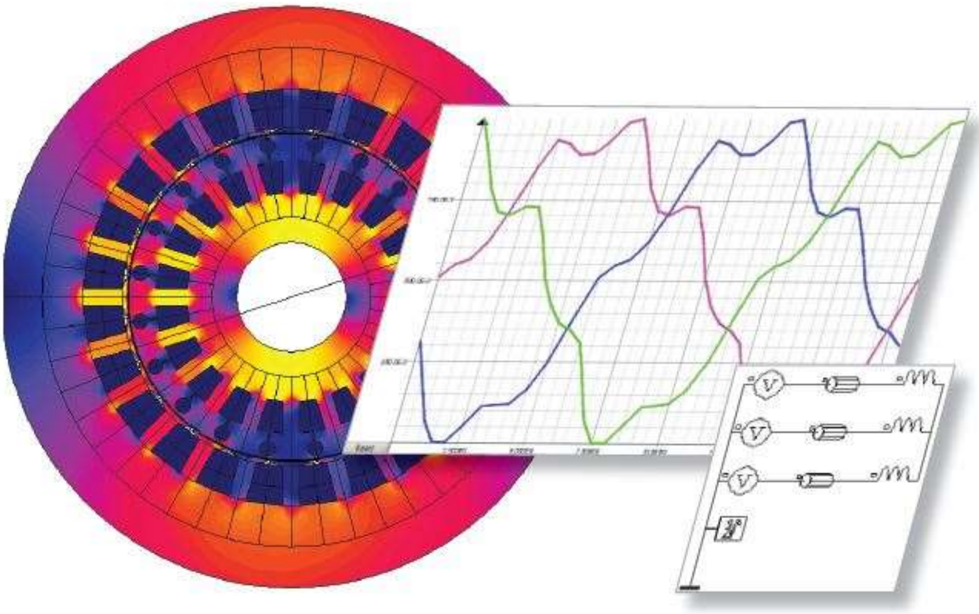
CAE package for electromagnetic and thermal analysis using finite elements

Altair® Flux®

Induction motor tutorial

2D technical example



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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 induction 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 “welcome interface” 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...

To view the completed phases of the example project, the user will find the .py files, including the geometry, physics and postprocessing descriptions. The .py files corresponding to the different study cases in this example are available in the folder:
…\DocExamples\Examples2D\Technical_InductionMotor_1\
Supplied files are command files written in Pyflux language. The user can launch them in order to automatically produce the Flux projects for each case.

***(.py files are launched by accessing **Project/Command file** from the Flux drop down menu.)*

Supplied files		Contents	.FLU file obtained after launching the .py file
CASE1	buildGeomesh.py	Geometry and mesh	Geomeshbuilt.FLU
	buildPhys.py	physics	BuiltPhys.FLU
	solving.py	Solving process	Solved.FLU
	postprocessing.py	Post processing	Postprocessed.FLU
CASE2	TestCase_INI.FLU	Initial Flux project	-
	solving.py	Solving process	Solved.FLU
	postprocessing.py	Post processing	Postprocessed.FLU
CASE3	TestCase_INI.FLU	Initial Flux project	-
	buildPhys.py	physics	BuiltPhys.FLU
	solving.py	Solving process	Solved.FLU
	postprocessing.py	Post processing	Postprocessed.FLU

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CASE4	TestCase_INI.FLU	Initial Flux project	-
	buildPhys.py	physics	BuiltPhys.FLU
	solving.py	Solving process	Solved.FLU
	postprocessing.py	Post processing	Postprocessed.FLU
CASE5	TestCase_INI.FLU	Initial Flux project	-
	buildPhys.py	physics	BuiltPhys.FLU
	solving.py	Solving process	Solved.FLU
	postprocessing.py	Post processing	Postprocessed.FLU

Note: Some directories may contain a main.py which enables command files launching.

Table of Contents

1. General information

Introduction

The goal of this technical tutorial is to demonstrate the ability and advantage of Flux in the simulation of induction motor computation problems.
This chapter presents the studied device, (an induction machine) and explains the strategies used for geometry construction and mesh generation.

Contents

This chapter contains the following topics:

1.1. Overview

Introduction

This section presents the studied device, an induction motor, and the strategy of the device description in Flux.

Contents

This section contains the following topics:

1.1.1. Description of the studied device

Foreword

This paragraph is a summary of cases treated in detail in the 2D example: "Induction motor technical paper".
The files relating to the studied cases are available in the documentation directory of the Flux DVD.

Studied device

The studied device is a 2-pole induction motor, 3-phase star connected, *Figure* 1-1, characterized by:

- rated-load power, P_n = 7.5 kW ;
- rated source voltage, U_{nf} = 380 V (phase to null value) ;
- rated source frequency, f_{1n} = 50 Hz .

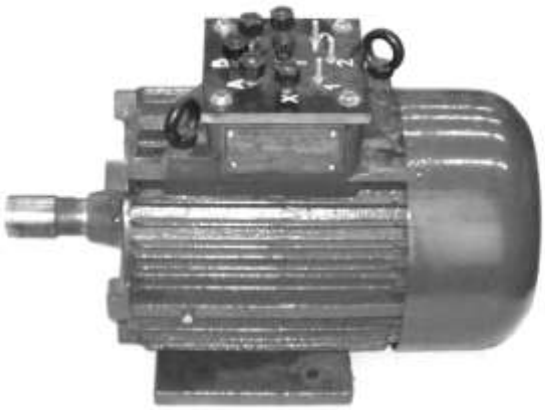

Figure 1-1: View of the induction motor to be modelled

Motor main characteristics

This motor has the following main characteristics:

- The stator armature has 24 slots,
- Figure 1-2, and the rotor armature has 20 slots.
- The outer diameter of the stator magnetic core is 212 mm.
- The inner diameter of the stator is 120 mm.
- The outer diameter of the rotor is 119 mm; the air-gap thickness is 0.5 mm.
- The inner diameter of the rotor magnetic core is 40 mm.
- The length of the stator and rotor magnetic cores is 125 mm.

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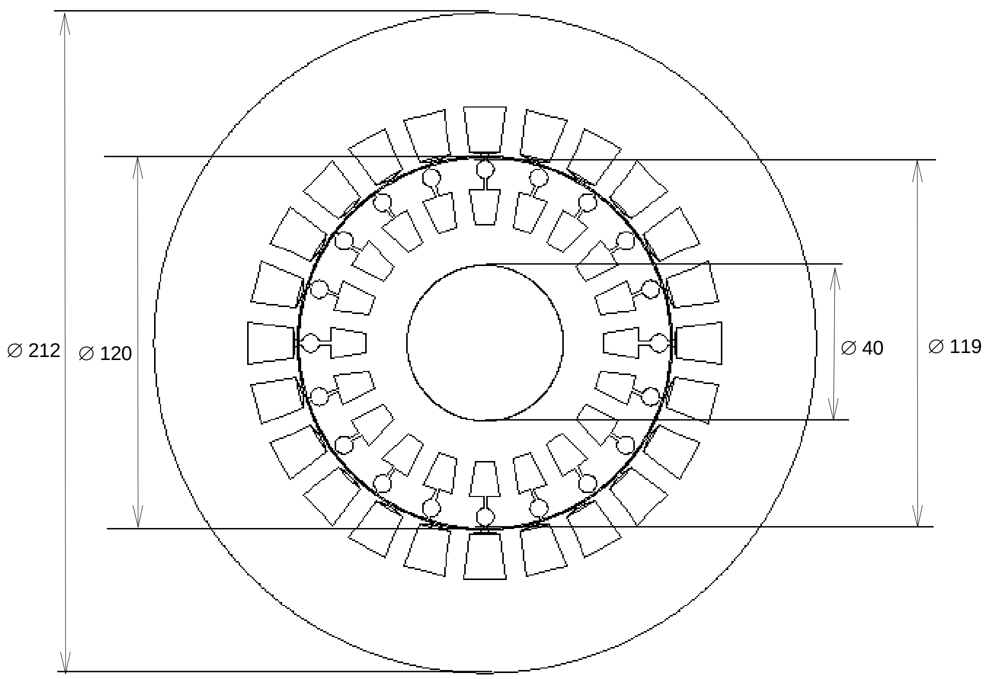

Figure 1-2: Cross-section of the stator and rotor armatures

The shape and dimensions of the stator and rotor slots are shown in Figure 1-3.

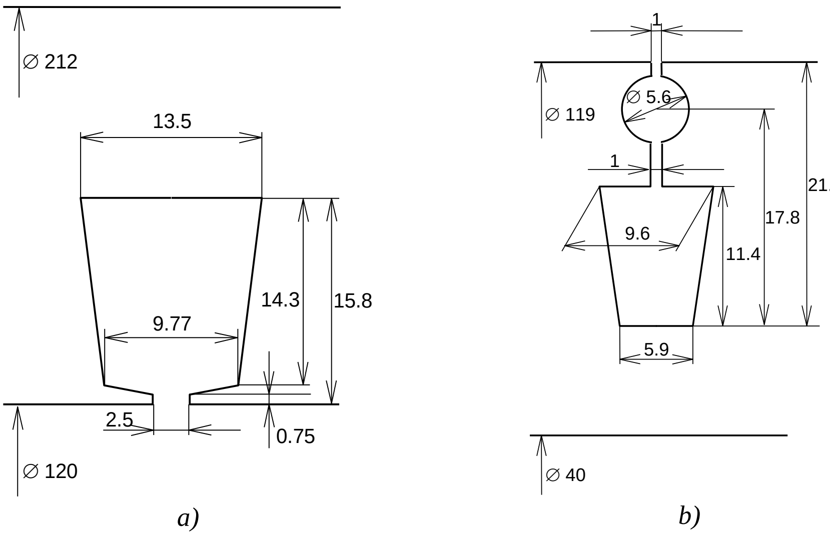

Figure 1-3: Slot dimensions
a) stator slot; b) rotor slot

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The stator winding is a two-layer copper winding, Figure 1-4, with shortened step of 8/12 and w_1 = 208 turns per phase as shown below.

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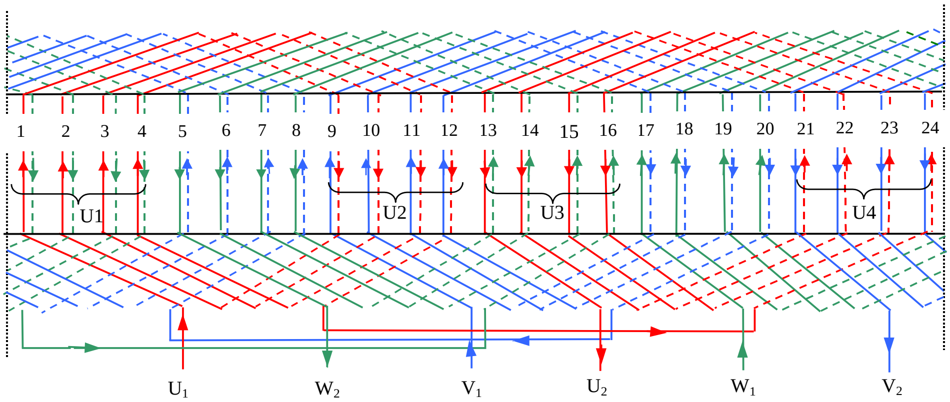


Figure 1-4: Stator winding

The rotor winding is a double squirrel cage and it is made of cast aluminum.

The magneto-harmonic simulations, the transient magnetic simulations for constant rotor speed and the DC braking simulation, consider the values of resistances corresponding to the rated temperature of the motor, 155 °C.

1.1.2. Studied cases

Studied cases

Five cases are carried out using Steady State Magnetic AC and Transient Magnetic applications:

- Case 1: Steady state study, to determine the rotor position.
- Case 2: Steady state study to compute the characteristics of the machine.
- Case 3: Steady state study, to compute the parameters for the equivalent circuit.
- Case 4: Transient study, to simulate the rated conditions.
- Case 5: Transient study, to simulate a single phase short circuit after rated conditions.

Case 1

The first case is a steady state magnetic AC study.

This study is a parameterized magneto-harmonic analysis at different values of rotor position in order to determine the position where torque is equal to average value.

Case 2

The second case is a steady state magnetic AC study.

This study is a parameterized magneto-harmonic analysis with values of rotor slip in order to evaluate the motor characteristics for rated load operation and display torque and current versus slip curves.

Case 3

The third case is a steady state magnetic AC study.

This simulation is a parametric analysis versus voltage in order to get no load current at locked rotor condition. With the previous case, at no load parameter value, it is possible then to obtain the parameters for the equivalent circuit of the machine

Case 4

The fourth case is a transient study.

This study is a transient simulation for rated load, initialized from a previous steady state computation at rated conditions obtained from case 2.

Case 5

The fifth case is a transient study.

The purpose of this simulation is to reproduce real working condition of the motor from the starting to the addition of the rated load and then applying a single phase fault in the stator windings, in order to display main quantities, like speed, torque, current, etc.

1.2. Strategy to build the Flux project

Introduction

This section presents outlines of the geometry building process and mesh generating process of the induction motor.

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 **IM** (**I**nduction **M**achine) **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?**

Contents

This section covers the following topics:

- 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, etc.)
- create the points and lines of the rotor and stator (slots, air-gap, etc.)
- build the faces
- mesh the device
- create the regions and assign to faces
- etc.

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

An **IM Motor** template is an **object** from the specific library:

- **IM** (**I**nduction **M**achine)

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

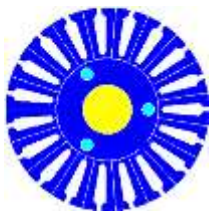
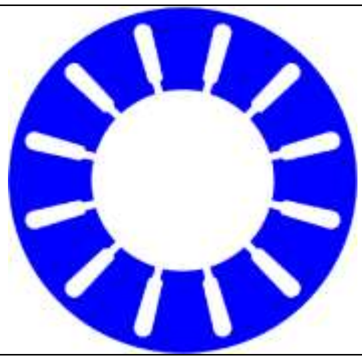
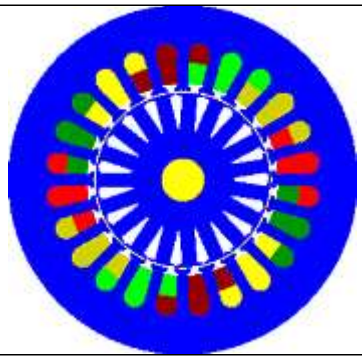
List of models

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
Single Cage	StatorAirGapWdg
Double Cage	StatorFlared
	StatorGH
	StatorGolfTee
	StatorHW
	StatorPllHW
	StatorPIIRound
	StatorPIISlot
	StatorPIISquare
	StatorPIISquareWedged
	StatorRound
	StatorSquare
	StatorVarDeth

Example

An example of motor template is presented in the figures below.

Rotor	Stator	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
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 an Induction Machine 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 …).

*The name of the parameters are the same in Speed and Flux

2. Geometry and mesh description of the motor

Geometry description	Mesh generation	Physic description	Solving process	Result post-processing

New Flux project

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

Contents

This chapter contains the following topics:

2.1. Load the IM overlay

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

Action (1) Close the sketcher context.

☞ **Project → Close Sketcher2D context** 

Action (2) Load the INDUCTION_MOTORS_V111.PFO overlay from the extension menu.

☞ **Extensions → Overlay → Load a certified overlay**

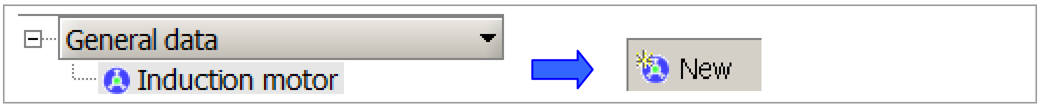
2.2. Create an induction motor using the overlay

Goal

The geometry of the motor is described using an overlay.

Action

From the data tree, create a **new** Induction motor.



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	Rotating air gap	Use periodicities
0.5	without eccentricity	2_layers_airgap	yes

Data (2)

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

Rotor description

General description

Rotor external radius	Number of poles	Shaft radius	Rotor shift angle
59.5	2	20.0	0.0

Cooling holes

Without cooling holes

Cage: single cage

Bar shape description: type 4b

Width of rotor slot opening	Depth of rotor slot opening	Diameter of rotor bars	Neck width	Tooth width	Depth of the rotor bar	Neck height
1.0	0.9	5.6	1.0	6.0	11.4	3.6

Number of bars

20

Continued on next page

Data (3) The characteristics of the stator are presented in the tables below.

Stator description

Slot shape description : Stator HW

General description

Stator tooth height (h1s)	Stator tooth width (w1s)	Stator tooth height (h2s)	Stator tooth width (w2s)	Stator tooth height (h3s)	Stator tooth width (w3s)	FILSO
0.75	2.5	0.75	9.77	14.3	13.5	0

Slot bottom description

Slot bottom form	Slot bottom fillet radius (FILSB)
Square	0

General description

Number of slots	Stator configuration	LamShape	Stator outer radius	Stator angle
24	normal	circle	106	0.0

Data (4) The characteristics of the winding are presented in the tables below.

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	8	4	superimposed

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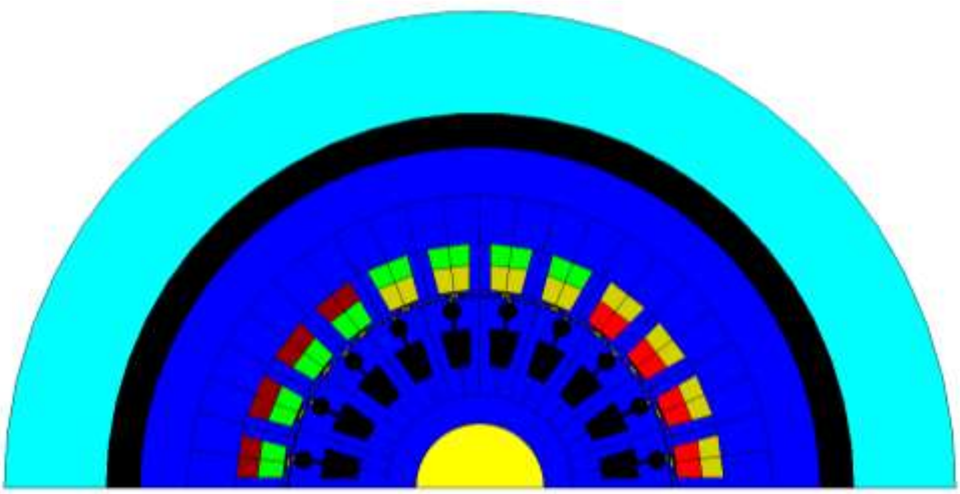
Result

The following motor is created with:
- Part of the geometry
- Part of the physics
- Ready to be meshed



Action

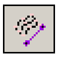
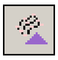
Leave the overlay context.

☞ 

2.3. Mesh the device

Action (1) Mesh the device

☞

Mesh → Mesh lines	
Mesh → Mesh faces	

Action (2) Save the project as GEOMESH.FLU.

☞

Project → Save as	

---

3. Case 1: Determination of initial rotor position

Case 1

The Flux2D magneto-harmonic simulations of the induction machine are performed for constant slip values (constant rotor speed values) and are problems that do not consider the rotor motion with respect to the stator. The current frequency in the rotor circuit is set at s·f, where f is the motor supply frequency.
Because the stator and rotor armatures are slotted, the results of magneto-harmonic simulations depend on the relative rotor-stator position. Thus we have to determine the rotor-stator relative position for which the electromagnetic torque is equal to the average value over a cycle of electromagnetic torque variation, when the position of the rotor changes with respect to the stator. This relative position that we consider as "initial position" of the rotor for magneto-harmonic simulations is calculated with respect to the rotor position used in geometry construction.

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.**

Contents

This chapter contains the following topics:

3.1. Case 1: Physical description

Geometry description	Mesh generation	**Physic description**	Solving process	Result post-processing

---

Introduction

This section presents the definition of the physical properties – materials and regions of the model.

Contents

This section contains the following topics:

3.1.1. Define the physical application

Goal The physical application is defined. The required physical application is the Steady State AC Magnetic 2D application.

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

Steady State AC Magnetic 2D application			
Definition			Coils Coefficient
Frequency [Hz]	2D domain type	Depth of the domain [mm]	
50	2D Plane	125	Automatic coefficient

☞ **Application → Define → Magnetic → Steady State AC Magnetic 2D**

3.1.2. Create materials

Goal

The creation of “material” entities enables the user to assign physical material properties to face regions.

Data

The following materials are used in this case :

B(H) Isotropic spline saturation		
Name	**Field value ($A.m^{-1}$)**	**Flux density value (T)**
STEEL_NLIN	0	0
	300	0.66
	500	1.09
	1000	1.45
	1500	1.56
	2000	1.61
	3000	1.69
	4000	1.73
	5000	1.76
	6000	1.79
	7000	1.83
	8000	1.85
	10000	1.89
	20000	2.04
	30000	2.11
	40000	2.14
	50000	2.16
	60000	2.18
	70000	2.1925

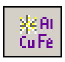
Type of equivalent B(H) curve: Sine wave flux density

B(H) linear isotropic

Name	**Relative permeability**
ALU_HOT	1

J(E) magnet with electrical properties

Name	**Isotropic resistivity**
ALU_HOT	4.8E-8

☞ **Physics → Material → New** 

3.1.3. Create I/O Parameters

Goal One I/O parameter will be created to define the slip

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

I/O parameters controlled via scenario	
Name	**Reference value**
SLIP	0.01

☞ **Parameter/Quantity→ I/O parameter → New**

3.1.4. 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 mechanical set ROTOR are presented in the table below:

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

Kinematics	
Type of kinematics	Optional value for slip
Multistatic	SLIP

☞ Physics → Mechanical set → New

Data (2)

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

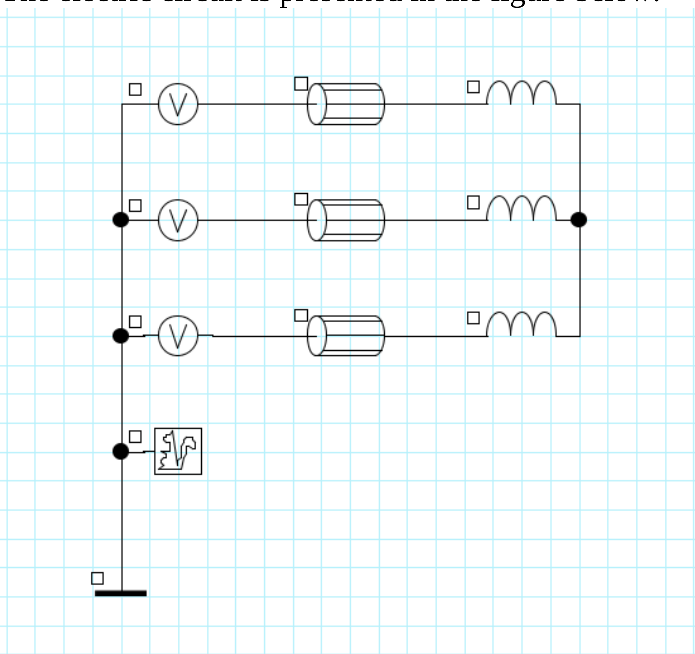
Name	Type of Mechanical set
STATOR	Fixed

☞ Physics → Mechanical set → New

3.1.5. Create a circuit

Goal The goal is to define a circuit for this project.

Data (1) The electric circuit is presented in the figure below.



☞ Physics → Circuit → Circuit editor context

Action Close the circuit editor context.

☞ Project → Return to standard geometry context

3.1.6. Modify a circuit

Goal

The circuit is modified in order to describe the physics.

Data (1)

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

Name of Stranded coil component	Resistance
B1, B2, B3	1.54 Ω

☞ Physics → Electrical components → Stranded coil conductor → Edit

Data (2)

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

Components	Values
L1, L2, L3	4.04 mH

☞ Physics → Electrical components → Inductor → Edit

Data (3)

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

Components	RMS value	Phase
V1	380 V	0º
V2	380 V	-120º
V3	380 V	120º

☞ Physics → Electrical components → Voltage source → Edit

Data (4)

The characteristics of the squirrel cage are described in the table below.

Components	Number of bars	R end ring	L end ring
SQUIRRELCAGE_1	10	1.39E-6 Ω	1.06E-8 H

☞ Physics → Electrical components → Squirrel cage → Edit

3.1.7. Modify face regions

Goal Two 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 of region	**Type of region**	**Material of region**	**Mechanical set**
STATOR	Magnetic non conducting region	STEEL_NLIN	STATOR
ROTOR	Magnetic non conducting region	STEEL_NLIN	ROTOR

☞ **Physics → Face region → Edit**

3.1.8. Modify face regions

Goal Eight 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 of region	**Type of region**	**Mechanical set**
INFINITE	Air or vacuum region	STATOR
PRESLOT	Air or vacuum region	STATOR
ROTATING_AIRGAP	Air or vacuum region	STATOR
ROTOR_AIR	Air or vacuum region	ROTOR
ROTOR_PRESLOT	Air or vacuum region	ROTOR
SHAFT	Air or vacuum region	ROTOR
STATOR_AIR	Air or vacuum region	STATOR
WEDGE	Air or vacuum region	STATOR

☞ **Physics→ Face Region → Edit** 

3.1.9. Modify face regions

Goal Four 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 of region	**Type of region**	**Region Compo nent**	**Number of Turns**	**Orientation**	**Series or parallel**	**Mechanical set**
PHASE_NEG_1	Coil conductor region	B1	104	Negative	series	STATOR
PHASE_NEG_3	Coil conductor region	B3	208	Negative	series	STATOR
PHASE_POS_1	Coil conductor region	B1	104	Positive	series	STATOR
PHASE_POS_2	Coil conductor region	B2	208	Positive	series	STATOR

☞ **Physics→ Face Region → Edit**

3.1.10. Modify face regions

Goal Ten 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 of the region	**Type of region**	**Material of region**	**Type of conductor**	**Associated solid conductor**	**Mechanical set**
ROTOR_CAGE1_BAR1	Solid conductor region	ALU_HOT	Circuit	BAR_1	ROTOR
ROTOR_CAGE1_BAR2	Solid conductor region	ALU_HOT	Circuit	BAR_2	ROTOR
ROTOR_CAGE1_BAR3	Solid conductor region	ALU_HOT	Circuit	BAR_3	ROTOR
ROTOR_CAGE1_BAR4	Solid conductor region	ALU_HOT	Circuit	BAR_4	ROTOR
ROTOR_CAGE1_BAR5	Solid conductor region	ALU_HOT	Circuit	BAR_5	ROTOR
ROTOR_CAGE1_BAR6	Solid conductor region	ALU_HOT	Circuit	BAR_6	ROTOR
ROTOR_CAGE1_BAR7	Solid conductor region	ALU_HOT	Circuit	BAR_7	ROTOR
ROTOR_CAGE1_BAR8	Solid conductor region	ALU_HOT	Circuit	BAR_8	ROTOR
ROTOR_CAGE1_BAR9	Solid conductor region	ALU_HOT	Circuit	BAR_9	ROTOR
ROTOR_CAGE1_BAR10	Solid conductor region	ALU_HOT	Circuit	BAR_10	ROTOR

☞ Physics→ Face Region → Edit

Action Check physics and save case 1.

☞ Physics → Check Physics

☞ Save Case1

3.2. Case 1: Solve the project

Geometry description	Mesh generation	Physic description	**Solving process**	Result post-processing

Goal

A solving scenario is created in order to solve CASE1. Then CASE1 is solved.

Data

The characteristics of the solving scenario used to solve the CASE1 are presented in the tables below:

Solving scenario

Name	Comment	Type
INITIAL_POSITION	Study using geometrical and physical parameter	multi-values

<table>
<tr><th colspan="6">Solving scenario</th></tr>
<tr><td colspan="6"></td></tr>
<tr><th colspan="6">Parameter control</th></tr>
<tr><th rowspan="2">Controlled parameter</th><th rowspan="2">Type</th><th colspan="4">Interval</th></tr>
<tr><th>Lower limit</th><th>Higher limit</th><th>Method</th><th>Step value</th></tr>
<tr><td>ANGPOS_ROTOR</td><td>Multi-values</td><td>0</td><td>18</td><td>Step value</td><td>0.5</td></tr>
</table>

☞ Solving → Solving scenario → New

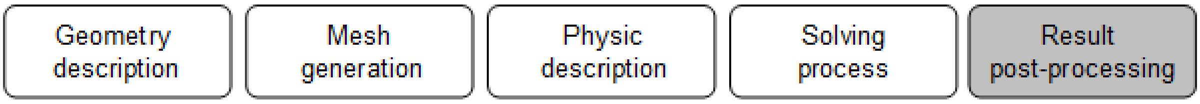
Action

Solve and save the project under the following conditions:

- Solve with: solving scenario INITIAL_POSITION
- Project name: CASE1_SOLVED

☞ Solving → Solve

3.3. Case 1: Results post-processing



Introduction

This section explains how to analyze the principal results of CASE 1.

Contents

This section contains the following topics:

3.3.1. 2D Curve of the electromagnetic torque

Goal The values of the electromagnetic torque versus the angular position of the rotor are computed and displayed in a curve

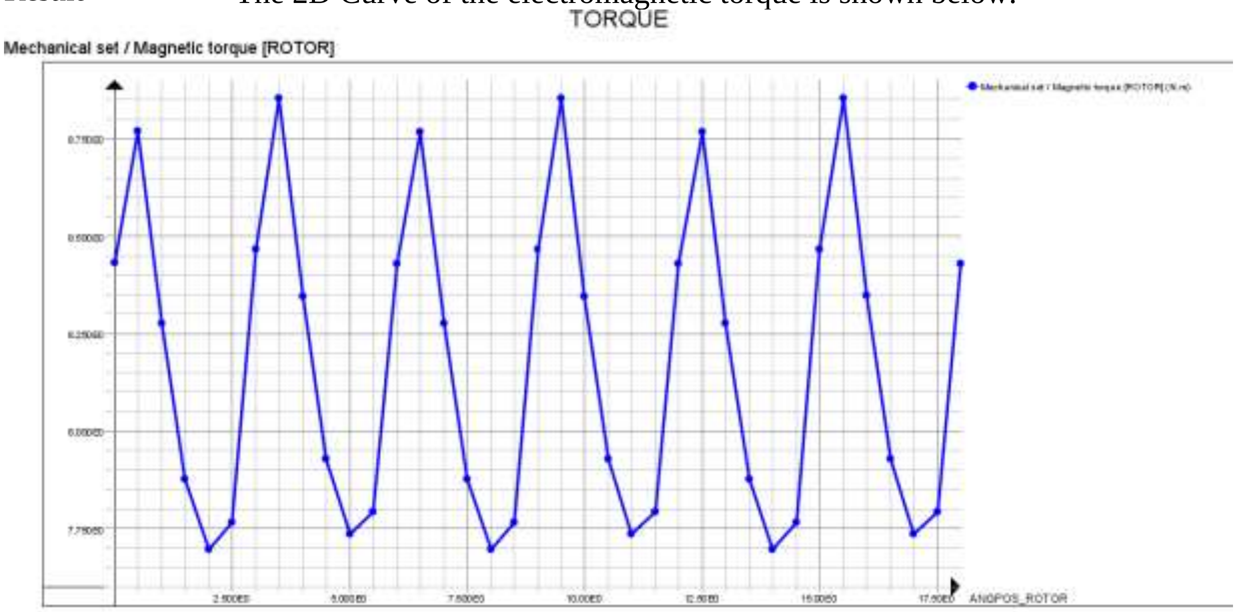
---

Data The characteristics of the curve are presented below.

2D curve (I/O parameter)							
Name	I/O Parameter on the abscissa			Formula on the ordinate		Mechanical set	
	Parameter name	Lower endpoint	Upper endpoint	Mech. set	Quantity	*Formula*	
TORQUE	ANG_POS_ROTOR	0	18	ROTOR	Electromagnetic torque	TorqueElecMag (ROTOR)	

☞ Curve → 2D Curve (I/O parameter)→ New 2D Curve (I/O parameter)

Result The 2D Curve of the electromagnetic torque is shown below.



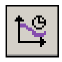
Note The torque is ranging from 7.69 N.m to 8.85 N.m due to slot effect. The average value of torque is 8.16 Nm, and this value is corresponding to a rotor position of 1.143°. This value will be used in order to directly compute the average torque with the torque menu.

3.3.2. 2D Curve of the currents

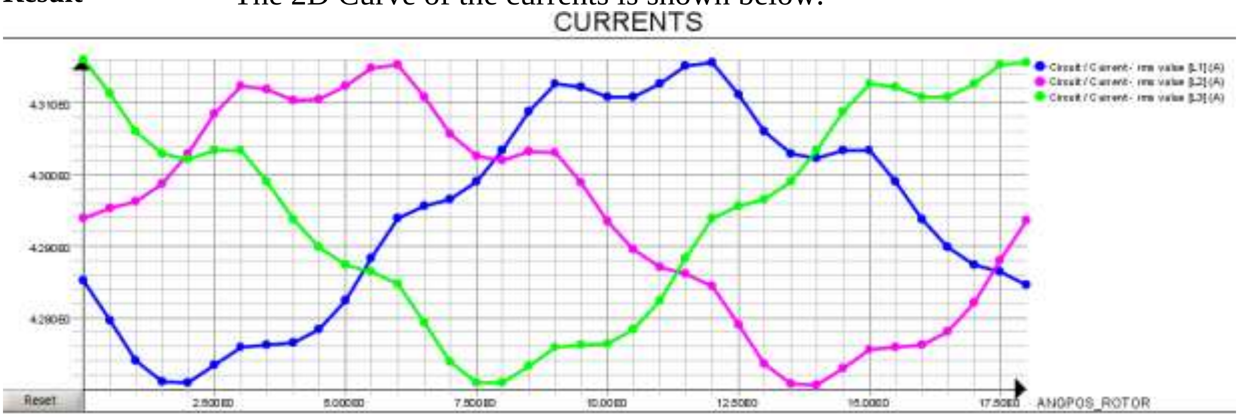
Goal The values of the current versus the angular position of the rotor are computed and displayed in a curve

Data The characteristics of the curve are presented below.

2D curve (I/O parameter)						
Name	**I/O Parameter on the abscissa**			**Formula on the ordinate** Circuit		
	Parameter name	**Lower endpoint**	**Upper endpoint**	**Electrical component**	**Quantity**	***Formula***
CURRENTS	ANG_POS _ROTOR	0	18	L1	Current - rms value [A]	*Mod(I(L1))/sqrt(2)*
				L2	Current - rms value [A]	*Mod(I(L2))/sqrt(2)*
				L3	Current - rms value [A]	*Mod(I(L3))/sqrt(2)*

☞ **Curve → 2D Curve (I/O parameter)→ New 2D Curve (I/O parameter)** 

Result The 2D Curve of the currents is shown below.



4. Case 2: Full characteristics versus slip

Case 2

The goal of this simulation is to obtain the main quantities of the machine as function of the slip. Results will be shown as 2D plots with the slip as a varying parameter. The rotor will be lined up with the average value of the torque (1.143°).

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

Contents

This chapter contains the following topics:

4.1. Case 2: Solve the project

Geometry description	Mesh generation	Physic description	**Solving process**	Result post-processing

Goal

A solving scenario is created in order to solve CASE2.

Data

The characteristics of the solving scenario used to solve the CASE 2 are presented in the tables below:

Name	Comment
CHARACTERISTICS	Study using geometrical and physical parameter

<table>
<tr><th colspan="6">Solving scenario</th></tr>
<tr><td colspan="6"></td></tr>
<tr><th colspan="6">Parameter control</th></tr>
<tr><th rowspan="2">Controlled parameter</th><th rowspan="2">Type</th><th colspan="4">Interval</th></tr>
<tr><th>Lower limit</th><th>Higher limit</th><th>Variation Method</th><th>Step value</th></tr>
<tr><td>ANGPOS_ROTOR</td><td>Mono -value</td><td colspan="4">1.143</td></tr>
<tr><td rowspan="3">SLIP</td><td rowspan="3">Multi-values</td><td>0.001</td><td>0.010</td><td>List of steps</td><td>0.001, 0.010</td></tr>
<tr><td>0.01</td><td>0.05</td><td>Step value</td><td>0.002</td></tr>
<tr><td>0.05</td><td>1.0</td><td>List of steps</td><td>0.05, 0.07, 0.09, 0.12, 0.15, 0.18, 0.20, 0.22, 0.25, 0.30, 0.40, 0.60, 0.80, 1.0</td></tr>
</table>

☞ Solving → Solving scenario → New

Action

Solve and save the project under the following conditions:

- Solve with: solving scenario CHARACTERISTICS
- Project name: CASE2_SOLVED

☞ Solving → Solve

4.2. Case 2: Results post-processing

Geometry description | Mesh generation | Physic description | Solving process | **Result post-processing**

Introduction This section explains how to analyze the principal results of CASE 2.

Contents This section contains the following topics:

4.2.1. Load and run a macro to calculate the iron losses

Goal

Load and run a macro in order to calculate iron losses with Bertotti model, for each value of the variation parameter SLIP of the considered scenario.
At the end, this macro create an I/O parameter "BertottiLosses" which can be used to make a power balance.

Action (1)

Load macro named **BertottiIronLossesVsSlipAcIm.PFM** (in "Macros_Flux2D_Postproc" directory) in the current project.

☞ **Extension → Macro → Load**

Action (2)

Run the macro.

☞ **Extension → Macro → Run**

Data (1)

The computation of magnetic losses based on the flux density chart uses the following characteristics of laminations:

- Hysteresis loss coefficient kh = 306.5 Ws/T^2m^3
- classical losses coefficient σ = 4500000 $\Omega^{-1}m^{-1}$
- loss in excess coefficient k_e = 0.61 $Ws^{1.5}/m^3/T^{1.5}$
- thickness of laminations d = 0.5 mm
- Stacking factor k_f = 0.98.

These data correspond to the value p10 = 2.8 W/kg of the magnetic losses for 1 T and 50 Hz.

Data (2)

The characteristics of the macro are presented below.

BertottiIronLossesVsSlipAcIm.PFM

Scenario	Variation parameter	Face region	Hysteresis loss coeff	Classical loss coeff	Loss in excess coeff	Thickness of steel iron	Fill factor
CHARACTERISTICS	SLIP	STATOR	306.5	4500000	0.61	5.0e-4	0.98

4.2.2. Create a sensor

Goal Create a sensor to calculate the stator joules losses in stator winding.

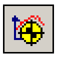
Data The characteristics of the sensor are presented in the table below :

Predefined sensor (Energy, Force, Torque): Losses by Joule Effect

Name	Comment	Stranded coil conductor
PJS	Stator joule losses	{B1, B2, B3}

☞ Advanced → Sensor → New 

Action Evaluate the sensor.

☞ Advanced → Sensor → Evaluate sensors 

4.2.3. Create I/O Parameters

Goal

Create some I/O parameter to help the user to carry out a power balance as a function of the rotor slip.

Data

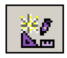
The characteristics of the I/O parameter defined by a formula are described in the table below.

I/O parameters defined by a formula

Name	Comment	Expression
PA	Absorbed power	-PowerP(V1)-PowerP(V2)-PowerP(V3)
PTR	Power transmitted to the rotor	PA-PJS
PU	Shaft power	(1-SLIP)*PTR
EFFY	Efficiency	(PU/(PA+(2*BERTOTTI_LOSSES)))*100

To create **PA** parameter, write the formula directly in the **Expression** area.
See the note below.

Parameter/Quantity→ I/O parameter → New



About PowerP function

Function **PowerP** is postprocessing function; this function is available via the command **Compute on Physic entity**, but this function is not directly available via the command **Parameter I/O / New**.

To create the **PA** parameter, the user can proceed in different ways:

- Write the formula directly in the **Expression** area as described above
- Recover the python command in the **buildPhys.py** file (included with examples)
  ```
  VariationParameterFormula
  (name='PA',formula='-PowerP(V1)-PowerP(V2)-PowerP(V3)')
  ```
- Write the complete formula (with using the formula editor) with the following information (in the user guide)

Usual global quantities (Electric component) in SSACM	Flux name	Flux unit	Explanation
Voltage (magnitude)	U	V	
Current (magnitude)	I	A	
Active power	PowerP	W	$Power\,P = Real\left(\frac{1}{2}U \cdot I^*\right)$

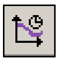
```
PA =-PowerP(V1)-PowerP(V2)-PowerP(V3)
PA =- Real(U(B1)*Conj(I(B1)/2))
     - Real(U(B2)*Conj(I(B2)/2))
     - Real(U(B3)*Conj(I(B3))/2)
```

4.2.4. 2D Curve of the power balance

Goal The values of the power balance versus the rotor slip are computed and displayed in a curve

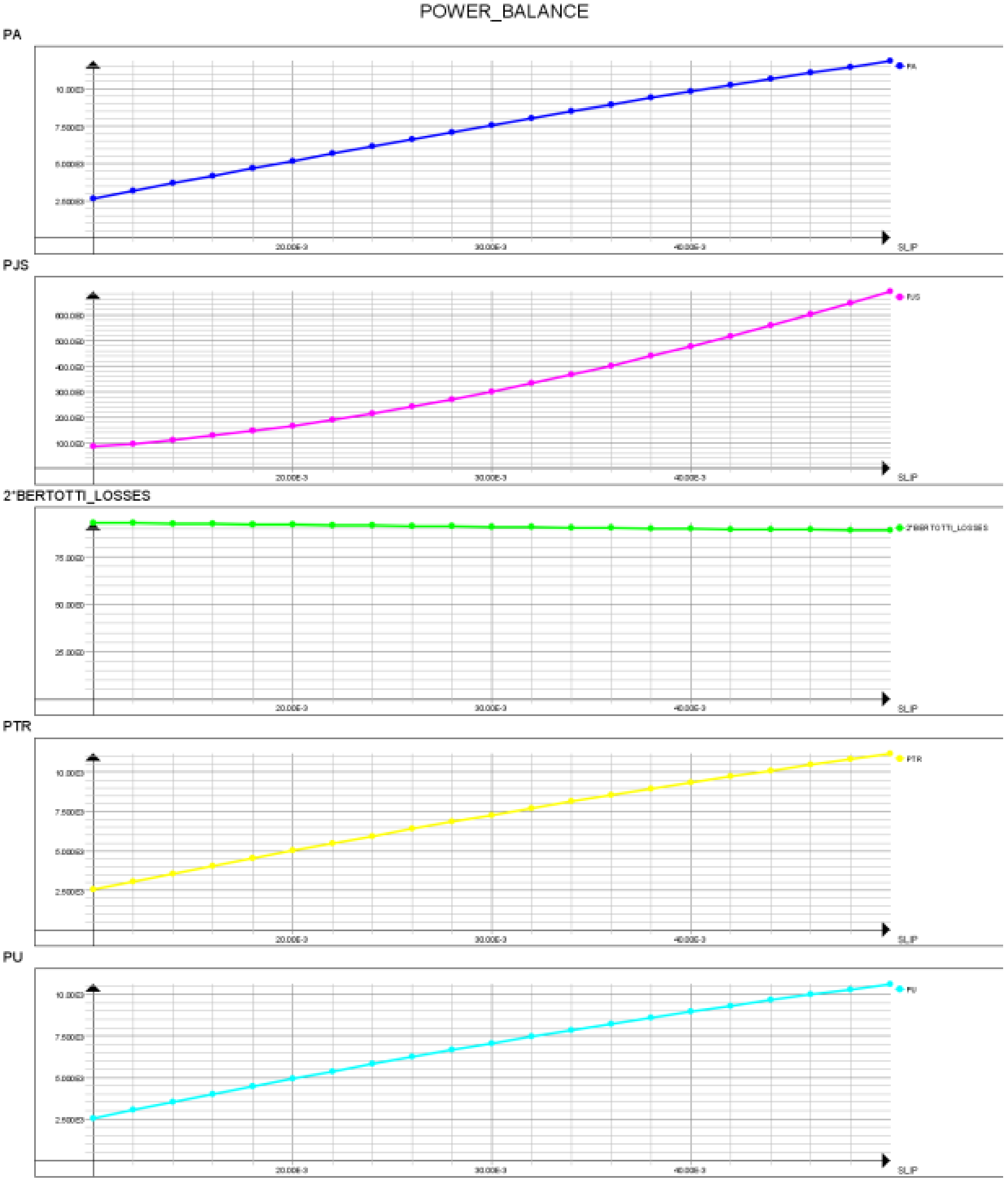
Data The characteristics of the curve are presented below.

<table>
<tr><th colspan="5">2D curve (I/O parameter)</th></tr>
<tr><td colspan="5"></td></tr>
<tr><th rowspan="2">Name</th><th colspan="3">I/O Parameter on the abscissa</th><th>Formula</th></tr>
<tr><th>Parameter name</th><th>Lower endpoint</th><th>Upper endpoint</th><th>f()</th></tr>
<tr><td rowspan="5">POWER_BALANCE</td><td rowspan="5">SLIP</td><td rowspan="5">0.01</td><td rowspan="5">0.05</td><td>PA</td></tr>
<tr><td>PJS</td></tr>
<tr><td>2*BERTOTTI_LOSSES</td></tr>
<tr><td>PTR</td></tr>
<tr><td>PU</td></tr>
</table>

☞ **Curve → 2D Curve (I/O parameter)→ New 2D Curve (I/O parameter)** 

Result

The 2D Curve of the power balance is shown below.



From the curve Pu(s), we obtain the rated slip value sn = 0.032 corresponding to the output power equal with the motor rated power Pn**.**

4.2.5. 2D Curve of the efficiency

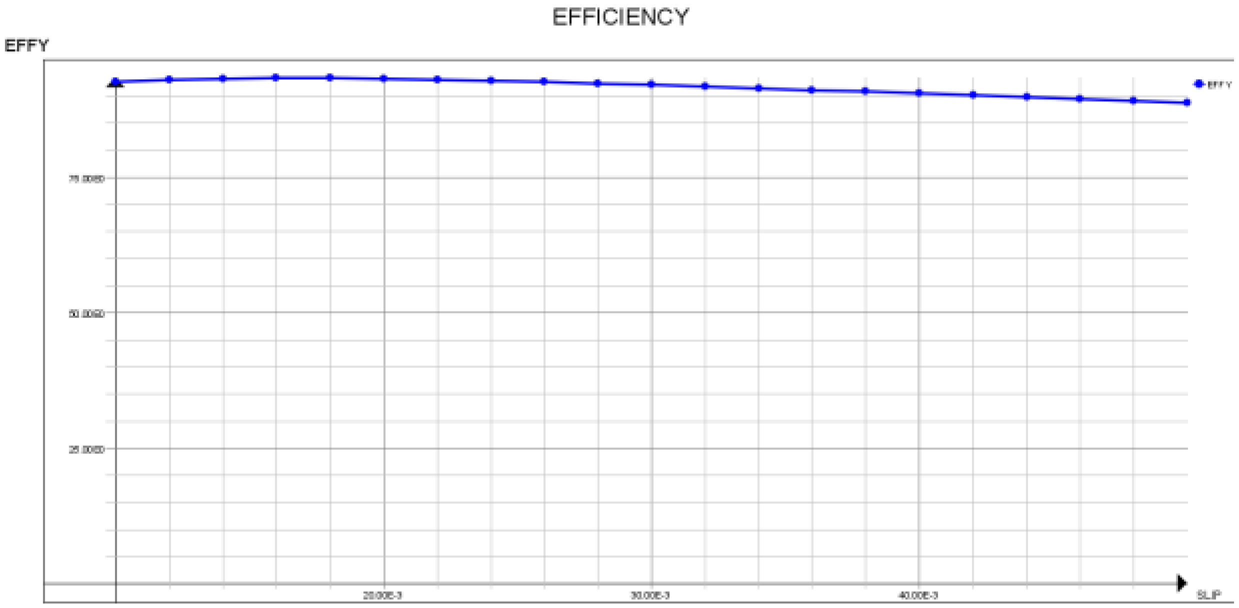
Goal The values of the efficiency versus rotor slip are computed and displayed in a curve

Data The characteristics of the curve are presented below.

2D curve (I/O parameter)				
Curve Name	**I/O Parameter on the abscissa**			**Formula**
	Parameter name	**Lower endpoint**	**Upper endpoint**	f()
EFFICIENCY	SLIP	0.01	0.05	EFFY

☞ **Curve → 2D Curve (I/O parameter)→ New 2D Curve (I/O parameter)**

Result The 2D Curve of the efficiency is shown below.



4.2.6. Compute efficiency

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

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

Physical quantities	values
Input electrical power	8041.4 W
Joule losses in stator winding	332.6 W
Core loss (Bertotti)	90.63 W
Power transmitted to the rotor	8041.4 - 332.6 = 7708.8 W
Output mechanical power	(1-0.032)*7708.8 = 7462.1 W
Efficiency : $\frac{Pu}{Pa + PFe}$	91.76 %

4.2.7. Steady state rated-load characteristics

Goal Characteristics of the motor for steady state rated-load operation

Data The characteristics of the motor for steady state rated-load operation are presented in the table below:

Steady state rated-load characteristics							
sn	**Nn [rpm]**	**I1n [A]**	**Men [Nm]**	**Mn [Nm]**	**Pu [W]**	**Pjs [W]**	**Cos ϕn**
0.032	2904	8.48	24.13	24.54	7462.1	332.6	0.834

Where :

- Nn is the speed corresponding to the nominal slip (input data)
- Men is determined from predefined Flux menu
- Mn is defined by $Mn = \frac{Pn}{\omega} = \frac{Pn}{2\pi f_{1n}}$
- Cos ϕn is the phase of the current in phase1

4.2.8. Display isolines

Goal

Select the step of the scenario corresponding to rated-load motor steady state operation (s = 0.032). Then, the isolines of the vector potential is computed on the device and isolines are displayed.

Data

The characteristics of the step selected are presented in the table below.

Scenario and step selection		
Scenario	**Computation step**	
CHARACTERISTICS	SLIP	0.032
	ANGPOS_ROTOR	1.143

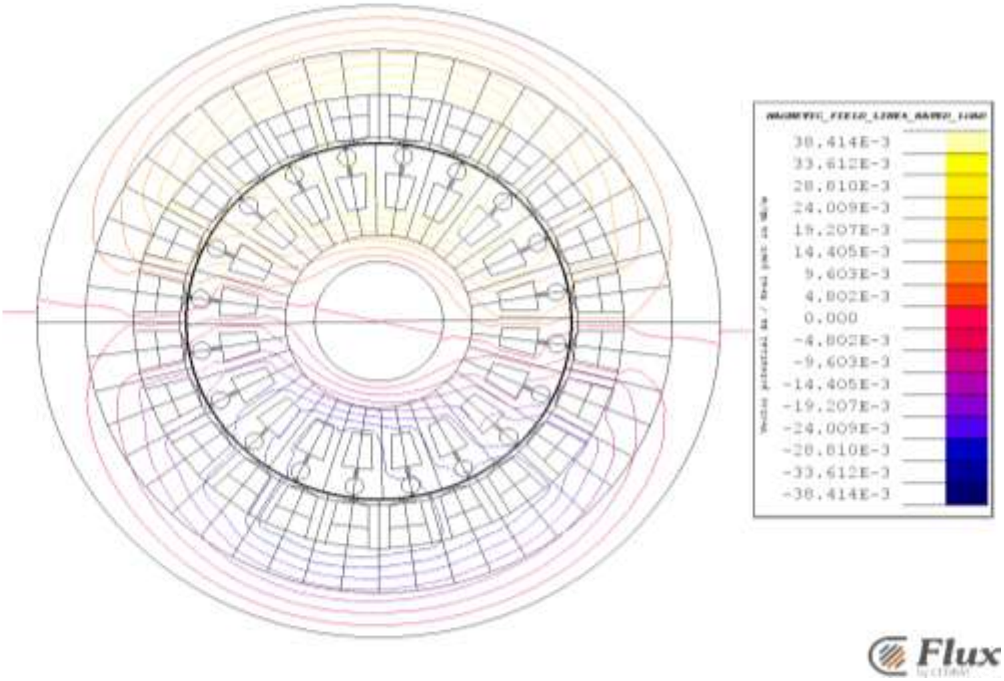
Action

Display isolines (1_ISOLIN_DOMAIN)

☞ **Graphic → Isolines → Display Isolines**

Result

The following chart shows the isolines of the vector potential (An) on the device (slip = 0.032).



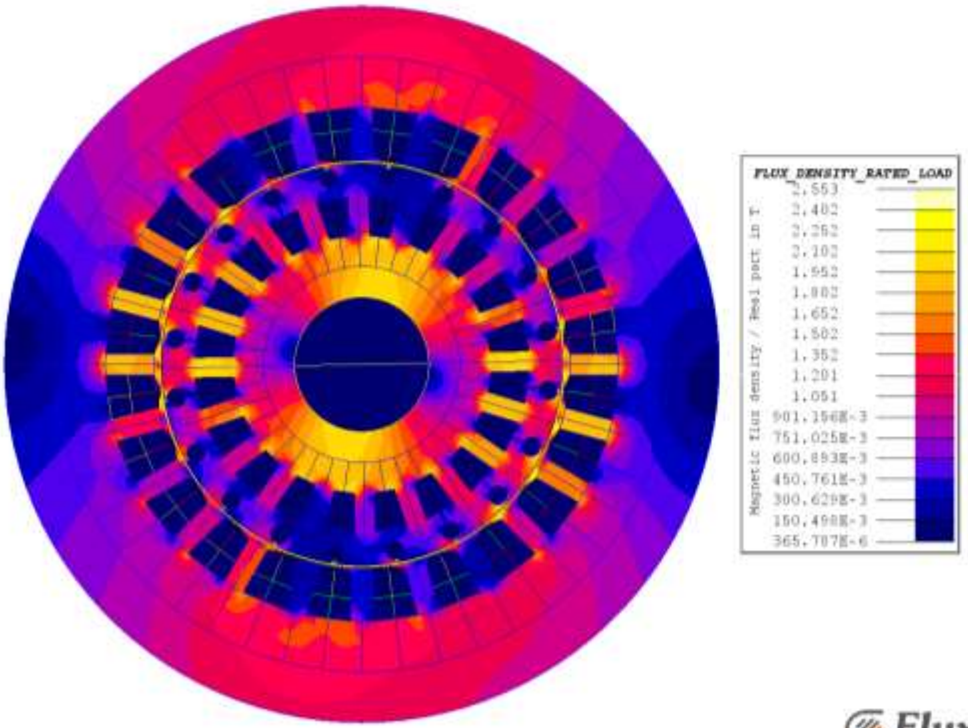
4.2.9. Display isovalues

Goal The magnetic flux density is computed on the device (excluding vacuum regions) and isovalues are displayed in color shadings.

Action Display isovalues (2_ISOVAL_NO_VACUUM)

☞ **Graphic → Isovalues → Display Isovalues**

Result The following chart shows the isovalues of the magnetic flux density on the device (s=0.032)



4.2.10. Display isovalues

Goal

Compute and display isovalues of the current density in rotor bars.

Data (1)

The characteristics of the new spatial group are presented below.

Spatial Group

Name	Comment	Spatial group	
		Type	Face regions
GROUP_ROTOR_CAGE1_BAR	Spatial group	Face region	ROTOR_CAGE1_BAR1
			…
			ROTOR_CAGE1_BAR10

☞ Support → Spatial group → New

Data (2)

The characteristics of the isovalues are presented below.

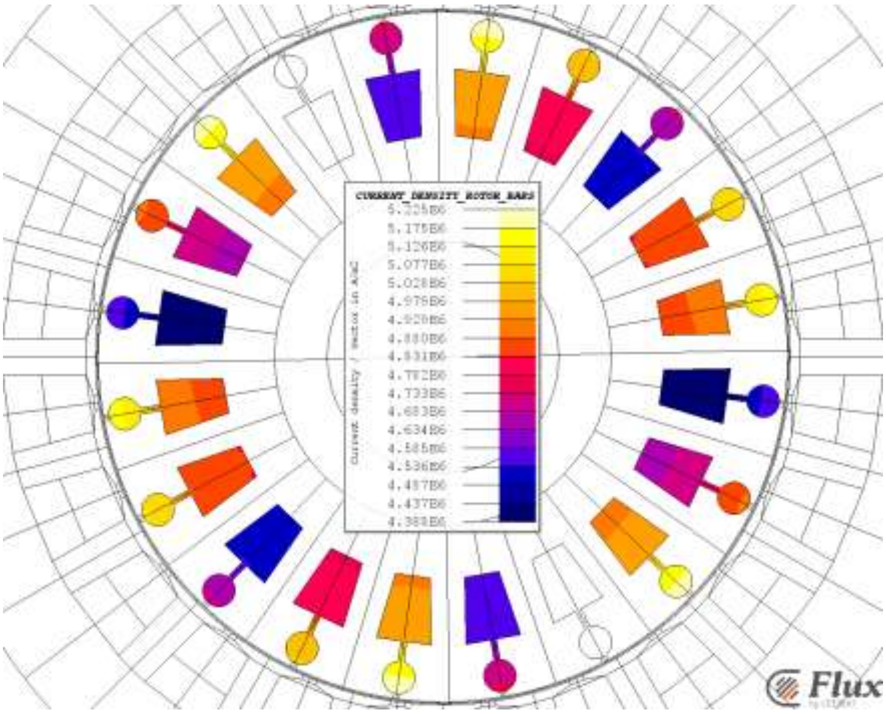
Isovalues on face regions

Name	Support for isovalues		Quantity	
	Support	Groups	Quantity	Formula
ISOVAL_I_BAR	Spatial group	GROUP_ROTOR_CAGE1_BAR	Current density – Vector [A/m2]	J

☞ Graphic → Isovalues → New	

Result

The following chart shows the isovalues of the current density on the bars for rated-load operation (s = 0.032).



4.2.11. 2D Curve of the electromagnetic torque

Goal The values of the electromagnetic torque versus rotor slip are computed and displayed in a curve

Data The characteristics of the curve are presented below.

2D curve (I/O parameter)						
Name	**I/O Parameter on the abscissa**			**Formula on the ordinate** Mechanical set		
	Parameter name	**Lower endpoint**	**Upper endpoint**	**Mech. set**	**Quantity**	**Formula**
TORQUE_VS_SLIP	SLIP	0.001	1.0	ROTOR	Electromagnetic torque	TorqueElecMag (ROTOR)

☞ Curve → 2D Curve (I/O parameter)→ New 2D Curve (I/O parameter)

Result (1) The 2D Curve of the torque is shown below.

Result (2) The characteristics of the motor for steady state rated-load operation are presented in the table below:

Motor characteristics for starting state amd critical slip rate						
Sm	**Mem [N.m]**	**Mes [N.m]**	**Mem/Men**	**Mes/Men**	**I1s [A]**	**I1s/I1n**
0.22	63.85	51.32	2.65	2.13	49.11	5.79

4.2.12. Define the transient initialization

Goal

The case 4 is initialized with case 2 final configuration. For that :
- Select the step of the scenario corresponding to rated speed
- Create transient startup file from the case 2 post-processed project
- Select this file in case 4 application**.**

Data (1)

The characteristics of the step selected are presented in the table below.

Scenario and step selection		
Scenario	**Computation step**	
CHARACTERISTICS	SLIP	0.032
	ANGPOS_ROTOR	1.143

Data (2)

The characteristics of the transient startup file are presented in the table below.

Create file for transient startup	
File name	**Phase for transient startup (degree)**
INITIAL_4	90

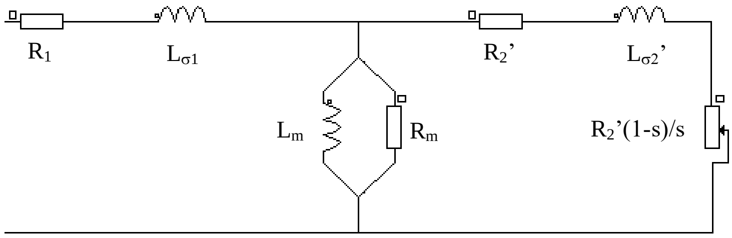
☞ **Data exchange → Create file for transient startup**

5. Case 3: Equivalent electric circuit

Case 3

This study is a steady state computation.
The first part of this study consists of locked-rotor simulation. To carry out this simulation, it is required to supply the motor with a reduced voltage, varying from 15 % to 30% of the nominal value.
The second part consists of no-load condition, that is a particular working point of the case 2 when s = 0.001.
With both parts, the user will be able to extract the equivalent electric circuit parameters of the induction motor.
The following parameters of the equivalent electric circuit of the motor are evaluated using the simulation results of no-load motor operation and of locked-rotor model of the induction machine:

- Magnetization inductance, L_m;
- Resistance corresponding to magnetic losses, R_m;
- Rotor leakage inductance, $L'_{\sigma 2}$ and resistance R'_2, corresponding to motor start-up.



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**

Contents

This chapter contains the following topics:

5.1. Case 3: Physical description

Geometry description	Mesh generation	**Physic description**	Solving process	Result post-processing

Introduction

This section presents the definition of the physical properties – materials and regions of the model.

Contents

This section contains the following topics:

5.1.1. Create I/O Parameters

Goal One I/O parameter will be created to define the value of voltage sources

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

I/O parameters controlled via scenario	
Name	**Reference value**
V_SUPPLY	380

☞ **Parameter/Quantity→ I/O parameter new → New** 

5.1.2. Modify voltage sources

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

Data The characteristics of the voltage sources are described in the table below.

Components	RMS value	Phase
V1	V_SUPPLY	0º
V2	V_SUPPLY	-120º
V3	V_SUPPLY	120º

☞

Physics→ Electrical components → Voltage source → Edit	

5.2. Case 3: Solve the project

Geometry description	Mesh generation	Physic description	**Solving process**	Result post-processing

Goal

A solving scenario is created in order to solve CASE3.

Data

The characteristics of the solving scenario used to solve the CASE 3 are presented in the tables below:

Solving scenario

Name	Comment
LOCKED_ROTOR	Study using geometrical and physical parameters

Solving scenario

Parameter control					
Controlled parameter	**Type**	**Interval**			
		Lower limit	**Higher limit**	**Method**	**Step value**
ANGPOS_ROTOR	Mono-value	1.143			
SLIP	Mono-value	1.0			
V_SUPPLY	Multi-values	60.0	120.0	Step value	2.0

☞ Solving → Solving scenario → New

Action

Solve and save the project under the following conditions:

- Solve with: solving scenario LOCKED_ROTOR
- Project name: CASE3_SOLVED

☞ Solving → Solve

5.3. Case 3: Results post-processing

Geometry description | Mesh generation | Physic description | Solving process | **Result post-processing**

Introduction (1) This section explains how to analyze the principal results of CASE 3 for locked-rotor conditions.

Contents (1) This section contains the following topics:

Introduction (2) This section explains how to analyze the principal results of CASE 3 for no-load conditions. For this post-processing, the user will open the CASE2_POSTPROCESSED, and will analyze a particular case when s = 0.001.

Contents (2) This section contains the following topics:

Introduction (3) This section explains how to obtain the different parameters of the equivalent electric circuit of the induction motor.

Contents (3) This section contains the following topics:

5.3.1. Create I/O Parameters (CASE3)

Goal Create some I/O parameters to help the user to represent the rms value of the current in a 2D curve.

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

I/O parameters defined by a formula		
Name	**Comment**	**Expression**
I_PH1	RMS value of the current in phase 1	Mod(I(V1))/Sqrt(2)
I_PH2	RMS value of the current in phase 2	Mod(I(V2))/Sqrt(2)
I_PH3	RMS value of the current in phase 3	Mod(I(V3))/Sqrt(2)
I_RMS	RMS value of the current	(I_PH1+I_PH2+I_PH3)/3

☞ **Parameter/Quantity→ I/O parameter → New** 

5.3.2. 2D Curve of the current (CASE3)

Goal The values of the rms current versus the voltage supply is displayed

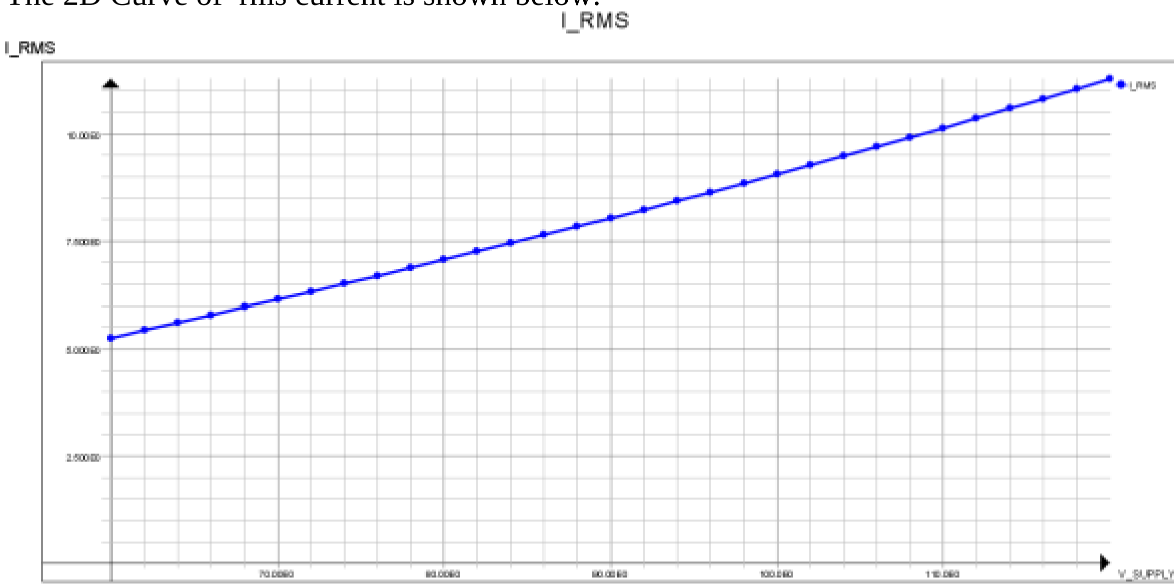
Data The characteristics of the curve are presented below.

2D curve (I/O parameter)

Name	I/O Parameter on the abscissa			Formula on the ordinate
	Name	Lower endpoint	Upper endpoint	f()
RMS_CURRENT	V_SUPPLY	60	120	I_RMS

☞ Curve → 2D Curve (I/O parameter) → New 2D Curve (I/O parameter)

Result The 2D Curve of rms current is shown below.



For the value of nominal current (8.48 A), the corresponding voltage supply is 94.478 V.

5.3.3. 2D Curve of the active power (CASE3)

Goal The values of the active power versus the voltage supply is displayed

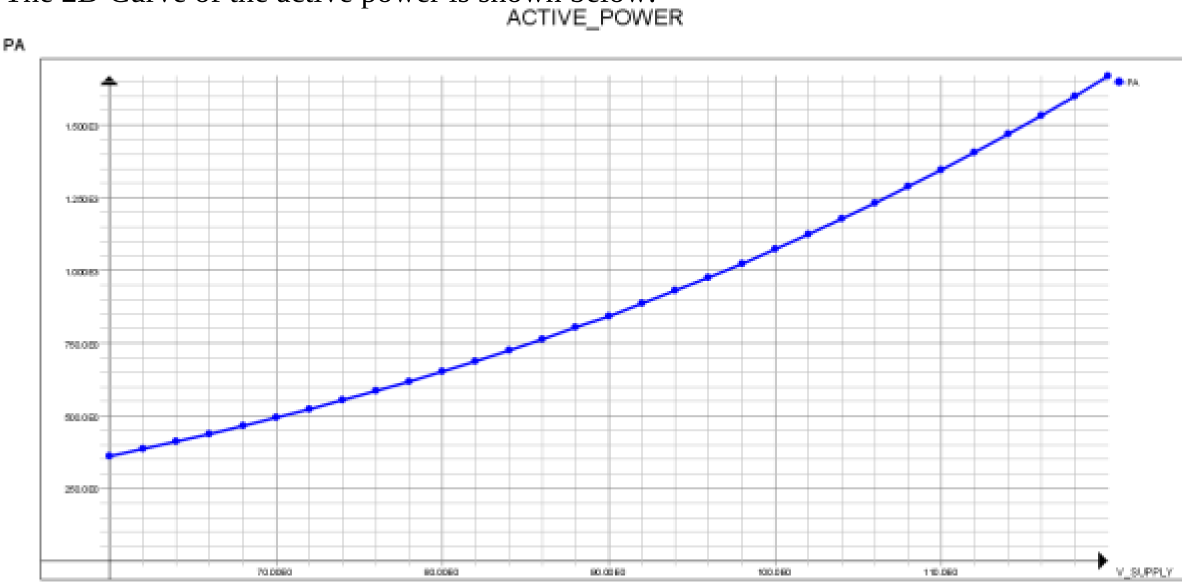
Data The characteristics of the curve are presented below.

2D curve (I/O parameter)

Name	I/O Parameter on the abscissa			Formula on the ordinate
	Parameter name	Lower endpoint	Upper endpoint	f()
ACTIVE_POWER	V_SUPPLY	60	120	PA

☞ Curve → 2D Curve (I/O parameter) → New 2D Curve (I/O parameter)

Result The 2D Curve of the active power is shown below.



For a voltage supply of 94.478 V, the corresponding active power is 941.4 Watts.

5.3.4. 2D Curve of the joule losses in stator core (CASE 3)

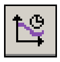
Goal The values of the joule losses in stator core versus the voltage supply is displayed

Data The characteristics of the curve are presented below.

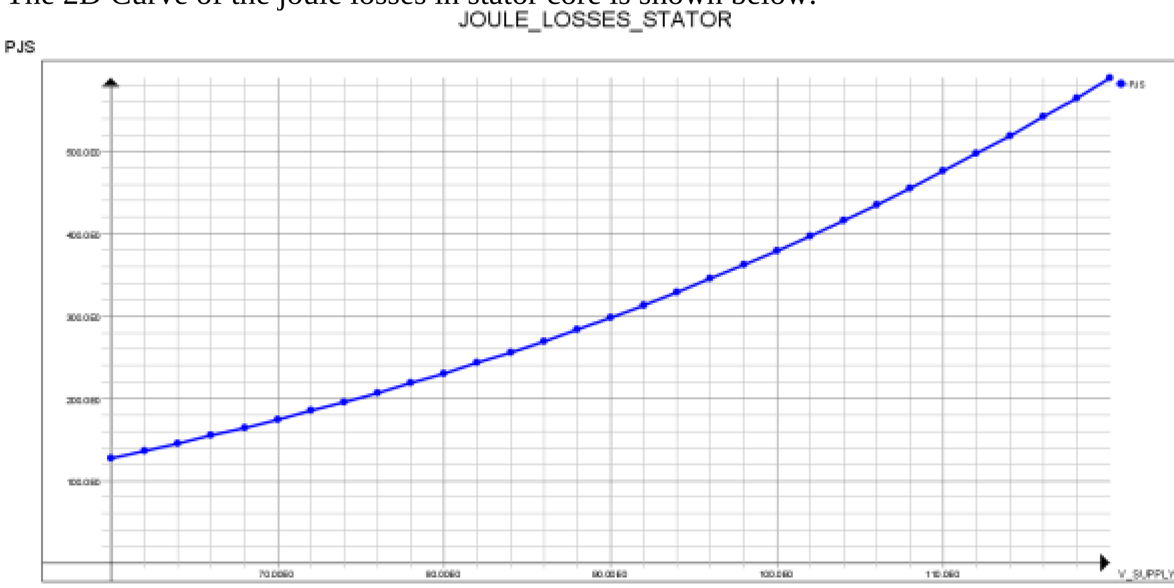
2D curve (I/O parameter)

Name	I/O Parameter on the abscissa			Formula on the ordinate
	Parameter name	Lower endpoint	Upper endpoint	f()
JOULE_LOSSES_ STATOR	V_SUPPLY	60	120	PJS

☞ Curve → 2D Curve (I/O parameter) → New 2D Curve (I/O parameter)



Result The 2D Curve of the joule losses in stator core is shown below.



For a voltage supply of 94.478 V, the corresponding stator joule losses is 332.77 Watts.

5.3.5. Display isovalues (CASE 3)

Goal

The magnetic flux density is computed on the device (excluding vacuum regions) and isovalues are displayed in color shadings.

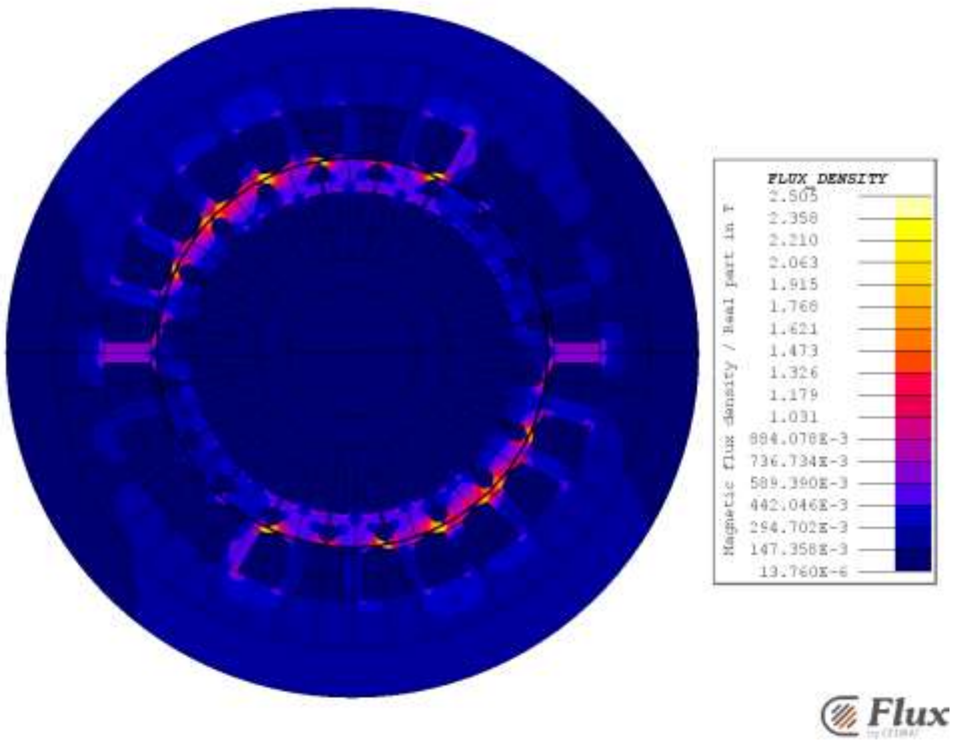
Action

Display isovalues (ISOVAL_NO_VACUUM)

☞ **Graphic → Isovalues → Display isovalues**

Result

The following chart shows the isovalues of the magnetic flux density on the device for locked-rotor operation (s = 1.0).



5.3.6. Display isovalues (CASE 3)

Goal Compute and display isovalues of the current density in rotor bars.

Data (1) The characteristics of the new spatial group are presented below.

Spatial Group			
Name	**Comment**	**Spatial group**	
		Type	**Face regions**
GROUP_ROTOR_ CAGE1_BAR	Spatial group	Face region	ROTOR_CAGE1_BAR1
			…
			ROTOR_CAGE1_BAR10

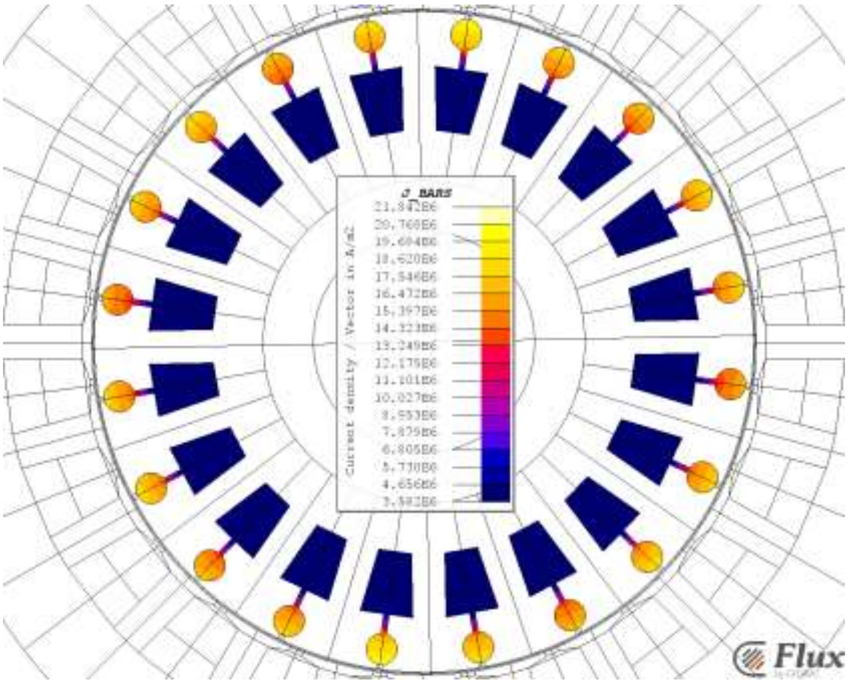
☞ **Support → Spatial group → New**

Data (2) The characteristics of the isovalues are presented below.

Isovalues on face regions				
Name	**Support for isovalues**		**Quantity**	
	Support	**Groups**	**Quantity**	**Formula**
ISOVAL_ I_BAR	Spatial group	GROUP_ROTOR_ CAGE1_BAR	Current density – Vector [A/m2]	J

☞ **Graphic → Isovalues → New**

Result The following chart shows the isovalues of the current density on the bars for for locked-rotor operation (s = 1.0).



5.3.7. Computation of no-load currents (CASE 2)

Goal

The goal of this part is to compute the no-load currents when the motor is supplied at rated voltage, in order to compute the magnetizing reactance and the iron loss resistance of the equivalent electric circuit of the machine.

For this post-processing, the user will open the CASE2_POSTPROCESSED, and will analyze a particular case when s = 0.001.

Action (1)

Open the CASE2_POSTPROCESSED and select the time step.

Scenario and step selection		
Scenario	**Computation step**	
CHARACTERISTICS	SLIP	0.001
	ANGPOS_ROTOR	1.143

Complements/ action (2)

Please note: In order to calculate the current in this project (CASE2), it is necessary to create the I_RMS parameter in this project (CASE2) as it is created in the current project (CASE3).

⇒

Repeat steps described in section 5.3.1 "Create I/O Parameters (CASE3)", in this Flux project (CASE2).

Data

The characteristics of the computation are presented in the table below

Compute on physic entity		
Name	**Computed formula** **Expression**	f()
NO_LOAD_CURRENT_1	I_RMS	

☞ **Computation → On physical entity → Compute**

Result

The result of the computation is presented below

Results of computation	
Label	**Value**
I_RMS	3.5926

5.3.8. Computation of iron losses in stator core (CASE2)

Goal

The goal is to compute the iron losses in the stator core to obtain the value of the iron loss resistance for the equivalent electric circuit of the machine.

Data

The characteristics of the computation are presented in the table below

Compute on physic entity		
Name	**Computed formula** / **Expression**	f()
IRON_LOSSES_STATOR	2*BERTOTTI_LOSSES	

☞ Computation → On physical entity → Compute

Result

The result of the computation is presented below

Results of computation	
Label	**Value**
2*BERTOTTI_LOSSES	94.21

5.3.9. Display isolines (CASE2)

Goal

The isolines of the vector potential (An) is computed on the device and isolines are displayed.

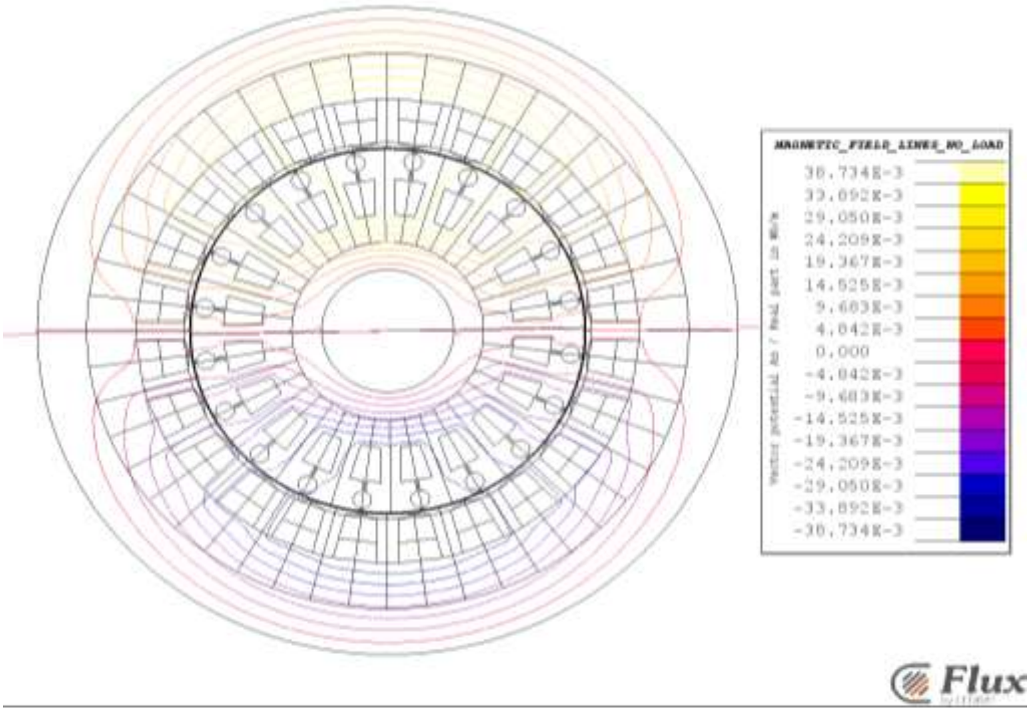
Action

Display isolines (1_ISOLIN_DOMAIN)

☞ | **Graphic → Isolines → Display Isolines** |

Result

The following chart shows the isolines of the vector potential (An) on the device for no-load operation (s = 0.001).



5.3.10. Display isovalues (CASE2)

Goal

The magnetic flux density is computed on the device (excluding vacuum regions) and isovalues are displayed in color shadings.

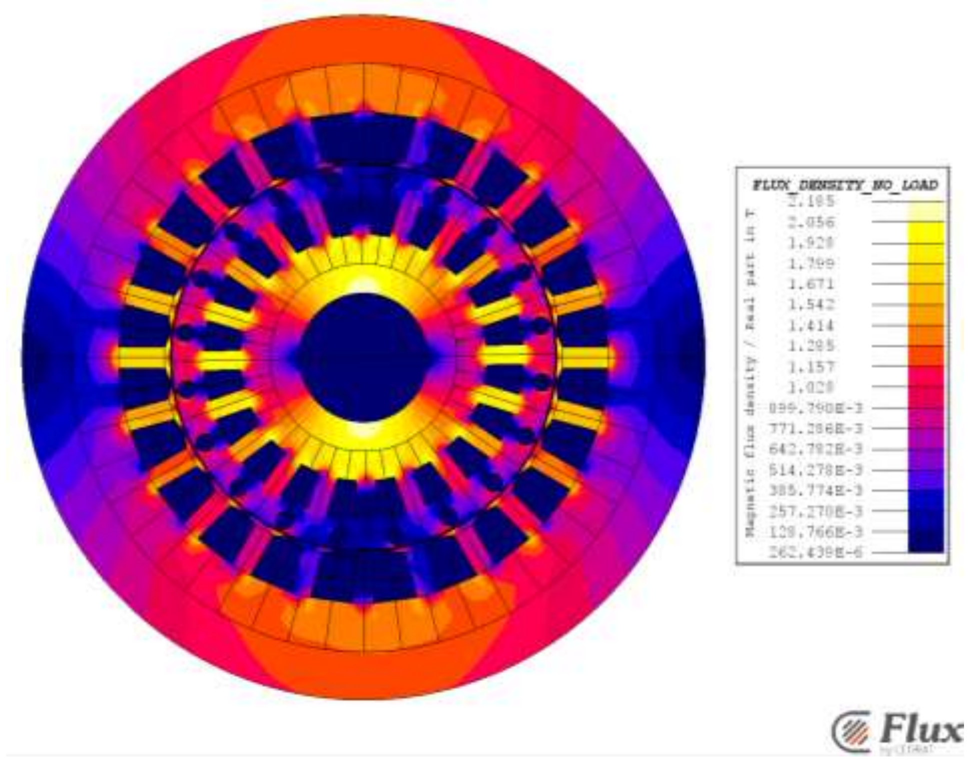
Action

Display isovalues (2_ISOVAL_NO_VACUUM)

☞ **Graphic → Isovalues → Display Isovalues**

Result

The following chart shows the isovalues of the magnetic flux density on the device for no-load operation (s = 0.001).



5.3.11. Computation of equivalent electric circuit parameters

Goal Compute the parameters of equivalent electric circuit of induction machine

Result The computation is presented below.

The parameters of the rotor electric circuit for locked-rotor conditions are computed as follows:

- the Joule losses in the stator winding, $P_{j1} = 3R_1 I_{1n}^2$;
- the Joule losses in the rotor circuit, $P_{j2} = sP_e = s(P_1 - P_{j1})$;
- the rotor resistance referred to the stator, $R_2^{'} = \frac{P_{j2}}{3I_{1n}^2} = 2.386\Omega$;
- the rotor leakage inductance referred to the stator,

$$L_{\sigma 2}^{'} = \frac{1}{2\pi f_{1n}} \sqrt{(\frac{U_1}{I_{1n}})^2 - (R_1 + R_2^{'})^2} - L_{\sigma 1} = 0.02492H;$$

Based on the results of the no-load simulation, the following equivalent electric circuit parameters of the motor are computed:

- the resistance R_m corresponding to the magnetic losses:

$$R_m = \frac{3U_{e1}^2}{P_{m0}} \cong \frac{3U_{1n}^2}{P_{m0}} = 4.598\ k\Omega$$

- the magnetization inductance of the motor:

$$L_m = \frac{1}{2\pi f_{1n}} \sqrt{\left[\frac{U_{1n}}{I_{10}}\right]^2 - R_1^2} - L_{\sigma 1} = 0.326\ H$$

Equivalent electric circuit parameters				
R1 [Ω]	Lσ1 [mH]	Rm [kΩ]	Lm [mH]	R'2 [Ω]
1.54	10.31	4.598	326	2.836

Note The value of total leakage inductance of stator winding (analytically computed) is $L_{\sigma 1} = 10.31 \cdot 10^{-3}$ H.

6. Case 4: Transient simulation for rated speed

Case 4

This study is a transient magnetic computation.
The goal is to analyze the transient behavior of the motor for rated speed taking into account the magnetic field harmonics due to the slotting of stator, rotor and the rotor motion.
In this section, based on transient magnetic simulations with constant rated rotor speed, we compute the values of the motor torque taking into account the magnetic field harmonics due to the armatures' slotting and rotor motion.
In order to decide when the computations are finished, proceed as follows:

- When analyzing the time variation of the instantaneous torque, you notice that the transient state is finished, you should calculate the mean value of electromagnetic torque on the last cycle of instantaneous torque oscillations;
- The simulation is continued over a time interval equal to the last cycle of electromagnetic torque oscillations, then the new mean value of the torque on this interval is compared with the preceding one;
- If the new mean value is almost equal with the preceding one, the transient analysis is finished; otherwise, the simulation will continue.

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**

Contents

This chapter contains the following topics:

6.1. Case 4: Physical description

Geometry description | Mesh generation | **Physic description** | Solving process | Result post-processing

---

Introduction

This section presents the definition of the physical properties – materials and regions of the model.

Contents

This section contains the following topics:

6.1.1. Define the physical application

Goal

After deleting the case 3 physical application, the case 4 physical application is defined. The required physical application is the 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**	**Type**	**File**
2D Plane	125	Initialized by file	INITIAL_4.FTS

☞ Application → Define → Magnetic → Transient Magnetic 2D

6.1.2. Modify mechanical sets

Goal

The two mechanical sets are modified.
For a slip g = 0.032, speed rotation is 2904 tr/min

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	
				First	Second
ROTOR	Rotation around one axis	Rotation around one axis parallel to Oz	XY1	0	0

kinematics		
Type of kinematics	General	
	Velocity (RPM)	Position at t=0
Imposed speed	2898	1.143

Data (2)

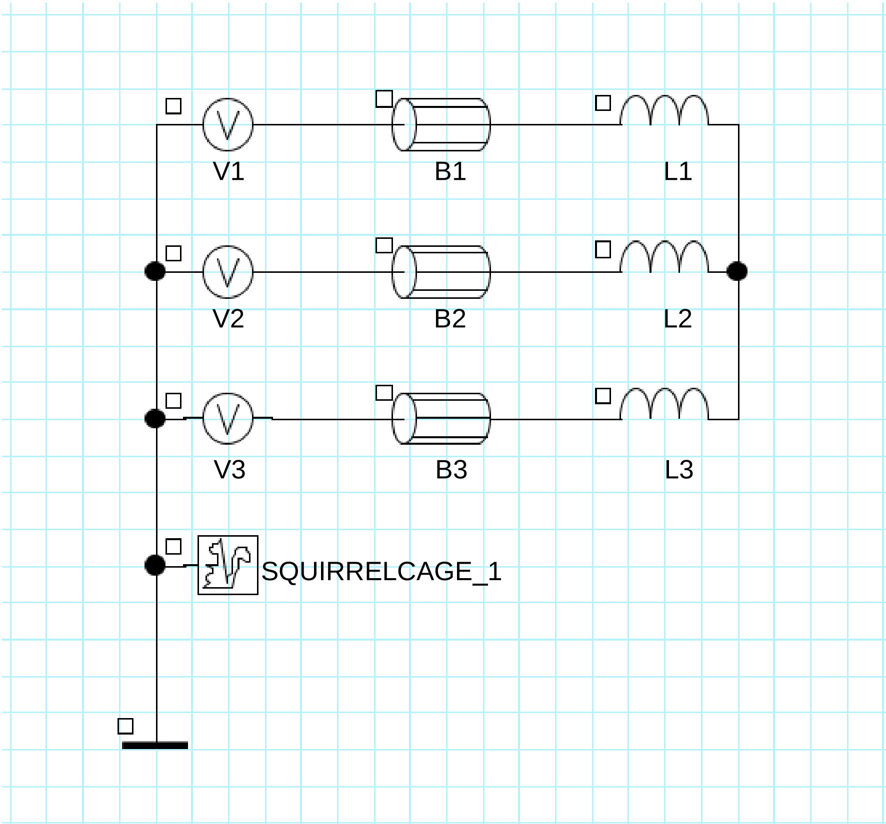
The characteristics of the mechanical set STATOR are presented in the table below:

Name	Type of Mechanical set
STATOR	Fixed

6.1.3. Create a circuit

Goal The goal is to define a circuit for this project.

Data (1) The electric circuit is presented in the figure below.



☞ | Physics → Circuit → Circuit editor context |

Action Close the circuit editor context.

☞ | Project → Return to standard geometry context |

6.1.4. Modify a circuit

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

Data (1) The characteristics of the stranded coil conductors are described in the table below.

Name of Stranded coil component	Resistance
B1, B2, B3	1.54 Ω

☞ Physics → Electrical components → Stranded coil conductor → Edit

Data (2) The characteristics of the inductors are described in the table below.

Components	Values
L1, L2, L3	4.04 mH

☞ Physics → Electrical components → Inductor → Edit

Data (3) The characteristics of the voltage sources are described in the table below.

Components	Formula
V1	380*sqrt(2)*Sin(2*Pi()*50*TIME+0)
V2	380*sqrt(2)*Sin(2*Pi()*50*TIME-2*Pi()/3)
V3	380*sqrt(2)*Sin(2*Pi()*50*TIME+2*Pi()/3)

☞ Physics → Electrical components → Voltage source → Edit

Data (4) The characteristics of the squirrel cage are described in the table below.

Components	Number of bars	R end ring	L end ring
SQUIRRELCAGE_1	10	1.39E-6 Ω	1.06E-8 H

☞ Physics → Electrical components → Squirrel cage → Edit

6.1.5. Modify face regions

Goal

Two 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 of region**	**Material of region**	**Mechanical set**
STATOR	Magnetic non conducting region	STEEL_NLIN	STATOR
ROTOR	Magnetic non conducting region	STEEL_NLIN	ROTOR

☞ **Physics → Face region → Edit**

6.1.6. Modify face regions

Goal Eight 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 of region**	**Mechanical set**
INFINITE	Air or vacuum region	STATOR
PRESLOT	Air or vacuum region	STATOR
ROTATING_AIRGAP	Air or vacuum region	STATOR
ROTOR_AIR	Air or vacuum region	ROTOR
ROTOR_PRESLOT	Air or vacuum region	ROTOR
SHAFT	Air or vacuum region	ROTOR
STATOR_AIR	Air or vacuum region	STATOR
WEDGE	Air or vacuum region	STATOR

☞

Physics→ Face Region → Edit	

6.1.7. Modify face regions

Goal Four 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 of region	Coil conductor region Component	Number of Turns	Orientation	Series or parallel	Mechanical set
PHASE_NEG_1	Coil conductor region	B1	104	Negative	series	STATOR
PHASE_NEG_3	Coil conductor region	B3	208	Negative	series	STATOR
PHASE_POS_1	Coil conductor region	B1	104	Positive	series	STATOR
PHASE_POS_2	Coil conductor region	B2	208	Positive	series	STATOR

☞ **Physics→ Face Region → Edit**

6.1.8. Modify face regions

Goal Ten 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 of region	Type of region	Material of region	Type of conductor	Associated solid conductor	Mechanical set
ROTOR_CAGE1_BAR1	Solid conductor region	ALU_HOT	Circuit	BAR_1	ROTOR
ROTOR_CAGE1_BAR2	Solid conductor region	ALU_HOT	Circuit	BAR_2	ROTOR
ROTOR_CAGE1_BAR3	Solid conductor region	ALU_HOT	Circuit	BAR_3	ROTOR
ROTOR_CAGE1_BAR4	Solid conductor region	ALU_HOT	Circuit	BAR_4	ROTOR
ROTOR_CAGE1_BAR5	Solid conductor region	ALU_HOT	Circuit	BAR_5	ROTOR
ROTOR_CAGE1_BAR6	Solid conductor region	ALU_HOT	Circuit	BAR_6	ROTOR
ROTOR_CAGE1_BAR7	Solid conductor region	ALU_HOT	Circuit	BAR_7	ROTOR
ROTOR_CAGE1_BAR8	Solid conductor region	ALU_HOT	Circuit	BAR_8	ROTOR
ROTOR_CAGE1_BAR9	Solid conductor region	ALU_HOT	Circuit	BAR_9	ROTOR
ROTOR_CAGE1_BAR10	Solid conductor region	ALU_HOT	Circuit	BAR_10	ROTOR

☞ **Physics→ Face Region → Edit**

Action Check physics and save case 4.

☞ **Physics → Check Physics**

☞ **Save Case4**

6.2. Case 4: Solving process

Geometry description	Mesh generation	Physic description	**Solving process**	Result post-processing

Goal

A solving scenario with a control of the time is created in order to solve CASE4.

Data

The characteristics of the solving scenario are presented in the tables below

Solving scenario

Name	Comment	Type
RATED_LOAD	Study using geometrical and physical parameter	Multi-values

<table>
<tr><th colspan="6">Solving scenario</th></tr>
<tr><td colspan="6"></td></tr>
<tr><th colspan="6">Parameter control</th></tr>
<tr><th rowspan="2">Controlled parameter</th><th rowspan="2">Type</th><th colspan="4">Interval</th></tr>
<tr><th>Lower limit</th><th>Higher limit</th><th>Method</th><th>Step value</th></tr>
<tr><td>TIME</td><td>-</td><td>0</td><td>0.11</td><td>Step value</td><td>2.5E-4</td></tr>
</table>

☞ Solving → Solving scenario → New

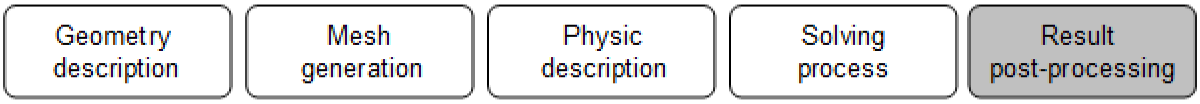
Action

Solve and save the project under the following conditions:

- Solve with: solving scenario RATED_LOAD
- Project name: CASE4_SOLVED

☞ Solving → Solve

6.3. Case 4: Results post-processing



Introduction This section explains how to analyze the principal results of CASE 4

Contents This section contains the following topics:

6.3.1. 2D curve of the electromagnetic torque versus time

Goal

The value of electromagnetic torque versus TIME are computed and displayed in a curve.
Because of the initialization with a transient file at time t = 0 s, the user must check that the initial value of the curve is equal to the torque value calculated for slip = 0.032 with the steady state model (see Case 2: Results post-processing, page 56).

Data

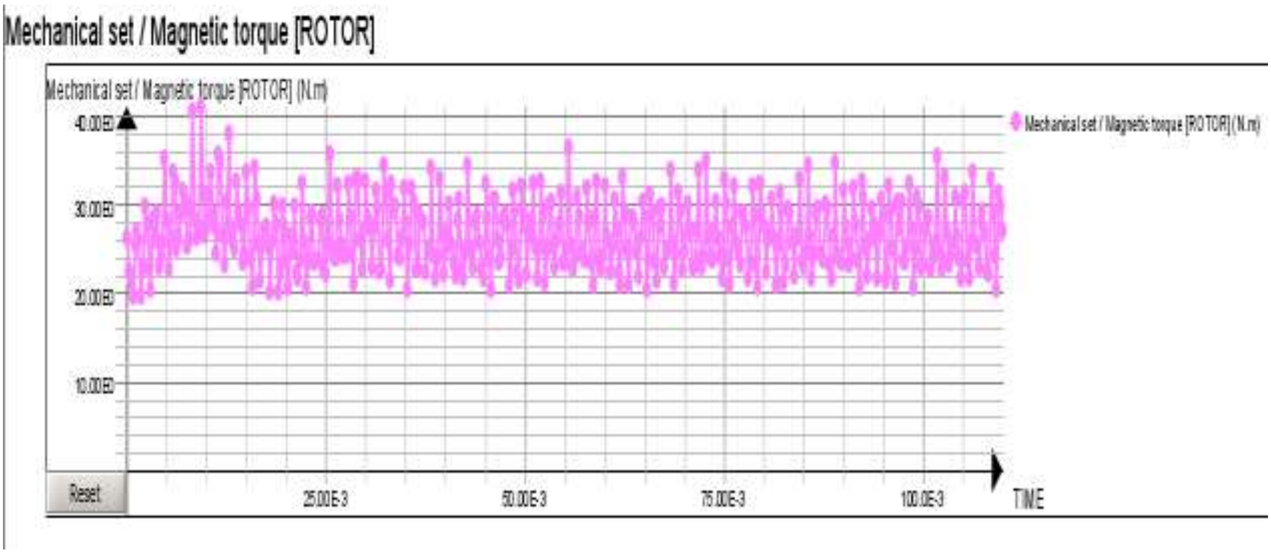
The characteristics of the curve are presented below.

2D curve (I/O parameter)						
Name	**I/O Parameter on the abscissa**			**Formula on the ordinate** Mechanical set		
	Parameter name	**Lower endpoint**	**Upper endpoint**	**Mech. set**	**Quantity**	**Formula**
TORQUE_VS_TIME	TIME	0.0	0.11	ROTOR	Electromagnetic torque	TorqueElecMag (ROTOR)

☞ **Curve → 2D Curve (I/O parameter)→ New 2D Curve (I/O parameter)**

Result

The 2D Curve of the torque is shown below.



For slip = 0.032, the torque value calculated with the steady state model was 24.13 N.m. With the transient model, the first value is 26.2 N.m

6.3.2. 2D curve of the current bar rotor

Goal

The value of current bar rotor versus TIME are computed and displayed in a curve.

Initialization value

For the same reason at time t = 0 s, the user must check that the initial value of the curve is equal to the value calculated for slip = 0.032 with the steady state model.
In the case of the bar number 10, the current calculated with the steady state model is:

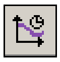
- 512 A for the magnitude
- 3.0744 rd for the phase.

By consequent, the first value for the transient model should be equal to 512 * sin(3.0744) = 34.78 A
With the transient model, we found the first value at t = 0 : 34.77 A.

Data

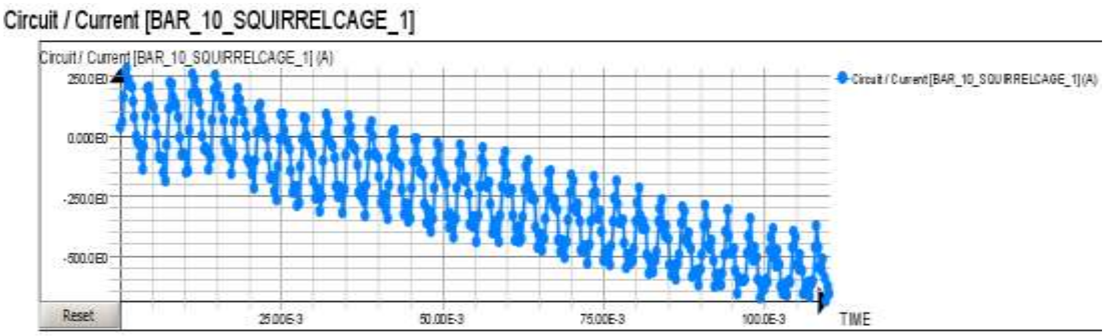
The characteristics of the curve are presented below.

2D curve (I/O parameter)						
Name	**I/O Parameter on the abscissa**			**Formula on the ordinate** Circuit		
	Parameter name	**Lower endpoint**	**Upper endpoint**	**Electrical component**	**Quantity**	**Formula**
IBAR_ VERSUS_ TIME	TIME	0.0	0.11	BAR_10_ SQUIRREL CAGE_1	Current [A]	I(BAR_10_ SQUIRREL CAGE_1)

☞ **Curve → 2D Curve (I/O parameter)→ New 2D Curve (I/O parameter)** 

Result

The 2D Curve of the current bar is shown below.



6.3.3. 2D curve of the stator current

Goal

The value of current bar rotor versus TIME are computed and displayed in a curve.

Initialization value

For the same reason at time t = 0 s, the user must check that the initial value of the curve is equal to the value calculated for slip = 0.032 with the steady state model.
In the case of the phase 1, the current value with the steady state model is :

- 11.969 A for the magnitude
- 2.547 rd for the phase.

By consequent, the first value for the transient model should be equal to 11.969 * sin(2.547) = 6.7 A
With the transient model, we found a first value at t = 0 equal to 6.13 A.

Data

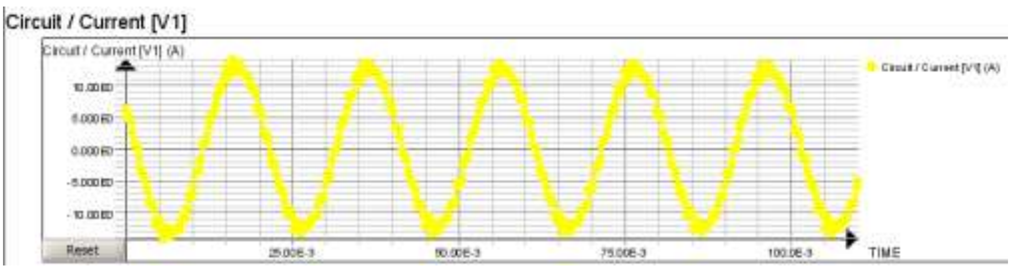
The characteristics of the curve are presented below.

2D curve (I/O parameter)						
Name	I/O Parameter on the abscissa			Formula on the ordinate	Circuit	
	Parameter name	Lower endpoint	Upper endpoint	Electrical component	Quantity	Formula
ISTAT_VERSUS _TIME	TIME	0.0	0.11	V1	Current [A]	I(V1)

☞ Curve → 2D Curve (I/O parameter)→ New 2D Curve (I/O parameter)

Result

The 2D Curve of the stator current is shown below.



7. Case 5: Real working conditions

Case 4

This study is a transient magnetic computation.
The purpose of this case is to simulate the behavior of the motor under real working conditions. For the first 0.4 seconds, the simulation will reproduce a no-load starting. After the starting, the machine will be loaded with the rated drag torque. Finally, 0.4 seconds after the load is applied, a fault condition will be reproduced. In this case, a single phase short-circuit (between one phase and neutral) will be simulated during 0.2 seconds.
In this period we can see the time evolution of main quantities like currents, torque, speed, etc.

Starting Flux project

The starting project is the Flux project CASE4_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 CASE4_SOLVED results are deleted. The Flux project is then saved under the name of **CASE5.FLU**

Contents

This chapter contains the following topics:

7.1. Case 5: Physical description

Geometry description	Mesh generation	**Physic description**	Solving process	Result post-processing

Introduction

This section presents the definition of the physical properties – materials and regions of the model.

Contents

This section contains the following topics:

7.1.1. Modify the physical application

Goal The physical application is modified. The required physical application is the 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	125	With zero initial solution (variables set to 0)

☞ **Application → Edit current application**

7.1.2. Create I/O Parameters

Goal

One I/O parameter will be created to define the rated load condition and others to define the short circuit condition

Data

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	Explanation
DRAG_TORQUE	24.83*Valid(TIME,0.4,100)	Load torque added at t=0.4s
R_PHASE_1	1.54*Valid(TIME,0,0.6) + 1.386*Valid(TIME,0.6,100)	Short-circuit simulated by decreasing the number of turns and resistance at t=0.6s
N_PHASE_1	104*Valid(TIME,0,0.6) + 62*Valid(TIME,0.6,100)	

☞ **Parameter/Quantity → I/O parameter → New**

7.1.3. Modify mechanical set

Goal

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

Data

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

Mechanical set

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

Kinematics		
Type of kinematics	General	
	Velocity at t = 0s (rpm)	Position at t = 0s
Coupled load	0	0.0

Kinematics			
Type of kinematics	Internal characteristics		
	Type of load	Moment of inertia (kg.m2)	Resistive torque (N.m)
Coupled load	Inertia and resistive torque	0.034	0.0

Kinematics			
Type of kinematics	External characteristics		
	Type of load	Moment of inertia (kg.m2)	Resistive torque (N.m)
Coupled load	Inertia and resistive torque	0.0	DRAG_TORQUE

☞ **Physics → Mechanical set → Edit**

7.1.4. Modify face regions

Goal Two face regions are modified in order to describe the short-circuit conditions.

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

Face region						
Name of region	**Type of region**	**Coil conductor region Component**	**Number of turns**	**Orientation**	**Series or parallel**	**Mechanical set**
PHASE_NEG_1	Coil conductor region	B1	N_PHASE_1	Negative	Series	STATOR
PHASE_POS_1	Coil conductor region	B1	N_PHASE_1	Positive	Series	STATOR

7.1.5. Modify a circuit

Goal

The circuit is modified in order to describe the short-circuit conditions.

Data

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

Name of Stranded coil component	Resistance
B1	R_PHASE_1

7.2. Case 5: Solving process

Geometry description	Mesh generation	Physic description	**Solving process**	Result post-processing

Goal

A solving scenario with a control of the time is created in order to solve CASE5.

Data

The characteristics of the solving scenario are presented in the tables below

Solving scenario

Name	Comment	Type
STARTING_LOAD_FAULT	Study using geometrical and physical parameter	Multi-values

Solving scenario

Parameter control					
		Interval			
Controlled parameter	Type	Lower limit	Higher limit	Variation method	Step value
TIME	-	0	0.8	Step value	0.0005

☞ Solving → Solving scenario → New

Action

Solve and save the project under the following conditions:

- Solve with: solving scenario STARTING_LOAD_FAULT
- Project name: CASE5_SOLVED

☞ Solving → Solve

7.3. Case 5: Results post-processing

Geometry description	Mesh generation	Physic description	Solving process	**Result post-processing**

Introduction

This section explains how to analyze the principal results of CASE 5

Contents

This section contains the following topics:

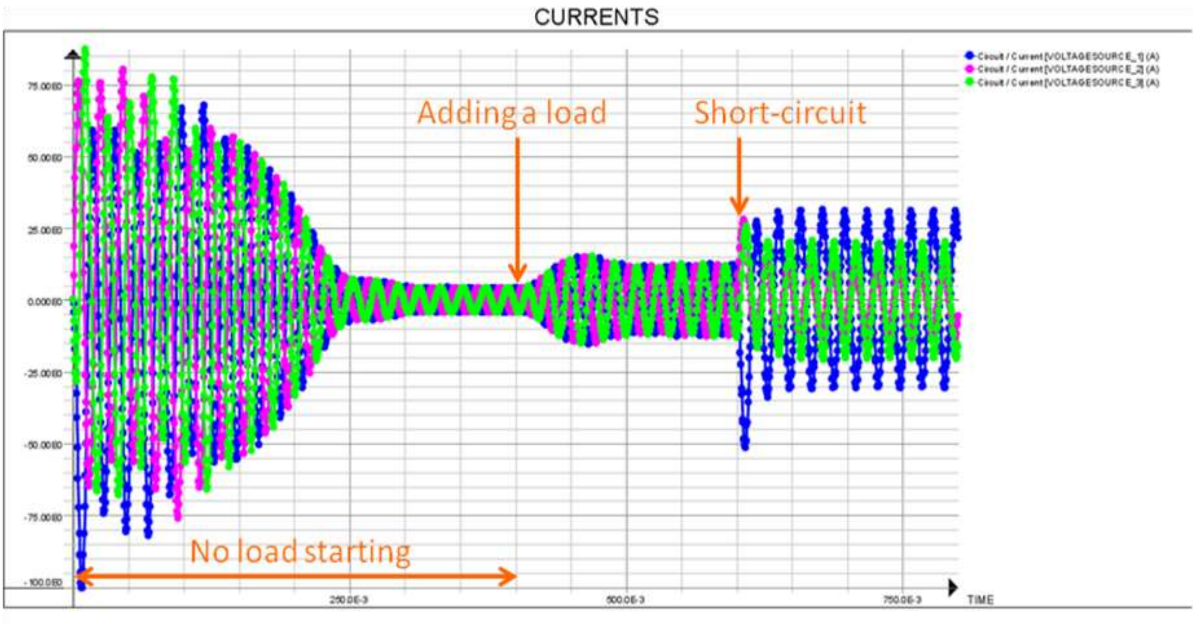
7.3.1. Plot a 2D Curve of the phase current

Goal Display a 2D curve of the phase current in the three phases.

Data The characteristics of the 2D curve are presented below.

2D curve (I/O parameter)						
Name	**I/O Parameter on the abscissa**			**Formula on the ordinate**	Circuit	
	Parameter name	**Lower endpoint**	**Upper endpoint**	**Electrical component**	**Quantity**	**Formula**
CURRENT	TIME	0.0	0.8	V1	Current [A]	I(V1)
				V2	Current [A]	I(V2)
				V3	Current [A]	I(V3)

Result



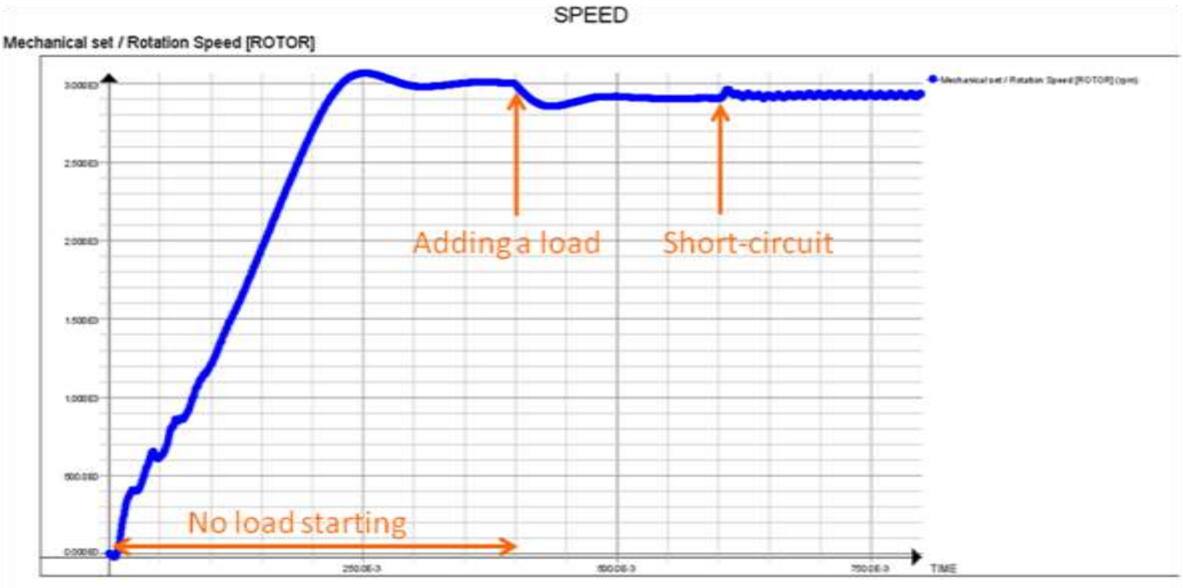
7.3.2. Plot a 2D Curve of the speed

Goal Display a 2D curve of the speed.

Data The characteristics of the 2D curve are presented below.

2D curve (I/O parameter)						
Name	**I/O Parameter on the abscissa**			**Formula on the ordinate** Mechanical set		
	Parameter name	**Lower endpoint**	**Upper endpoint**	**Mech. set**	**Quantity**	**Formula**
SPEED	TIME	0.0	0.8	ROTOR	Angular speed	AngSpeed (ROTOR)

Result The result appears in the figure below.



7.3.3. Plot a 2D Curve of the torque

Goal Display a 2D curve of the torque.

Data The characteristics of the 2D curve are presented below.

2D curve (I/O parameter)						
Name	**I/O Parameter on the abscissa**			**Formula on the ordinate** Mechanical set		
	Parameter name	**Lower endpoint**	**Upper endpoint**	**Mech. set**	**Quantity**	**Formula**
TORQUE	TIME	0.0	0.8	ROTOR	Electromagnetic torque	TorqueElecMag (ROTOR)

Result The result appears in the figure below.