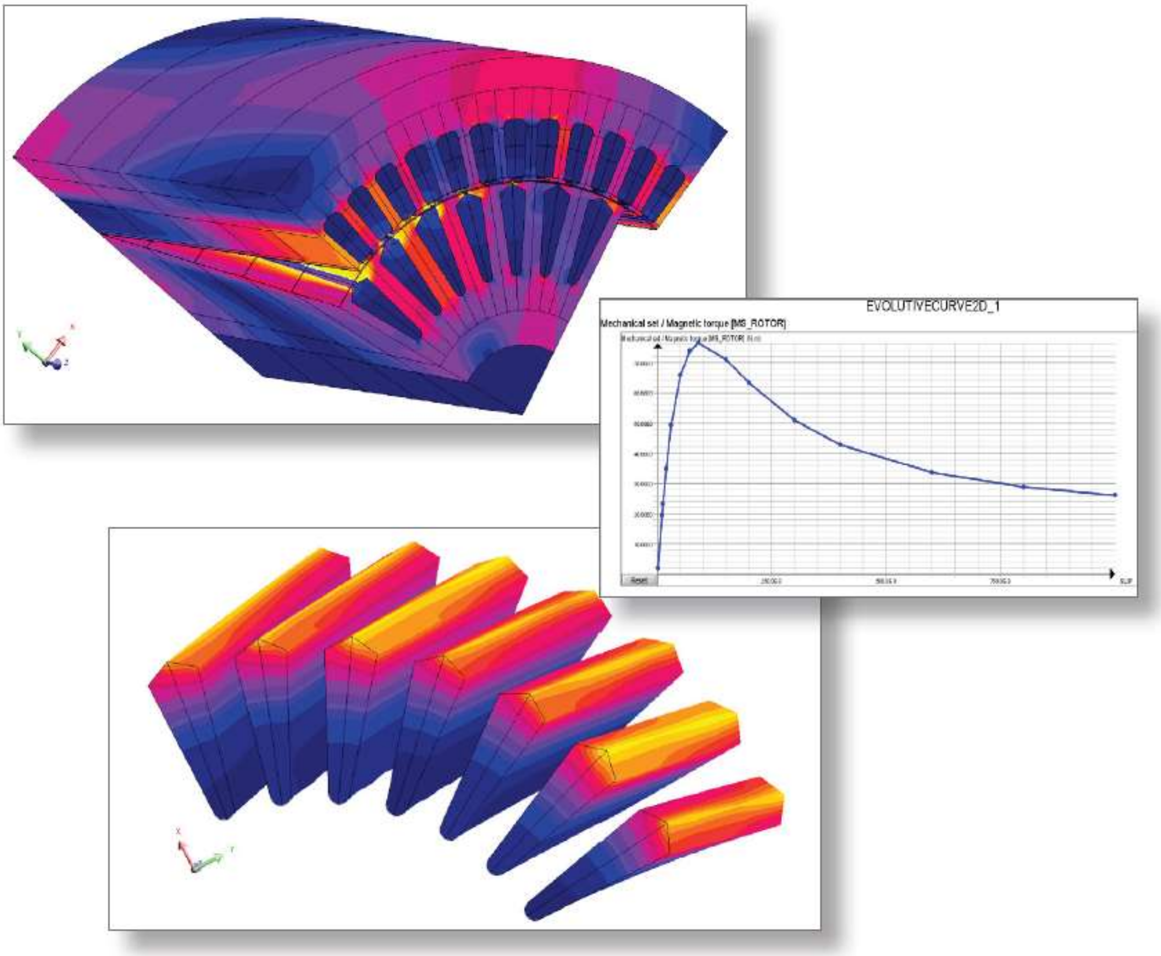
CAE package for electromagnetic and thermal analysis using finite elements

Altair® Flux®

Induction motor with skew tutorial

Skew technical example



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This tutorial was edited on 23 November 2022

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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 a skewed 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 "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...

To 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\InductionMotor_SKEW\
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.

(*.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

Note : some directories may contain a main.py enabling the launch of the other command files

Table of Contents

1. General information

Introduction

The goal of this technical paper is to demonstrate Flux capabilities in modeling an induction machine with a skewed rotor. This chapter presents the studied device, (an induction machine with a skewed rotor) and explains the strategies used for geometry construction and mesh generation.

Contents

This chapter contains the following topics:

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.

Contents

This section contains the following topics:

1.1.1. Description of the device

Foreword

This paragraph is a summary of cases treated in detail in the Skew example: "Induction Skewed 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 4 poles induction skewed 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 skewed slots.

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

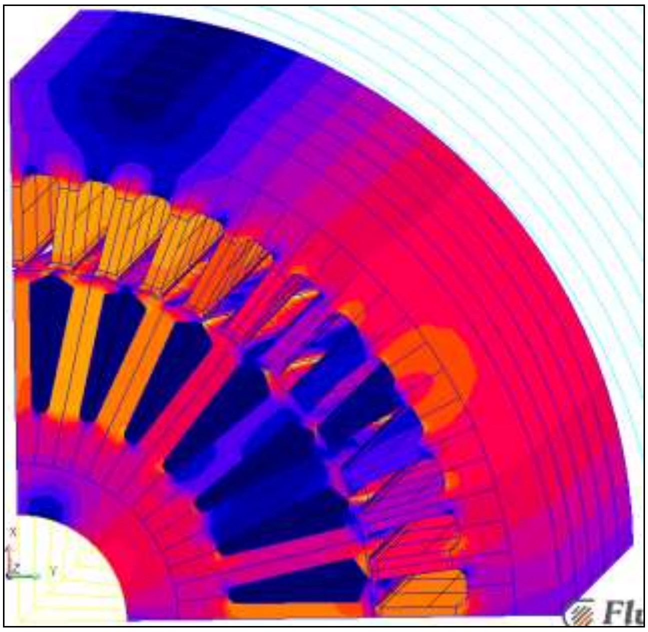


Figure 0-1

View of the induction motor calculated with Flux

Motor ratings

This motor has the following main ratings :

- Rated power : 5.5 kW
- Power supply voltage : 400 V.
- cos φ = 0.78
- Rated current : 11.9A
- Speed : 1471.5 rpm

Continued on next page

Geometric characteristics

This motor has the following geometric characteristic :
- Stator external diameter : 168 mm
- Cylinder bore diameter : 110 mm
- Airgap thickness : 0.4 mm
- Rotor external diameter : 109.2 mm
- Shaft diameter : 33 mm
- Number of stator slots : 48
- Number of rotor bars : 28
- Number of pairs of poles : 2
- Stator length : 140 mm

Motor winding characteristics

This motor has the following winding characteristics :
- Type of winding Concentric with consequent poles
- Number of slots per pole and per phase : 4
- Number of turns in series per phase : 80
- Diameter of a spire : 0.8 mm
- Number of windings in parallel per phase : 1
- Throw : 0 to 15

Material

Material used are :
- Material of the rotor and the stator : M1000-65D
- Material of the squirrel cage : Copper

1.1.2. Studied cases

Studied cases

Fhree cases are studied in this technical paper:

- Case 1: Steady State at no load
- Case 2: Steady State study to compute the characteristics of the machine at rated Speed
- Case 3: Transient study at no load

Case 1

The first case is a steady state magnetic AC study.

Steady state simulation of no load operation of the motor in order to evaluate stator current at no load.

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 transient study.

This study is a transient simulation at no load. Stator current and torque are computed and display versus time. At steady state; values must be similar to the values calculated with the case 1.

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 **Induction 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?

Contents

This section contains the following topics:

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

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

- **Induction 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 induction motors

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

List of models

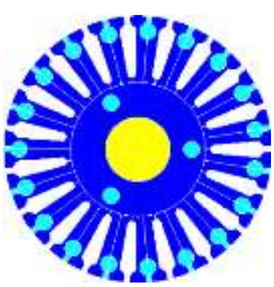
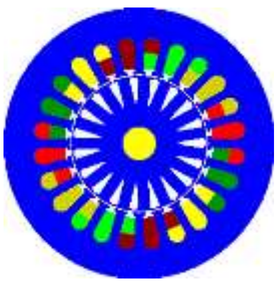
The different models in the library are not detailed in the on line help because their documentation is included in the software. An interactive image is displayed in the object editor. The editor displays a direct visualization of the parameters entered by the user.

The list of models provided for the 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 Induction Machine (double cage)	Stator (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 **induction 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* • *creatio*n 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 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 (CASE0).**

Contents

This chapter contains the following topics:

2.1. Load the Induction Motor overlay

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

Action (1) Close the sketcher2D context.

☞ **Project → Close Sketcher2D context** 

Action (2) Load the INDUCTION_MOTORS_V11.1.PFO overlay.

☞ **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	Rotating air gap	Use periodicities
0.4	no	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 [Deg]
54.6	4	16.5	0.0

Cooling holes
1. Without cooling holes

Cage
1 – Single cage

Bars shape				
Type 0	Bridge	Rotor slot depth	Rotor tooth width	Rotor tang angle
	0.2	21.8	4.908	30.0

Number of bars :
28

Continued on next page

Data (3)

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

Stator description							
Slot shape description : Stator flared							
General description							
Slot Depth	**Stator tooth width**	**Slot Opening**	**Radial depth**	**Under cut angle**	**Slot width inside tooth tang**	**filSO**	**filSB**
14.5	3.0	2.8	0.62	41.5	3.53	0.4	1.85

General description				
Number of slots	**Stator configuration**	**LamShape**	**Stator outer radius**	**Stator angle**
48	normal	circle	84	0.0

Data (4)

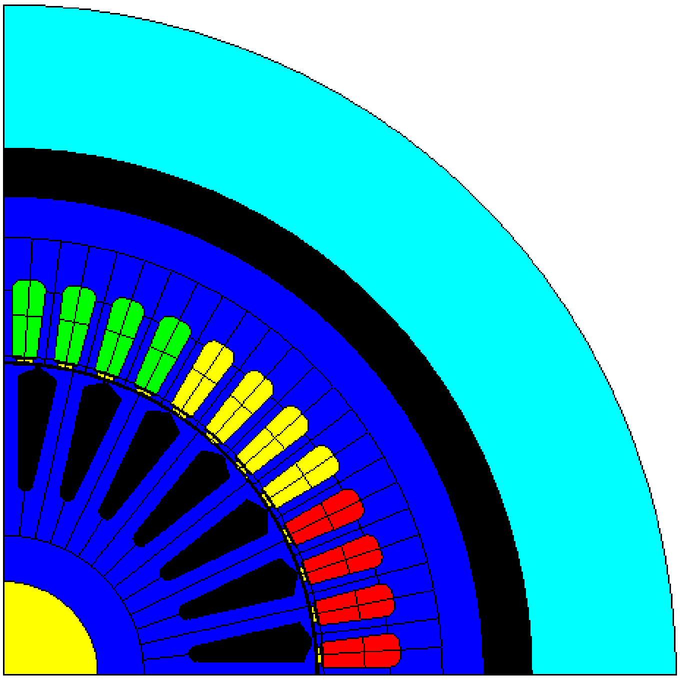
The characteristics of the winding are presented in the tables below.

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	Concentric winding per pole	15	4	superimposed

Continued on next page

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. 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.

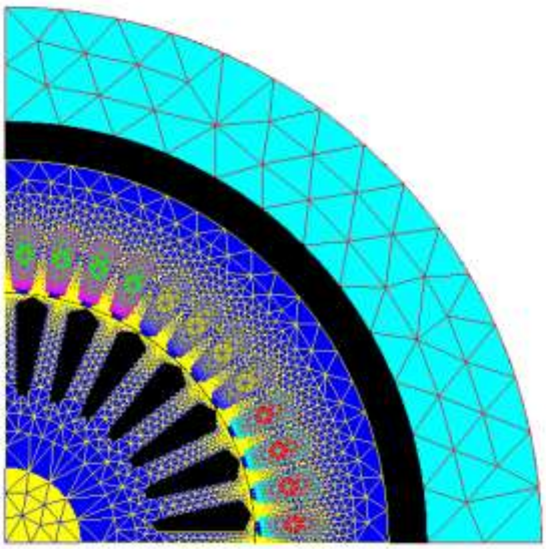
Mesh Point	
Name	**Value**
AIRGAP	(((DMINSTATOR-DMAXROTOR)/NB_REGION_IN_AIRGAP)*10**3 *LENGTH_UNIT)***2**
CAGE1_P2	(1.5*MESH_CAGE1_P2/(1+MESH_FACTOR)*10**3*LENGTH_UNIT)***4**

☞ **Mesh → Mesh point → Edit**

Action (1) Mesh the device.

☞ **Mesh → Mesh domain**

Result The meshed device is presented in the figure below.



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

☞ **Project → Save as**

3. Case 1: Steady State - No load

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.

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 process

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

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 **Rotating Induction Machine (Skewed Model) in Steady State AC Magnetic .**

Data

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

Rotating Induction Machine (Skewed Model) in Steady State AC Magnetic	
Physical Definition	
Frequency in Hertz	50

Geometric Definition				
Skewed rotor or stator	**Multilayer model**	**Elevation in meter**	**Angle of rotation in degrees**	**Number of slices in the elevation**
Rotor with skewed slots	Multilayers 2D model	0.14	10.23	5

Coil Coeffcient
Automatic coefficient (Symmetry & Periodicity take into account)

☞ Application → Define → Magnetic → Rotating Induction Machine (Skewed Model) in Steady State AC Magnetic

3.1.2. Create materials

Goal

Two materials are created in order to define the physics.

Data (1)

The magnetic characteristic $B(H)$ of material comprising the stator and rotor areas is modeled by an isotropic scalar analytic saturation, with 2 coefficients

Material			
B(H) magnetic property**: isotropic analytic saturation** (arctg, 2 coef)			
Name	**Initial relative permeability**	**Saturation Magnetization (T)**	**Type of equivalent B(H) curve**
FEV_1000	1400	1.96	Sine wave flux density

☞ Physics → Material → New

Data (2)

The second material to be characterized is the copper (it is the material comprising the squirrel-cage and the stator winding). For the modeling we will assume it is purely resistive. The resistivity of pure copper at room temperature 20°C is: $\rho_{Cu}^{20} = 1.7241.10^{-8}\ \Omega.m$.

Since the temperature coefficient of resistance of copper at 20°C is of $3.93.10^{-3}$ per degree, the resistivity at another given temperature T can be found by the equation:

$$\rho_{Cu}^{T} = \rho_{Cu}^{20}\left[1+\alpha_{Cu}^{20}(T-20)\right]\times IACS_{Cu}$$

where $IACS_{Cu}$ (97% in our case) is the **I**nternational **A**nnealed **C**opper **S**tandard.

Thus at 130° the resistivity of copper is

$$\rho_{Cu}^{130} = 2.39534.10^{-8}\ \Omega.m$$

Material		
Name	**B(H)** magnetic property: **linear isotropic**	**J(E)** electrical property: **isotropic resistivity**
	Relative permeability	**Resistivity [Ohm.m]**
Copper	1	2.3953 e-8

☞ Physics → Material → New

3.1.3. Create I/O parameters

Goal One I/O parameter will be created in order to define the physics.

Data (1) The characteristics of the I/O parameter defined by a formula are described in the table below.

I/O parameter defined by a formula		
Name	**Comment**	**Expression**
VRMS	rms value of voltage source	400/Sqrt(3)

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

3.1.4. Create mechanical sets

Goal

Two mechanical sets are created to define kinematic properties of the motor:

- one mechanical set for the fixed part: the stator
- one mechanical set for the moving part: the rotor

Data

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

Fixed mechanical set	
Name	**Comment**
MS_STATOR	Fixed part

Rotation around one axis mechanical set							
Name	**Comment**	**Axis**				**Kinematics**	
		Rotation axis	**Coord. system**	**Pivot point coordinates**		**Type**	**Slip**
				1st	**2nd**		
MS_ ROTOR	Moving part	parallel to Z-axis	XY1	0	0	Multi-static	0.001

☞ **Physics → Mechanical set → New** 

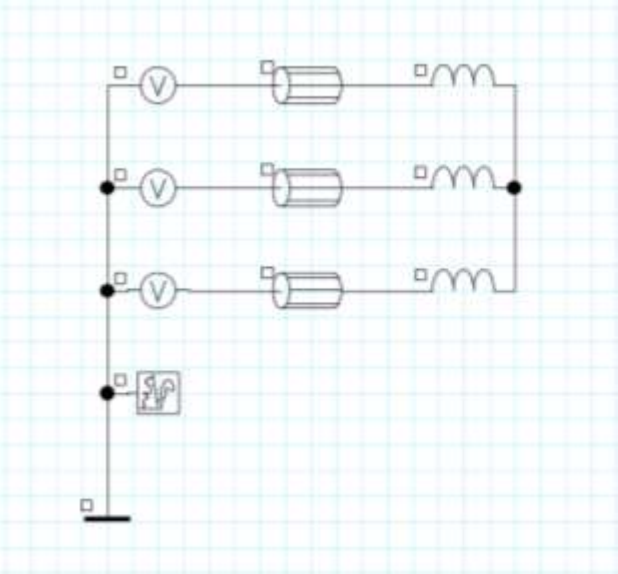
3.1.5. Create a circuit

Goal

The goal is to define a circuit for this project.

Data

The circuit to be created is as follows:



☞ **Physics → Circuit → Circuit editor context**

Note: the coils and inductances are corresponding to the stator coils. A typical electric circuit associated with an induction machine reveals two parts electrically independent of each other but connected to establish a common ground:

- one that describes the stator with voltage source, end winding resistances, inductances and stator's coils
- one that describes the rotor () with inter-bar end ring resistances and inductances and the rotor bars

Action

This circuit will also be used for case 3. For reusing this circuit, it is advisable to export it to xcir format with the name: InductionSkewedMotor.xcir

☞ **Circuit → Export circuit to a xcir file**

In the absence of recording, the circuit is saved by default under the project name: CASE1.xcir

Action

Close the circuit editor context.

☞ **Project → Return to standard geometry context**

3.1.6. Modify characteristics of electrical components

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

Data (1) The characteristics of voltage sources are described in the table below.

Voltage source		
Name	**rms value [V]**	**Phase [degree]**
V1	VRMS	0
V2	VRMS	-120
V3	VRMS	120

☞ Physics → Electrical components → Voltage source → Edit

Data (2) The characteristics of the stranded coil conductors are described in the table below.

Coil conductor belonging to a circuit	
Name	**Resistance formula [Ohm]**
B1, B2, B3	4*0.32392 = 1.29568

☞ Physics → Electrical components → Coil conductor → Edit

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

Inductor	
Name	**Inductance [Henry]**
L1, L2, L3	$4*1.408.10^{-3}$ = 5.632e-3

☞ Physics → Electrical components → Inductor → 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	7	4.7e-7 Ω	5.3e-9 H

☞ Physics → Electrical components → Squirrel cage → Edit

3.1.7. Modify face regions

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

Data The characteristics of the face regions used to describe the materials are presented in the tables below.

Face region			
Name	**Type**	**Material**	**Mechanical set**
STATOR	Magnetic non conducting	FEV_1000	MS_STATOR
ROTOR	Magnetic non conducting	FEV_1000	MS_ROTOR

Face region						
Name	**Type**	**Material**	**Circuit / No circuit**	**Associated solid conductor**	**Orientation**	**Mechanical set**
ROTOR_CAGE1 _BAR1	Solid conductor	Copper	Circuit	BAR_1_SQUIRREL CAGE_1	Positive	MS_ROTOR
ROTOR_CAGE1 _BAR2	Solid conductor	Copper	Circuit	BAR_2_SQUIRREL CAGE_1	Positive	MS_ROTOR
ROTOR_CAGE1 _BAR3	Solid conductor	Copper	Circuit	BAR_3_SQUIRREL CAGE_1	Positive	MS_ROTOR
ROTOR_CAGE1 _BAR4	Solid conductor	Copper	Circuit	BAR_4_SQUIRREL CAGE_1	Positive	MS_ROTOR
ROTOR_CAGE1 _BAR5	Solid conductor	Copper	Circuit	BAR_5_SQUIRREL CAGE_1	Positive	MS_ROTOR
ROTOR_CAGE1 _BAR6	Solid conductor	Copper	Circuit	BAR_6_SQUIRREL CAGE_1	Positive	MS_ROTOR
ROTOR_CAGE1 _BAR7	Solid conductor	Copper	Circuit	BAR_7_SQUIRREL CAGE_1	Positive	MS_ROTOR

Face region		
Name	**Type**	**Mechanical set**
INFINITE	Air or Vacuum region	MS_STATOR
PRESLOT	Air or Vacuum region	MS_STATOR
ROTATING_AIRGAP	Air or Vacuum region	MS_STATOR
STATOR_AIR	Air or Vacuum region	MS_STATOR
WEDGE	Air or Vacuum region	MS_STATOR
ROTOR_AIR	Air or Vacuum region	MS_ROTOR
SHAFT	Air or Vacuum region	MS_ROTOR

☞ **Physics → Face region → Edit**

3.1.8. Modify coil conductors 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**	**Symmetries and periodicities**	**Mechanical set**
PHASE_POS_1	Coil conductor	B1	80	Positive	All in series	MS_STATOR
PHASE_POS_2	Coil conductor	B2	80	Positive	All in series	MS_STATOR
PHASE_NEG_3	Coil conductor	B3	80	Negative	All in series	MS_STATOR

☞ 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

CASE1 project is solved using reference value.

Action

Solve and save the project under the following conditions:

- Solve with: **reference values**
- Project name: CASE1_SOLVED

☞ **Solving → Solve**

3.3. Case 1: 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 CASE1.

Contents

This section contains the following topics:

3.3.1. Display isovalues of the magnetic flux density on face regions

Goal

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

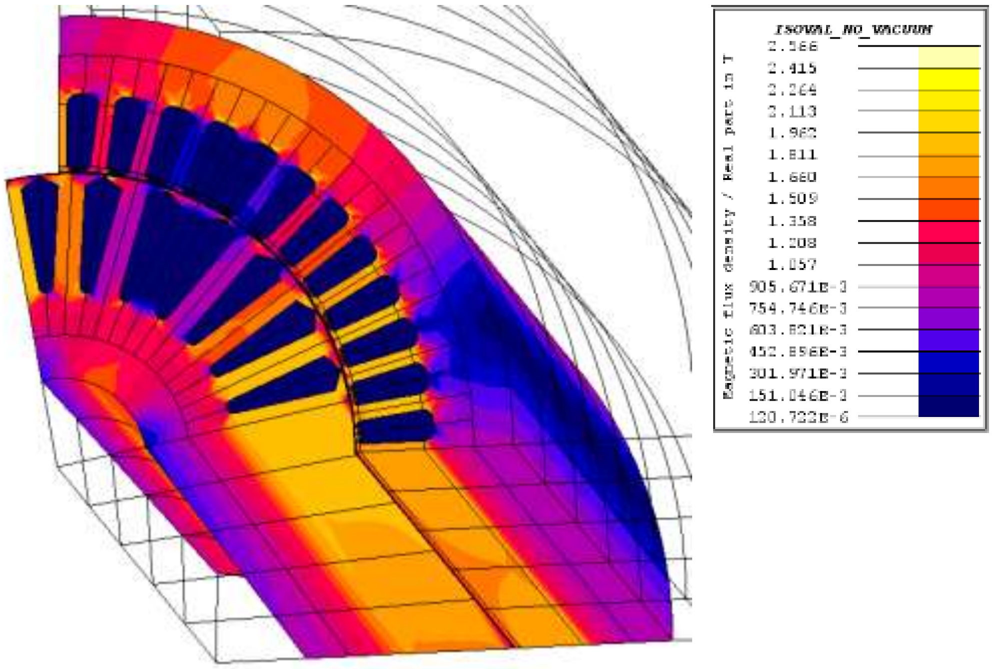
Action

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.



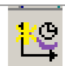
3.3.2. Compute the stator current and torque at no load

Goal The RMS stator current and torque are computed for the steady state case.

Data The characteristics of the different computations are presented in the table below.

Compute on physic entity				
Name	**Computed formula** Circuit			
	Electrical comp.		**Quantity**	
	Type	**Name**	**Quantity**	***Formula***
COMPUTE PHYSIC_1	Coil conductor	B1	Current – rms value [A]	*Mod(I(B1))/Sqrt(2)*
		B2	Current – rms value [A]	*Mod(I(B2))/Sqrt(2)*
		B3	Current – rms value [A]	*Mod(I(B3))/Sqrt(2)*

Name	**Computed formula** Mechanical set		
	Mechanical set	**Quantity**	***Formula***
COMPUTE PHYSIC_1	MS_ROTOR	Electromagnetic torque	*TorqueElecMag(MS_ROTOR)*

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

Result The result of the computation is presented below.

Computed formulas	**Results of computation**	
	Label	**Value**
Mod(I(B1))/Sqrt(2)	Current – rms value [B1]	7.067 A
Mod(I(B2))/Sqrt(2)	Current – rms value [B2]	7.068A
Mod(I(B3))/Sqrt(2)	Current – rms value [B3]	7.067 A
TorqueElecMag(MS_ROTOR)	Mechanical set / magnetic torque [MS_ROTOR]	2.0 N.m

Action Do not forget to store the result of computation COMPUTEPHYSIC_1.

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 a 2D plots with the slip as a varying parameter. The rated values are computed with a slip coefficient of 0.0193 (~ 2%).

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.**

Contents

This chapter contains the following topics:

4.1. Case 2: physical description process

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

Contents This section contains the following topics:

4.1.1. Create I/O parameters

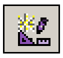
Goal

One I/O parameter will be created in order to define the physics.

Data (1)

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

I/O parameter controlled via a scenario	
Name	**Reference value**
SLIP	0.019

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

4.1.2. Modify a mechanical set

Goal A mechanical set is modified to describe the physics.

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

Mechanical set of type: **rotation around one axis**							
Name	**Comment**	**Axis**				**Kinematics**	
		Rotation axis	**Coord. system**	**Pivot point coordinates**		**Type**	**Slip**
				1st	**2nd**		
MS_ ROTOR	Moving part	parallel to Z-axis	XY1	0	0	Multi-static	SLIP

☞ **Physics → Mechanical set → Edit**

4.2. 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. Then CASE2 is solved.

Data

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

Solving scenario	
Name	**Comment**
CHARACTERISTICS	Study using geometrical and physical parameter

Solving scenario					
Parameter control					
Controlled parameter	**Type**	**Interval**			
		Lower limit	**Higher limit**	**Method**	**Value**
SLIP	Multi-values	0.001	1.0	List of steps	0.001, 0.010, 0.012, 0.019, 0.03, 0.05, 0.07, 0.09, 0.15, 0.2, 0.3, 0.4, 0.6, 0.8, 1.0

☞ **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**

4.3. 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 CASE2.

Contents

This section contains the following topics:

4.3.1. 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**	**Computation domain**	
PJCS	Stator joules losses	Stranded coil conductor	B1, B2, B3

☞ Advanced → Sensor → New

Action Evaluate the sensor.

☞ Advanced → Sensor → Evaluate sensors

4.3.2. 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.
In the end, this macro create an I/O parameter "BertottiLosses" which can be used to make a power balance.

Action (1)

Load macro named **BertottiIronLossesVsSlipAcImSk.PFM** (located in the directory: Macros_FluxSkewed_Postproc) in the current project.

☞ Project → Macro → Load

Action (2)

Run the macro.

☞ In the Data Tree: Extensions → Macros → Run

Data

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

- hysteresis losses coefficient kh = 363 Ws/T^2m^3
- classical losses coefficient σ = 4739300 $\Omega^{-1}m^{-1}$
- losses in excess coefficient k_e = 16.2 $Ws^{1.5}/m^3/T^{1.5}$
- thickness of laminations d = 0.65 mm
- stacking factor k_f = 0.97

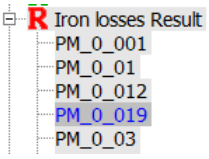
The characteristics of the macro (**BertottiIronLossesVsSlipAcImSk.PFM**) are presented below.

BertottiIronLossesVsSlipAcIm.PFM							
Scenario	**Variation parameter**	**Volume region**	**Hysteresis losses coeff.**	**Classical losses coeff.**	**Loss in excess coeff.**	**Thickness of lamination**	**Stacking factor**
CHARACTERISTICS	SLIP	STATOR	363	4.7393 e6	16.2	0.65 e-3	0.97

Continued on next page

Result for a slip value equal to 0.019

In the data tree, in the Post processing directory, edit the result PM_0_019.



The following results appear:

Name of the result	Result	
	Average iron losses (over a period) (W)	Values
PM_0_019	Total	**50.17 W**
	By hysteresis	13.71 W
	Classical by eddy currents	6.23 W
	In excess	30.23 W

Technical note

The iron stator losses for the modelled part (1/4 of the motor) are 50.17 W. The total core loss for the whole motor is **200.6** W.

4.3.3. Create I/O parameter

Goal Create some I/O parameter to help the user to carry out a power balance.

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

I/O parameters defined by a formula

Name	Comment	Expression
PERIODICITY	Periodicity of the machine	4
FREQ	Frequency	50
MECHANICAL_ LOSSES	Mechanical losses	554.0
PABS	Absorbed power	- PowerP(V1) - PowerP(V2) - PowerP(V3)
SABS	Absorbed apparent power	PowerS(V1) + PowerS(V2) + PowerS(V3)

To create **PABS** and **SABS** parameters, write the formula directly in the **Expression** area. See the note at the end of section.

Name	Comment	Expression
SPEED	Angular Velocity	(1-SLIP) * FREQ *60 / (POLES/2)
I_STA	Stator Current	Mod(I(B1) / sqrt(2))
COS_PHI	Cos ϕ	PABS / SABS
PTR	Power transmitted to the rotor	PABS - PJCS
PJR	Joules Rotor Losses	SLIP * PTR
PU	Shaft power	(1-SLIP)*PTR-MECHANICAL_LOSSES
TORQUE	Util Torque	PU/(2*pi() * FREQ / (POLES/2))
EFFI	Efficiency	100*(PU/(PABS+(PERIODICITE* BERTOTTI_LOSSES)))

☞ **Advanced → Parameter I/O → New**

Remarks

To perform the power balancing, P_{TR}, the power given to the rotor part is calculated with the following formula :

$$P_{TR} = P_{ABS} - P_{JCS}$$

Consideration on equivalent electric circuit give joule rotor losses :

$$P_{JR} = g * P_{TR}$$

In Flux, Iron Losses are calculated at posteriori - during the processing stage. As a result, these are only taking in count at the end of calculation of the power balancing (see parts relative to this determination).

About PowerP and PowerS functions

Functions **PowerP** and **PowerS** are postprocessing functions; these functions are available via the command **Compute on Physic entity**, but these functions are not directly available via the command **Parameter I/O / New**.

To create the **PABS** and **SABS** parameters, 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='PABS',formula='-PowerP(V1)-PowerP(V2)-PowerP(V3)')
VariationParameterFormula
(name='SABS',formula='PowerS(V1)+PowerS(V2)+PowerS(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	
Apparent power	PowerS	VA	$\text{PowerS} = \text{ModC}\left(\frac{1}{2} U \cdot I^*\right)$
Active power	PowerP	W	$\text{PowerP} = \text{Real}\left(\frac{1}{2} U \cdot I^*\right)$
Reactive power	PowerQ	VAR	$\text{PowerQ} = \text{Im}\left(\frac{1}{2} U \cdot I^*\right)$

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

SABS =PowerS(V1)+PowerS(V2)+PowerS(V3)
SABS = ModC(U(B1)*Conj(I(B1)/2))
      +ModC(U(B2)*Conj(I(B2)/2))
      +ModC(U(B3)*Conj(I(B3)/2))
```

4.3.4. Steady state rated-load characteristics

Goal

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

Data (1)

The characteristics* of the computation step are presented in the table below.

Scenario and computation step selection		
Scenario	**Computation step**	
	Parameter name	**Value**
CHARACTERISTICS	SLIP	0.019

* These characteristics are located in the dialog box below the data tree.

Data (2)

The characteristics of the computation (motor for steady state rated-load operation) are presented in the table below.

Compute on physic entity	
Name	**Computed formula**
	Expression
COMPUTEPHYSIC_1	SPEED
	I_STA
	TORQUE
	COS_PHI

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

Result

The result of the computation is presented below.

Physical quantities	**Results of computation**	
	Label	**Value**
Angular speed (tr/mn)	SPEED	**1471.5**
I stator (A)	I_STA	11.79
Torque (N.m)	TORQUE	30.77
Power factor	COS_PHI	0.73

Action

Do not forget to store the result of computation COMPUTEPHYSIC_1.

4.3.5. Power balance and efficiency for rated value

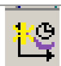
Goal

In this part, we propose to determine the machine's efficiency using the above results. By using an equivalent electrical circuit, there is a very easy way to calculate the joule rotor losses

Data (1)

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

Compute on physic entity		
Name	**Computed formula** / **Expression**	f()
POWER_BALANCE	PABS	
	PJCS	
	PERIODICITE* BERTOTTI_LOSSES	
	PJR	
	MECHANICAL_LOSSES	
	PU	
	EFFI	

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

Result

The result of the computation is presented below.

Physical quantities	**Results of computation**	
	Label	**Value**
Input Electrical Power	PABS	6034 W
Stator Joules Losses	PJCS	540.8 W
Total Stator Core Losses	PERIODICITE* BERTOTTI_LOSSES	200.7 W
Rotor Joule Losses (P_{jr})	PJR	104.3 W
Mechanical Losses (P_m)	MECHANICAL_LOSSE S	552.4 W
Output Mechanical Power (P_{mec})	PU	4836.48 W
Efficiency $\frac{PU}{P_{ABS}+P_{Fe}}$	EFFI	77 %

Action

Do not forget to store the result of computation POWER_BALANCE.

4.3.6. 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.

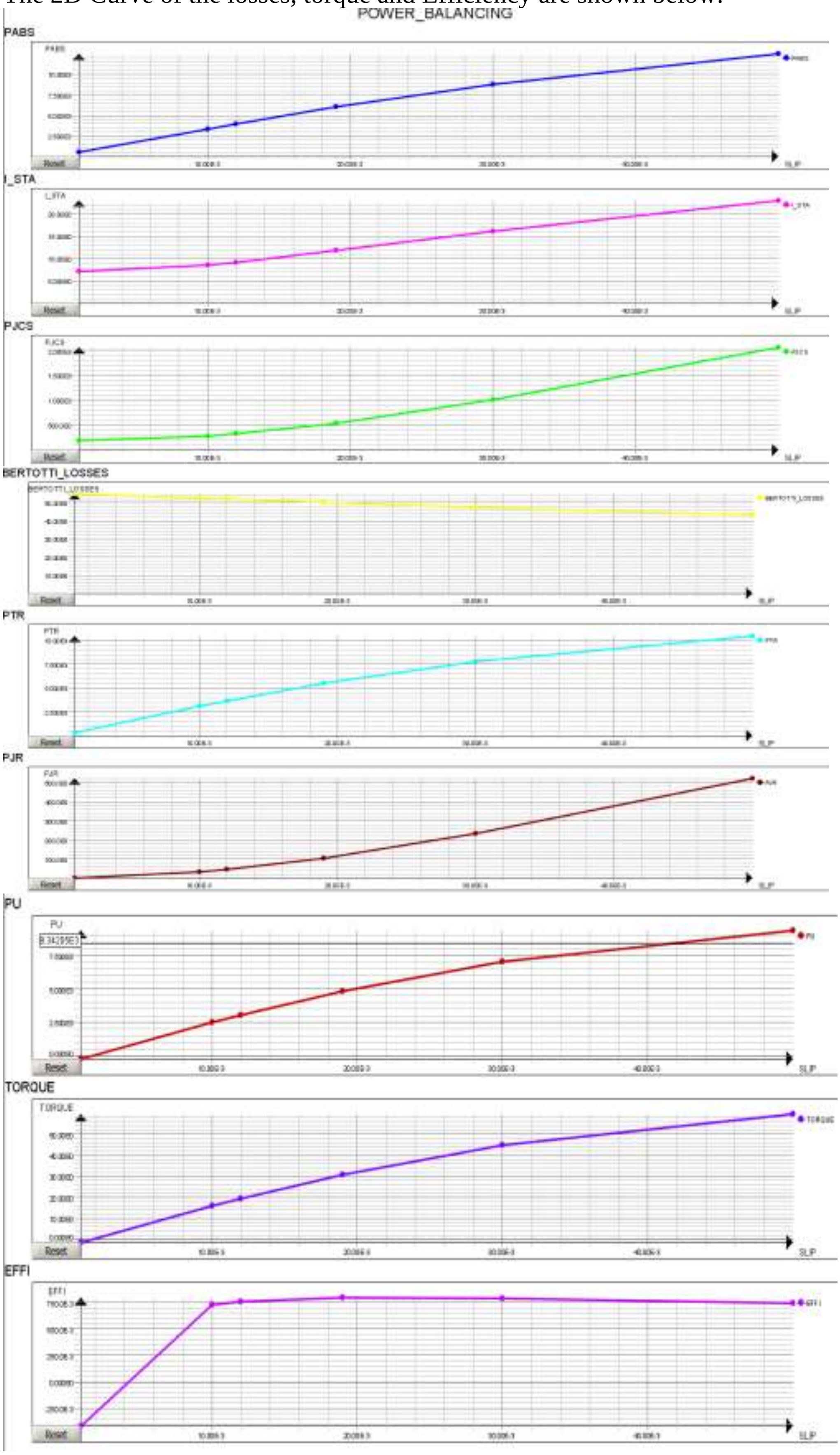
2D curve (I/O parameter)				
Name	**I/O Parameter on the abscissa**			**Formula on the ordinate**
	Parameter name	**Lower endpoint**	**Upper endpoint**	f()
POWER_BALANCE	SLIP	0.001	0.05	PABS
				I_STA
				PJCS
				PERIODICITE* BERTOTTI_LOSSES
				PTR
				PJR
				PU
				TORQUE
				EFFI

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

Continued on next page

Result

The 2D Curve of the losses, torque and Efficiency are shown below.



4.3.7. Display isovalues of magnetic flux density

Goal

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

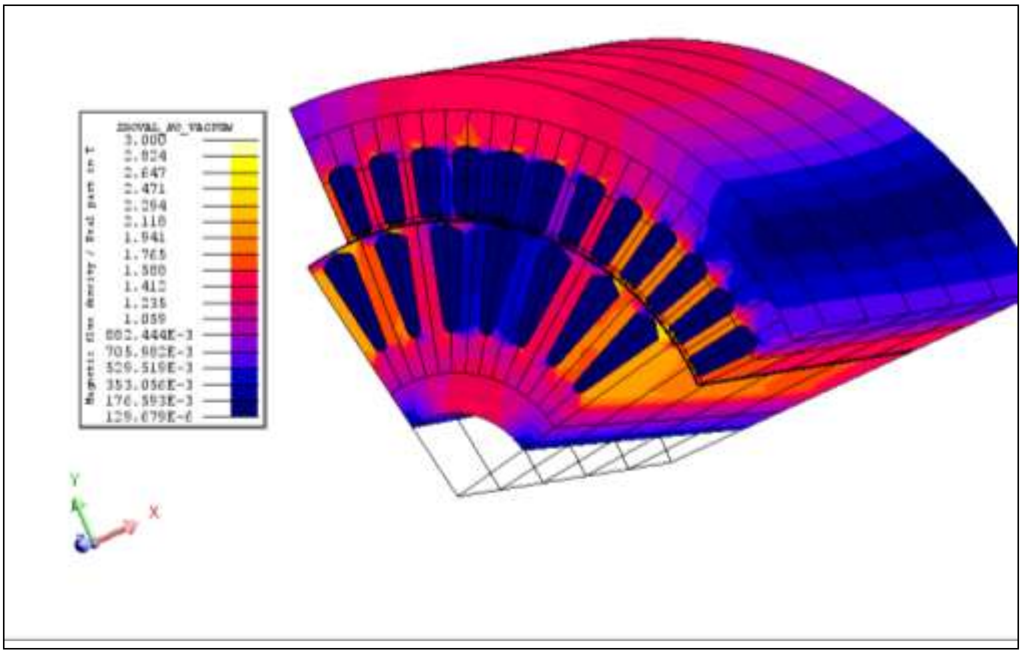
Action

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.



4.3.8. Display isovalues of current density in rotor bars

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	Volume regions
GROUP_ROTOR_CAGE1_BAR	Spatial group	Volume regions	ROTOR_CAGE1_BAR1
			…
			ROTOR_CAGE1_BAR7

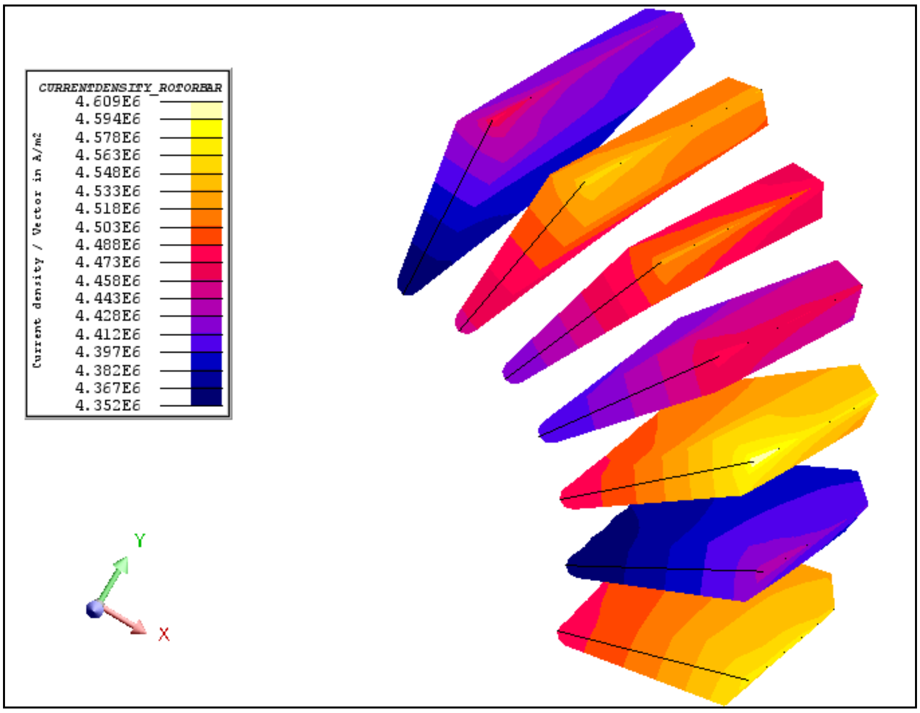
☞ Support → Spatial group → New

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 = 0.019).



5. Case 3: Transient Analysis - No load case

Case 3

The no load state is now computed with the transient magnetic application.

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: define the physics

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

Contents

This section contains the following topics:

5.1.1. Define the physical application

Goal The choice of the physical application determines the set of options available to the user in terms of physical properties.

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

Rotating Machine (Skewed Model) in Transient Magnetic				
Physical Definition				
Skewed rotor or stator	Multilayer model	Elevation in meter	Angle of rotation (deg.)	Number of slices in the elevation
Rotor with skewed slots	Multilayers 2D model	0.14	10.23	5

Coil Coeffcient
Automatic coefficient (Symmetry & Periodicity take into account)

Transient initialization
With zero initial solution (variables set to 0)

☞ **Application → Delete current application**

☞ **Application → Define→ Magnetic → Rotating Machine (Skewed Model) in Transient Magnetic**

5.1.2. Modify a mechanical set

Goal

The study of the no load state is performed using the Imposed speed kinematic model

Data

The characteristics of the MS_ROTOR mechanical set are presented in the table below.

Rotation around one axis mechanical set						
Name	Comment	Axis				Kinematics
		Rotation axis	Coord. system	Pivot point coordinates		Type of kinematics
				1st	2nd	
MS_ROTOR	Movable part	parallel to Z-axis	XY1	0	0	**Imposed Speed**

Kinematics (continued)						
General		Internal characteristics				
Velocity	Position t = 0 s	Type of load	Moment of inertia	Friction coef.		
				Cst	Viscous	Friction
1500	**0**	**Inertia, friction coeff. and spring**	**0.4936**	**0**	**3.927 e-4**	**0**

☞ **Physics → Mechanical set → Edit**

5.1.3. Create I/O parameters

Goal Three new I/O parameters will be created in order to define the physics.

Data (1) The characteristics of the I/O parameter are described in the tables below.

I/O parameters defined by a formula	
Name	**Expression**
SPEED	1500
FREQ	(SPEED/60)*(POLES/2)
OMEGA	2*Pi()*FREQ

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

5.1.4. Import a created circuit

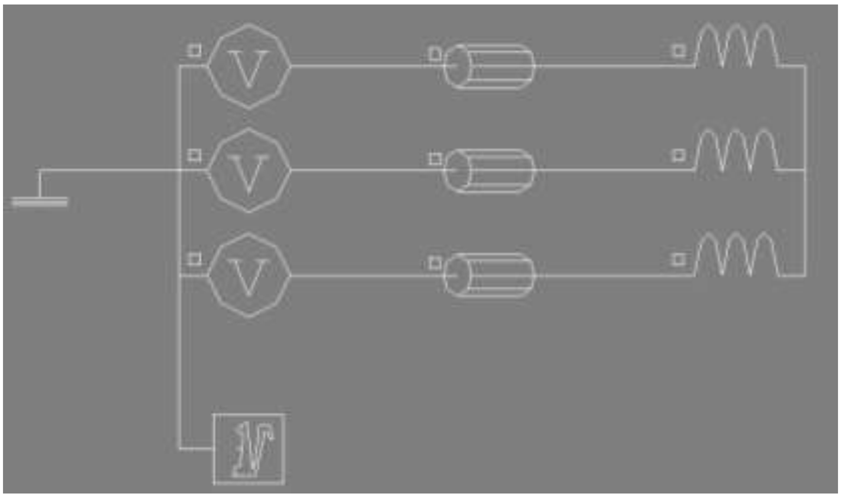
Action

Import the .xcir circuit named « InductionSkewedMotor.xcir ».

☞ | Physics → Circuit → Import a circuit from a .xcir file |

Result

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



5.1.5. Modify characteristics of electrical components

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

Data (1) The characteristics of the voltage sources are described in the table below.

Voltage source by formula	
Name	**Value [V]**
V1	VRMS * Sqrt(2) * sin(OMEGA*TIME)
V2	VRMS * Sqrt(2) * sin(OMEGA*TIME – 2*pi()/3)
V3	VRMS * Sqrt(2) * sin(OMEGA*TIME + 2*pi()/3)

☞ **Physics → Electrical components → Voltage source → Edit**

Data (2) The characteristics of the stranded coil conductors are described in the table below.

Stranded coil conductors belonging to a circuit	
Name	**Resistance formula [Ohm]**
B1, B2, B3	1.29568

☞ **Physics → Electrical components → Stranded coil conductor → Edit**

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

Inductor	
Name	**Inductance [Henry]**
L1, L2, L3	1.408 e-3 * 4

☞ **Physics → Electrical components → Inductor → Edit**

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

Squirrel cage		
Number of bars	7	
Resistance of the portion of end rings between two adjacent bars	4.7e-7	Ω
Inductance of the portion of end rings between two adjacent bars	5.3e-9	H

☞ **Physics → Electrical components → Squirrel cage → Edit**

5.1.6. Modify face regions

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

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

Face region			
Name	**Type**	**Component**	**Mechanical set**
STATOR	Magnetic non conducting	FEV_1000	MS_STATOR
ROTOR	Magnetic non conducting	FEV_1000	MS_ROTOR

Face region						
Name	**Type**	**Material**	**No / uit**	**Associated solid conductor**	**Orientati**	**Mechanical**
ROTOR_CAGE1_ BAR1	Solid conductor	Copper	Circuit	BAR_1_SQUIRRE LCAGE_1	Positive	MS_ROTOR
ROTOR_CAGE1_ BAR2	Solid conductor	Copper	Circuit	BAR_2_SQUIRRE LCAGE_1	Positive	MS_ROTOR
ROTOR_CAGE1_ BAR3	Solid conductor	Copper	Circuit	BAR_3_SQUIRRE LCAGE_1	Positive	MS_ROTOR
ROTOR_CAGE1_ BAR4	Solid conductor	Copper	Circuit	BAR_4_SQUIRRE LCAGE_1	Positive	MS_ROTOR
ROTOR_CAGE1_ BAR5	Solid conductor	Copper	Circuit	BAR_5_SQUIRRE LCAGE_1	Positive	MS_ROTOR
ROTOR_CAGE1_ BAR6	Solid conductor	Copper	Circuit	BAR_6_SQUIRRE LCAGE_1	Positive	MS_ROTOR
ROTOR_CAGE1_ BAR7	Solid conductor	Copper	Circuit	BAR_7_SQUIRRE LCAGE_1	Positive	MS_ROTOR

Face region		
Name	**Type**	**Mechanical set**
INFINITE	Air or Vacuum region	MS_STATOR
PRESLOT	Air or Vacuum region	MS_STATOR
ROTATING_AIRGAP	Air or Vacuum region	MS_STATOR
STATOR_AIR	Air or Vacuum region	MS_STATOR
WEDGE	Air or Vacuum region	MS_STATOR
ROTOR_AIR	Air or Vacuum region	MS_ROTOR
SHAFT	Air or Vacuum region	MS_ROTOR

☞ **Physics → Face region → Edit**

5.1.7. Modify coil conductors 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**	**Series / Parallel**	**Symetries and periodicities**	**Mechanical set**
PHASE_POS_1	Coil conductor region	B1	80	Positive	All in series	In series	MS_STATOR
PHASE_POS_2	Coil conductor region	B2	80	Positive	All in series	In series	MS_STATOR
PHASE_NEG_3	Coil conductor region	B3	80	Negative	All in series	In series	MS_STATOR

☞ Physics → Face region → Edit

Action

Check physics and save case 3.

☞ Physics → Check Physics

☞ Save Case3

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. Then CASE3 is solved with modified solving options.

Data (1)

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

Solving scenario					
Name	**Type**	**Lower limit**	**Upper limit**	**Variation method**	**Step value**
TIME_PARAM	Control by time	0	0.12	Step value	4 e-4

☞ Solving → Solving scenario → New

Data (2)

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**
1.0 e-4	100	Fujiwara method

☞ Solving → Solving process option → Edit

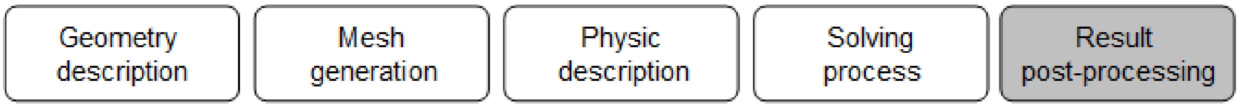
Action

Solve and save the project under the following conditions:

- Solve with: scenario TIME_PARAM
- Project name: CASE1_SOLVED

☞ Solving → Solve

5.3. Case 3: result post processing



Introduction

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

Contents

This section contains the following topics:

5.3.1. Display isovalues of magnetic flux density

Goal

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

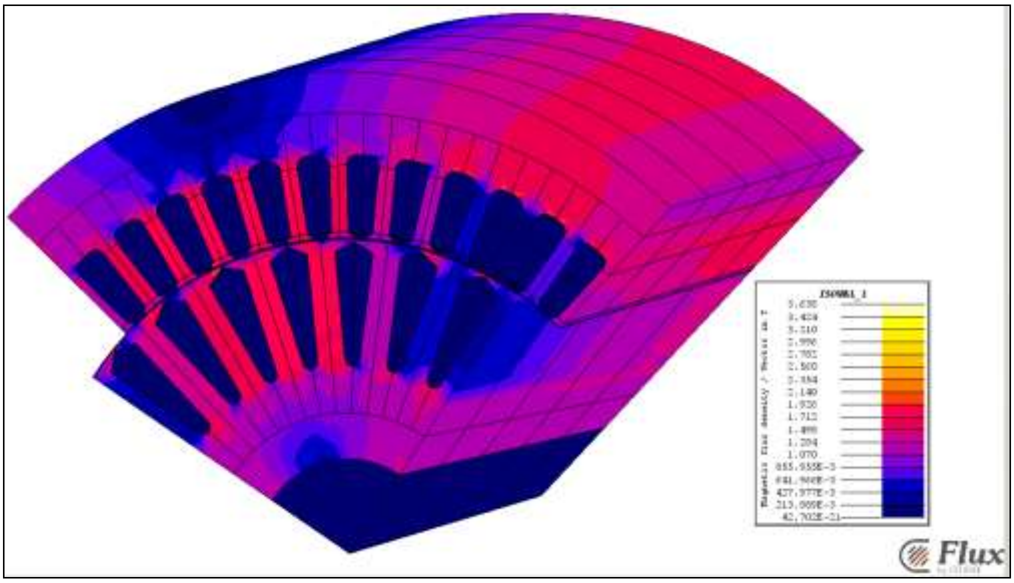
Action

Display isovalues (ISOVAL_NO_VACUUM)

☞ **Graphic → Isovalues → Display isovalues**

Result

The following chart shows the isovalues of the magnetic flux density on the device.



5.3.2. 2D Curve of current through the different coils

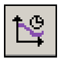
Goal

The values of the current through the different coils versus time are computed and displayed in a curve.

Data (1)

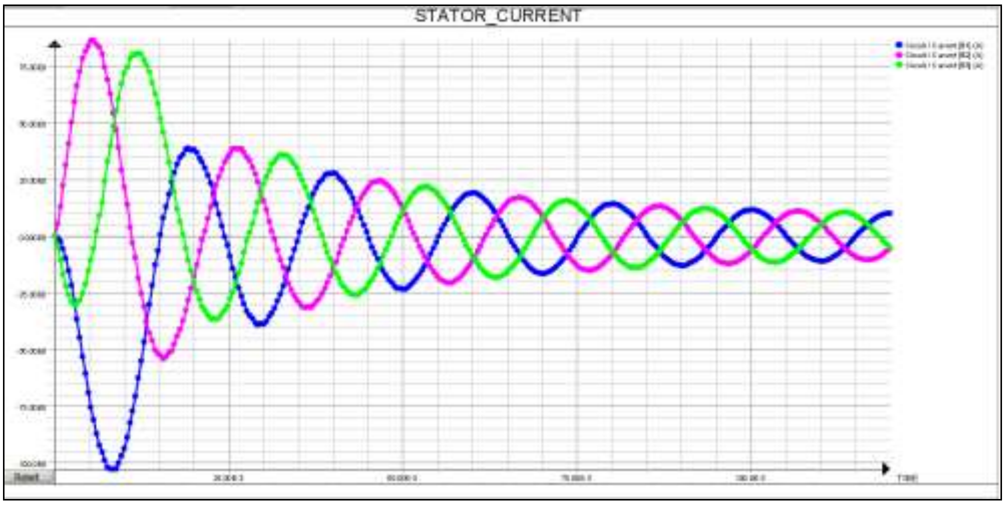
The characteristics of the curve are presented below.

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*
STATOR_ CURRENT	TIME	0.0	0.12	B1	Current [A]	*I(B1)*
				B2	Current [A]	*I(B2)*
				B3	Current [A]	*I(B3)*

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

Result (1)

The stator current versus time over the full analysis is shown below.



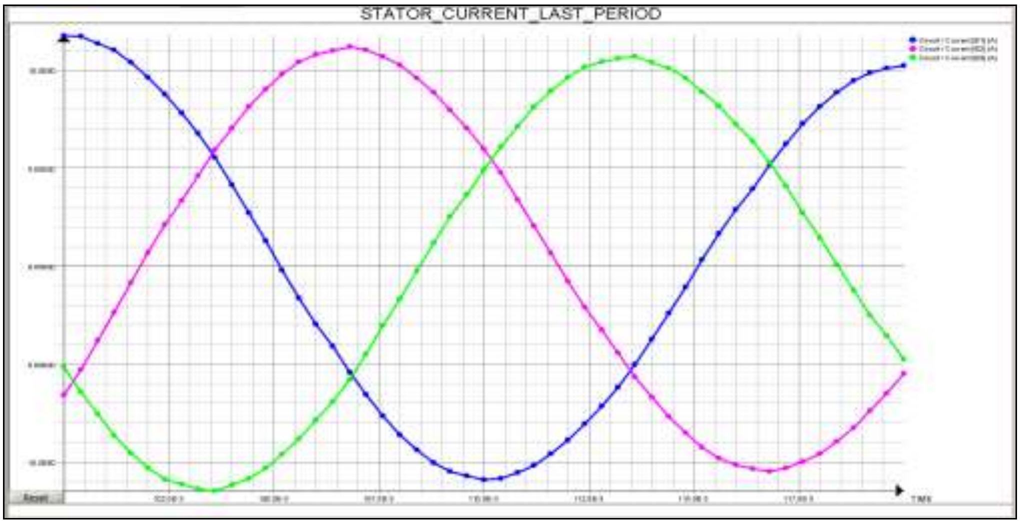
Continued on next page

Data (2) 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***
STATOR_ CURRENT	TIME	0.1	0.12	B1	Current [A]	*I(B1)*
				B2	Current [A]	*I(B2)*
				B3	Current [A]	*I(B2)*

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

Result (2) The current versus time over the last period is shown below.

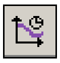


5.3.3. 2D Curve of torque versus time

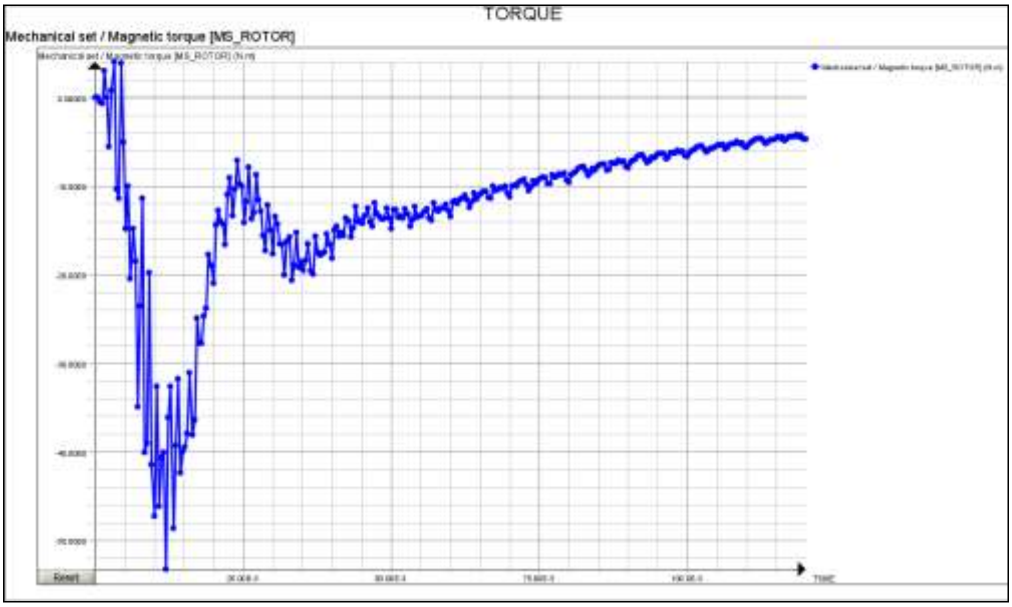
Goal The values of the torque versus time are computed and displayed in a curve.

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***
STATOR_ CURRENT	TIME	0.0	0.12	MS_ ROTOR	Electromagnetic torque	TorqueElecMag (MS_ROTOR)

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

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



6. Bibliographie

[LIW - 55] M. LIWSCHITZ, "Calcul des machines électriques", Tome I, Editions SPES, Lausanne, 1967.

7. Annexe

Contents

This chapter contains the following topics:

7.1. Mechanical Data

Contents

This section contains the following topics:

7.1.1. Determination of mechanical losses and friction coefficient

Introduction

We suggest a method below to calculate the losses by friction and ventilation and thus the coefficient of viscous frictions and the resistive torque. These parameters supplement the essential mechanical equation for the modeling and the simulation of the motor in startup mode.
The test corresponds to a no-load test in rotation. The phases of the stator winding are supplied by an alternating voltage source. Because the induction machine does not involve a mechanical load, the useful output is null. The machine thus functions in no-load mode. There is, however, a very low value of resistive torque, equivalent to the losses by friction and ventilation. Thus the slip is not completely null. As $P_u = 0$ then $P_{meca} = p_{f+V}$ and $g \approx 0$.

Operation description

We measure:

- The phase to phase voltage U_0
- The line current I_0
- The absorptive power P_0
- The no-load speed to make sure that the value of the slip is low.

The absorptive current I_0 is primarily limited by the stator impedance and the magnetizing impedance. Since the useful power is null, the absorptive power P_0 represents the sum of the following losses:

- Ohmic losses due to the no-load current I_0 : $3R_s I_0^2$
- The iron losses: p_{Iron}
- The mechanical losses due to frictions and ventilation: p_{f+v}

$$P_0 = 3R_s I_0^2 + p_{Iron} + p_{f+v} \qquad (22)$$

Knowing by measurement the values of P_0 , R_s and I_0, we can determine the sum of the iron, friction and ventilation losses:

$$P_0 - 3R_s I_0^2 = p_{Iron} + p_{f+v}$$

To differentiate these two losses, it is necessary to take measurements for various voltages included between $0.2U_n$ and $1.2U_n$.
The mechanical losses are roughly constant as long as the rotation speed does not vary too much.
The iron losses vary with the square of the voltage applied at the boundaries.
By tracing the variation of $P_0 - 3R_s I_0^2$ according to U_0^2, one obtains the characteristic shown in Figure 1, which is a line that one extrapolates until $U_0 = 0$. The corresponding ordinate is equal to the losses by friction and ventilation. In effect, with null tension, the losses irons are null.

Continued next page

Figure

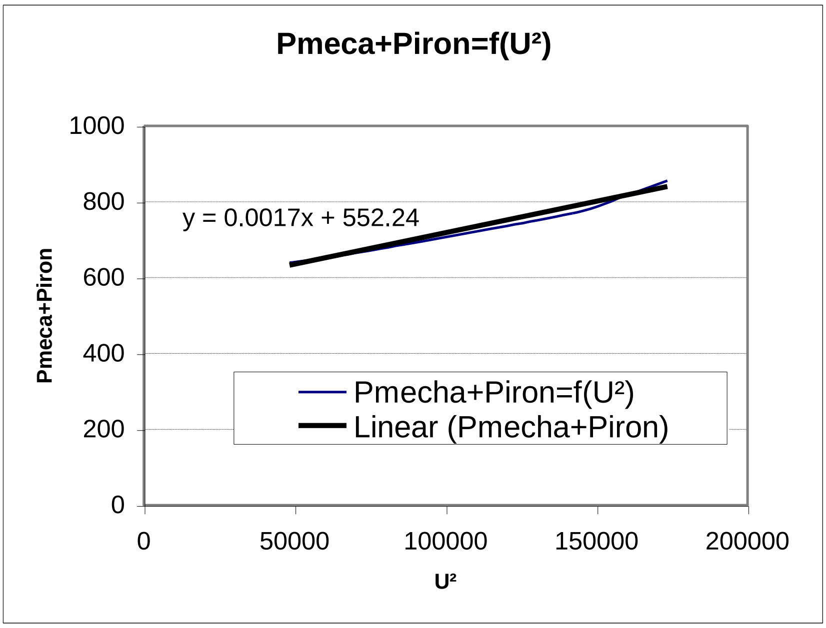


Figure 1 : P_iron + P_meca = f(U²)

Results obtained

In our case we obtained:

$$p_{f+v} = 552{,}4\,W$$

As

$$p_{f+v} = C_{f+v}\Omega_0$$

and

$$C_{f+v} = f\Omega_0$$

then the friction coefficient is given by

$$f = p_{f+v} / \Omega_0^2 = 2{,}25.10^{-2}\,N.m.s.rad^{-1}$$

7.1.2. Determination of inertia

Introduction

Simulations in coupled load also require the user to enter certain mechanical data, such as the inertia and the friction coefficient.
The aim of this section is to provide the user with analytical and experimental methods to determine the values of the parameters essential to the development of a model.

Operation descritpion

The determination of the inertia of the induction machine is done by measuring the speed according to the time of deceleration (see Figure 2).
The studied machine is brought to a speed approximately 20% higher than the nominal speed by means of a DC machine. Then when the power of the DC drive machine is cut, the studied machine slows down under the effect of the involved losses: the total mechanical losses of the group.

The time of deceleration depends on inertia and also on the involved losses.

The equation of motion gives:

$$J\frac{d\Omega}{dt}=M_r \qquad (20)$$

where

- J Inertia (kg.m^2)
- M_r Resistive torque due to losses (N.m) $\Rightarrow M_r = \dfrac{\sum Losses}{\Omega}$
- Ω Angular velocity (rad.s^{-1}) $\Rightarrow \Omega = \dfrac{2\pi.n}{60}$

With the preceding expression, inertia can be calculated by:

$$J = \frac{\sum Losses}{\Omega.\dfrac{d\Omega}{dt}} \cong \frac{\sum Losses}{\Omega.\dfrac{\Delta\Omega}{\Delta t}} \qquad (21)$$

where $\Delta\Omega/\Delta t$ represents the slope of the tangent to the curve of deceleration at point A. Point A corresponds to the point where the speed is nominal, because it is at this speed that the losses are known.

Continued next page

Numerical application

$$\Omega_{nom} = 154{,}09\ rad.s^{-1}$$
$$\Delta\Omega = 199{,}7\ rad.s^{-1}$$
$$\Delta t = 27{,}5\ s$$
$$p_{méca} = 552{,}4\ W$$

One finds then

$$J = \frac{552{,}4}{154{,}09 \times \frac{199{,}7}{27.5}} = 0{,}4936\ kg.m^2 \text{ and } M_r = \frac{552{,}4}{154{,}09} = 3{,}58\ N.m$$

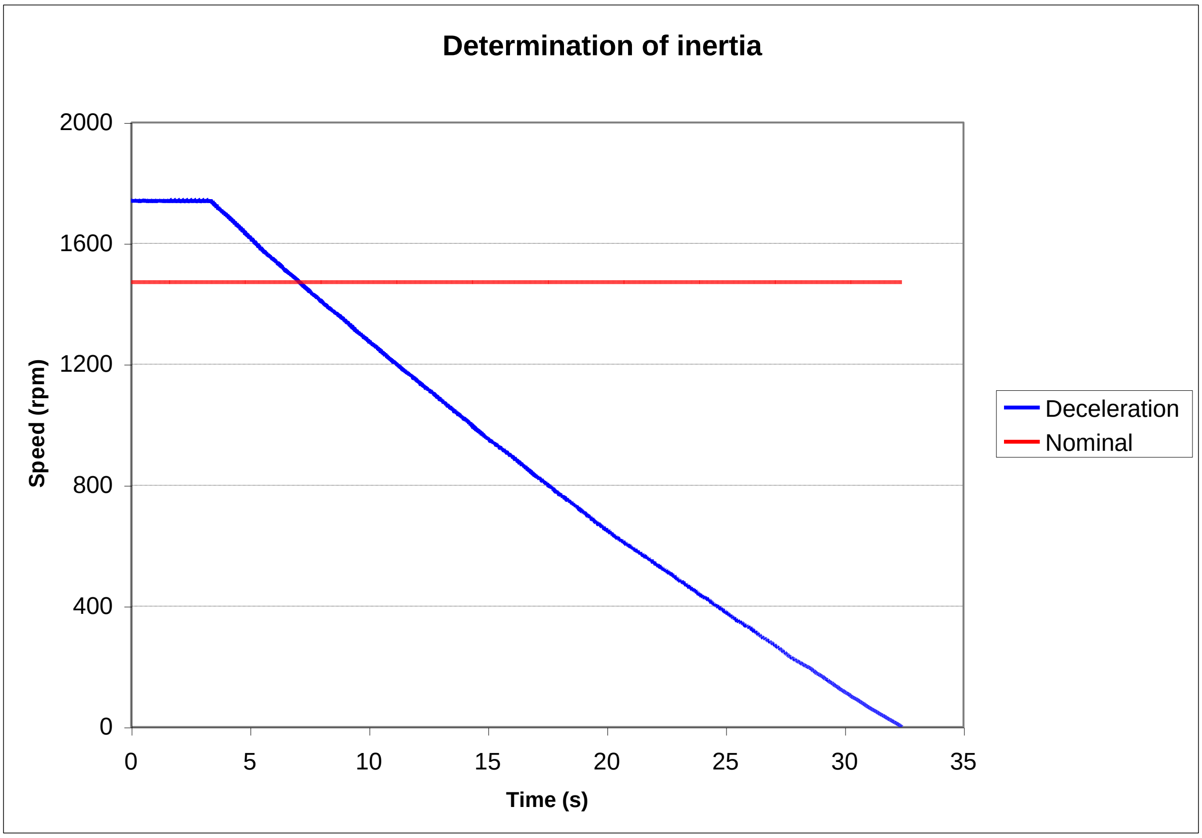


Figure 2: *determination of inertia*

7.2. Circuit Data

Contents This section contains the following topics:

7.2.1. Introduction of circuit data

The winding is concentric with consequent poles. It is represented in Figure 3.

The modeling of induction machines under Flux2D considers only the straight section of the geometry (as for SKEW application). Effects relating to the parts located at the end of the machine are taken into account by the addition of an electric circuit to the model with finite elements. This electric circuit integrates the end winding resistance and inductance to supplement the modeled part of the stator and the end ring resistance and inductance to supplement the modeled part of the rotor.
In addition simulations in coupled load require the user to enter certain mechanical data, such as the inertia and the friction coefficient.

The aim of this section is to provide to the user analytical and experimental methods in order to determine the values of the essential parameter to the development of a model.

Figure

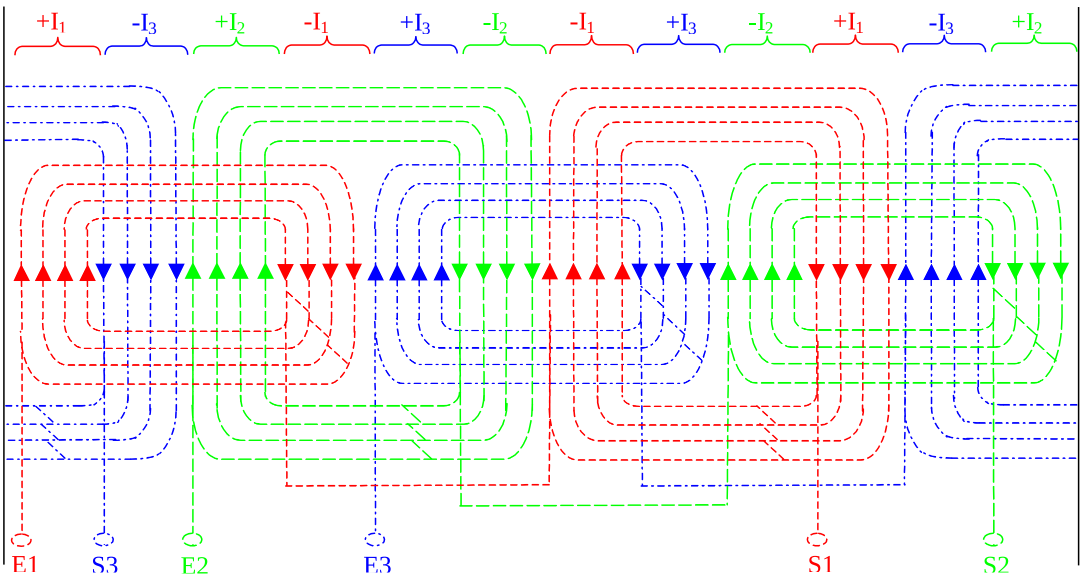
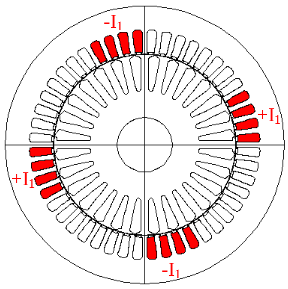
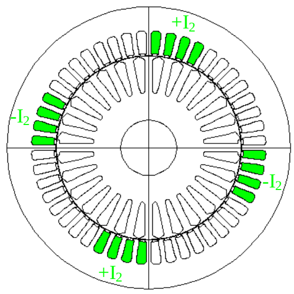
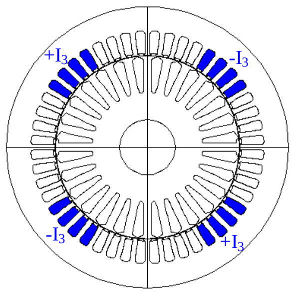


Figure 3 : Windings

Phase

		
Phase 1	Phase 2	Phase 3

7.2.2. Determination of the end winding impedance

Resistance per phase

The resistance per phase due to the end winding is given by

$$R_{ew} = \frac{8\rho\ell_{ew}N_{tpp}N_{spp}}{N_c N_w \pi d_w^2}, \qquad (1)$$

where

- ρ is the resistivity of a wire $(\Omega.m)$
- ℓ_{ew} is the length of the end winding (m)
- N_{tpp} is the number of turns per slot per phase
- N_{spp} is the number of slots per pole per phase
- N_c is the number of coils in parallel per phase
- N_w is the number of wires in series per phase
- d_w is the diameter of a wire (m^2).

End winding length

The calculation of the end winding length can be obtained by the following formulation

$$\ell_{ew} = \frac{\pi}{2p}\left(D_{ext} + 2h_{ss}\right) + 2h_{ss}, \qquad (2)$$

where

- D_{ext} is the internal diameter of the stator,
- h_{ss} is the height of a stator slot.

This first calculation gives an acceptable approximation of the end winding resistance.

Numerical application

$$\ell_{ew} = \frac{\pi}{2\times 2}\left(0{,}11 + 2\times 1{,}45.10^{-2}\right) + 2\times 1{,}45.10^{-2} = 13{,}8.10^{-2}\ m$$

$$R_{ew} = \frac{8\times 2{,}42.10^{-8}\times 9{,}16.10^{-2}\times 20\times 4}{1\times 1\times \pi\times 3{,}06.10^{-6}} = 0{,}147\ \Omega$$

Continued next page

End winding reactance

The end winding reactance is obtained by the following relation

$$X_{tb} = \frac{\mu_0 \omega}{18p}\left(\frac{N_{ss} N_{tpp}}{N_c}\right)^2 P\,, \qquad (3)$$

where

- N_{ss} is the number of stator slots
- μ_0 is the magnetic permeability of vacuum
- ω is the electrical pulsation relating to stator currents.

P is a parameter which depends on the winding. For a concentric winding with non-consequent poles, we have

$$P = 0.47\ell_{ew} - 0.3L_{ap} \qquad (4)$$

for a winding with consequent poles

$$P = 0.67\ell_{ew} - 0.43L_{ap} \qquad (5)$$

where

$$L_{ap} = \frac{\pi}{2p}\left(D_{ext} + h_{ss}\right) \qquad (6)$$

Numerical application

$$L_{ap} = \frac{\pi}{2\times 2}\left(0{,}11 + 0{,}0145\right) = 0{,}09778\ m$$

$$P = 0.67 \times 13{,}8.10^{-2} - 0.43 \times 0{,}09778 = 0{,}0504146\ \ m$$

$$L_{tb} = \frac{4\times\pi\times 10^{-7}}{18\times 2}\left(\frac{48\times 20}{1}\right)^2 0{,}0504146 = 1{,}62.10^{-3}\ H$$

7.2.3. Determination of the end ring impedance

Figure

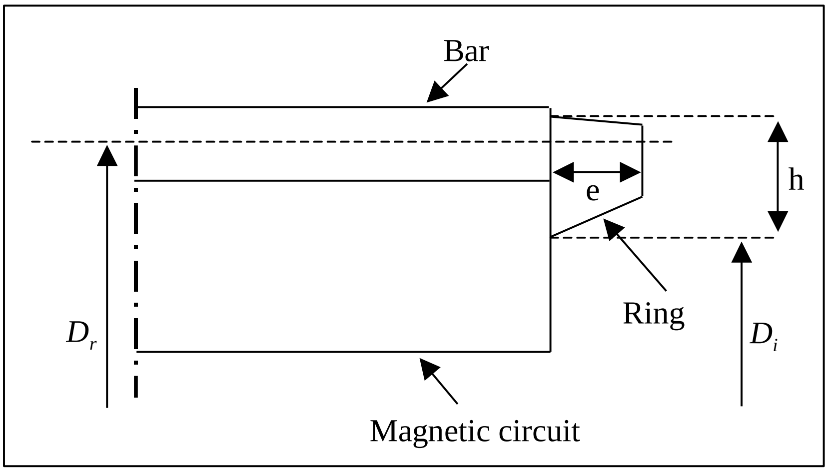


Figure 4: representation of the intersection bar-rings

End ring resistance

TRICKEY shows that the end ring resistance can be calculated from the following equation

$$R_{er} = \frac{2\pi . D_r \rho}{N_r e \left(D_r - D_i\right)} K_{ring} , \qquad (7)$$

where the coefficient of correction is given by

$$K_{ring} = \left[\frac{1 + \left(\frac{D_i}{D_r}\right)^{2p}}{1 - \left(\frac{D_i}{D_r}\right)^{2p}} \right] \left(1 - \frac{D_i}{D_r}\right) \qquad (8)$$

Skin effect

With Formulation 7 (above) it is possible to take into account the skin effect, which appears in two different ways:

- the first translates the variation of the useful height h_p of the bar,
- the second corresponds to that occurring in the thickness of the ring.

If the current does not penetrate completely into the width of a rotor bar, one understands easily that the diameter D_r to be used $\left(D_{réq}\right)$ is larger than that indicated in Figure 4.

According to the preceding assumptions, one can set the relation

$$D_{réq} = D_{ext} - h_p , \qquad D_{aext} = D_i + h \qquad (9)$$

Continued next page

Skin effect (continued)

where the penetration depth of the current in the bars h_p can be given according to the method suggested by M.M. LIWSCHITZ-GARIK [LIW-55].

This approach initially requires one to determine the skin effect coefficient in the thickness of a bar

$$\varepsilon(\xi) = \xi \frac{\sinh(2\xi) + \sin(2\xi)}{\cosh(2\xi) - \cos(2\xi)} \qquad (10)$$

where

$$\xi = e\sqrt{\frac{\pi\mu_0 fs}{\rho}} \qquad s\text{- } slip \qquad (11)$$

The coefficient must be corrected by a factor K calculated according to the contact surfaces between the bar and the ring. Let $X = \frac{h_{éq}}{h_b}$ the relationship between these two surfaces:

- If $X < 2{,}36$ then $K = 0{,}01X^2 - 0.08X + 1{,}07$ (12)
- If $X > 2{,}36$ then $K = -0{,}017X + 0{,}977$ (13)

It follows then

$$h_b = h_p - (\frac{D_{ext} - D_{aext}}{2}); \qquad h_{éq} = \frac{\rho\pi D_{aext}}{R_a e + \pi\rho}; \qquad e_{éq} = \frac{eK}{\varepsilon(\xi)}; \qquad (14)$$

where R_a is resistance of end ring

$$R_a = \frac{\rho\pi p}{eh}(D_r - D_i)\left(\frac{D_r^{2p} + D_i^{2p}}{D_r^{2p} - D_i^{2p}}\right) \qquad (15)$$

So the useful width of the bar is

$$h_p = \frac{H}{\varepsilon(\xi)} \qquad (16)$$

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Figure

All of these calculations shown above enabled us to determine an equivalent thickness of the ring and a useful width of bar according to the frequency. One obtains an equivalent model (which takes into account the skin effect) represented in Figure 5.

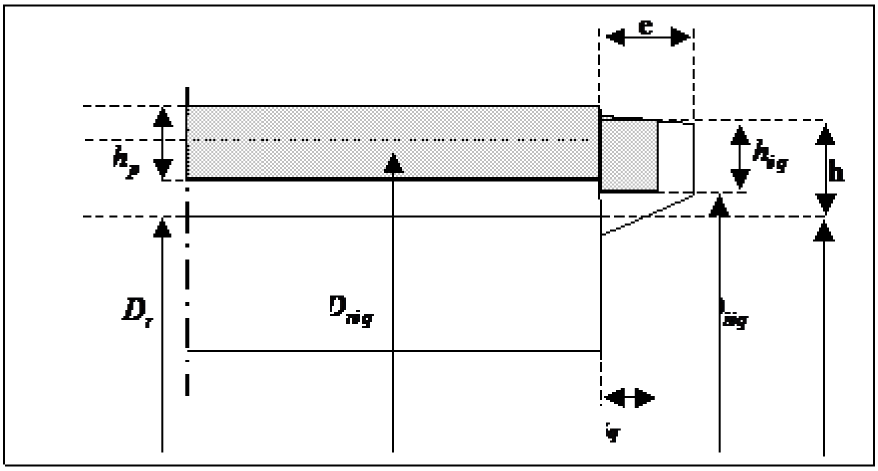

Figure 5: representation of the intersection bar-rings with skin thickness

Resistance inter-bar

The resistance of an inter-bar segment is obtained by applying Formula 7 to the equivalent ring, remembering to divide the result by the number of bars that make up the rotor:

$$r_a = \frac{1}{N_r}\frac{\rho\pi p}{e_{éq}h}\left(D_{réq} - D_i\right)\left(\frac{D_{réq}^{2p} + D_i^{2p}}{D_{réq}^{2p} - D_i^{2p}}\right) \quad (17)$$

Reactance

The calculation of the reactance is made by applying Formulation 18 to the equivalent ring

$$X_a = \pi\frac{\mu_0\omega}{N_r}\left(D_{aext} - h_{eq}\right)\lambda_a \quad (18)$$

$$\lambda_a = 0.365 Log\frac{3\pi\left(D_{aext} - h_{eq}\right)}{4\left(h_{eq} + e_{eq}\right)} \quad (19)$$

Continued on next page

Numerical application

All results obtained are presented in the table below.

Numerical application:	
$p = 2$	Number of pole pairs,
$e = 1{,}8.10^{-2}$	Ring thickness (m),
$h = 2{,}8.10^{-2}$	Ring height (m),
$H = 1{,}45.10^{-2}$	Slot height (m),
$D_r = 8{,}7.10^{-2}$	Diameter at the bar center (m),
$D_r = 5.10^{-2}$	Ring lower diameter (m),
$N_r = 28$	Number of rotor slots,
$\mu_0 = 4\pi 10^{-7}$	Magnetic permeability (H/m),
$f = 50$	Current stator frequency (Hz),
$D_{ext} = 1.092.10^{-1}$	Rotor external diameter (m)

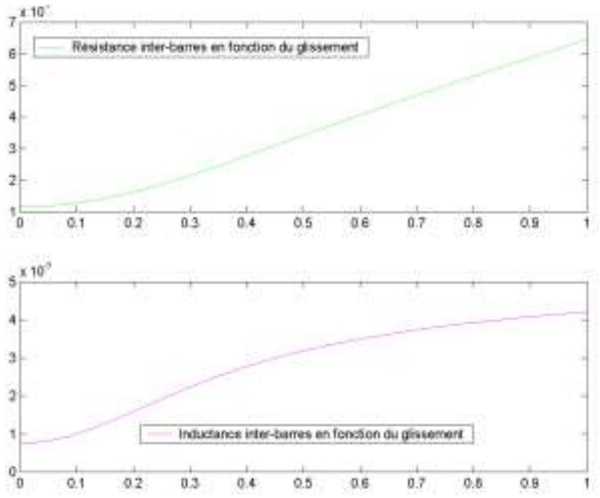

Figure 3: Results