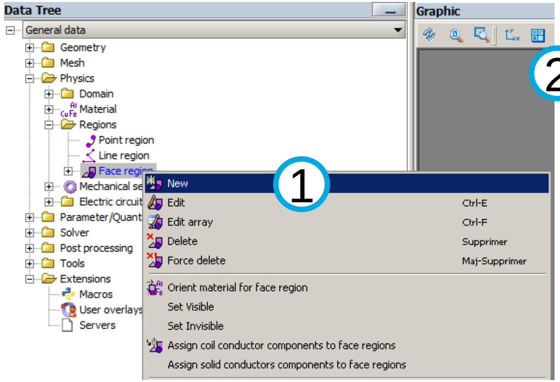
2.2 Magnetic Analysis: Physical description process

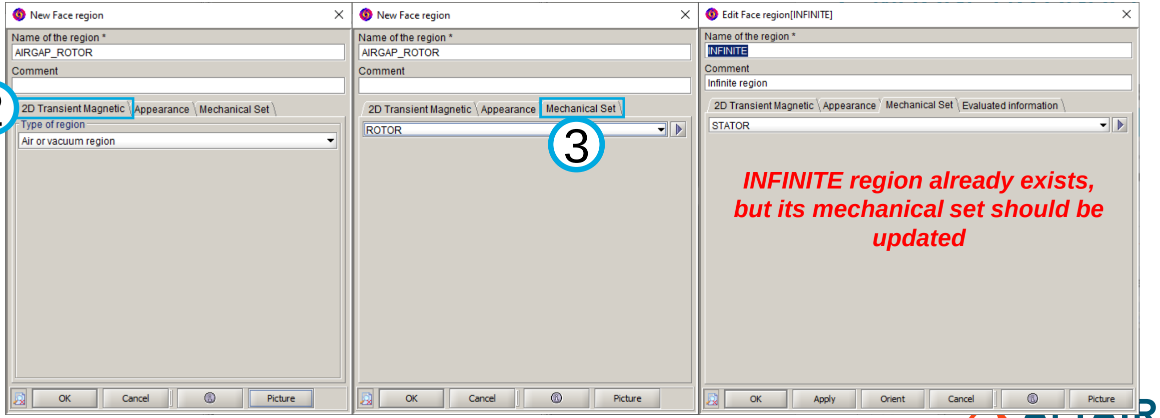
2.2.6 Create face regions

- Define non laminated, non magnet Face regions

Step	Action
1	Right click on the **Data Tree** [Physics] - [Regions] – [Face region], click on [New]
2	Define the [2D Transient Magnetic] type
3	Define the Mechanical Set

Volume region name	Type of region	Material	Mechanical set
AIRGAP_ROTOR	Air or vacuum region	-	ROTOR
SHAFT	Magnetic non conducting region	FLU_ALUMINIUN	ROTOR
AIRGAP_STATOR	Air or vacuum region	-	STATOR
WEDGE	Air or vacuum region	-	STATOR
AIR	Air or vacuum region	-	STATOR
INFINITE	Air or vacuum region	-	STATOR



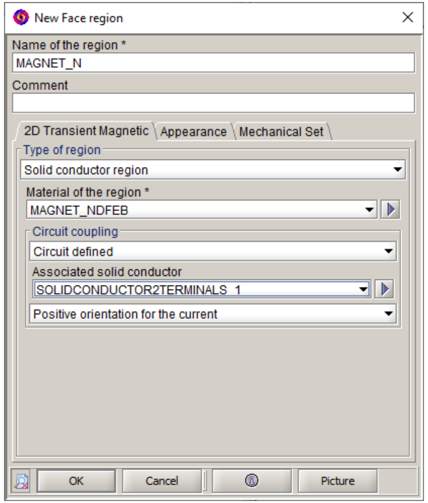


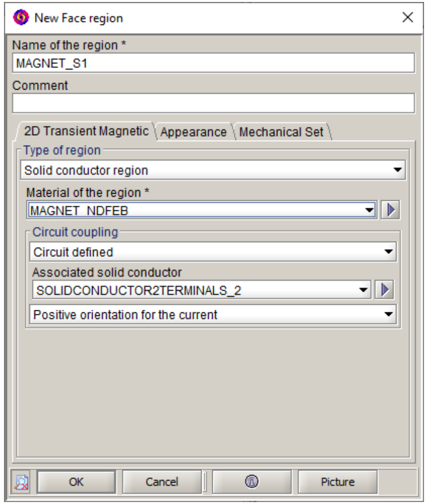
2.2 Magnetic Analysis: Physical description process

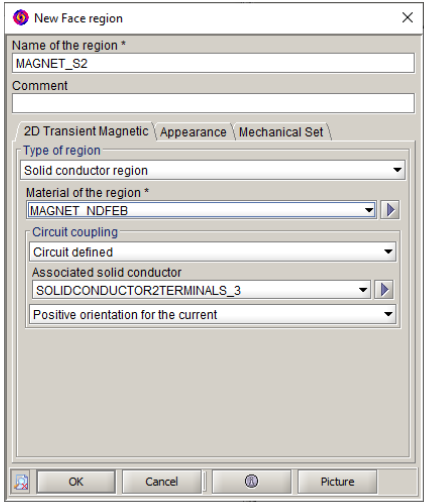
2.2.6 Create face regions

- Define magnet Face regions

Volume region name	Type of region	Material	Circuit coupling	Associated solid conductor	Orientation	Mechanical set
MAGNET_N	Solid conductor region	MAGNET_NDFEB	Circuit defined	SOLIDCONDUCTOR2TERMINALS_1	Positive	ROTOR
MAGNET_S1	Solid conductor region	MAGNET_NDFEB	Circuit defined	SOLIDCONDUCTOR2TERMINALS_2	Positive	ROTOR
MAGNET_S2	Solid conductor region	MAGNET_NDFEB	Circuit defined	SOLIDCONDUCTOR2TERMINALS_3	Positive	ROTOR







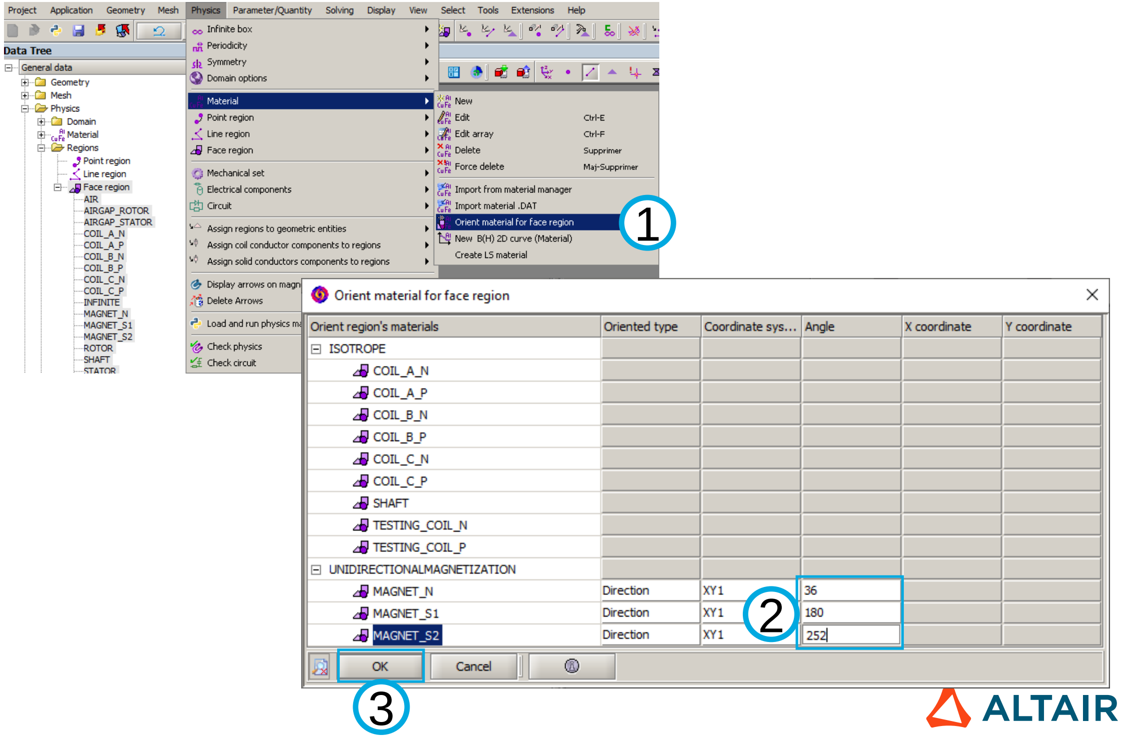
ALTAIR

2.2 Magnetic Analysis: Physical description process

2.2.6 Create face regions

- Define magnet Face regions

Step	Action
1	Click on the [Physics] - [Material] – [Orient material for face region]
2	Define the oriented angle for the three magnet regions
3	Click on [OK]



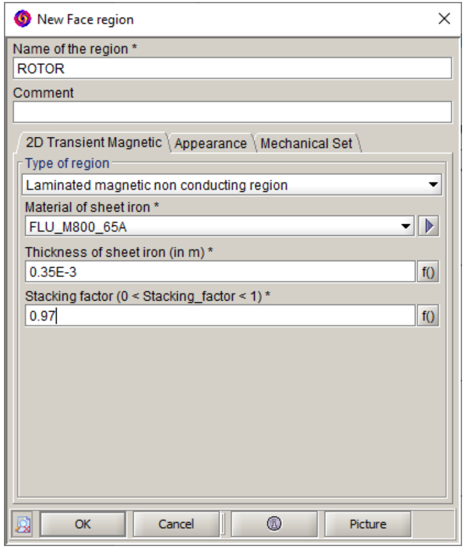
ALTAIR

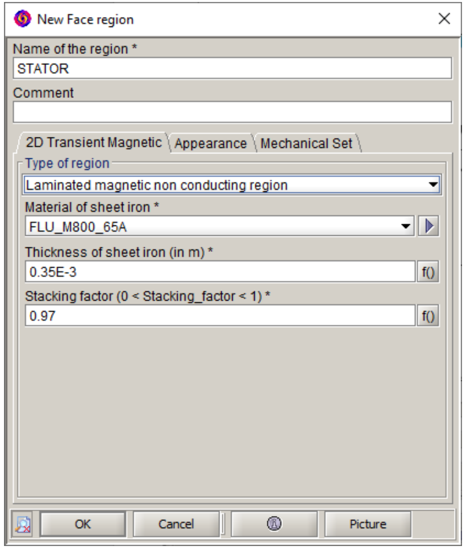
2.2 Magnetic Analysis: Physical description process

2.2.6 Create face regions

- Define laminated Face regions

Volume region name	Type of region	Material	Thickness	Stacking factor	Mechanical set
ROTOR	Laminated magnetic non conducting region	FLU_M800_65A	0.35E-3	0.97	ROTOR
STATOR	Laminated magnetic non conducting region	FLU_M800_65A	0.35E-3	0.97	STATOR





2.2 Magnetic Analysis: Physical description process

2.2.6 Create face regions

- Define coil Face regions

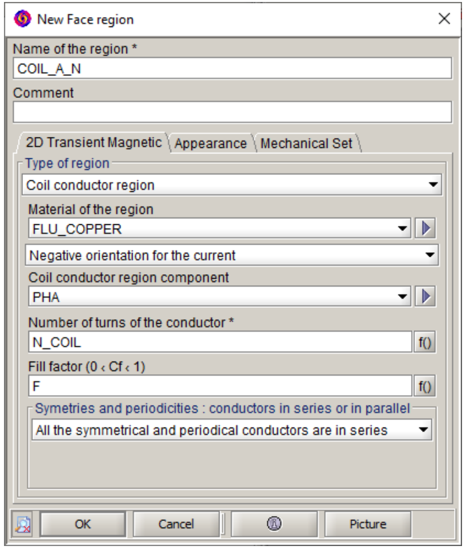
Volume region name	Type of region	Material	Orientation	Coil conductor	Number of turns	Fill factor	Symmetry	Mechanical set
COIL_A_N	Coil conductor region	FLU_COPPER	Negative	PHA	N_COIL	F	in series	STATOR
COIL_A_P	Coil conductor region	FLU_COPPER	Positive	PHA	N_COIL	F	in series	STATOR
COIL_B_N	Coil conductor region	FLU_COPPER	Negative	PHB	N_COIL	F	in series	STATOR
COIL_B_P	Coil conductor region	FLU_COPPER	Positive	PHB	N_COIL	F	in series	STATOR
COIL_C_N	Coil conductor region	FLU_COPPER	Negative	PHC	N_COIL	F	in series	STATOR
COIL_C_P	Coil conductor region	FLU_COPPER	Positive	PHC	N_COIL	F	in series	STATOR
TESTING_COIL_N	Coil conductor region	FLU_COPPER	Negative	TESTING_COIL	N_COIL	F	in series	STATOR
TESTING_COIL_P	Coil conductor region	FLU_COPPER	Positive	TESTING_COIL	N_COIL	F	in series	STATOR

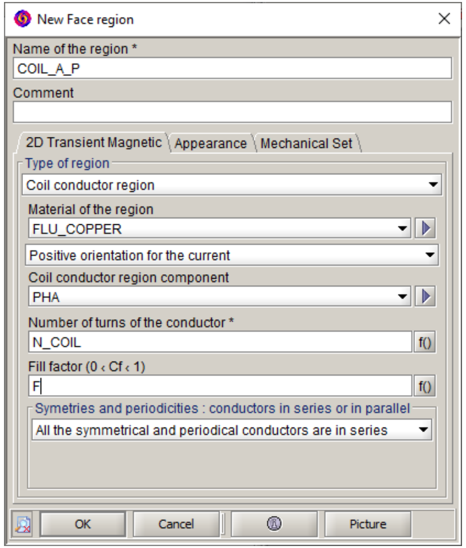
ALTAIR

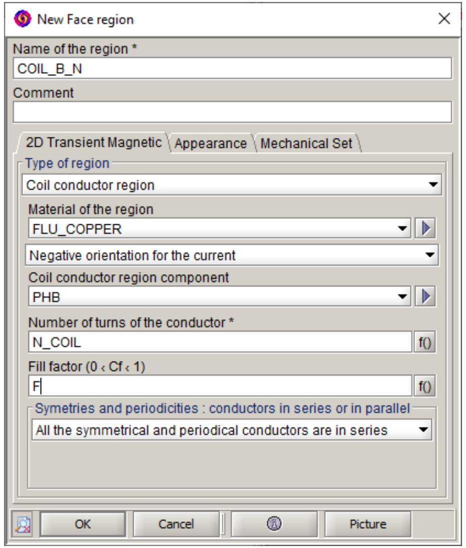
2.2 Magnetic Analysis: Physical description process

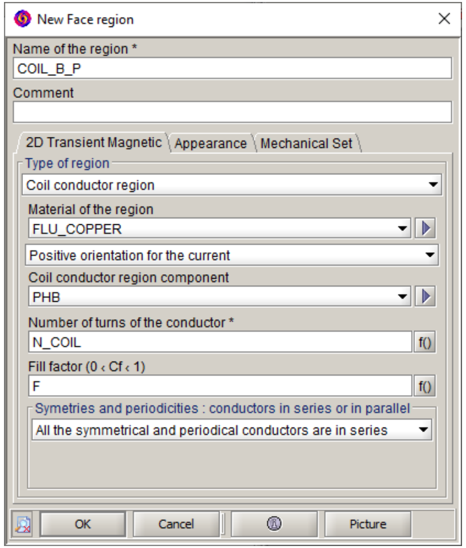
2.2.6 Create face regions

- Define coil Face regions









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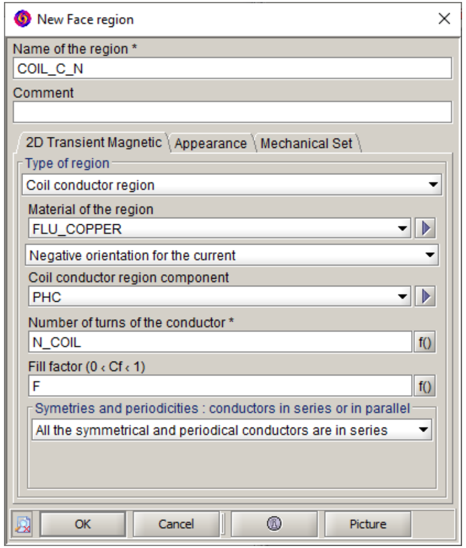
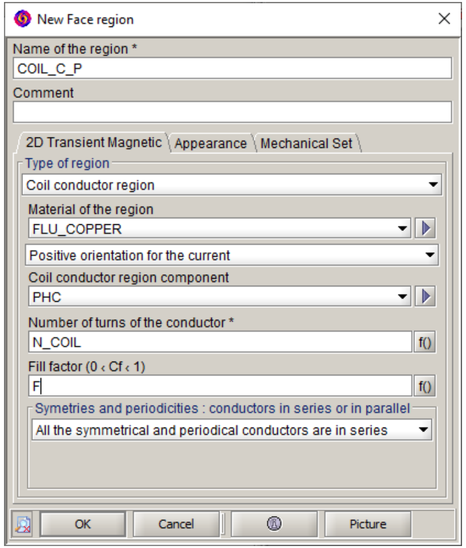
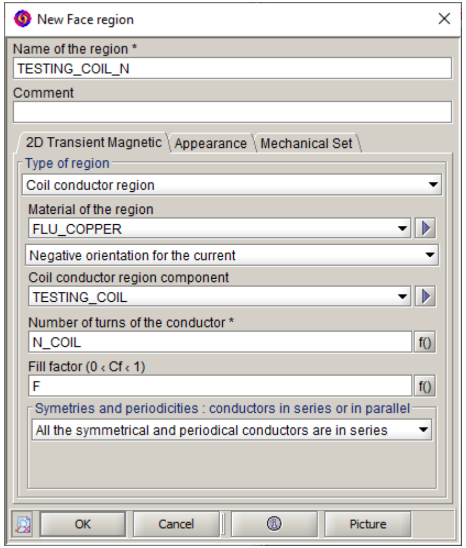
2.2 Magnetic Analysis: Physical description process

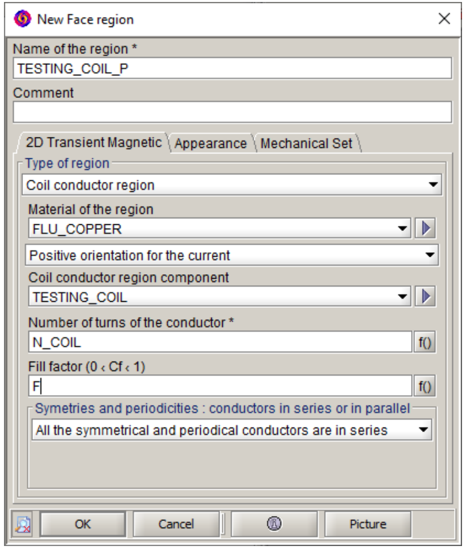
2.2.6 Create face regions

- Define coil Face regions





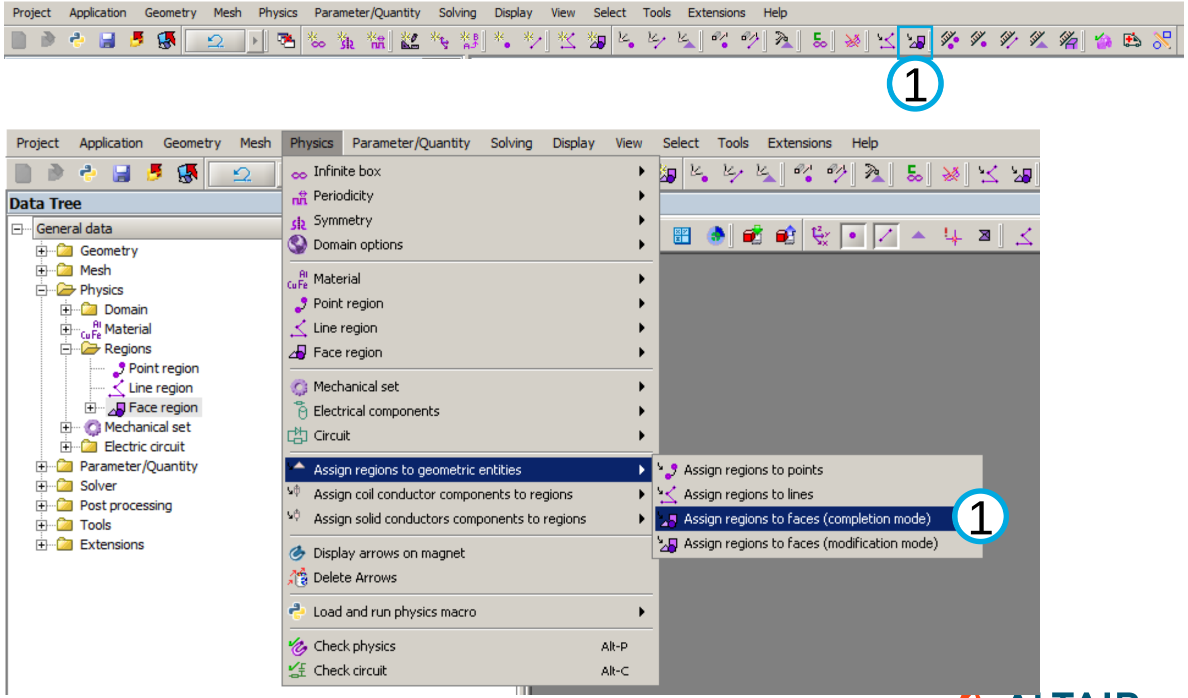




2.2 Magnetic Analysis: Physical description process

2.2.7 Assign the Face regions to the Faces

Step	Action
1	Click on the icon  to assign regions to volumes. Or click on the [Physics] - [Assign regions to geometric entities] – [Assign regions to faces (completion mode)]
2	Assign the created Volume regions to the Volumes



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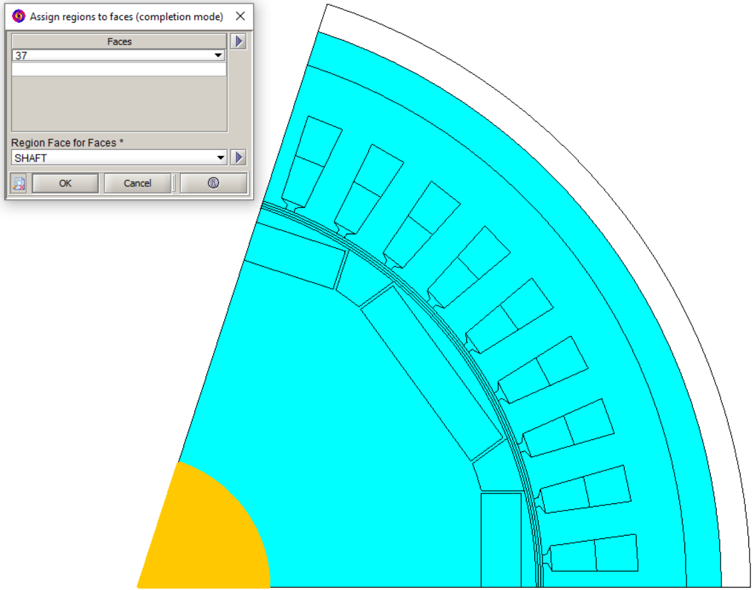
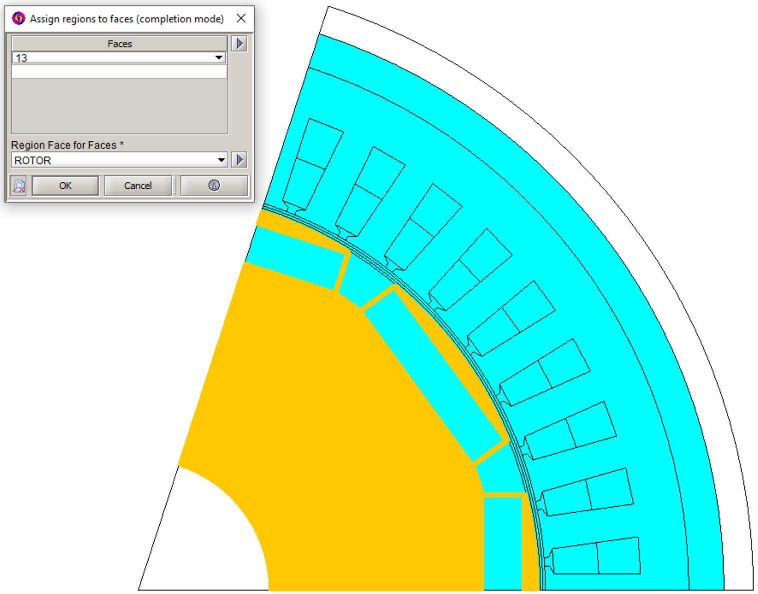
2.2 Magnetic Analysis: Physical description process

2.2.7 Assign the Face regions to the Faces

- Assign regions in ROTOR mechanical set
- SHAFT and ROTOR





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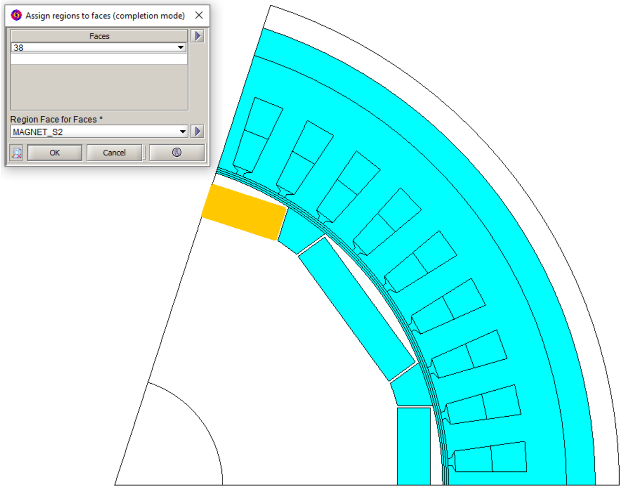
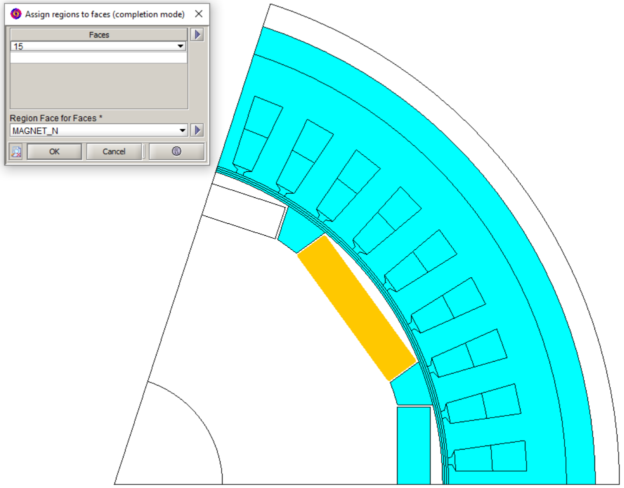
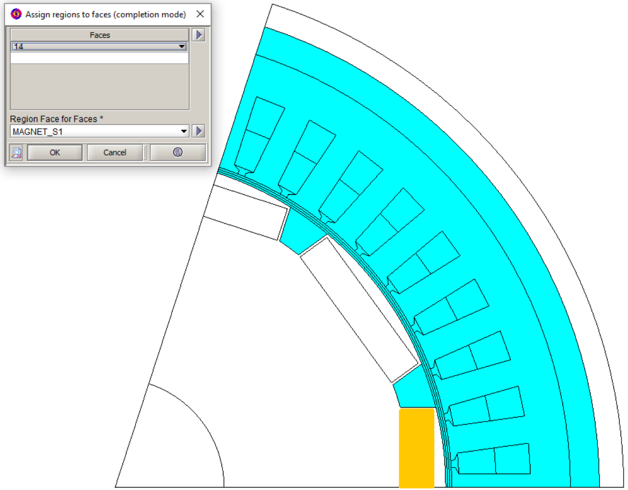
2.2 Magnetic Analysis: Physical description process

2.2.7 Assign the Face regions to the Faces

- Assign regions in ROTOR mechanical set
- MAGNETs



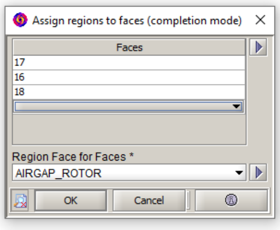


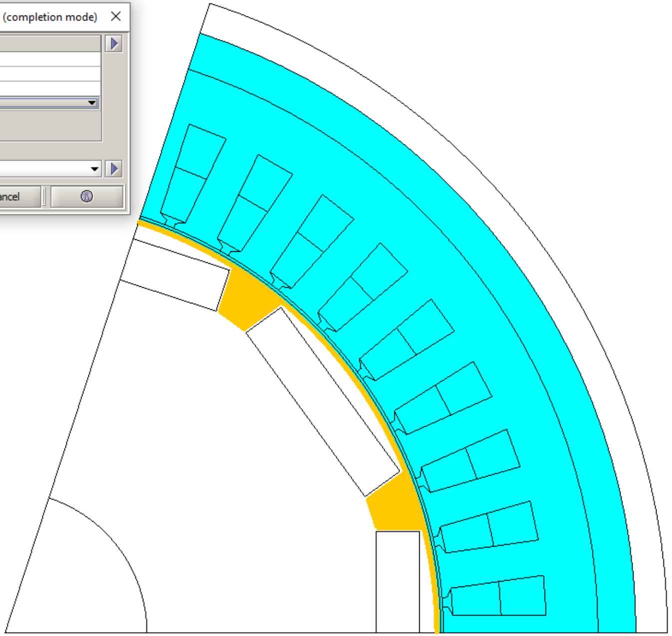


2.2 Magnetic Analysis: Physical description process

2.2.7 Assign the Face regions to the Faces

- Assign regions in ROTOR mechanical set
- AIRGAP_ROTOR





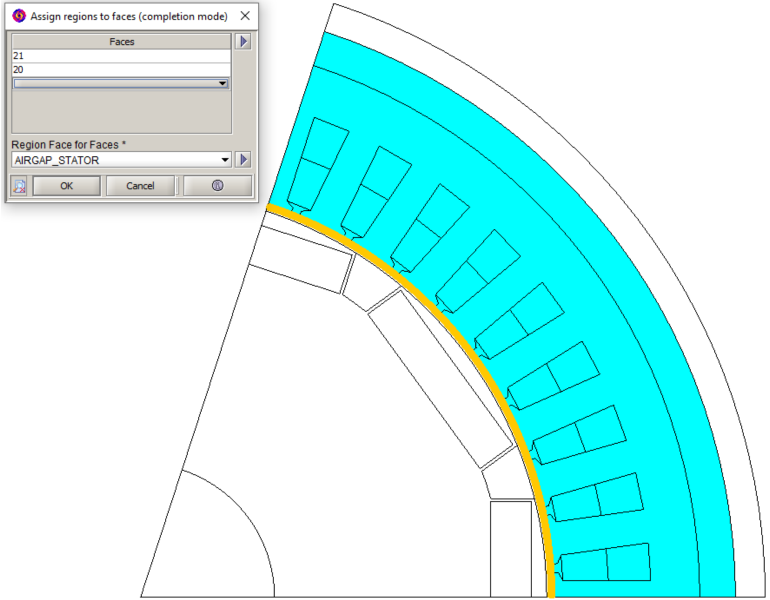
Attention: the airgap of rotor has just ONE layer

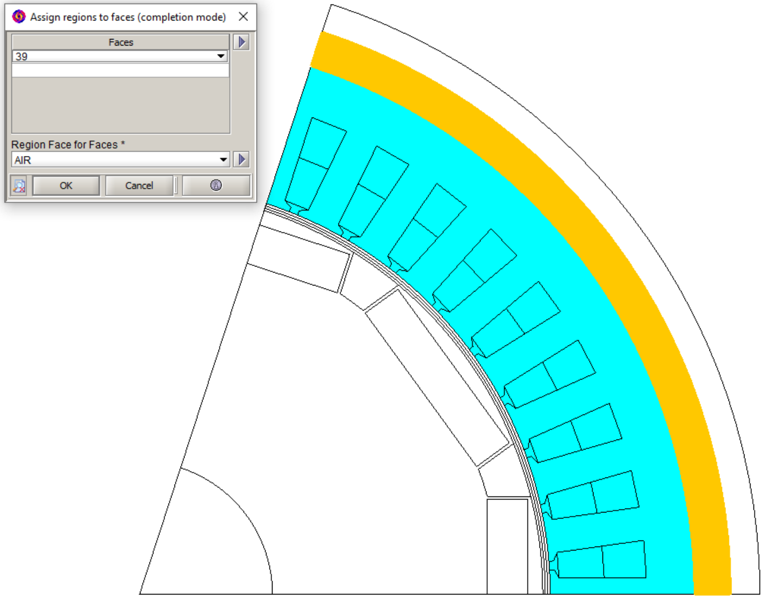
ALTAIR

2.2 Magnetic Analysis: Physical description process

2.2.7 Assign the Face regions to the Faces

- Assign regions in STATOR mechanical set
- AIRGAP_STATOR and AIR



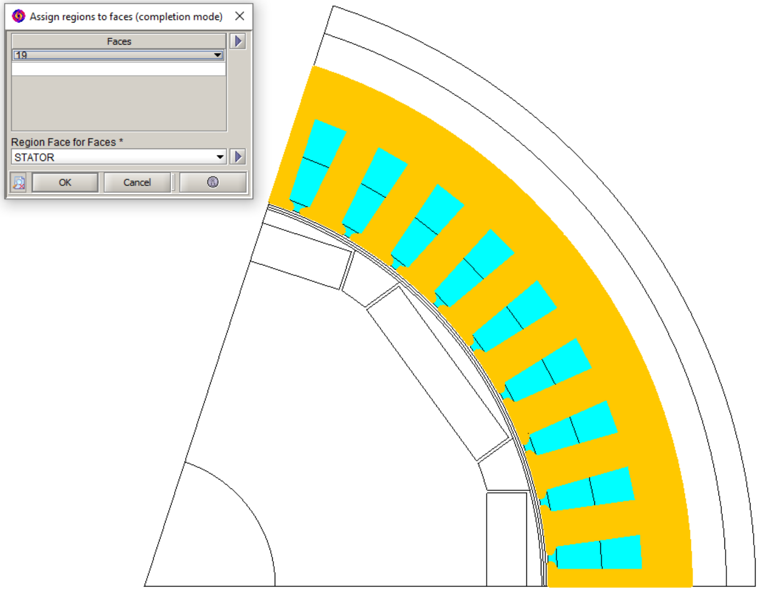


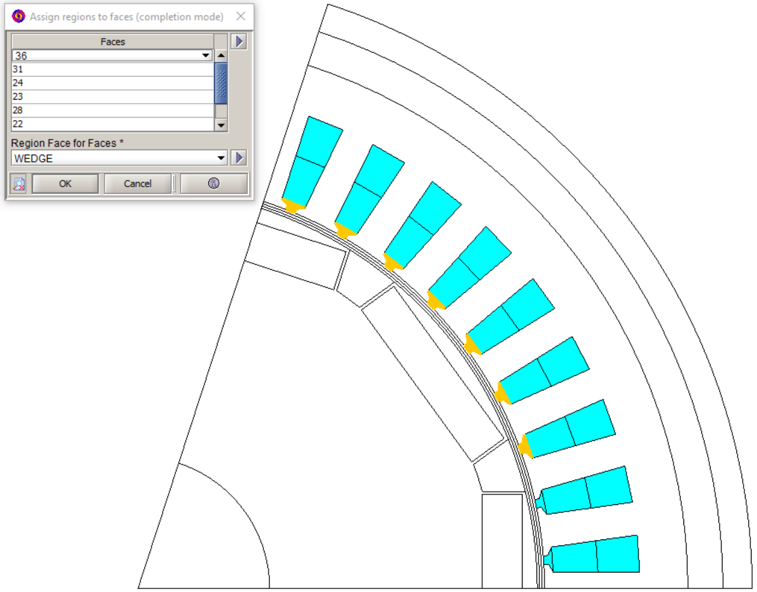
Attention: the airgap of stator has TWO layers

2.2 Magnetic Analysis: Physical description process

2.2.7 Assign the Face regions to the Faces

- Assign regions in STATOR mechanical set
- STATOR and WEDGE





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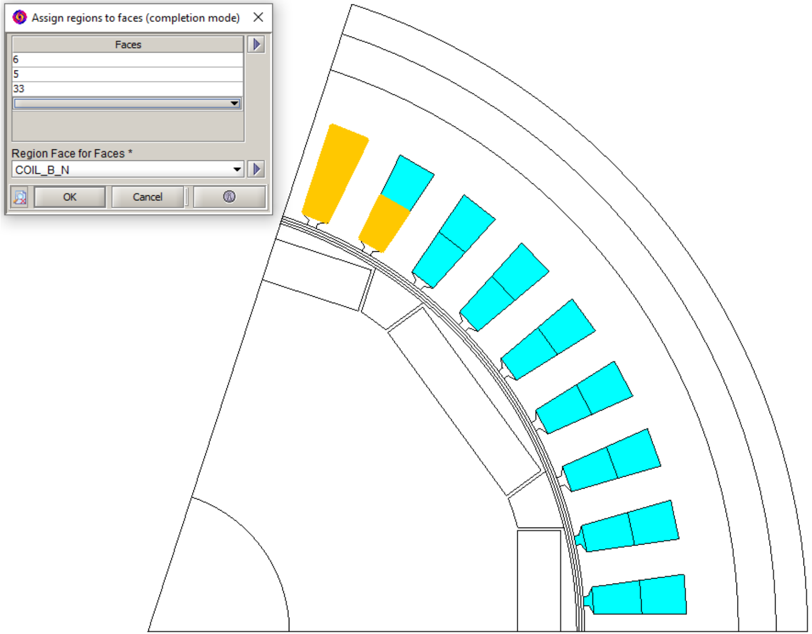
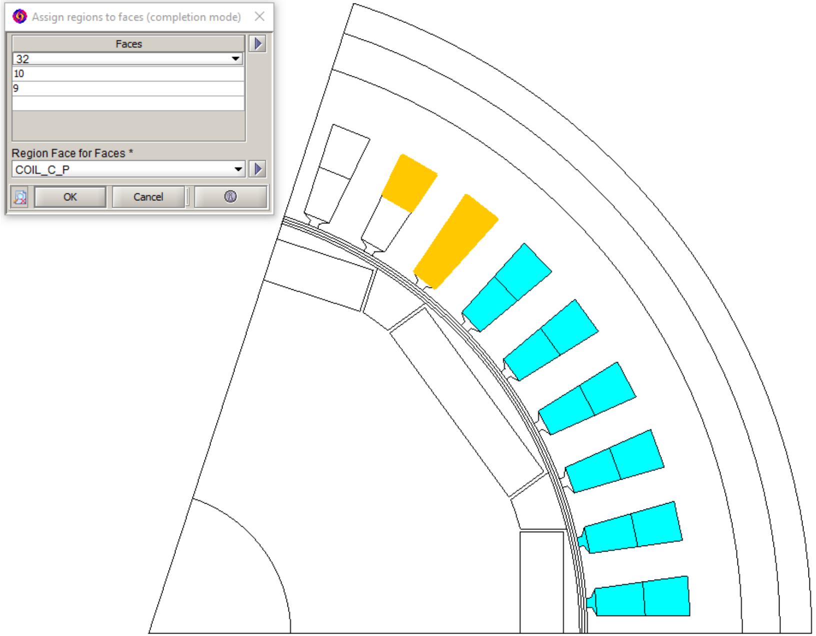
2.2 Magnetic Analysis: Physical description process

2.2.7 Assign the Face regions to the Faces

- Assign regions in STATOR mechanical set





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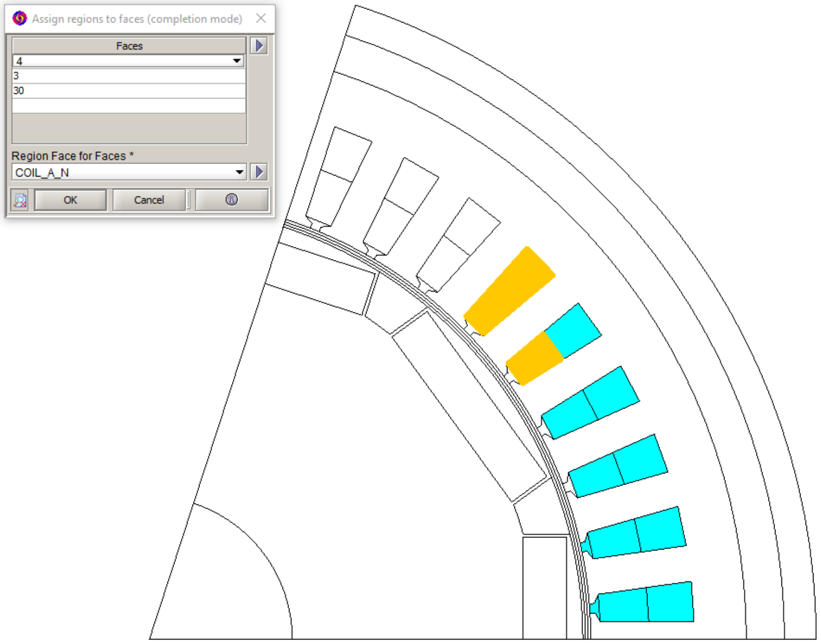
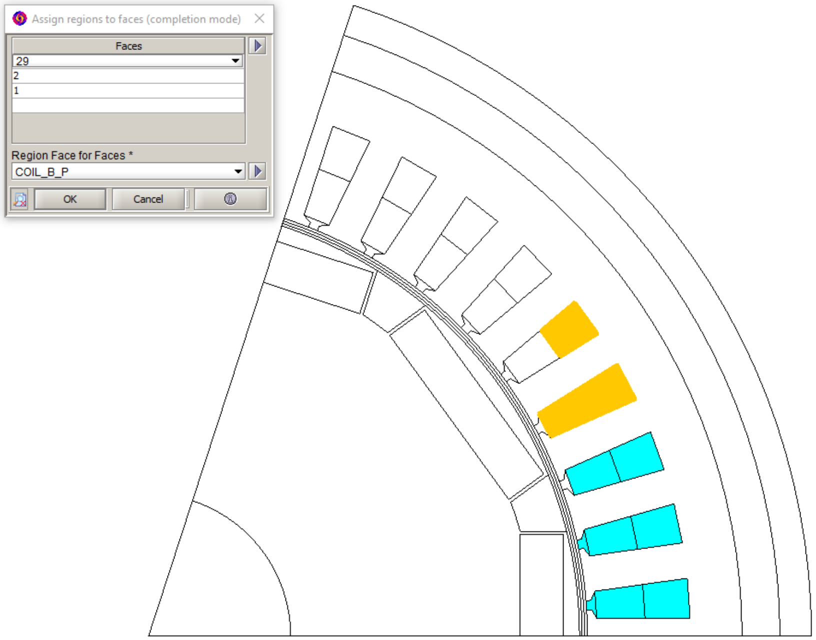
2.2 Magnetic Analysis: Physical description process

2.2.7 Assign the Face regions to the Faces

- Assign regions in STATOR mechanical set





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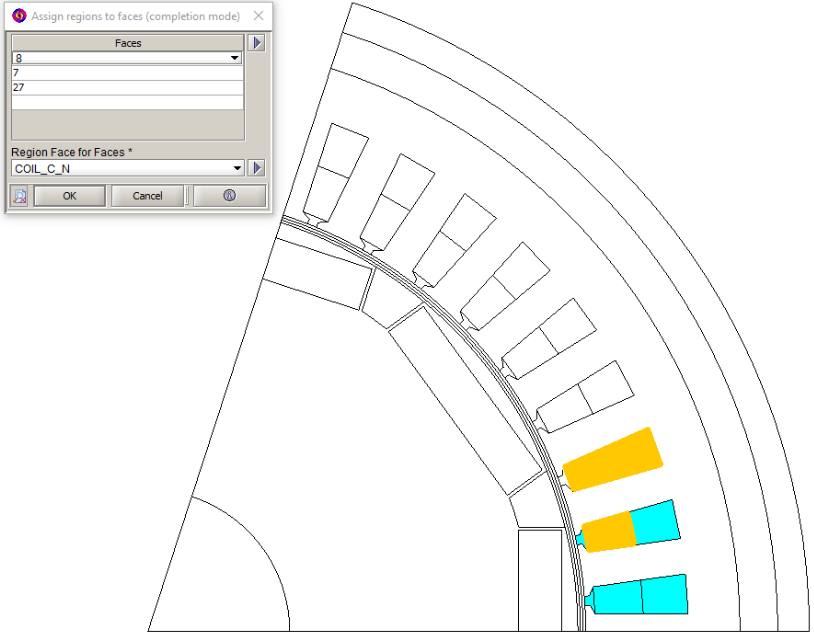
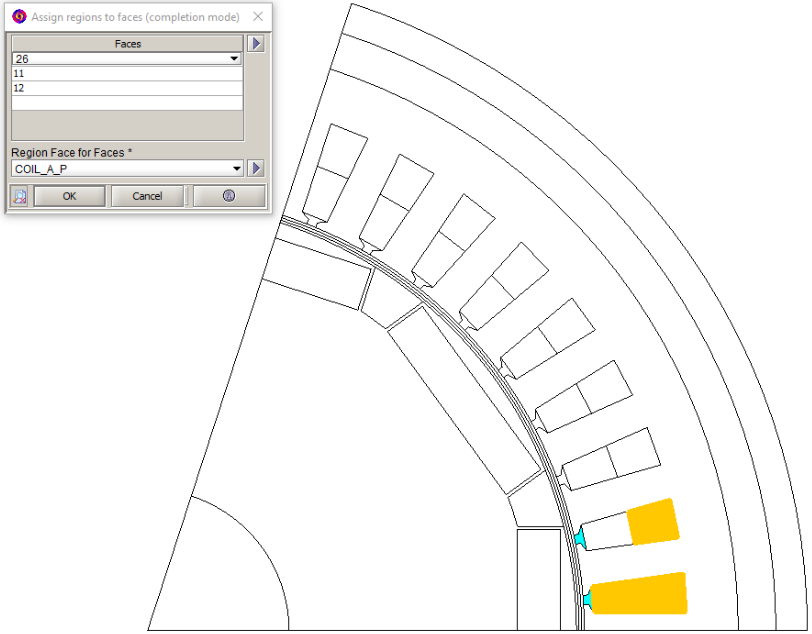
2.2 Magnetic Analysis: Physical description process

2.2.7 Assign the Face regions to the Faces

- Assign regions in STATOR mechanical set





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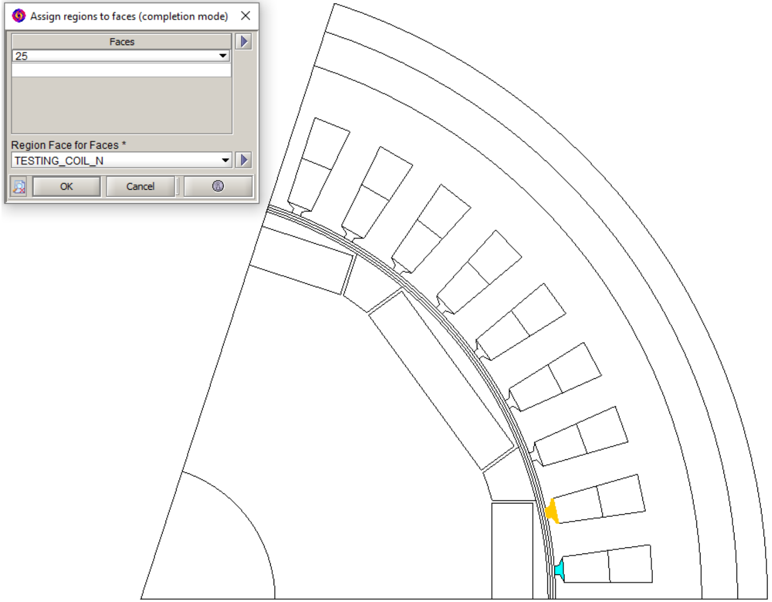
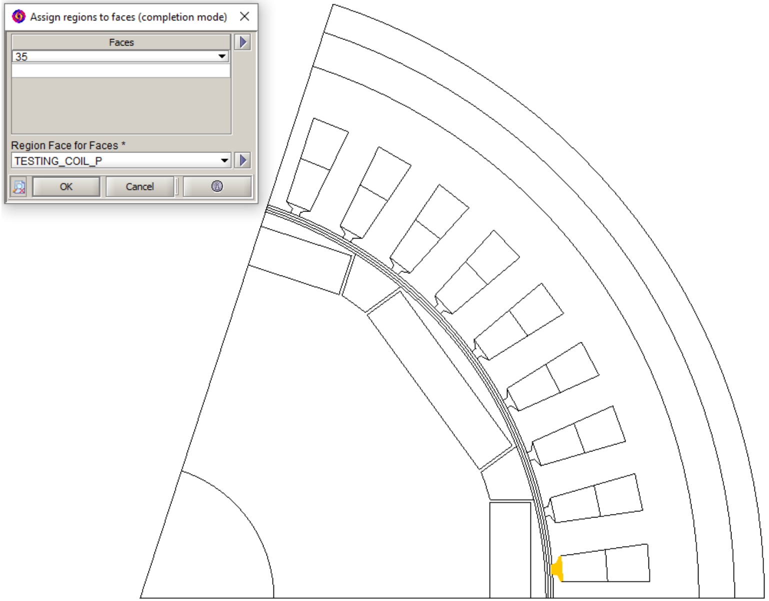
2.2 Magnetic Analysis: Physical description process

2.2.7 Assign the Face regions to the Faces

- Assign regions in STATOR mechanical set
- COILs





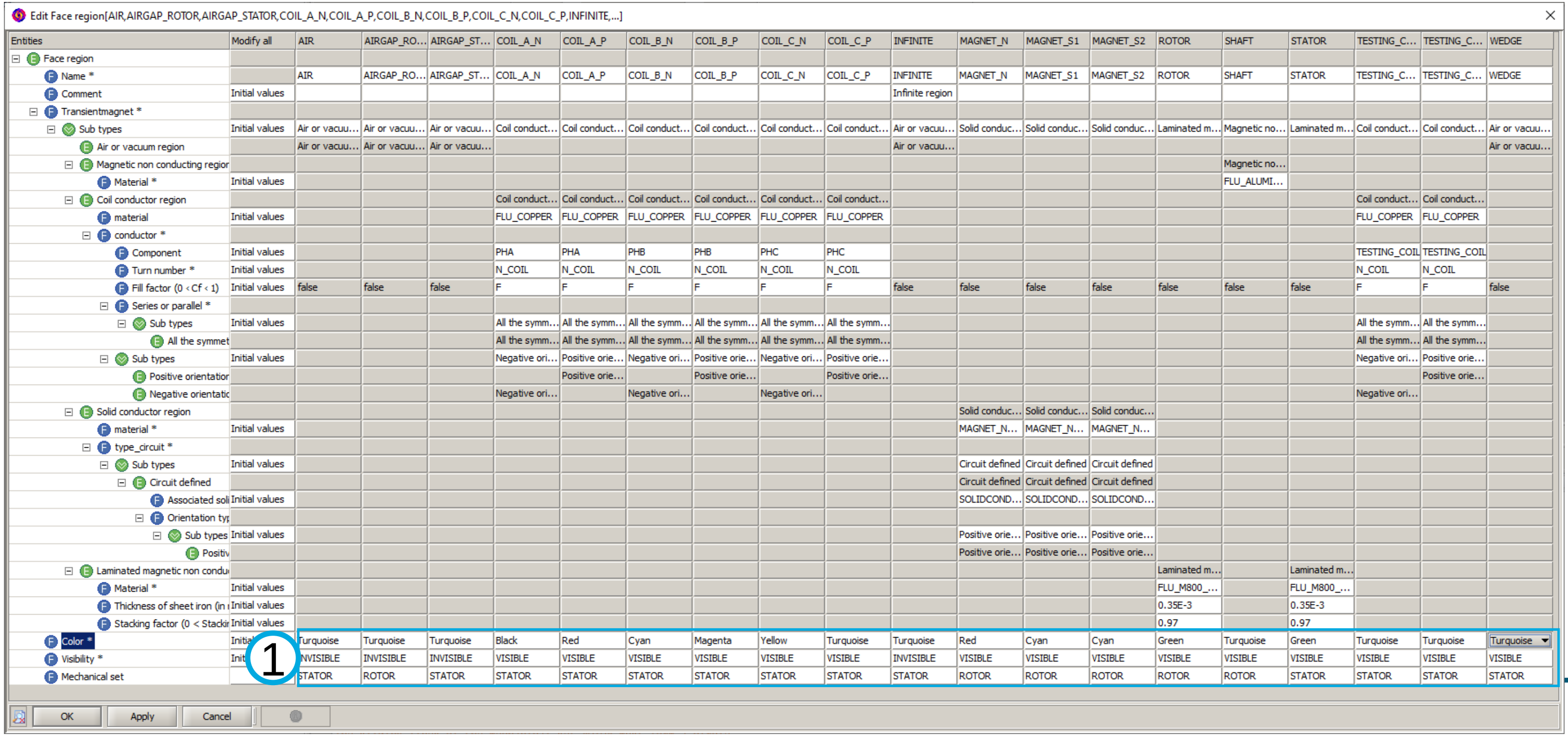
ALTAIR

2.2 Magnetic Analysis: Physical description process

2.2.7 Assign the Face regions to the Faces

- Improve the region visibility

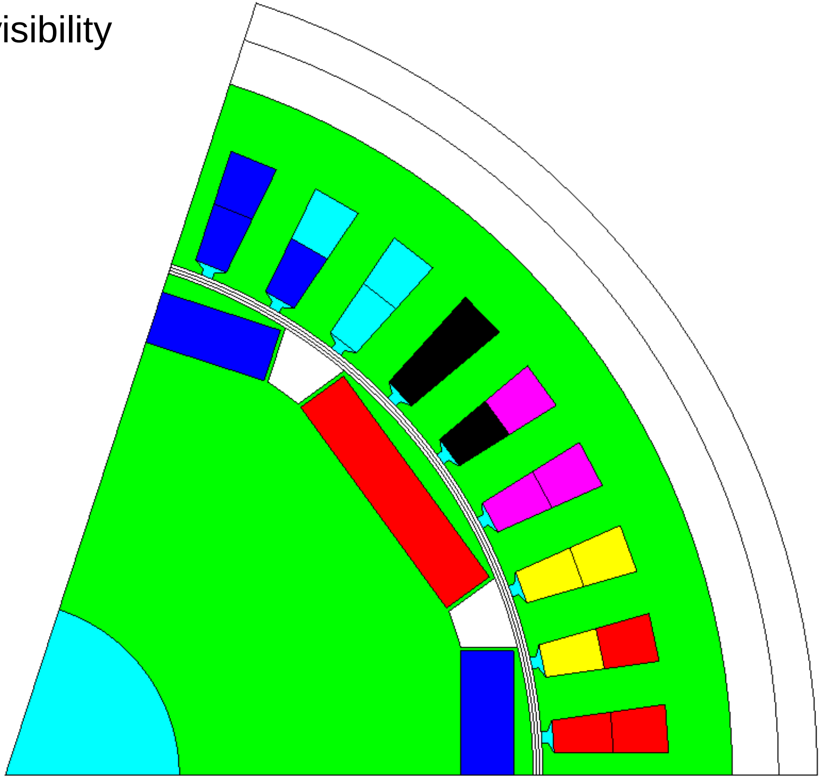
Step	Action
1	Select all the Face regions from the Data tree, right click and click on [Edit array]
2	Change the color and the visibility for all regions



2.2 Magnetic Analysis: Physical description process

2.2.7 Assign the Face regions to the Faces

- Improve the region visibility



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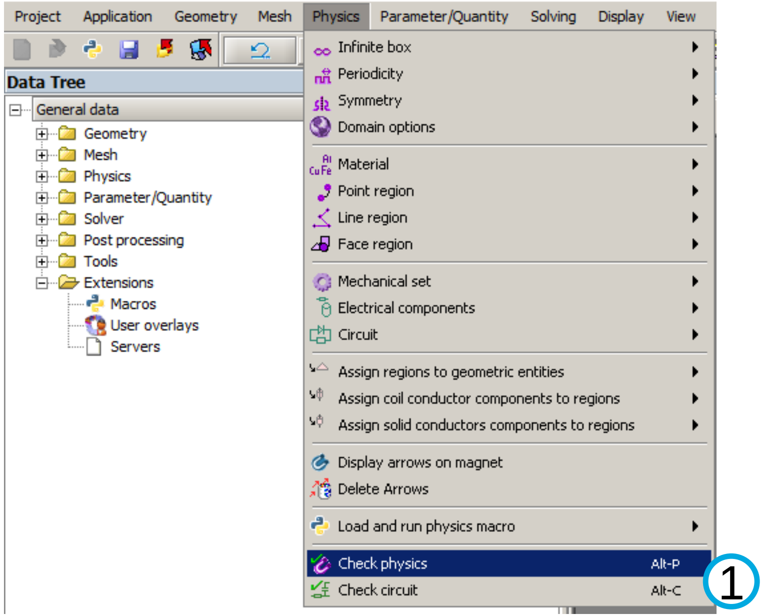
2.2 Magnetic Analysis: Physical description process

2.2.8 Finish the physical description

- Check physics

Step	Action
1	Click on [Physics] – [Check physics]

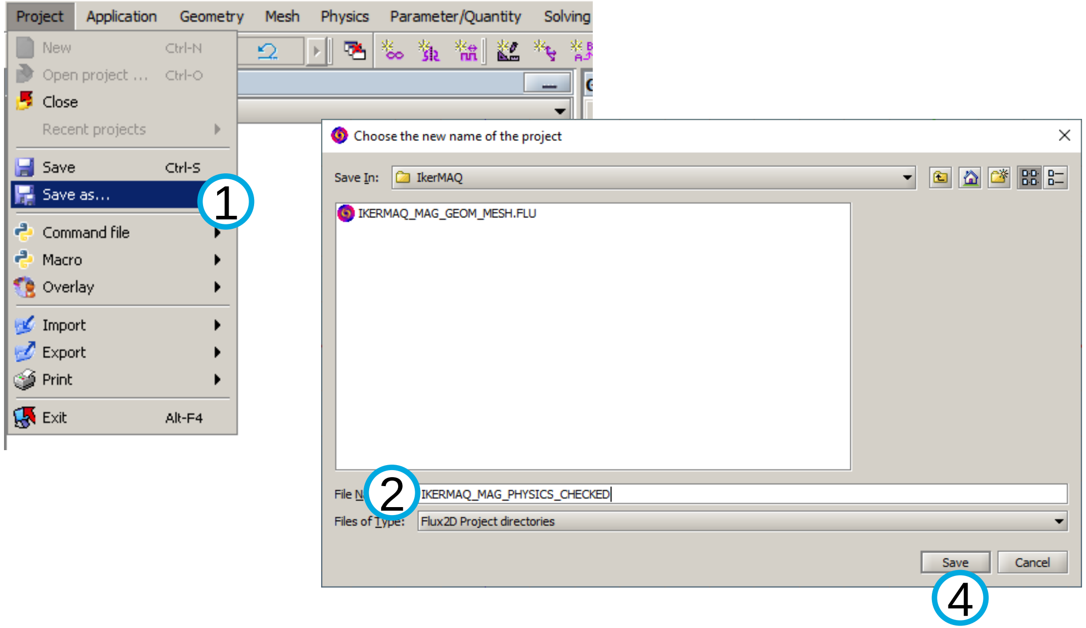


2.2 Magnetic Analysis: Physical description process

2.2.8 Finish the physical description

- Save the project as: IKERMAQ_MAG_PHYSICS_CHECKED.FLU

Step	Action
1	Click on [Project] – [Save as]
2	Define the project name as "IKERMAQ_MAG_PHYSICS_ CHECKED"
3	Verify the location
4	Click on [OK]



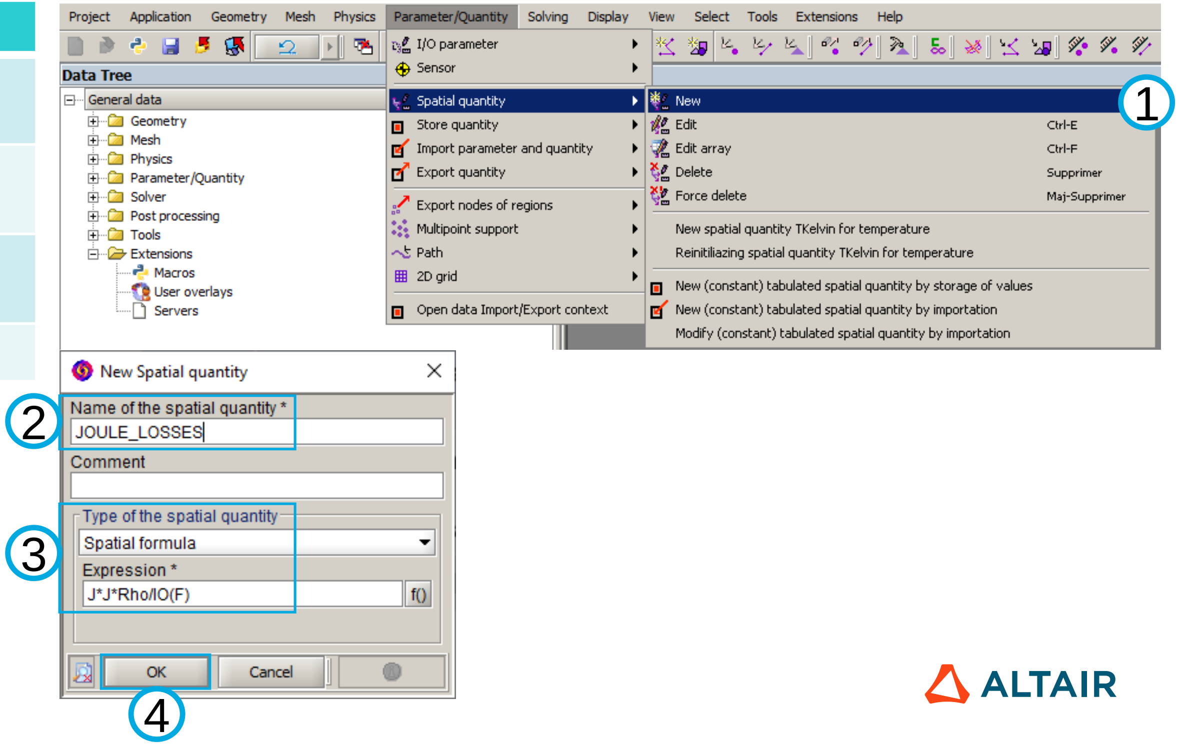
2.3 SOLVING AND POSTPROCESSING

2.3 Magnetic Analysis: Solving and postprocessing

2.3.1 Create a spatial quantity

- Spatial quantity: JOULE_LOSSES

Step	Action
1	Click on [Parameter/Quantity] – [Spatial quantity] – [new]
2	Define a new Spatial quantity "JOULE_LOSSES"
3	Define the expression as "J*J*Rho/IO(F)"
4	Click on [OK]



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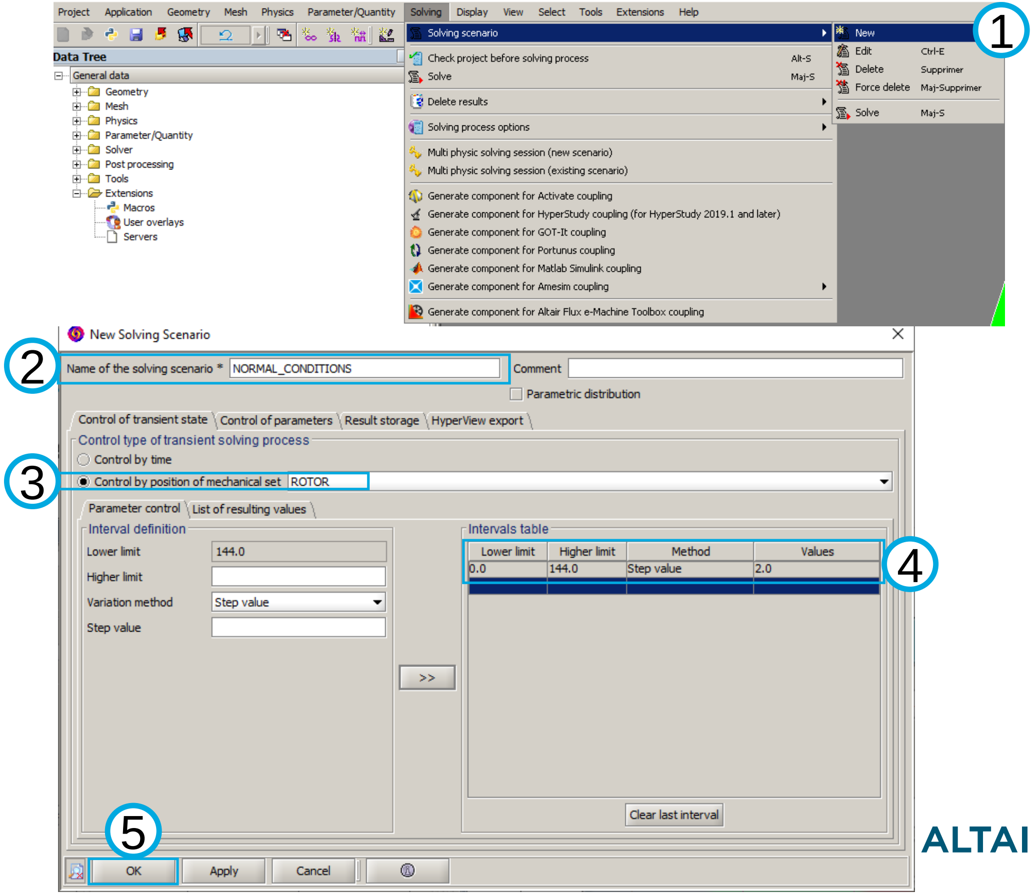
2.3 Magnetic Analysis: Solving and postprocessing

2.3.2 Solving process

- Create a new Solving scenario

Step	Action
1	Create a new Solving scenario by clicking on [Solving] – [Solving scenario] – [New]
2	Define the scenario name as “NORMAL_CONDITIONS”
3	Click [Control by position of mechanical set] – [ROTOR]
4	Define the interval as [0.0, 144.0], with a step value as 2.0
5	Click on [OK]



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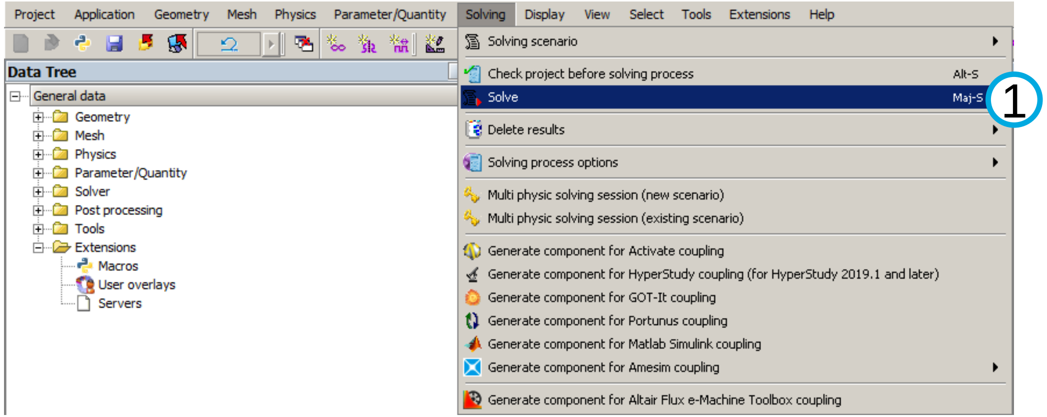
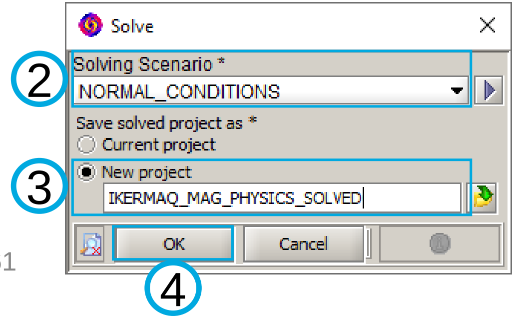
2.3 Magnetic Analysis: Solving and postprocessing

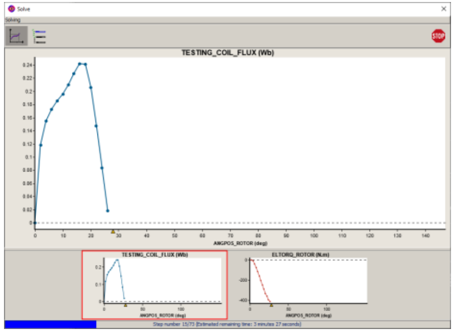
2.3.2 Solving process

- Solve the scenario

Step	Action
1	Solve the Scenario by clicking on [Solving] – [Solve]
2	Select the solving scenario “NORMAL_CONDITIONS”
3	Save as a New project “IKERMAQ_MAG_PHYSICS_SOLVED”
4	Click on [OK]





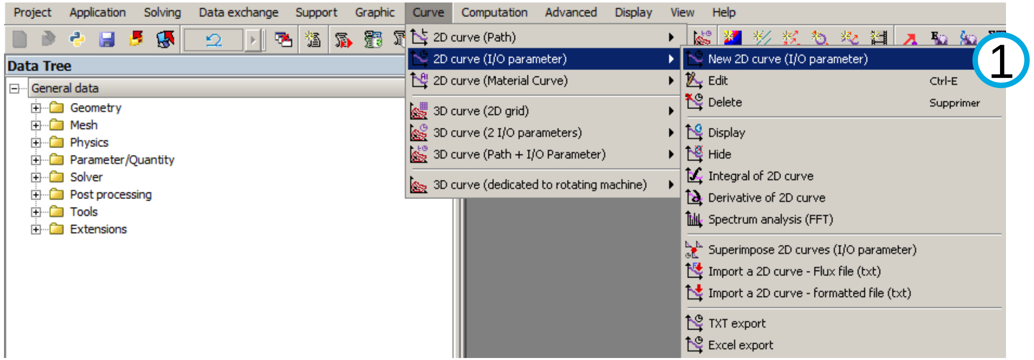


2.3 Magnetic Analysis: Solving and postprocessing

2.3.3 Postprocessing

- Plot 2D curves (I/O parameter)

Step	Action
1	Create a new 2D curve by clicking on [Curve] – [2D curve (I/O parameter)] – [New 2D curve (I/O parameter)]
2	Plot the following curves: - TORQUE - LOAD_PHASE_CURRENTS - LOAD_PHASE_VOLTAGES - MECHANICAL_ELECTRIC_POWER - TESTING_COIL_MAG_FLUX - COPPER_LOSSES



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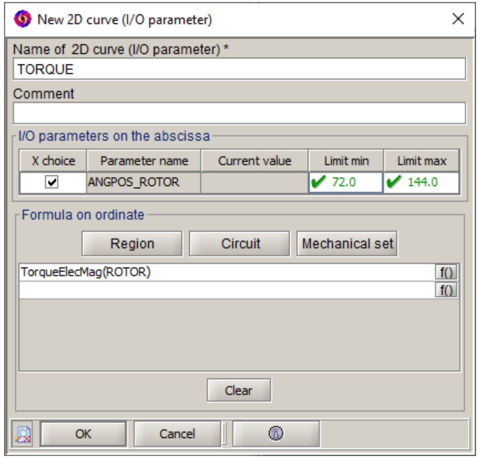
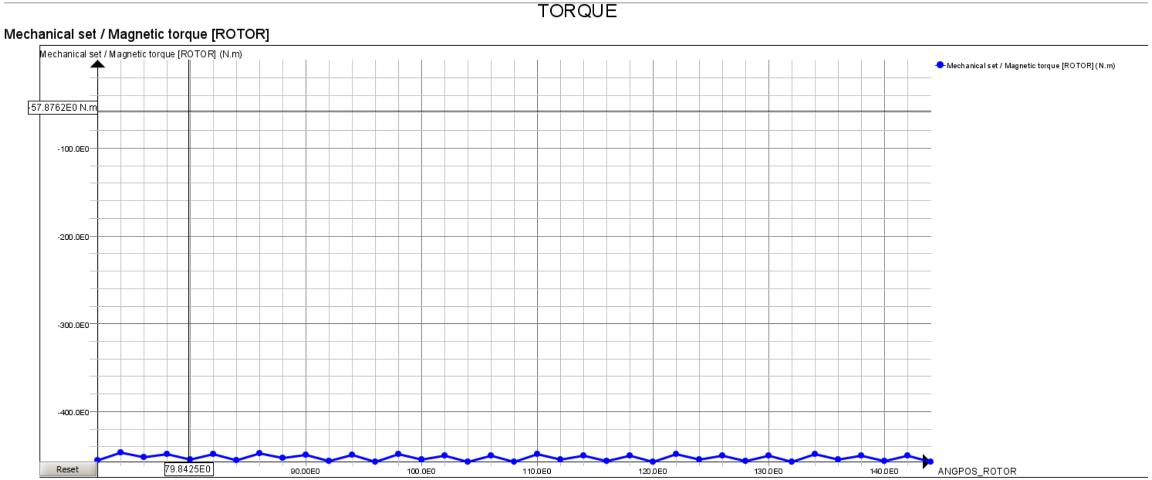
2.3 Magnetic Analysis: Solving and postprocessing

2.3.3 Postprocessing

- Plot the magnetic torque



Setting	Value or expression
Curve name	TORQUE
Limit min	72.0
Limit max	144.0
Formula	TorqueElecMag(ROTOR)




```
TorqueElecMag(ROTOR)
  ANGPOS_ROTOR
   Interval = 72 (72, 144)
     Minimal value = -457.20476773253
     Maximal value = -446.798926726456
     Mean value              = -452.389
     Rectified mean value    = 452.389
     R.m.s value             = 452.402
     Integral along the curve = -32572
```

$$Torque_{rms} = 452.40\ N.m$$

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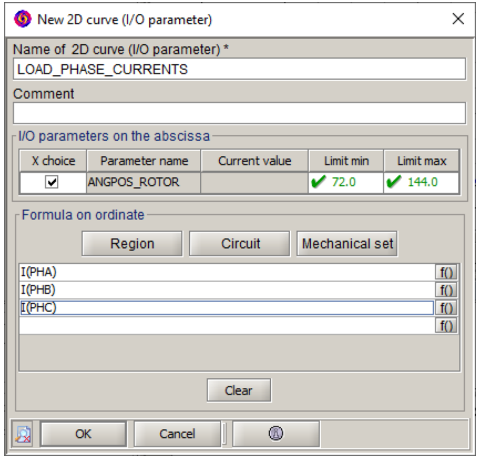
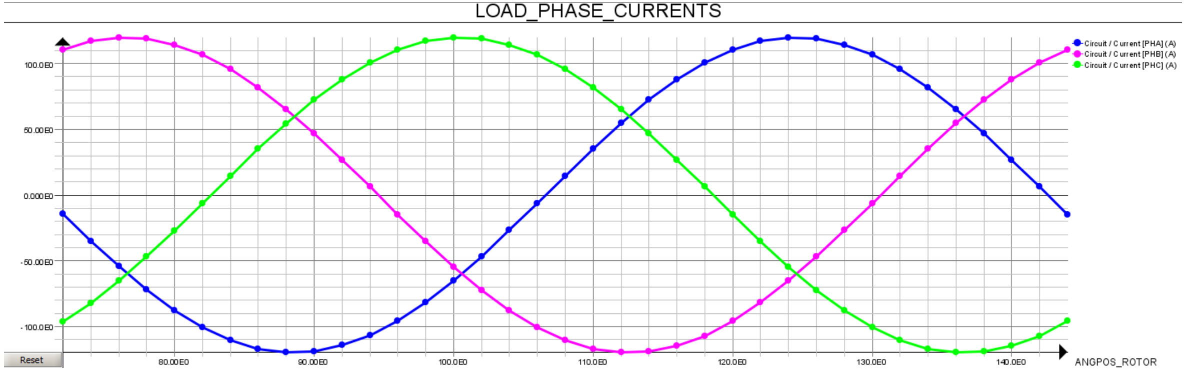
2.3 Magnetic Analysis: Solving and postprocessing

2.3.3 Postprocessing

- Plot the phase voltages and phase currents in the load





Setting	Value or expression
Curve name	LOAD_PHASE_CURRENTS
Limit min	72.0
Limit max	144.0
Formula 1	I(PHA)
Formula 2	I(PHB)
Formula 3	I(PHC)

```
I(PHA)
  ANGPOS_ROTOR
   Interval = 72 (72, 144)
     Minimal value = -119.364975308642
     Maximal value = 119.54174490291
     Mean value                = 0.095398
     Rectified mean value      = 76.3072
     R.m.s value               = 84.7258
     Integral along the curve = 6.86864
```

```
I(PHB)
  ANGPOS_ROTOR
   Interval = 72 (72, 144)
     Minimal value = -119.52850718722
     Maximal value = 119.510640120803
     Mean value                = -0.007586
     Rectified mean value      = 76.3848
     R.m.s value               = 84.7937
     Integral along the curve = -0.54622
```

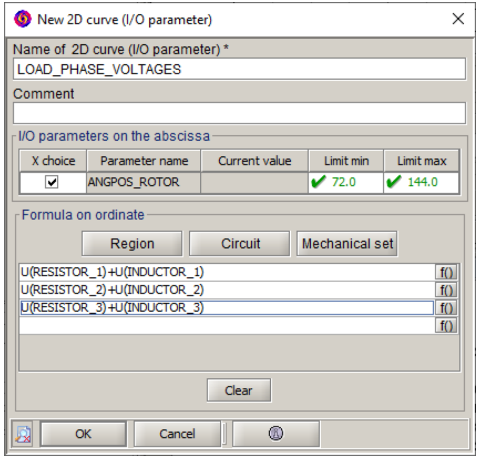
```
I(PHC)
  ANGPOS_ROTOR
   Interval = 72 (72, 144)
     Minimal value = -119.535521430332
     Maximal value = 119.464639904278
     Mean value                = -0.087811
     Rectified mean value      = 76.405
     R.m.s value               = 84.8045
     Integral along the curve = -6.32242
```

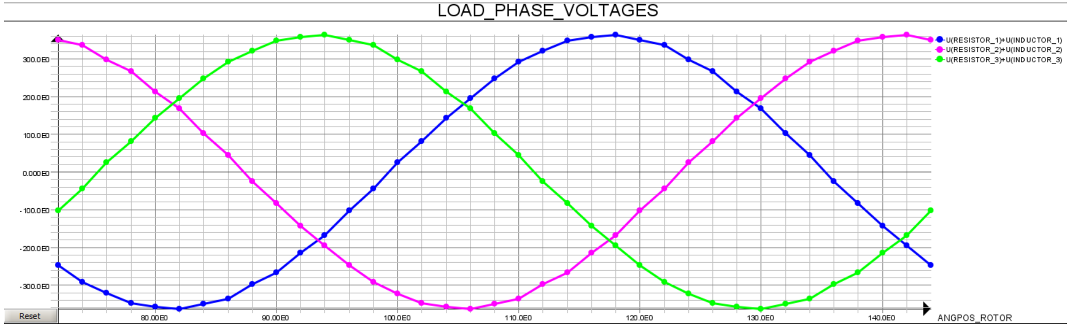
$I_{phaseA,\ rms} = 84.73\ A$ $I_{phaseB,\ rms} = 84.79\ A$ $I_{phaseC,\ rms} = 84.80\ A$

2.3 Magnetic Analysis: Solving and postprocessing

2.3.3 Postprocessing

- Plot the voltages and currents of each phases in the load





Setting	Value or expression
Curve name	LOAD_PHASE_VOLTAGES
Limit min	72.0
Limit max	144.0
Formula 1	U(RESISTOR_1)+U(INDUCTOR_1)
Formula 2	U(RESISTOR_2)+U(INDUCTOR_2)
Formula 3	U(RESISTOR_3)+U(INDUCTOR_3)

```
U(RESISTOR 1)+U(INDUCTOR 1)
  ANGPOS_ROTOR
   Interval = 72 (72, 144)
     Minimal value = -362.9812088842
     Maximal value = 363.132177522017
     Mean value                    = 0.060476
     Rectified mean value          = 230.717
     R.m.s value                   = 255.821
     Integral along the curve = 4.35428
```

```
U(RESISTOR 2)+U(INDUCTOR 2)
  ANGPOS_ROTOR
   Interval = 72 (72, 144)
     Minimal value = -363.151810667877
     Maximal value = 363.160250714062
     Mean value                    = -0.01329
     Rectified mean value          = 230.753
     R.m.s value                   = 255.867
     Integral along the curve = -0.956912
```

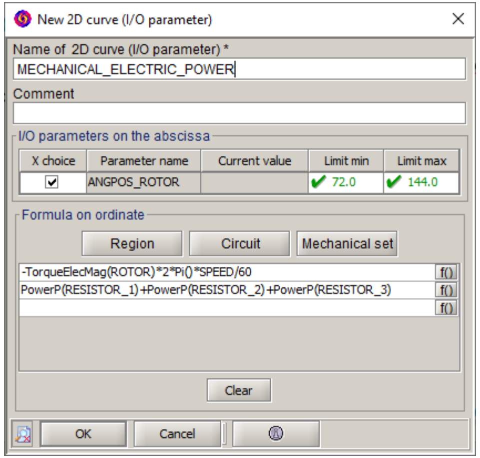
```
U(RESISTOR 3)+U(INDUCTOR 3)
  ANGPOS_ROTOR
   Interval = 72 (72, 144)
     Minimal value = -363.151883046122
     Maximal value = 363.060261140822
     Mean value                    = -0.047186
     Rectified mean value          = 230.739
     R.m.s value                   = 255.849
     Integral along the curve = -3.39736
```

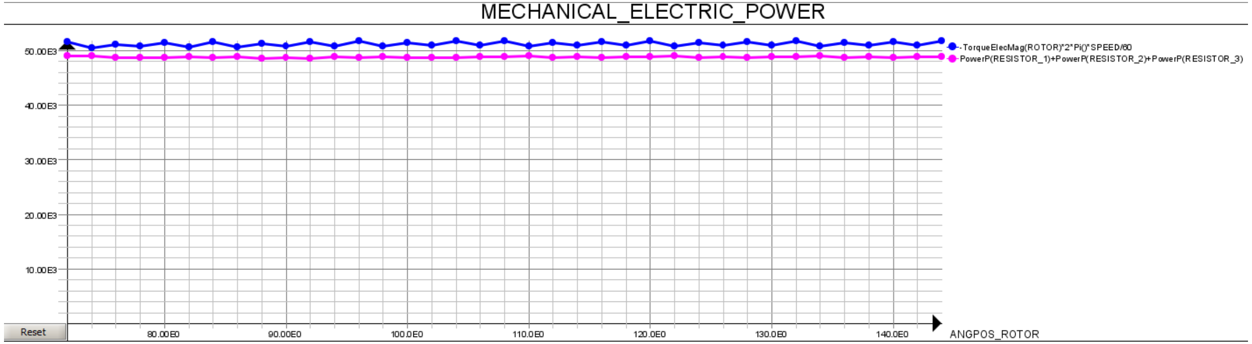
$U_{phaseA,\ rms} = 255.82\ V$ $U_{phaseB,\ rms} = 255.87\ V$ $U_{phaseC,\ rms} = 255.85\ V$

2.3 Magnetic Analysis: Solving and postprocessing

2.3.3 Postprocessing

- Plot the mechanical and the electric power





Setting	Value or expression
Curve name	MECHANICAL_ELECTRIC_POWER
Limit min	72.0
Limit max	144.0
Formula 1	-TorqueElecMag(ROTOR)*2*Pi()*SPEED/60
Formula 2	PowerP(RESISTOR_1)+PowerP(RESISTOR_2)+PowerP(RESISTOR_3)

```
-TorqueElecMag(ROTOR)*2*Pi()*SPEED/60
  ANGPOS_ROTOR
   Interval = 72 (72, 144)
     Minimal value = 50531.7681300829
     Maximal value = 51708.6410218108
     Mean value                  = 51164
     Rectified mean value        = 51164
     R.m.s value                 = 51165.4
     Integral along the curve = 0.368E+07
```

```
PowerP(RESISTOR 1)+PowerP(RESISTOR 2)+PowerP(RESISTOR 3)
  ANGPOS_ROTOR
   Interval = 72 (72, 144)
     Minimal value = 48576.1737219588
     Maximal value = 49039.8436356082
     Mean value                  = 48784.9
     Rectified mean value        = 48784.9
     R.m.s value                 = 48785
     Integral along the curve = 0.351E+07
```

$P_{meca, mean} = 51.17$ kW

$P_{elec, mean} = 48.79$ kW

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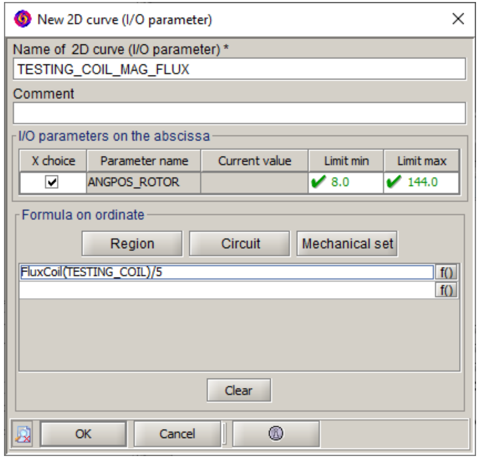
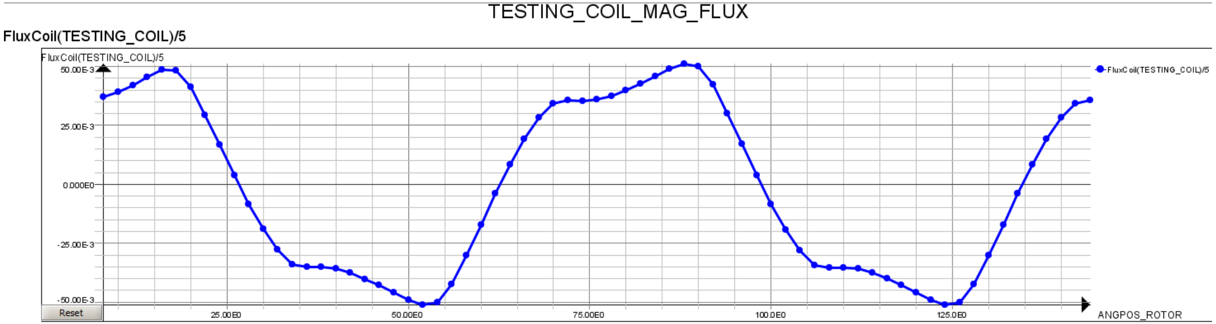
2.3 Magnetic Analysis: Solving and postprocessing

2.3.3 Postprocessing

- Plot the magnetic flux flowing in the test coil





Setting	Value or expression
Curve name	TESTING_COIL_MAG_FLUX
Limit min	8.0
Limit max	144.0
Formula 1	FluxCoil(TESTING_COIL)/5

```
FluxCoil(TESTING COIL)/5
  ANGPOS_ROTOR
   Interval = 136 (8, 144)
     Minimal value = -0.051131007848197
     Maximal value = 0.050970489118695
     Mean value                = -0.002426
     Rectified mean value      = 0.033218
     R.m.s value               = 0.035874
     Integral along the curve = -0.329868
```

Warning: only ONE testing coil is installed in the test-bench. However, due to the periodicity in the modeling, the model is considered to have FIVE testing coils.
So the flux value should be divided by 5 to compare with the measurement.

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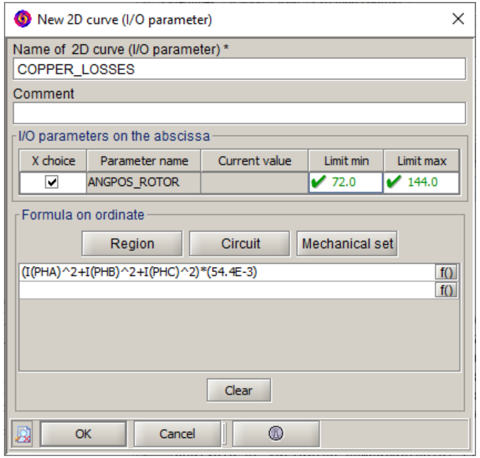
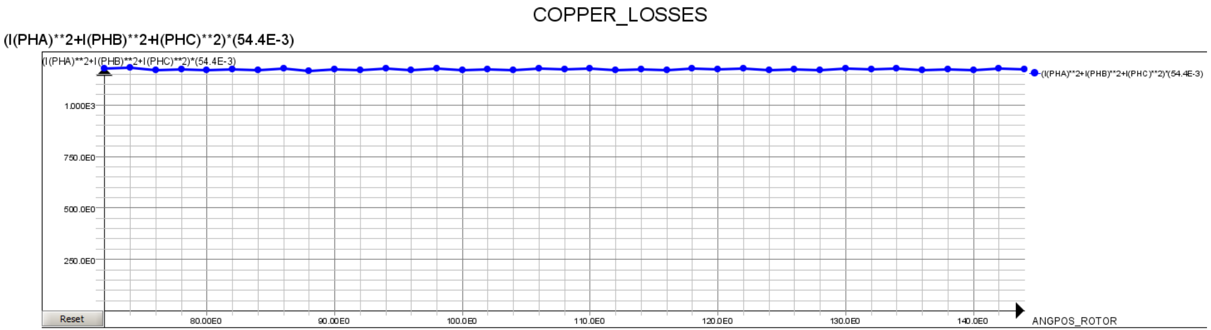
2.3 Magnetic Analysis: Solving and postprocessing

2.3.3 Postprocessing

- Plot the copper losses





Setting	Value or expression
Curve name	COPPER_LOSSES
Limit min	72.0
Limit max	144.0
Formula 1	(I(PHA)^2+I(PHB)^2+I(PHC)^2)*(54.4E-3)

```
(I(PHA)**2+I(PHB)**2+I(PHC)**2)*(54.4E-3)
  ANGPOS_ROTOR
   Interval = 72 (72, 144)
     Minimal value = 1165.64437874295
     Maximal value = 1180.08076942986
     Mean value                = 1172.88
     Rectified mean value      = 1172.88
     R.m.s value               = 1172.88
     Integral along the curve = 84447.1
```

$$P_{\text{copper\_losses, mean}} = 1.17\ \text{kW}$$

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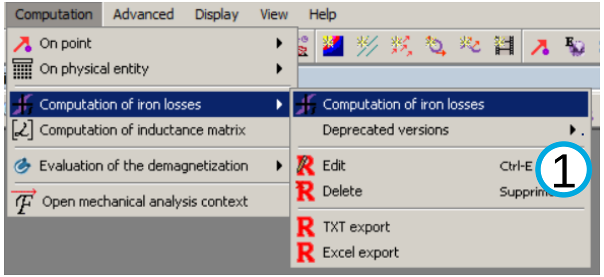
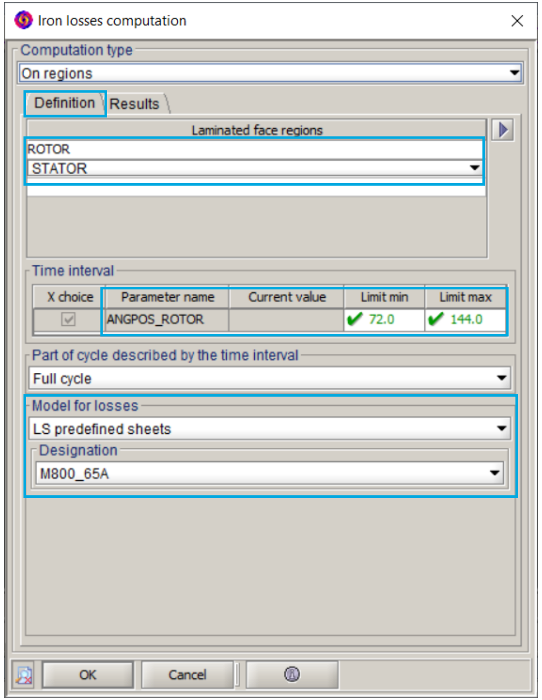
2.3 Magnetic Analysis: Solving and postprocessing

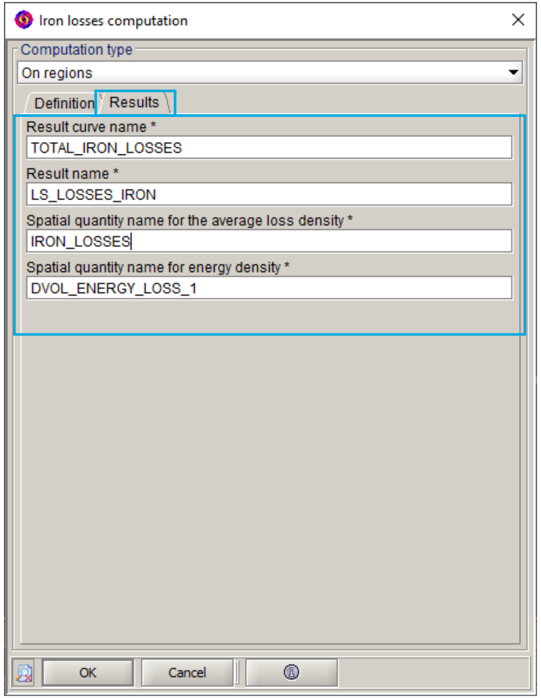
2.3.3 Postprocessing

- Calculate the iron losses

Step	Action
1	Create a new 2D curve for iron losses by clicking on [Computation] – [Computation of iron losses] – [Computation of iron losses]
2	Edit the settings in the following tabs







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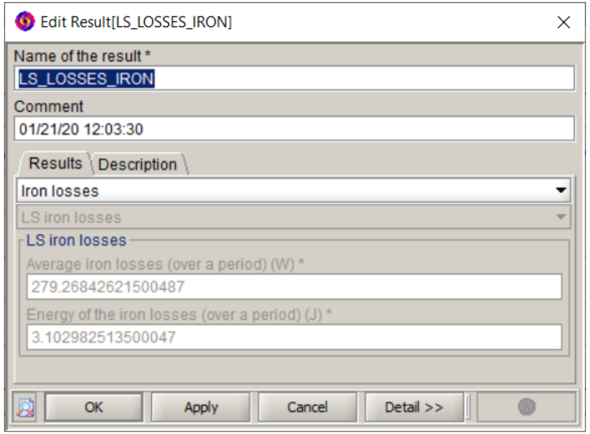
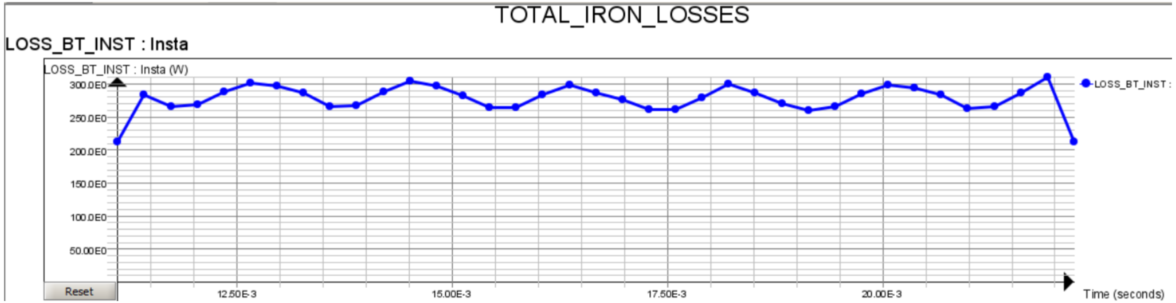
2.3 Magnetic Analysis: Solving and postprocessing

2.3.3 Postprocessing

- Calculate the iron losses





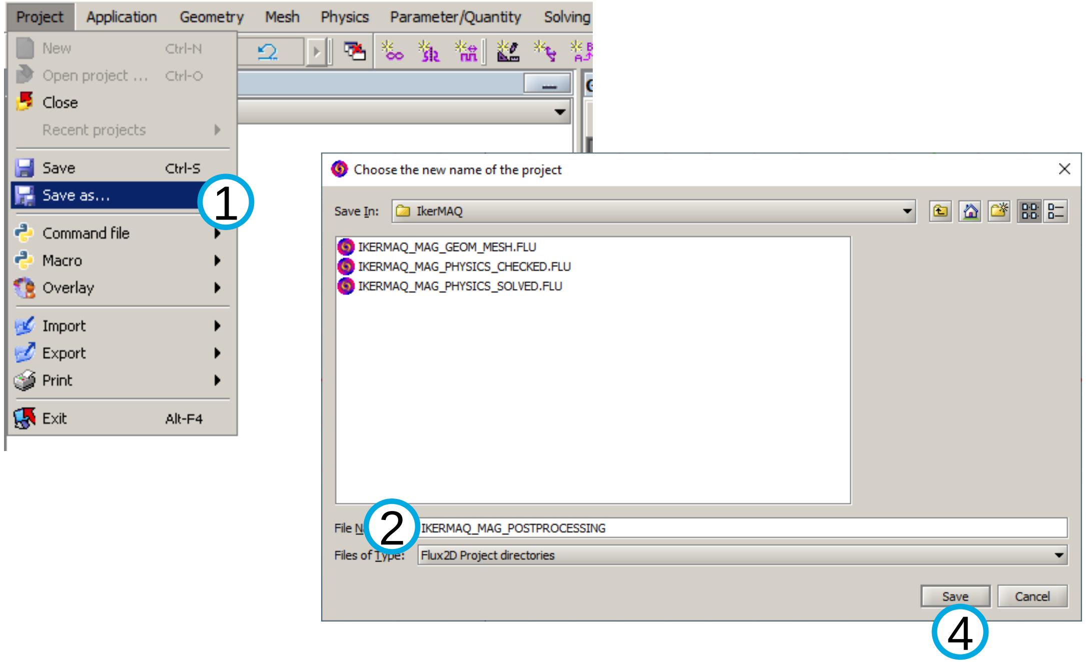
$$P_{\text{iron\_losses, mean}} = 0.28\ \text{kW} * 5 = 1.40\ \text{kW}$$

2.3 Magnetic Analysis: Solving and postprocessing

2.3.4 Finish the postprocessing

- Save the project as: IKERMAQ_MAG_POSTPROCESSING.FLU

Step	Action
1	Click on [Project] – [Save as]
2	Define the project name as “IKERMAQ_MAG_ POSTPROCESSING.FLU”
3	Verify the location
4	Click on [OK]



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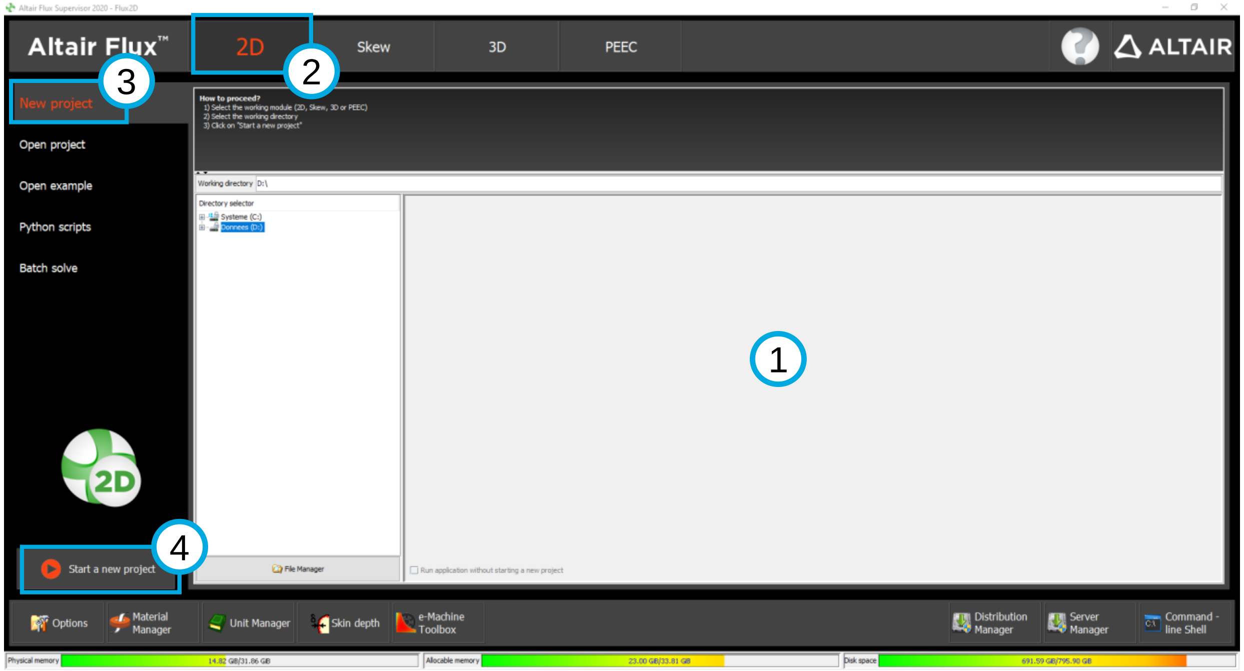
3. THERMAL ANALYSIS

3.1 GEOMETRY AND MESHING

3.1 Thermal Analysis: Geometry and meshing

3.1.1 Create a new 2D project

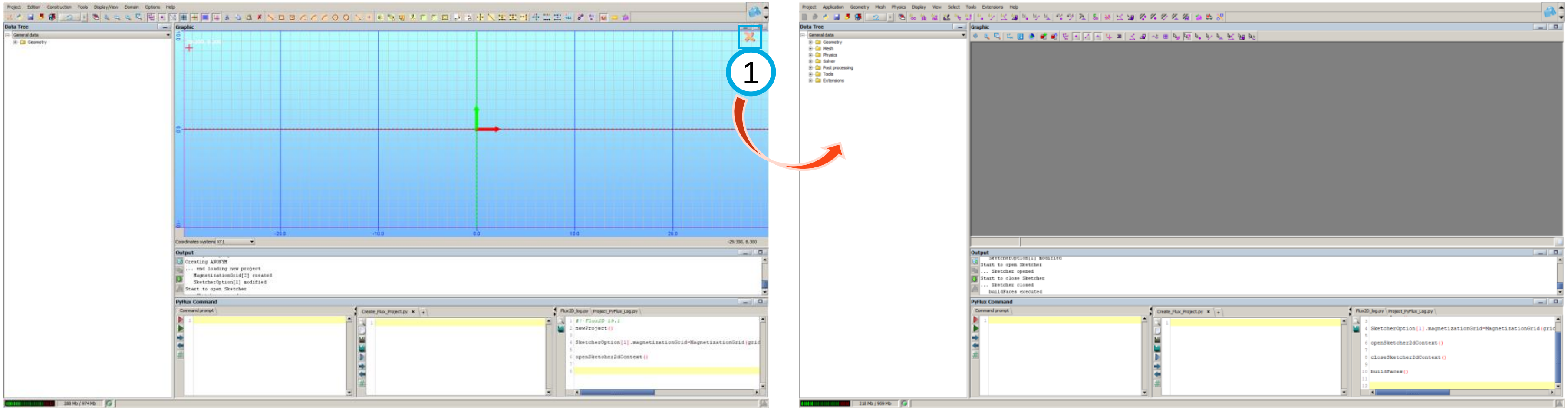


Step	Action
1	Go to Flux supervisor
2	Select the [2D] simulation context
3	Click on [New project]
4	Click on [Start a new project]

3.1 Thermal Analysis: Geometry and meshing

3.1.2 Close the sketch context

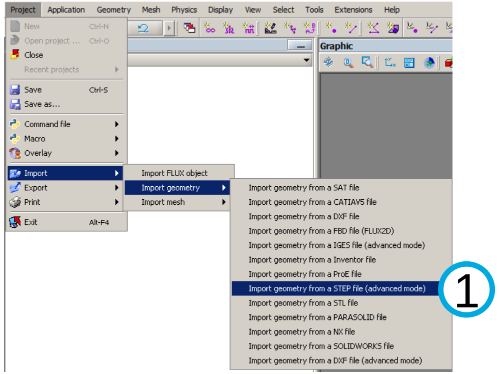
Step	Action
1	Click on the icon to close the Flux Sketch context

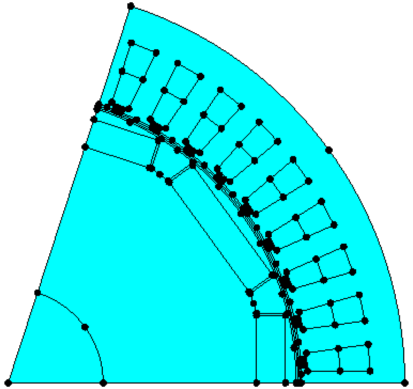


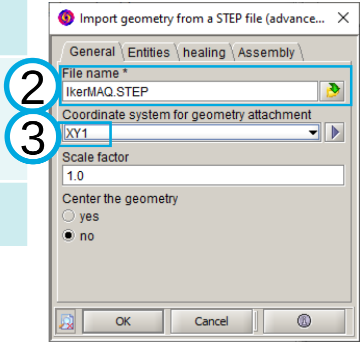
3.1 Thermal Analysis: Geometry and meshing

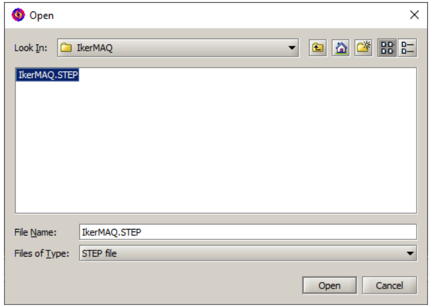
3.1.3 Import the geometry

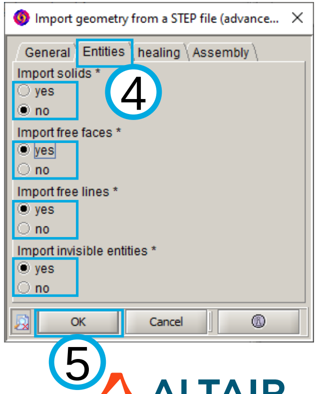
Step	Action
1	Import the IkerMAQ motor geometry by clicking on [Project] –[Import] – [Import geometry] – [Import geometry from a STEP file (advanced mode)]
2	Click on the icon and locate the file "IkerMAQ.STEP"
3	Select "XY1" as the coordinate system
4	Click on [Entities] tab, import the faces, lines, and invisible entities, and DO NOT import the solids
5	Click on [OK]











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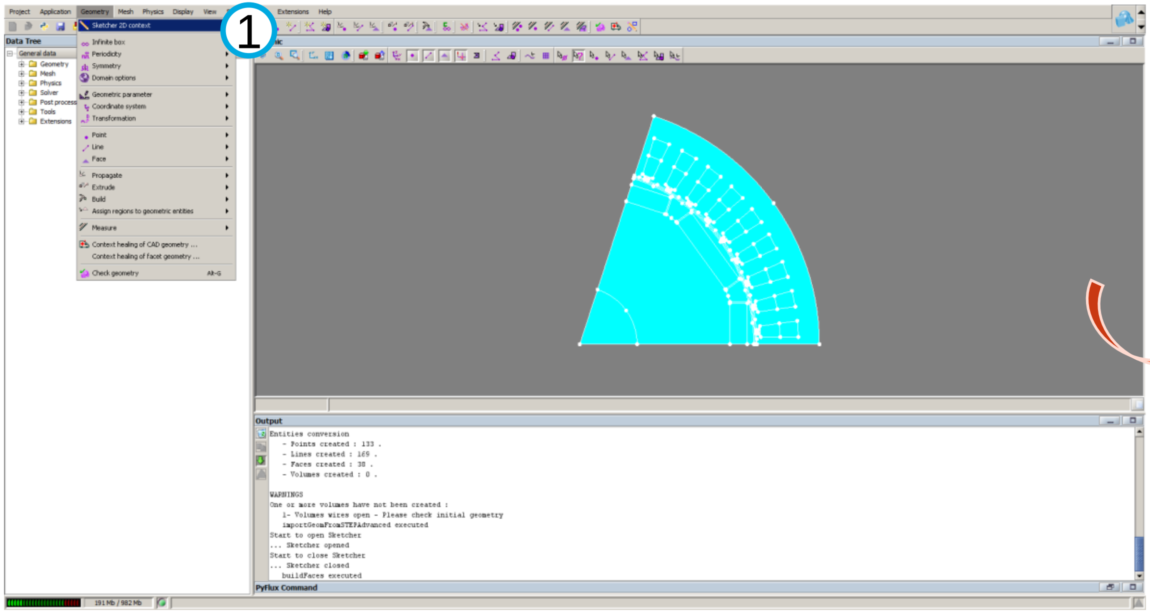
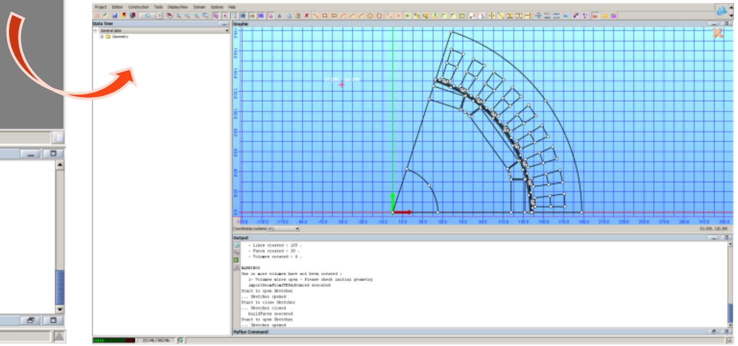
3.1 Thermal Analysis: Geometry and meshing

3.1.4 Adapt the geometry to thermal analysis

- Open the Sketcher 2D Context



Step	Action
1	Click on [Geometry] – [Sketcher 2D Context] to open the Flux 2D Sketcher

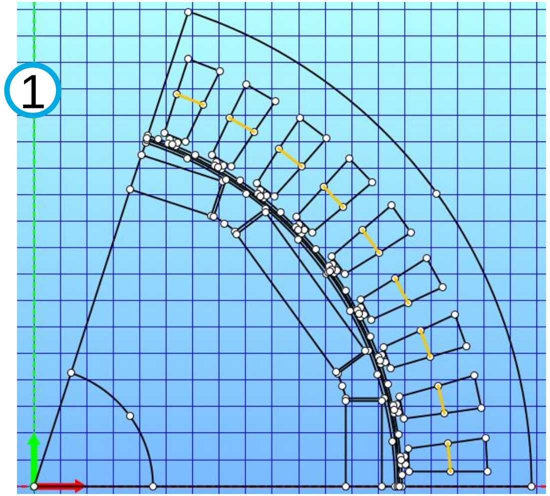


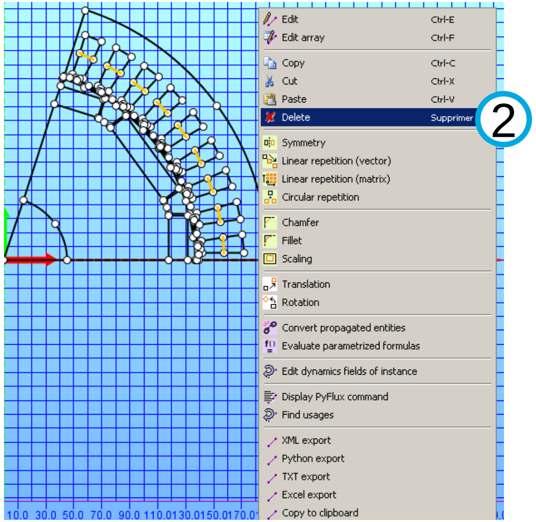
3.1 Thermal Analysis: Geometry and meshing

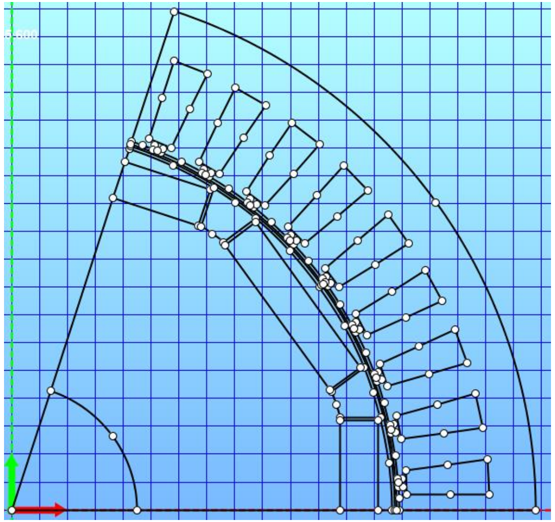
3.1.4 Adapt the geometry to thermal analysis

- Delete Lines

Step	Action
1	Press [Ctrl] to multi-select all the middle lines in the stator slots
2	Right click and click on [Delete]







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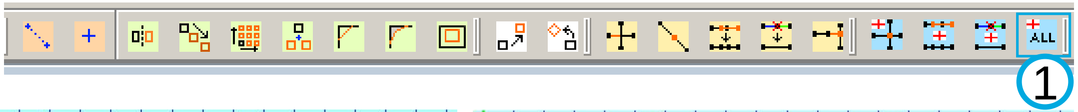
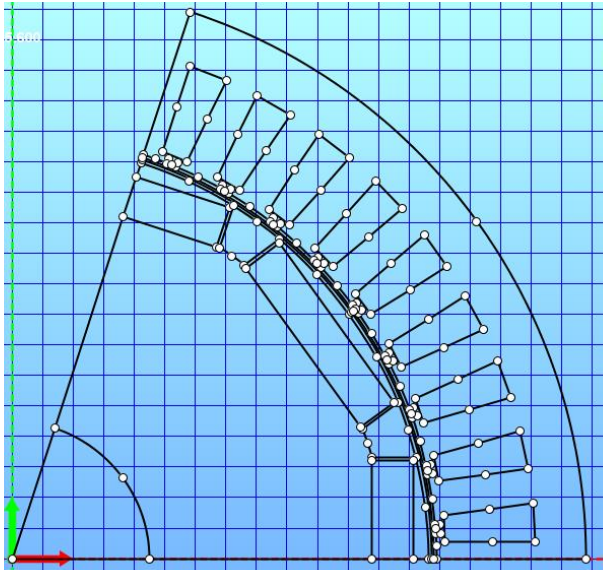
3.1 Thermal Analysis: Geometry and meshing

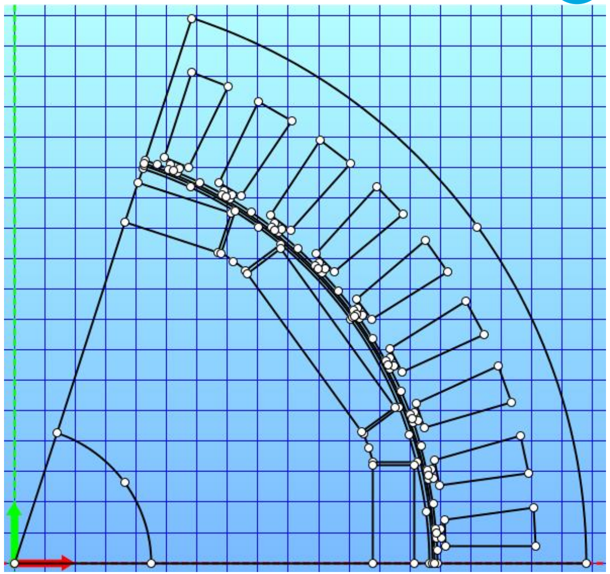
3.1.4 Adapt the geometry to thermal analysis

- Simplify the geometry



Step	Action
1	Click on the icon  to automatically simplify the motor geometry



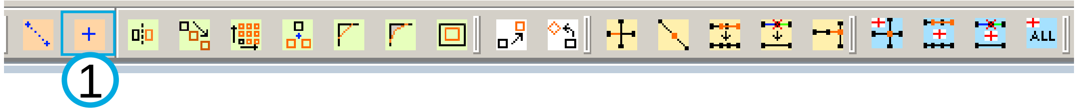


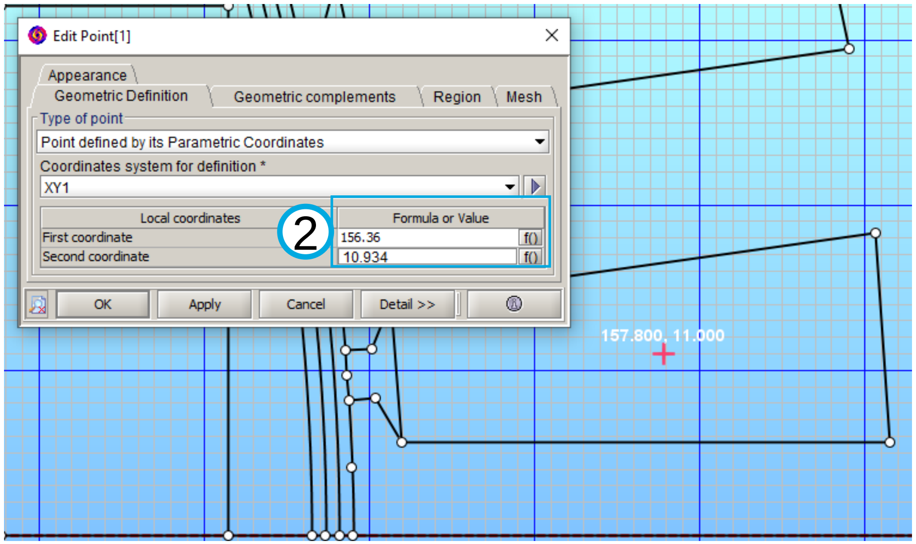
3.1 Thermal Analysis: Geometry and meshing

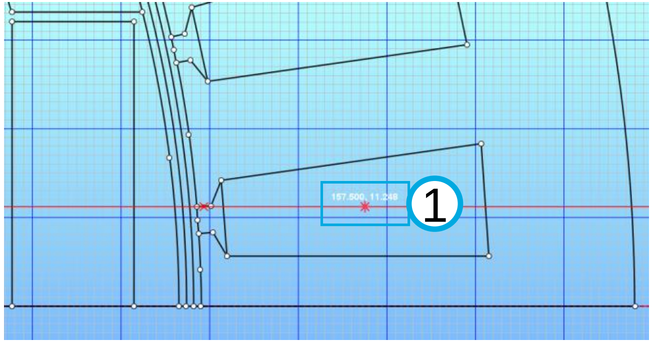
3.1.5 Create coil regions

- Create a reference center point in the bottom slot

Step	Action
1	Click on the icon + to create an reference point close to the middle point of the bottom slot area
2	Double click on the point and adjust the coordinates by (156.36, 10.934)
3	Click on [OK]







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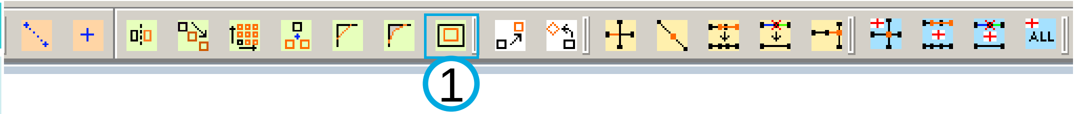
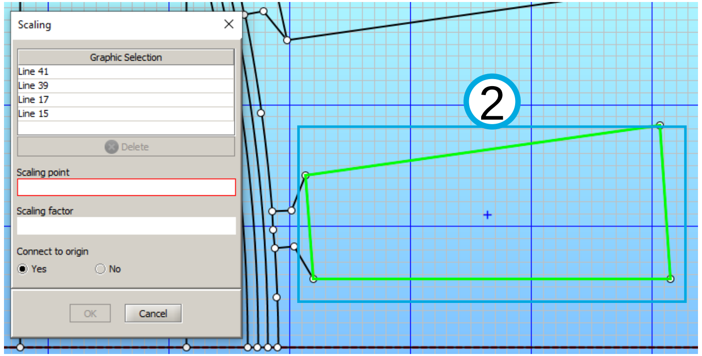
3.1 Thermal Analysis: Geometry and meshing

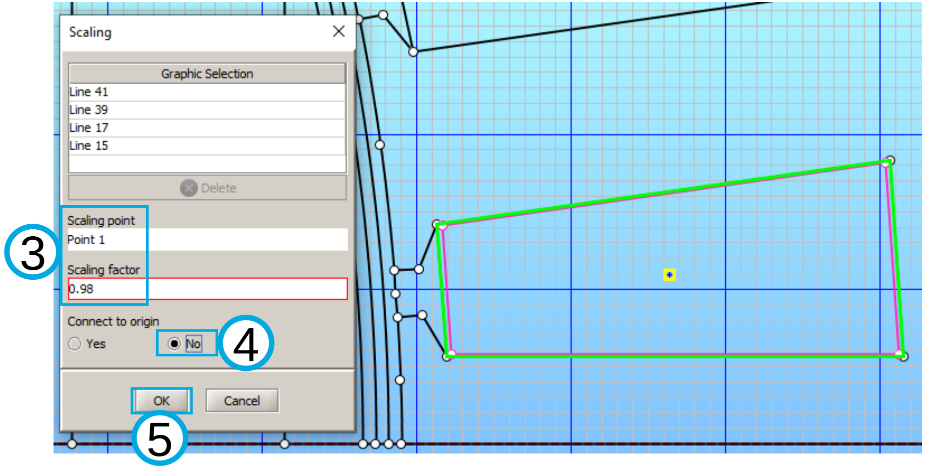
3.1.5 Create coil regions

- Create a coil area in the bottom slot



Step	Action
1	Click on the icon to create a reduce geometry for the coil areas
2	Select the 4 lines around the bottom slot area
3	Select the created reference point as the Scaling point, define the Scaling factor as 0.98
4	Do not connect to origin
5	Click on [OK]



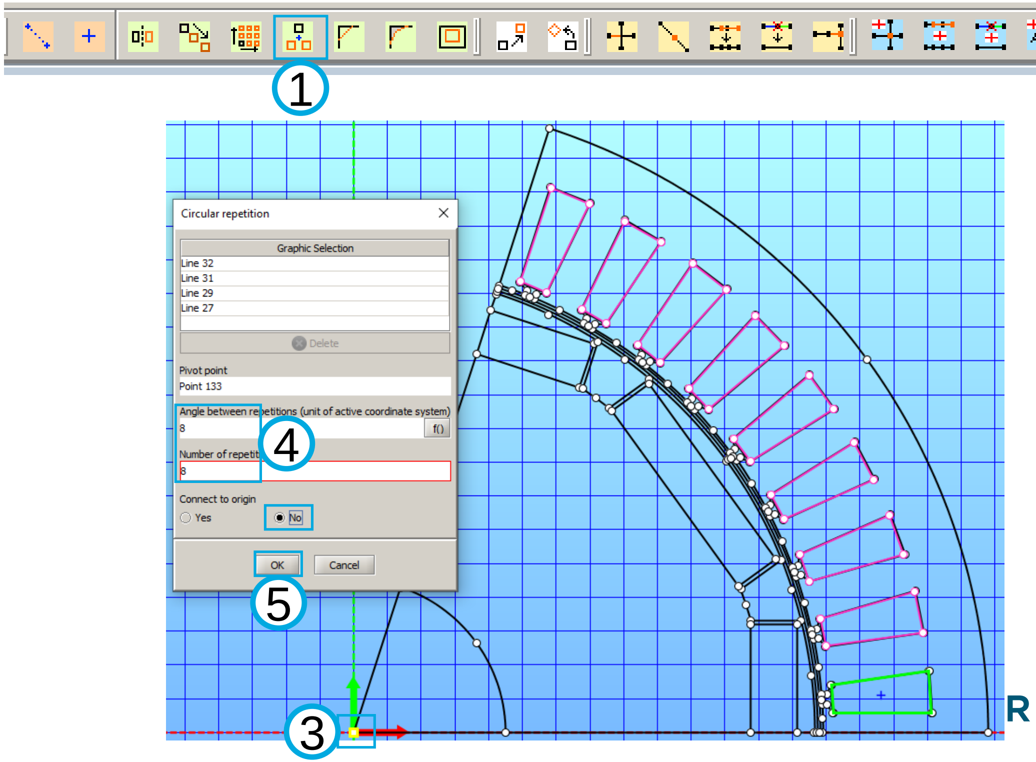


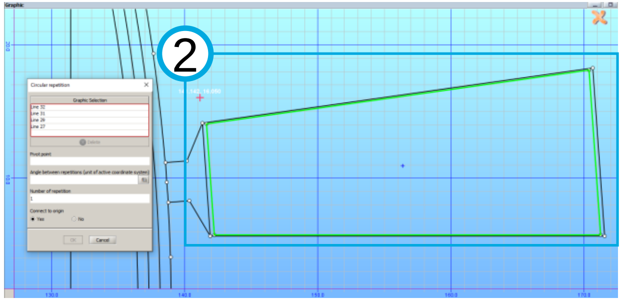
3.1 Thermal Analysis: Geometry and meshing

3.1.5 Create coil regions

- Create coil areas

Step	Action
1	Click on the icon to build circular repetition of the created coil area
2	Select the 4 lines around the coil area
3	Select the center point of motor as the Pivot point of this repetition
4	Define the repetition angle as 8, Define the repetition number as 8
5	Click on [OK]

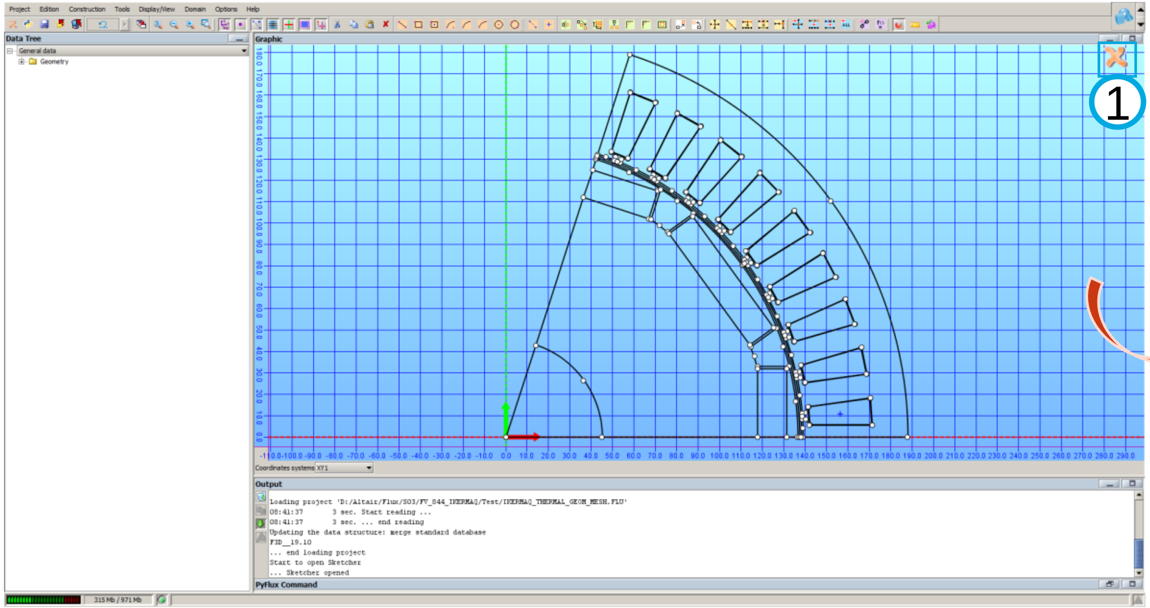




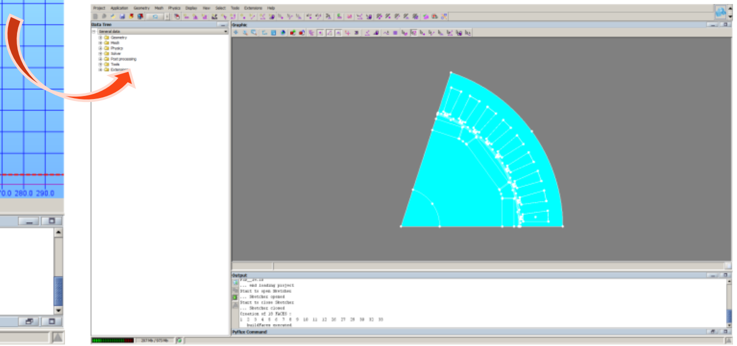
3.1 Thermal Analysis: Geometry and meshing

3.1.5 Create coil regions

- Close the Sketcher 2D Context



Step	Action
1	Click on the icon to close the Flux 2D Sketcher



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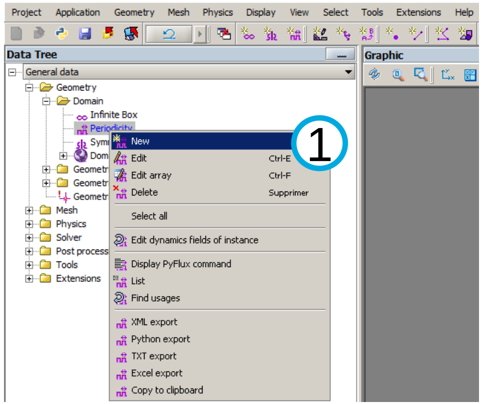
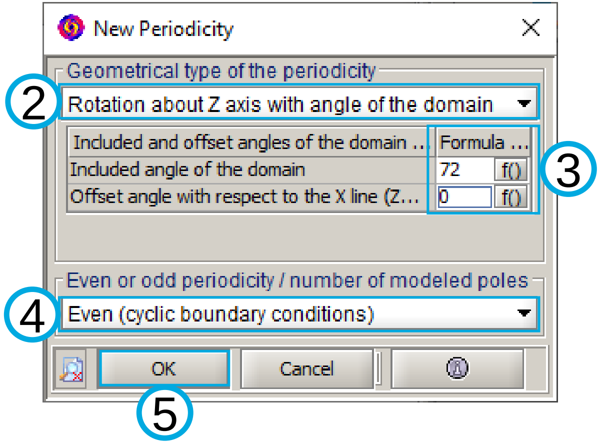
3.1 Thermal Analysis: Geometry and meshing

3.1.6 Define the periodicity of the domain

- Define the Periodicity

Step	Action
1	Right click on the **Data Tree** [Geometry] – [Domain] - [Periodicity], and click on [New]
2	Select “Rotation about Z axis with angle of the domain”
3	Enter the periodicity parameters
4	Select “Even” periodicity
5	Click on [OK]





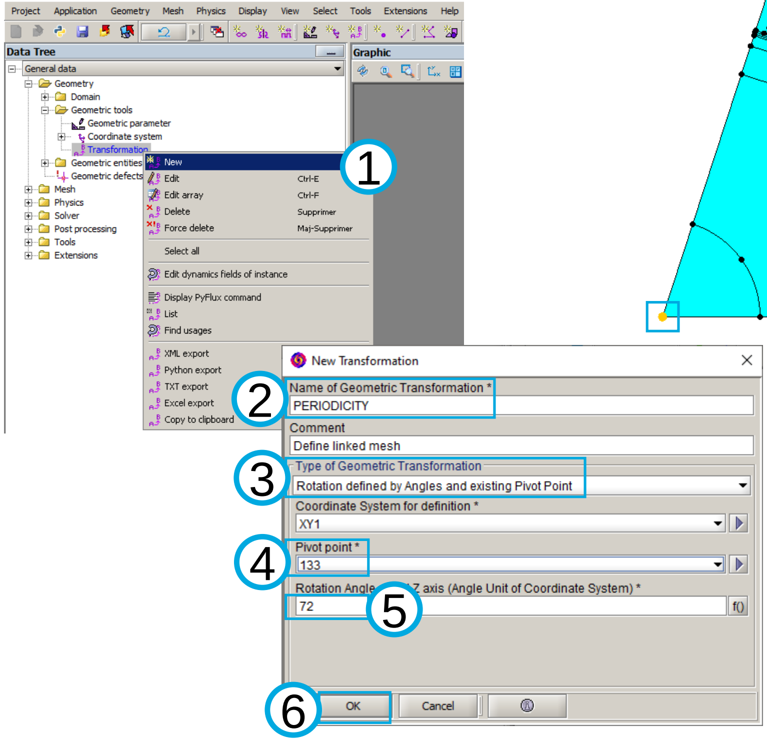
ALTAIR

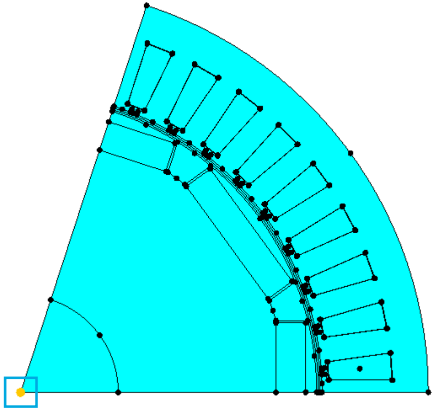
3.1 Thermal Analysis: Geometry and meshing

3.1.6 Define the periodicity of the domain

- Define the Transformation

Step	Action
1	Right click on the **Data Tree** [Geometry] – [Geometric tools] - [Transformation], and click on [New]
2	Define the name as "PERIODICITY"
3	Select "Rotation define by Angles and existing Pivot Point"
4	Select the center point of the motor as the Pivot point
5	Define the Rotation angle as 72
6	Click on [OK]





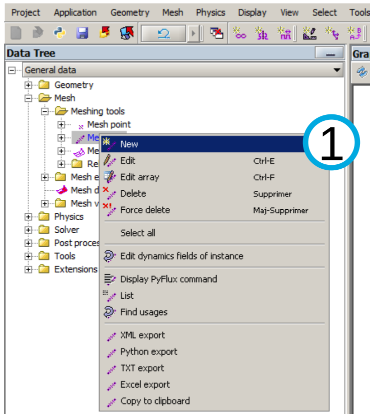
ALTAIR

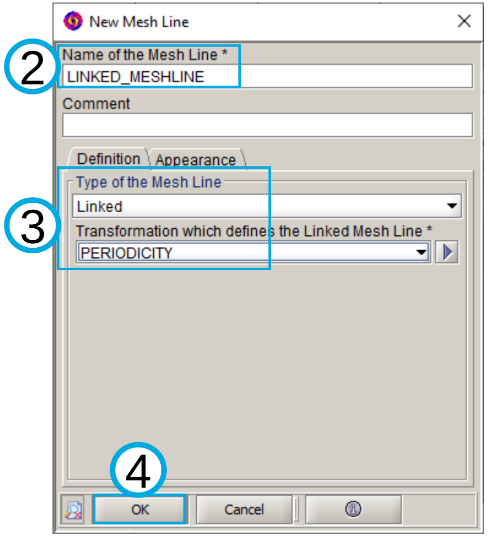
3.1 Thermal Analysis: Geometry and meshing

3.1.7 Mesh generation process

- Create a new Mesh line

Step	Action
1	Right click on the **Data Tree** [Mesh] – [Meshing tools] - [Mesh line], and click on [New]
2	Define the name as “LINKED_MESHLINE”
3	Define the type as “Linked”, select the PERIODICITY transformation
4	Click on [OK]





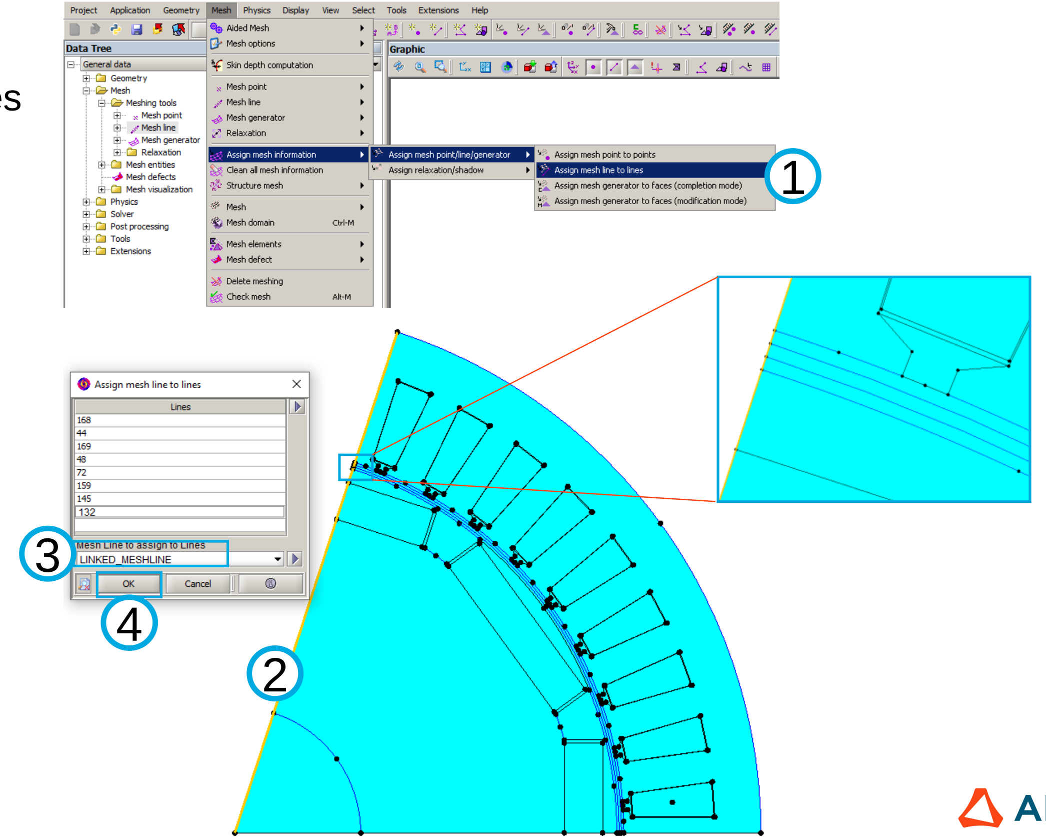
ALTAIR

3.1 Thermal Analysis: Geometry and meshing

3.1.7 Mesh generation process

- Assign the Mesh line to Lines

Step	Action
1	Click on [Mesh] – [Assign mesh information] – [Assign mesh point/line/generator] – [Assign mesh line to lines]
2	Select all the lines in the in the left border of the domain
3	Select "LINKED_MESHLINE"
4	Click on [OK]

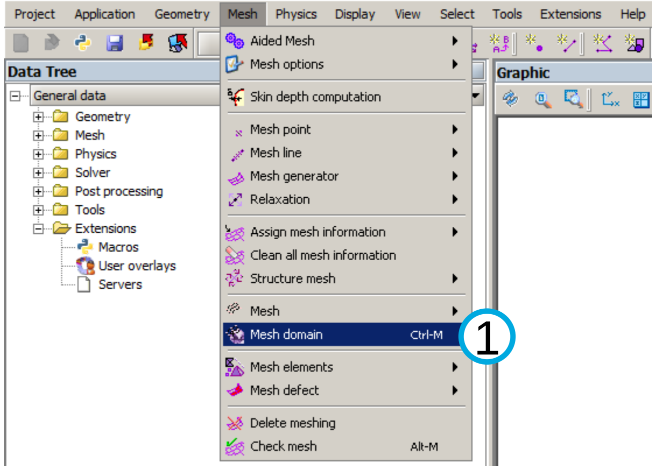


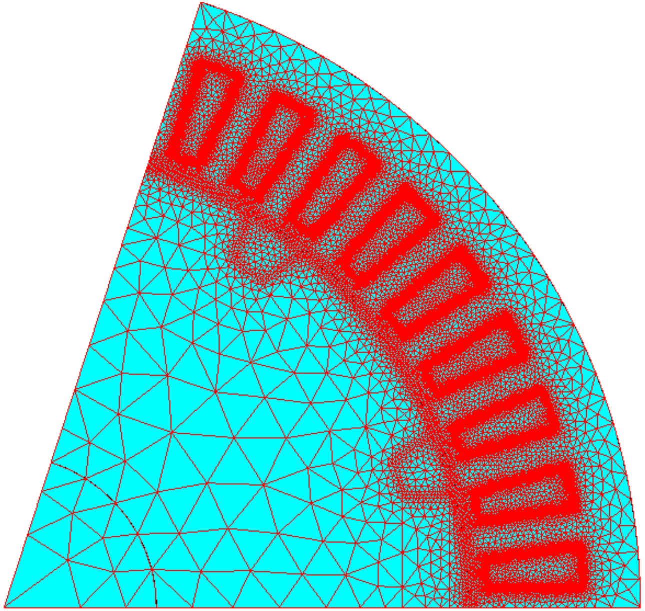
3.1 Thermal Analysis: Geometry and meshing

3.1.7 Mesh generation process

- Mesh domain

Step	Action
1	Click on [Mesh] – [Mesh domain]





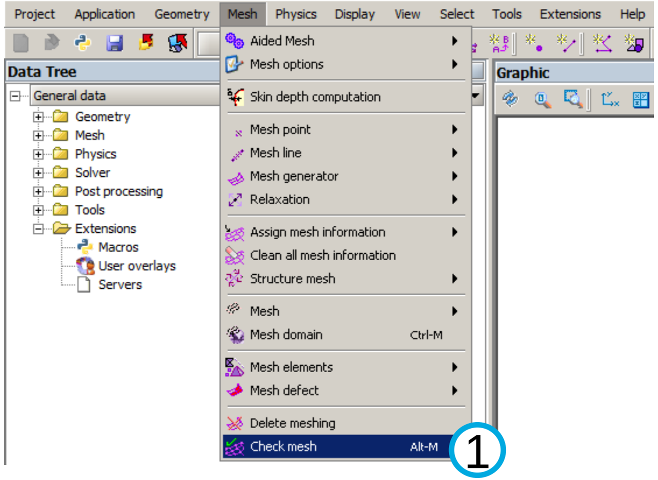
ALTAIR

3.1 Thermal Analysis: Geometry and meshing

3.1.7 Mesh generation process

- Check the mesh

Step	Action
1	Click on [Mesh] – [Check mesh]




```
Surface elements :
   Number of elements not evaluated     : 0  %
   Number of excellent quality elements : 99.39  %
   Number of good quality elements      : 0.48  %
   Number of average quality elements   : 0.09  %
   Number of poor quality elements      : 0.04  %

Number of nodes : 164931
Number of line elements : 12937
Number of surface elements : 82414
Mesh order : 2nd order
```

Tips: exact number of elements may depend on Flux version

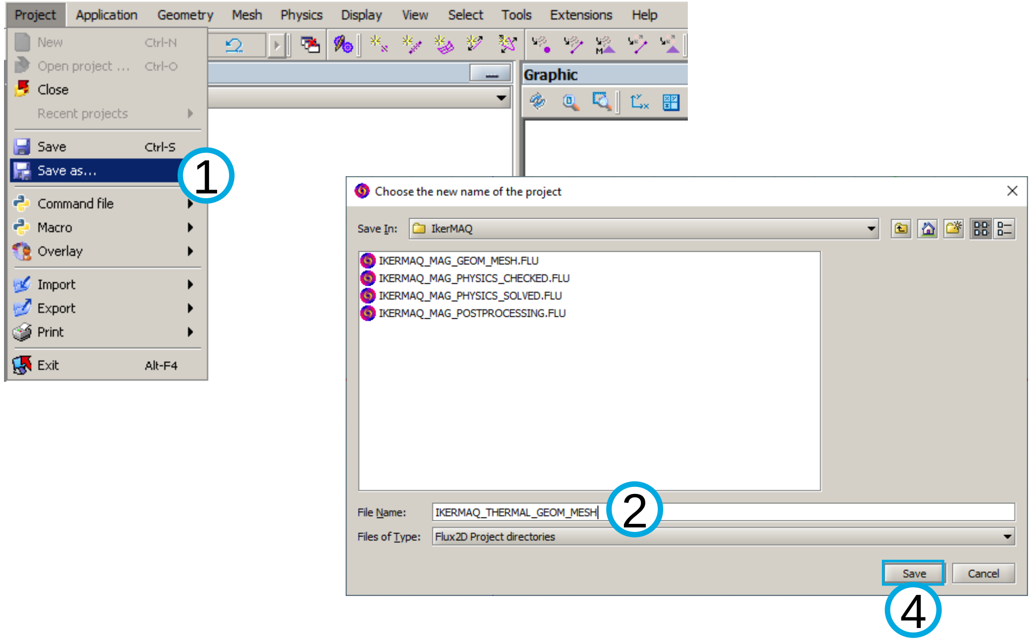
ALTAIR

3.1 Thermal Analysis: Geometry and meshing

3.1.8 Save the project

- Project name: IKERMAQ_THERMAL_GEOM_MESH.FLU

Step	Action
1	Click on [Project] – [Save as]
2	Define the project name as "IKERMAQ_THERMAL_GEOM_MESH.FLU"
3	Verify the location
4	Click on [Save]



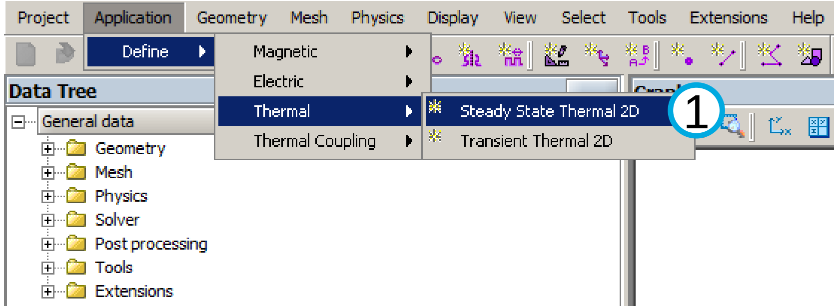
ALTAIR

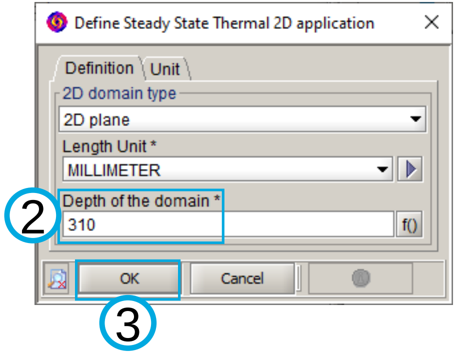
3.2 PHYSICAL DESCRIPTION PROCESS

3.2 Thermal Analysis: Physical description process

3.2.1 Define the simulation application

Step	Action
1	Click on [Application] – [Define] – [Magnetic] – [Transient Magnetic 2D]
2	In the [Definition] tab, define “310” as the 2D plane domain depth
3	Click on [OK]



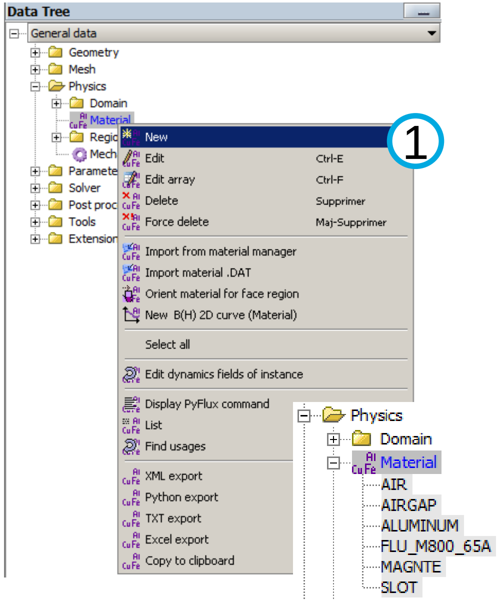


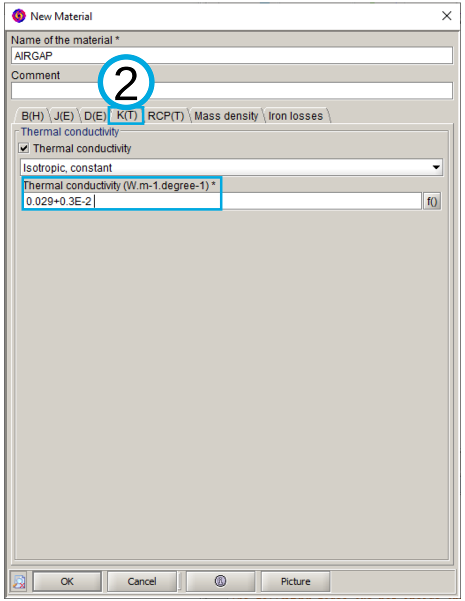
3.2 Thermal Analysis: Physical description process

3.2.2 Define materials

Step	Action
1	Right click on the **Data Tree** [Physics] – [Material], and click on [New]
2	Create the following materials, modify the properties in the K(T) tab

Name	Type of thermal conductivity	Thermal conductivity
AIR	Isotropic, constant	0.029
AIRGAP	Isotropic, constant	0.029+0.3E-2
ALUMINUM	Isotropic, constant	235
MAGNET	Isotropic, constant	9
FLU_M800_65A	Isotropic, constant	34
SLOT	Isotropic, constant	1

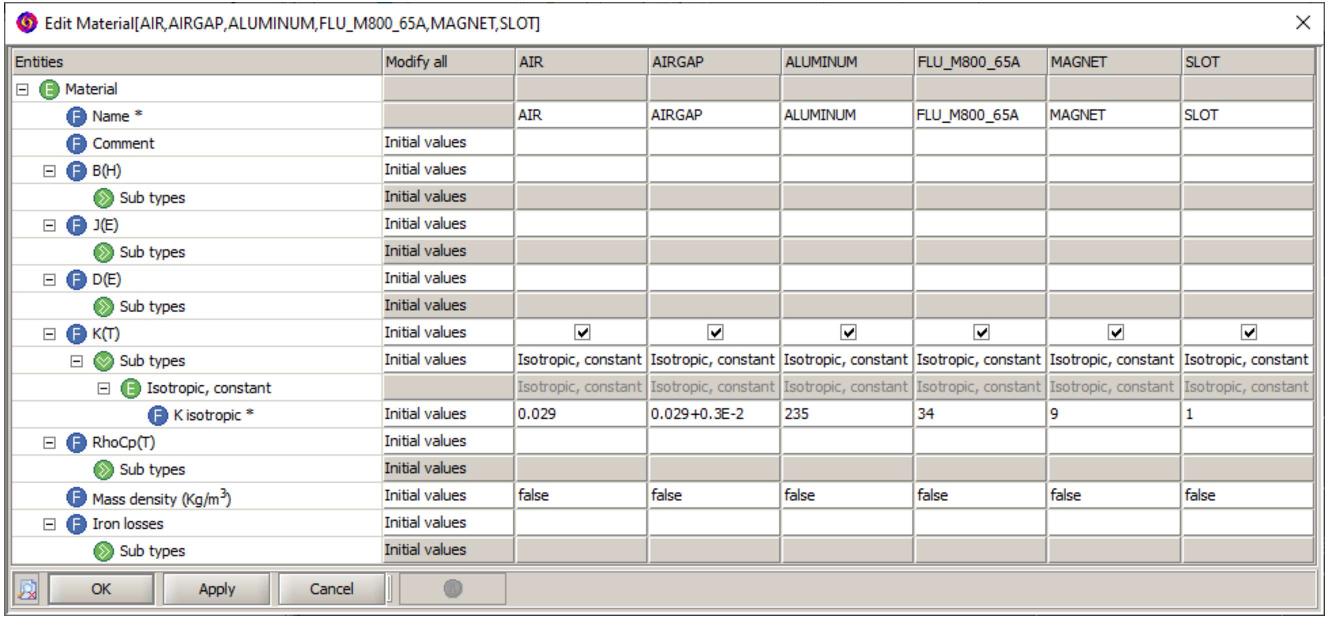




ALTAIR

3.2 Thermal Analysis: Physical description process

3.2.2 Define materials



Edit Material[AIR,AIRGAP,ALUMINUM,FLU_M800_65A,MAGNET,SLOT]

Entities	Modify all	AIR	AIRGAP	ALUMINUM	FLU_M800_65A	MAGNET	SLOT
Material							
Name *		AIR	AIRGAP	ALUMINUM	FLU_M800_65A	MAGNET	SLOT
Comment	Initial values						
B(H)	Initial values						
Sub types	Initial values						
J(E)	Initial values						
Sub types	Initial values						
D(E)	Initial values						
Sub types	Initial values						
K(T)	Initial values	☑	☑	☑	☑	☑	☑
Sub types	Initial values	Isotropic, constant	Isotropic, constant	Isotropic, constant	Isotropic, constant	Isotropic, constant	Isotropic, constant
Isotropic, constant		Isotropic, constant	Isotropic, constant	Isotropic, constant	Isotropic, constant	Isotropic, constant	Isotropic, constant
K isotropic *	Initial values	0.029	0.029+0.3E-2	235	34	9	1
RhoCp(T)	Initial values						
Sub types	Initial values						
Mass density (Kg/m^3)	Initial values	false	false	false	false	false	false
Iron losses	Initial values						
Sub types	Initial values						

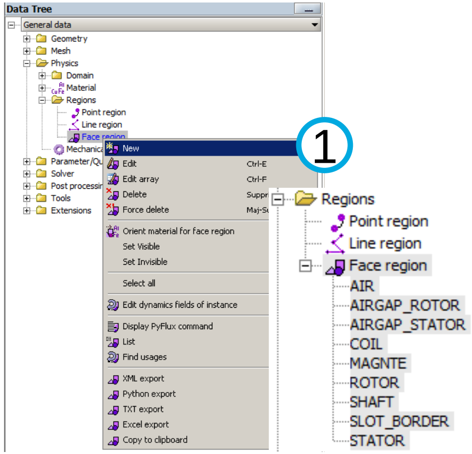
OK Apply Cancel

ALTAIR

3.2 Thermal Analysis: Physical description process

3.2.3 Define face regions

Step	Action
1	Right click on the **Data Tree** [Physics] – [Region] – [Face region], and click on [New]
2	Create the following Face regions



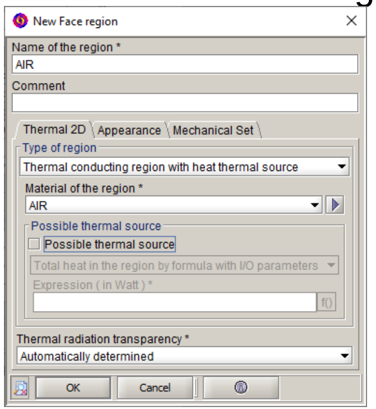
Name	Type of region	Material	Thermal source	Expression[2]
AIR	Thermal conducing region	AIR	-	-
AIRGAP_ROTOR	Thermal conducing region	AIR[1]	-	-
AIRGAP_STATOR	Thermal conducing region	AIRGAP	-	-
COIL	Thermal conducing region	SLOT	Uniform volume density	1
MAGNET	Thermal conducing region	MAGNET	Uniform volume density	1
ROTOR	Thermal conducing region	FLU_M800_65A	Uniform volume density	1
SHAFT	Thermal conducing region	ALUMINUM	-	-
SLOT_BORDER	Thermal conducing region	AIR	-	-
STATOR	Thermal conducing region	FLU_M800_65A	Uniform volume density	1

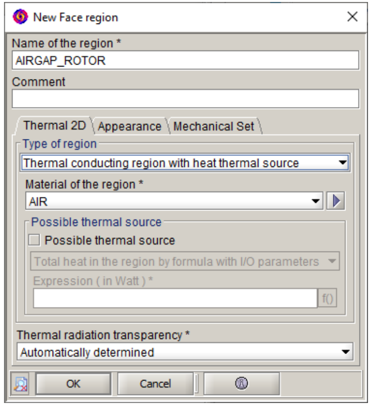
Keep in mind:
1. The material of region AIRGAP_ROTOR is AIR
2. The thermal source expression will be modified in the later section

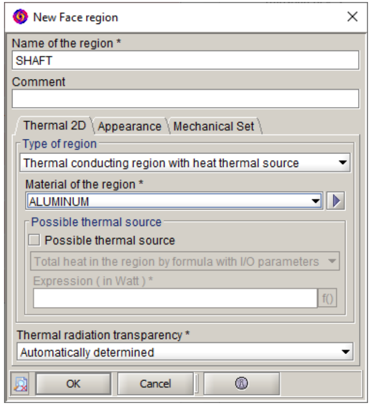
ALTAIR

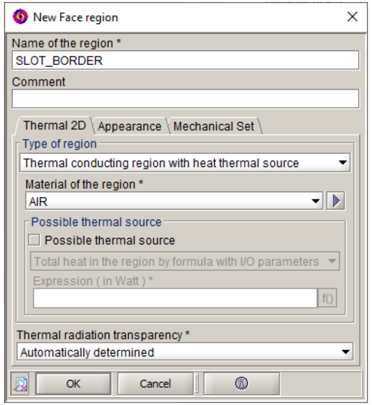
3.2 Thermal Analysis: Physical description process

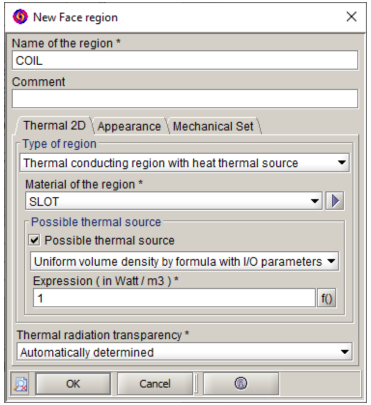
3.2.3 Define face regions

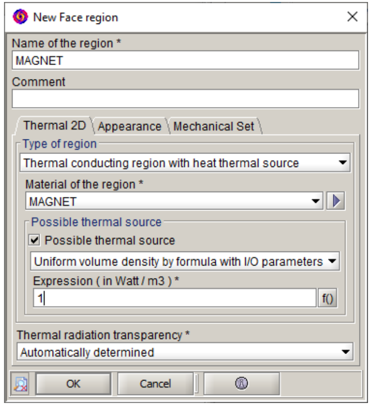


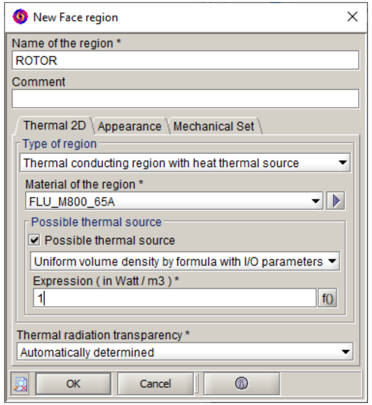


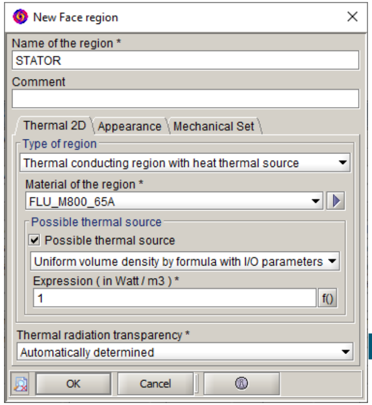






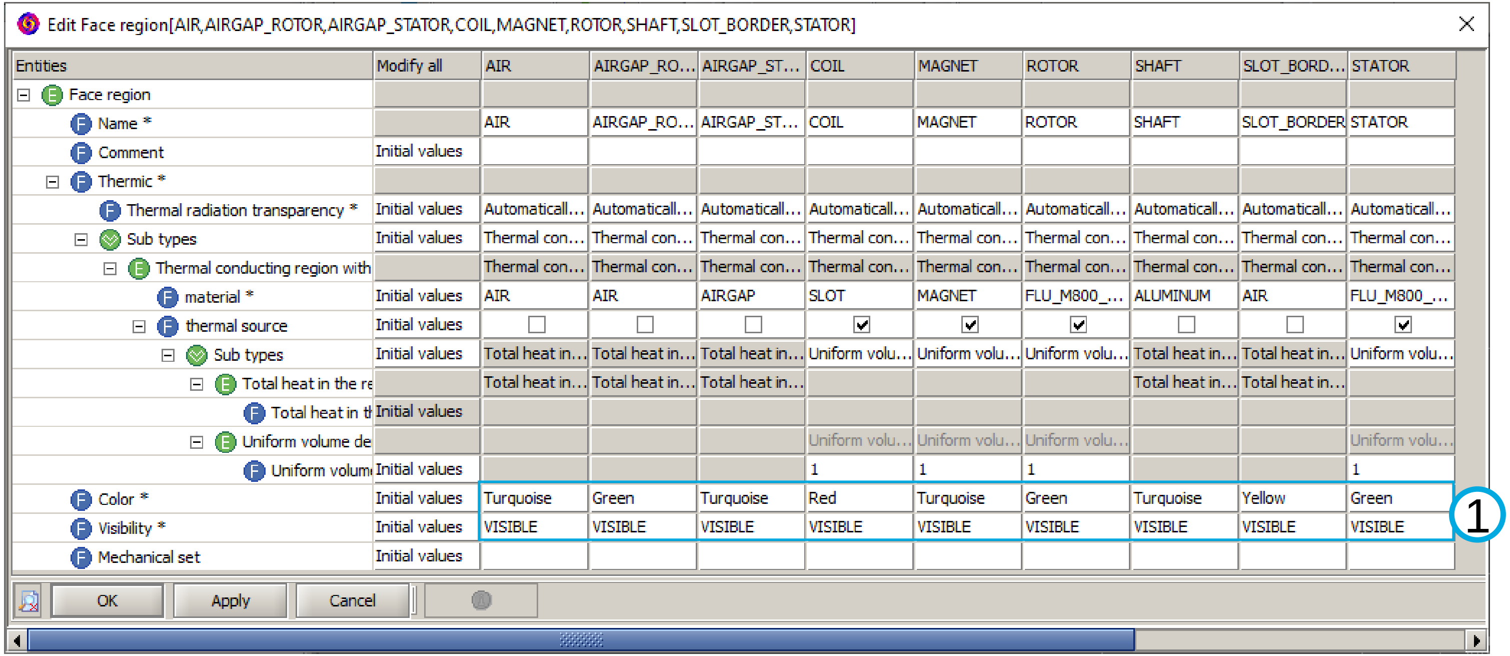






3.2 Thermal Analysis: Physical description process

3.2.3 Define face regions



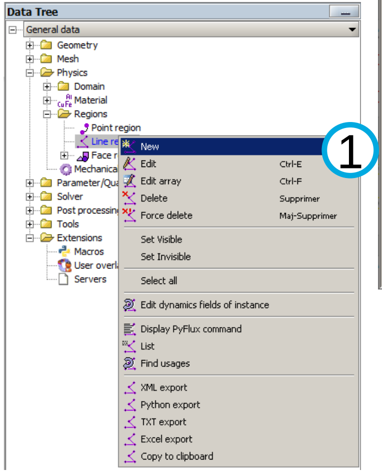
Entities	Modify all	AIR	AIRGAP_RO...	AIRGAP_ST...	COIL	MAGNET	ROTOR	SHAFT	SLOT_BORD...	STATOR
Face region										
Name *		AIR	AIRGAP_RO...	AIRGAP_ST...	COIL	MAGNET	ROTOR	SHAFT	SLOT_BORDER	STATOR
Comment	Initial values									
Thermic *										
Thermal radiation transparency *	Initial values	Automaticall...	Automaticall...	Automaticall...	Automaticall...	Automaticall...	Automaticall...	Automaticall...	Automaticall...	Automaticall...
Sub types	Initial values	Thermal con...	Thermal con...	Thermal con...	Thermal con...	Thermal con...	Thermal con...	Thermal con...	Thermal con...	Thermal con...
Thermal conducting region with		Thermal con...	Thermal con...	Thermal con...	Thermal con...	Thermal con...	Thermal con...	Thermal con...	Thermal con...	Thermal con...
material *	Initial values	AIR	AIR	AIRGAP	SLOT	MAGNET	FLU_M800_...	ALUMINUM	AIR	FLU_M800_...
thermal source	Initial values	☐	☐	☐	☑	☑	☑	☐	☐	☑
Sub types	Initial values	Total heat in...	Total heat in...	Total heat in...	Uniform volu...	Uniform volu...	Uniform volu...	Total heat in...	Total heat in...	Uniform volu...
Total heat in the re		Total heat in...	Total heat in...	Total heat in...				Total heat in...	Total heat in...	
Total heat in th	Initial values									
Uniform volume de					Uniform volu...	Uniform volu...	Uniform volu...			Uniform volu...
Uniform volum	Initial values				1	1	1			1
Color *	Initial values	Turquoise	Green	Turquoise	Red	Turquoise	Green	Turquoise	Yellow	Green
Visibility *	Initial values	VISIBLE	VISIBLE	VISIBLE	VISIBLE	VISIBLE	VISIBLE	VISIBLE	VISIBLE	VISIBLE
Mechanical set	Initial values									

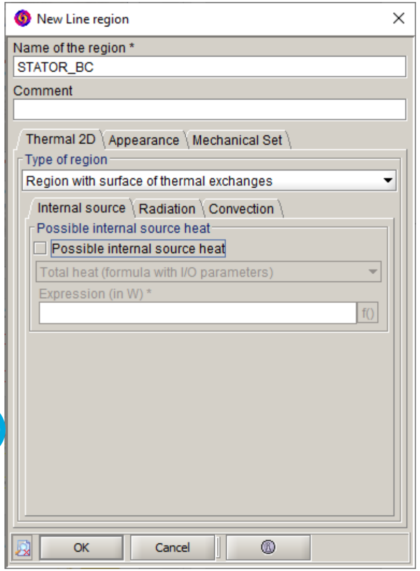
3.2 Thermal Analysis: Physical description process

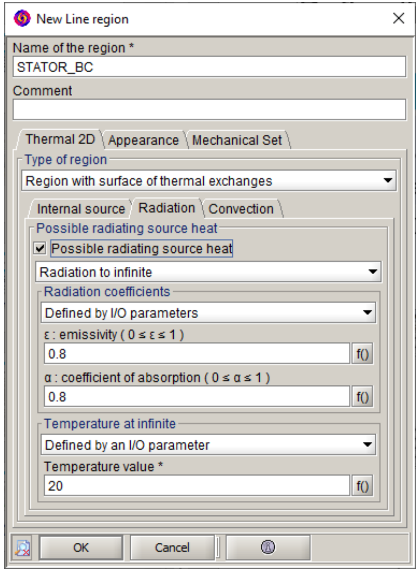
3.2.4 Define line regions for thermal boundary conditions

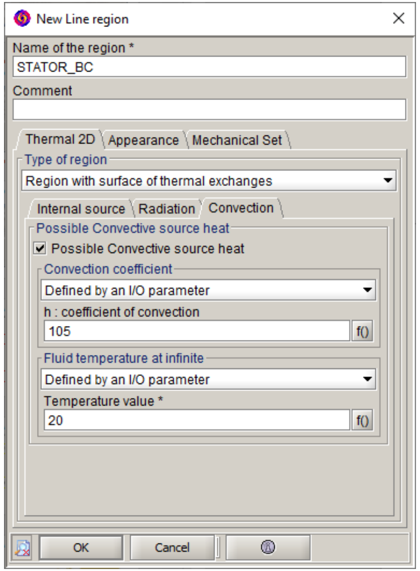
- STATOR_BC

Step	Action
1	Right click on the **Data Tree** [Physics] – [Region] – [Line region], and click on [New]
2	Create the following two Line regions





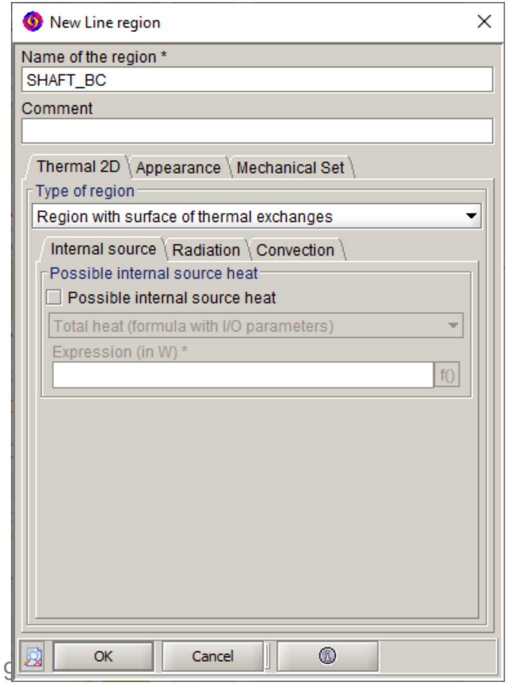


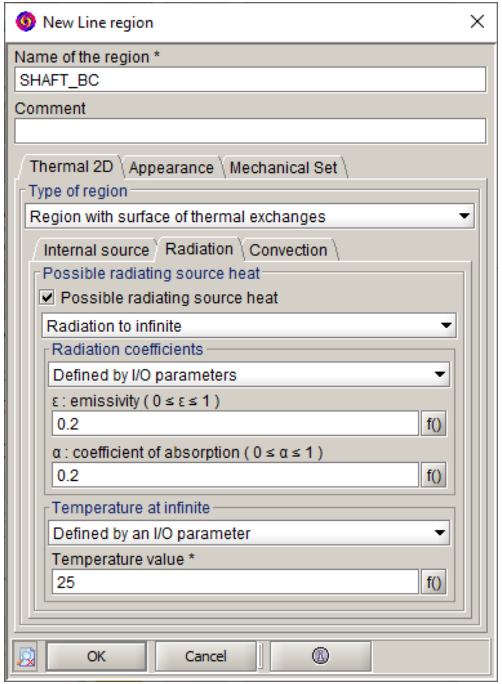


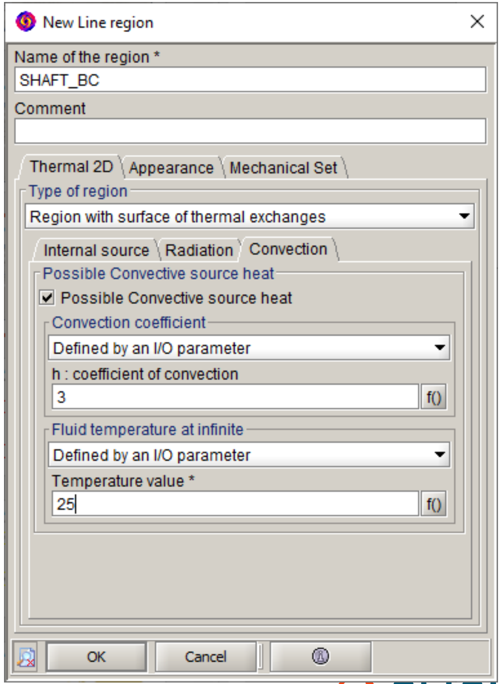
3.2 Thermal Analysis: Physical description process

3.2.4 Define line regions for thermal boundary conditions

- SHAFT_BC



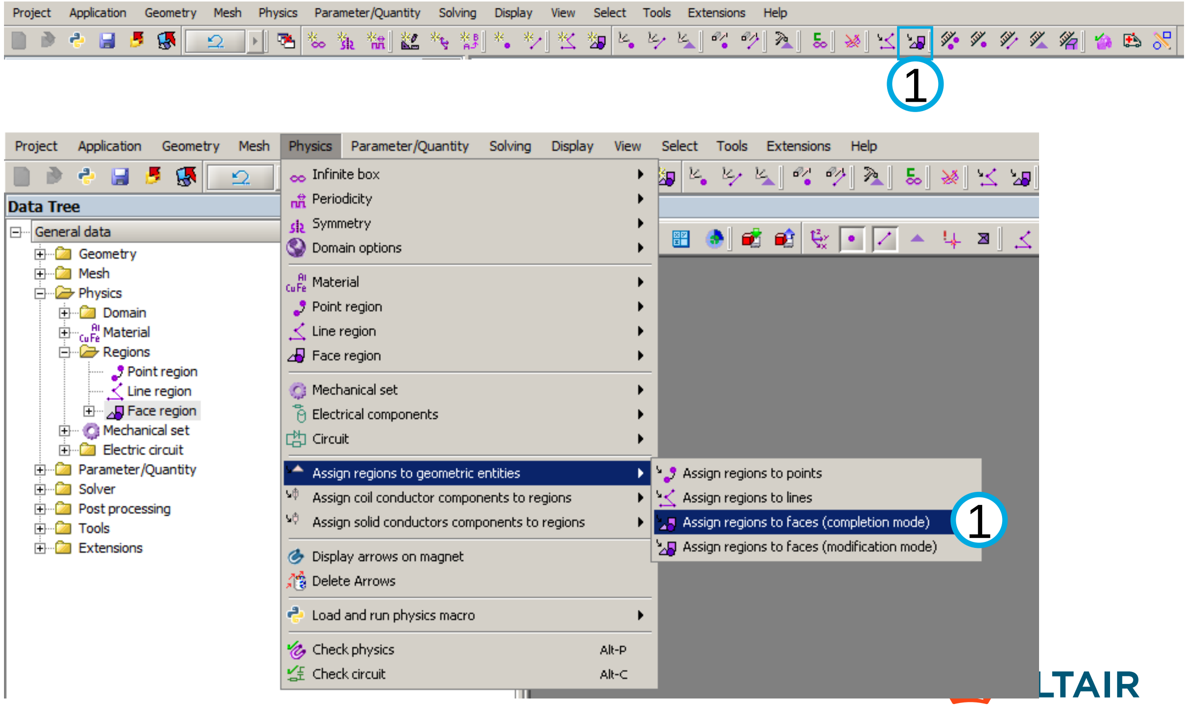




3.2 Thermal Analysis: Physical description process

3.2.5 Assign the Face regions to the Faces

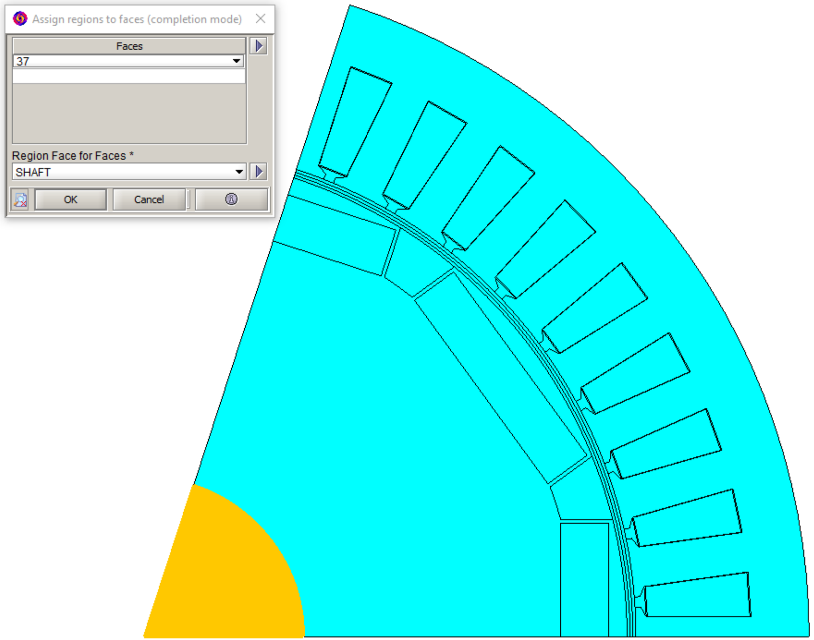
Step	Action
1	Click on the icon to assign regions to volumes. Or click on the [Physics] - [Assign regions to geometric entities] – [Assign regions to faces (completion mode)]
2	Assign the created Volume regions to the Volumes

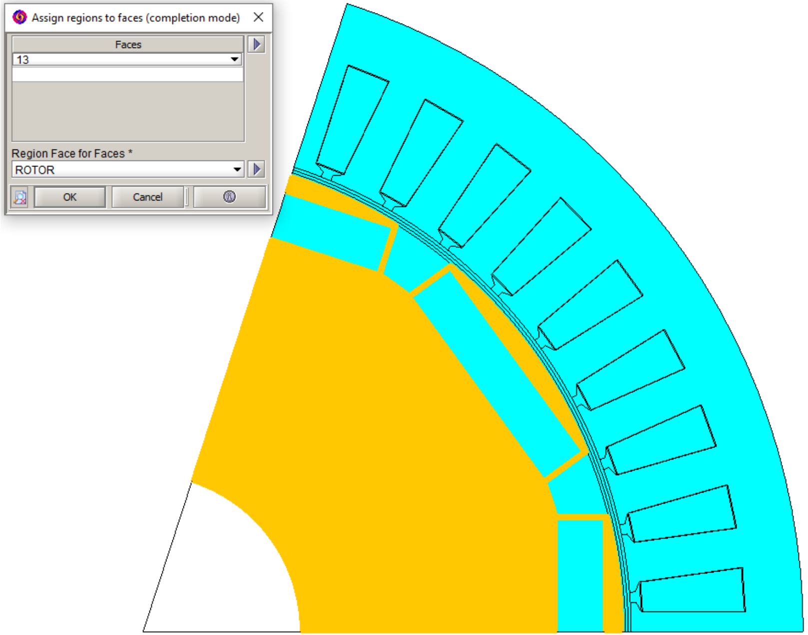


3.2 Thermal Analysis: Physical description process

3.2.5 Assign the Face regions to the Faces

- SHAFT and ROTOR



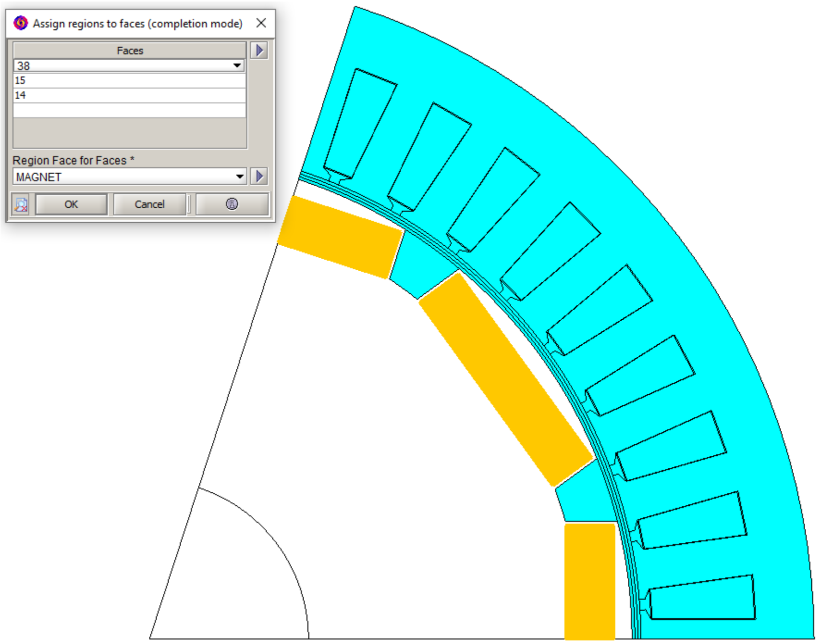


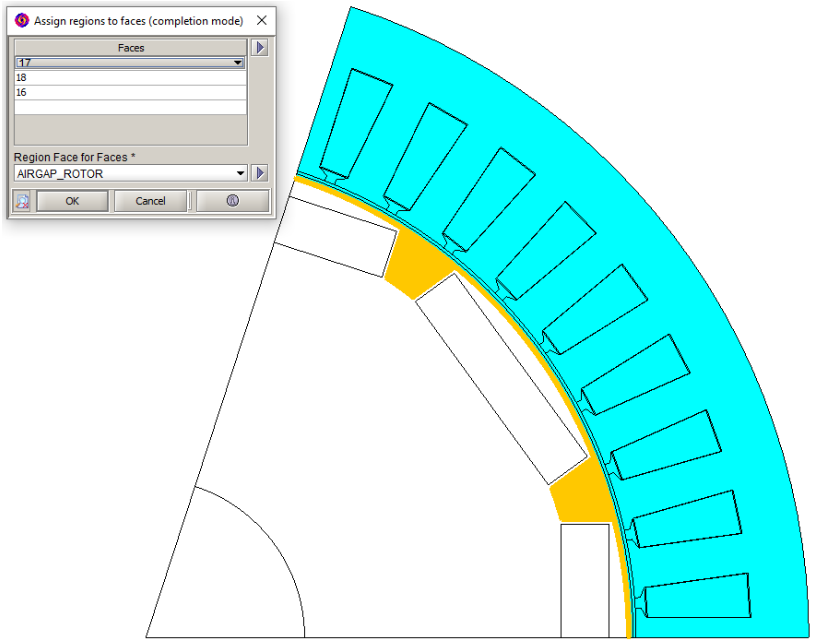
ALTAIR

3.2 Thermal Analysis: Physical description process

3.2.5 Assign the Face regions to the Faces

- MAGNET and AIRGAP_ROTOR



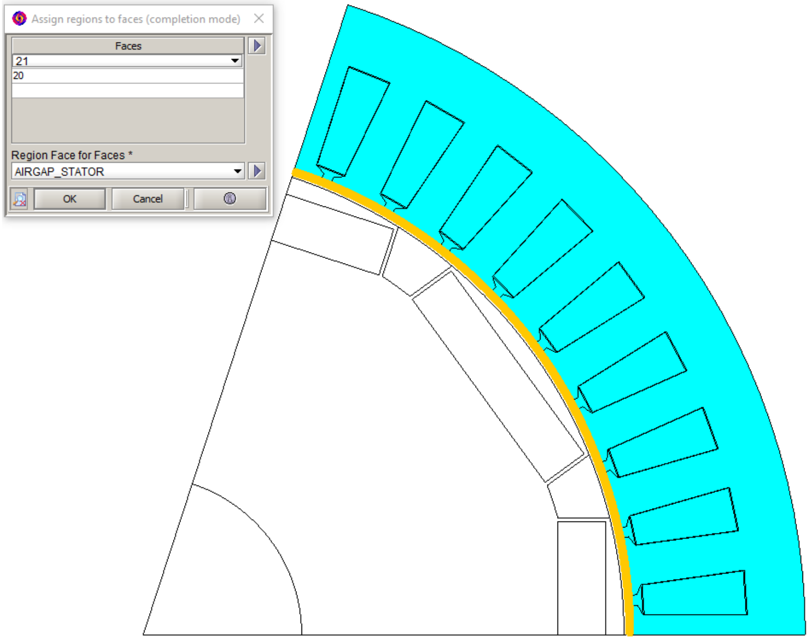


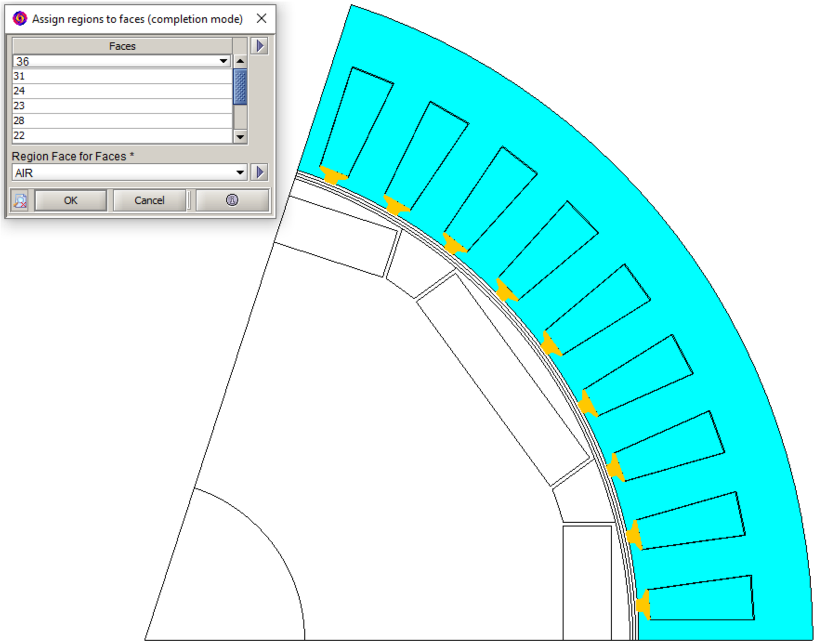
ALTAIR

3.2 Thermal Analysis: Physical description process

3.2.5 Assign the Face regions to the Faces

- AIRGAP_STATOR and AIR



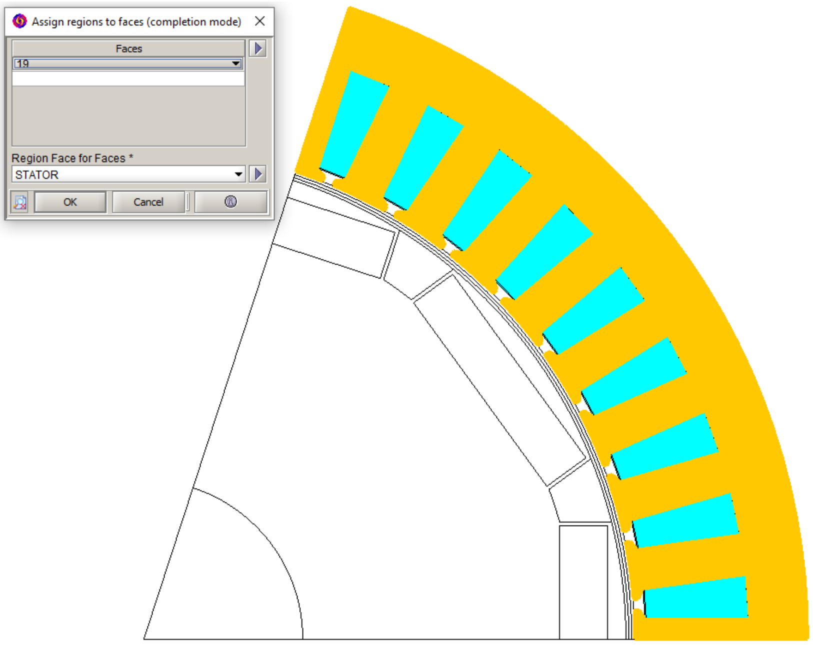


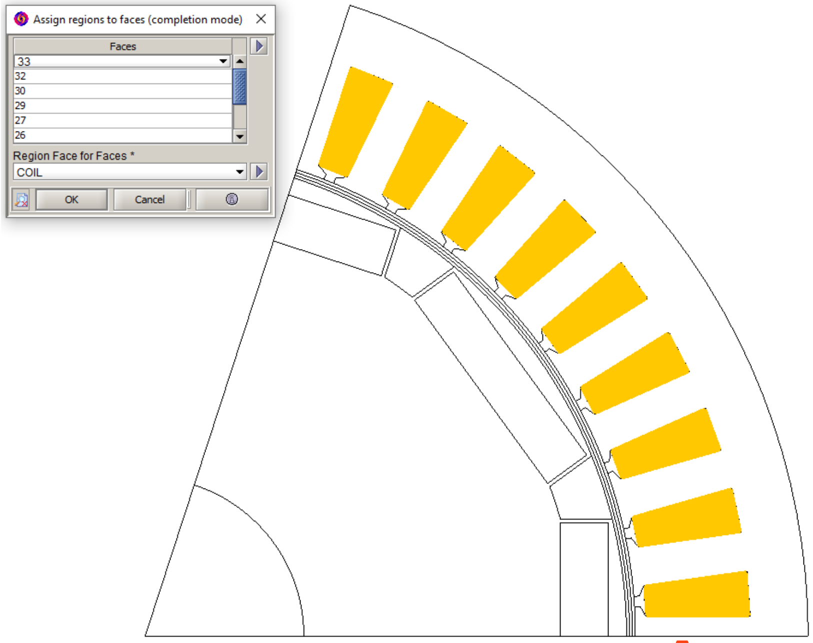
ALTAIR

3.2 Thermal Analysis: Physical description process

3.2.5 Assign the Face regions to the Faces

- STATOR and COIL

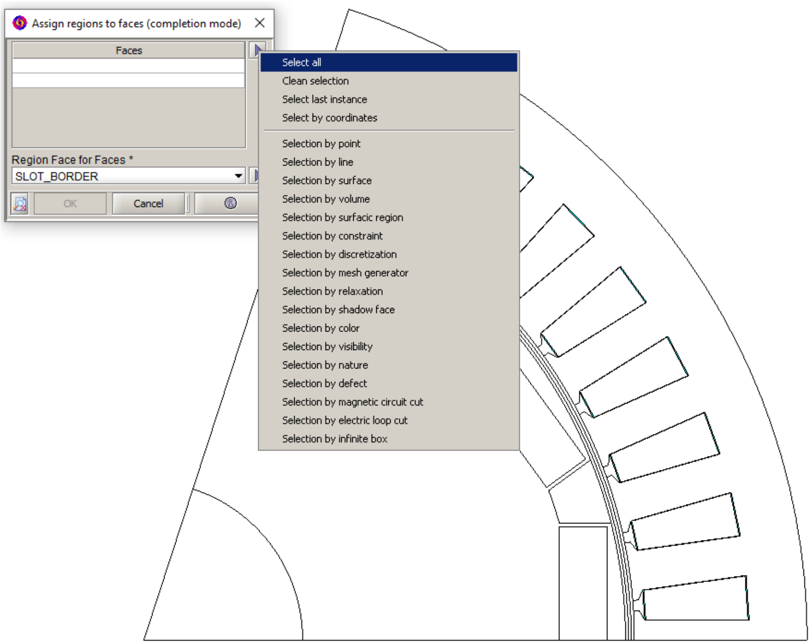


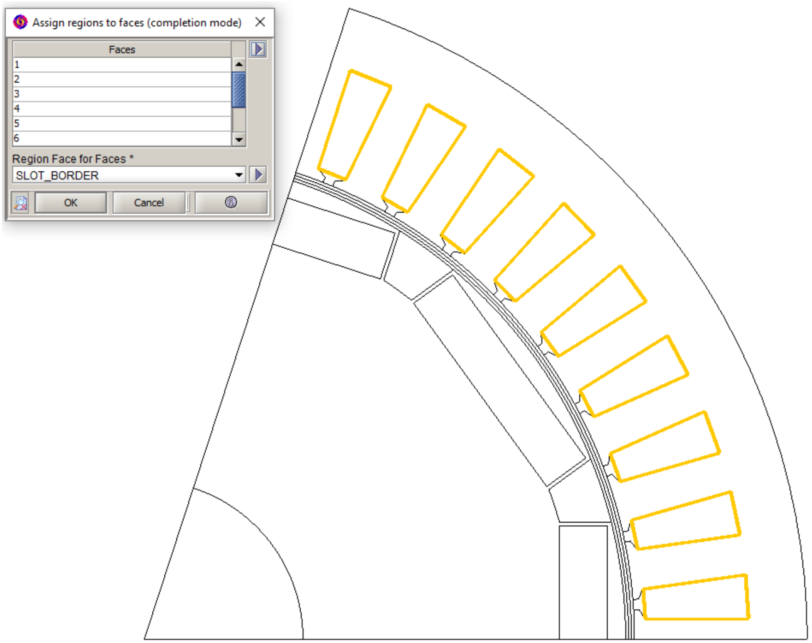


3.2 Thermal Analysis: Physical description process

3.2.5 Assign the Face regions to the Faces

- SLOT_BORDER





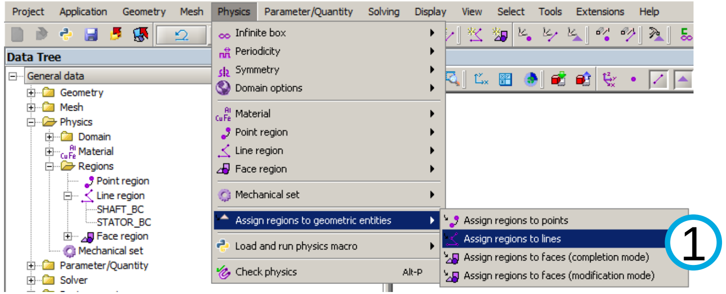
ALTAIR

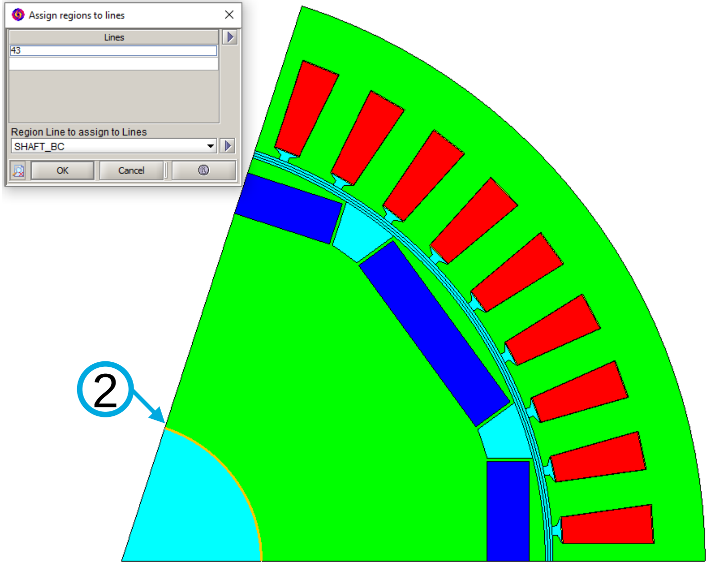
3.2 Thermal Analysis: Physical description process

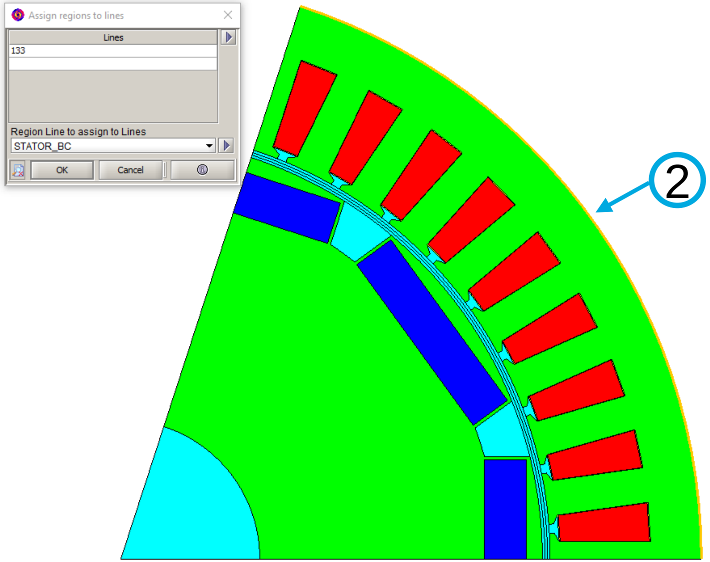
3.2.6 Assign Line regions to line

- SHAFT_BC

Step	Action
1	Click on the [Physics] - [Assign regions to geometric entities] – [Assign regions to lines]
2	Assign the created Line regions to the Lines







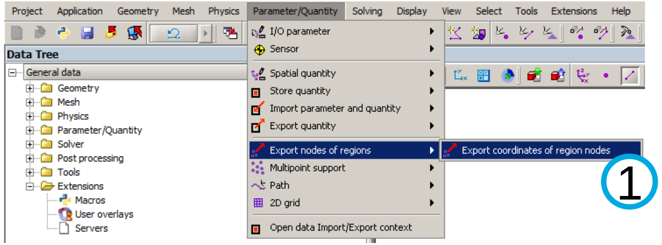
ALTAIR

3.2 Thermal Analysis: Physical description process

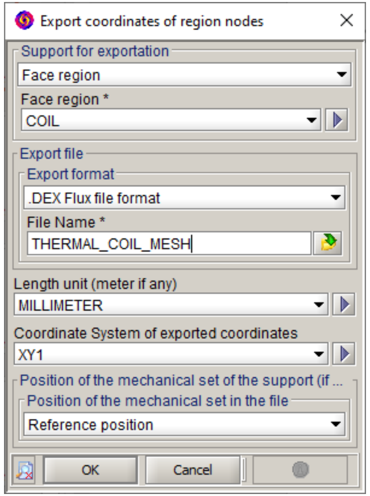
3.2.7 Export mesh files

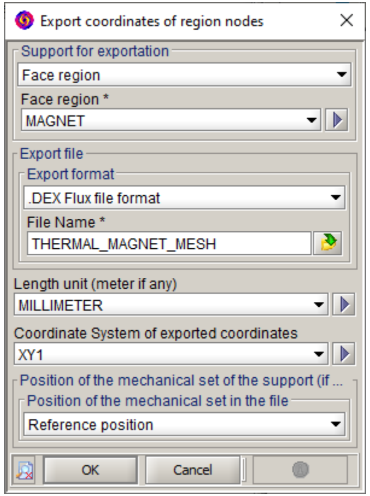
- COIL, STATOR, ROTOR and MAGNET regions

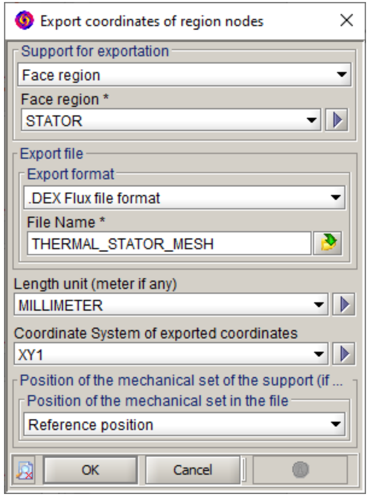
Step	Action
1	Click on the [Parameter/Quantity] - [Export nodes of regions] – [Export coordinates of region nodes]
2	Export the four region meshes

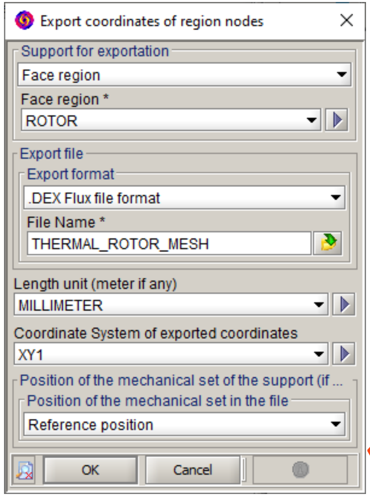


Face region	Export file name
COIL	THERMAL_COIL_MESH
MAGNET	THERMAL_MAGNET_MESH
STATOR	THERMAL_STATOR_MESH
ROTOR	THERMAL_ROTOR_MESH









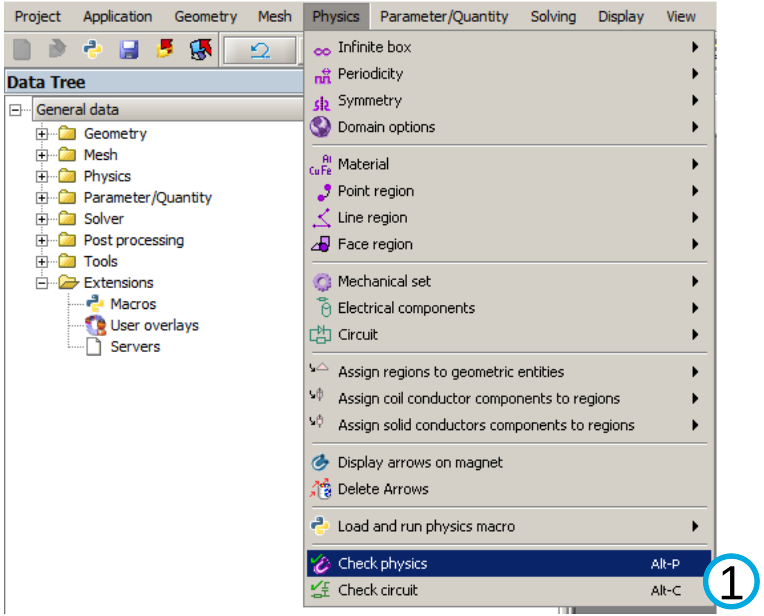
ALTAIR

3.2 Thermal Analysis: Physical description process

3.2.8 Finish the physical description

- Check physics

Step	Action
1	Click on [Physics] – [Check physics]



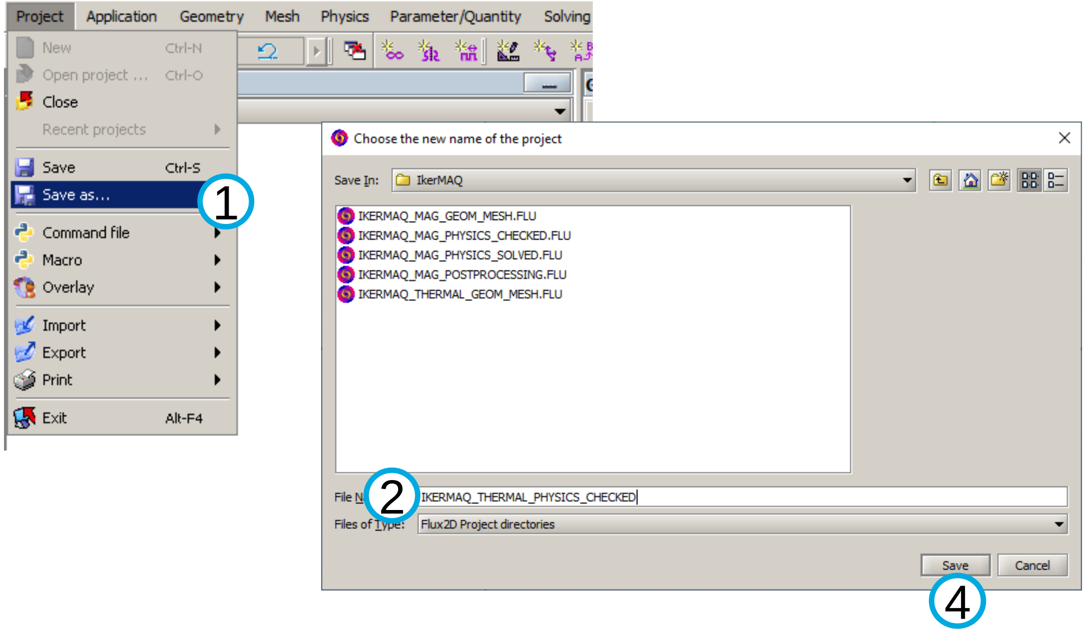
ALTAIR

3.2 Thermal Analysis: Physical description process

3.2.8 Finish the physical description

- Save the project as: IKERMAQ_THERMAL_PHYSICS_CHECKED.FLU

Step	Action
1	Click on [Project] – [Save as]
2	Define the project name as "IKERMAQ_MAG_PHYSICS_ CHECKED"
3	Verify the location
4	Click on [OK]
5	Click on [project] – [Exit] to close the project

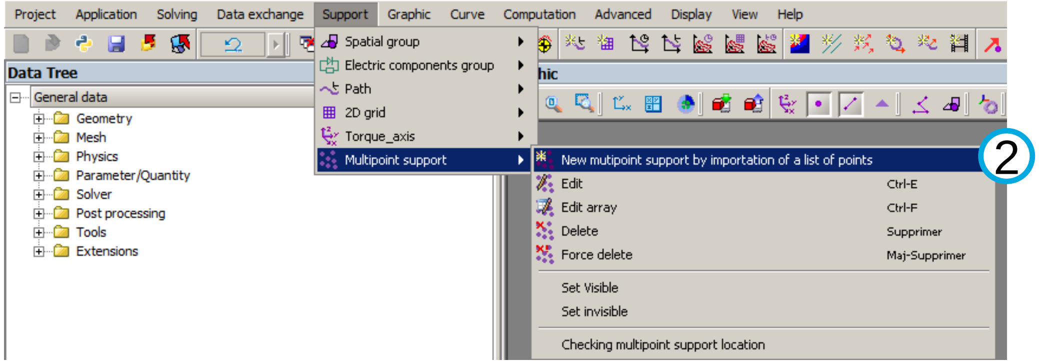


3.3 SOLVING AND POSTPROCESSING

3.3 Thermal Analysis: Solving and postprocessing

3.3.1 Create supports for thermal analysis

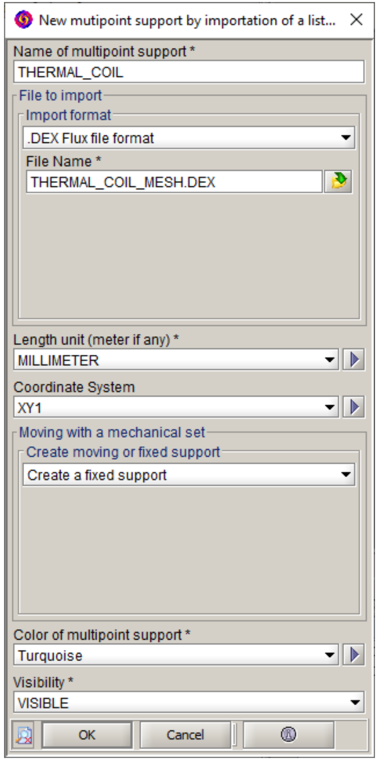
Step	Action
1	Open project “IKERMAQ_MAG_POSTPROCESSING.FLU” from the Flux supervisor
2	Click on [Support] – [Multiple support] – [New multiple support by importation of a list of points]
3	Create the four supports - THERMAL_COIL - THERMAL_MAGNET - THERMAL_ROTOR - THERMAL_STATOR

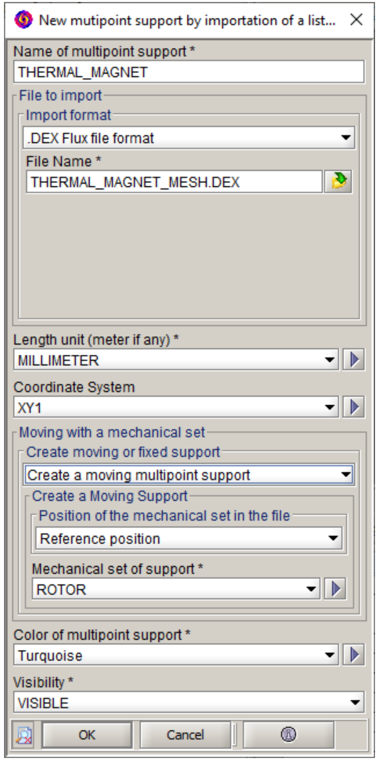


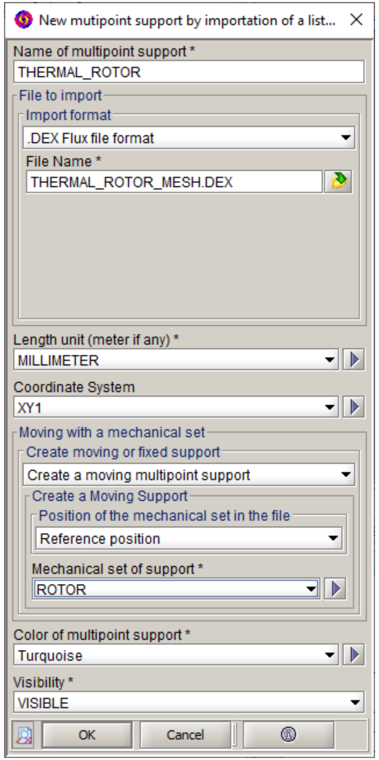
Support name	Import file name	Moving or fixed support	Mechanical set
THERMAL_COIL	THERMAL_COIL_MESH.DEX	Fixed support	-
THERMAL_MAGNET	THERMAL_MAGNET_MESH.DEX	Moving support	ROTOR
THERMAL_ROTOR	THERMAL_ROTOR_MESH.DEX	Moving support	ROTOR
THERMAL_STATOR	THERMAL_STATOR_MESH.DEX	Fixed support	-

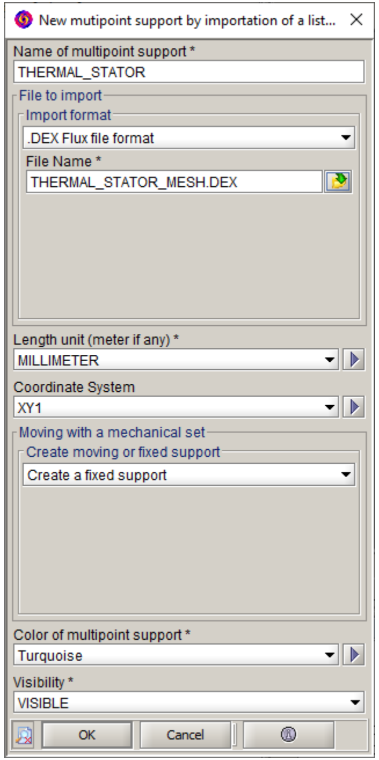
3.3 Thermal Analysis: Solving and postprocessing

3.3.1 Create supports for thermal analysis









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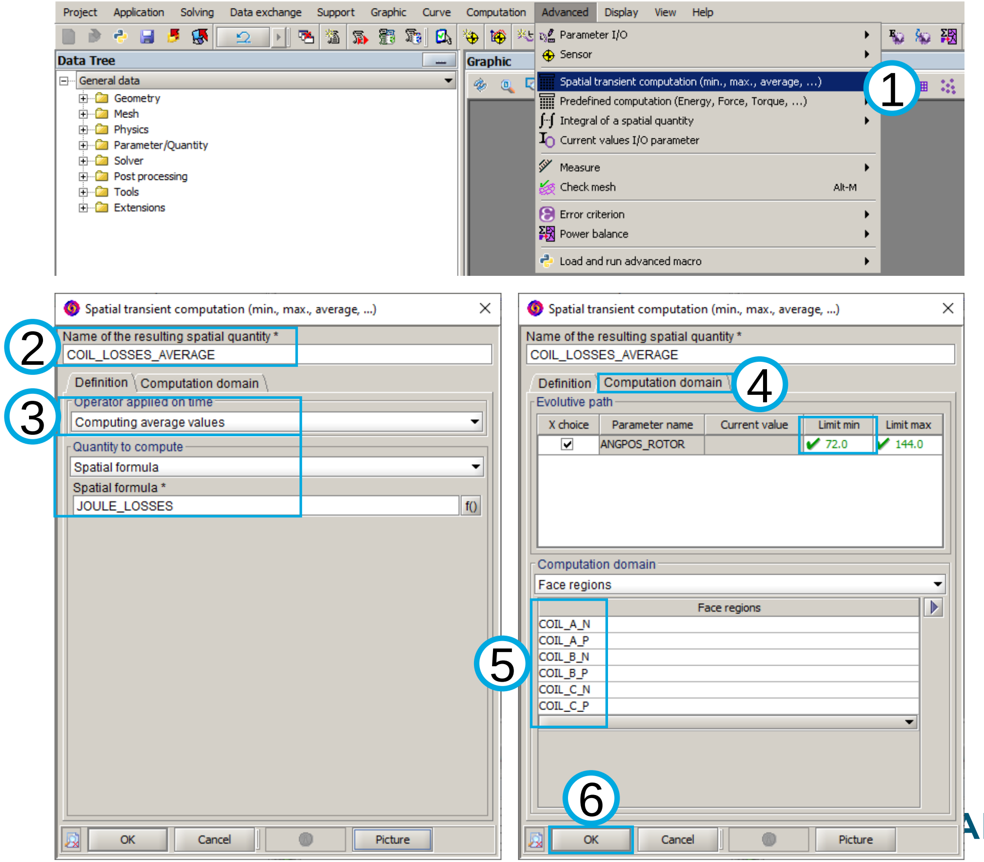
3.3 Thermal Analysis: Solving and postprocessing

3.3.2 Create new Spatial quantities

- COIL_LOSSES_AVERAGE

Step	Action
1	Click on [Advanced] – [Spatial transient computation]
2	Define a new quantity "COIL_LOSSES_AVERAGE"
3	Select "Computing average values", "Spatial formula", and enter "JOULE_LOSSES"
4	In the [Computation domain] page, select the [Limit min] as 72
5	Select the related [Face regions] in the list
6	Click on [OK]

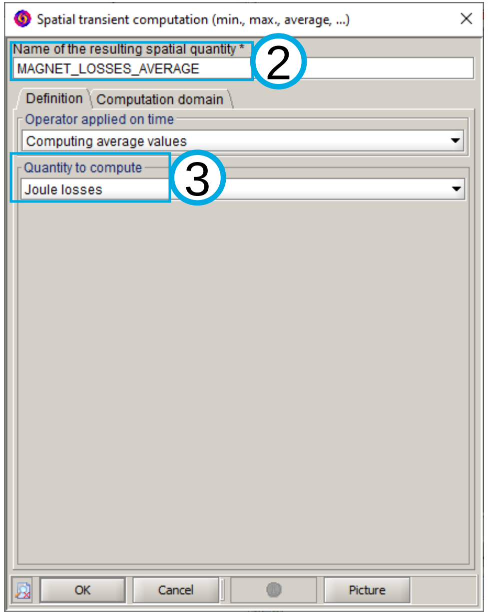


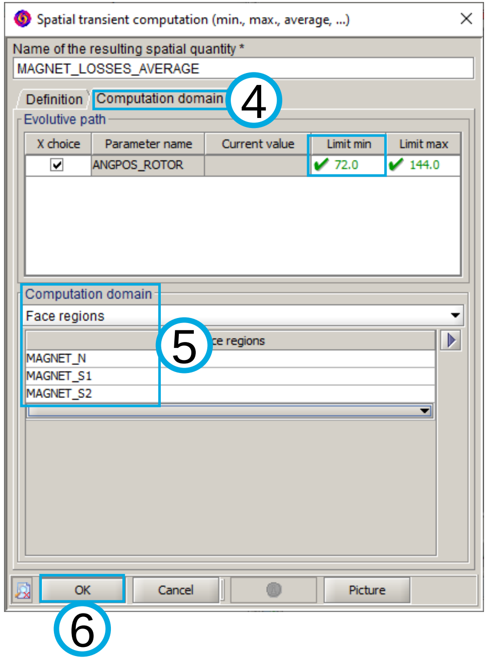
3.3 Thermal Analysis: Solving and postprocessing

3.3.2 Create new Spatial quantities

- MAGNET_LOSSES_AVERAGE

Step	Action
1	Click on [Advanced] – [Spatial transient computation]
2	Define a new quantity "MAGNET_LOSSES_AVERAGE"
3	Select "Joule losses"
4	In the [Computation domain] page, select the [Limit min] as 72
5	Select the related [Face regions] in the list
6	Click on [OK]





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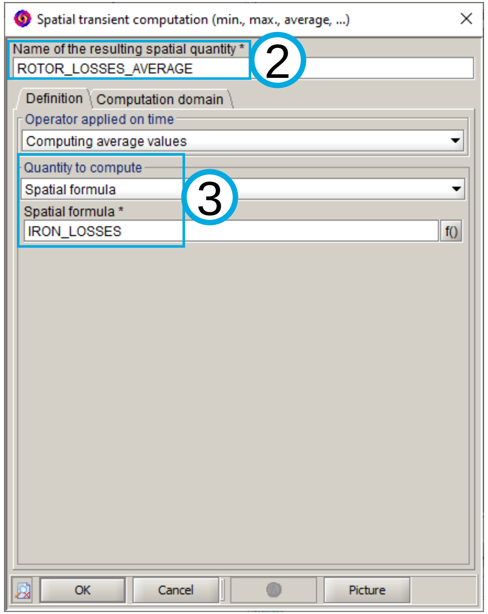
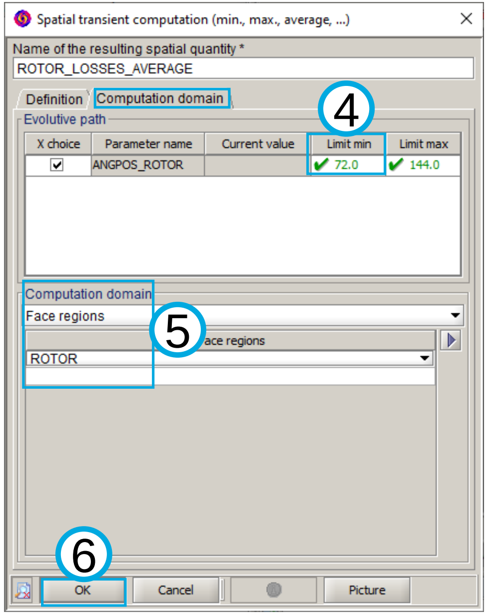
3.3 Thermal Analysis: Solving and postprocessing

3.3.2 Create new Spatial quantities

- ROTOR_LOSSES_AVERAGE

Step	Action
1	Click on [Advanced] – [Spatial transient computation]
2	Define a new quantity “ROTOR_LOSSES_AVERAGE”
3	Select “Spatial formula”, and enter “IRON_LOSSES”
4	In the [Computation domain] page, select the [Limit min] as 72
5	Select the related [Face regions] in the list
6	Click on [OK]





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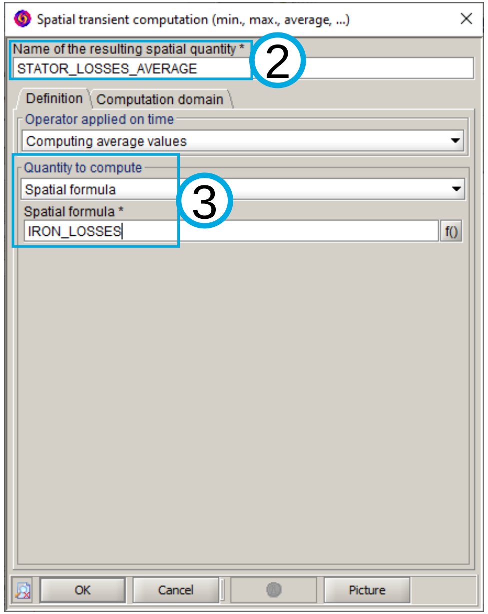
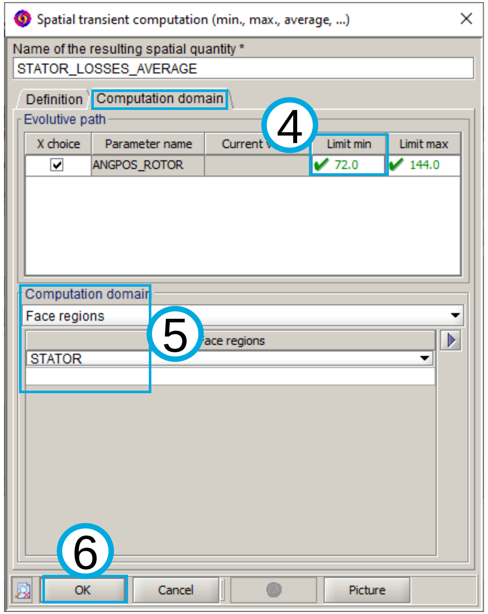
3.3 Thermal Analysis: Solving and postprocessing

3.3.2 Create new Spatial quantities

- STATOR_LOSSES_AVERAGE

Step	Action
1	Click on [Advanced] – [Spatial transient computation]
2	Define a new quantity “STATOR_LOSSES_AVERAGE”
3	Select “Spatial formula”, and enter “IRON_LOSSES”
4	In the [Computation domain] page, select the [Limit min] as 72
5	Select the related [Face regions] in the list
6	Click on [OK]

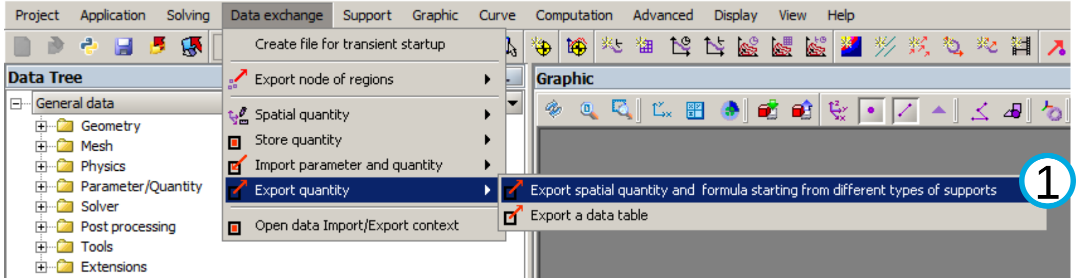




3.3 Thermal Analysis: Solving and postprocessing

3.3.3 Export average losses in each domain

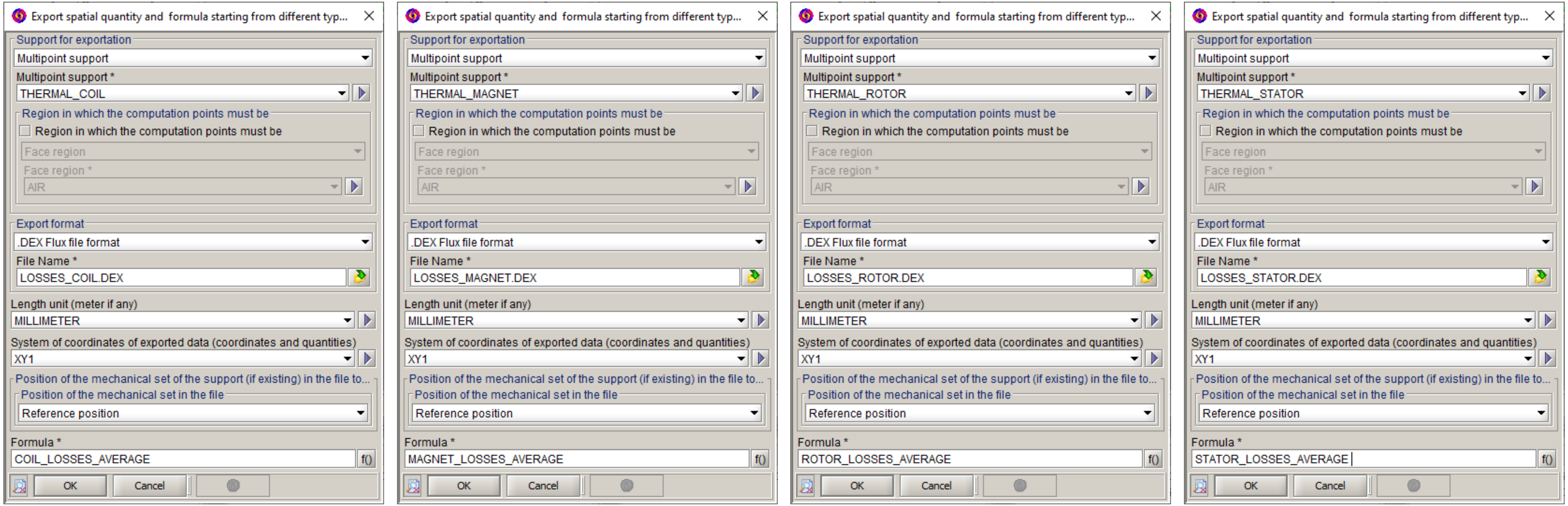
Step	Action
1	Click on [Data exchange] – [Export quantity] – [Export spatial quantity and formula starting from different types of support]
2	Export the average losses for the following four supports



Support for exportation	Support name	Export file	Position	Formula
Multipoint support	THERMAL_COIL	LOSSES_COIL.DEX	Reference position	COIL_LOSSES_AVERAGE
Multipoint support	THERMAL_MAGNET	LOSSES_MAGNET.DEX	Reference position	MAGNET_LOSSES_AVERAGE
Multipoint support	THERMAL_STATOR	LOSSES_STATOR.DEX	Reference position	ROTOR_LOSSES_AVERAGE
Multipoint support	THERMAL_ROTOR	LOSSES_ROTOR.DEX	Reference position	STATOR_LOSSES_AVERAGE

3.3 Thermal Analysis: Solving and postprocessing

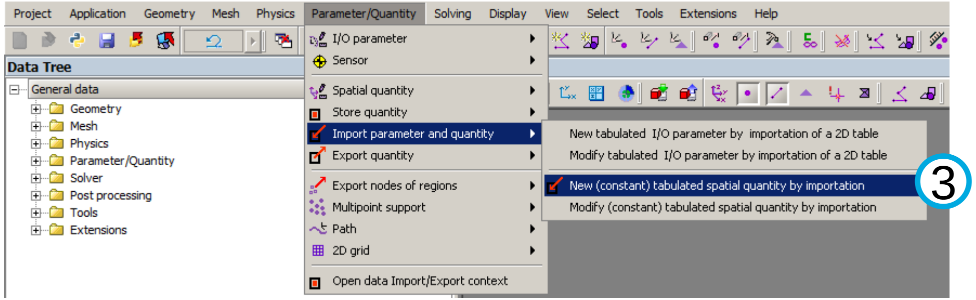
3.3.3 Export average losses in each domain



3.3 Thermal Analysis: Solving and postprocessing

3.3.4 Import spatial quantities from magnetic project

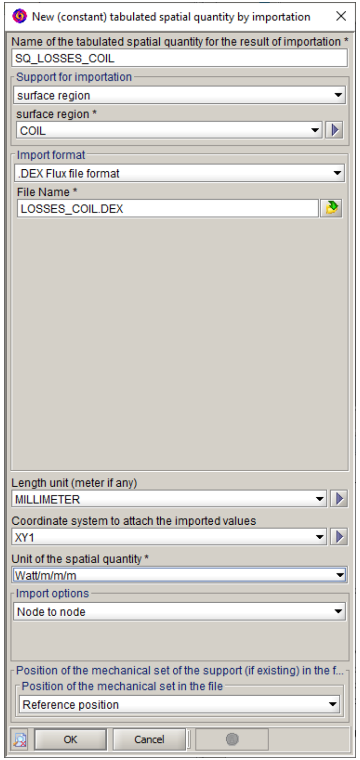
Step	Action
1	Save and close the project “IKERMAQ_MAG_POSTPROCESSING.FLU”
2	Open the project “IKERMAQ_THERMAL_PHYSICS_CHECKED”
3	Click on [Parameter/Quantity] –[Import parameter and quantity] –[New (constant) tabulated spatial quantity by importation]
4	Export the average losses for the following four supports

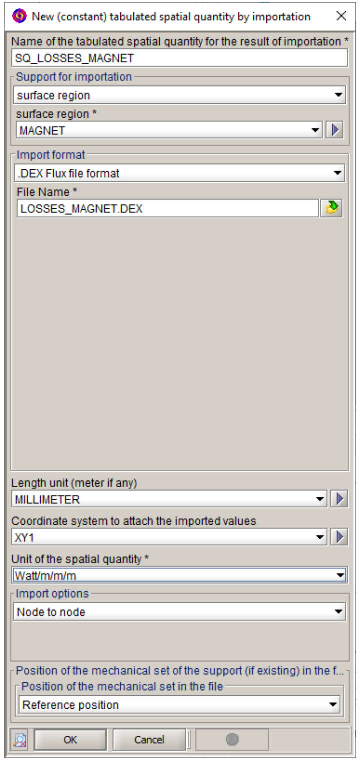


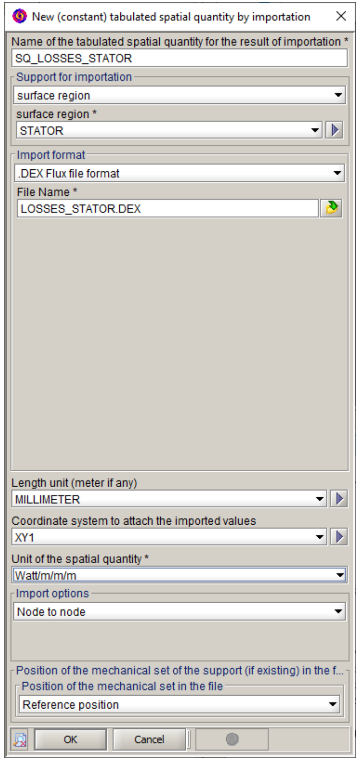
Spatial quantity name	Surface region	Import file	Unit	Import option	Position
SQ_LOSSES_COIL	COIL	LOSSES_COIL.DEX	Watt/m/m/m	Node to node	Reference position
SQ_LOSSES_MAGNET	MAGNET	LOSSES_MAGNET.DEX	Watt/m/m/m	Node to node	Reference position
SQ_LOSSES_STATOR	STATOR	LOSSES_STATOR.DEX	Watt/m/m/m	Node to node	Reference position
SQ_LOSSES_ROTOR	ROTOR	LOSSES_ROTOR.DEX	Watt/m/m/m	Node to node	Reference position

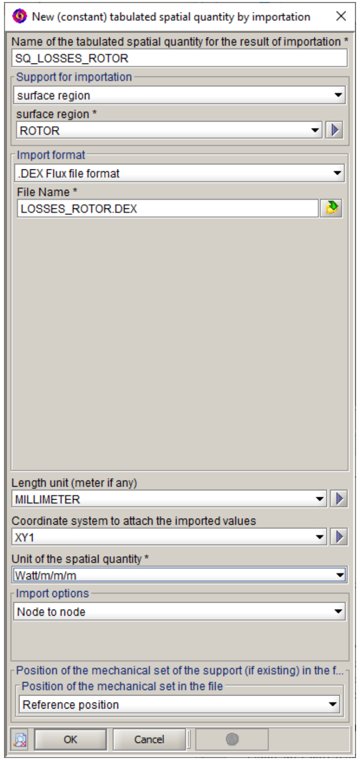
3.3 Thermal Analysis: Solving and postprocessing

3.3.4 Import spatial quantities from magnetic project







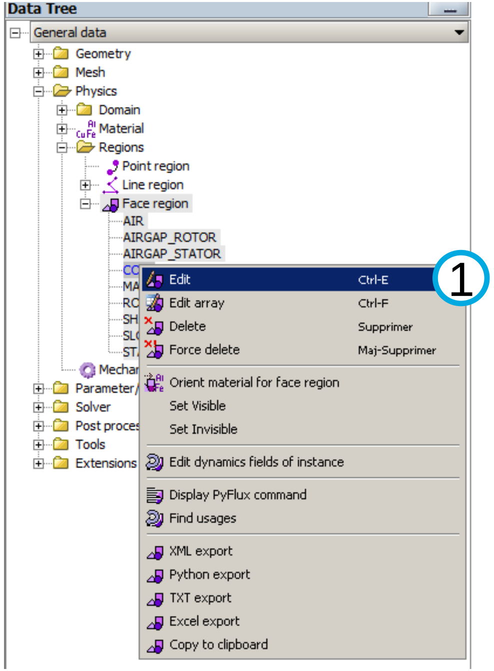


3.3 Thermal Analysis: Solving and postprocessing

3.3.5 Assign imported spatial quantity to regions

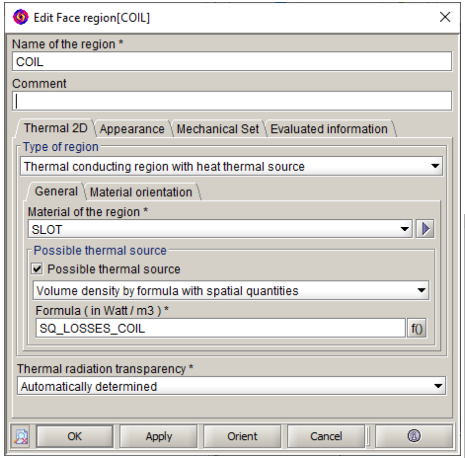
Step	Action
1	Right click on the four following regions in **Data Tree** [Physics] – [Regions] – [Face region]: - COIL - MAGNET - STATOR - ROTOR
2	Update the thermal source setting

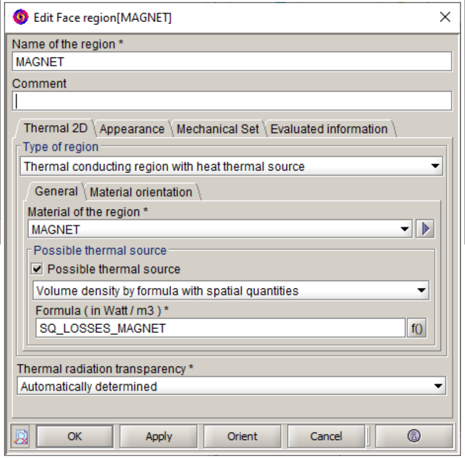
Region name	Thermal source type	Formula
COIL	Volume density by formula with spatial quantities	SQ_LOSSES_COIL
MAGNET	Volume density by formula with spatial quantities	SQ_LOSSES_MAGNET
ROTOR	Volume density by formula with spatial quantities	SQ_LOSSES_ROTOR
STATOR	Volume density by formula with spatial quantities	SQ_LOSSES_STATOR

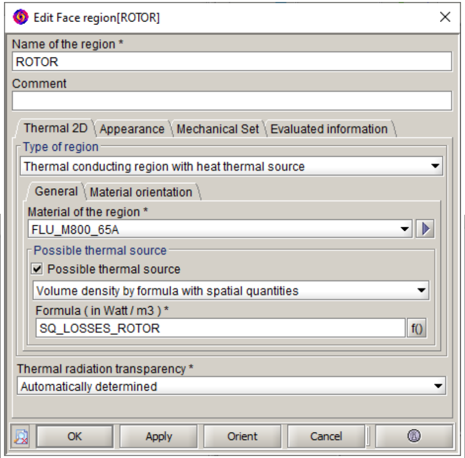


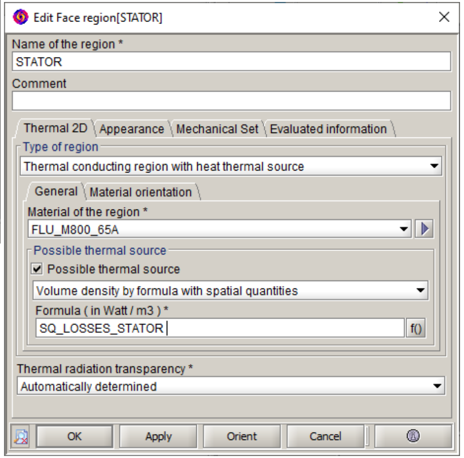
3.3 Thermal Analysis: Solving and postprocessing

3.3.5 Assign imported spatial quantity to regions





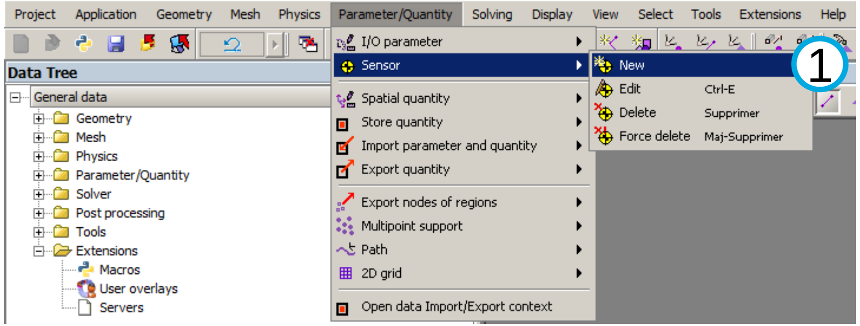




3.3 Thermal Analysis: Solving and postprocessing

3.3.6 Create temperature sensors in regions

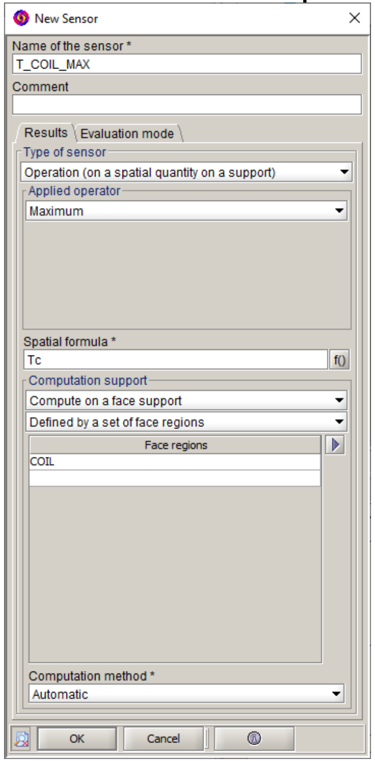
Step	Action
1	Click on [Parameter/Quantity] – [Sensor] – [New] to create the following four sensors
2	Edit the thermal source setting

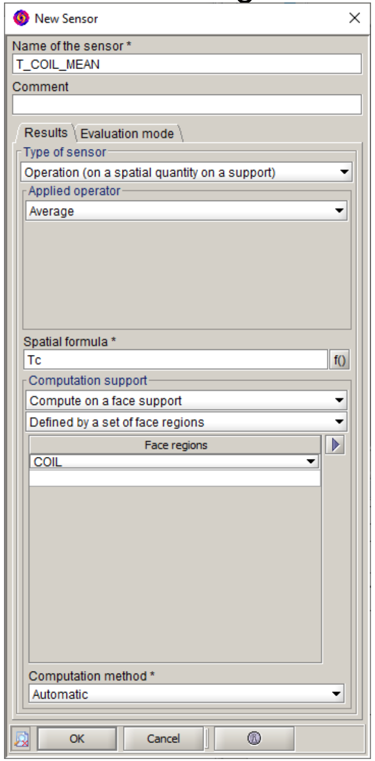


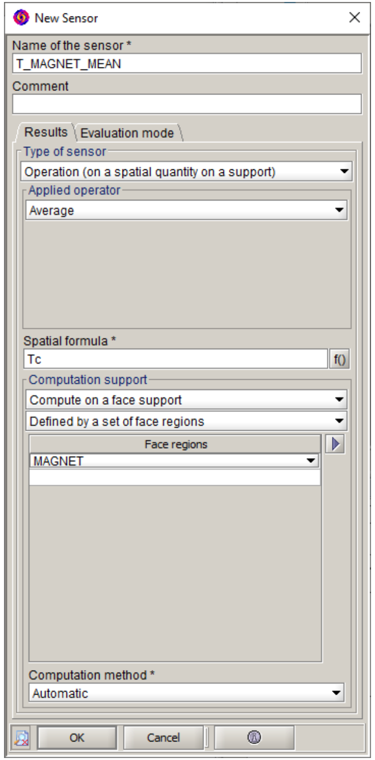
Sensor name	Sensor type	Spatial formula	Computation support	Face regions	Method
T_COIL_MAX	Operation (on a spatial quantity): Maximum	Tc	Face support – face regions	COIL	Automatic
T_COIL_MEAN	Operation (on a spatial quantity): Average	Tc	Face support – face regions	COIL	Automatic
T_MAGNET_MEAN	Operation (on a spatial quantity): Average	Tc	Face support – face regions	MAGNET	Automatic
T_STATOR_MEAN	Operation (on a spatial quantity): Average	Tc	Face support – face regions	STATOR	Automatic

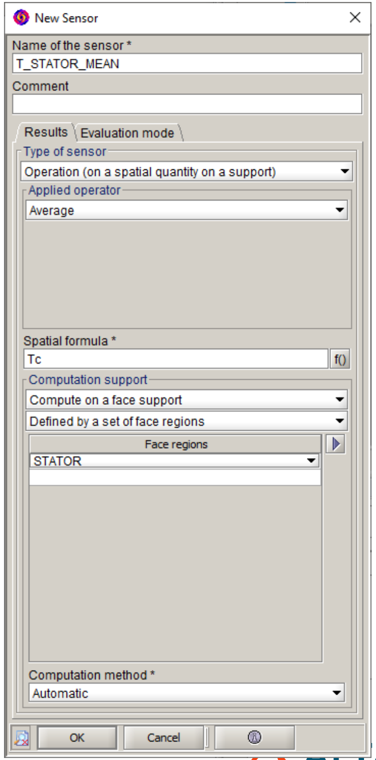
3.3 Thermal Analysis: Solving and postprocessing

3.3.6 Create temperature sensors in regions







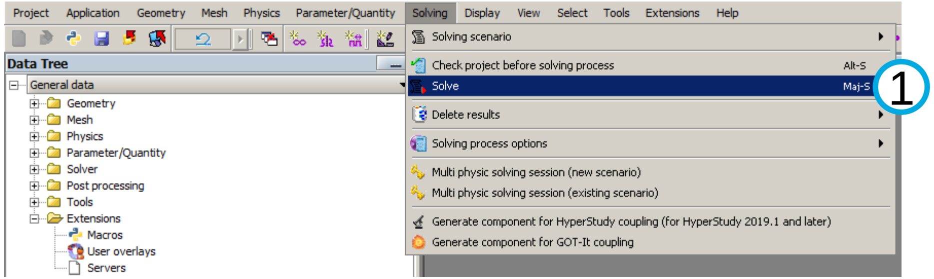


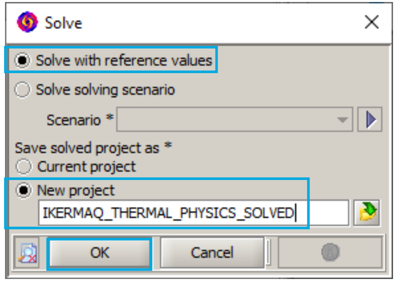
3.3 Thermal Analysis: Solving and postprocessing

3.3.7 Solving process

- Solve the scenario

Step	Action
1	Solve the Scenario by clicking on [Solving] – [Solve]
2	Select the “Solve with reference values”
3	Save as a New project “IKERMAQ_THERMAL_PHYSICS_SOLVED”
4	Click on [OK]



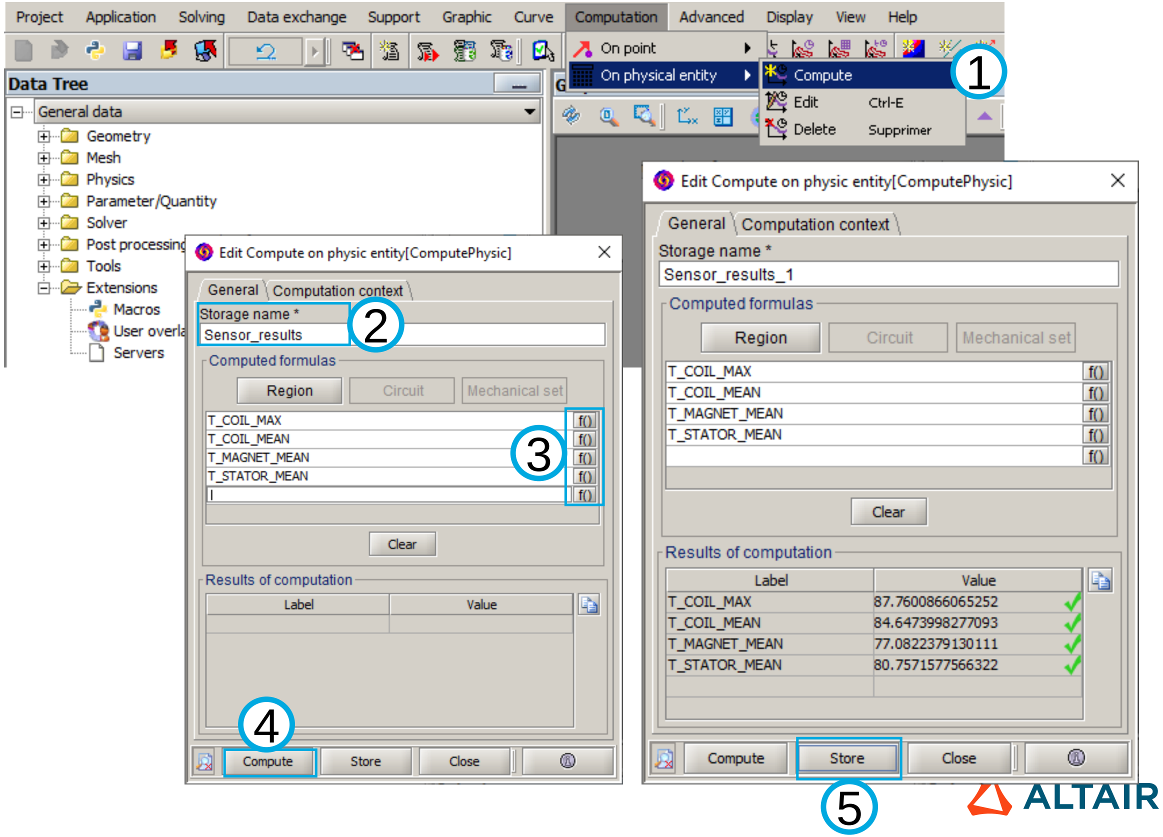


3.3 Thermal Analysis: Solving and postprocessing

3.3.8 Postprocessing

- Compute all the sensor

Step	Action
1	Click on [Computation] – [On physical entity] – [Compute]
2	Define name as “Sensor_results”
3	Click on [f()] to select the four sensors
4	Click on [Compute]
5	Click on [Store]

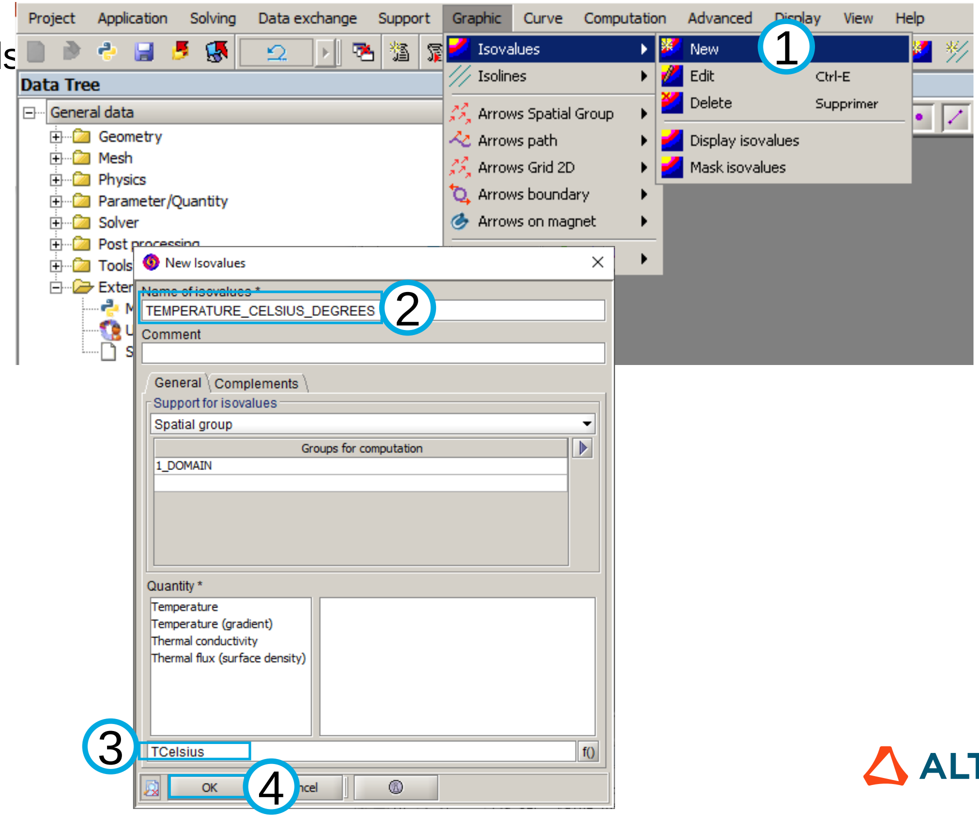


3.3 Thermal Analysis: Solving and postprocessing

3.3.8 Postprocessing

- Show machine temperature in Cels

Step	Action
1	Click on [Graphic] – [Isovalues] – [New]
2	Define name as “TEMPERATURE_CELSIUS _DEGREES”
3	Enter “TCelsius”
4	Click on [OK]



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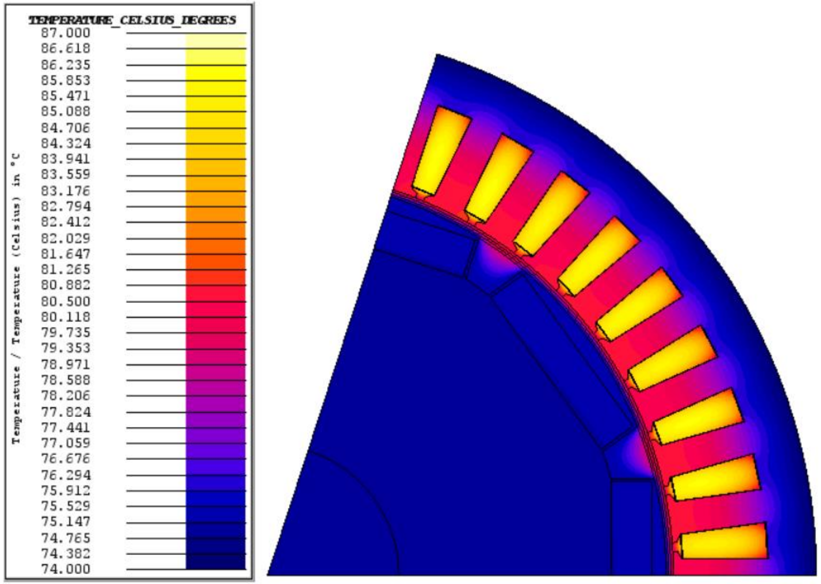
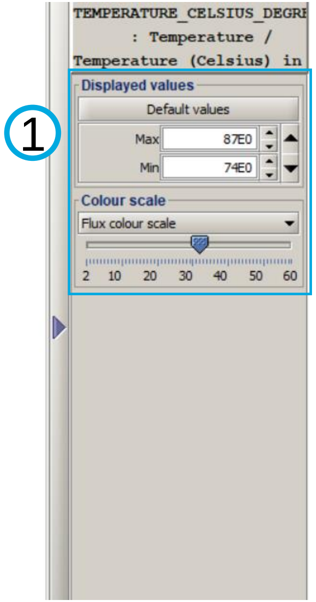
3.3 Thermal Analysis: Solving and postprocessing

3.3.8 Postprocessing

- Show machine temperature in Celsius

Step	Action
1	Use the sliding bar and the max/min values to adapt the scale





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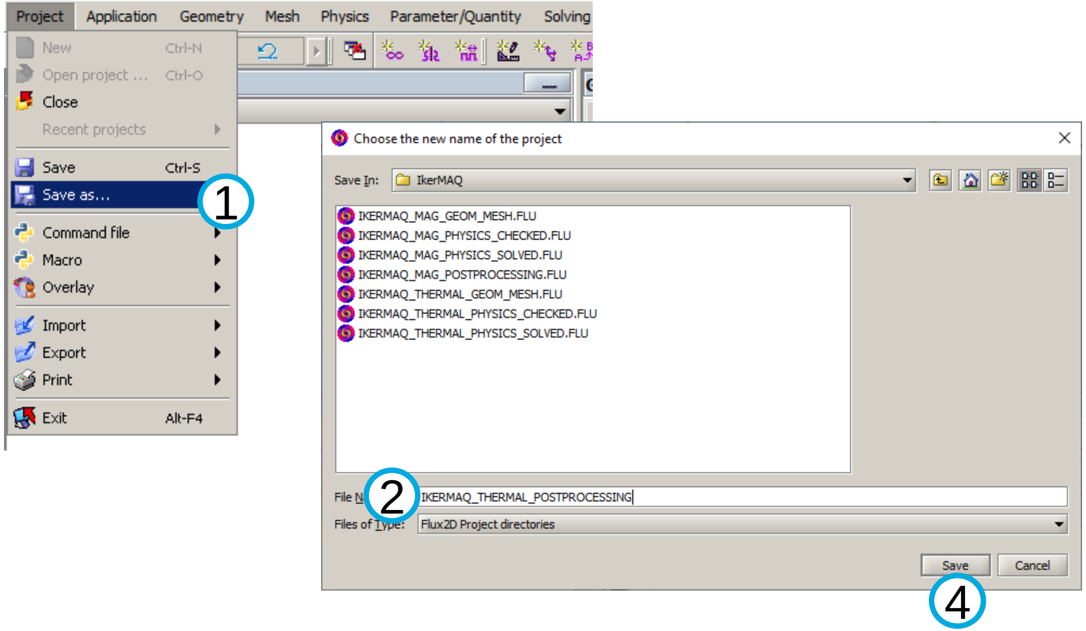
3.2 Thermal Analysis: Physical description process

3.3.9 Finish the project

- Save the project as: IKERMAQ_THERMAL_POSTPROCESSING.FLU

Step	Action
1	Click on [Project] – [Save as]
2	Define the project name as "IKERMAQ_THERMAL_POSTPROCESSING"
3	Verify the location
4	Click on [OK]
5	Click on [project] – [Exit] to close the project



4. COMPARISON WITH MEASUREMENTS

4. Comparison with Measurements

4.1 Electric circuit comparison

- Simulation values have been obtained from explained postprocessing
- Test measurements:
  - **Mechanical variables** (**torque** and **speed**) have been measured by the control system of the **driven machine**
  - **Electric variables** (**voltage**, **current**, and **electrical power**) have been measured by **oscilloscope** and **multimeter** applied to the **passive load**

	Simulated	Measured	Error (%)
Mechanical power (kW)	51.10	51.11	0.02
Electrical power (kW)	49.09	48.17	1.91
Phase voltage (V_{rms})	255.65	255.00	0.25
Phase current (A_{rms})	84.72	87.97	3.69
Iron losses (kW)	1.40	1.59	8.81
Copper losses (kW)	1.17	1.36	13.97

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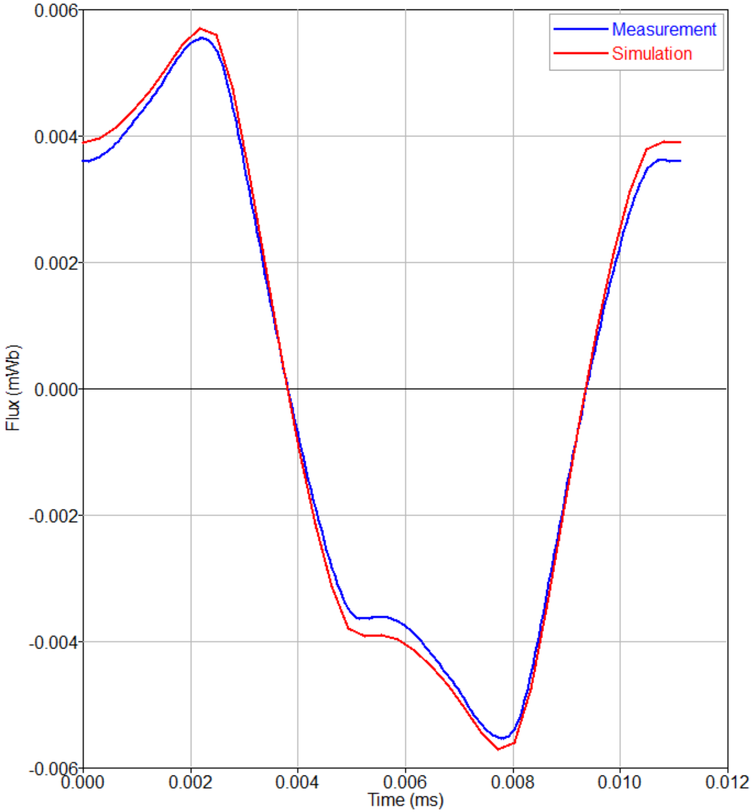
4. Comparison with Measurements

4.2 Magnetic flux comparison

- A **coil embracing one tooth** has been added to the prototype to know the **magnetic flux** flowing through it as a **representative variable of machine behavior**
- Same test coil has been added **in simulation**
- Very **good correlation** between simulated and measured flux
- Measurements versus simulation plot are accessible through **Altair Compose script IkerMAQ_Mes_Simul_Comparison.oml**
- **Measured values** are **available** in mat file **Tooth_Flux_Results**



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4. Comparison with Measurements

4.3 Thermal comparison

- Measurements: Thermocouples have been used to obtain temperature in key points: Magnets, slot, end-winding, and several points in the housing.
- From these measured temperatures in other points, such as stator, can be deduced

	Simulated	Measured	Error
Slot (mean)	83.05 ºC	85.60 ºC	2.55 ºC
Slot (max)	86.13 ºC	86.30 ºC	0.17 ºC
Stator (mean)	79.15 ºC	79.50 ºC	0.35 ºC
Magnet (mean)	75.13 ºC	76.00 ºC	0.87 ºC

ACKNOWLEDGMENT

ACKNOWLEDGMENT

IkerMAQ PMSM has been designed by the technological center **IK4-Ikerlan**, which has also performed the practical measures.

Special thanks for letting us use them.

ikerlan

More information about IkerMAQ measurement procedure and measures values available in the Ph.D. dissertation:

Rodríguez González, Alejandro L., “Development of a Multidisciplinary and Optimized Design Methodology for Surface Permanent Magnets Synchronous Machines”, Ph.D. dissertation, University of Santiago de Compostela, 2016

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THANK YOU

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