ALTAIR

ONLY FORWARD

Altair® Flux®

Brushless IPM Motor Tutorial - 2D Technical Example

Updated: 11/08/2022

altair.com

Foreword

Please read before starting this document

Description of the example

The goal of this technical example is to demonstrate the ability and advantage of Flux for the simulation of brushless IPM motor computation problems. This document contains the general steps and all the data needed to describe the different simulations.

To begin

This example is designed for the user who is already familiar with the basic functions of Flux software.

For beginner users, please report to the "Flux Starting Guide" opened automatically by the supervisor. (If not opened, please open it by clicking on the button "?" on the top right of the supervisor). The interface contains videos, which helps the beginners while using Flux for the first time.

Support files included...

TTo view the completed phases of the example project, the user will find the .py files, including the geometry, physics and post-processing descriptions. The .py files corresponding to the different study cases in this example are available in the folder: `…\DocExamples\Examples2D\Tutorial_Technical\BrushlessIPM_Motor\`

Supplied files are command files written in Pyflux language. The user can launch them in order to automatically recover the Flux projects for each case.

> **Note:** *.py files are launched by accessing **Project** > **Command file** from the Flux drop down menu.*

Files

Supplied files		Contents	Flux file obtained after launchnig the .py file
Cogging torque	geomesh.py	Geometry and mesh	…/GEOMESH.FLU
	buildPhys.py	Physics	…/physbuilt.FLU
	solving.py	Solving process	…/Solved.FLU
	postprocessing.py	Post processing	…/Postprocessed.FLU

> **Note:** Some directories may contain a main.py enabling the launch of the command files

Contents

General information

1

This chapter covers the following:

Introduction

The goal of this technical paper is to demonstrate the ability and advantage of Flux in the simulation of brushless motor computation problems.

This chapter presents the studied device, (a brushless AC embedded permanent magnet motor designed for hybrid electric vehicle traction/generation) and explains the strategies used for geometry construction and mesh generation.

1.1 Overview

Introduction

This section is an overview of the sample problem. It contains a brief description of the device and of the studied cases.

- Description of the device
- Studied cases

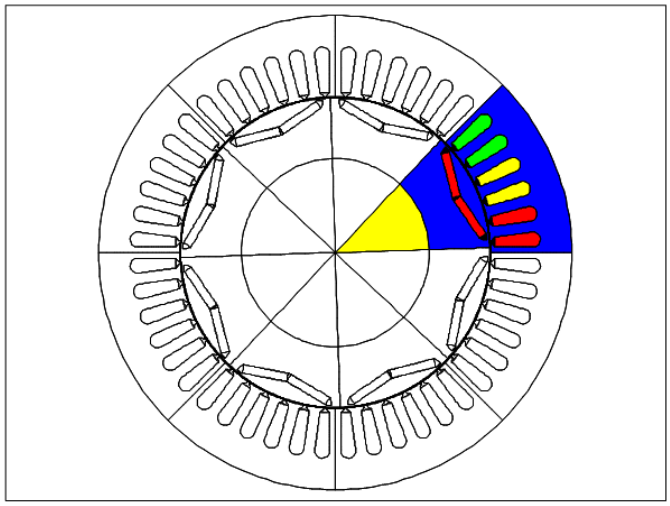
1.1.1 Description of the device

Studied device

The studied device, a brushless AC embedded permanent magnet motor presented in the figure below, includes the following elements:

- a fixed part (stator) including yoke, slots, and windings
- an air gap
- a movable part (rotor) with embedded magnets

A section of the model of the studied device is presented in the figure below.



Motor ratings

This motor is designed for hybrid electric vehicle traction/generation with the following ratings:

- Max bus voltage: 500 V
- Peak torque: 400 N.m
- Max speed: 6000 rpm
- Peak power rating: 50 kW at 1200-1500 rpm

Motor main characteristics

This motor has the following main characteristics

- 48 stator slots
- 3 phase wye connected
- 4 pole pairs
- NdFeB magnet
- Lamination type M270-35A
- Outer diameter: 242 mm
- Stack length: 75 mm

1.1.2 Studied cases

Studied cases

Five cases are studied in this technical paper:

- Case 1: Study to compute the cogging torque of the motor
- Case 2: Study to compute the back electromotive force
- Case 3: Study to compute the motor performances at constant speed
- Case 4: Study to compute the motor performances at start up
- Case 5: Multi static study to compute inductances and static torque

Case 1

The cogging torque is computed with a multi-position simulation and no current. The multi-position is simulated with a transient application at constant speed. The speed is chosen to be 1/6 rpm which corresponds to 1 mechanical degree per second.

Case 2

The back electromotive force EMF is computed with the speed of 1000 rpm and external circuit connections. It corresponds to the motor being in generator mode at no load. The computed back EMF allows determining the current control angle.

Case 3

The motor is driven with a 3 phase sine current and running at constant speed.

The simulated motor performances are used to compute shaft torque, torque ripples, core losses (Bertotti and LS model) and efficiencies.

Case 4

The dynamic behavior of the motor during start up is simulated with a proposed current control strategy. The winding is supplied in current depending on the rotor position.

Case 5

This simulation consists of computing the inductances and torque vs. current and rotor position.

1.2 Strategy to build the Flux project

Introduction

An outline of the strategy employed to model the geometry and mesh description of the motor is presented in the table below.

Stage	Description	
1	Description of the motor geometry using an overlay	• Load an overlay • Modify the overlay
2	Meshing of the device	• Mesh

Theoretical aspect

The basic knowledge necessary to describe a motor is provided by utilizing an overlay and is presented in the following section.

1.3 About the Overlay (motor template)

Introduction

This section deals with the BPM (Brushless Permanent Magnet) Motor Template and answers the following three questions:

- What is possible to model with FLUX? (presentation of the object editor, available library)
- How to describe the problem in FLUX? (use the object editor)
- What are the possible links with Speed?

- Motor Template: Presentation
- Motor Template: The library
- Motor Template: Principle of description in FLUX
- Motor Object: Speed importation

1.3.1 Motor Template: Presentation

Presentation

The complete description of a motor in FLUX can be somewhat long and involved.

To describe a motor utilizing the standard Flux interface, the user must:

- prepare the tools of geometric description (parameters, coordinate systems, …)
- create the points and lines of the rotor and stator (slots, air-gap, …)
- build the faces
- mesh the device
- create the regions and assign to faces
- ...

These different stages must be repeated for each type of motor that is being modeled.

Now it is possible for FLUX to simplify this process, by providing a library of predefined motor templates.

With this new description mode, the stages of model construction are simplified. The user chooses a type of motor and winding from the library and interactively enters the parameters of the motor.

Motor object: definition

A **BPM Motor** template is an object from the specific library:

- BPM (Brushless Permanent Magnet) Motor

This covers information related to geometry and mesh. There is no information about physics.

1.3.2 Motor Template: The library

Introduction

The library of Motor objects is a library of motors with permanent magnets (without brushes).

The models are standard models. This library corresponds to the one provided in the Speed software.

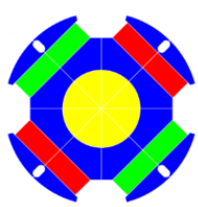
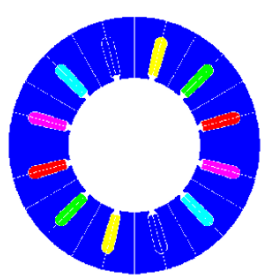
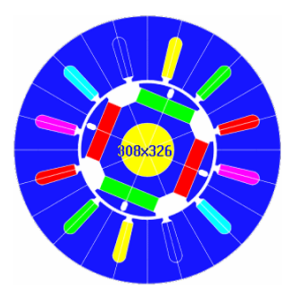
List of models

The different models in the library are not detailed in the on line help because their documentation is included in the software. An interactive image is displayed in the object editor. The editor displays a direct visualization of the parameters entered by the user.

The list of models provided for the rotor and stator is presented in the table below.

Rotor	Stator
BreadLoaf	Flared
FullRing	HW
InsCP	PIIRound
InsRel	PIISlot
IPM	PIISquare
LSIPM	Round
Spoke	Square
SurfPII	
SurfRad	

Example

Rotor IPM (4 poles)	Stator HW(12 Slots)	Whole Motor
		

1.3.3 Motor Template: Principle of description in FLUX

General operation

The template editor provided in FLUX is an "assistant to the creation of the model" which is part of the overall construction process of a finite element project. The motor template editor simplifies the stage of the geometry construction and the mesh building as shown in the table below.

Stage	"Standard" description	"Assisted" description
1	Geometry building	Direct construction of a meshed motor
2	Mesh construction	
3	Physical properties description	Identical
4	Solving process	
5	Results post-processing	

Principle

The user builds the motor directly in FLUX using the template editor and the **BPM Motor Object** library.

The general principle of operation is given in the table below.

Stage	The user provides ...	FLUX carries out ...
1	Geometric characteristics: • general: units/... • of stator: shape/dimension/number of slots/ • of rotor: shape/dimension/number of poles/ Choices for FE modeling: • taking periodicities into account • influence of eccentricities	Geometry building: • creation of parameters, coordinate systems, transformations • creation of points, lines, faces Grouping of the faces in regions: • creation of regions : shaft, rotor, stator, magnet, air-gap, air • assigning of the regions to faces
2	A coefficient to adjust the mesh density (value comprised between 0.5 and 1)	Mesh construction: • automatic mesh and linked mesh to faces

Stage	The user provides ...	FLUX carries out ...
3	Winding characteristics: • Distribution of the phases in the slots: “standard” winding or particular winding	Grouping of the faces in regions (continued) • Creation of regions corresponding to the coils (grouping by phase) • Assigning of the regions to faces

...To continue

The user continues the description of the finite element project in the usual way: description of the physical properties, creation of the mechanical assemblies, description of the electric circuit and importing it into FLUX, solving and post-processing of the results.

1.3.4 Motor Object: Speed importation

Introduction

The Flux/Speed link is created by the introduction in FLUX of a Brushless PM object from the Speed library.

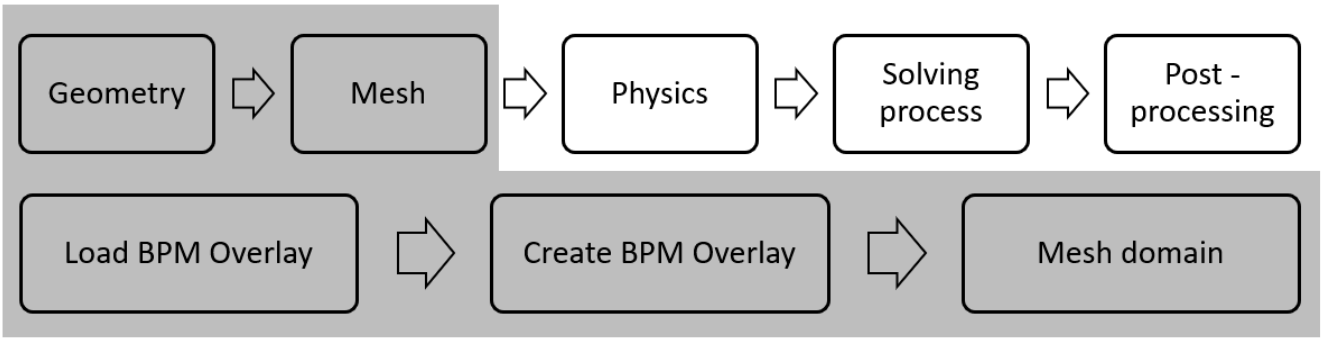
Speed Importation

The user can import a motor described with Speed (Speed file) into FLUX. The Speed/Flux compatibility makes this possible. All the information concerning the geometric characteristics and the winding characteristics are preserved (dimensional parameters, number of poles, of phases, …).

Note: The name of the parameters are the same in Speed and Flux

Geometry and mesh description of the motor

2



This chapter covers the following:

New Flux project

The new Flux project is saved under the name **GEOMESH.FLU**.

2.1 Load the BPM overlay

Goal

First, the geometry and mesh is carried out utilizing an overlay.

Action

The overlay **BRUSHLESS_PERMANENT_MAGNET_MOTORS_V11.1.PFO** is loaded from the **Extension** menu.

Access

- by menu: **Extensions** > **Overlay** > **Load a certified overlay**

2.2 Create a brushless permanent motor using the overlay

Goal

The geometry of the motor is described using an overlay.

Data (1)

The general characteristics of the motor are presented in the tables below.

General description			
Length unit	**Mesh density**	**Infinite box**	
		Inner radius	**Outer radius**
Millimeter	0.5	110	140

Airgap description			
Air gap	**Eccentricities and periodicities**	**Use periodicities**	**Rotating air gap**
0.6	Without eccentricity	Yes	Two layers airgap

Data (2)

The characteristics of the rotor are presented in the tables below.

Rotor description			
Magnet shape description : Rotor IPM			
General description			
Shaft radius	**Thickness of magnet**	**Magnet pole arc**	**Number of magnet block per pole**
56	5	140	1

Embedded magnet type									
Rotortype	**Web**	**Magnet width**	**Bridge**	**Depth of pole cap**	**Rad web length**	**Gutter**	**Hub width**	**Inset**	**Slits**
Type 4	10	54	1.0	10	2.75	0.0	24.0	0.0	0

General description		
Number of poles	**Rotor external radius**	**Rotor shift angle**
8	92	0.0

Data (3)

The characteristics of the stator are presented in the tables below.

Stator description					
Slot shape description : Stator round					
General description					
Slot opening	**Radial depth**	**Slot depth**	**Tooth width stator**	**Slot opening angle**	**FILSO**
2.0	1.0	30	6.5	40	1.0

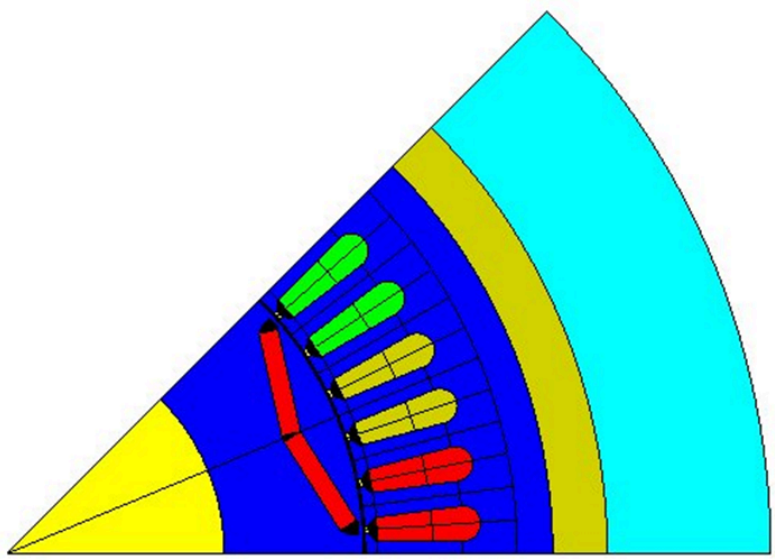
General description				
Number of slots	**LamShape**	**Stator outer radius**	**Stator configuration**	**Stator angle**
48	Circle	141	Normal	0.0

Winding description					
Winding	**Number of phases**	**Classical winding type**	**Throw**	**Number of coils per pole per phase**	**Coils position in slot in case of two layers**
Classical winding	3	Lap per pole winding	6	2	Superimposed

Result

The following motor is created with:

- Part of the geometry
- Part of the physics
- Ready to be meshed



2.3 Modify mesh point and mesh the device

Goal

Mesh points will be edited and modified in order to improve the mesh.

Data

The characteristics of the mesh points are presented in the table below.

Mesh point	Value
AIRGAP	((DMINSTATOR-DMAXROTOR)/NB_REGION_IN_AIRGAP)*10**3*LENGTH_UNIT*2
ROTOR_MAGIN	1.5*ROTOR_MESH_MAGIN/(1+MESH_FACTOR)*2
ROTOR_WEB	1.5*ROTOR_MESH_WEB/(1+MESH_FACTOR)/2

Access

- by menu: **Mesh** > **Mesh point** > **Edit**

Action

Mesh the device.

Access

- by menu: **Mesh** > **Mesh domain**
- by icon: 

Case 1: Computation of the cogging torque

3

This chapter covers the following:

Case 1

The cogging torque is computed with a multi-position simulation and no current.

The multi-position is simulated with a transient application at constant speed. The speed is chosen to be 1/6 rpm which corresponds to 1 mechanical degree per second.

The angle of the rotor will be varying over 1 slot pitch (360°/48 slots = 7.5°). In this parametric study, the position of the rotor is varying in the range [0°, 7.5°] with a step of 0.1875° (7.5°/40) in order to have 40 steps over 1 slot pitch.

Starting Flux project

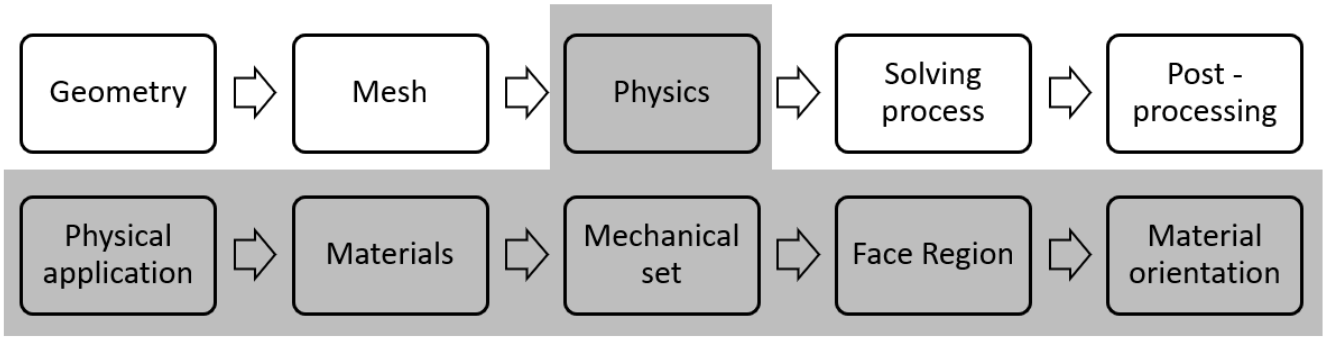
The starting project is the Flux project **GEOMESH.FLU**. This project contains:

- the geometry description of the device
- the mesh

Project name

The new Flux project is saved under the name of **CASE1.FLU.**

3.1 Case 1: Physical description process



- Define the physical application
- Create materials
- Create mechanical sets
- Modify face region and orient material for face region
- Modify the face regions

3.1.1 Define the physical application

Goal

First, the physical application is defined. The required physical application is **Transient Magnetic 2D application**.

Data

The characteristics of the application are presented in the table below.

Transient Magnetic 2D application		
Definition		**Transient initialization**
2D domain type	**Depth of the domain**	
2D plane	75	Initialized by static computation

Access

- by menu: **Application** > **Define** > **Magnetic** > **Transient magnetic 2D**

3.1.2 Create materials

Goal

One material is created and the other is imported from the material database in order to define the physics.

Data (1)

The characteristics of the material import are presented in the table below:

Material import	
Material database	**Material name**
FLUX_111_MATERI.DAT	FLU_M270-35A

Access (1)

- by menu: **Physics** > **Material** > **Import Material.dat**
- by icon: 

Data (2)

The characteristics of the material are presented in the table below:

B(H) linear magnet described in the B_r module		
Name	**Remanent flux density (T)**	**Relative permeability**
NDFEB	1.2	1.05

Access (2)

- by menu: **Physics** > **Material** > **New**
- by icon: 

3.1.3 Create mechanical sets

Goal

Two mechanical sets are created to describe the physics of the motor. It will define which is fixed and which part is mobile (in rotation or in translation).

Data (1)

The characteristics of the **ROTOR** mechanical set are presented in the table below:

Name	Type of mechanical set	Axis			
		Rotation axis	Coordinate system	Pivot point coordinates	
				First	Second
ROTOR	Rotation around one axis	Rotation around on axis parallel to Oz	XY1	0	0

Kinematic		
Type of kinematics	General	
	Velocity	Position at t = 0s
Imposed speed	1/6	0.0

Access (1)

- by menu: **Physics** > **Mechanical set** > **New**
- by icon: 

Data (2)

The characteristics of the **STATOR** mechanical set are presented in the table below:

Name	Type of mechanical set
STATOR	Fixed

3.1.4 Modify face region and orient material for face region

Goal

Face region are edited and modified in order to describe the physics.

Data (1)

The characteristics of the face regions used to describe the materials are presented in the table below:

Face region			
Name	**Type**	**Material**	**Mechanical set**
MAGNET1_1_POLE1	Magnetic non conducting region	NDFEB	ROTOR
MAGNET2_1_POLE1	Magnetic non conducting region	NDFEB	ROTOR
STATOR	Magnetic non conducting region	FLU_M270-35A	STATOR
ROTOR	Magnetic non conducting region	FLU_M270-35A	ROTOR

Access (1)

- by menu: **Physics** > **Face region** > **Edit**

Data (2)

The characteristics of the magnet orientation are presented in the table below.

Orient material for face region			
Name	**Oriented type**	**Coordinate system**	**Angle**
MAGNET1_1_POLE1	Direction	ROTOR_COORD	10
MAGNET2_1_POLE1	Direction	ROTOR_COORD	-10

Access (2)

- by menu: **Physics** > **Material** > **Orient material for face region**
- by icon: 

3.1.5 Modify the face regions

Goal

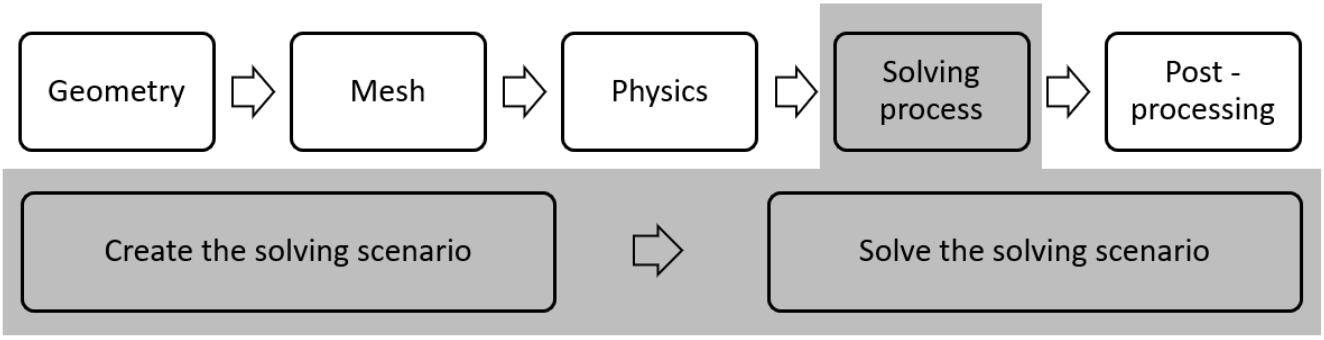
The nine regions are modified on order to model the physics.

Data

The characteristics of the face regions used to describe the three are presented in the table below:

Name	Type	Mechanical set
PHASE_POS_1	Air or vacuum region	STATOR
PHASE_POS_2	Air or vacuum region	STATOR
PHASE_NEG_3	Air or vacuum region	STATOR
ROTATING_AIRGAP	Air or vacuum region	STATOR
ROTOR_AIR	Air or vacuum region	ROTOR
SHAFT	Air or vacuum region	ROTOR
WEDGE	Air or vacuum region	STATOR
PRESLOT	Air or vacuum region	STATOR
STATOR_AIR	Air or vacuum region	STATOR
INFINITE	Air or vacuum region	STATOR

3.2 Case 1: Solve the project



Introduction

This part describes how **CASE1** is solved.

- Create a scenario
- Modify solving option and solve the project

3.2.1 Create a scenario

Goal

A solving scenario is created in order to solve **CASE1**.

Data

The characteristics of the scenario used to solve **CASE1** are presented in the table below:

Solving scenario					
Name	**Control by position**				
	Mechanical set	**Interval**			
		Lower limit	**Higher limit**	**Method**	**Step value**
COGGING	ROTOR	0	7.5	Step value	0.1875

Access

- by menu: **Solving** > **Solving scenario** > **New**
- by icon: 

3.2.2 Modify solving option and solve the project

Goal

CASE1 project is solved using a solving scenario and solving option.

Data (1)

The characteristics of the solving process options are presented in the table below:

Solving process options for non linearsystem solver		
Precision	**Max number of iteration**	**Method to compute relaxation factor**
1.0E-4	100	Fujiwara method

Data (2)

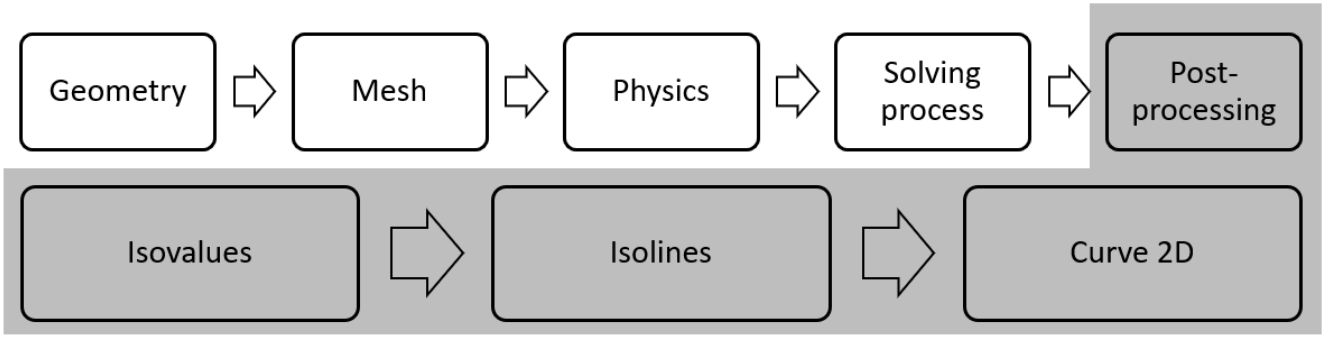
The characteristics of the solving process are presented in the table below:

Solve		
Solving scenario	**Solve saved project as**	**Project name**
COGGING	New Project	CASE1_SOLVED

Action

CASE1 is solved using **COGGING** scenario.

3.3 Case 1: Results postprocessing



Introduction

This section explains how to analyze the principal results of **CASE1**.

- Compute and display isovalues of the magnetic flux density on face regions
- Compute and display flux isolines on faces region
- Plot a 2D curve of the cogging torque

3.3.1 Compute and display isovalues of the magnetic flux density on face regions

Goal

The magnitude of the magnetic flux density is computed on the selected face regions and displayed via the isovalue plot of color shadings.

Data

The characteristics of the isovalues are presented in the table below:

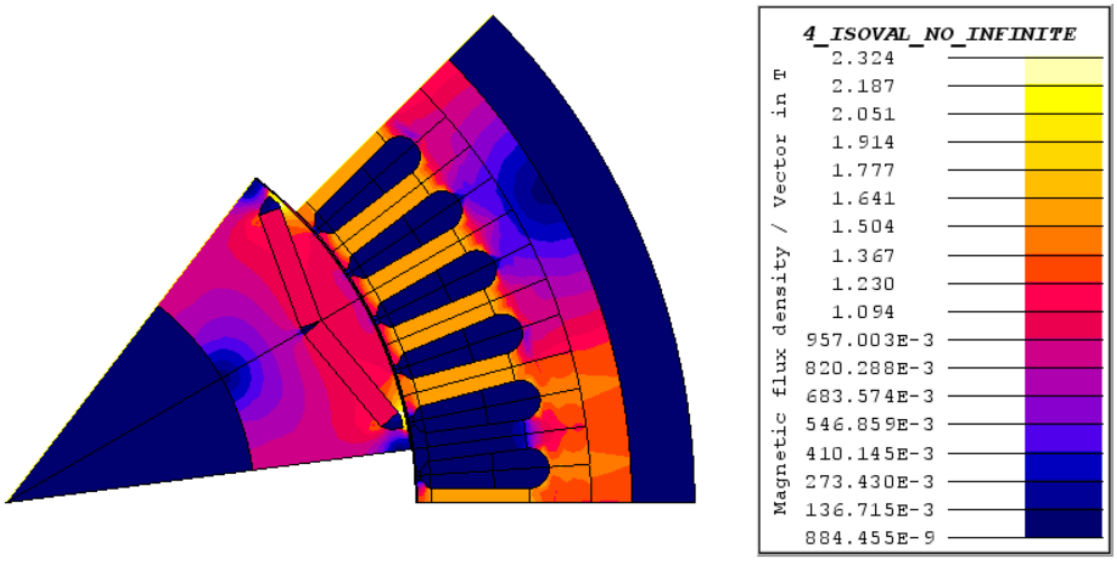
Isovalues on face region	
Face region	**Formula**
MAGNET1_1_POLE_1	B
MAGNET2_1_POLE_1	
PHASE_NEG_3	
PHASE_POS_1	
PHASE_POS_2	
PRESLOT	
ROTATING_AIRGAP	
ROTOR	
ROTOR_AIR	
SHAFT	
STATOR	
STATOR_AIR	
WEDGE	

Access

- by menu: **Graphic** > **Isovalues** > **New**
- by icon: 

Result

The following chart shows the magnetic flux density on the selected face regions.



3.3.2 Compute and display flux isolines on faces region

Goal

The normal component A_n of the magnetic vector potential is computed on the selected face regions and displayed in the form of isolines.

Data

The characteristics of the isolines are presented in the table below.

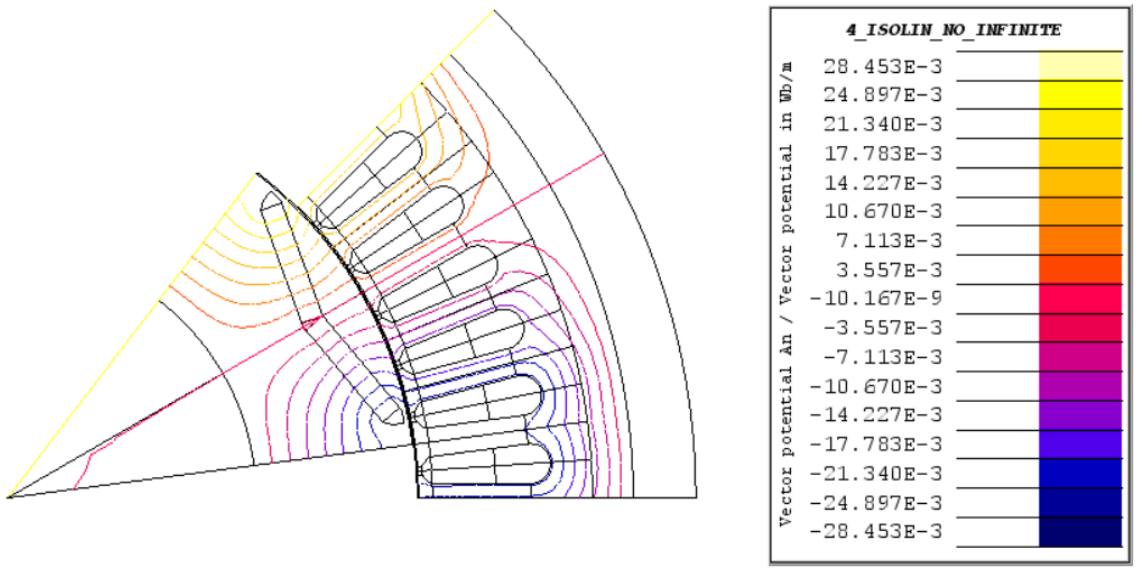
Isovalues on face region	
Face region	**Formula**
MAGNET1_1_POLE_1	An
MAGNET2_1_POLE_1	
PHASE_NEG_3	
PHASE_POS_1	
PHASE_POS_2	
PRESLOT	
ROTATING_AIRGAP	
ROTOR	
ROTOR_AIR	
SHAFT	
STATOR	
STATOR_AIR	
WEDGE	

Access

- by menu: **Graphic** > **Isolines** > **New**
- by icon: 

Result

The following chart shows the isolines of the magnetic vector potential normal component A_n.



Note:

In 2D, the magnetic vector potential is reduced to its normal component perpendicular to the represented cross section.

In the area where the lines are crowded, it corresponds to high values of flux density (highly saturated). In the area where the lines are sparse, it corresponds to lower values of flux density.

3.3.3 Plot a 2D curve of the cogging torque

Goal

Create a 2D curve of the cogging torque according to the angular position of the rotor.

Data

The characteristics of the 2D curve are presented in the table below.

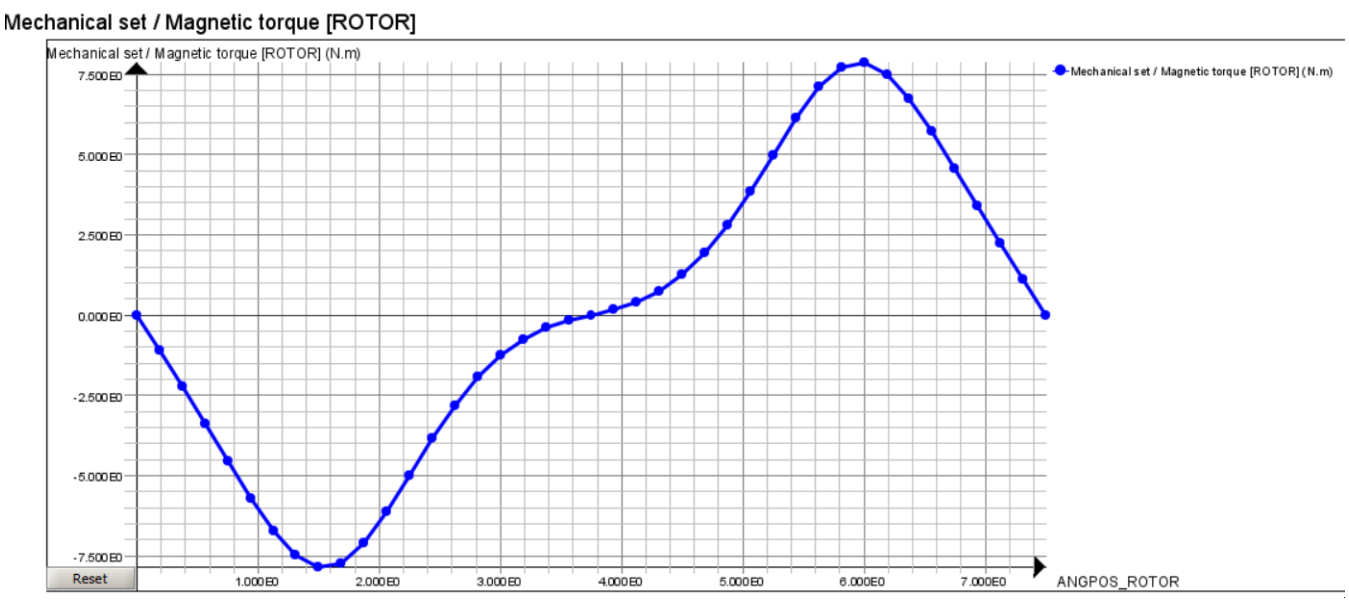
2D curve (parameter (I/O)		
Name	**I/O parameter**	**Formula on ordinate**
COGGING_TORQUE	ANGPOS_ROTOR	Electromagnetic torque

Access

- by menu: **Curve** > **2D Curve (I/O parameter)** > **New 2D Curve (I/O parameter)**
- by icon:

Result

The following graph shows the cogging torque over 1 slot pitch.



Note on the stable position

As shown in the graph, the zero degree position corresponds to the stable position whereas the 3.75 degree position is the unstable position. In the stable position, if the rotor rotates in positive degrees, then the torque is negative and tends to go back to the initial position. In the opposite position, if the rotor rotates in negative degrees, then the torque is positive and tends to go back to the initial position.

Note on choosing the period

Considering the rotor has n_r slots and the stator n_s slots, the cogging torque period corresponds to 360°/the least common multiplier of n_r and n_s.

Over one mechanical period, the least common multiplier of n_s and n_r represents the number of periods of the cogging torque.

n_r	n_s	Least common multiplier	Period of cogging torque
8	48	$n_r=2^3$ $n_s=2^4*3$ $2^4*3=48$	360/48=7.5
14	24	$n_r=2*7$ $n_s=2^3*3$ $2^3*3*7=168$	360/168=2.14

Case 2: Back electromotive force computation

4

This chapter covers the following:

Case 2

The back electromotive force EMF is computed with the speed of 1000 rpm and external circuit connections over 1 electric cycle. It corresponds to the motor being in generator mode at no load. The computed back EMF allows determining the current control angle.

Starting Flux project

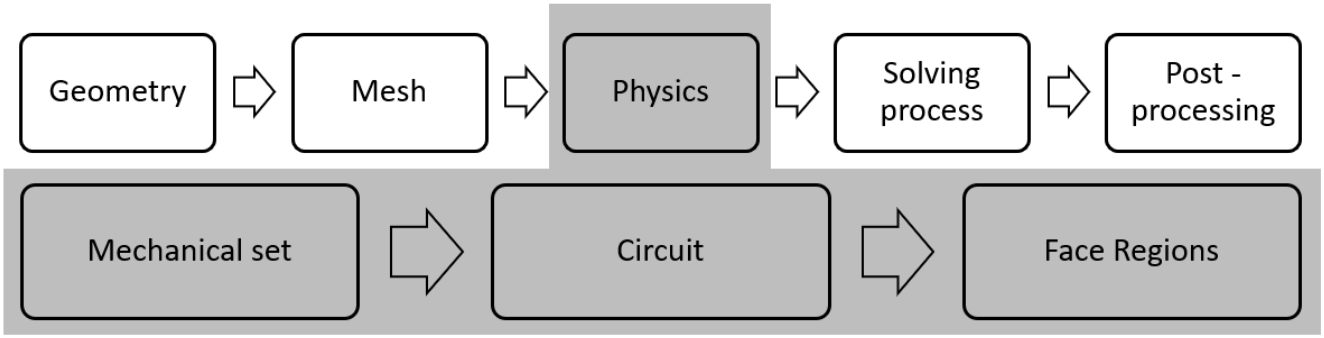
The starting project is the Flux project CASE1_SOLVED.FLU. This project contains:

- the geometry description of the device
- the mesh
- the initial physical description of the motor
- the **CASE1** solved

New project

All the **CASE1_SOLVED** project results are deleted. The Flux project is then saved under the name of **CASE2.FLU.**

4.1 Case 2: Physical description process



Contents

This section contains the following topics:

4.1.1 Modify a mechanical set

Goal

A mechanical set is modified to describe the physics. The speed is modified from 1/6 rpm to 1000 rpm.

Data

The characteristics of the mechanical set are described in the table below.

Name	Type of mechanical set	Rotation axis	Kinematic		
			Type of kinematics	General	
				Velocity (rpm)	Position at time t=0s
ROTOR	Rotation around an axis	Rotation around on axis parallel to Oz	Imposed speed	1000	0

Access

- by menu: **Physics** > **Mechanical set** > **Edit**

4.1.2 Create a circuit

Goal

The goal is to define a circuit for this project.

Action

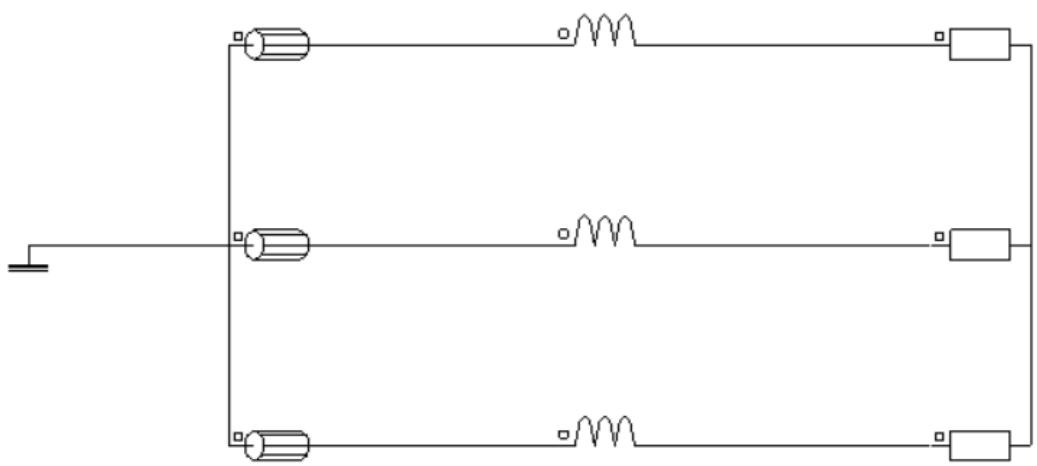
Create a circuit.

Access

- by menu: **Physics** > **Circuit** > **Circuit editor context**
- by icon:

Data

The circuit to be created is as follows:



Note: The coils and inductances are corresponding to the stator coils. The resistances are representative of the load of the generator. In order to compute the back EMF, the values of resistances are designated large values.

4.1.3 Modify a circuit

Goal

The circuit is modified in Flux in order to describe the physics.

Action

Close the circuit editor context.

Data (1)

Stranded coil conductors	
Name	**Resistance formula**
COILCONDUCTOR_1	0.088
COILCONDUCTOR_2	
COILCONDUCTOR_3	

Access (1)

- by menu: **Physics** > **Electrical components** > **Stranded coil conductor** > **Edit**

Data (2)

Inductors	
Name	**Inductance (Henry)**
INDUCTOR_1	0.159E-3
INDUCTOR_2	
INDUCTOR_3	

Resistors	
Name	**Resistance (Ohm)**
RESISTOR_1	1E4
RESISTOR_2	
RESISTOR_3	

4.1.4 Modify face regions

Goal

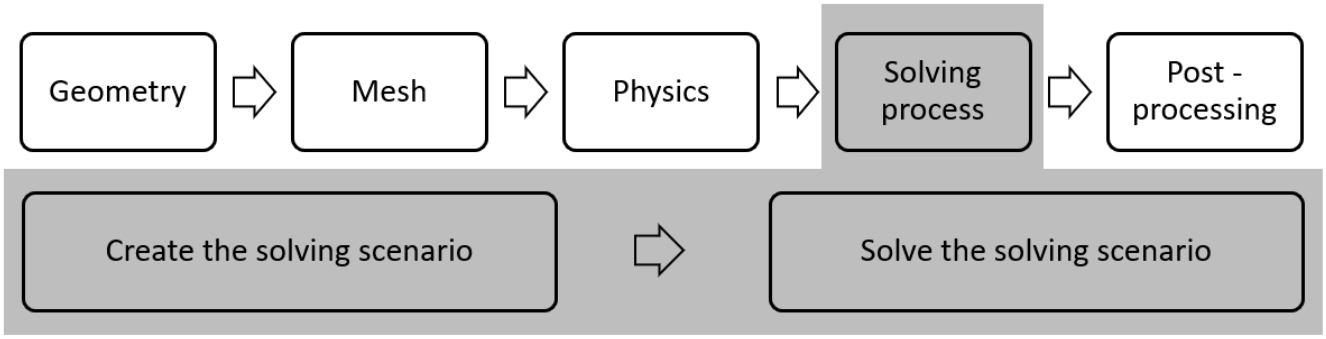
Three face regions are modified in order to describe the physics.

Data

The characteristics of the face regions are described in the table below.

Face region				
Name	**Type**	**Component**	**Turn number**	**Orientation**
PHASE_POS_1	Coil conductor region	COILCONDUCTOR_1	26	Positive
PHASE_POS_2	Coil conductor region	COILCONDUCTOR_2	26	Positive
PHASE_NEG_3	Coil conductor region	COILCONDUCTOR_3	26	Negative

4.2 Case 2: Solve the project



Introduction

This section describes how **CASE2** is solved.

- Create a scenario
- Modify solving option and solve the project

4.2.1 Create a scenario

Goal

A solving scenario is created in order to solve **CASE2**.

Data

The characteristics of the scenario used to solve **CASE2** are presented in the table below:

Solving scenario					
Name	**Control by position of a mechanical set**				
	Mechanical set	**Interval**			
		Lower endpoint	**Upper endpoint**	**Method**	**Step value**
BACK_EMF	ROTOR	0	90	Step value	0.5

Note: 90 mechanical degrees corresponds to 1 electric cycle (360 degrees electrical) as the motor has 4 pole pairs.

Technical note

How to choose the step value?

When selecting the step value, some items must be considered:

- Electrical view point: it is important to check that you have enough points over a cycle. Usually, for a sine function, 40 points over a cycle is enough. In this case, it can be interesting to look at higher harmonics through a FFT, so more than 40 points over a cycle is required.
- Mechanical view point: it is important to check that the mobile part has not moved too much between two consecutive time steps.

In conclusion, the choice of the step value is often a compromise between the duration of computation (time computation is reduced if the number of steps is reduced) and the accuracy of the computation (the computation is more accurate if there are more steps).

4.2.2 Modify solving option and solve the project

Goal

CASE2 project is solved using a solving scenario and solving option.

Data

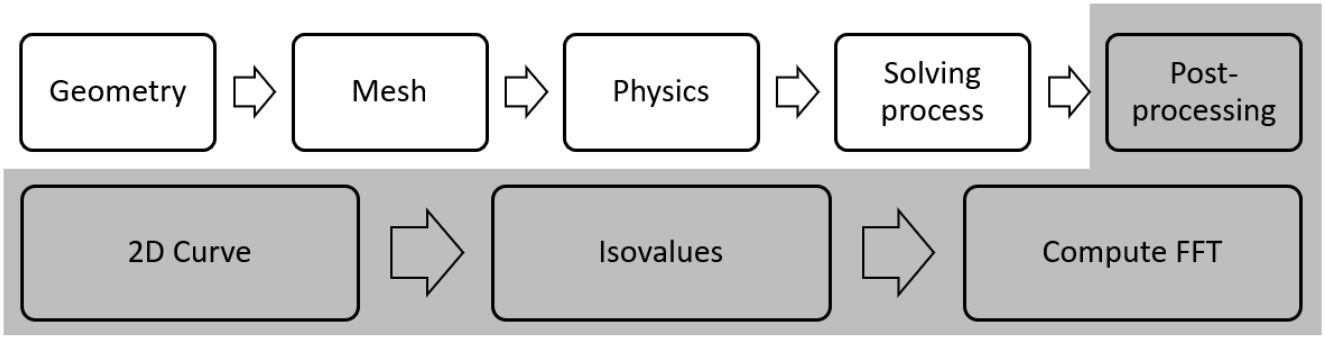
The characteristics of the solving process options are presented in the table below:

Solving process options for non linear system solver		
Precision	**Max number of iteration**	**Method to compute relaxation factor**
1.0E-4	100	Fujiwara method

Action

Solve the project with the **BACK_EMF** scenario and save it under a new project name: **CASE2_SOLVED**.

4.3 Case 2: Results post-processing



Introduction

This section explains how to analyze the principal results of **CASE2**.

- Plot a 2D curve of the voltage through coil conductors according to the angular position of the rotor
- Compute and display isovalues of the magnetic flux density on face region
- Compute the FFT on at the voltage through a stranded coil

4.3.1 Plot a 2D curve of the voltage through coil conductors according to the angular position of the rotor

Goal

Voltage passing through coil conductors depending on the rotor position is computed.

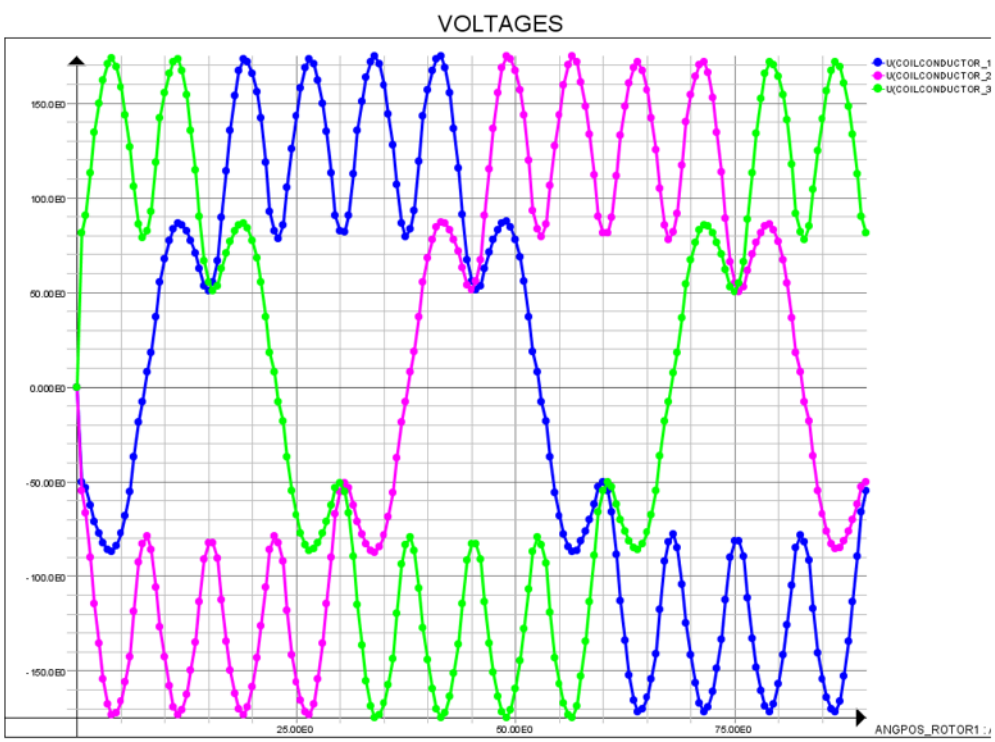
Data

The characteristics of the 2D curve are presented in the table below.

2D curve (I/O parameter)				
Name	**I/O parameter**	**Limit min.**	**Limit max.**	**Formula**
VOLTAGES	ANGPOS_ROTOR1	0	90	U(COILCONDUCTOR_1) U(COILCONDUCTOR_2) U(COILCONDUCTOR_3)

Result

The following curve shows the voltage through stranded coils according to the angular position of the rotor.



Technical note

From the above graph, we can determine the angle of the different phase currents through the zero-cross over of the induced back emf waveform for each phase.

Phase	Mechanical Angle	Electrical Angle
1	7.5	30
2	37.5	150
3	67.5	270

4.3.2 Compute and display isovalues of the magnetic flux density on face region

Goal

The magnitude of the magnetic flux density are computed on the selected face regions and displayed via the color shaded plot. By default, the last time step is displayed.

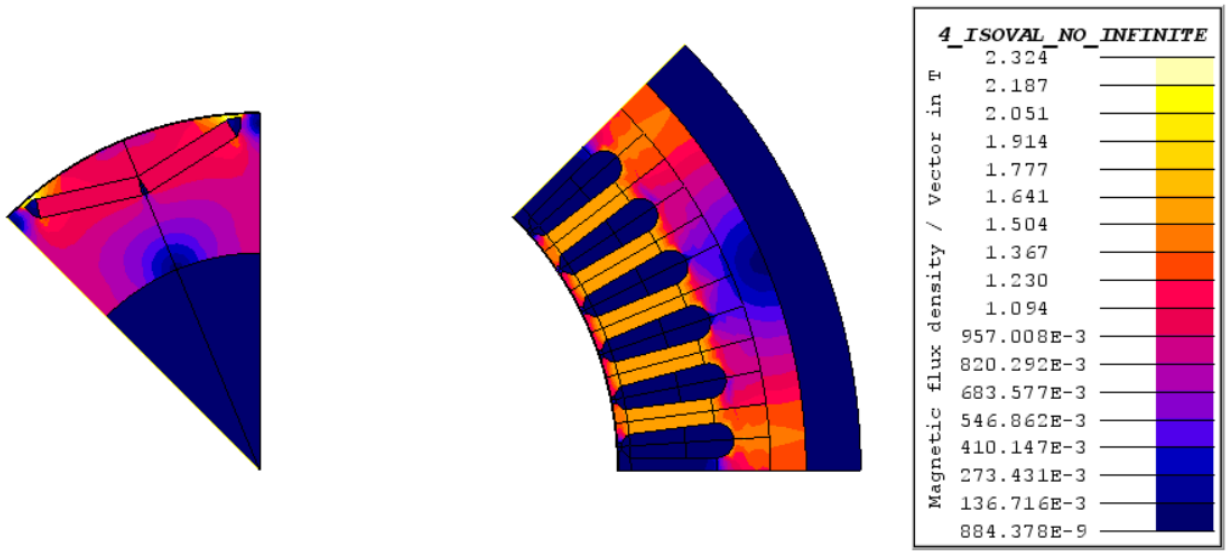
Data (1)

The characteristics of the arrows are presented in the table below.

Isovalues on face region	
Face region	**Formula**
MAGNET1_1_POLE_1	B
MAGNET2_1_POLE_1	
PHASE_NEG_3	
PHASE_POS_1	
PHASE_POS_2	
ROTATING_AIRGAP	
ROTOR	
ROTOR_AIR	
SHAFT	
STATOR	
STATOR_AIR	
WEDGE	

Result

The following chart shows the magnetic flux density on the selected regions.



4.3.3 Compute the FFT on at the voltage through a stranded coil

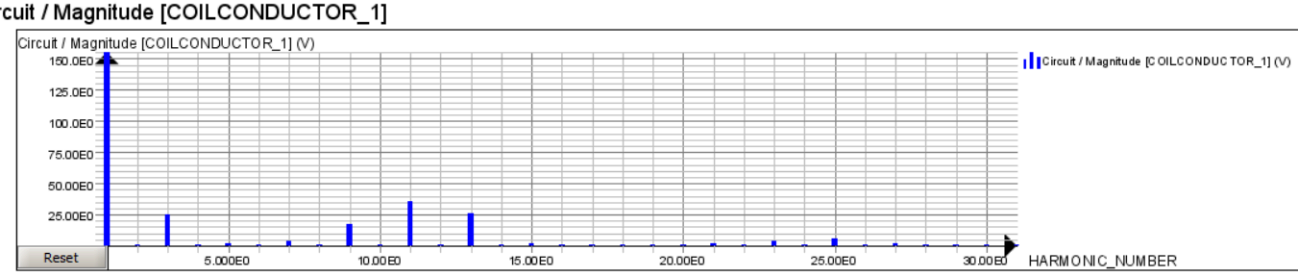
Data

The characteristics of the 2D curve are presented in the table below.

Extrapolated 2D curve (I/O parameter) Spectrum analysis (FFT)		
2D Curve	**Curve to be analyzed**	**Number of harmonics**
VOLTAGES	U(COILCONDUCTOR_1)	30

Results

Circuit / Magnitude [COILCONDUCTOR_1]



HARMONIC_NUMBER	Circuit / Magnitude [COILCONDUCTOR_1] (V)
1.0	155.08256186505295
2.0	0.8573880682153046
3.0	24.531729051509647
4.0	0.8571228270288583
5.0	1.1002573198185455
6.0	0.856683469771638
7.0	3.6009436221090665
8.0	0.8560740407046091
9.0	16.62419870802039
10.0	0.855300156560263
11.0	35.17330022153707
12.0	0.8543689614725535
13.0	25.317638352358557
14.0	0.8532890691825348
15.0	1.6869609361963476
16.0	0.8520704926568519
17.0	0.8792797473162222
18.0	0.8507245621612306
19.0	0.7461837475270732
20.0	0.8492638306704331
21.0	1.1964652661171988
22.0	0.847701968228905
23.0	3.0704354828584304
24.0	0.8460536450675145
25.0	5.1918887998006165
26.0	0.8443344051387826
27.0	1.2637973051799116
28.0	0.8425605281112468
29.0	0.8778966238337175
30.0	0.8407488848075447
31.0	0.5866328901172231

Case 3: Constant speed computation

5

This chapter covers the following:

Case 3

The motor is driven with a 3-phase sine current running at constant speed. The simulated motor performances are used to compute shaft torque, torque ripples, core losses (Bertotti and LS model) and efficiencies.

Starting Flux project

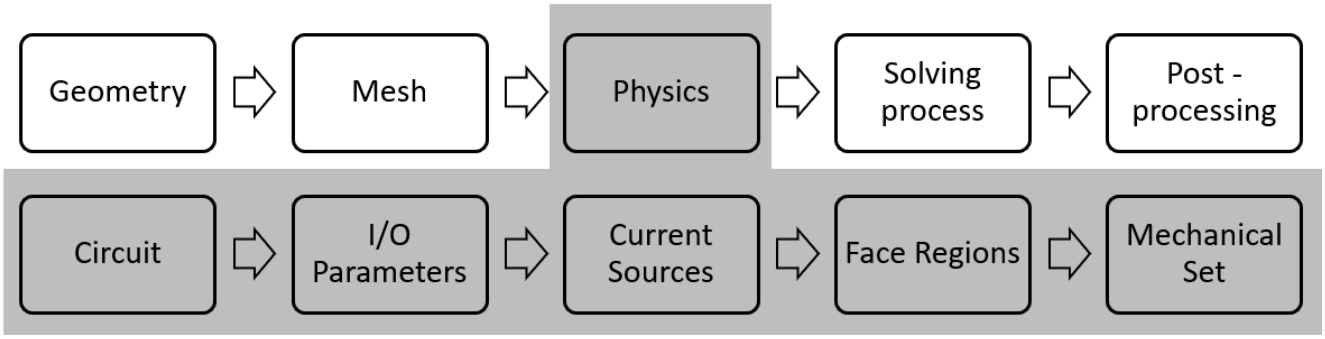
The starting project is the Flux project **CASE2_SOLVED.FLU**. This project contains:

- the geometry description of the device
- the mesh
- the initial physical description of the motor
- the **CASE2** solved

New project

All the **CASE2_SOLVED** results are deleted. The Flux project is then saved under the name of **CASE3.FLU.**

5.1 Case 3: Define the physics



Contents

This section contains the following topics:

5.1.1 Modify a circuit in the circuit context editor

Action

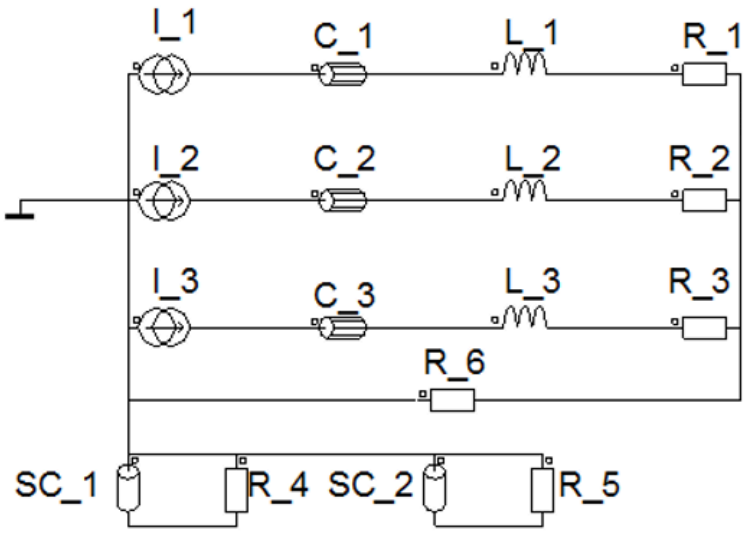
Modify the existing circuit in the circuit context editor.

Access

- by menu: **Physics** > **Circuit** > **Circuit editor context**
- by icon: 

Result

The following circuit is integrated in the project and the circuits components appear in the **Data** tree.



Technical note

The eddy currents in the magnets are included in this model. The eddy current patterns in each magnet are enforced with the zero total current constraint. This is done by representing the magnet as a solid conductor connected in series with a large resistance

5.1.2 Modify circuit component

Goal

The circuit are modified in Flux in order to describe the physics.

Data (1)

The characteristics of the stranded coil conductors are described in the table below.

Stranded coil conductors	
Name	**Resistance formula**
C_1	0.088
C_2	
C_3	

Data (2)

The characteristics of the inductors are described in the table below.

Inductors	
Name	**Inductance formula**
L_1	0.159E-3
L_2	
L_3	

Data (3)

The characteristics of the resistors are described in the table below.

Resistors	
Name	**Resistance formula**
R_1	1E-4
R_2	
R_3	

Resistors	
Name	**Resistance formula**
R_4	1E4
R_5	
R_6	

Data (4)

The characteristics of the solid conductor are described in the table below.

Solid conductors	
Name	**Symetries and periodicities**
SC_1	In series
SC_2	

5.1.3 Create I/O parameters

Goal

Five I/O parameters will be created in order to define the physics.

Data (1)

The characteristics of the I/O parameter defined by a scenario are described in the table below.

I/O parameters controlled via a scenario	
Name	**Reference value**
SPEED	1200

Access (1)

- by menu: **Parameter / Quantity** > **I/O parameter new** > **New**
- by icon: 

Data (2)

The characteristics of the I/O parameters defined by a formula are described in the table below.

I/O parameters defined by a formula	
Name	**Expression**
GAMMA	45
FREQUENCY	SPEED/60*POLES/2
OMEGA	2*Pi()*FREQUENCY
MAX_CURRENT	200

Technical note

GAMMA is the control angle between the phase current and the corresponding phase back emf (cf. Plot a 2D curve of the voltage through coil conductors according to the angular position of the rotor). It is in electrical degree.

5.1.4 Modify current sources

Goal

The three current sources are modified to describe the physics.

Data

The characteristics of the current sources are described in the table below.

Currents sources	
Name	**Expression**
I_1	MAX_CURRENT*Sin(OMEGA*TIME+GAMMA*Pi()/180)
I_2	MAX_CURRENT*Sin(OMEGA*TIME+GAMMA*Pi()/180-2*Pi()/3)
I_3	MAX_CURRENT*Sin(OMEGA*TIME+GAMMA*Pi()/180-4*Pi()/3)

Access

- by menu: **Physics** > **Electrical component** > **Current source** > **Edit**

5.1.5 Modify a material

Goal

NDFEB material is modified in order to describe the physics. Electrical properties are added to the material so that eddy current effects can be taken into account.

Data

The characteristics of the material are described in the table below.

J(E) magnet with electrical properties	
Name	**Isotropic resistivity**
NDFEB	1.4E-6

Access

- by menu: **Physics** > **Material** > **Edit**

5.1.6 Modify face regions and orient material for face region

Goal

Two face regions are modified to describe the physics.

Data (1)

The characteristics of the face regions are described in the table below.

Face region						
Name	**Type**	**Material**	**Conductor type**	**Solid conductor**	**Mechanical set**	**Orientation**
MAGNET1_1_POLE1	Solid conductor region	NDFEB	Circuit	SC_1	ROTOR	Positive
MAGNET2_1_POLE1	Solid conductor region	NDFEB	Circuit	SC_2	ROTOR	Positive

Access (1)

- by menu: **Physics** > **Face region** > **Edit**

Data (2)

The characteristics of the material orientation for face regions are described in the table below.

Orient material for face region			
Name	**Oriented type**	**Coordinate system**	**Angle**
MAGNET1_1_POLE1	Direction	ROTOR_COORD	10
MAGNET2_1_POLE1	Direction	ROTOR_COORD	-10

Access (2)

- by menu: **Physics** > **Material** > **Orient material for face region**
- by icon: 

5.1.7 Modify mechanical set

Goal

Rotor mechanical set is modified in order to describe the physics.

Data

The characteristics of the mechanical set are described in the table below.

Mechanical set				
Name	**Type of mechanical set**	**Type of kinematics**	**General**	
			Velocity	**Position at t = 0s**
ROTOR	Rotation around an axis	Imposed speed	SPEED	7.5

Access

- by menu: **Physics** > **Mechanical set** > **Edit**

Technical note

The initial rotor position is set to 7.5 degrees so that the phase current is aligned with the phase back emf when **GAMMA** is zero.

5.1.8 Assign coil conductor to face region

Goal

The coil conductor components are assigned to face regions to describe the physics.

Action

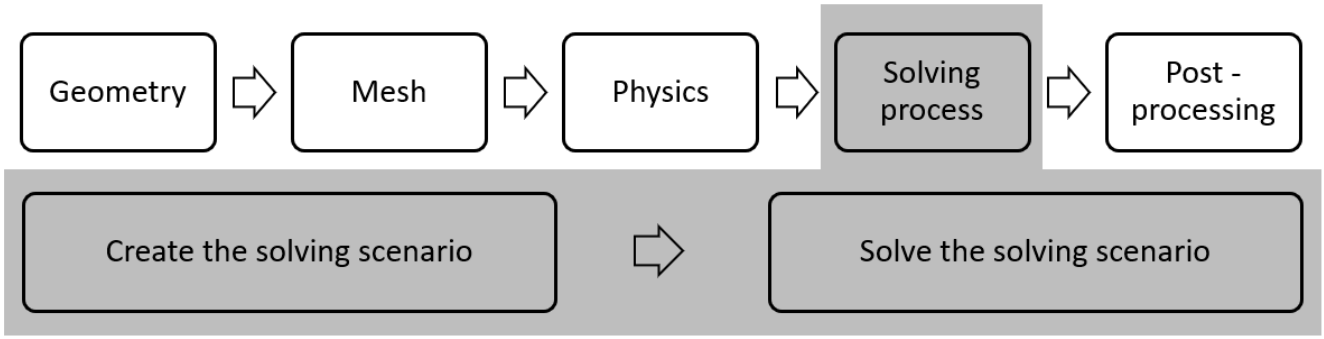
The coil conductor components are assigned to face regions from the menu Physics/assign coil conductor to region/face region.

Data

The characteristics of the face region are described in the table below.

Face region				
Name	**Type**	**Component**	**Turn number**	**Orientation**
PHASE_POS_1	Coil conductor region	C_1	26	Positive
PHASE_POS_2	Coil conductor region	C_2	26	Positive
PHASE_NEG_3	Coil conductor region	C_3	26	Negative

5.2 Case 3: Solve the project



Introduction

This part describes how **CASE3** is solved.

- Create a scenario
- Modify solving option and solve the project

5.2.1 Create a scenario

Goal

A solving scenario is created in order to solve **CASE3**.

Data

The characteristics of the scenario used to solve **CASE3** are presented in the table below:

Solving scenario					
Name	**Control by position of a mechanical set**				
	Mechanical set	**Interval**			
		Lower endpoint	**Upper endpoint**	**Method**	**Step value**
CST_SPEED	ROTOR	0	92	Step value	1

Access

- by menu: **Solving** > **Solving scenario** > **New**
- by icon: 

5.2.2 Modify solving option and solve the project

Goal

CASE3 project is solved using a solving scenario and solving option.

Data

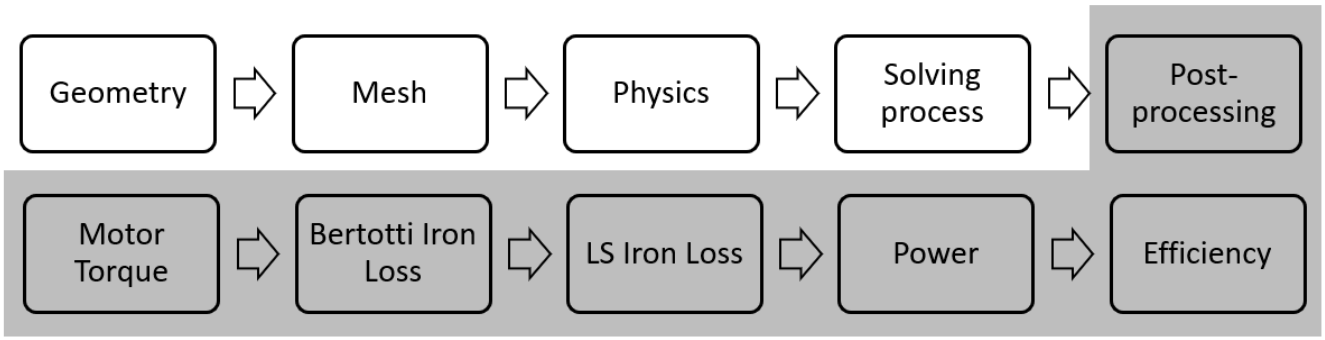
The characteristics of the solving process options are presented in the table below:

Solving process options for non linearsystem solver		
Precision	**Max number of iteration**	**Method to compute relaxation factor**
1.0E-4	100	Fujiwara method

Action

Solve the project with the **CST_SPEED** scenario and save it under a new project name: **CASE3_SOLVED**.

5.3 Case 3: Result post processing



Introduction

This section explains how to analyze the principal results of **CASE3**.

- Compute and display motor torque
- Compute the Bertotti iron loss
- Display isovalues of Bertotti iron loss on face region
- Compute LS iron loss
- Create a sensor and display a curve of loss in magnets
- Compute input electrical power
- Compute mechanical power
- Compute efficiency

5.3.1 Compute and display motor torque

Goal

The goal is to compute and display the motor torque over 1 electric cycle (ie from 0° to 90° mechanical degree).

Data

The characteristics of the 2D curve are presented in the table below.

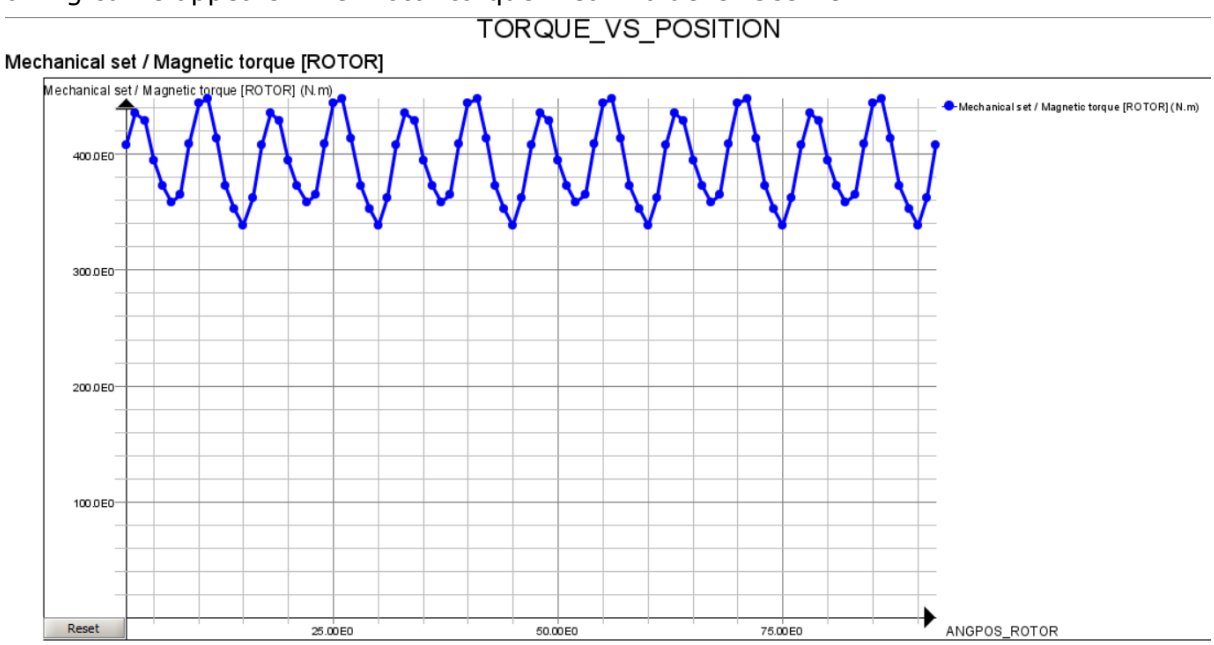
2D curve (I/O parameter)				
Name	**I/O parameter**	**Limit min.**	**Limit max.**	**Formula**
MOTOR_TORQUE	ANGPOS_ROTOR	0	90	Electromagnetic torque

Access

- by menu: **Curve** > **2D Curve (I/O parameter)** > **New 2D Curve (I/O parameter)**
- by icon:

Result

The following curve appears. The motor torque mean value is: 389.294 N.m



Technical note

From the torque variation over 1 electric cycle graph, we can see the torque ripples that are due to the harmonic effects of the back emf.

5.3.2 Compute the Bertotti iron loss

Goal

Iron loss is computed from Bertotti coefficients.

Reminder

Bertotti coefficient can be found thanks to a specific FAQ available for the moment with this tutorial. The folder contaning Flux files of this tutorial also contains a zipped file with:

- An FAQ entitled "How to determine iron loss coefficients"
- An excell sheet for iron loss coefficient determination
- A paper discribing the method used

Data

The characteristics of the Bertotti iron loss computation are presented in the table below:

Bertotti iron loss							
Sheet iron					Regions	Rotor position	
Hysteresis loss coeff	Classical loss coeff	Loss in excess coeff	Thickness of steel iron	Stacking factor		Limit min.	Limit max.
130.246	1923077	0.357	0.35E-3	0.97	STATOR ROTOR	2	92

Access

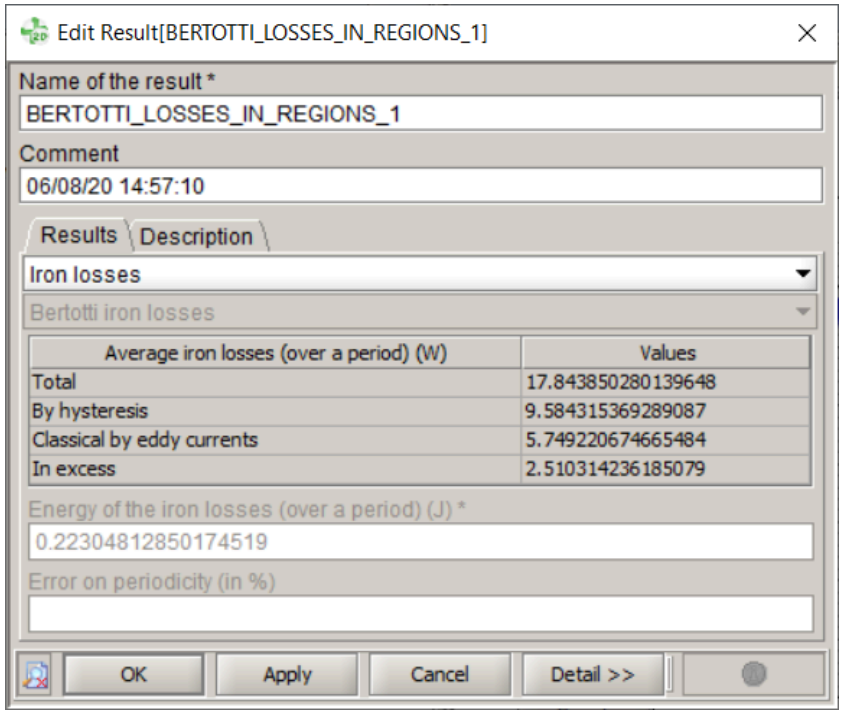
- by menu: **Computation** > **Iron losses computation** > **Bertotti iron losses**

Technical note

The minimum limit for the time selection is negative (-7.6387813E-4 seconds) is because the initial position in the mechanical set is 7.5 deg to align the phase back emf with the phase current at time t = 0 s.

Result (1)

The following results appear.

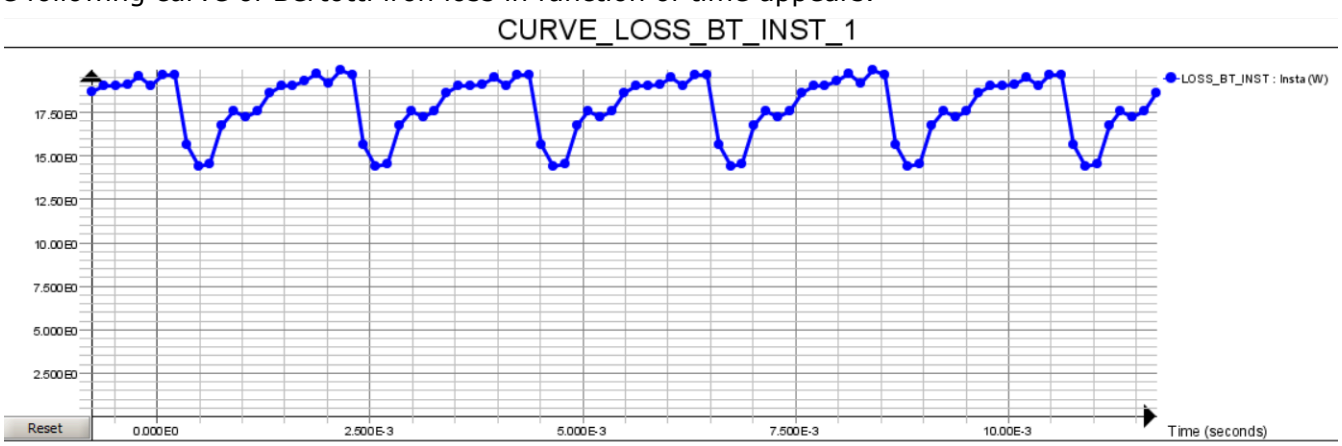


Technical note

The average value for the modeled part (1/8 of the motor) is 18,967 W. The total core loss for the whole motor is 151,73 W.

Result (2)

The following curve of Bertotti iron loss in function of time appears.



Technical note

From the Bertotti iron loss curve, we can see the slotting effects (6 slots for 1 electric cycle).

5.3.3 Display isovalues of Bertotti iron loss on face region

Goal

Isovalues of the Bertotti iron loss on **ROTOR** and **STATOR** region at the angular position of 30° for the rotor are computed and displayed.

Action

Select the step computation by clicking on **Select the step** button, in the zone located below the data tree.

Data (1)

The characteristics of the step selection are presented in the table below:

Computation step	
Scenario	**Step value**
CST_SPEED	30

Data (2)

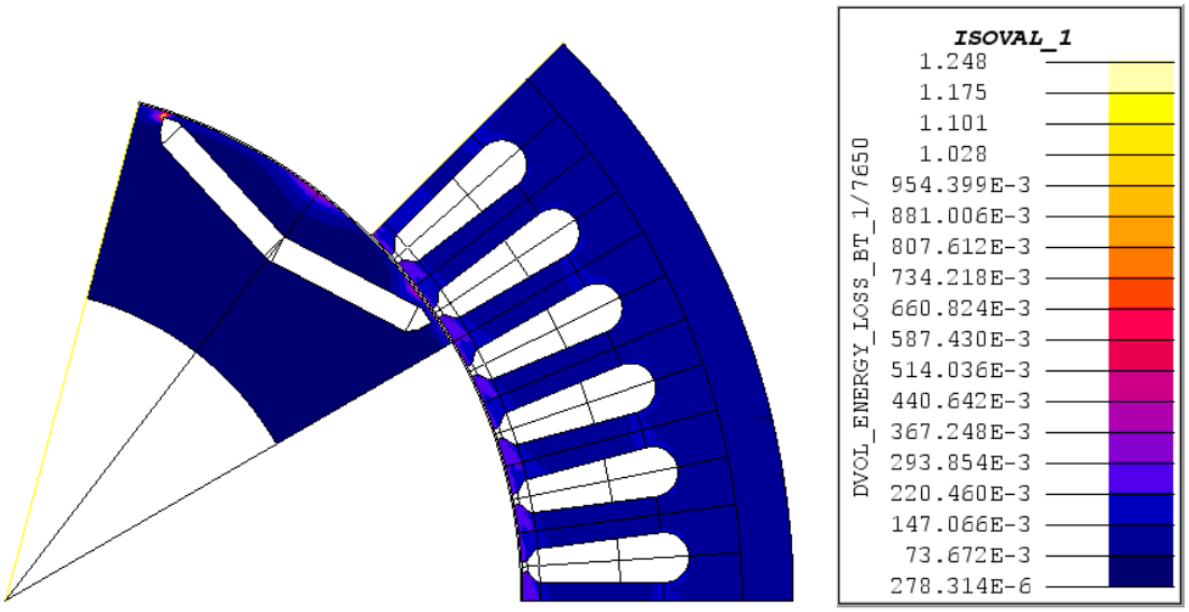
The characteristics of the isovalues are presented in the table below:

Isovalues on face regions	
Face regions	**User Formula**
ROTOR	DVOL_ENERGY_LOSS_BT_1/7650
STATOR	

Note: Note: the power volume density is in W/m^3. in order to display it in W/kg, we divide it by the mass density.

Result

The following results appear.



5.3.4 Compute LS iron loss

Goal

LS Iron loss is computed on face regions.

Data

The characteristics of the LS iron loss computation are presented in the table below:

LS iron loss			
Sheet iron	**Regions**	**Limit min.**	**Limit max.**
M27035A	ROTOR STATOR	2	92

Access

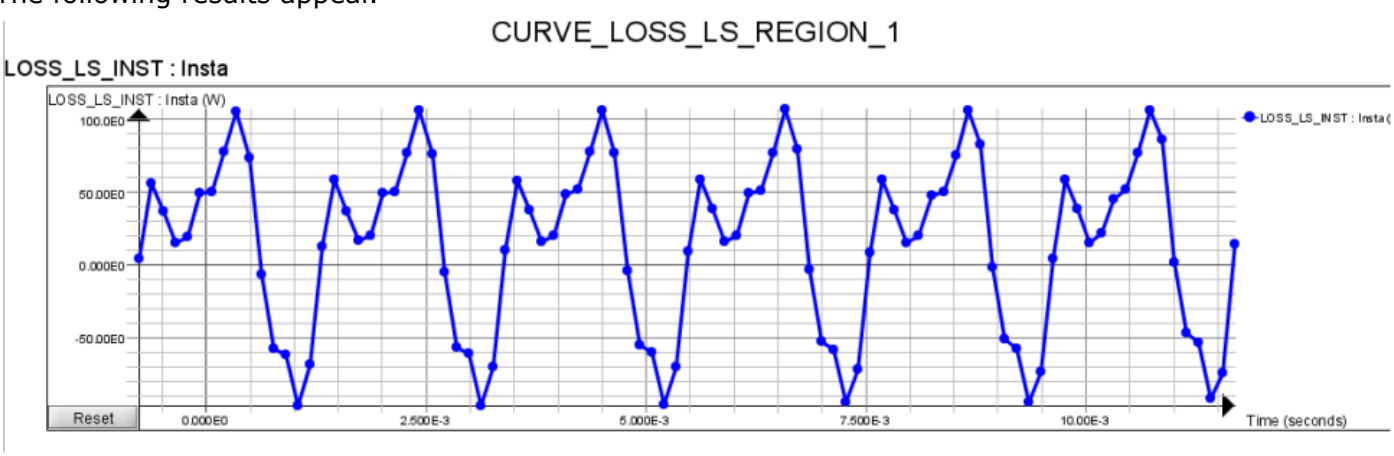
- by menu: **Computation** > **Iron losses computation** > **LS iron losses on regions**

Technical note

As reminder, the minimum limit for the time selection is negative (- 7.6387813E-4 seconds) is because the initial position in the mechanical set is 7.5 degree to align the phase back emf with the phase current at time t = 0s.

Result

The following results appear.



Technical note (1)

The average value for the modeled part (1/8 of the motor) is 14.69 W. The total core loss for the whole motor is 117,52 W.

Technical note (2)

From the LS Iron Loss curve, we can notice that the loss values are negative. This occurs when the magnetic field decreases, thus, the motor gives back the power to the system, resulting in negative values by convention.

5.3.5 Create a sensor and display a curve of loss in magnets

Goal

Eddy current loss is computed for magnet that has conductive material properties.

Data

The characteristics of the sensor are presented in the table below:

Predefine sensor: Loss by Joule Effect		
Name	**Comment**	**Face region**
MAGNET_LOSS	Eddy currents loss in pole 1 magnets	MAGNET1_1_POLE_1 MAGNET1_1_POLE_2

Access

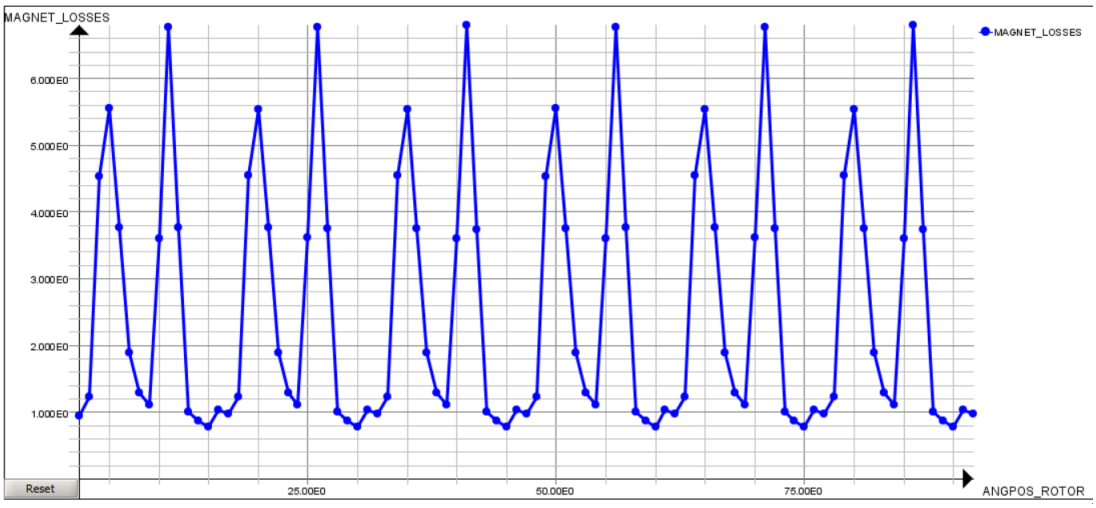
- Step 1:
  - **Advanced** > **Sensor** > **New**
  - by icon: 
- Step 2:
  - **Advanced** > **Sensor** > **Evaluate sensors**
  - by icon: 

Action

The characteristics of the curve are presented in the table below:

2D curve I/O parameter			
Name	**AnG Pos parameter**		**Formula**
	Min	**Max**	
LOSS_JOULE_EFFECT	2.0	92.0	MAGNET_LOSS

Result



The average value over the period for one magnet is: 2.70 W. for the modelled part (1/8 motor). The average result for the whole motor is 21.6 W.

> **Note:** This curve represents the eddy current losses of two magnets only. To determine the value for the whole motor, we must multiply by the number of periodicities.

5.3.6 Compute input electrical power

Goal

A 2D curve is created in order to compute the input of electrical power.

Data

The characteristics of the 2D curve are presented in the table below:

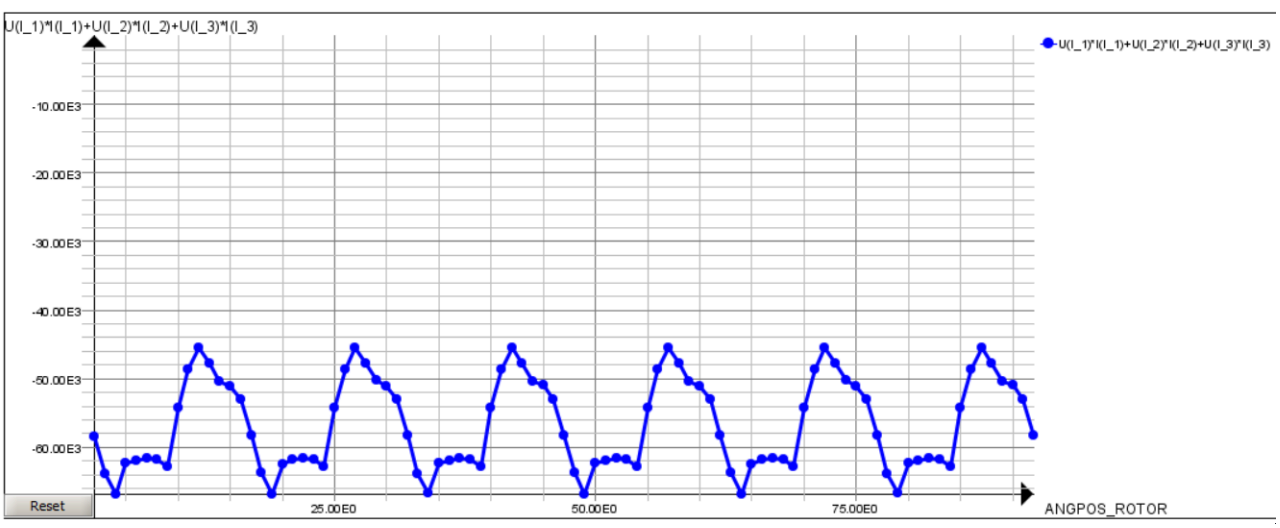
2D curve (I/O parameter)				
Name	**I/O parameter**	**Limit min.**	**Limit max.**	**Formula**
INPUT_ELECTRICAL_POWER	ANGPOS_ROT	2.0	92.0	U(I_1)*I(I_1)+U(I_2)*I(I_2)+U(I_3)*I(I_3))

Access

- by menu: **Curve** > **2D Curve (I/O parameter)** > **New 2D Curve (I/O parameter)**
- by icon:

Result

The average input of electrical power is -56247.5 W



Reminder

The negative power corresponds to the input power over one electric cycle.

5.3.7 Compute mechanical power

Goal

A 2D curve is created in order to compute the mechanical power.

Data

The characteristics of the 2D curve are presented in the table below:

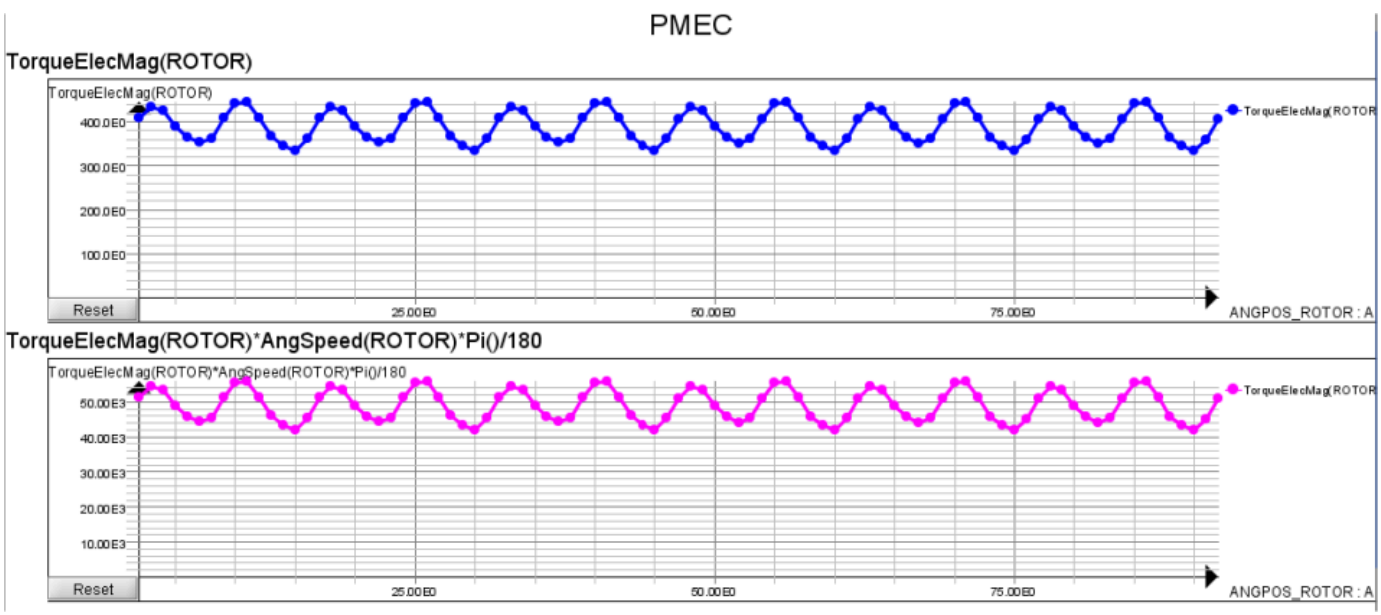
2D curve (I/O parameter)				
Name	**I/O parameter**	**Limit min.**	**Limit max.**	**Formula**
PMEC	ANGPOS_ROTOR	2.0	92.0	TorqueElecMag(ROTOR)
				TorqueElecMag(ROTOR)*AngSpeed(ROTOR)*Pi()/180

Access

- by menu: **Curve** > **2D Curve (I/O parameter)** > **New 2D Curve (I/O parameter)**
- by icon: 

Result

The output mechanical power is 48915 W.



5.3.8 Compute efficiency

Goal

The efficiency of the motor can be calculated using the above results.

Data

The characteristics of the efficiency computation are presented in the table below:

Physical quantities	Values
Input electrical power	56247
Output mechanical power	48915
Core loss (average between Bertotti an LS)	134
Efficiency : $\frac{\text{Pmec-Pcoreloss}}{\text{Input Electrical Power}}$	86.72%

Case 4: Starting

6

This chapter covers the following:

Case 4

The fourth case is the study of the starting of this motor at no load. It will allow us to see the time of response to reach the constant speed.

The supplying strategy is to feed the motor in order to work at constant speed. To achieve it, the stator supply depends on the rotor position in order to impose a constant shift angle between the rotor magnetic field created by magnets and the stator magnetic field created by currents in stator coils.

Starting Flux project

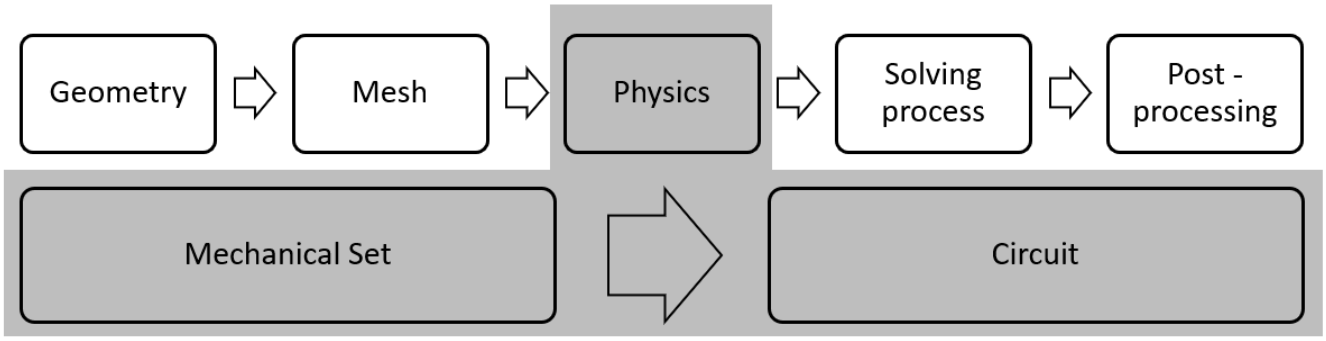
The starting project is the Flux project **CASE3_SOLVED.FLU**. This project contains:

- the geometry description of the device
- the mesh
- the initial physical description of the motor
- the **CASE3** solved

New project

All the **CASE3_SOLVED** results are deleted. The Flux project is then saved under the name of **CASE4.FLU.**

6.1 Case 4: Define the physics



Contents

This section contains the following topics:

6.1.1 Modify a mechanical set

Goal

The **Rotor mechanical set** is modified to add inertia and friction data. Compared to previous case, we have to modify the mechanical set in order to switch from **constant speed** to **coupled load**.

Data

The characteristics of the sensor are presented in the table below.

Kinematic description			
Name	**Type of kinematics**	**General**	
		Velocity	**Position at t = 0s**
ROTOR	Coupled load	0	7.5

Internal characteristics				
Type of load	**Moment of inertia**	**Constant friction**	**Viscous friction coeff.**	**Friction coeff.**
Inertia, friction coefficient and spring	0.0637	0	389/1200/6	0

External characteristics				
Type of load	**Moment of inertia**	**Constant friction**	**Viscous friction coeff.**	**Friction coeff.**
Inertia, friction coefficient and spring	0	0	0	0

Access

- by menu: **Physics** > **Mechanical set** > **Edit**

Note on the friction coefficient (1)

The mechanical equation to be solved is the following one :

$$J*\ddot{\theta} = \Gamma_e - f*\dot{\theta}$$

With:

- J inertia (in kg.m²)
- $\ddot{\theta}$ angular acceleration
- Γ_e electromagnetic torque (in Nm)
- f friction coefficient (in Nm/s)
- $\dot{\theta}$ angular speed (in degree/s)

When reaching the steady state, the final speed is nearly constant (meaning that $\ddot{\theta}$ is equal to zero). Then we have:

$$0 = \Gamma_e - f*\dot{\theta}$$

That is to say:

$$f = \Gamma_e / \dot{\theta}$$

In our case, we want to have as final speed 1200 rpm. When looking at the previous computation, the torque was 389 Nm. Then, the friction coefficient must be 389/(1200*6). In Flux, the angular speed has to be in degree by second and not in round per minute.

Note:

1. In real life, the friction coefficient should be deduced from tests, or extrapolated from other motors of the same type.
2. These values are for the whole motor even when only a part of the motor is modeled.

6.1.2 Modify a circuit

Goal

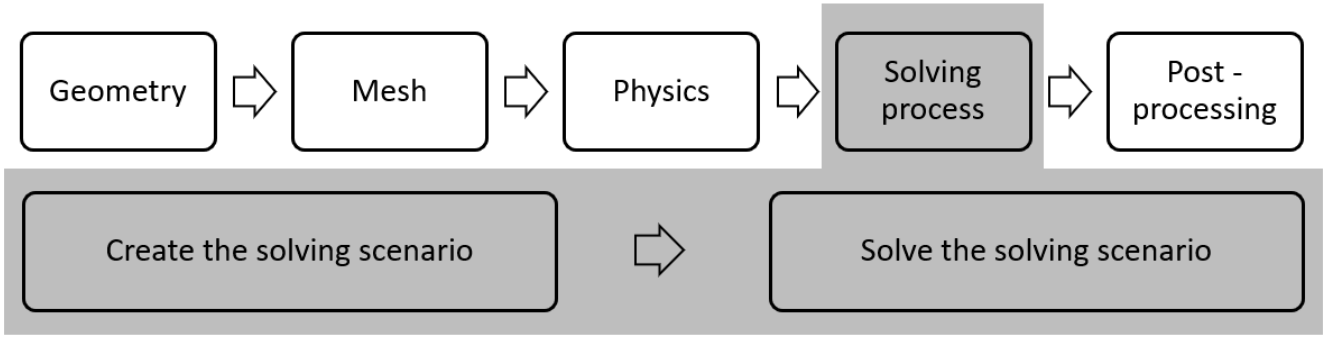
The three current sources are modified to describe the physics. The current in the stator is depending on the rotor position.

Data

The characteristics of the current sources are described in the table below.

Currents sources	
Name	**Expression**
I1	MAX_CURRENT*Sin(((AngPos(ROTOR)-7.5)*POLES/2+GAMMA)*Pi()/180-0*PI()/3)
I2	MAX_CURRENT*Sin(((AngPos(ROTOR)-7.5)*POLES/2+GAMMA)*Pi()/180-2*Pi()/3)
I3	MAX_CURRENT*Sin(((AngPos(ROTOR)-7.5)*POLES/2+GAMMA)*Pi()/180-4*Pi()/3)

6.2 Case 4: Solve the project



Introduction

This part describes how **CASE4** is solved.

- Create a scenario
- Modify solving option and solve the project

6.2.1 Create a scenario

Goal

A solving scenario is created in order to solve **CASE4**.

Data

The characteristics of the scenario used to solve CASE4 are presented in the table below:

Solving scenario					
Name	**Type**	**Lower limit**	**Upper limit**	**Variation method**	**Step value**
STARTING	Control by time	0	0.04	Step value	0.001

Access

- by menu: **Solving** > **Solving scenario** > **New**
- by icon: 

6.2.2 Modify solving option and solve the project

Goal

CASE4 project is solved using a solving scenario and solving option.

Data

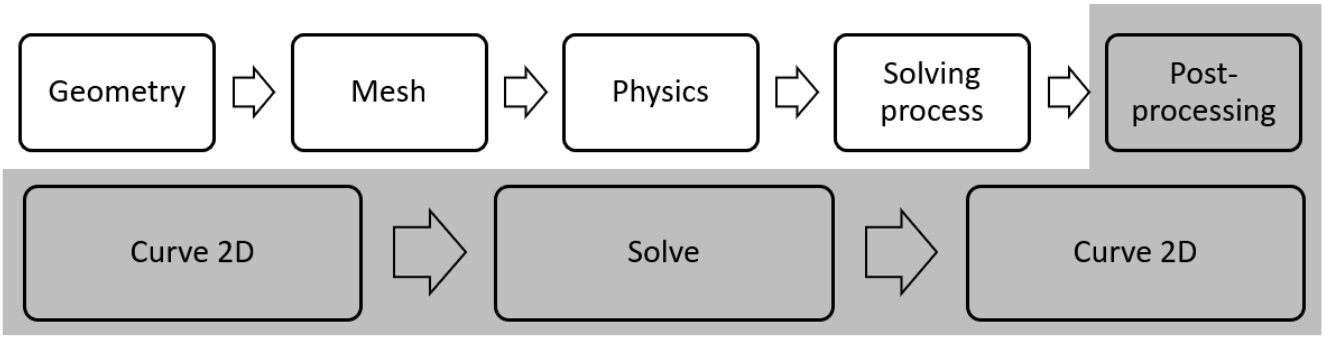
The characteristics of the solving process options are presented in the table below:

Solving process options for non linearsystem solver		
Precision	**Max number of iteration**	**Method to compute relaxation factor**
1.0E-4	100	Fujiwara method

Action

Solve the project with the starting scenario and save it under a new project name: **CASE4_SOLVED**.

6.3 Case 4: Results post-processing



Introduction

This section explains how to analyze the main results of **CASE4**.

- Plot a 2D curve of position, speed and torque versus time
- Modify a scenario and continue to solve
- Plot a 2D curve of 3 phase currents and position versus time

6.3.1 Plot a 2D curve of position, speed and torque versus time

Goal

Position, speed and torque versus time are computed.

Data

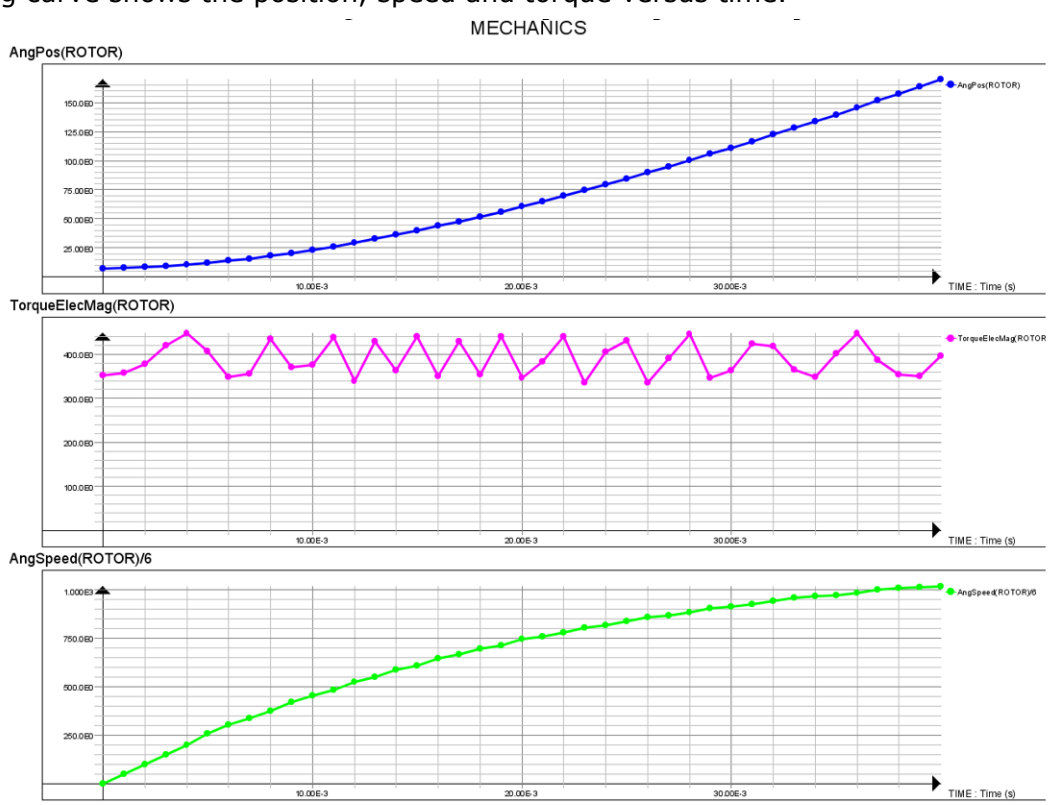
The characteristics of the 2D curve are presented in the table below.

2D curve (I/O parameter)				
Name	**I/O parameter**	**Limit min.**	**Limit max.**	**Formula**
MECHANICS	TIME	0	0.04	AngPos(ROTOR), TorqueElecMag(ROTOR), AngSpeed (ROTOR)/6

As the unit by default for angular speed is in°.s, the angular speed is divided by 6 to obtain a result in rpm.

Result

The following curve shows the position, speed and torque versus time.



We can see that the motor starts, and reaches the speed of 1016 rpm) at no load (with the selected friction coefficient). The torque is oscillating around 389 Nm, which is the goal of our current command strategy.

Technical note

Take note that the speed limit is not reached yet. The solution is to continue the solving process.

6.3.2 Modify a scenario and continue to solve

Data

The characteristics of the scenario used to continue to **CASE4** are presented in the table below:

Solving scenario					
Name	**Type**	**Lower limit**	**Upper limit**	**Variation method**	**Step value**
STARTING	Control by time	0.04	0.08	Step value	0.001

Action

The solving process can be continued with the command **Solving** > **Continue**, Continue to solve a scenario.

6.3.3 Plot a 2D curve of 3 phase currents and position versus time

Goal

3 phase currents and position versus time are computed.

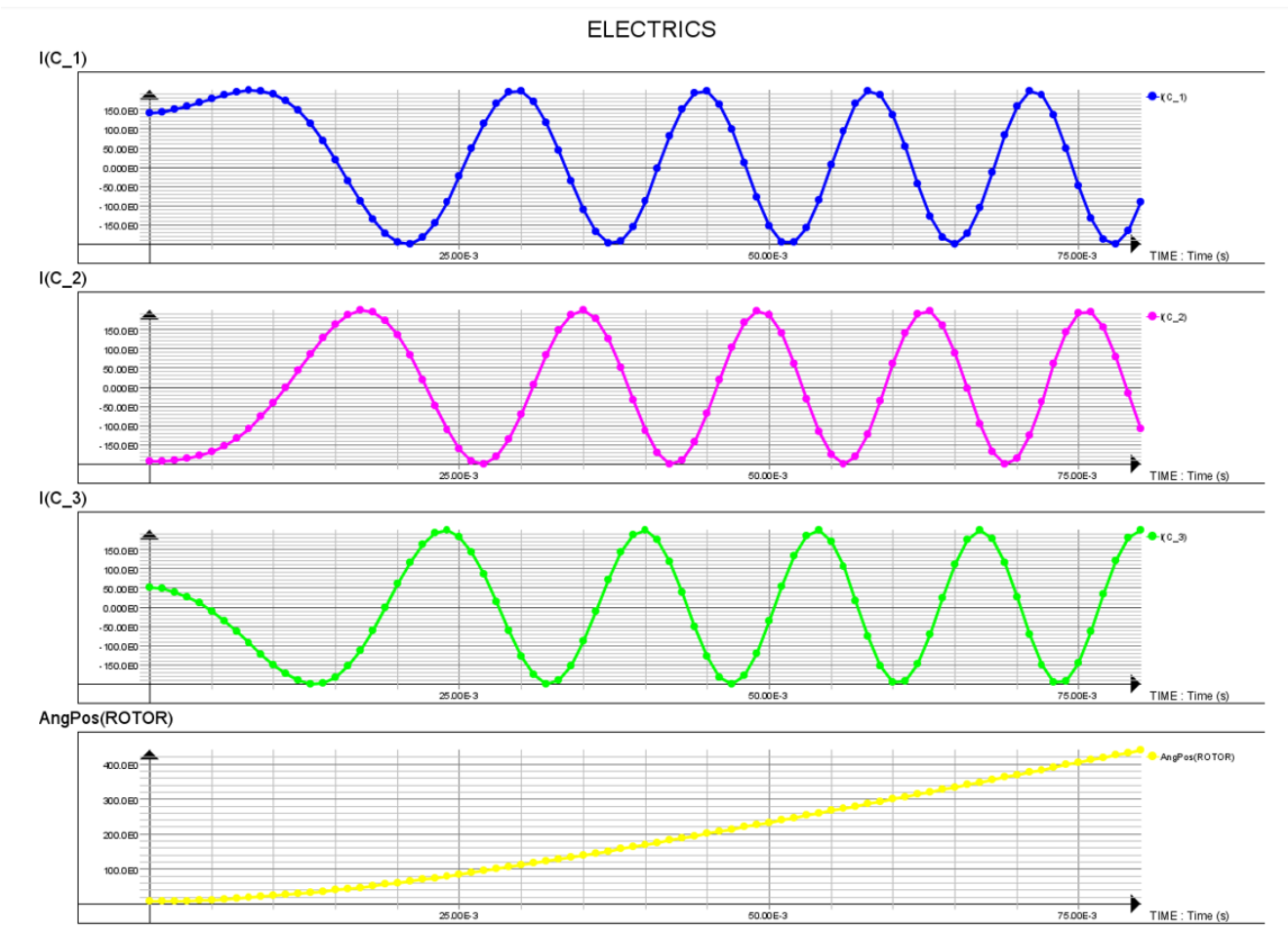
Data

The characteristics of the 2D curve are presented in the table below.

2D curve (I/O parameter)				
Name	**I/O parameter**	**Limit min.**	**Limit max.**	**Formula**
ELECTRIC	TIME	0	0.08	I(C_1), I(C_2), I(C_3), AngPos (ROTOR)

Result (1)

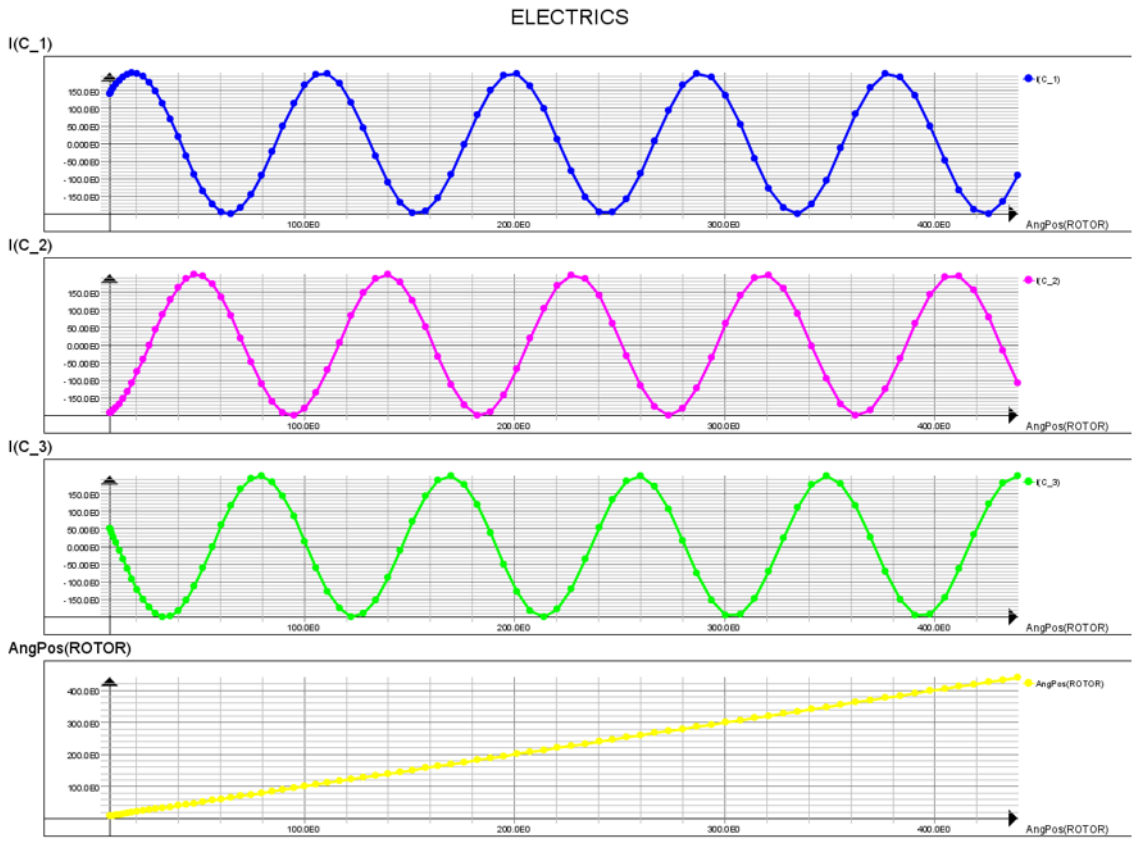
The following curve shows the 3-phase currents versus time.



Note: Due to the command, in order to have a constant torque, the frequency of the rotor current is adapted to the position, and hence the speed of the motor.

Result (2)

It is possible to display the graph versus position instead of time.



In this case, the current in coils is sine versus rotor position, which is normal. As the rotor rotates, the currents in the stator have to rotate, in order to maintain a constant difference of phase between rotor magnetic field and stator magnetic field.

Case 5: Multi static

7

This chapter covers the following:

Case 5

The fifth case is a parametric computation.

The angle of the rotor will be varying. In this parametric study, the geometric parameter is the angle **ALPHA** that varies in the range [75°, 195°] with a step of 3°.

Starting Flux project

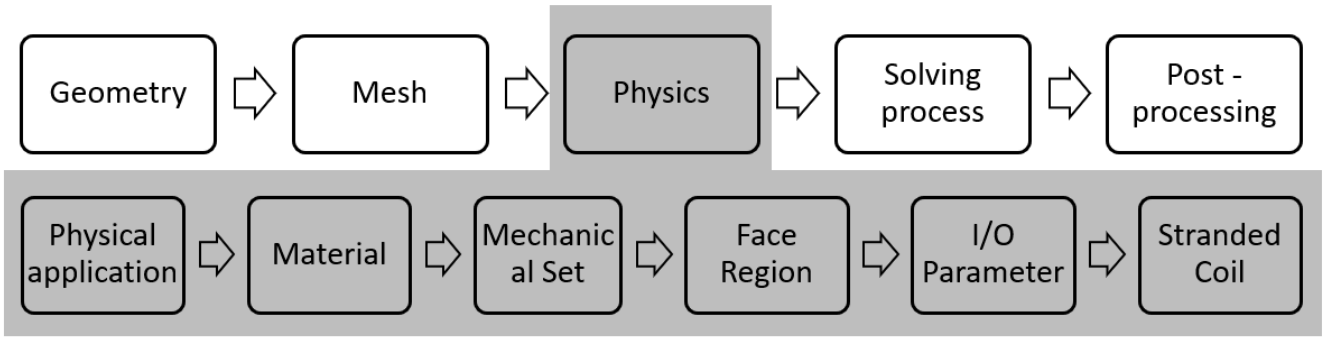
The starting project is the Flux project **GEOMESH.FLU**. This project contains:

- the geometry description of the device
- the mesh
- the initial physical description of the motor

New project

The Flux project is saved under the name of **CASE5.FLU.**

7.1 Case 5: Define the physics



Contents

This section contains the following topics:

7.1.1 Define the physical application

Action

First, define the physical application. The required physical application is **Magneto static 2D application.**

Data

The characteristics of the application are presented in the table below.

Magneto static 2D application		
Definition		**Solver**
2D domain type	**Depth of the domain**	
2D plane	75	Flux3D solver

Access

- by menu: **Application** > **Define** > **Electric** > **Electro Static 2D**

7.1.2 Create materials

Goal

One material is created and the other is imported from the material database in order to define the physics.

Data (1)

The characteristics of the material import are presented in the table below:

Material import	
Material database	**Material name**
FLUX_101_MATERI.DAT	FLU_M270-35A

Access (1)

- by menu: **Physics** > **Material** > **New**
- by icon: 

Data (2)

The characteristics of the material are presented in the table below:

B(H) linear magnet described in the Br module		
Name	**Remanent flux density (T)**	**Relative permeability**
NDFEB	1.2	1.05

7.1.3 Create mechanical set

Action

Create two mechanical sets to describe the physics of the motor.

Data (1)

The characteristics of the “ROTOR” mechanical set are presented in the table below:

Name	Type of mechanical set	Axis				
		Rotation axis	Coordinate system	Pivot point coordinates		Kinematics
				First	Second	
ROTOR	Rotation around an axis	Rotation around on axis parallel to Oz	XY1	0	0	MultiStatics

Data (2)

The characteristics of the “STATOR” mechanical set are presented in the table below:

Name	Type of mechanical set
STATOR	fixed

Access (2)

- by menu: **Physics** > **Mechanical set** > **New**
- by icon: 

7.1.4 Modify magnet face region and orient material for face region

Action

Edit and modify face region in order to described the physics.

Data (1)

The characteristics of the face regions used to describe the magnets are presented in the table below:

Face region			
Name	**Type**	**Material**	**Mechanical set**
MAGNET1_1_POLE1	Magnetic non conducting region	NDFEB	ROTOR
MAGNET2_1_POLE1	Magnetic non conducting region	NDFEB	ROTOR

Data (2)

The characteristics of the magnet orientation are presented in the table below.

Orient material for face region			
Name	**Oriented type**	**Coordinate system**	**Angle**
MAGNET1_1_POLE1	Direction	ROTOR_COORD	10
MAGNET2_1_POLE1	Direction	ROTOR_COORD	-10

Access (2)

- by menu: **Physics** > **Material** > **Orient material for face region**
- by icon: 

7.1.5 Create I/O parameters

Goal

Five I/O parameters will be created in order to define the physics.

Data (1)

The characteristics of the I/O parameter controlled via a scenario are described in the table below.

I/O parameters controlled via a scenario	
Name	**Reference value**
CURRENT	100

Access (1)

- by menu: **Parameter / Quantity** > **I/O parameter new** > **New**
- by icon: 

7.1.6 Create stranded coils

Action

Create three stranded coils in order to describe the physics.

Data

The characteristics of the stranded coils are described in the table below.

Stranded coil conductors		
Name	**Type**	**Reference value**
C_1	Stranded coil with imposed current (A)	CURRENT
C_2	Stranded coil with imposed current (A)	-CURRENT/2
C_3	Stranded coil with imposed current (A)	-CURRENT/2

Access

- by menu: **Physics** > **Electrical components** > **Stranded coil conductor** > **New**
- by icon:

Note

In a 3 phase system:

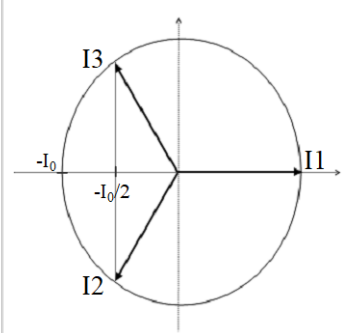
- $I1 = I_0 \cos(\omega t)$
- $I2 = I_0 \cos(\omega t - 2\pi/3)$
- $I3 = I_0 \cos(\omega t - 4\pi/3)$

At time t = 0s:

- $I1 = I_0 \cos(0) = I_0$
- $I2 = I_0 \cos(-2\pi/3) = -I_0/2$
- $I3 = I_0 \cos(2\pi/3) = -I_0/2$

In this case, at time t = 0s:

- I (C_1) corresponds to CURRENT
- I (C_2) corresponds to -CURRENT/2
- I (C_3) corresponds to -CURRENT/2



7.1.7 Modify the faces region

Action

Modify the face regions in order to model the physics.

Data (1)

The characteristics of the face regions used to describe the three phases are presented in the table below:

Face region					
Name	**Type**	**Component**	**Turn number**	**Orientation**	**Mechanical set**
PHASE_POS_1	Coil conductor region	C_1	26	Positive	STATOR
PHASE_POS_2	Coil conductor region	C_2	26	Positive	STATOR
PHASE_NEG_3	Coil conductor region	C_3	26	Negative	STATOR

Access (1)

- by menu: **Physics** > **Face region** > **Edit**

Data (2)

The characteristics of the face regions used to describe the three phases are presented in the table below:

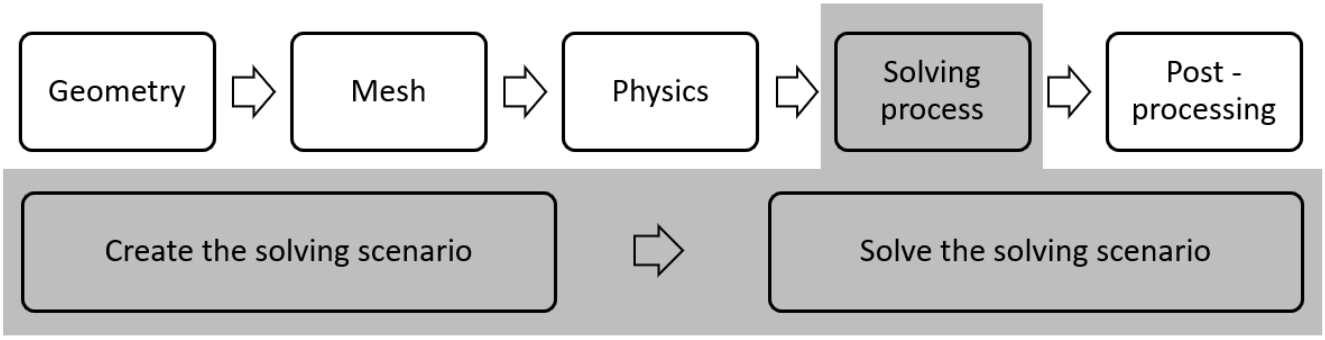
Name	Type	Mechanical set
ROTATING_AIRGAP	Air or vacuum region	STATOR
ROTOR_AIR	Air or vacuum region	ROTOR
SHAFT	Air or vacuum region	ROTOR
STATOR_AIR	Air or vacuum region	STATOR
INFINITE	Air or vacuum region	STATOR
PRESLOT	Air or vacuum region	STATOR
WEDGE	Air or vacuum region	STATOR

Data (3)

The characteristics of the face regions used to describe the three phases are presented in the table below:

Name	Type	Material	Mechanical set
ROTOR	Magnetic non conducting region	FLU_M270-35A	ROTOR
STATOR	Magnetic non conducting region	FLU_M270-35A	STATOR

7.2 Case 5: Solve the project



Introduction

This part describes how **CASE5** is solved.

- Create a scenario
- Modify solving options and solve the project

7.2.1 Create a scenario

Action

Create a scenario in order to solve **CASE5**.

Data

The characteristics of the scenario used to solve CASE5 are presented in the table below:

Solving scenario	
Name	**Type**
MULTISTATIC	Controled by a parameter

Solving scenario				
Parameter name	**Control by physical parameter**			
	Interval			
	Lower endpoint	**Upper endpoint**	**Method**	**Step value**
CURRENT	0	200	Step value	20
ANGPOS_ROTOR	0	90	Step value	1

Access

- by menu: **Solving** > **Solving scenario** > **New**
- by icon: 

7.2.2 Modify solving options and solve the project

Action

Solve the project utilizing the created scenario.

Data

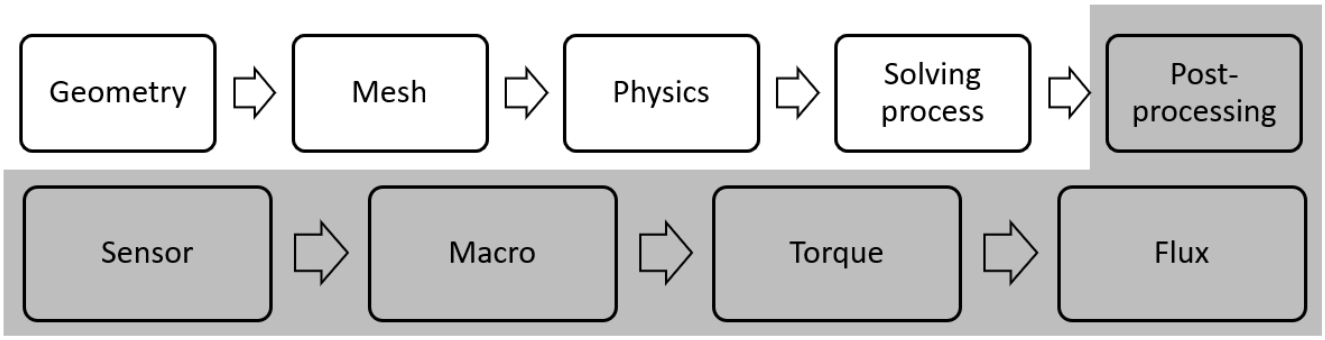
The characteristics of the solving process options are presented in the table below:

Solving process options for non linear system solvers		
Precision	**Max number of iteration**	**Method to compute relaxation factor**
1.0E-4	100	Fujiwara method

Action

Solve the project with the starting scenario and save it under a new project name: **CASE5_Solved**

7.3 Case 5: Result post-processing



Introduction

This section explains how to analyze the main results of **CASE5**.

- Create and evaluate a sensor
- Load and run a macro
- Display torque versus position and current
- Display flux versus position and current
- Display incremental inductance versus position and current

7.3.1 Create and evaluate a sensor

Data

The characteristics of the sensor are presented in the table below:

Predefine sensor: flux through a coil conductor	
Name	**Coil conductor**
FLUX_C1	C_1

Access

- Step 1:
  - **Advanced** > **Sensor** > **New**
  - by icon: 
- Step 2:
  - **Advanced** > **Sensor** > **Evaluate sensors**
  - by icon: 

7.3.2 Load and run a macro

Goal

Load and run a macro in order to export some result in a table.

Action (1)

Load macro named **EXPORT3DCURVEPARAMPARAMTOEXCEL** in the current project.

Access (1)

- by menu: **Extension** > **Macro** > **Load**

Action (2)

Run the macro.

Access (2)

- by menu: **Extension** > **Macro** > **Run**

Data

The characteristics of the macro are presented in the table below:

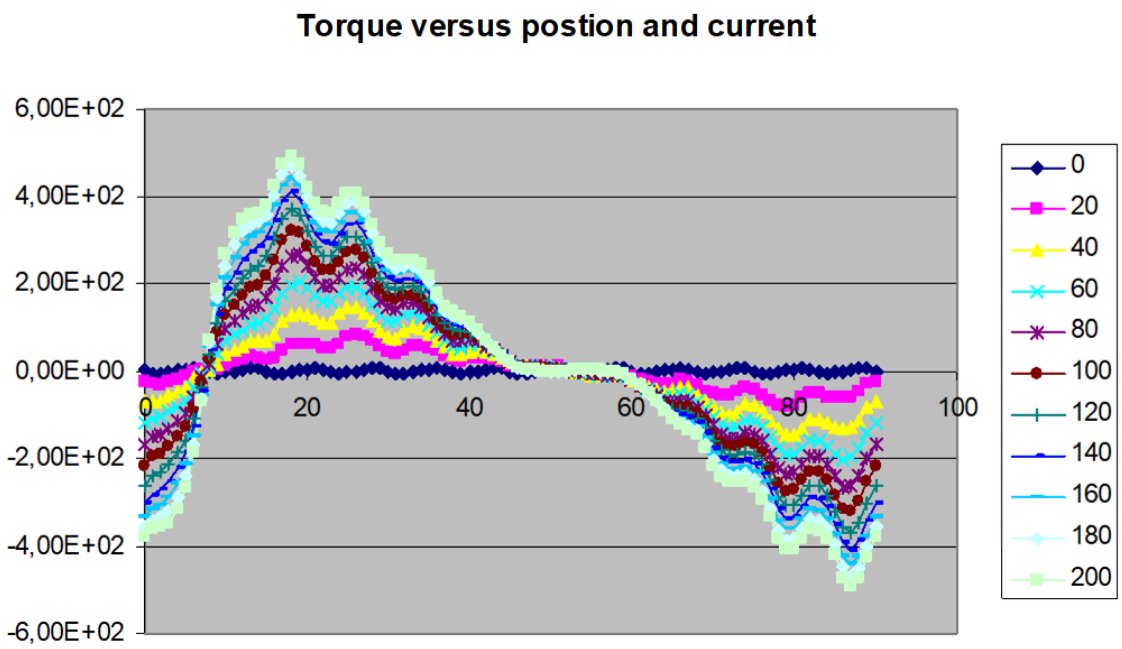
EXPORT3DCURVEPARAMPARAMTOEXCEL			
Scenario	**First parameter**	**Second parameter**	**I/O parameter or scalar sensor to export**
MULTISTATIC	ANGPOS_ROTOR	CURRENT	FLUX_C1
			ELTORQ_ROTOR

7.3.3 Display torque versus position and current

Goal

The goal is to display a curve of the torque versus current in the exported results (Excel table).

Result

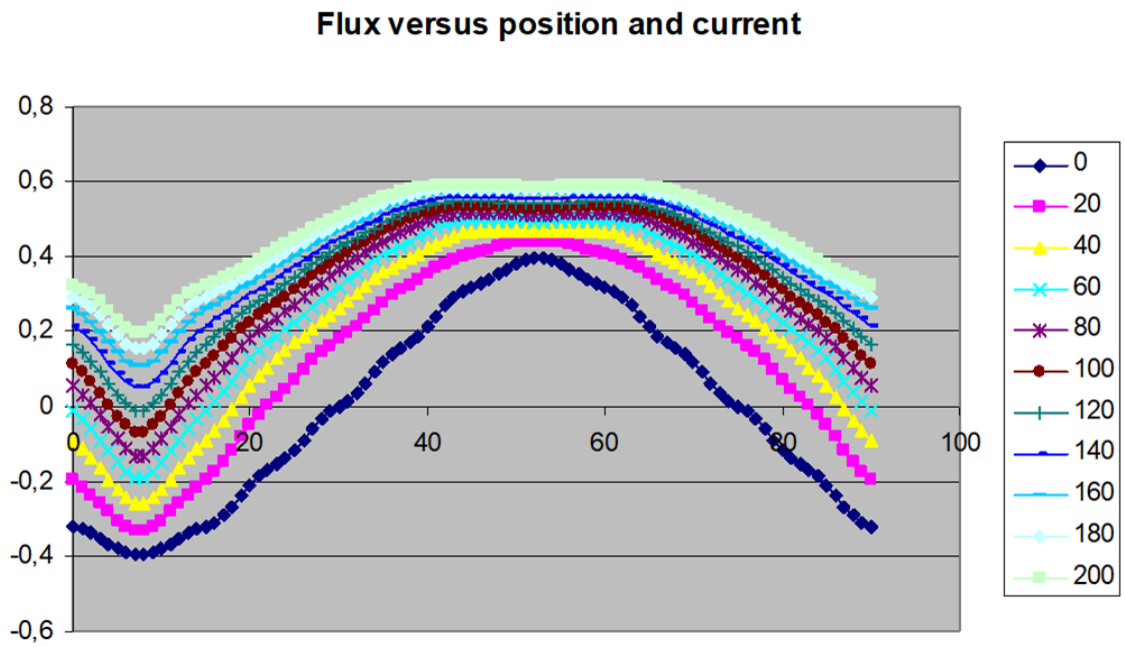


7.3.4 Display flux versus position and current

Goal

The goal is to display a curve of the torque and flux versus position and current in the exported results (Excel table).

Result



Note:

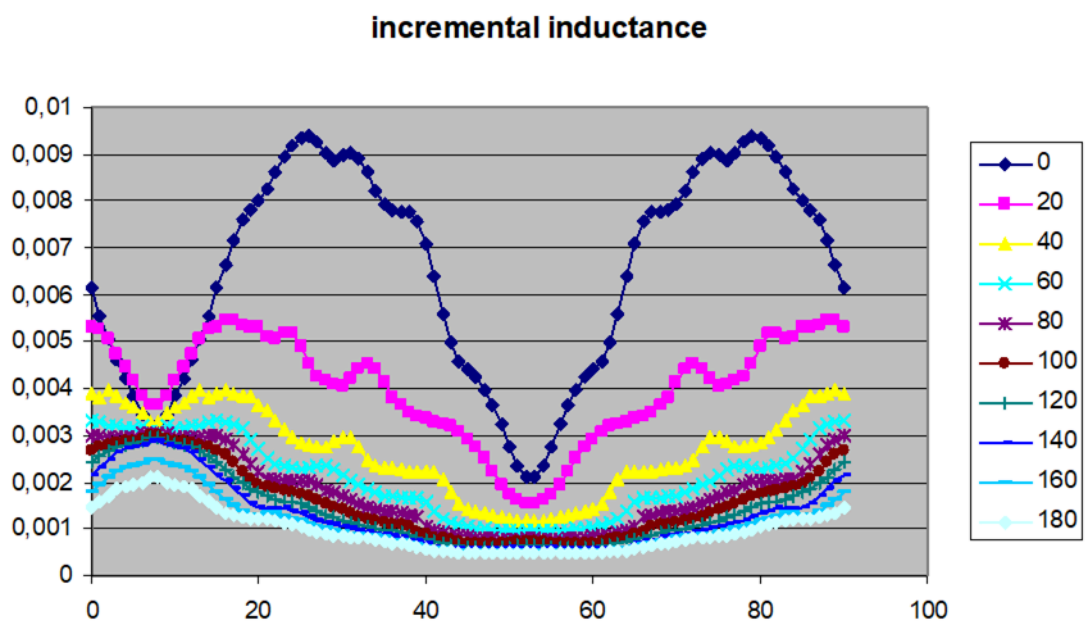
1. When the flux is at its maximum value for the zero current, it is corresponding to the direct axis position. It is corresponding to 52.5°.
2. When the flux is crossing the zero value for the zero current, it is corresponding to the quadrature axis position. It is corresponding to 30.0°.

7.3.5 Display incremental inductance versus position and current

Goal

The goal is to display a curve of the inductance versus position and current in the exported results (Excel table). The inductance is considered as the derivative of the flux versus the varying current (inductance = (flux_1-flux_2)/(I_1-I_2)).

Result

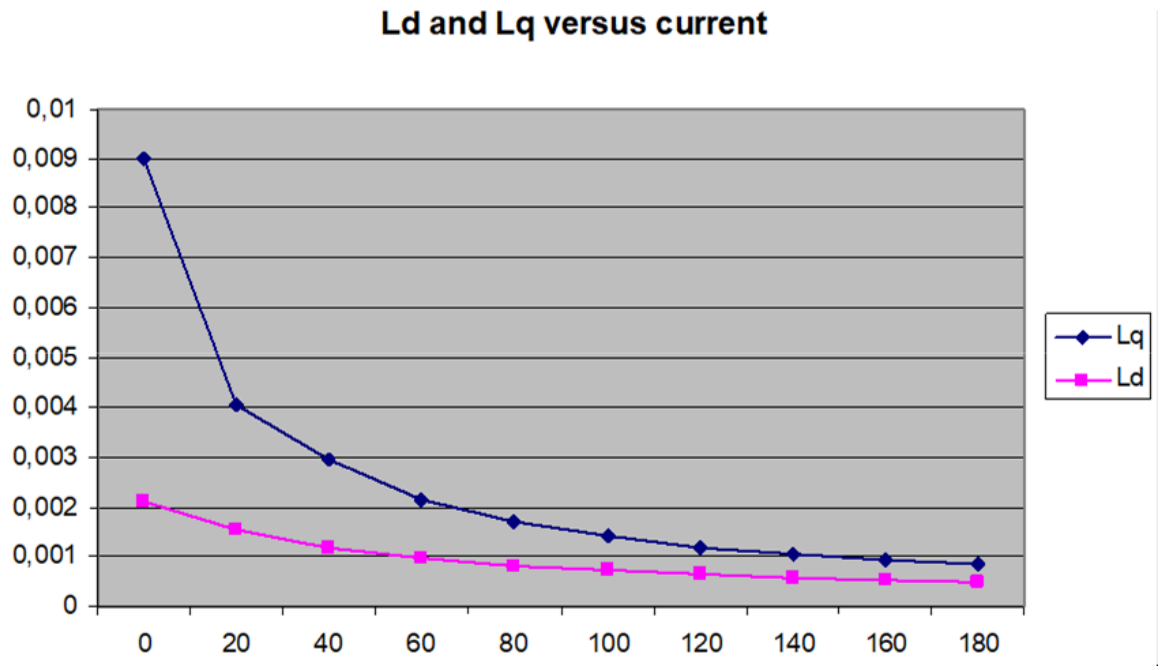


Note:

1. For the 30° position, and for the zero current, the inductance is equal to the quadrature inductance Lq, and is equal to 8.98mH.
2. For the 52.5° position, and for the the zero current, the inductance is equal to the direct inductance Ld, and is equal to 2.11 mH.
3. This result is given without the end turn inductance which is equal to 0.159E-3H.

Ld and Lq versus current

It is possible to display the direct and quadrature inductance versus current. The inductance is decreasing when the current is increasing due to saturation.


Ld and Lq versus current
0,01
0,009
0,008
0,007
0,006
0,005
0,004
0,003
0,002
0,001
0
0
20
40
60
80
100
120
140
160
180
Lq
Ld