Altair® FluxMotor® 2024.1

Synchronous machines – Permanent magnets - Inner & Outer rotor

Motor Factory – Test – Characterization

General user information

Altairhyperworks.com

Contents

1 CHARACTERIZATION – OPEN CIRCUIT – MOTOR & GENERATOR – COGGING TORQUE

1.1 Overview

1.1.1 Positioning and objective

The aim of the test “**Characterization - Open circuit – Motor & Generator - Cogging torque**” is to get the characteristics of the cogging torque of the machine.
Thanks to this test it is possible to evaluate the impact of the machine topology (slots and magnets – number and dimensions) on the cogging torque characteristics (magnitude and period).

The following table helps to classify the test “Open circuit - Cogging torque”.

Family	Characterization
Package	Open circuit
Convention	Motor & Generator
Test	Cogging Torque

Positioning of the test “Characterization - Open circuit – Motor & Generator - Cogging torque”

1.1.2 User inputs

No user input parameter is necessary to perform this test. Only the operating temperature of the magnet can be defined in settings.

1.1.3 Main outputs

Test results are illustrated with data, graphs, and tables.

Table of results:

1) Flux in magnetic circuit
- Flux in airgap
- Flux density in iron

2) Cogging torque
- Characteristics (The cogging torque magnitude (peak-peak value) and its period)

Curves and graphs:

- Cogging torque versus rotor angular position (over one cogging torque period)
- Cogging torque harmonic analysis (bar graph and table)

1.2 Settings

One button gives access to the following setting definition:

- Thermal settings – Definition of the temperature of active components.
  Only the temperature of magnets is considered.

  For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section "thermal settings"

1.3 Inputs

1.3.1 Introduction

The total number of user inputs (parameters) is equal to four in addition to magnet temperature. All these are advanced input parameters.

1.3.2 Standard inputs

No standard user inputs are needed.

1.3.3 Advanced inputs

1.3.3.1 Number of computations per cogging torque period

The computation of cogging torque versus the rotor angular position is performed using a Finite Element Modeling.
"**No. comp. / cogging period**" (Number of computations per cogging torque period) influences the accuracy of results and the computation time.

The default value is equal to 45. The minimum allowed value is 13. This default value provides a good compromise between the accuracy of results and computation time.

1.3.3.2 Maximum harmonic order

The cogging torque is computed over one cogging torque period.

Harmonics are extracted from the frequency analysis (F.F.T. Fast Fourier Transform) of the cogging torque signal versus rotor angular position.

The order of harmonics displayed on bar graphs and in tables can be selected with this advanced user input parameter "**Max. harmonic order**" (Maximum harmonic order selected for visualization).

Note: From mathematical point of view, the maximum allowed harmonic order depends on the number of computations per electrical period. In case of too small number of computations per electrical period, the harmonic order considered will be lower than which user has set.
The default value is equal to 20. The minimum allowed value is 1.

1.3.3.3 Rotor initial position

The computations are carried out by considering a given initial relative angular position between the rotor and the stator.
This initial relative angular position of the rotor must be set in the field « **Rotor initial position** ».
This relative angular position corresponds to the angular distance between the direct axis of the rotor north pole and the axis of the stator phase 1 (reference phase). The default value is equal to 0. The range of possible values is [-360, 360].

For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section "Rotor and stator relative position"

1.3.3.4 Skew model – Number of layers

When the rotor magnets or the stator slots are skewed, the number of layers used in Flux® Skew environment to model the machine can be modified: "**Skew model - No. of layers"** (*Number of layers for modelling the skewing in Flux® Skew environment*).

Note: When there is magnet step skew topology, the number of layers is defined at the design level.

Warning: The default number of layers is equal to 3 but in some cases, this value must be increased to get more accurate results of cogging torque.

1.3.3.5 Airgap mesh coefficient

The airgap mesh density is a very sensitive parameter for cogging torque computation. To get better results, sometimes it is necessary to modify the default mesh considered by FluxMotor®.

The advanced user input "**Airgap mesh coefficient**" is a coefficient, which adjusts the size of mesh elements inside the airgap. When the value of "Airgap mesh coefficient" decreases, the mesh elements get smaller, leading to a higher mesh density inside the airgap, increasing the computation accuracy.

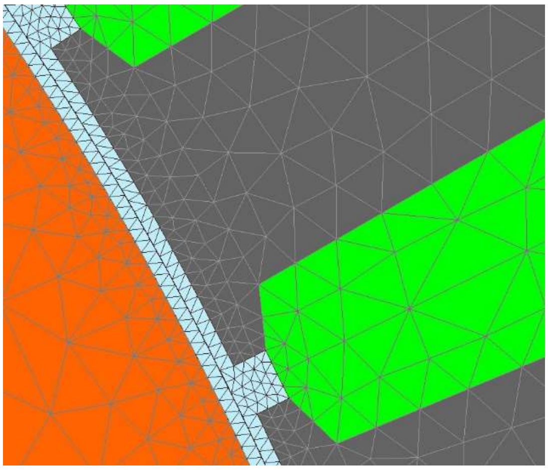
The imposed Mesh Point (size of mesh elements touching points of the geometry), inside the Altair® Flux® software, is described as:

$$\text{MeshPoint} = (\text{airgap}) \times (\text{airgap mesh coefficient})$$

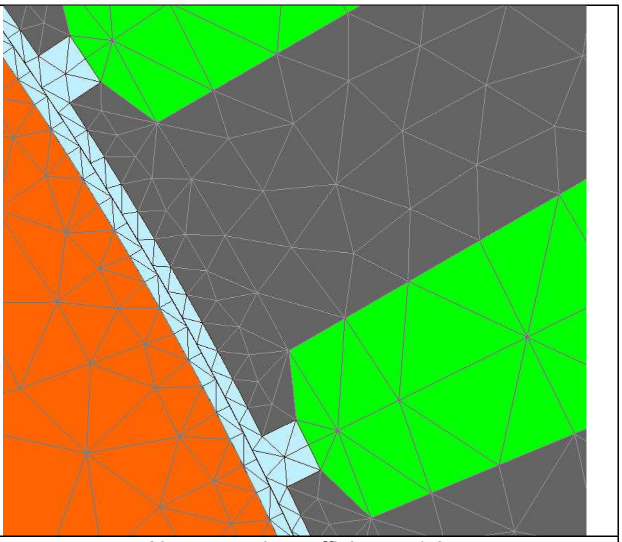
Airgap mesh coefficient is set to 0.45 by default.
The variation range of values for this parameter is [0.05; 2]
0.05 giving a very high mesh density and 2 giving a very coarse mesh density.

Caution:
Be aware, a very high mesh density does not always mean a better result quality. However, this always leads to a huge number of nodes in the corresponding finite element model. So, it means a need of huge numerical memory and increases the computation time considerably.

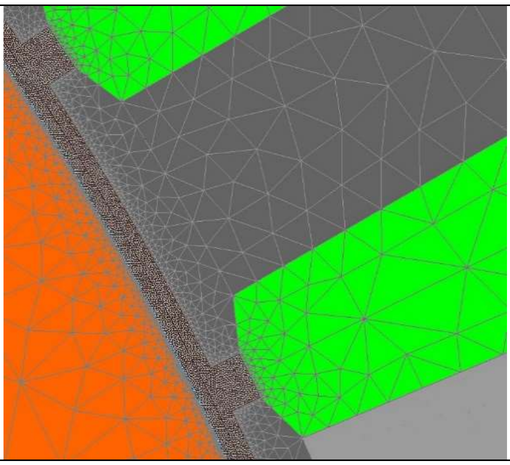
The impact of the airgap mesh coefficient on resultant meshing is illustrated bellow:



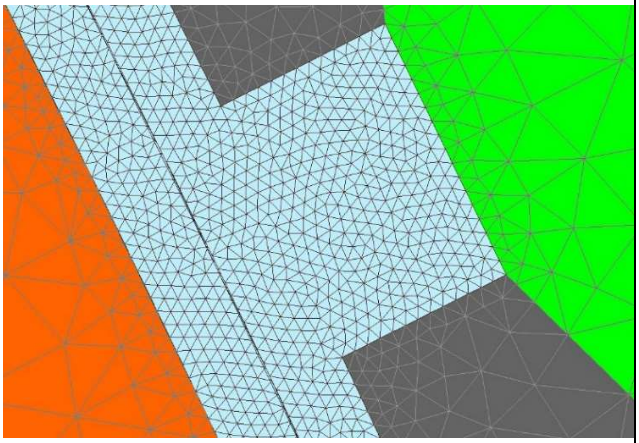
Airgap mesh coefficient = 0.45 = default value



Airgap mesh coefficient = 1.0



Airgap mesh coefficient = 0.1



Airgap mesh coefficient = 0.1 (zoomed view)

1.4 Main principles of computation

1.4.1 Cogging torque computation, overview

The electromagnetic torque computation is performed by using Magnetostatic application of Flux® (Finite Element software) inside FluxMotor®. The computation is done by considering multiple positions of the rotor.

To study electromagnetic devices, two types of energies (Magnetic field energy and co-energy) are considered.
The magnetic energy is expressed in terms of magnetic flux density B and magnetic field H by the following relation:

$$\mathrm{dWm} = \int_0^B \vec{\mathrm{H}} \cdot \mathrm{d}\vec{\mathrm{B}}$$

The magnetic energy in a volume is given by the integral:

$$\mathrm{Wm} = \int_V (\mathrm{dWm}) \times \mathrm{dV}$$

The magnetic co-energy is defined as:

$$\mathrm{dWm}' = \int_0^H \vec{\mathrm{B}} \cdot \mathrm{d}\vec{\mathrm{H}}$$

The magnetic co-energy in a volume is given by the integral:

$$\mathrm{Wm}' = \int_V (\mathrm{dWm}') \times \mathrm{dV}$$

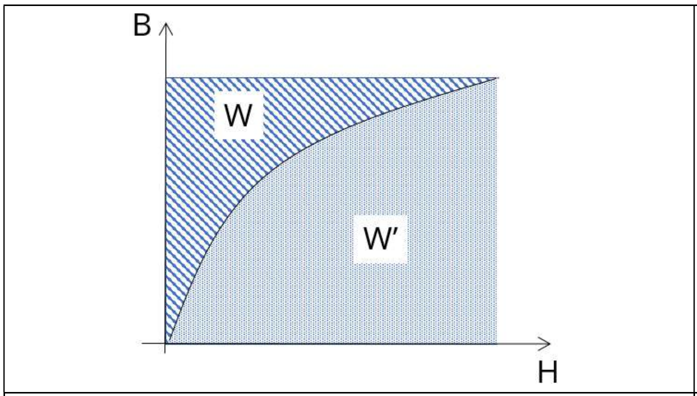
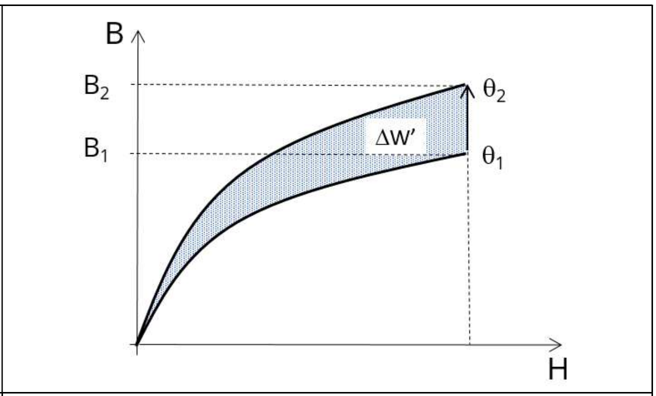


Illustration of magnetic energy and co-energy



Variation of co-energy
during movement of rotation from θ_1 to θ_2

Depending on the position of the rotor (from θ_1 to θ_2), the reluctance of the system changes, causing a variation of magnetic flux density, represented by the colored area $\Delta W'$ on the right graph. This area represents the variation of the co-energy when moving from θ_1 to θ_2.

As there is no exciting current in the device during the cogging torque test, cogging torque will appear only due to permanent magnet.

The cogging torque is derived from the airgap flux and reluctance variation in the magnetic circuit with respect to rotor angular displacement.
The electromagnetic torque (T_{em}) can be derived by differentiating the magnetic field energy or total co-energy with respect to mechanical angle using virtual work method as:

$$\mathrm{T_{em}} = -\frac{\partial \mathrm{W_m}}{\partial \theta}$$

Where θ = rotor angular displacement.

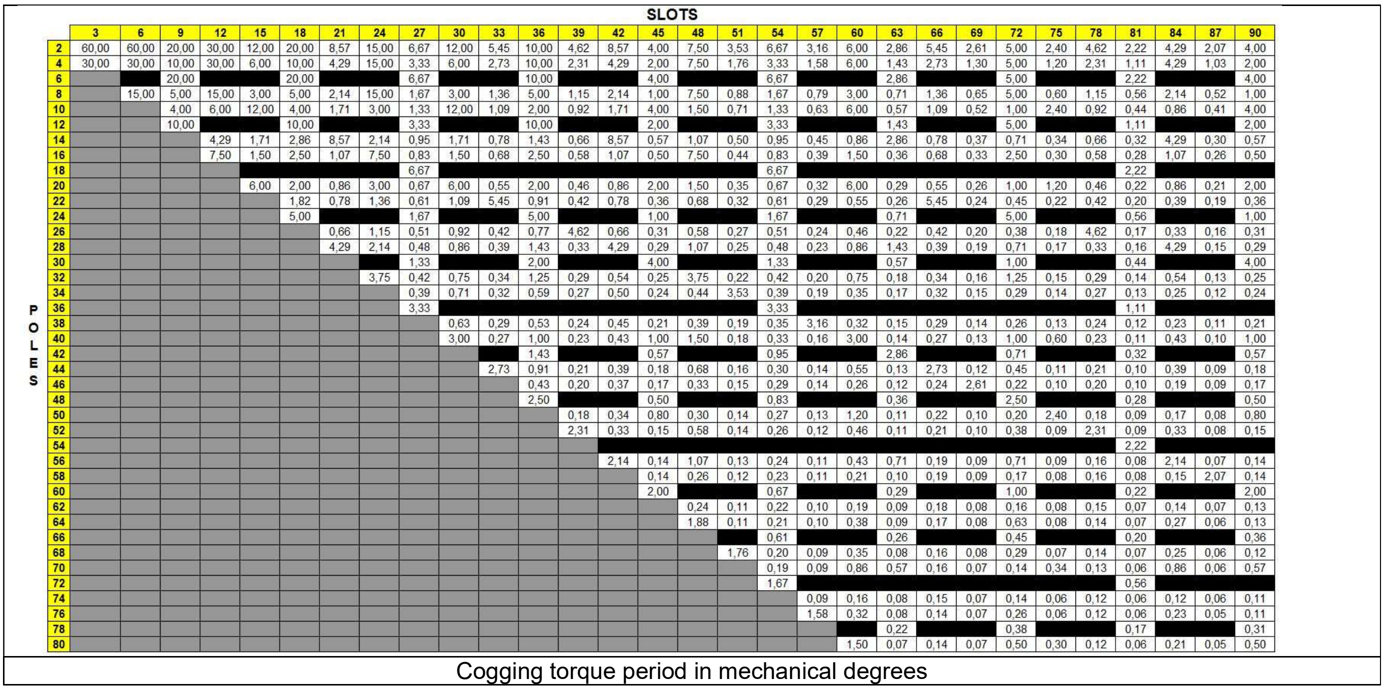
Note: In case of relative important airgap length, the relative variation of airgap reluctance is low, and the resulting cogging torque magnitude can be very small.

1.4.2 Cogging torque period

The cogging torque period depends on the number of slots (N_S) and the number of poles (N_P).
It is given by the dividing 360°, circular mechanical degree in space, by the least common multiple of number of stator slots (N_S) and number of rotor poles (N_P).

$$\theta_{\text{cog-period}} = \frac{360^{\circ}}{\mathrm{LCM}(N_s, N_p)}$$

In general, with increasing number of slots and poles, cogging torque period decreases as shown in the following table.



SLOTS

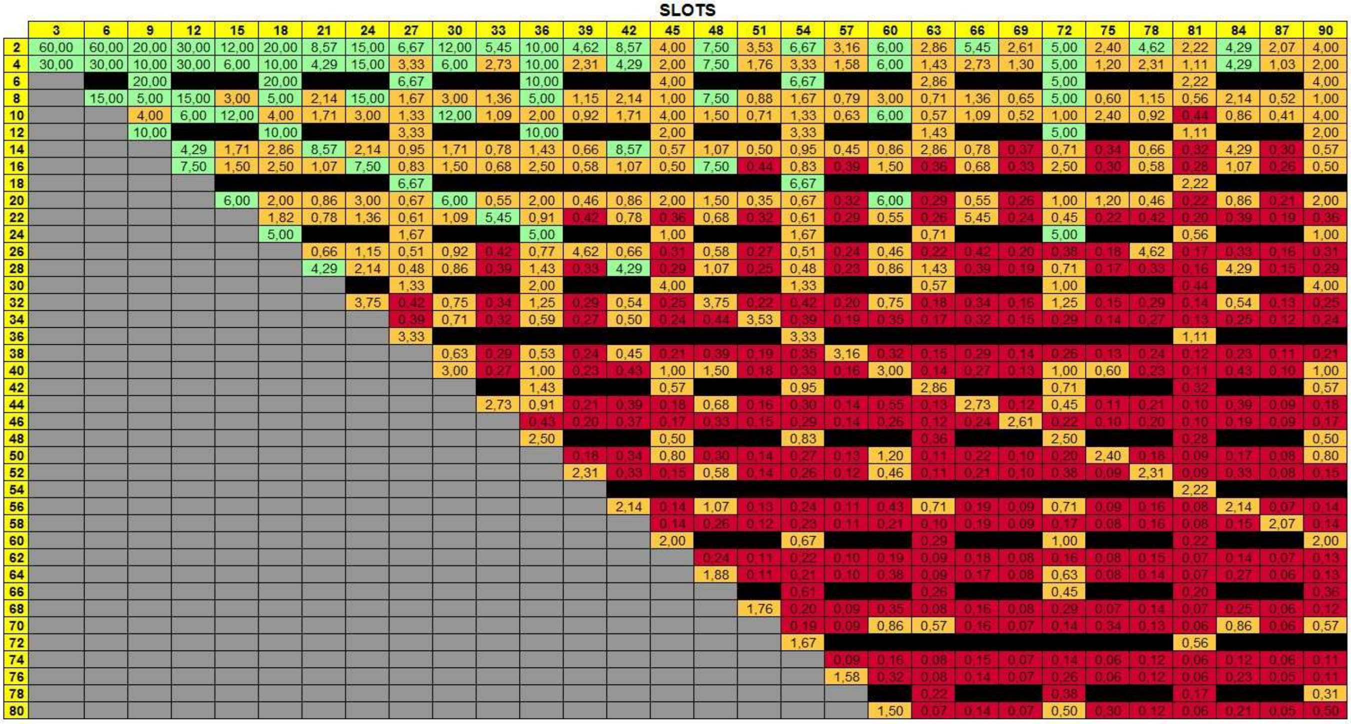
POLES	3	6	9	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	63	66	69	72	75	78	81	84	87	90
2	60,00	60,00	20,00	30,00	12,00	20,00	8,57	15,00	6,67	12,00	5,45	10,00	4,62	8,57	4,00	7,50	3,53	6,67	3,16	6,00	2,86	5,45	2,61	5,00	2,40	4,62	2,22	4,29	2,07	4,00
4	30,00	30,00	10,00	30,00	6,00	10,00	4,29	15,00	3,33	6,00	2,73	10,00	2,31	4,29	2,00	7,50	1,76	3,33	1,58	6,00	1,43	2,73	1,30	5,00	1,20	2,31	1,11	4,29	1,03	2,00
6		■	20,00	■	■	20,00	■	■	6,67	■	■	10,00	■	■	4,00	■	■	6,67	■	■	2,86	■	■	5,00	■	■	2,22	■	■	4,00
8		15,00	5,00	15,00	3,00	5,00	2,14	15,00	1,67	3,00	1,36	5,00	1,15	2,14	1,00	7,50	0,88	1,67	0,79	3,00	0,71	1,36	0,65	5,00	0,60	1,15	0,56	2,14	0,52	1,00
10			4,00	6,00	12,00	4,00	1,71	3,00	1,33	12,00	1,09	2,00	0,92	1,71	4,00	1,50	0,71	1,33	0,63	6,00	0,57	1,09	0,52	1,00	2,40	0,92	0,44	0,86	0,41	4,00
12			10,00	■	■	10,00	■	■	3,33	■	■	10,00	■	■	2,00	■	■	3,33	■	■	1,43	■	■	5,00	■	■	1,11	■	■	2,00
14				4,29	1,71	2,86	8,57	2,14	0,95	1,71	0,78	1,43	0,66	8,57	0,57	1,07	0,50	0,95	0,45	0,86	2,86	0,78	0,37	0,71	0,34	0,66	0,32	4,29	0,30	0,57
16				7,50	1,50	2,50	1,07	7,50	0,83	1,50	0,68	2,50	0,58	1,07	0,50	7,50	0,44	0,83	0,39	1,50	0,36	0,68	0,33	2,50	0,30	0,58	0,28	1,07	0,26	0,50
18					■	■	■	■	6,67	■	■	■	■	■	■	■	■	6,67	■	■	■	■	■	■	■	■	2,22	■	■	■
20					6,00	2,00	0,86	3,00	0,67	6,00	0,55	2,00	0,46	0,86	2,00	1,50	0,35	0,67	0,32	6,00	0,29	0,55	0,26	1,00	1,20	0,46	0,22	0,86	0,21	2,00
22						1,82	0,78	1,36	0,61	1,09	5,45	0,91	0,42	0,78	0,36	0,68	0,32	0,61	0,29	0,55	0,26	5,45	0,24	0,45	0,22	0,42	0,20	0,39	0,19	0,36
24						5,00	■	■	1,67	■	■	5,00	■	■	1,00	■	■	1,67	■	■	0,71	■	■	5,00	■	■	0,56	■	■	1,00
26							0,66	1,15	0,51	0,92	0,42	0,77	4,62	0,66	0,31	0,58	0,27	0,51	0,24	0,46	0,22	0,42	0,20	0,38	0,18	4,62	0,17	0,33	0,16	0,31
28							4,29	2,14	0,48	0,86	0,39	1,43	0,33	4,29	0,29	1,07	0,25	0,48	0,23	0,86	1,43	0,39	0,19	0,71	0,17	0,33	0,16	4,29	0,15	0,29
30								■	1,33	■	■	2,00	■	■	4,00	■	■	1,33	■	■	0,57	■	■	1,00	■	■	0,44	■	■	4,00
32								3,75	0,42	0,75	0,34	1,25	0,29	0,54	0,25	3,75	0,22	0,42	0,20	0,75	0,18	0,34	0,16	1,25	0,15	0,29	0,14	0,54	0,13	0,25
34									0,39	0,71	0,32	0,59	0,27	0,50	0,24	0,44	3,53	0,39	0,19	0,35	0,17	0,32	0,15	0,29	0,14	0,27	0,13	0,25	0,12	0,24
36									3,33	■	■	■	■	■	■	■	■	3,33	■	■	■	■	■	■	■	■	1,11	■	■	■
38										0,63	0,29	0,53	0,24	0,45	0,21	0,39	0,19	0,35	3,16	0,32	0,15	0,29	0,14	0,26	0,13	0,24	0,12	0,23	0,11	0,21
40										3,00	0,27	1,00	0,23	0,43	1,00	1,50	0,18	0,33	0,16	3,00	0,14	0,27	0,13	1,00	0,60	0,23	0,11	0,43	0,10	1,00
42											■	1,43	■	■	0,57	■	■	0,95	■	■	2,86	■	■	0,71	■	■	0,32	■	■	0,57
44											2,73	0,91	0,21	0,39	0,18	0,68	0,16	0,30	0,14	0,55	0,13	2,73	0,12	0,45	0,11	0,21	0,10	0,39	0,09	0,18
46												0,43	0,20	0,37	0,17	0,33	0,15	0,29	0,14	0,26	0,12	0,24	2,61	0,22	0,10	0,20	0,10	0,19	0,09	0,17
48												2,50	■	■	0,50	■	■	0,83	■	■	0,36	■	■	2,50	■	■	0,28	■	■	0,50
50													0,18	0,34	0,80	0,30	0,14	0,27	0,13	1,20	0,11	0,22	0,10	0,20	2,40	0,18	0,09	0,17	0,08	0,80
52													2,31	0,33	0,15	0,58	0,14	0,26	0,12	0,46	0,11	0,21	0,10	0,38	0,09	2,31	0,09	0,33	0,08	0,15
54														■	■	■	■	■	■	■	■	■	■	■	■	■	2,22	■	■	■
56														2,14	0,14	1,07	0,13	0,24	0,11	0,43	0,71	0,19	0,09	0,71	0,09	0,16	0,08	2,14	0,07	0,14
58															0,14	0,26	0,12	0,23	0,11	0,21	0,10	0,19	0,09	0,17	0,08	0,16	0,08	0,15	2,07	0,14
60															2,00	■	■	0,67	■	■	0,29	■	■	1,00	■	■	0,22	■	■	2,00
62																0,24	0,11	0,22	0,10	0,19	0,09	0,18	0,08	0,16	0,08	0,15	0,07	0,14	0,07	0,13
64																1,88	0,11	0,21	0,10	0,38	0,09	0,17	0,08	0,63	0,08	0,14	0,07	0,27	0,06	0,13
66																	■	0,61	■	■	0,26	■	■	0,45	■	■	0,20	■	■	0,36
68																	1,76	0,20	0,09	0,35	0,08	0,16	0,08	0,29	0,07	0,14	0,07	0,25	0,06	0,12
70																		0,19	0,09	0,86	0,57	0,16	0,07	0,14	0,34	0,13	0,06	0,86	0,06	0,57
72																		1,67	■	■	■	■	■	■	■	■	0,56	■	■	■
74																			0,09	0,16	0,08	0,15	0,07	0,14	0,06	0,12	0,06	0,12	0,06	0,11
76																			1,58	0,32	0,08	0,14	0,07	0,26	0,06	0,12	0,06	0,23	0,05	0,11
78																				■	0,22	■	■	0,38	■	■	0,17	■	■	0,31
80																				1,50	0,07	0,14	0,07	0,50	0,30	0,12	0,06	0,21	0,05	0,50

Cogging torque period in mechanical degrees

Note: An extremely small cogging torque period implies the need of a very thin mesh to get accurate results (by using a low airgap mesh coefficient value – See advanced parameter definition). Thus, the number of elements in the corresponding model will be very high (it means a high mesh density).
In the case of a very small cogging torque period, consideration of the airgap length is also relatively important.

In these conditions it is not possible to get good results because the numerical error induced by the mesh (meshing noise) has the same magnitude order than the cogging torque.

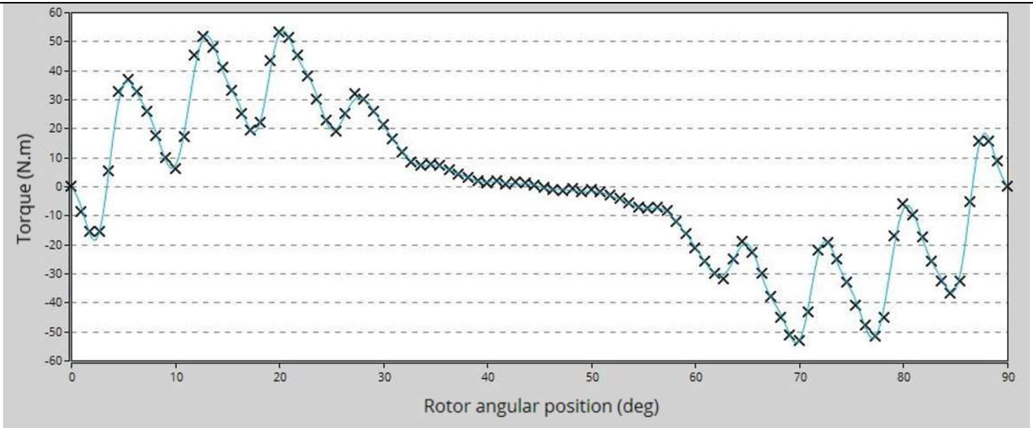
Dedicated mesh methods are needed for such situations but are not yet implemented in FluxMotor®.
In those cases, the advanced solution is to export the model to Flux and to adapt the mesh manually to reach the expected accuracy.
For information, the following table gives a general idea of easy computations (green cells), difficult ones (orange cells) and in some instances impossible ones (red cells) in FluxMotor®.



	SLOTS																													
POLES	3	6	9	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	63	66	69	72	75	78	81	84	87	90
2	60,00	60,00	20,00	30,00	12,00	20,00	8,57	15,00	6,67	12,00	5,45	10,00	4,62	8,57	4,00	7,50	3,53	6,67	3,16	6,00	2,86	5,45	2,61	5,00	2,40	4,62	2,22	4,29	2,07	4,00
4	30,00	30,00	10,00	30,00	6,00	10,00	4,29	15,00	3,33	6,00	2,73	10,00	2,31	4,29	2,00	7,50	1,76	3,33	1,58	6,00	1,43	2,73	1,30	5,00	1,20	2,31	1,11	4,29	1,03	2,00
6			20,00			20,00			6,67			10,00			4,00			6,67			2,86			5,00			2,22			4,00
8		15,00	5,00	15,00	3,00	5,00	2,14	15,00	1,67	3,00	1,36	5,00	1,15	2,14	1,00	7,50	0,88	1,67	0,79	3,00	0,71	1,36	0,65	5,00	0,60	1,15	0,56	2,14	0,52	1,00
10			4,00	6,00	12,00	4,00	1,71	3,00	1,33	12,00	1,09	2,00	0,92	1,71	4,00	1,50	0,71	1,33	0,63	6,00	0,57	1,09	0,52	1,00	2,40	0,92	0,44	0,86	0,41	4,00
12			10,00			10,00			3,33			10,00			2,00			3,33			1,43			5,00			1,11			2,00
14				4,29	1,71	2,86	8,57	2,14	0,95	1,71	0,78	1,43	0,66	8,57	0,57	1,07	0,50	0,95	0,45	0,86	2,86	0,78	0,37	0,71	0,34	0,66	0,32	4,29	0,30	0,57
16				7,50	1,50	2,50	1,07	7,50	0,83	1,50	0,68	2,50	0,58	1,07	0,50	7,50	0,44	0,83	0,39	1,50	0,36	0,68	0,33	2,50	0,30	0,58	0,28	1,07	0,26	0,50
18									6,67									6,67									2,22			
20					6,00	2,00	0,86	3,00	0,67	6,00	0,55	2,00	0,46	0,86	2,00	1,50	0,35	0,67	0,32	6,00	0,29	0,55	0,26	1,00	1,20	0,46	0,22	0,86	0,21	2,00
22						1,82	0,78	1,36	0,61	1,09	5,45	0,91	0,42	0,78	0,36	0,68	0,32	0,61	0,29	0,55	0,26	5,45	0,24	0,45	0,22	0,42	0,20	0,39	0,19	0,36
24						5,00			1,67			5,00			1,00			1,67			0,71			5,00			0,56			1,00
26							0,66	1,15	0,51	0,92	0,42	0,77	4,62	0,66	0,31	0,58	0,27	0,51	0,24	0,46	0,22	0,42	0,20	0,38	0,18	4,62	0,17	0,33	0,16	0,31
28							4,29	2,14	0,48	0,86	0,39	1,43	0,33	4,29	0,29	1,07	0,25	0,48	0,23	0,86	1,43	0,39	0,19	0,71	0,17	0,33	0,16	4,29	0,15	0,29
30									1,33			2,00			4,00			1,33			0,57			1,00			0,44			4,00
32								3,75	0,42	0,75	0,34	1,25	0,29	0,54	0,25	3,75	0,22	0,42	0,20	0,75	0,18	0,34	0,16	1,25	0,15	0,29	0,14	0,54	0,13	0,25
34									0,39	0,71	0,32	0,59	0,27	0,50	0,24	0,44	3,53	0,39	0,19	0,35	0,17	0,32	0,15	0,29	0,14	0,27	0,13	0,25	0,12	0,24
36									3,33									3,33									1,11			
38										0,63	0,29	0,53	0,24	0,45	0,21	0,39	0,19	0,35	3,16	0,32	0,15	0,29	0,14	0,26	0,13	0,24	0,12	0,23	0,11	0,21
40										3,00	0,27	1,00	0,23	0,43	1,00	1,50	0,18	0,33	0,16	3,00	0,14	0,27	0,13	1,00	0,60	0,23	0,11	0,43	0,10	1,00
42												1,43			0,57			0,95			2,86			0,71			0,32			0,57
44											2,73	0,91	0,21	0,39	0,18	0,68	0,16	0,30	0,14	0,55	0,13	2,73	0,12	0,45	0,11	0,21	0,10	0,39	0,09	0,18
46												0,43	0,20	0,37	0,17	0,33	0,15	0,29	0,14	0,26	0,12	0,24	2,61	0,22	0,10	0,20	0,10	0,19	0,09	0,17
48												2,50			0,50			0,83			0,36			2,50			0,28			0,50
50													0,18	0,34	0,80	0,30	0,14	0,27	0,13	1,20	0,11	0,22	0,10	0,20	2,40	0,18	0,09	0,17	0,08	0,80
52													2,31	0,33	0,15	0,58	0,14	0,26	0,12	0,46	0,11	0,21	0,10	0,38	0,09	2,31	0,09	0,33	0,08	0,15
54																											2,22			
56														2,14	0,14	1,07	0,13	0,24	0,11	0,43	0,71	0,19	0,09	0,71	0,09	0,16	0,08	2,14	0,07	0,14
58															0,14	0,26	0,12	0,23	0,11	0,21	0,10	0,19	0,09	0,17	0,08	0,16	0,08	0,15	2,07	0,14
60															2,00			0,67			0,29			1,00			0,22			2,00
62																0,24	0,11	0,22	0,10	0,19	0,09	0,18	0,08	0,16	0,08	0,15	0,07	0,14	0,07	0,13
64																1,88	0,11	0,21	0,10	0,38	0,09	0,17	0,08	0,63	0,08	0,14	0,07	0,27	0,06	0,13
66																		0,61			0,26			0,45			0,20			0,36
68																	1,76	0,20	0,09	0,35	0,08	0,16	0,08	0,29	0,07	0,14	0,07	0,25	0,06	0,12
70																		0,19	0,09	0,86	0,57	0,16	0,07	0,14	0,34	0,13	0,06	0,86	0,06	0,57
72																		1,67									0,56			
74																			0,09	0,16	0,08	0,15	0,07	0,14	0,06	0,12	0,06	0,12	0,06	0,11
76																			1,58	0,32	0,08	0,14	0,07	0,26	0,06	0,12	0,06	0,23	0,05	0,11
78																					0,22			0,38			0,17			0,31
80																				1,50	0,07	0,14	0,07	0,50	0,30	0,12	0,06	0,21	0,05	0,50

Cogging torque computation: Green= easy / Orange = difficult / Red = very difficult or even impossible

To be noted that in case of square shape lamination, the analysis of the cogging torque will be done at least over 90 mechanical degrees (see the following example).



Cogging torque analysis over 90 mechanical degrees

1.5 Test results

1.5.1 Test conditions

1.5.1.1 Inputs

All the input parameters, belonging to standard inputs or advanced inputs, are described in this section.
It shows the initial conditions considered for the test.
Here are the displayed subsections:

- Context
- Advanced parameters

For more information refer to the section 1.3 (Inputs)

1.5.1.2 Settings

All the settings dedicated to the test and dealing with the thermal are displayed in this section.
Here is the displayed subsection:

- Thermal

For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section “thermal settings”

1.5.1.3 Magnet characteristics

All magnets characteristics are presented in the table “Magnets characteristics”.
Here is the displayed subsection:

- Magnets

Note: All these characteristics are described in the section settings.
For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section “Magnet characteristics”

1.5.2 Main results

1.5.2.1 Flux in magnetic circuit

Here are the displayed subsections:

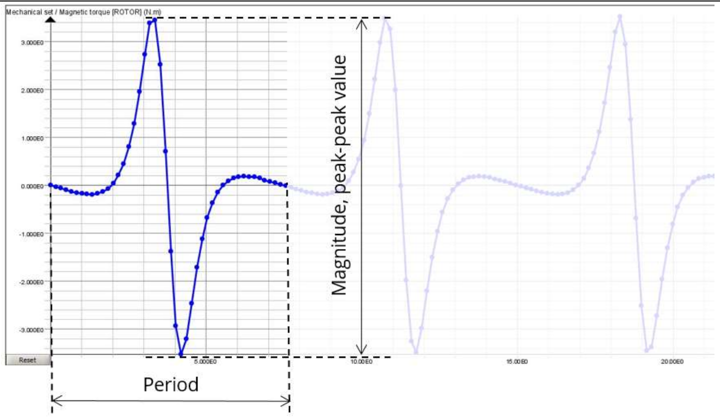
- Flux in airgap
- Flux density in iron

1.5.2.2 Cogging torque

Here is the displayed subsection:

- Cogging torque

The cogging torque period and the cogging torque magnitude, peak-peak value are displayed in this subsection.

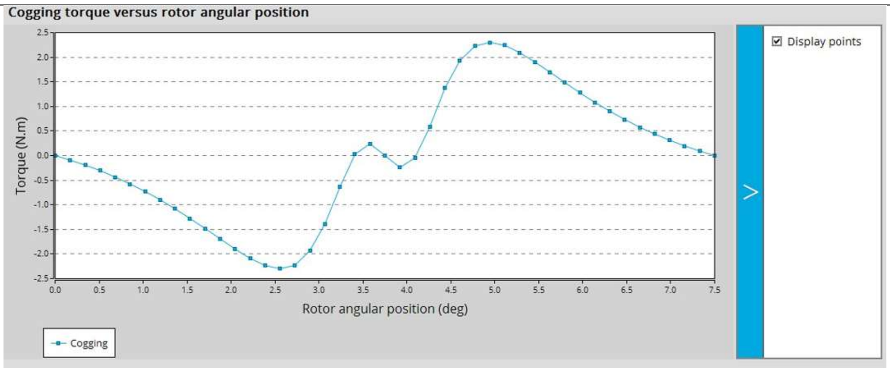


Computation of the cogging torque data from finite element software Flux®

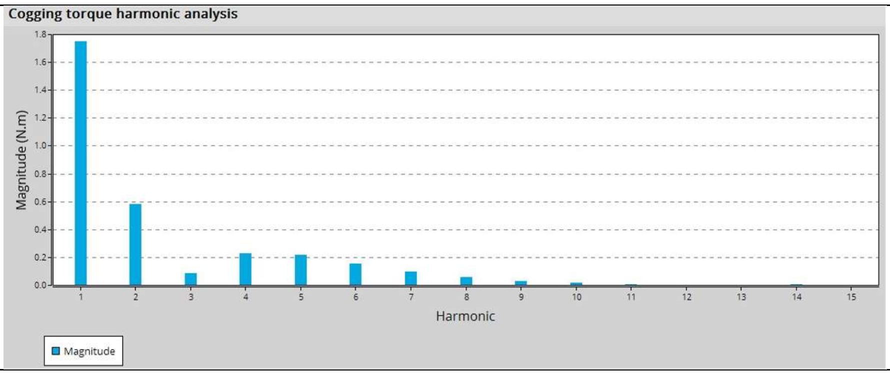
1.5.3 Graphs & tables

In this section, the cogging torque variation versus the rotor angular position is illustrated with a curve. A bar graph is also displayed to illustrate the cogging torque harmonic content.

Note:
As already explained in previous sections, the computation of the electromagnetic torque is done using finite element software.
This harmonic analysis is performed by considering one cogging torque period. The harmonic order, frequency and phase are relative to the cogging torque period.

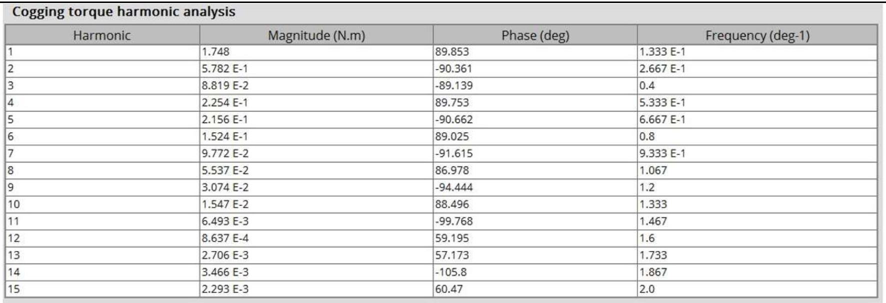


Visualization of the cogging torque curve



Visualization of the cogging torque harmonic analysis

All the harmonic data are summarized in a table.


Cogging torque harmonic analysis

Harmonic	Magnitude (N.m)	Phase (deg)	Frequency (deg-1)
1	1.748	89.853	1.333 E-1
2	5.782 E-1	-90.361	2.667 E-1
3	8.819 E-2	-89.139	0.4
4	2.254 E-1	89.753	5.333 E-1
5	2.156 E-1	-90.662	6.667 E-1
6	1.524 E-1	89.025	0.8
7	9.772 E-2	-91.615	9.333 E-1
8	5.537 E-2	86.978	1.067
9	3.074 E-2	-94.444	1.2
10	1.547 E-2	88.496	1.333
11	6.493 E-3	-99.768	1.467
12	8.637 E-4	59.195	1.6
13	2.706 E-3	57.173	1.733
14	3.466 E-3	-105.8	1.867
15	2.293 E-3	60.47	2.0

Visualization of the cogging torque harmonic analysis

2 CHARACTERIZATION – OPEN CIRCUIT – MOTOR & GENERATOR – BACK – EMF

2.1 Overview

2.1.1 Positioning and objective

The aim of the test “**Characterization - Open circuit – Motor & Generator - Back-EMF**” is to characterize the behavior of the machine when running in open circuit state.
The analysis of back-EMF characteristics is a first step to evaluate the relevance of the machine design regarding parameters such as: topology, winding architecture, composition of coils and choice of materials.

Warning! When a delta winding connection is considered, the computation doesn’t consider circulation currents. That can lead to a different result than what expected in transient computation.
In such case it is recommended to perform a transient computation in Flux® environment. The application “Export to Flux” allows exporting this kind of model with the corresponding scenario ready to be solved.

The following table helps to classify the test “Open circuit – Back-EMF”.

Family	Characterization
Package	Open circuit
Convention	Motor & Generator
Test	Back-EMF

Positioning of the test “Characterization - Open circuit – Motor & Generator - Back-EMF”

2.1.2 User inputs

The rotation speed is the only necessary input parameter to run this test. The operating temperature of magnets can be defined in the settings “Thermal”.

2.1.3 Main outputs

Test results are illustrated with data, graphs and tables.

Table of results:

1) Machine performance – Open circuit

- Back-EMF characteristics (voltage constant and voltage magnitudes)
- Flux linkage
- Flux in airgap
- Flux density in iron
- Magnet behavior

Curves & tables

1) Phase voltage

- Phase voltage versus time – Open circuit
- Phase voltage harmonic analysis – Open circuit (bar graph and table)

2) Line-line voltage

- Line-line voltage versus time – Open circuit
- Line-line voltage harmonic analysis – Open circuit (bar graph and table)

3) Flux density in airgap

- Flux density in the airgap versus angular position – Open circuit
- Flux density in the airgap harmonic analysis – Open circuit (bar graph and table)

4) Flux linkage

- Flux linkage versus angular position – Open circuit

2.2 Settings

One button gives access to the following setting definition:

- Thermal settings – Definition of the temperature of active components.
  Only the temperature of magnets is considered.

For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section “thermal settings”

2.3 Inputs

2.3.1 Introduction

The total number of user inputs is seven in addition to Magnet temperature entered in Settings.
Among inputs parameters, speed is the only default input parameter. Other six are available as advanced input parameters.

2.3.2 Standard inputs

2.3.2.1 Speed

Operating speed of the machine is the only standard input parameter to be used in the back-EMF test.

Note: Once the computation is performed, it is possible to change the speed and update the results instantaneously.

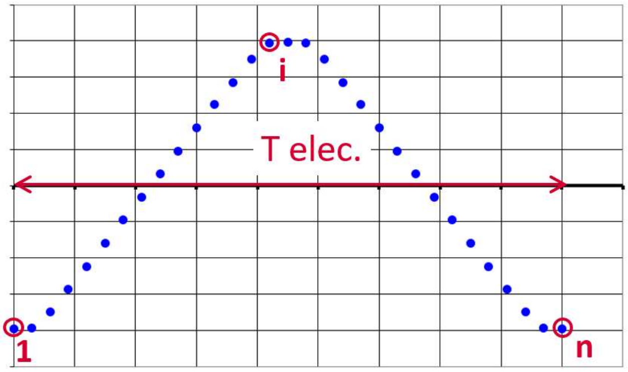
2.3.3 Advanced inputs

2.3.3.1 Number of computations per electrical period

To get the Back-EMF versus time, the flux through each phase of the machine versus rotor angular position is computed.
This computation is performed using a Finite Element Modeling.
The number of computations per electrical period “**No. comp. / elec. period**” (Number of computations per electrical period) influences the accuracy of results and the computation time.

The default value is equal to 50. The minimum allowed value is 13. This default value provides a good compromise between the accuracy of results and computation time.

Note: The real number of computations per electrical period can be equal to the requested one +/- 1. That is due to our internal computation process since the raw computation is performed over one electrical half period. The result on a whole electrical period is rebuilt from the raw data.



Number of computations per electrical period

2.3.3.2 Maximum harmonic order

To get the Back-EMF versus time, the flux through each phase of the machine is computed versus rotor angular position.

Harmonics are extracted from the frequency analysis (F.F.T. Fast Fourier Transform) of the Back-EMF signal versus time.
The order of harmonics displayed on bar graphs and in tables can be selected with this advanced user input parameter "**Max. harmonic order**" (*Maximum harmonic order selected for visualization*).

Note: From mathematical point of view, the maximum allowed harmonic order depends on the number of computations per electrical period. In case of a too small number of computations per electrical period, the maximum harmonic order considered will be lower than the one set up by the user.

The default value is equal to 20. The minimum allowed value is 1.

2.3.3.3 Rotor initial position

By default, the "**Rotor initial position**" is set to "**Auto**".

When the "**Rotor initial position mode**" is set to "**Auto**", the initial position of the rotor is automatically defined by an internal process.
The resulting relative angular position corresponds to the alignment between the axis of the stator phase 1 (reference phase) and the direct axis of the rotor north pole.

When the "**Rotor initial position**" is set to "User input" (i.e. toggle button on the right), the initial position of the rotor considered for computation must be set by the user in the field « **Rotor initial position** ». The default value is equal to 0. The range of possible values is [-360, 360].

For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section "Rotor and stator relative position".

2.3.3.4 Skew model – Number of layers

When the rotor magnets or the stator slots are skewed, the number of layers used in Flux® Skew environment to model the machine can be modified: "**Skew model - No. of layers"** (*Number of layers for modelling the skewing in Flux® Skew environment*).

Note: When there is magnet step skew topology, the number of layers is defined at the design level.

2.3.3.5 Mesh order

To get results, Finite Element Modelling computations are performed.
The geometry of the machine is meshed.
Two levels of meshing can be considered: First order and second order.
This parameter influences the accuracy of results and the computation time.

The default level is second order mesh.

2.3.3.6 Airgap mesh coefficient

The advanced user input "**Airgap mesh coefficient**" is a coefficient which adjusts the size of mesh elements inside the airgap. When you decrease the value of "**Airgap mesh coefficient**", you reduce the size of mesh elements and then increase the mesh density inside the airgap and the accuracy of results.

The imposed Mesh Point (size of mesh elements touching points of the geometry), inside the Flux® software, is described as:

$$\text{MeshPoint} = (\text{airgap}) \times (\text{airgap mesh coefficient})$$

Airgap mesh coefficient is set to 1.5 by default.
The variation range of values for this parameter is [0.05; 2].
0.05 giving a very high mesh density and 2 giving a very coarse mesh density.

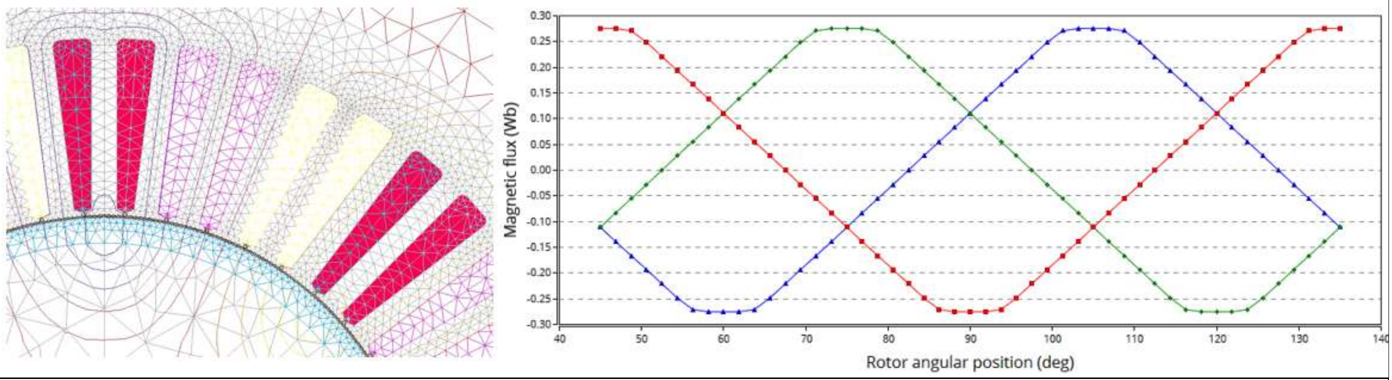
Caution:
Be aware, a very high mesh density does not always mean a better result quality. However, this always leads to a huge number of nodes in the corresponding finite element model. So, it means a need of huge numerical memory and increases the computation time considerably.

2.4 Main principles of computation

2.4.1 Back – emf computation

To get the Back-EMF versus time, the flux through each phase of the machine is computed for each rotor position over one half of electrical period.
Inside FluxMotor®, this computation is carried out using Magnetostatic application of Flux® (Finite Element software). The computation is done by considering multiple positions of the rotor.

A frequency analysis (Fast Fourier Transform F.F.T.) is then performed to extract the main harmonics of the signals.



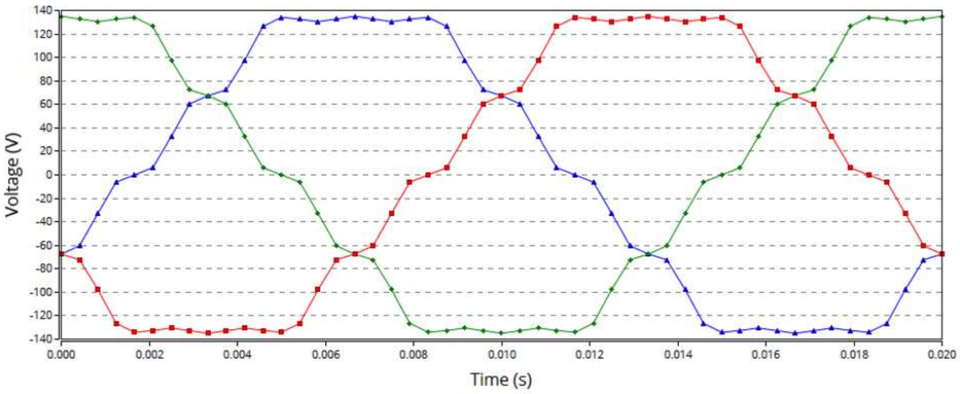
Flux linkage versus rotor angular position

The time variation of the phase voltage is deduced by derivation of the flux linkage. It is performed by considering the following formula:

$$E = \frac{d\Phi}{dt} = \frac{d\Phi}{d\theta} \times \frac{d\theta}{dt} = \frac{d\Phi}{d\theta} \times \Omega$$

Where Φ is the flux linkage and Ω is angular speed in rad/s.

The line-line voltages are deduced from the three phase voltages.



Open circuit - Line-Line voltage

2.4.2 Flux density in airgap

During the computation, a sensor put inside the airgap allows computing the flux density in the airgap versus rotor angular position.
It is located close to the stator bore diameter (at third quarter-length of airgap - stator side) in front of a stator tooth and remains motionless.

Like for the flux linkage, a Fast Fourier Transform is performed, and the main harmonics are extracted for flux density in airgap also.
The corresponding graphs and table are displayed.

2.5 Test results

Once a test is finished, the corresponding results are automatically displayed in the central window.

2.5.1 Test conditions

2.5.1.1 Inputs

All the parameter values, belonging to standard inputs or advanced inputs are described in this section.
It shows the initial conditions considered for the test.
Here are the displayed subsections:

- Context
- Standard parameters
- Advanced parameters

For more information refer to the section 2.3 (Inputs)

2.5.1.2 Settings

All the settings dedicated to the test and dealing with the thermal are displayed in this section.
Here is the displayed subsection:

- Thermal

For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section “thermal settings”.

2.5.1.3 Winding and magnet characteristics

All winding and magnet characteristics are displayed in the following subsections:

- Magnet characteristics
- Winding characteristics (The winding connection star (Y) or delta (Δ) is listed)

For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section “Machine characteristics”

2.5.2 Main results

2.5.2.1 Machine performance – Open circuit

Here are the displayed subsections:

- Back-emf characteristics
- Flux linkage
- Flux in airgap
- Flux density in iron
- Magnet behavior

2.5.3 Graphs & tables

Curves illustrate the variation of the flux linkage, the phase voltage, the Line-Line voltage and the flux density in the airgap over time or rotor angular position.
Illustrations of harmonic analysis with bar graphs and harmonic tables are displayed for phase voltage, line-line voltage and flux density in airgap.

Note: The computation of the flux linkage through each phase of the machine is performed using finite element modeling.

Here is the list of displayed curves and graphs:

1) Phase voltage
- Phase voltage versus time – Open circuit
- Phase voltage harmonic analysis – Open circuit (bar graph and table)

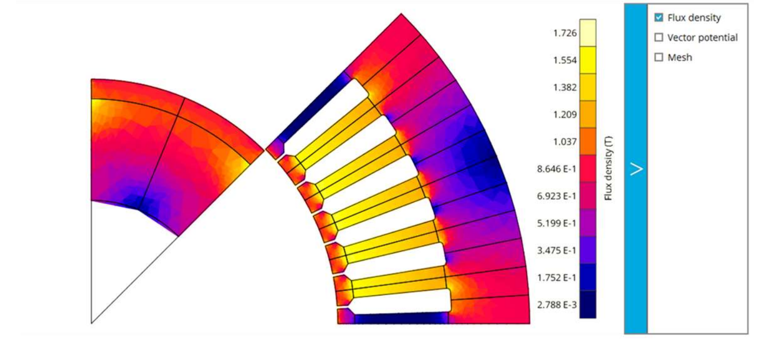
2) Line-line voltage
- Line-line voltage versus time – Open circuit
- Line-line voltage harmonic analysis – Open circuit (bar graph and table)

3) Flux density in the airgap
- Flux density in the airgap versus angular position – Open circuit
- Flux density in the airgap harmonic analysis – Open circuit (bar graph and table)

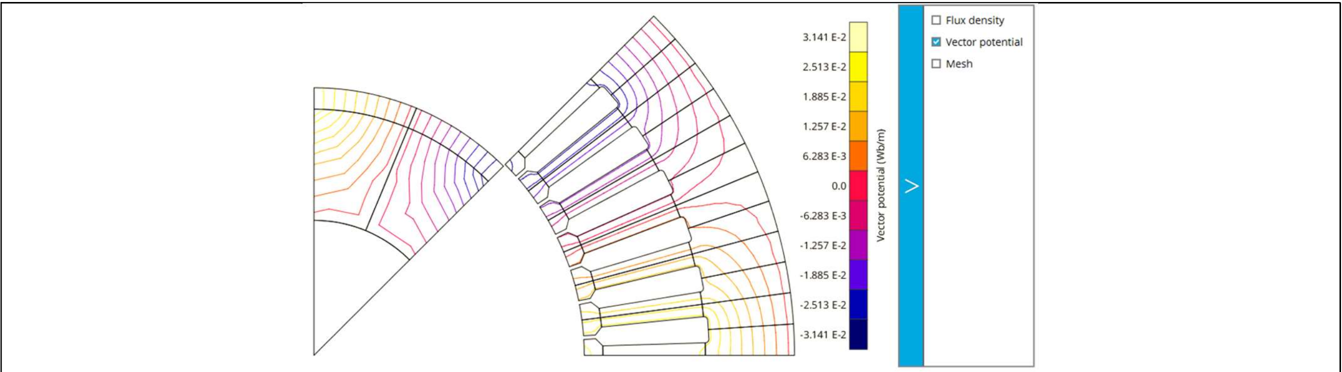
4) Flux linkage
- Flux linkage versus angular position – Open circuit

2.5.4 Isovalues and isolines

The flux density isovalues and the vector potential isolines can be displayed.



Visualization of the flux density isovalues



Visualization of the vector potential isolines

Note: The visualization of the meshing of the model can also be displayed.

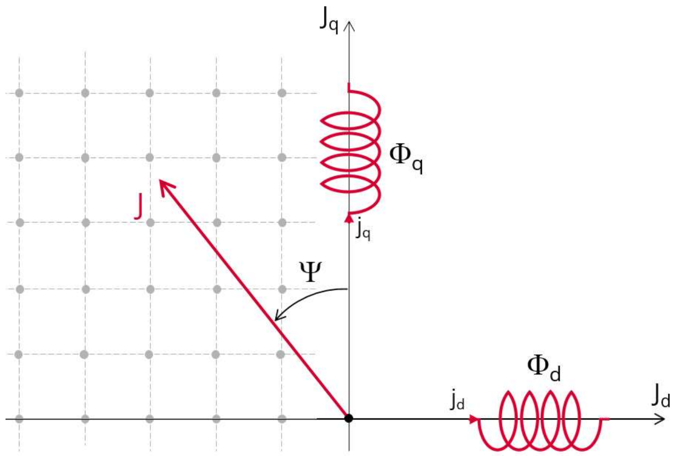
3 CHARACTERIZATION – MODEL – MOTOR – MAPS

3.1 Positioning and objective

The aim of the test “Characterization - Model - Motor - Maps” is to give 2D maps in J_d-J_q plane for characterizing the 3-Phase synchronous machines with permanent magnets.

These maps allow predicting the behavior of the electrical rotating machine at a system level.

In this test engineers will find a system integrator and / or control-command tool adapted to their needs and able to provide accurate maps ready to be used in system simulation software like Activate or PSIM.



“Characterization - Model - Motor - Maps” illustration. Example for a second quadrant calculus.

Performance of the machine in steady state can be deduced from the results obtained in this test in association with the drive and control mode to be considered.

The following table helps to classify the test:

Family	Characterization
Package	Model
Convention	Motor
Test	Maps

Positioning of the test “Characterization - Model - Motor - Maps”

3.1.1 User inputs

Maps are mainly function of the following user inputs: the maximum value of the electrical current, the speed and the number of quadrants to be considered and the rotor position dependency.

3.1.2 Main outputs

Test results are illustrated with data, graphs, and tables.

Maps in J_d-J_q plane

1) Flux linkage
- D-axis flux-linkage Φ_d
- Q-axis flux-linkage Φ_q

2) Flux linkage derivative
- D-axis flux-linkage derivative with respect to the rotor position $\Phi_d/d\theta_r$ in $J_d - J_q$ area
- Q-axis flux-linkage derivative with respect to the rotor position $\Phi_q/d\theta_r$ in $J_d - J_q$ area

3) Inductance
- D-axis inductance (dynamic, cross dynamic and static)
- Q-axis inductance (dynamic, cross dynamic and static)

4) Torque
- Electromagnetic torque T_{em}

5) Losses
- Stator iron losses W_{iron} versus speed
- Joule losses W_{Cus} in stator winding
- Power electronics losses
- Total losses W_{total} versus speed

Curves

1) Permanent magnets and cross flux effects
2) Mechanical losses versus speed

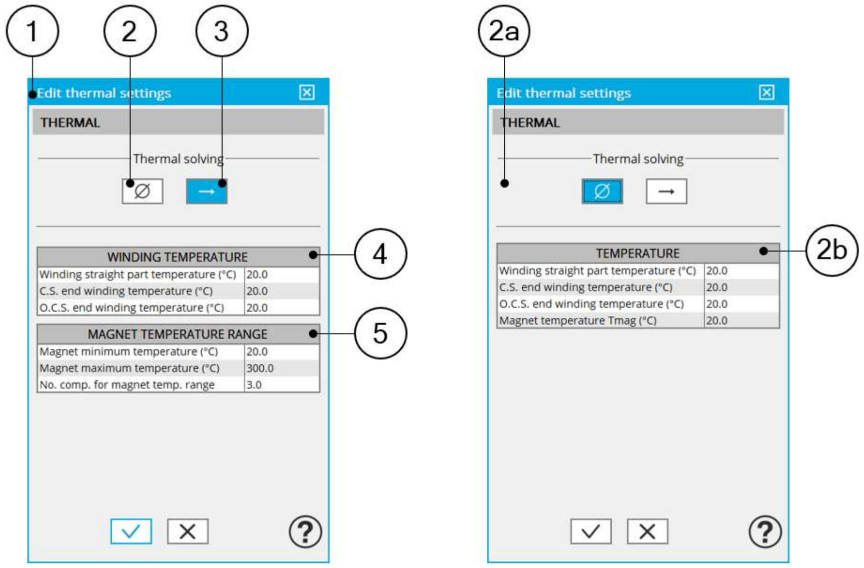
3.2 Settings

3.2.1 Thermal settings

- This dialog box allows us to define the temperature of active components.
  For the considered test, these settings concern the temperature of the winding and magnets. In the thermal settings you have two main possible choices:

  - You can define the temperatures of the winding to define the physical properties of the materials needed to run directly the tests without any thermal computation.

  - Or you can perform a thermal solving. This means, that it will be possible to consider the impact of the magnet temperature in a predefined range of temperature.



Edit thermal settings

THERMAL

Thermal solving

WINDING TEMPERATURE	
Winding straight part temperature (°C)	20.0
C.S. end winding temperature (°C)	20.0
O.C.S. end winding temperature (°C)	20.0

MAGNET TEMPERATURE RANGE	
Magnet minimum temperature (°C)	20.0
Magnet maximum temperature (°C)	300.0
No. comp. for magnet temp. range	3.0

Edit thermal settings

THERMAL

Thermal solving

TEMPERATURE	
Winding straight part temperature (°C)	20.0
C.S. end winding temperature (°C)	20.0
O.C.S. end winding temperature (°C)	20.0
Magnet temperature Tmag (°C)	20.0

1	Dialog box to define the thermal settings. Buttons allow to choose one of the two thermal solving modes
2	The first option of thermal setting is to run the test with only electromagnetic computation without any thermal analysis. This option is the default one available for all the tests.
2a	Dialog box allowing to define the winding temperatures to run test without any thermal analysis.
2b	Temperatures of the winding (in three locations) and temperature of the magnets to be considered for characterizing the physical properties of the associated materials.
3	Thermal solving mode with only one iteration between electromagnetic and thermal computations.
4	Temperatures of the machine winding (in three locations).
5	Temperature of magnets to be considered: • Range of temperatures between the minimum and the maximum ones • Number of computations to be considered within the previous range of temperatures. The default number of computations is 3. The minimum allowed value is 2. Higher is this number, better is the quality of results, but higher is the computation time. The default value “3 computations is a good compromise.

For more details, please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – section “thermal settings”.

3.2.2 Power electronics parameters

Dialog box to define the power electronics parameters:

- Inverter control strategy
- Inputs for evaluating the power electronics stage losses

For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – sections dealing with settings.

3.2.3 Mechanical loss model parameters

Dialog box to define mechanical loss computation model.

For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – sections dealing with settings.

3.3 Inputs

3.3.1 Introduction

The total number of user inputs is equal to 10.
Among these inputs, 4 are standard inputs and 6 are advanced inputs.

3.3.2 Standard inputs

3.3.2.1 Operating quadrants

It defines the quadrants in the J_d - J_q plane, where the test will be carried out. By default, the only considered quadrant is the 2nd one (i.e., the grid is only defined for negative values of the current in the d axis and positive ones in the q axis). This corresponds to the motor behavior of the machine.

Options allow computing and displaying 1, 2 or 4 quadrants.
Note: Export / System LUT (Activate or PSIM) has been updated for exporting data based on 1, 2 or 4 quadrants

Among the standard inputs, the operating quadrants can be selected.
This allows defining the quadrants in the Jd-Jq plane, where the test will be carried out.
By default, the only considered quadrant is the 2nd one (i.e., the grid is only defined for negative values of the current in the d axis and positive ones in the q axis). This corresponds to the motor behavior of the machine.

The other possible values for this input are: “2nd and 3rd “, “1st and 2nd “and “all”.

3.3.2.2 Current definition mode

There are 2 common ways to define the electrical current.

Electrical current can be defined by the current density in electric conductors.
In this case, the current definition mode should be « **Density** ».

Electrical current can be defined directly by indicating the value of the line current (the RMS value is required).
In this case, the current definition mode should be « **Current** ».

3.3.2.3 Maximum line current, rms

When the choice of current definition mode is “**Current**”, the maximum rms value of the line current supplied to the machine “**Max. line current, rms”** (*Maximum line current, rms value*) must be provided.

Note: The number of parallel paths and the winding connections are automatically considered in the results.

3.3.2.4 Maximum current density, rms

When the choice of current definition mode is “**Density**”, the maximum rms value of the current density in electric conductors “**Max. current dens., rms”** (*Maximum current density in conductors, rms value*) must be provided.

Note: The number of parallel paths and the winding connection are automatically considered in the results.

3.3.2.5 Maximum speed

The analysis of test results is performed over a given speed range, to evaluate losses as a function of speed like iron losses, mechanical losses and total losses.
The speed range is fixed between 0 and the maximum speed to be considered « **Maximum speed** » (*Maximum speed*).

3.3.2.6 Rotor position dependency

It defines the rotor position dependency, where the test will be carried out. By default, the rotor position dependency is set to “No” but it can be set to “Yes”. In this case the computation will be done in the J_d - J_q plane with an additional third axis corresponding to the rotor position θ_r.

Note: In case the rotor dependency is set to “Yes”, whatever the operating quadrant choice, the finite element computation is done over all selected quadrants (in case the rotor dependency is set to “No”, symmetries are used).

Note: Export / System LUT (Activate or PSIM) has been updated for exporting data based on the rotor position dependency.

3.3.3 Advanced inputs

3.3.3.1 Number of computed electrical periods

The user input “**No. computed elec. periods**” (Number of computed electrical periods only required with rotor position dependency set to “Yes”) influences the computation time of the results.

The default value is equal to 0.5. The maximum allowed value is 1 according to the fact that computation is done to characterize steady state behavior based on magnetostatic finite element computation. The default value provides a good compromise between the accuracy of results and computation time.

3.3.3.2 Number of points per electrical period

The user input “**No. points / electrical period**” (Number of computed electrical periods only required with rotor position dependency set to “Yes”) influences the accuracy of results (computation of the peak-peak ripple torque, iron losses…) and the computation time.

The default value is equal to 40. The minimum recommended value is 20. The default value provides a good balance between the accuracy of results and the computation time.

3.3.3.3 Number of computations for D-axis and Q-axis phase currents

To get maps in the J_d-J_q plan, a grid is defined. The number of computation points along the d-axis and q-axis can be defined with the user input « **No. comp. for current J_d, J_q** » *(Number of computations for D-axis and Q-axis phase currents)*.
The default value is equal to 10. This default value provides a good compromise between the accuracy of results and computation time. The minimum allowed value is 5.

3.3.3.4 Number of computations for speed

The number of computations for speed corresponds to the number of points to consider in the range of speed. It can be defined via the user input “**No. comp. for speed”** *(Number of computations for speed)*.
The default value is equal to 10. The minimum allowed value is 5.

3.3.3.5 Rotor initial position

By default, the “**Rotor initial position**” is set to “**Auto**”.

When the “**Rotor initial position mode**” is set to “**Auto**”, the initial position of the rotor is automatically defined by an internal process of FluxMotor®.
The resulting relative angular position corresponds to the alignment between the axis of the stator phase 1 (reference phase) and the direct axis of the rotor north pole.

When the “**Rotor initial position**” is set to “User input” (i.e. toggle button on the right), the initial position of the rotor considered for computation must be set by the user in the field « **Rotor initial position** ». The default value is equal to 0. The range of possible values is [-360, 360].
For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section “Rotor and stator relative position”.

3.3.3.6 Skew model – Number of layers

When the rotor magnets or the stator slots are skewed, the number of layers used in Flux® Skew environment to model the machine can be modified: “**Skew model - No. of layers”** (*Number of layers for modelling the skewing in Flux® Skew environment*).

Note: When there is magnet step skew topology, the number of layers is defined at the design level.

3.3.3.7 Mesh order

To get results, Finite Element Modelling computations are performed.
The geometry of the machine is meshed.
Two levels of meshing can be considered: First order and second order.
This parameter influences the accuracy of results and the computation time.

The default level is second order mesh.

3.3.3.8 Airgap mesh coefficient

The advanced user input “**Airgap mesh coefficient**” is a coefficient which adjusts the size of mesh elements inside the airgap. When the value of “Airgap mesh coefficient” decreases, the mesh elements get smaller, leading to a higher mesh density inside the airgap, increasing the computation accuracy.

The imposed Mesh Point (size of mesh elements touching points of the geometry), inside the Flux® software, is described as:

MeshPoint = (airgap) x (airgap mesh coefficient)

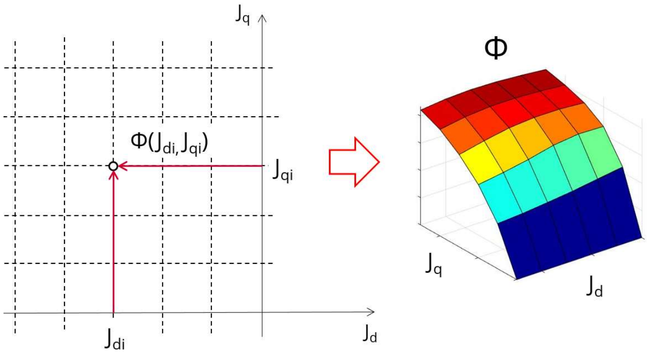
Airgap mesh coefficient is set to 1.5 by default.
The variation range of values for this parameter is [0.05; 2].
0.05 giving a very high mesh density and 2 giving a very coarse mesh density.

Caution:
Be aware, a very high mesh density does not always mean a better result quality. However, this always leads to a huge number of nodes in the corresponding finite element model. So, it means a need of huge numerical memory and increases the computation time considerably.

3.4 Main principles of computation

3.4.1 Flux linkage

One of the goals is to compute the D-axis and Q-axis flux linkage in the J_d, J_q plane.
To do that, a grid of values (J_d, J_q) is considered.
For each node of this grid, the corresponding flux linkage through each phase is extracted (Φ_a, Φ_b, Φ_c) through corresponding phases a, b, c). This is done using Finite Element modelling (Flux® software – Magnetostatic application).
D-axis flux-linkage component - Φ_d and **Q-axis flux-linkage component - Φ_q** are deduced according to Park's transformation.



Computation on a grid in J_d, J_q plane

Our modeling considers cross-saturation. However, neither winding harmonics nor the variation of reluctance as a function of angular position of the rotor are considered.

Note: The impact on accuracy will be more important for machine with high level of saturation.
Iron loss computations are based on both a Finite Element modelling and on an analytical method where leakage flux between stator teeth is neglected.
In case of high level of saturation, this hypothesis leads to more errors particularly in the area where there is field weakening.

Note: In the examples shown in the images, positive value of J_d and positive value of J_q are considered. These values ranges correspond to the working conditions for a motor. However, the considered quadrants can be chosen through dedicated input (e.g., user can choose all quadrants, or only the 2nd, the 2nd and 3rd one, etc.) allowing the characterization of the machine behavior for other control conditions.

Note: In case the Rotor position dependency is set to "Yes", the computation is done in the J_d - J_q plane with an additional third axis corresponding to the rotor position θ_r.

3.4.2 Flux-linkage derivative respect to the rotor position

D-axis flux-linkage derivative with respect to the rotor position - $\Phi_d/d\theta_r$ and **Q-axis flux-linkage derivative with respect to the rotor position -** $\Phi_q/d\theta_r$ are computed from the flux linkage maps and using the following formulae:

$$\frac{\Delta\Phi_d}{\Delta\theta_r} \qquad \frac{\Delta\Phi_q}{\Delta\theta_r}$$

These maps are available only when the input Rotor position dependency is set to "Yes". The computation is done in the J_d - J_q plane with an additional third axis corresponding to the rotor position θ_r.

Note 1: The rotor position derivative is always in radians per second to simplify the usage of this map while considering the Park's voltage equations.

3.4.3 Dynamic inductances

D-axis synchronous inductance - L$_{d\text{–dynamic}}$ and **Q-axis synchronous inductance - L$_{q\text{-dynamic}}$** are computed from the flux linkage maps and using the following formulae:

$$\mathrm{L}_{\mathrm{d-dynamic}} = \frac{\Delta\Phi_{\mathrm{d}}}{\Delta\mathrm{J}_{\mathrm{d}}} \qquad \mathrm{L}_{\mathrm{q-dynamic}} = \frac{\Delta\Phi_{\mathrm{q}}}{\Delta\mathrm{J}_{\mathrm{q}}}$$

Note 1: The end-winding leakage inductance L_{endw}, computed in the winding area, is included in the computation of D-axis and Q-axis flux-linkage. The values of the dynamic inductances $L_{d\text{–dynamic}}$ and $L_{q\text{-dynamic}}$ consider the value of the end-winding inductance.

Note 2: In the previous formulae, one considers peak values for both flux and current.

Note 3: In case the Rotor position dependency is set to “Yes”, the computation is done in the J_d - J_q plane with an additional third axis corresponding to the rotor position θ_r.

3.4.4 Dynamic cross inductances

D-axis synchronous cross inductance - L$_{dq\text{–dynamic}}$ and **Q-axis synchronous cross inductance - L$_{qd\text{-dynamic}}$** are computed from the flux linkage maps and using the following formulae:

$$\mathrm{L}_{\mathrm{dq-dynamic}} = \frac{\Delta\Phi_{\mathrm{d}}}{\Delta\mathrm{J}_{\mathrm{q}}} \qquad \mathrm{L}_{\mathrm{qd-dynamic}} = \frac{\Delta\Phi_{\mathrm{q}}}{\Delta\mathrm{J}_{\mathrm{d}}}$$

Note 1: The end-winding leakage inductance Lendw, computed in the winding area, is included in the computation of D-axis and Q-axis flux-linkage. However, the values of the dynamic cross inductances Ldq–dynamic and Lqd-dynamic are not impacted by the end-winding inductance value since they are obtained with the derivative of respectively D-axis and Q-axis flux-linkage with respect to current variation along the corresponding quadrature axis (Q-axis and D-axis respectively).

Note 2: In the previous formulae, one considers peak values for both flux and current.

Note 3: In case the Rotor position dependency is set to “Yes”, the computation is done in the J_d - J_q plane with an additional third axis corresponding to the rotor position θ_r.

3.4.5 Static inductances

D-axis synchronous inductance - L$_{d\text{-static}}$ and **Q-axis synchronous inductance - L$_{q\text{-static}}$** are computed from the flux linkage maps and using the following formulae:

$$\mathrm{L}_{\mathrm{d-static}} = \frac{(\Phi_d - \Phi_0)}{\sqrt{2} \times J_d} \qquad \mathrm{L}_{\mathrm{q-static}} = \frac{\Phi_q}{\sqrt{2} \times J_q}$$

Note 1: The end-winding leakage inductance L_{endw}, computed in the winding area, is included in the computation of D-axis and Q-axis flux-linkage. The values of the static inductances $L_{d\text{–static}}$ and $L_{q\text{–static}}$ consider the value of the end-winding inductance.

Note 2: ϕ_0 corresponds to the permanent magnet flux included the cross-flux effects.

Note 3: In the previous formulae, one considers peak values for both flux and current.

Note 4: In case the Rotor position dependency is set to “Yes”, the computation is done in the J_d - J_q plane with an additional third axis corresponding to the rotor position θ_r.

3.4.6 Permanent magnet flux

The permanent magnet flux ϕ_0 corresponds to the magnetic flux provided by the magnet added to the magnetic flux provided by J_q along the q-axis.
As a result, ϕ_0 is a vector which corresponds to magnetic flux defined for $J_d = 0$, all along the q-axis.

Note: In case the Rotor position dependency is set to “Yes”, ϕ_0 is a vector that corresponds to magnetic flux defined for $J_d = 0$ and $\theta_r = 0$, all along the q-axis. To get values function of θ_r referred to the results given by the map **D-axis flux-linkage component -** Φ_d.

3.4.7 Electromagnetic torque

The **Electromagnetic torque** T_{em} is computed in different way in a function of the input Rotor position dependency value.

3.4.7.1 Rotor position dependency set to “No”

The flux linkage maps and the following formula are used:

$$T_{em} = \frac{m}{2} \times p \times \left(\Phi_d \times J_q - \Phi_q \times J_d\right)$$

Where m is the number of phases (3) and p is the number of pole pairs. J_d and J_q are the d and q axis peak current.

3.4.7.2 Rotor position dependency set to “Yes”

The **Electromagnetic torque** $\mathbf{T_{em}}$ is computed thanks to finite element computation and virtual work method to get the best evaluation of the ripple torque.

Note: In case the Rotor position dependency is set to “Yes”, **Electromagnetic torque** $\mathbf{T_{em}}$ average value computed with the Park’s equation or with virtual works are equal.

3.4.8 Iron loss computation

The **iron losses** are computed in a different way in the function of the value of the “Rotor position dependency” input.

3.4.8.1 Rotor position dependency set to “No”

A dedicated process has been developed to compute the **stator iron losses** (rotor iron losses not computed).
Stator iron losses are computed only for the stator magnetic circuit built with lamination material (computation is not applicable for solid materials).

Our method of computation doesn’t allow computing iron losses on the rotor side. However, iron loss level is generally not very important on the rotor side in comparison with iron losses on the stator side.

For each node of the grid, in the J_d-J_q space defined and illustrated above, magnetic flux densities in stator teeth are obtained from a dedicated semi-numerical method based on the integration of the flux density in the airgap.

For each considered region (foot teeth, teeth and yoke) we get the magnetic flux density as a function of the angular position. Then, the derivative of each magnetic flux density is computed as a function of the angular position.

At last, for each considered speed, a mathematical transformation is applied to get the derivative of magnetic flux density as a function of time

$$\frac{dB}{dt}(t) = \frac{dB}{d\theta}(\theta) \times \frac{d\theta}{dt}$$

Total iron losses are computed considering the magnetic circuit volume, the density of materials used, and the stacking coefficient considered for the stator lamination.

3.4.8.2 Rotor position dependency set to “Yes”

The **iron losses, stator and rotor** are computed thanks to the magnetostatic application of Flux (Finite Element modeling - MS FE) based on the magnetic flux derivative obtained over the finite element meshing.

The accuracy obtained is the same as the one with a magnetic transient finite element computation (MT FE) and for a given scenario the MS FE computation time is approximately reduced by a factor 2 times lower than MT FE.

3.4.8.3 Model used to compute iron losses

The model used to compute iron losses (W_{iron}) is:

$$W_{\mathrm{iron}} = \left[\left(K_h \cdot \left(\frac{B_{\mathrm{max}}}{K_f}\right)^{\alpha_h} \cdot f^{\beta_h}\right) + \left(K_c \cdot \frac{1}{T_{elec}} \cdot \int_0^{Telec} \left[\frac{\left(\frac{dB}{dt}\right)}{K_f}\right]^{\alpha_c} dt\right) + \left(K_e \cdot \frac{1}{T_{elec}} \cdot \int_0^{Telec} \left[\frac{\left(\frac{dB}{dt}\right)}{K_f}\right]^{\alpha_e} dt\right)\right] . V_{\mathrm{iron}} . K_f$$

With:

B_{max}:	Peak value of the magnetic flux density (T)
f:	Electrical frequency (Hz)
V_{iron}:	Stator core lamination volume
K_f:	Stacking factor

The other parameters of this model are defined in the application dedicated to materials in FluxMotor®, i.e. “Materials”.

Note: In case the “Rotor position dependency” input is set to “No”, the impact on accuracy will be more important for machine with high level of saturation. In fact, the semi-numerical method used to compute magnetic flux density of the stator teeth neglects flux leakage between teeth. This hypothesis will lead to more errors particularly in areas where there is field weakening (generally applicable at high speeds).

3.4.9 Joule losses

Joule losses in stator winding W_{Cus} are computed using the following formulae:

$$W_{\mathrm{Cus}} = m \times R_{\mathrm{ph}} \times (J)^2$$

$$\underline{J} = J_d + jJ_q$$

$$\left|\underline{J}\right| = J = \sqrt{J_d^2 + J_q^2}$$

Where m is the number of phases (3 in the first version of FluxMotor®),
J is the rms value of the phase current (I is the line current. I = J with a Wye winding connection),

R_{ph} is the phase resistance computed according to the temperatures defined by user in the test settings.

Note 1: R_{ph} considers the resistance factor defined in the winding settings (DESIGN area of Motor Factory).

Note 2: In case the Rotor position dependency is set to “Yes”, the computation is done in the J_d - J_q plane with an additional third axis corresponding to the rotor position θ_r.

3.4.10 Mechanical losses

The mechanical losses are computed as a function of the speed.
For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section “Mechanical loss model settings”

3.4.11 Total losses

For each considered value of speed and currents J_d, J_q, the amount of losses described above (iron loss, Joule loss and mechanical losses) is computed and displayed.

Note: In case the Rotor position dependency is set to “Yes”, the computation is done in the J_d - J_q plane with an additional third axis corresponding to the rotor position θ_r.

3.5 Test results

Once the test is solved, the corresponding results are automatically displayed in the central window.
When a thermal solving has been selected in the settings section, all the temperature of magnets defined in the thermal settings are considered. A set of output data is computed and can be displayed for each temperature when selected.

3.5.1 Test conditions

3.5.1.1 Inputs

All the parameter values, belonging to standard inputs or advanced inputs are described in this section.
It shows the initial conditions considered for the test.
Here are the displayed subsections:

- Context
- Standard parameters
- Advanced parameters

3.5.1.2 Settings

All the settings dedicated to the test and dealing with the thermal are displayed in this section.
Here is the displayed subsection:

- Thermal
- Electronics
- Mechanics

3.5.1.3 Winding and magnet characteristics

All winding and magnet characteristics are displayed in the following subsections:

- Magnet characteristics
- Winding characteristics

For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – sections dealing with settings.

3.5.2 Main results

3.5.2.1 Machine performance – Open circuit

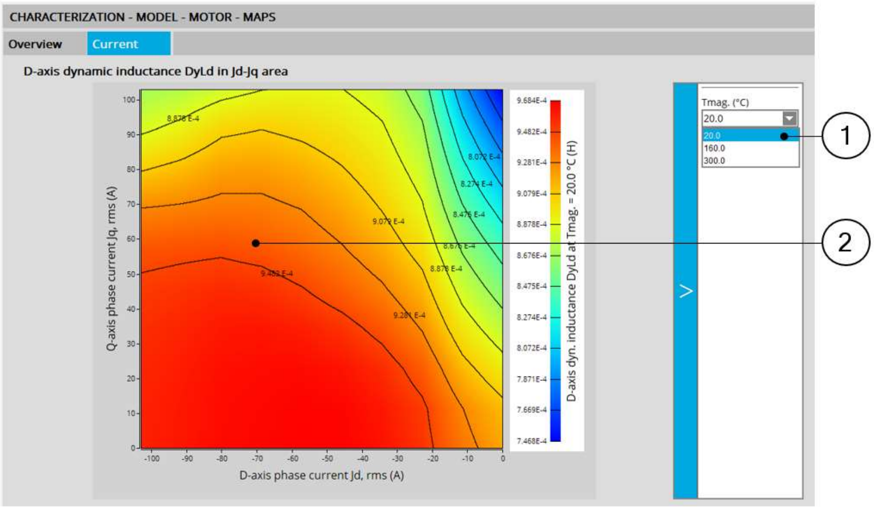
Here is the displayed subsection:

- Results

Note: « No load flux» is displayed in the section “Data”. It corresponds to the maximum amount of flux linkage through one phase due to magnets only (without current excitation).

3.5.3 Maps

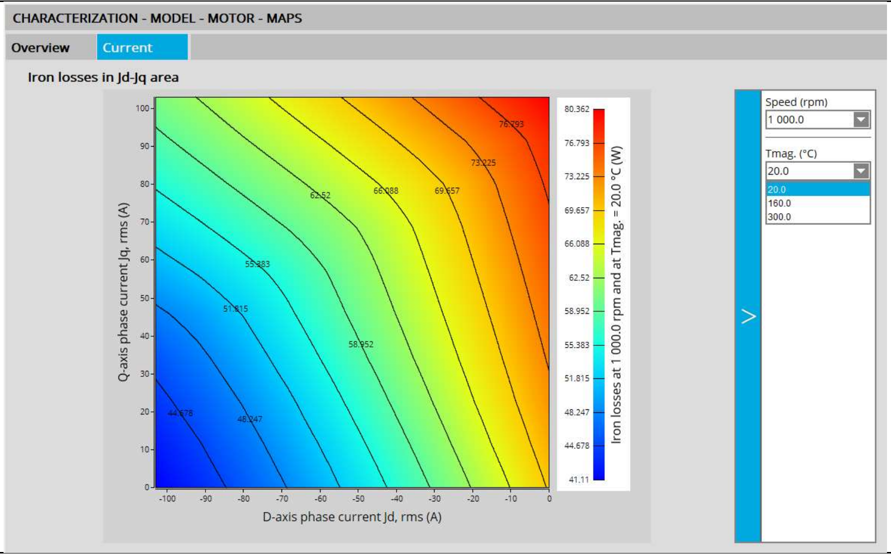
Maps illustrating the following quantities (Φ_d, Φ_q, $\Phi_d/d\theta_r$, $\Phi_q/d\theta_r$, $L_{d\text{-dynamic}}$, $L_{q\text{ dynamic}}$, $L_{dq\text{-dynamic}}$, $L_{qd\text{ dynamic}}$, $L_{d\text{-static}}$, $L_{q\text{ static}}$, torque) are displayed in the J_d-J_q plane.



Tmag. (°C): 20.0
20.0
160.0
300.0

D-axis dynamic inductance in J_d - J_q area - Selection of temperature (1) in the drop-down menu the map is instantaneously updated (2)

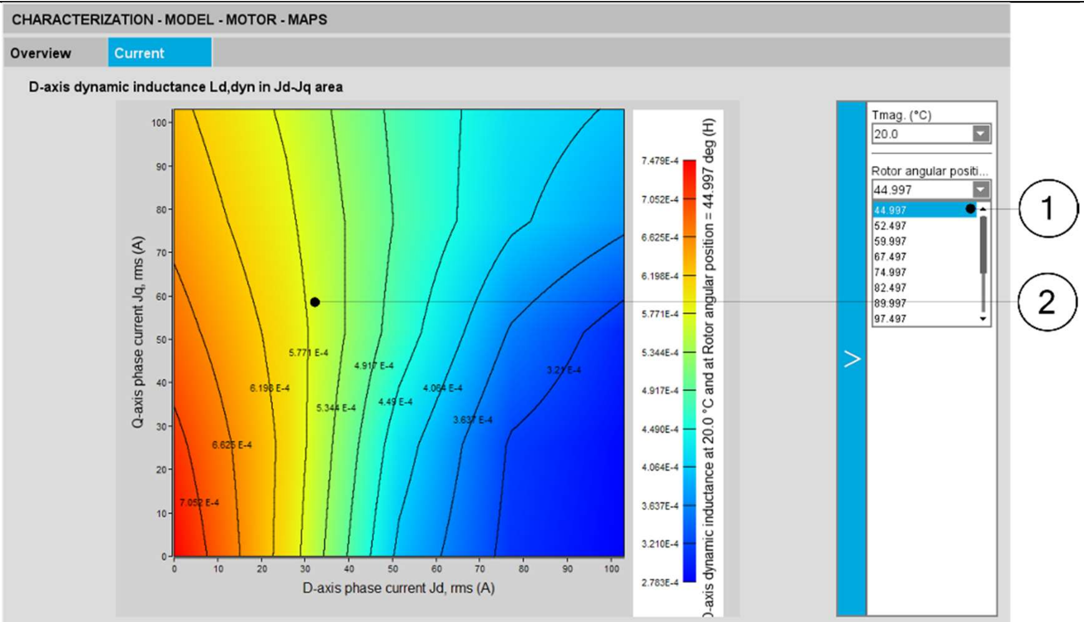
Iron loss maps, total loss maps and power electronics loss maps are displayed in the J_d-J_q plane and they are also parameterized as a function of speed and magnet temperature.
The desired speed as well as the magnet temperature can be chosen in the drop-down menu on the right of the graph.



Speed (rpm): 1 000.0
Tmag. (°C): 20.0
20.0
160.0
300.0

Iron losses in J_d - J_q area - Selection of speed in the drop-down menu

Illustrations of results depending on the user’s inputs dealing with the Rotor position dependency (“Yes“ or “No”). In case the Rotor position dependency is set to “Yes”, computations are done in the J_d - J_q plane with an additional third axis corresponding to the rotor position θ_r.



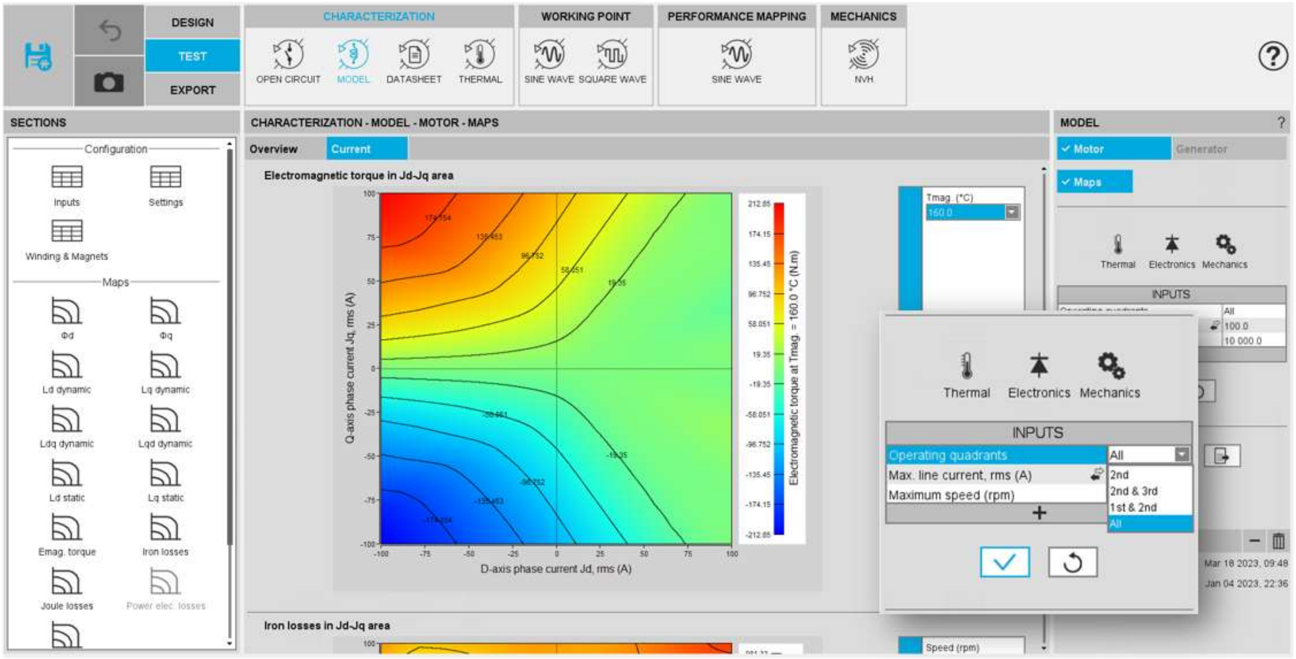
CHARACTERIZATION - MODEL - MOTOR - MAPS

Tmag. (°C): 20.0

Rotor angular positi...: 44.997

D-axis dynamic inductance in J_d - J_q area - Selection of rotor angular position (1) in the drop-down menu the map is instantaneously updated (2)

Illustrations of results depending on the user's inputs dealing with the selection of the operating quadrants ("2nd and 3rd ", "1st and 2nd "and "all") are presented below.



Thermal Electronics Mechanics

INPUTS

Operating quadrants: All

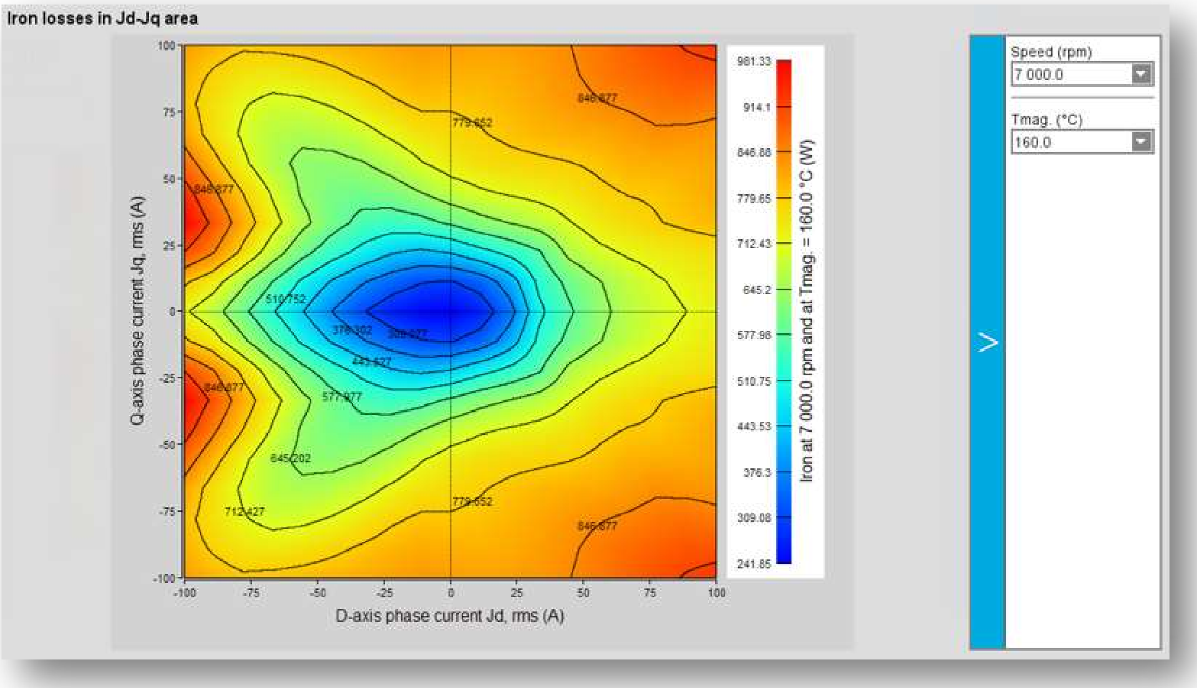
Max. line current, rms (A)

Maximum speed (rpm)

2nd
2nd & 3rd
1st & 2nd
All

Characterization / Model / Maps for SMPM - New user's inputs to select the operating quadrants.

Illustrations with few examples of map displaying:



Speed (rpm): 7 000.0

Tmag. (°C): 160.0

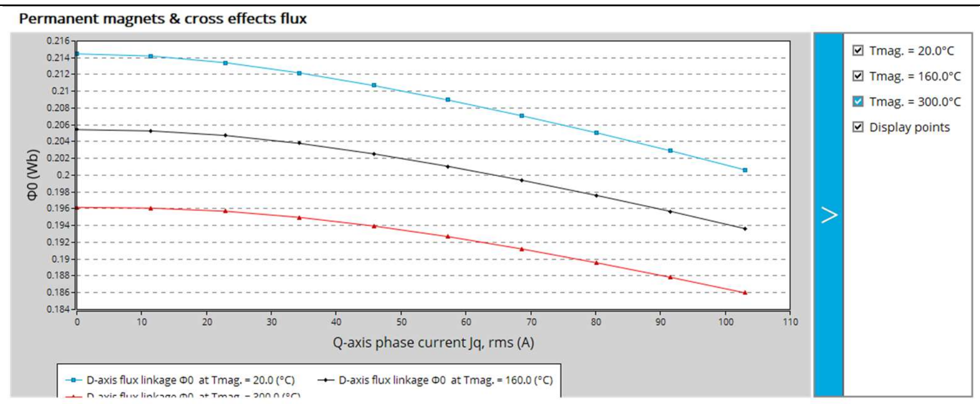
Iron losses in J_d - J_q area - Selection of speed in the drop-down menu

Note: Maps can be displayed depending on the magnet temperature, and the rotor speed when relevant.

3.5.4 Curves

3.5.4.1 Permanent magnet flux

Curves showing the permanent magnet flux ϕ_0 can be displayed for each considered magnet temperatures defined in the thermal settings. This corresponds to the magnetic flux provided by the magnet added to the magnetic flux provided by J_q along the q-axis.



☑ Tmag. = 20.0°C

☑ Tmag. = 160.0°C

☑ Tmag. = 300.0°C

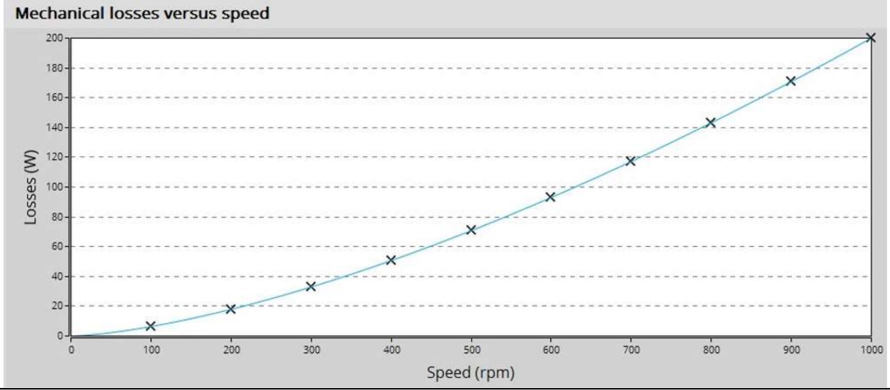
☑ Display points

Mechanical losses versus speed - Visualization of the mechanical loss curve

Note: In case the Rotor position dependency is set to "Yes", ϕ_0 is a vector which corresponds to magnetic flux defined for $J_d = 0$ and $\theta_r = 0$, all along the q-axis. To get values function of θ_r referred to the results given by the map **D-axis flux-linkage component - Φ_d.**

3.5.4.2 Mechanical losses

A curve showing the evolution of mechanical losses versus speed is displayed.



Mechanical losses versus speed - Visualization of the mechanical loss curve

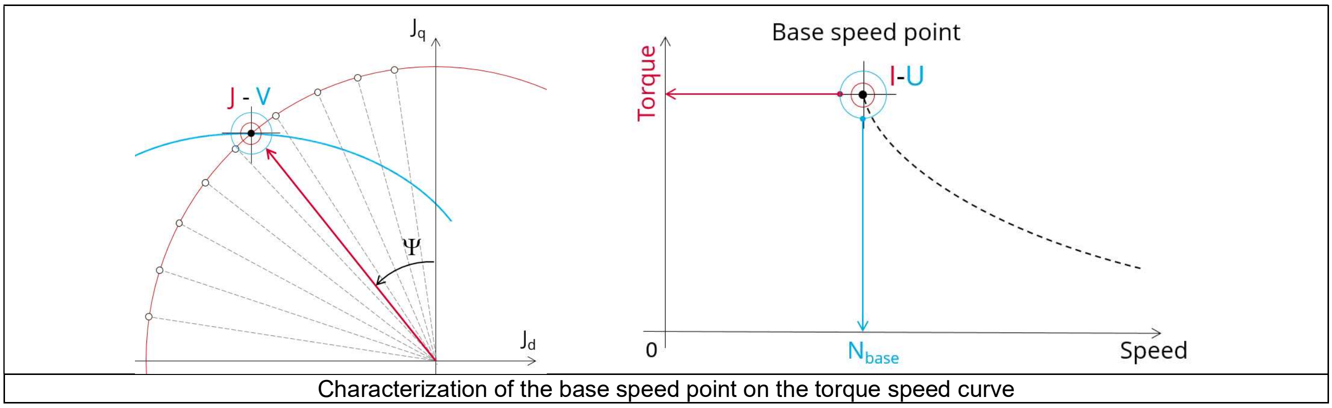
4 CHARACTERIZATION – DATASHEET – MOTOR – I, U

4.1 Overview

4.1.1 Positioning and objective

The aim of the test “**Characterization - Datasheet – Motor – I, U**” is to characterize the behavior of the machine when operating at the working point that is located at the base speed point.
The working point or base speed point of the torque-speed curve is defined by considering the maximum allowed line-line voltage and the maximum allowed line current.

Note: In FluxMotor® terminology, the last working point on the constant torque part of the torque-speed curve is called “Base speed point” only when it is obtained for the maximum allowed line-line voltage and the maximum line current. If it is not the case, we called as “Corner speed point”.



Characterization of the base speed point on the torque speed curve

This test gives an overview of the electromagnetic analysis of the motor considering the machine topology, the maximum allowed supplied line-line voltage and line current.
For this working point, general data of the machine, like machine constants, power balance and magnet behavior are computed and displayed. The magnetic flux density is also computed in every part of the machine to evaluate the design.

The test results also include all the necessary constants to build the equivalent model of the machine and to simulate the behavior of the machine in its electrical environment. In the results, a set of inductances is computed (unsaturated and at the base speed point).
The ripple torque at the base speed point is computed.
An overview of the machine performance at no-load is also given in this test.

The following table helps to classify the test “Characterization – Datasheet – Motor – I, U”.

Family	Characterization
Package	Datasheet
Convention	Motor
Test	I, U

Positioning of the test “Characterization – Datasheet – Motor – I, U”

4.1.2 User inputs

The main user input parameters to perform this test are the maximum allowed supplied line-line voltage, the line current and the command mode. In addition, temperatures of winding and magnets must be set.

4.1.3 Main outputs

Test results are illustrated with data, graphs, and tables

4.1.3.1 Tables of results

1) Machine performance – Base speed point
    - General data
    - Machine constants
    - Power balance
    - Flux in airgap
    - Flux density in iron
    - Magnet behavior including evaluation of demagnetization rate

2) Power electronics
    - Inverter
    - Working point

3) Inductances
    - Unsaturated inductances
    - Base speed point
    - D-Q model representation

4) Machine performance – open circuit
    - Back emf characteristics
    - Flux in airgap
    - Flux density in iron
    - Magnet behavior including evaluation of demagnetization rate

5) Ripple mechanical torque
    - Working point

6) Synthesis for catalog
    - Operating conditions
    - Performance
    - Machine characteristics
    - Masse & Inertia

4.1.3.2 Curves

1) Ripple mechanical torque versus rotor angular position
2) Mechanical torque versus current and control angle
3) Phase voltage versus time – Open circuit
4) Line-line voltage versus time – Open circuit
5) Flux linkage versus rotor angular position – Open circuit
6) Flux density in airgap versus rotor angular position – Open circuit

4.2 Settings

Three buttons give access to the following setting definition:

- Thermal settings – Definition of the temperature of active components.
  For the considered test this concerns the temperature of the winding and magnets.
- Power electronics settings - Definition of the power electronics parameters
- Mechanics settings - Definition of mechanical loss model parameters

For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – sections dealing with settings.

4.3 Inputs

4.3.1 Introduction

The total number of user inputs is equal to 10.
Among these inputs, 3 are default inputs and 7 are advanced inputs.

4.3.2 Standard inputs

4.3.2.1 Current definition mode

There are 2 common ways to define the electrical current.

Electrical current can be defined by the current density in electric conductors.
In this case, the current definition mode should be « **Density** ».

Electrical current can be defined directly by indicating the value of the line current (the RMS value is required).
In this case, the current definition mode should be « **Current** ».

4.3.2.2 Maximum line current, rms

When the choice of current definition mode is “**Current**”, the rms value of the maximum line current supplied to the machine: “**Max. line current, rms”** (*Maximum line current, rms value*) must be provided.

Note: The number of parallel paths and the winding connection are automatically considered in the results.

4.3.2.3 Maximum current density, rms

When the choice of current definition mode is “**Density**”, the rms value of the maximum current density in electric conductors “**Max. current dens., rms”** (*Maximum current density in conductors, rms value*) must be provided.

Note: The number of parallel paths and the winding connection are automatically considered in the results.

4.3.2.4 Maximum Line-Line voltage, rms

To supply the machine the rms value of the maximum Line-Line voltage: “**Max. Line-Line voltage, rms”** (*Maximum Line-Line voltage, rms value*) must be provided.

Note: The number of parallel paths and the winding connection are automatically considered in the results.

4.3.2.5 Command mode

Two commands are available: Maximum Torque Per Voltage (MTPV) and Maximum Torque Per Amps (MTPA) command mode.
For the base speed point computation, both commands lead to the same results. In fact, the base speed point corresponds to the working point which maximize the mechanical torque at maximum current and at maximum voltage. Following this, MTPA and MTPV commands give the same results on this test.

Note: The computed maximum speed depends on the chosen command mode.

4.3.2.6 Additional losses

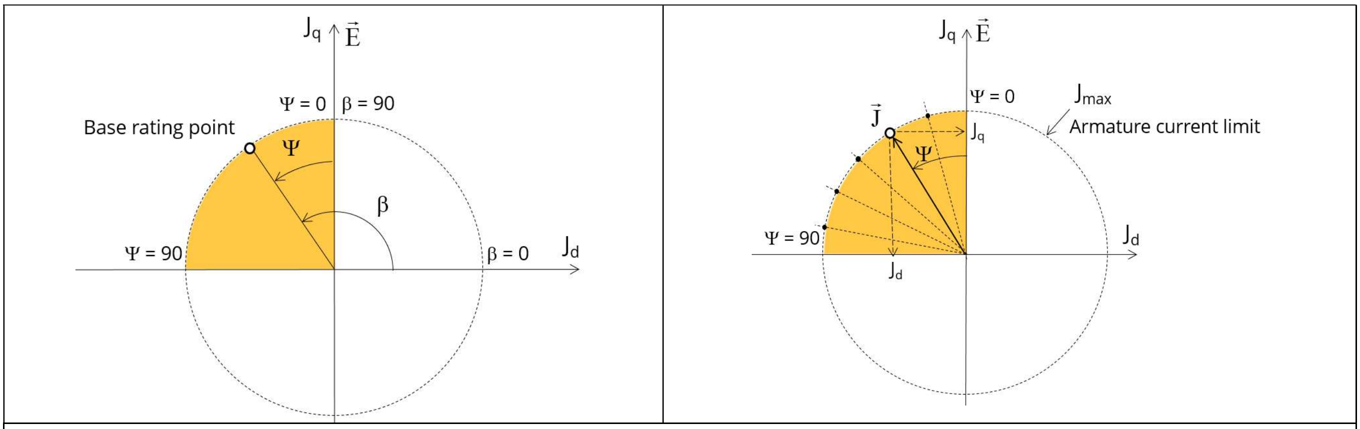
“Additional losses” input is not available in the current version (The input label is written in grey).

4.3.3 Advanced inputs

4.3.3.1 Number of computations for the control angle

Considering the vector diagram shown below, the control angle Ψ is the angle between the electrical current (J) and the electromotive force E (Ψ = (J, E)).
The computation to get the corner point location is performed by considering control angle (Ψ) over a range of 0 to 90 electrical degrees.
The user input "**No. comp. for ctrl. angle**" (*Number of computations for the control angle)* allows to choose between accuracy of results and computation time by using a number of computations between $\psi = 0°$ and $\psi = 90°$. The variation area for ψ is represented by the quarter circle (colored yellow in the diagram). This discretization is necessary to find the working point corresponding to the base speed point of the torque-speed curve.

The default value of Number of computations for the control angle is equal to 5. The minimum allowed value is 5.



Variation area for control angle Ψ

4.3.3.2 Number of computations per electrical period

For analysis like open circuit - Back-EMF or unsaturated inductances, performed over an electrical period, the user input "**No. comp. / elec. period**" *(Number of computations per electrical period)* influences the accuracy of results and the computation time.

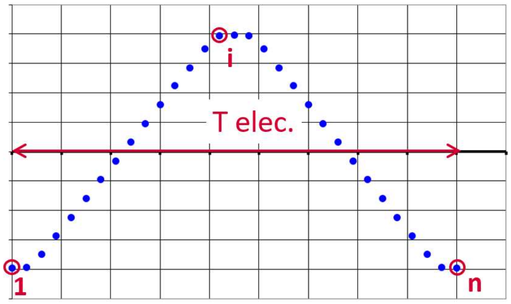
Computations over electrical period are performed using a Finite Element Modelling.

The default value is equal to 50. The minimum allowed value is 13. The default value provides a good compromise between the accuracy of results and computation time.

Note: This user input is needed for both open circuit computations and unsaturated inductance computations.
For computing the open circuit machine performance, the process is the same as in the "Characterization – Open circuit – Motor & Generator – Back-emf.
In that case, the raw computations are performed over one electrical half period. The result on a whole electrical period is rebuilt from the raw data.
The real number of computations per electrical period can be equal to the requested one +/- 1.

For the computation of unsaturated inductances, the requested number of computations over the whole electrical period is directly applied.

At last, the number of computations per electrical period displayed in outputs is always the requested one even if there is a little difference (+/- 1) with the one used for the computation of back-emf.

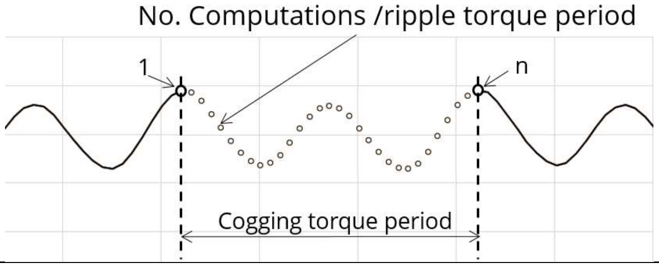


Number of computations per electrical period

4.3.3.3 Number of computations per ripple torque period

To compute peak-peak ripple torque more precisely, the user input “**No. comp. / ripple period**” *(Number of computations per ripple torque period)* influences the accuracy of results and the computation time. It has also a significant impact on the computation of the magnet behavior as well as on computation of the flux density in iron.

The default value is equal to 30. The minimum allowed value is 25. The default value provides a good compromise between the accuracy of results and computation time.



Definition of the number of computations per ripple torque period

4.3.3.4 Current coefficient

Linear conditions must be considered to compute unsaturated inductances.
To obtain a linear magnetic behavior for materials used in the magnetic circuit, the “**Current coefficient**” is used to define the corresponding maximum current which still allows linear conditions (magnetic behavior).

From practical point of view, the maximum phase current is multiplied by this current coefficient. Thus, the resulting current is used to compute the unsaturated inductances.

Note: The maximum phase current is deduced from the maximum line current defined as a user input parameter.

The range of possible values is from 0 to 1.

4.3.3.5 Rotor initial position

By default, the “**Rotor initial position**” is set to “**Auto**”.

When the “**Rotor initial position mode**” is set to “**Auto**”, the initial position of the rotor is automatically defined by an internal process of FluxMotor.
The resulting relative angular position corresponds to the alignment between the axis of the stator phase 1 (reference phase) and the direct axis of the rotor north pole.

When the “**Rotor initial position**” is set to “User input” (i.e. toggle button on the right), the initial position of the rotor considered for computation must be set by the user in the field « **Rotor initial position** ». The default value is equal to 0. The range of possible values is [-360, 360].
For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section “Rotor and stator relative position”.

4.3.3.6 Skew model – Number of layers

When the rotor magnets or the stator slots are skewed, the number of layers used in Flux® Skew environment to model the machine can be modified: “**Skew model - No. of layers”** (*Number of layers for modelling the skewing in Flux Skew environment*).

Note: When there is magnet step skew topology, the number of layers is defined at the design level.

4.3.3.7 Mesh order

To get the results, Finite Element Modelling computations are performed.
The geometry of the machine is meshed.
Two levels of meshing can be considered: First order and second order.
This parameter influences the accuracy of results and the computation time.
By default, second order mesh is used.

4.3.3.8 Airgap mesh coefficient

The advanced user input “**Airgap mesh coefficient**” is a coefficient which adjusts the size of mesh elements inside the airgap. When the value of “**Airgap mesh coefficient**” decreases, the mesh elements get smaller, leading to a higher mesh density inside the airgap, increasing the computation accuracy.

The imposed Mesh Point (size of mesh elements touching points of the geometry), inside the Flux® software, is described as:

MeshPoint = (airgap) x (airgap mesh coefficient)

Airgap mesh coefficient is set to 1.5 by default.
The variation range of values for this parameter is [0.05; 2].
0.05 giving a very high mesh density and 2 giving a very coarse mesh density.

Caution:
Be aware, a very high mesh density does not always mean a better result quality. However, this always leads to a huge number of nodes in the corresponding finite element model. So, it means a need of huge numerical memory and increases the computation time considerably.

4.4 Main principles of computation

4.4.1 Introduction

The aim of this test is to give a good overview of the electromagnetic potential of the machine by characterizing the base speed point of the torque speed curve.

For this, several computation processes are involved:

- Determination of base speed point,
- Analysis of the electromagnetic behavior
- Computation of the ripple torque
- Computation of unsaturated inductances
- Computation of inductances at the base speed point
- Computation of open circuit characteristics

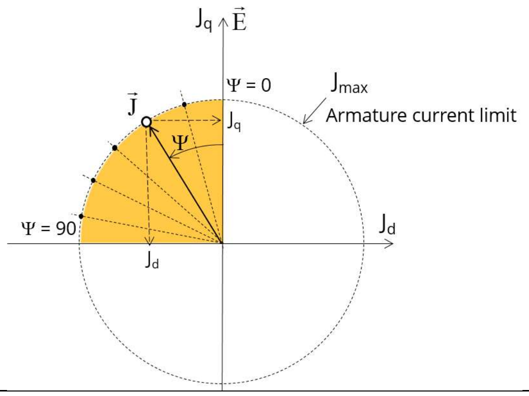
4.4.2 Determination of the base speed point

The base speed point of the torque speed curve corresponds to the working point obtain by considering the maximum allowed values of line current and line-line voltage ($I_{max.}$ and $U_{max.}$).

The quarter of circle corresponding to the maximum phase current in the J_d-J_q plane is discretized by considering the number of computations for control angle (Ψ) which is a user input parameter.

Several quantities, like the flux in the coils and flux density in (teeth and yoke of the machine) regions are computed as a function of the control angle (Ψ).
These computations are done by using Finite Element Modelling (Flux® software – Magnetostatic application).

- $\Phi d = f(\Psi)$
- $\Phi q = f(\Psi)$
- $B = f(\Psi)$



Discretization of the circle corresponding to $J_{max.}$

Then, an optimization process is performed to get the base speed point which corresponds to the working point at maximum line current and maximum line-line voltage: $I = I_{max.}$ and $U = U_{max.}$.

The resulting data (called general data) include:

- The control angle (Ψ) and thereby J_d and J_q
- The base speed
- The electrical frequency
- The torque
- The voltage components (V_d, V_q)

In addition, the power balance and machine constants are computed for the base speed point.
The torque constant “kT” is computed.

4.4.3 Electrical synchronous machines – Parameters and equations

For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section “Electrical machine – Theoretical equations”.

4.4.4 Electromagnetic behavior

4.4.4.1 Flux in airgap

Thanks to a static computation (1 rotor position to be considered) done with results obtain for the base speed point (with line current, control angle and speed obtained for the base speed point), the airgap flux density is computed along a path in the airgap in Flux® software.
The resulting signal is obtained over at least one electric period (rebuilt if less than an electrical period represented in Flux® software). The average and the peak value of the flux density are computed. A harmonic analysis of the flux density in airgap versus rotor position is done to compute the magnitude of the first harmonic of the flux density.

These quantities are also computed for the “Flux per pole”.

4.4.4.2 Flux density in iron

Mean and maximum values of flux density of each iron region are computed thanks to sensors in Flux® software.

4.4.4.3 Magnet behavior

Mean values of flux density and magnetic field inside the magnets are computed over one ripple torque period thanks to sensors in Flux® software. Based on these results, demagnetization rate of the magnets is computed.

4.4.5 Ripple torque

A specific computation is performed to determine precisely the rate of ripple torque.
Considering J_d and J_q at the base speed point, a computation is performed over one ripple torque period by using Finite Element modelling (Flux® software – Magnetostatic application).
Many computation points are considered over the ripple torque period (advanced user input: **No. comp. / ripple period**).
The following steps are performed to determinate the mechanical torque.

4.4.5.1 Original computation of the electromagnetic torque

The magnetic torque exerted on a non-deformable part of the study domain is computed by the virtual work method. The torque in a given direction is obtained by deriving the system energy with respect to a virtual displacement of the part in this direction.
The magnetic torque T_{em} is given by the following derivative:

$$T_{em} = -\frac{\partial W_m}{\partial \theta}$$

$\partial\theta$ = elementary angular displacement,
W_m = magnetic energy in a volume region

The electromagnetic ripple torque is computed over the ripple torque period versus the rotor angular position $T_{em,\theta}$. The mean value “$T_{em, mean}$” is computed

4.4.5.2 Mechanical ripple torque based on Park’s model

The mechanical ripple torque must be computed at the base speed.
First, we compute the electromagnetic torque “$T_{em, Park}$” with Park’s model:

$$T_{em,Park} = \frac{m}{2} \times p \times \left(\Phi_d \times J_q - \Phi_q \times J_d\right)$$

Then, the iron loss torque, the mechanical loss torque and the additional loss torque are subtracted from “$T_{em, Park}$ “ to get the corresponding mean value of the mechanical torque “$T_{mech, Park}$”.

4.4.5.3 Resulting mechanical torque versus rotor angular position

To compute the resulting mechanical ripple torque, the original electromagnetic torque previously computed is weighted by the ratio of the mean value of the mechanical torque based on Park's model ($T_{mech,\ Park}$) and of the mean value of the original electromagnetic ripple torque ($T_{em,\ mean}$).

$$T_{mech.,\theta} = T_{em,\theta} \times \frac{T_{mech,Park}}{T_{em,mean}}$$

The peak-peak value of the mechanical ripple torque is then computed. The rate of ripple torque is deduced as a percentage or per unit of the nominal torque.

Warning: When the ripple torque computation is not requested, the computation of the working point is performed by considering only one position within the electrical period. It means that all the data characterizing the behavior of the machine can change based on the selection of ripple torque (Yes/No).
Flux density in magnetic circuit and the magnet behavior will be more accurately computed when the computation of the ripple torque will be requested.

4.4.6 Inductances

4.4.6.1 Unsaturated inductances

1) Initial conditions

To compute the unsaturated inductances, the reference phase (Phase 1) is supplied with a very low DC current.

The value of this DC current $J_{dc}$is computed as follows:

$$J_{dc} = k_J \times (J_{rms})_{max}$$

k_J is the current constant defined as an advanced user input parameter (default value = 0.05)
$(J_{rms})_{max}$ is the maximum phase current (rms value) deduced from the standard user input parameter "**Max. Line current**" by considering the winding connection (Y or Δ).

Note: To perform this computation, the magnets are replaced by a solid material with the same relative magnetic permeability.

2) Test description

The computation is performed by using Finite Element modelling (Flux® software – Magnetostatic - application).
The reference phase (Phase 1) is supplied with a DC current and the rotor rotates over a range of angular positions corresponding to one electrical period (= 2 poles).

The flux linkages through all the phases are computed over this equivalent electrical period.
Considering a linear behavior of the magnetic circuit, fluxes Φ_1, Φ_2, Φ_3, through phases 1, 2 and 3 respectively are defined as follows:

$$\begin{pmatrix}\Phi_1\\ \Phi_2\\ \Phi_3\end{pmatrix} = \begin{vmatrix}L_1 & L_{12} & L_{13}\\ L_{21} & L_2 & L_{23}\\ L_{31} & L_{32} & L_3\end{vmatrix} \times \begin{pmatrix}J_1\\ J_2\\ J_3\end{pmatrix}$$

L_i is the self-inductances of phase "i",
L_{ij} is the mutual inductances between phases "i" and "j"

Self-inductance and mutual inductances are computed as a function of rotor angular position θ.
Considering the initial conditions of our computation, expression for self-inductance for the phase 1 is:

$$L_1 = L_{1av} + L_{2h} \times \mathrm{Cos}(2\theta)$$

$L_{i\,av}$ is the average value of the self-inductance L_i
L_{2h} is the first harmonic of the frequency representation of L_i

Considering the initial conditions of our computation, expression for mutual inductances between phases 1, 2 and 3 are:

$$L_{12} = L_{12av} + L_{2h} \times \mathrm{Cos}\left(\theta - \frac{\pi}{3}\right)$$
$$L_{13} = L_{12av} + L_{2h} \times \mathrm{Cos}\left(\theta + \frac{\pi}{3}\right)$$

$L_{ij\,av}$ is the average value of the mutual inductance L_{ij}
L_{2h} is the first harmonic of the frequency representation of L_{ij}

Using Park's equations and the corresponding transformation the D-axis and Q-axis flux linkages can be deduced:

$$\begin{pmatrix}\Phi_d\\ \Phi_q\\ \Phi_0\end{pmatrix} = \begin{vmatrix}\text{Cos }(\theta) & \text{Cos }\left(\theta-\frac{2\pi}{3}\right) & \text{Cos }\left(\theta+\frac{2\pi}{3}\right)\\ \text{Sin }(\theta) & \text{Sin }\left(\theta-\frac{2\pi}{3}\right) & \text{Sin }\left(\theta+\frac{2\pi}{3}\right)\\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2}\end{vmatrix} \times \begin{pmatrix}\Phi_1\\ \Phi_2\\ \Phi_3\end{pmatrix}$$

The D-axis and Q-axis unsaturated inductances can be deduced as:

$$L_d = L_{1av} - L_{12av} + \frac{3}{2} \times L_{2h}$$

$$L_q = L_{1av} - L_{12av} - \frac{3}{2} \times L_{2h}$$

Note: The end-winding leakage inductance L_{endw} is considered as a part of L_{1av}.

The slot leakage inductance (L_{lk_slot}) is computed from the magnetic energy stored in the slots along the half part of the airgap close to the stator bore diameter.

The total value of the leakage inductance (L_{lk}) is computed as follows:

$$L_{lk} = L_{endw} + L_{lk\_slot}$$

The D-axis and Q-axis magnetization inductances are deduced using the following formulae:

$$L_{md} = L_d - L_{lk}$$

$$L_{mq} = L_q - L_{lk}$$

4.4.6.2 Inductances at the base speed point

Considering the base point defined by (J_d, J_q), low variations of current (corresponding to ΔJ_d, ΔJ_q) are injected into the stator phases. The resulting variation of D-axis and Q-axis flux linkage are computed.

D-axis synchronous inductance - L_d and **Q-axis synchronous inductance - L_q** are obtained by using the following formulae:

$$L_d = \frac{\Delta\Phi_d}{\Delta J_d} \qquad L_q = \frac{\Delta\Phi_q}{\Delta J_q}$$

Note 1: The end-winding leakage inductance L_{endw}, computed in the winding area, is included in the computation of D-axis and Q-Axis flux linkage. The values of the synchronous inductances L_d and L_q consider the value of the end-winding inductance.

Note 2: In the previous formulae, one considers peak values for both flux and current.

4.4.7 Open circuit

The same principles as for the "**Characterization - Open circuit – Motor & Generator - Back-EMF**" test is used. For information, see the corresponding section.

4.5 Test results

Once a test is finished, the corresponding results are automatically displayed in the central window.

4.5.1 Test conditions

4.5.1.1 Inputs

All the parameter values, belonging to standard inputs or advanced inputs are described in this section.
It shows the initial conditions considered for the test.
Here are the displayed subsections:

- Context
- Standard parameters
- Advanced parameters

For more information refer to the section 4.3 Inputs .

4.5.1.2 Settings

All the settings dedicated to the test and dealing with the thermal are displayed in this section.
Here is the displayed subsection:

- Thermal
- Electronics
- Mechanics

4.5.1.3 Winding and magnet characteristics

All winding and magnet characteristics are displayed in the following subsections:

- Magnet characteristics
- Winding characteristics

For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section “Machine characteristics”.

4.5.2 Main results

4.5.2.1 Base speed point performance

Output data displayed in the following subsections are described in section Working point – Sine wave –Motor.
Here are the displayed subsections:

- General data
- Machine constants
- Power balance
- Flux in airgap
- Flux density in iron
- Magnet behavior

4.5.2.2 Power electronics

- Inverter

When power electronics stage is selected by the user, the inverter control strategy and the DC bus voltage are reminded. For information, the corresponding maximum line-line voltage, rms value is computed and displayed.

- Working point

The power balance and the corresponding efficiencies are computed and displayed for the machine, the power electronics stage and for the system (i.e. machine + power electronics stage).

4.5.2.3 Inductance data

1) Unsaturated inductances

Label	Symbol	Tooltip, note, formula
D-axis inductance L_{du}	L_{du}	D-axis unsaturated inductance L_{du}.
Q-axis inductance L_{qu}	L_{qu}	Q-axis unsaturated inductance L_{qu}.
D-axis magnetization ind. L_{md}	L_{md}	D-axis unsaturated magnetization inductance – L_{md}.
Q-axis magnetization ind. L_{mq}	L_{mq}	Q-axis unsaturated magnetization inductance – L_{mq}.
Leakage inductance - L_{lk}	L_{lk}	Leakage inductance (total value).
End winding inductance. – L_{endw}	L_{endw}	End-winding leakage inductance.
Phase self-inductance, mean	L_{iav}	Mean value of the phase self-inductance
Phase self-inductance 2nd harm, peak	L_2	Phase self-inductance - Peak value of the 2nd harmonic.
Phase mutual inductance, mean	L_{ijav}	Mean value of the phase mutual inductance.
Phase mutual inductance 2nd harm, peak	M_2	Phase mutual-inductance - Peak value of the 2nd harmonic.

2) Base speed point inductances

Label	Symbol	Tooltip, note, formula
D-axis ind. L_d	L_d	D-axis inductance - L_d.
Q-axis ind. L_q	L_q	Q-axis inductance - L_q.

3) D-Q model representation

Label	Symbol	Tooltip, note, formula
D-axis phase current, peak	J_d	D-axis phase current, peak value.
D-axis phase voltage, peak	V_d	D-axis phase voltage, peak value.
D-axis flux	Φ_d	D-axis magnetic flux.
Q-axis phase current, peak	J_q	Q-axis phase current, peak value.
Q-axis phase voltage, peak	V_q	Q-axis phase voltage, peak value.
Q-axis flux	Φ_q	Q-axis magnetic flux.

4.5.2.4 Open circuit data

The same principles as for the Characterization – open circuit – Back-emf test are used. For more details, see the section 2.4 (Main principles of computation).

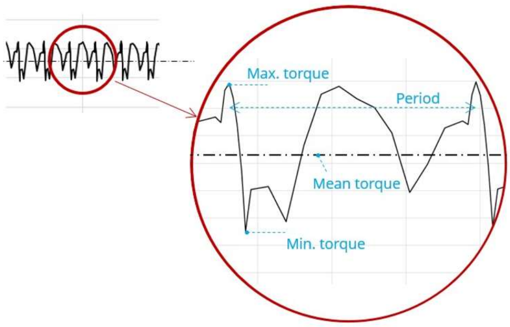
Output data displayed in the following area list are described in the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section Working point – Sine wave – Display of results.

- Back-emf characteristics
- Flux in airgap
- Flux density in iron
- Magnet behavior

4.5.2.5 Ripple mechanical torque

The analysis of the ripple torque is applied on the useful torque.

Label	**Symbol**	**Tooltip, note, formula**
Mechanical torque	T_{mean}	Mean value of the mechanical torque over a ripple torque period.
Ripple mech. torque, pk-pk	ΔT $T_{max} - T_{min}$	Ripple mechanical torque, peak-peak value
Ripple mech. Torque +- vs avg.	$\Delta T_{\%}$	Ripple mechanical torque magnitude versus average value
Ripple torque period	T_ripple	Ripple torque period



Computation of ripple torque characteristics

4.5.2.6 Synthesis for catalog

This section groups all the extracted quantities which are sent to the catalog datasheet of the considered machine.

4.5.3 Curves

4.5.3.1 Working point performance – Curves

- Ripple mechanical torque versus rotor angular position
- Mechanical torque versus current and control angle

4.5.3.2 Open circuit test – Curves

- Phase voltage versus time – Open circuit
- Line-Line voltage versus time – Open circuit
- Flux linkage versus angular position – Open circuit
- Flux density in the airgap versus angular position – Open circuit

5 CHARACTERIZATION – THERMAL – MOTOR & GENERATOR – STEADY STATE

5.1 Overview

5.1.1 Positioning and objective

The aim of “Characterization – Thermal – Motor & Generator – Steady state” test is to evaluate the impact of electromagnetic performance on thermal behavior of the machine.
A thermal working point defined by a speed and a set of losses can be considered to compute the temperature charts and the main thermal parameters. The inputs describing the thermal working point can be set manually or imported from electromagnetic tests that were previously solved.

This test helps to answer the following questions:

- Can the machine operate at the targeted working point without any overheating? Yes / No
- Can the different kinds of proposed cooling help to reach good performance? Yes / No

The following table helps to classify the test “Characterization – Thermal – Motor & Generator – Steady state”.

Family	Characterization
Package	Thermal
Convention	Motor & Generator
Test	Steady state

Positioning of the test “Characterization – Thermal – Motor & Generator – Steady state”.

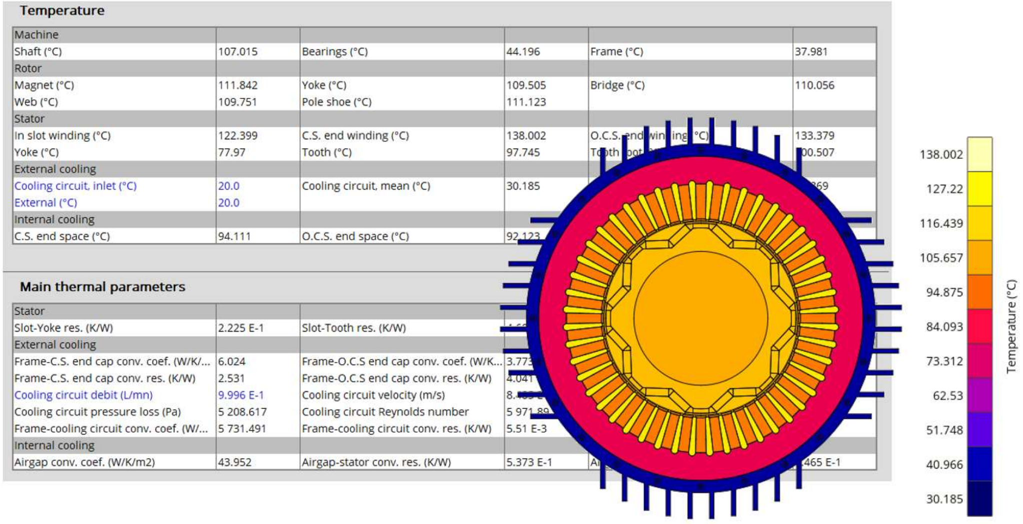
5.1.2 User inputs

The main inputs are the losses to be considered for evaluating the corresponding thermal behavior of the machine and the speed.

5.1.3 Main outputs

Here are the main results available:

- Temperature charts – radial and axial view
- Temperature table
- Main thermal parameters



Temperature

Machine					
Shaft (°C)	107.015	Bearings (°C)	44.196	Frame (°C)	37.981
Rotor					
Magnet (°C)	111.842	Yoke (°C)	109.505	Bridge (°C)	110.056
Web (°C)	109.751	Pole shoe (°C)	111.123		
Stator					
In slot winding (°C)	122.399	C.S. end winding (°C)	138.002	O.C.S. end win ing °C)	133.379
Yoke (°C)	77.97	Tooth (°C)	97.745	T oth ot	00.507
External cooling					
Cooling circuit, inlet (°C)	20.0	Cooling circuit, mean (°C)	30.185	[illegible]	69
External (°C)	20.0				
Internal cooling					
C.S. end space (°C)	94.111	O.C.S. end space (°C)	92.123	[illegible]	[illegible]

Main thermal parameters

Stator					
Slot-Yoke res. (K/W)	2.225 E-1	Slot-Tooth res. (K/W)	[illegible]	[illegible]	[illegible]
External cooling					
Frame-C.S. end cap conv. coef. (W/K/...	6.024	Frame-O.C.S end cap conv. coef. (W/K...	3.773	[illegible]	[illegible]
Frame-C.S. end cap conv. res. (K/W)	2.531	Frame-O.C.S end cap conv. res. (K/W)	4.041	[illegible]	[illegible]
Cooling circuit debit (L/mn)	9.996 E-1	Cooling circuit velocity (m/s)	8.	[illegible]	[illegible]
Cooling circuit pressure loss (Pa)	5 208.617	Cooling circuit Reynolds number	5 971.89	[illegible]	[illegible]
Frame-cooling circuit conv. coef. (W/...	5 731.491	Frame-cooling circuit conv. res. (K/W)	5.51 E-3	[illegible]	[illegible]
Internal cooling					
Airgap conv. coef. (W/K/m2)	43.952	Airgap-stator conv. res. (K/W)	5.373 E-1	Ai	.465 E-1

Illustration of results

5.2 Settings

One button gives access to the thermal settings:

- External fluid temperature
- Cooling circuit fluid temperature

Note 1: The external fluid temperature corresponds to the temperature of the fluid surrounding the machine. It is also considered as the temperature at the “infinite” for the computation of radiation from the frame to the infinite.

Note 2: The cooling circuit fluid temperature is relevant only when a cooling circuit has been added by the user in the design environment. In this case, this input describes its fluid inlet temperature.

5.3 Inputs

5.3.1 Introduction

The main inputs of these test correspond to a set of losses to be considered for evaluating the thermal behavior of the machine.

5.3.2 Standard inputs

5.3.2.1 Speed

The speed of the machine to be considered.

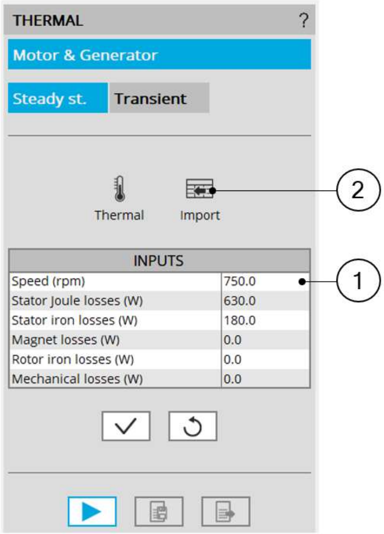
5.3.2.2 Set of losses

The losses to be defined are the following ones:

- Stator Joule losses
- Stator iron losses
- Magnet losses
- Rotor iron losses
- Mechanical losses

5.3.2.3 Input import

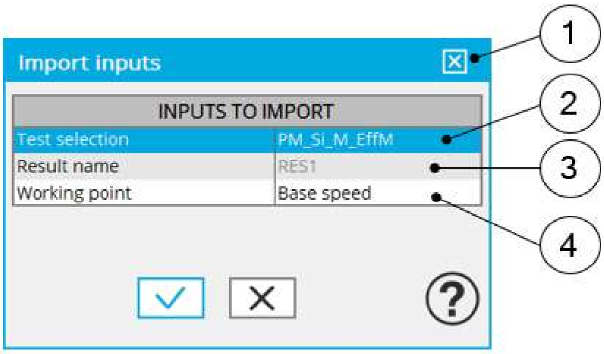
The set of inputs can be imported from another test already performed in Motor Factory Test environment.
It can be current results or saved test results.



INPUTS	
Speed (rpm)	750.0
Stator Joule losses (W)	630.0
Stator iron losses (W)	180.0
Magnet losses (W)	0.0
Rotor iron losses (W)	0.0
Mechanical losses (W)	0.0

How to define a set of losses

1	Fill in the table to define the speed and all the losses to be considered
2	Click on the button “import” to import inputs corresponding to a solved test. All existing data of the selected test will be imported into the inputs of the thermal characterization. The data which does not exist in the outputs of the selected test are set to 0.



Import inputs

INPUTS TO IMPORT

Test selection	PM_Si_M_EffM
Result name	RES1
Working point	Base speed

Dialog box to select the test from which a set of losses must be imported

1	Opened dialog box after having clicking on the button “import” on the main panel.
2	Selection of the test. Only solved tests are available in the drop-down list.
3	Current tests as well as saved test can be selected.
4	When several working points are computed in the selected test, each of them can be selected to consider the corresponding losses.

Note: The imported data are the output data directly shown in the considered solved test. For some tests, some values are not defined (like for instance the Joule magnet losses or rotor iron losses). In that case, the corresponding values are set to 0 in the thermal characterization input table.

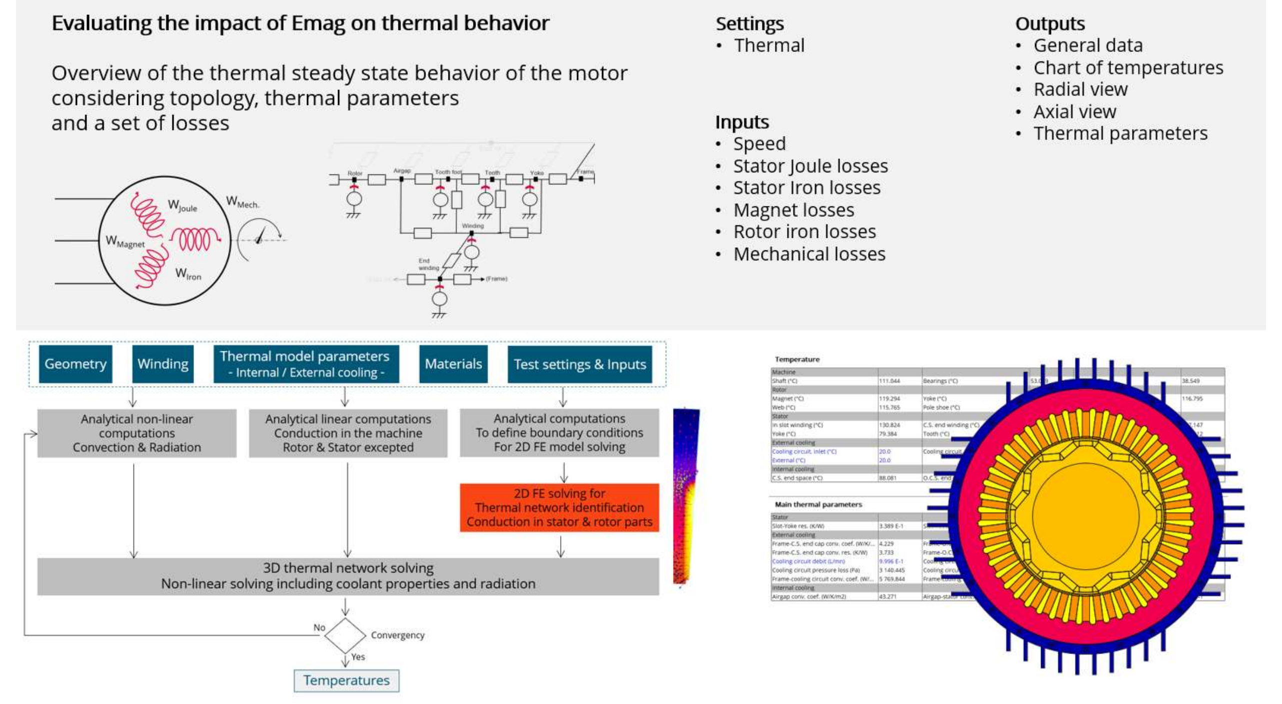
5.3.3 Advanced input

There are no advanced inputs required for this test.

5.4 Main principles of computation

5.4.1 Introduction

Here are illustrations which give an overview of the thermal test:



Evaluating the impact of Emag on thermal behavior

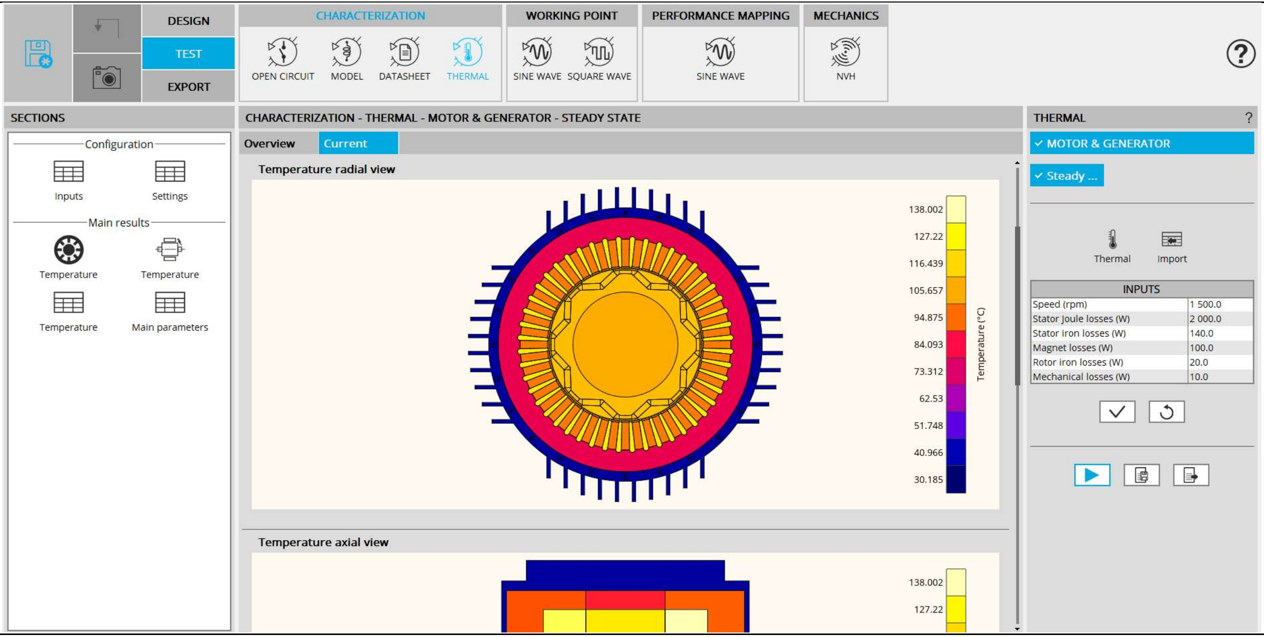
Overview of the thermal steady state behavior of the motor considering topology, thermal parameters and a set of losses

Settings
- Thermal

Inputs
- Speed
- Stator Joule losses
- Stator Iron losses
- Magnet losses
- Rotor iron losses
- Mechanical losses

Outputs
- General data
- Chart of temperatures
- Radial view
- Axial view
- Thermal parameters

Characterization – Thermal – Steady state – Synchronous machine - Overview

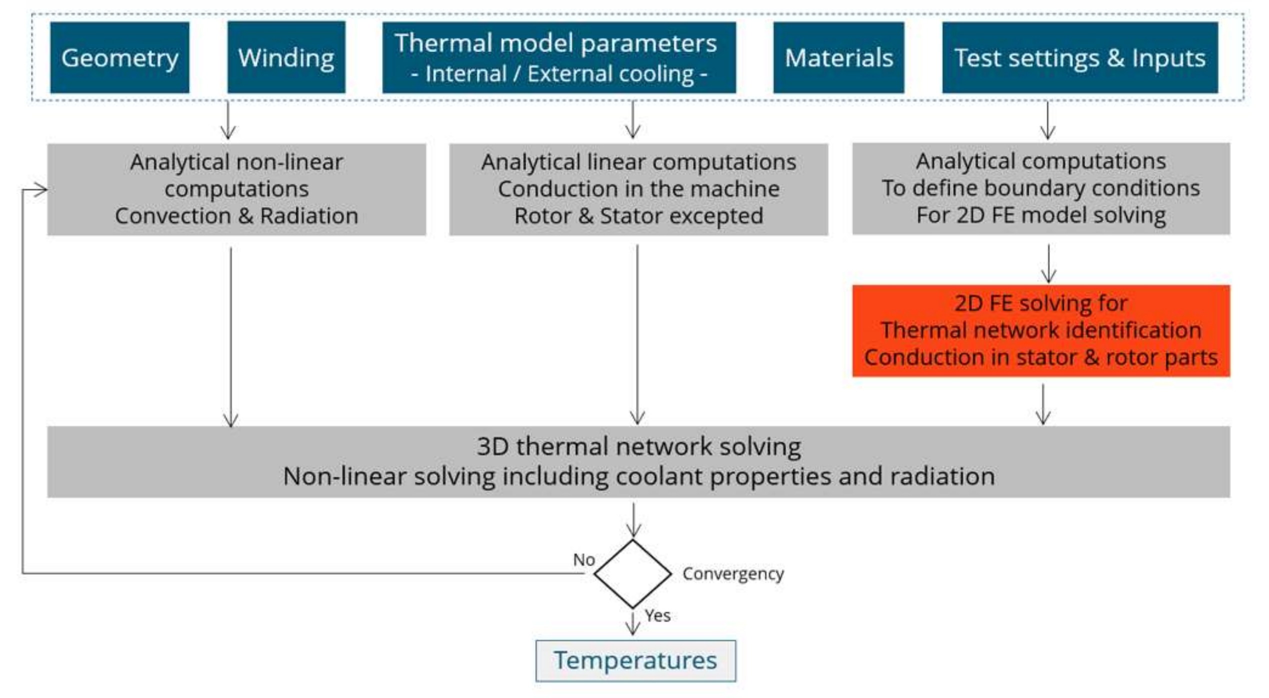


INPUTS	
Speed (rpm)	1 500.0
Stator Joule losses (W)	2 000.0
Stator iron losses (W)	140.0
Magnet losses (W)	100.0
Rotor iron losses (W)	20.0
Mechanical losses (W)	10.0

Characterization – Thermal – Steady state – Synchronous machine – Test results

5.4.2 Flow chart

Here is the flowchart illustrating the internal process of the thermal test.



Thermal test – Internal process flowchart

The inputs of the internal process are the parameters of:

- Geometry
- Winding
- Internal cooling
- External cooling
- Materials
- Test settings and inputs

Note: A 2D Finite Element model is solved to identify a thermal network which corresponds accurately to any kind of rotor or stator parts, including user parts.

Then, the resulting network is extended with analytical computations to consider the 3D effect of the geometry.

The solving allows to get and to display the whole chart of temperatures of the machines.

5.5 Test results

Once a test is finished, the corresponding results are automatically displayed in the central window.

5.5.1 Test conditions

5.5.1.1 Inputs

The speed and the set of losses to be considered in the test are reminded in the head of results

5.5.1.2 Settings

The thermal settings are reminded:

- External fluid temperature
- Cooling circuit temperature

5.5.2 Main results

- Temperature radial and axial views
- Temperature table

5.5.2.1 Main thermal parameters

1) For the stator

Label	**Tooltip, note formula**
Slot-Yoke res.	Slot-Yoke resistance
Slot-Tooth res.	Slot-Tooth resistance
Slot-Tooth foot res.	Slot-Tooth foot resistance

Each of these resistances corresponds to the thermal total resistance computed between the in-slot winding and the corresponding part of the magnetic circuit. In each case, it includes two resistances in series:

- The conduction resistance through the winding and the magnetic circuit
- The conduction resistance through the possible interface gaps between the slot and the magnetic circuit

2) For External cooling

Label	Tooltip, note formula
Frame-C.S. end cap conv. coef.	Frame-Connection Side end cap convection coefficient When a forced convection is defined, this coefficient is the total resulting convection coefficient corresponding to the mix of natural and forced convection on the end cap.
Frame-O.C.S. end cap conv. coef.	Frame-Opposite Connection Side end cap convection coefficient When a forced convection is defined, this coefficient is the total resulting convection coefficient corresponding to the mix of natural and forced convection on the end cap.
Frame straight part conv. coef.	Frame-Straight part convection coefficient When a forced convection is defined, this coefficient is the total resulting convection coefficient corresponding to the mix of natural and forced convection on the straight part of the frame.
Frame-C.S. end cap conv. res.	Frame-Connection Side end cap convection resistance When a forced convection is defined, this resistance is the total resulting convection resistance corresponding to the mix of natural and forced convection on the end cap.
Frame-O.C.S. end cap conv. res.	Frame-Opposite Connection Side end cap convection resistance When a forced convection is defined, this resistance is the total resulting convection resistance on Opposite Connection Side end cap, corresponding to the mix of natural and forced convection on the end cap.
Frame straight part conv. res.	Frame-Straight part convection resistance When a forced convection is defined, this resistance is the total resulting convection resistance corresponding to the mix of natural and forced convection on the straight part of the frame.
Cooling circuit debit	Cooling circuit debit
Cooling circuit velocity	Cooling circuit velocity
Cooling circuit section	Cooling circuit section
Cooling circuit pressure	Cooling circuit regular pressure loss The singular pressure loss (for instance corresponding to duct bends, inlet and outlet duct shapes) are not taken into account in this pressure loss.
Cooling circuit Reynolds number	Cooling circuit Reynolds number
Cooling circuit roughness	Cooling circuit roughness
Frame-cooling circuit conv. coef.	Frame-cooling circuit convection coefficient
Frame-cooling circuit conv. res.	Frame-cooling circuit convection resistance

3) For internal cooling

Label	Tooltip, note formula
Airgap conv. coef.	Airgap convection coefficient
Airgap-stator conv. res.	Airgap-stator convection resistance
Airgap-rotor conv. res.	Airgap-rotor convection resistance

5.6 Limitation of computations - Advice for use

Notes:

1) The resistance network identification of a machine is always done without any skew angle.
This can bring some inaccuracy in the results for highly skewed machines.

2) Please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section “Limitation of thermal computations – Advice for use”

6 CHARACTERIZATION – THERMAL – MOTOR & GENERATOR – TRANSIENT

6.1 Overview

6.1.1 Positioning and objective

The aim of “Characterization – Thermal – Motor & Generator – Transient” test is to evaluate the impact of electromagnetic performance on thermal behavior of the machine in a transient mode.
A thermal working point defined by a speed and a set of losses can be considered to compute the temperature charts and the main thermal parameters. The inputs describing the thermal working point can be set manually or imported from electromagnetic tests that were previously solved.
In addition to that, a maximum evaluation duration and a time step are added as inputs to set the transient mode.

This test helps to answer the following questions:

- Can the machine operate at the targeted working point without any overheating? Yes / No
- Can the different kinds of proposed cooling help to reach good performance? Yes / No
- How long does it take to reach the thermal steady state and what are the thermal time constants of the machine?

The following table helps to classify the test “Characterization – Thermal – Motor & Generator – Steady state”.

Family	Characterization
Package	Thermal
Convention	Motor & Generator
Test	Transient

Positioning of the test “Characterization – Thermal – Motor & Generator – Transient”

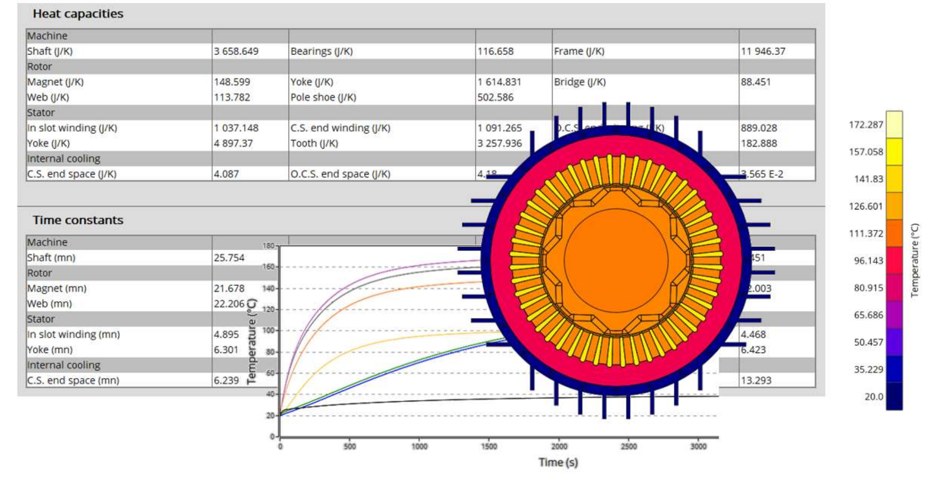
6.1.2 User inputs

The main inputs are the losses to be considered for evaluating the corresponding thermal behavior of the machine, the speed, a maximum evaluation duration and a time step.

6.1.3 Main outputs

Here are the main results available:

- Temperature charts versus time – radial and axial view
- Main temperature curve versus time and final temperature table
- Heat capacity and time constant table



Heat capacities

Machine					
Shaft (J/K)	3 658.649	Bearings (J/K)	116.658	Frame (J/K)	11 946.37
Rotor					
Magnet (J/K)	148.599	Yoke (J/K)	1 614.831	Bridge (J/K)	88.451
Web (J/K)	113.782	Pole shoe (J/K)	502.586		
Stator					
In slot winding (J/K)	1 037.148	C.S. end winding (J/K)	1 091.265	[illegible]	889.028
Yoke (J/K)	4 897.37	Tooth (J/K)	3 257.936	[illegible]	182.888
Internal cooling					
C.S. end space (J/K)	4.087	O.C.S. end space (J/K)	4.18	[illegible]	3.565 E-2

Time constants

Machine					
Shaft (mn)	25.754	[illegible]	[illegible]	[illegible]	[illegible]
Rotor					
Magnet (mn)	21.678	[illegible]	[illegible]	[illegible]	[illegible]
Web (mn)	22.206	[illegible]	[illegible]		
Stator					
In slot winding (mn)	4.895	[illegible]	[illegible]	[illegible]	4.468
Yoke (mn)	6.301	[illegible]	[illegible]	[illegible]	6.423
Internal cooling					
C.S. end space (mn)	6.239	[illegible]	[illegible]	[illegible]	13.293

Illustration of results

6.2 Settings

One button gives access to the thermal settings:

- External fluid temperature
- Cooling circuit fluid temperature

Note 1: The external fluid temperature corresponds to the temperature of the fluid surrounding the machine. It is also considered as the temperature at the “infinite” for the computation of radiation from the frame to the infinite.

Note 2: The cooling circuit fluid temperature exists only when a cooling circuit has been added by the user in the design environment. In this case, this input describes its fluid inlet temperature.

6.3 Inputs

6.3.1 Introduction

The main inputs of this test correspond to a set of losses to be considered for evaluating the thermal behavior of the machine in a transient mode.

6.3.2 Standard inputs

6.3.2.1 Speed

The speed of the machine to be considered.

6.3.2.2 Set of losses

The losses to be defined are the following ones:

- Stator Joule losses
- Stator iron losses
- Magnet losses
- Rotor iron losses
- Mechanical losses

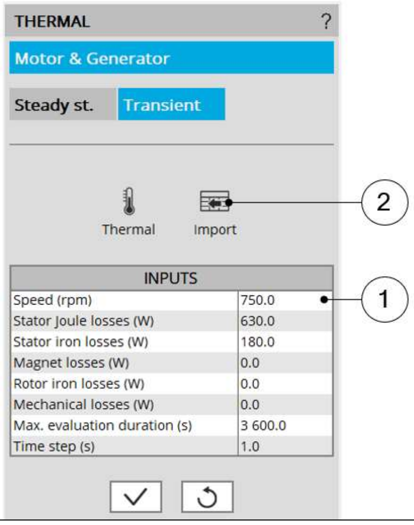
6.3.2.3 Time definition

The time during which the test is performed, defined by:

- Maximum evaluation duration
- Time step

6.3.2.4 Input import

The set of inputs concerning the speed and the losses, can be imported from another test already performed in Motor Factory Test environment.
It can be current results or saved test results.
Then the duration of the evaluation and the time step must be defined.

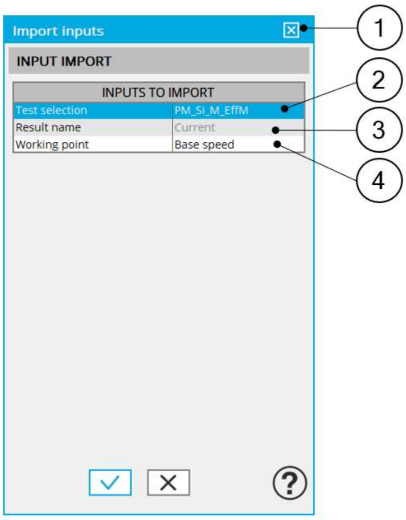


INPUTS

Speed (rpm)	750.0
Stator Joule losses (W)	630.0
Stator iron losses (W)	180.0
Magnet losses (W)	0.0
Rotor iron losses (W)	0.0
Mechanical losses (W)	0.0
Max. evaluation duration (s)	3 600.0
Time step (s)	1.0

How to define the inputs

1	Fill in the table to define the speed, all the losses to be considered, the max evaluation duration and the time step.
2	Click on the button “import” to import inputs corresponding to a solved test. All existing data of the selected test will be imported into the inputs of the thermal characterization. The data which does not exist in the outputs of the selected test are set to 0.



INPUTS TO IMPORT

Test selection	PM_SI_M_EffM
Result name	Current
Working point	Base speed

Dialog box to select the test from which a set of losses must be imported

1	Opened dialog box after having clicked on the button “import” on the main panel.
2	Selection of the test. Only solved tests are available in the drop-down list.
3	Current tests as well as saved test can be selected.
4	When several working points are computed in the selected test, each of them can be selected to consider the corresponding losses and speed.

Note: The imported data are the output data directly shown in the considered solved test. For some tests, some values are not defined (like for instance the Joule magnet losses or rotor iron losses). In that case, the corresponding input in transient thermal test will remain at the value existing before the import.

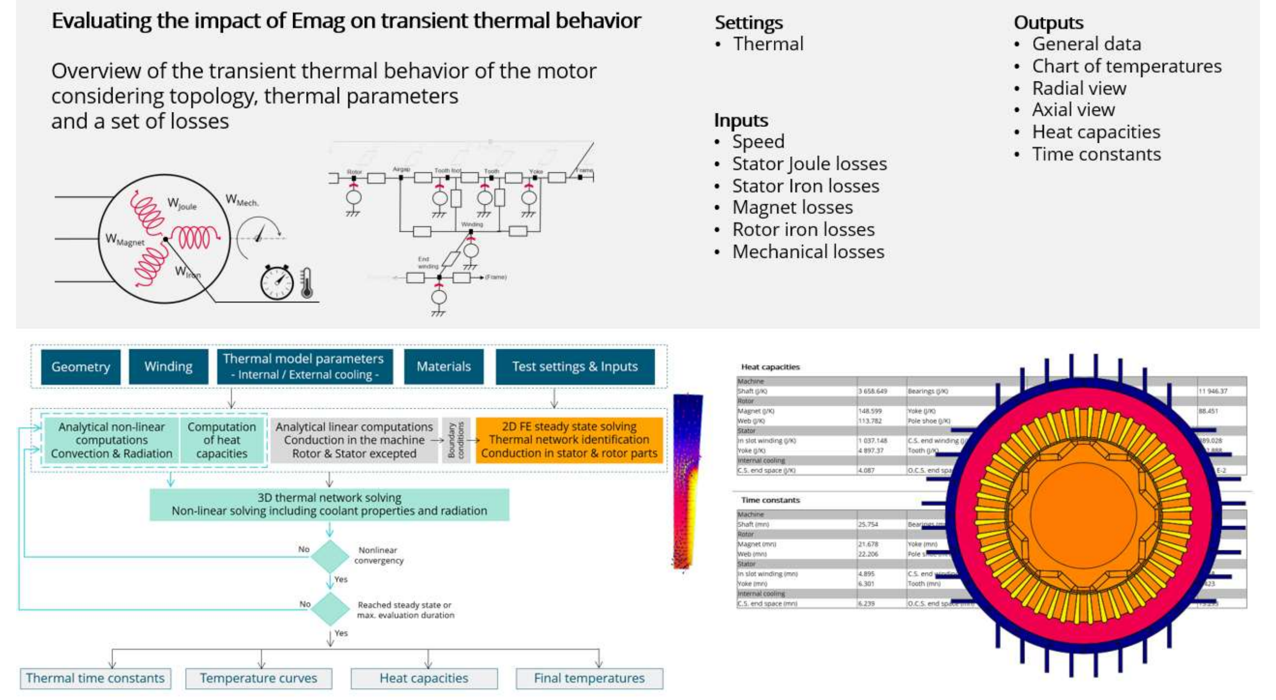
6.3.3 Advanced input

There are no advanced inputs required for this test.

6.4 Main principles of computation

6.4.1 Introduction

Here are illustrations which give an overview of the thermal transient test:



Evaluating the impact of Emag on transient thermal behavior

Overview of the transient thermal behavior of the motor considering topology, thermal parameters and a set of losses

Settings
- Thermal

Inputs
- Speed
- Stator Joule losses
- Stator Iron losses
- Magnet losses
- Rotor iron losses
- Mechanical losses

Outputs
- General data
- Chart of temperatures
- Radial view
- Axial view
- Heat capacities
- Time constants

Geometry | Winding | Thermal model parameters - Internal / External cooling - | Materials | Test settings & Inputs

Analytical non-linear computations Convection & Radiation

Computation of heat capacities

Analytical linear computations Conduction in the machine Rotor & Stator excepted

Boundary conditions

2D FE steady state solving Thermal network identification Conduction in stator & rotor parts

3D thermal network solving Non-linear solving including coolant properties and radiation

Nonlinear convergency (No / Yes)

Reached steady state or max. evaluation duration (No / Yes)

Thermal time constants | Temperature curves | Heat capacities | Final temperatures

Characterization – Thermal – Transient – Synchronous machine - Overview

Final temperatures

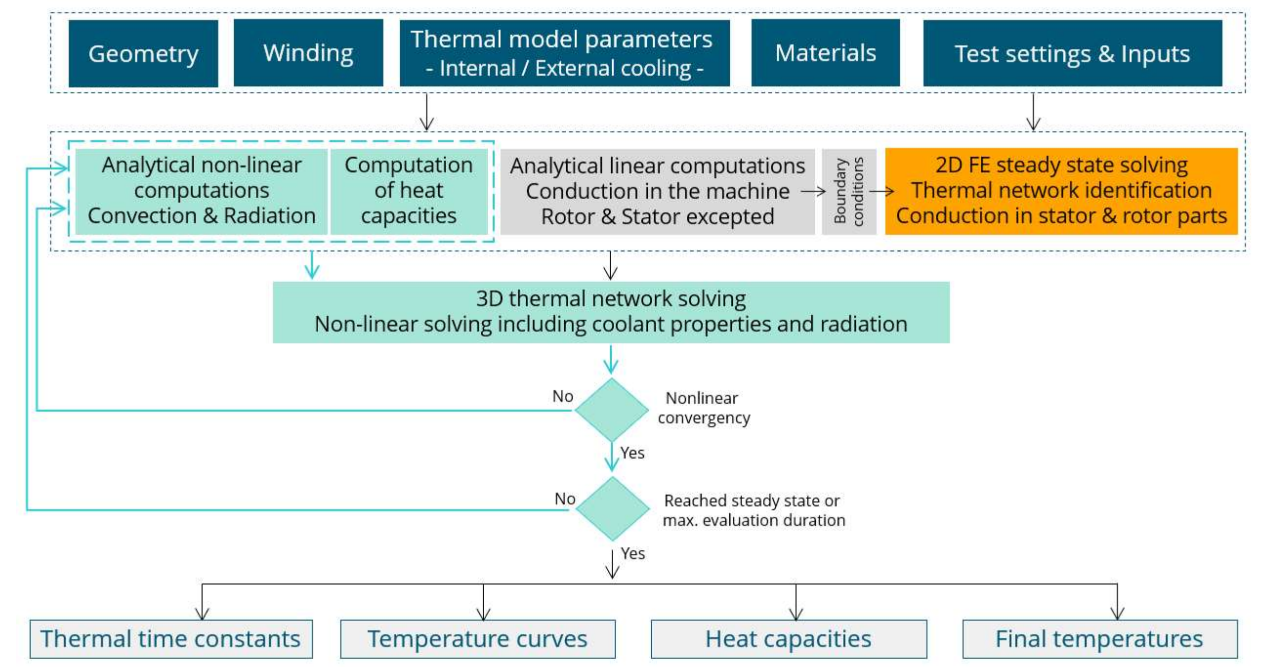
Machine					
Shaft (°C)	104.975	Bearings (°C)	34.988	Frame (°C)	25.151
Rotor					
Magnet (°C)	108.718	Yoke (°C)	107.263	Bridge (°C)	107.641
Web (°C)	107.378	Pole shoe (°C)	108.57		
Stator					
In slot winding (°C)	150.26	C.S. end winding (°C)	175.335	O.C.S. end winding (°C)	167.997
Yoke (°C)	82.525	Tooth (°C)	110.471	Tooth foot (°C)	115.39
External cooling					

INPUTS	
Speed (rpm)	1 680.0
Stator Joule losses (W)	2 930.0
Stator iron losses (W)	180.0
Magnet losses (W)	50.0
Rotor iron losses (W)	40.0
Mechanical losses (W)	60.0
Max. evaluation duration (s)	3 600.0
Time step (s)	1.0

Characterization – Thermal – Transient– Synchronous machine – Test results

6.4.2 Flow chart

Here is the flowchart illustrating the internal process of the thermal transient test.



Thermal transient test – Internal process flow chart

The inputs of the internal process are the parameters of:

- Geometry
- Winding
- Internal cooling
- External cooling
- Materials
- Test settings and inputs

A 2D Finite Element model is solved to identify a thermal network which corresponds accurately to any kind of rotor or stator parts, including user parts.

Then, the resulting network is extended with analytical computations to consider the 3D effect of the geometry at each time step. For that, a non-linear computation is performed in the solving of the transient thermal test.

Each thermal node of the machine is associated to a thermal capacitance, depending of the specific heat and density of the material(s) composing the node, and the associated volume.

Thus, the main provided outputs are the whole chart of temperatures of the machines versus time, the heat capacities, and the time constants.

Note: What are the criteria that allow to see if the steady state is reached while thermal transient solving?

First, from the thermal steady state computation, one gets a good estimation of the final temperature (θ_f).

From the thermal transient computation, variation of the temperature versus the time, one deduces the inverse function, i.e. the variation of the time versus the temperature.

Knowing that the time constant to reach 63% of a temperature step is equal to:

$$\theta_\tau = \theta_0 + (1- e^{-1}) \times (\theta_f - \theta_0).$$

We are looking for the time t that corresponds to θ_τ. If found, it corresponds to tau.

If the evaluation time t considered is lower than τ ($t < \tau$), there is no convergency yet.

If $\tau < t < 5\tau$, there is no convergency, the thermal steady state is not reached yet, but an estimation of time needed to converge can be estimated and given to the user.

If $t > \tau$ The solving has converged, and the steady state is reached.

6.5 Test results

Once a test is finished, the corresponding results are automatically displayed in the central window.

6.5.1 Test conditions

6.5.1.1 Inputs

The speed, the set of losses to be considered in the test in addition to the max evaluation duration and the time step are reminded in the head of results

6.5.1.2 Settings

The thermal settings are reminded:

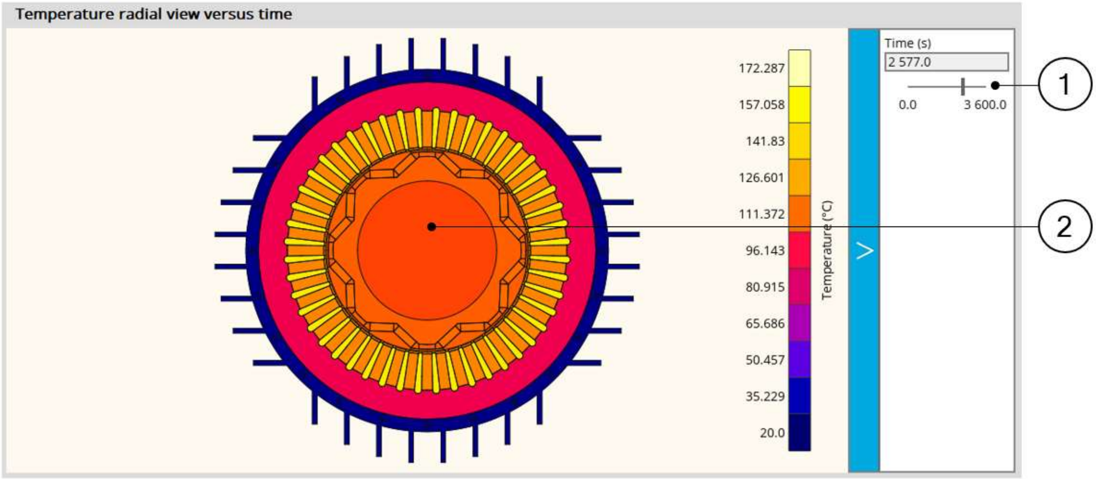
- External fluid temperature
- Cooling circuit temperature

6.5.2 Main results

- Temperature charts versus time (slider) – radial and axial view
- Main temperatures curve versus time
- Final temperatures table
- Heat capacity table
- Time constant table

6.5.3 Presentation of temperature charts

A slider allows automatically updating the displaying of chart temperature in function of time



Temperature chart versus time

1	Slider to select the time at which the chart is displayed
2	Temperature chart updated according to the position of the slider

6.6 Limitation of computations - Advice for use

Notes:

1) The resistance network identification of a machine is always done without any skew angle.
This can bring some inaccuracy in the results for highly skewed machines.

2) Please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section “Limitation of thermal computations – Advice for use”

7 CHARACTERIZATION – THERMAL – MOTOR & GENERATOR – FITTING

7.1 Overview

7.1.1 Positioning and objective

The aim of the “Characterization – Thermal – Motor & Generator – Fitting” test is based on a steady state thermal computation.

Whatever the considered machine, FluxMotor creates a thermal network based on the machine topology design. However, if needed, it is possible to adjust the thermal resistances with some calibration factors (X-Factors, for external cooling as well as internal cooling) to be consistent with the measurement results for instance. This has an impact on the resulting temperatures one gets in steady state or transient mode.
The user can adjust the calibration factors, step by step, and evaluate the final temperatures by performing a manual iterative process.

This can be used either when the users want to impose the reference temperatures that are coming from measurements or when the users want to keep the same temperatures after a modification of the internal thermal architecture model.

With the test Characterization-Thermal-Motor&Generator-Fitting, the calibration for the X-factors is fully automatic. The user must target the temperatures to be obtained and the X-Factors that can be used to reach this goal. As a result, one gets X-Factors values to be applied for reaching the targeted temperatures.
This can be used either when the users want to impose the reference temperatures that are coming from measurements or when the users want to keep the same temperatures whatever the modifications of the internal thermal model architecture.

Note: This test is based on a steady state thermal computation.

Note: In the first step, this test is dedicated to the Synchronous Machines with Permanent Magnets – Inner Rotor.

The following table helps to classify the test: “Characterization – Thermal – Motor & Generator – Fitting”.

Family	Characterization
Package	Thermal
Convention	Motor & Generator
Test	Fitting

Positioning of the test “Characterization – Thermal – Motor & Generator – Fitting”

7.1.2 User inputs

First, the targeted temperatures and the calibration factors to be used for the calibration. Then, the main inputs are the losses to be considered for evaluating the corresponding thermal behavior of the machine and the speed.

7.1.3 Main outputs

Here are the main results available:
Final X-Factors
Chart of temperatures - Radial and axial view
Chart of deviations
Thermal parameters

7.2 Settings

7.2.1 Thermal settings

One button gives access to the thermal settings:

- External fluid temperature
- Cooling circuit fluid temperature

Note 1: The external fluid temperature corresponds to the temperature of the fluid surrounding the machine. It is also considered the temperature at the “infinite” for the computation of radiation from the frame to the infinite.

Note 2: The cooling circuit fluid temperature exists only when a cooling circuit has been added by the user in the design environment. In this case, this input describes its fluid inlet temperature.

7.2.2 Target temperatures

The aim of this dialog box is to collect the targeted temperatures to be reached. They are defined at each main node of the internal thermal network. See the illustration below.

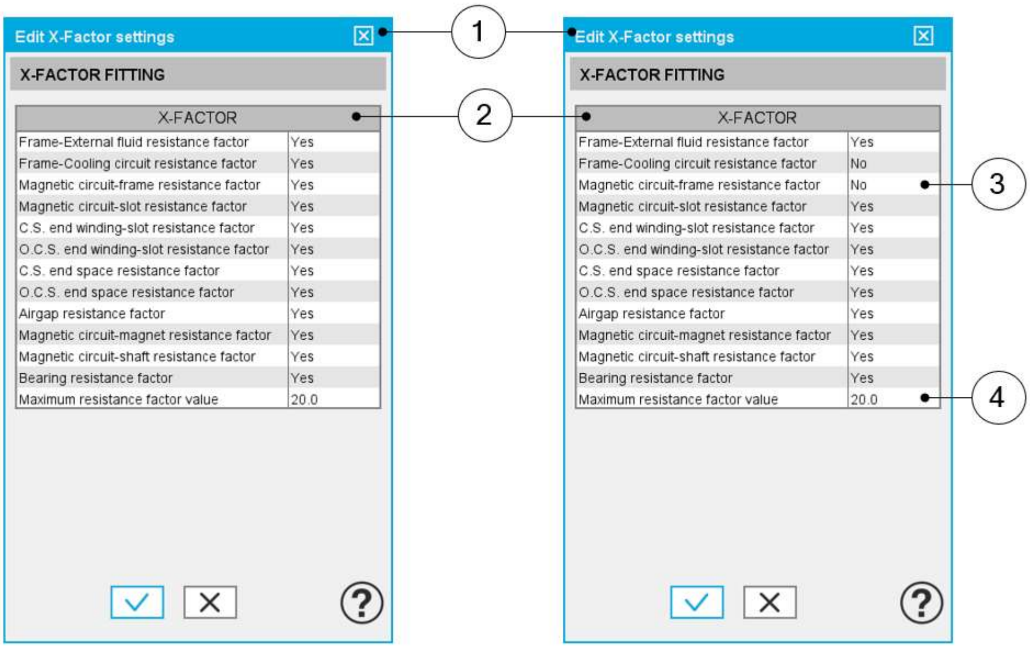
Shaft (°C)	Auto	Auto
Shaft extension C.S. (°C)	Auto	Auto
Shaft extension OCS (°C)	Auto	Auto
Bearing inner C.S. (°C)	Auto	Auto
Bearing inner O.C.S. (°C)	Auto	Auto
Bearing outer C.S. (°C)	Auto	Auto
Bearing outer O.C.S. (°C)	Auto	Auto
Frame (°C)	Auto	Auto
End cap C.S. (°C)	Auto	Auto
End cap O.C.S. (°C)	Auto	Auto
Magnet (°C)	Auto	80.0
Rotor yoke (°C)	Auto	Auto
In slot winding (°C)	Auto	100.0
C.S. end winding (°C)	Auto	90.0
O.C.S. end winding (°C)	Auto	90.0
Stator yoke (°C)	Auto	Auto
Stator tooth (°C)	Auto	Auto
Stator tooth foot (°C)	Auto	Auto
C.S. end space (°C)	Auto	Auto
O.C.S. end space (°C)	Auto	Auto
Airgap (°C)	Auto	Auto

Target temperatures

1	Opening of the dialog box for defining the target temperatures.
2	The main temperature nodes are listed. A target temperature can be set at each listed node.
3	Auto/User mode switches allow you to select the thermal nodes and set the corresponding target temperatures.

Note: By default, the target temperatures are all set to “Auto”, meaning that the thermal behavior of the machine will be computed based on a thermal working point defined by a speed and a set of losses.
This is the same test process as the one described above in the section dedicated to the Characterization – Thermal – Motor & Generator- steady state.
Note: In such a case, all the resulting calibration factors (X-Factors) are set to 1 whatever the user inputs set in the X-Factor fitting settings. See the section below.

7.2.3 X-Factors



X-FACTOR	
Frame-External fluid resistance factor	Yes
Frame-Cooling circuit resistance factor	Yes
Magnetic circuit-frame resistance factor	Yes
Magnetic circuit-slot resistance factor	Yes
C.S. end winding-slot resistance factor	Yes
O.C.S. end winding-slot resistance factor	Yes
C.S. end space resistance factor	Yes
O.C.S. end space resistance factor	Yes
Airgap resistance factor	Yes
Magnetic circuit-magnet resistance factor	Yes
Magnetic circuit-shaft resistance factor	Yes
Bearing resistance factor	Yes
Maximum resistance factor value	20.0

X-FACTOR	
Frame-External fluid resistance factor	Yes
Frame-Cooling circuit resistance factor	No
Magnetic circuit-frame resistance factor	No
Magnetic circuit-slot resistance factor	Yes
C.S. end winding-slot resistance factor	Yes
O.C.S. end winding-slot resistance factor	Yes
C.S. end space resistance factor	Yes
O.C.S. end space resistance factor	Yes
Airgap resistance factor	Yes
Magnetic circuit-magnet resistance factor	Yes
Magnetic circuit-shaft resistance factor	Yes
Bearing resistance factor	Yes
Maximum resistance factor value	20.0

List of the calibration factors (X-Factors) to be considered during the fitting process.

1	Opening of the dialog box for defining the list of the calibration factors (X-Factors) to be considered during the fitting process.
2	List of the calibration factors (X-Factors) to be considered during the fitting process. By default, all the X-Factors are considered for the fitting process. The user must select the ones that must not be considered while operating the process.
3	Set the value to No when the corresponding X-Factors must not be considered during the process.
4	The optimization process considers the X-Factor variations in a value range between 1 and the "maximum resistance factor value". The default value of the "maximum resistance factor value" is set to 20. However, when the robustness of the convergency process must be strengthened, it is recommended to decrease this value. Note: Anyway, the internal optimization process always tries to find X-Factors as close as possible to 1..

7.3 Inputs

7.3.1 Introduction

The main inputs of this test correspond to a set of losses to be considered for evaluating the thermal behavior of the machine in a transient mode.

7.3.2 Standard inputs

7.3.2.1 Speed

The speed of the machine is to be considered.

7.3.2.2 Set of losses

The losses to be defined are the following:

- Stator Joule losses
- Stator iron losses
- Magnet losses
- Rotor iron losses
- Mechanical losses

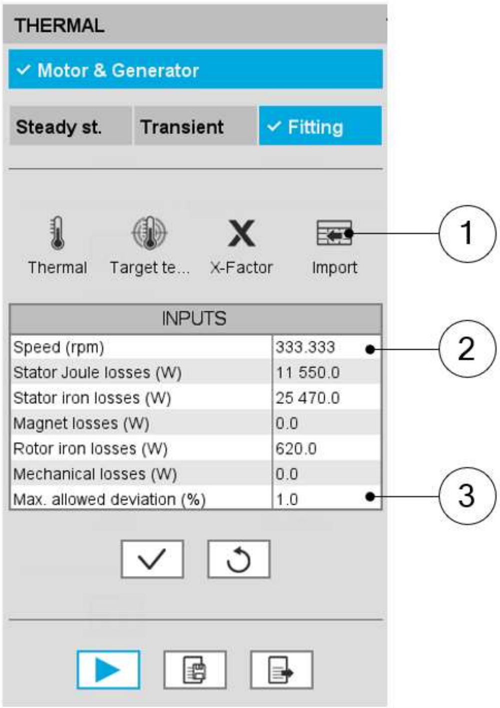
7.3.2.3 Maximum allowed deviation

The maximum temperature deviation allowed to consider the optimization algorithm has converged. All the final temperatures must have a lower deviation.

7.3.2.4 Input import

The set of inputs concerning speed and losses, can be imported from another test already performed in Motor Factory Test environment. It can be current results or saved test results.

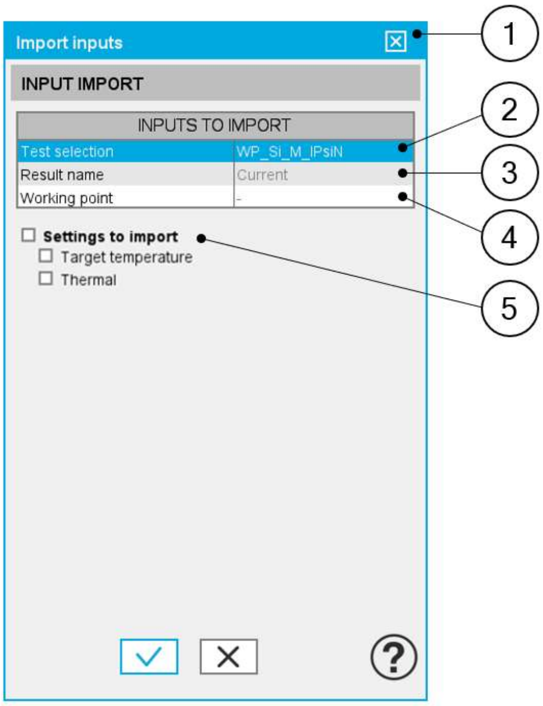
If the referent test has been performed with the thermal computations, the resulting temperatures can also be imported.
See the illustration below.



INPUTS	
Speed (rpm)	333.333
Stator Joule losses (W)	11 550.0
Stator iron losses (W)	25 470.0
Magnet losses (W)	0.0
Rotor iron losses (W)	620.0
Mechanical losses (W)	0.0
Max. allowed deviation (%)	1.0

How to define the inputs

1	Fill in the table to define the speed, all the losses to be considered, the maximum evaluation duration, and the time step.
2	Click on the button “import” to import inputs corresponding to a solved test. All existing data from the selected test will be imported into the inputs of the thermal characterization. The data that does not exist in the outputs of the selected test is set to 0.
3	Choose what must be the maximum temperature deviation that will allow us to consider that the optimization algorithm has converged.



Import inputs

INPUT IMPORT

INPUTS TO IMPORT	
Test selection	WP_Si_M_IPsiN
Result name	Current
Working point	-

☐ **Settings to import**
  ☐ Target temperature
  ☐ Thermal

Dialog box to select the test from which a set of data (losses and thermal) must be imported

1	Opened the dialog box after having clicked on the button “import” on the main panel.
2	Selection of the test. Only solved tests are available in the drop-down list.
3	Current tests as well as saved tests can be selected.
4	When several working points are computed in the selected test, each of them can be selected to consider the corresponding losses and speed.
5	Thermal data can also be imported. The resulting temperatures computed in the selected test can be imported as target temperatures. The thermal settings can also be imported like the external fluid temperature and the cooling circuit fluid temperature.

Note: The imported data are the output data directly shown in the considered solved test. For some tests, some values are not defined (like for instance the Joule magnet losses or rotor iron losses). In that case, the corresponding input in the transient thermal test will remain at the value existing before the import.

Note: If the thermal results from the imported test have been obtained with the current internal thermal scheme, then all the target temperatures in the dialog box will be affected by the target temperature. However, if the temperatures are imported from a test solved using a previous version of the thermal scheme (with less thermal nodes), then the new thermal nodes (which did not exist in the previous thermal scheme) will remain in the Auto mode.

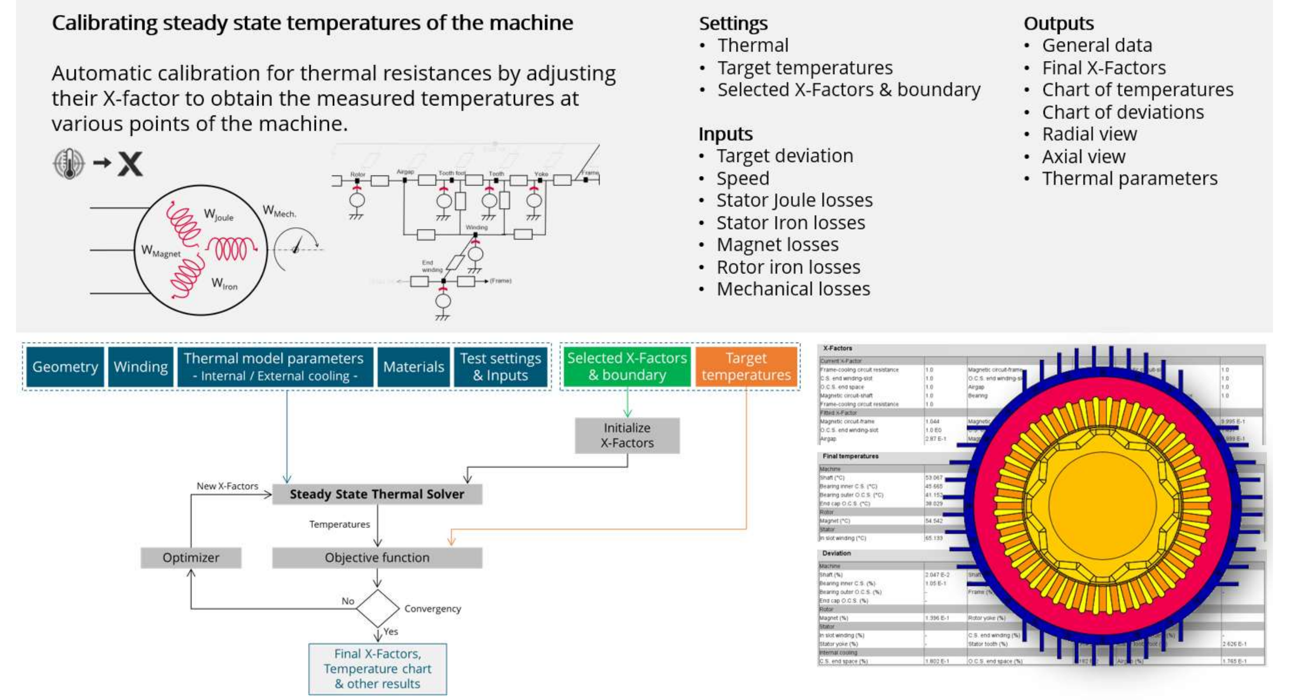
7.3.3 Advanced inputs

There are no advanced inputs required for this test.

7.4 Main principles of computation

7.4.1 Introduction

Here are illustrations that give an overview of the thermal transient test:



Calibrating steady state temperatures of the machine

Automatic calibration for thermal resistances by adjusting their X-factor to obtain the measured temperatures at various points of the machine.

Settings
- Thermal
- Target temperatures
- Selected X-Factors & boundary

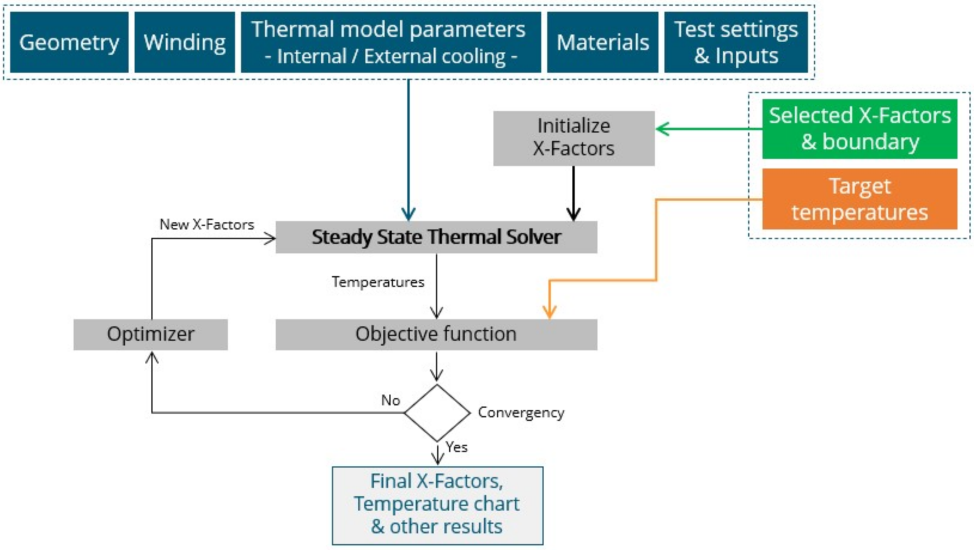
Inputs
- Target deviation
- Speed
- Stator Joule losses
- Stator Iron losses
- Magnet losses
- Rotor iron losses
- Mechanical losses

Outputs
- General data
- Final X-Factors
- Chart of temperatures
- Chart of deviations
- Radial view
- Axial view
- Thermal parameters

Characterization – Thermal – Fitting – Synchronous machine - Overview

7.4.2 Flow chart

Here is the flowchart illustrating the internal process of the X-Factor thermal fitting test.



X-Factor thermal fitting test – Internal process flow chart

Note: The internal algorithm always tends to minimize the error between the target temperatures and the temperature in the model. Thanks to the "maximum resistance factor value", the variation of all the X-Factors is limited to this maximum value. Any X-Factor won't be able to exceed this maximum value. This boundary helps to stabilize the test. In case of convergency problem, it is recommended to decrease this value. The default value is set to 20.

The inputs of the internal process are the parameters of:

- Geometry
- Winding
- Internal cooling
- External cooling
- Materials
- Test settings and inputs
- + Selected X-factors and boundary for operating the fitting process.
- + target temperatures

Note: A 2D Finite Element model is solved to identify a thermal network that corresponds accurately to any kind of rotor or stator parts, including user parts.

Then, the resulting network is extended with analytical computations to consider the 3D effect of the geometry.

The solving allows to get and display the whole chart of the temperatures of the machines.

7.5 Test results

Once a test is finished, the corresponding results are automatically displayed in the central window.

7.5.1 Test conditions

7.5.1.1 Inputs

The speed, the set of losses to be considered in the test, and the maximum allowed deviation for the temperature are mentioned in the head of results.

7.5.1.2 Settings

The thermal settings are as follows:

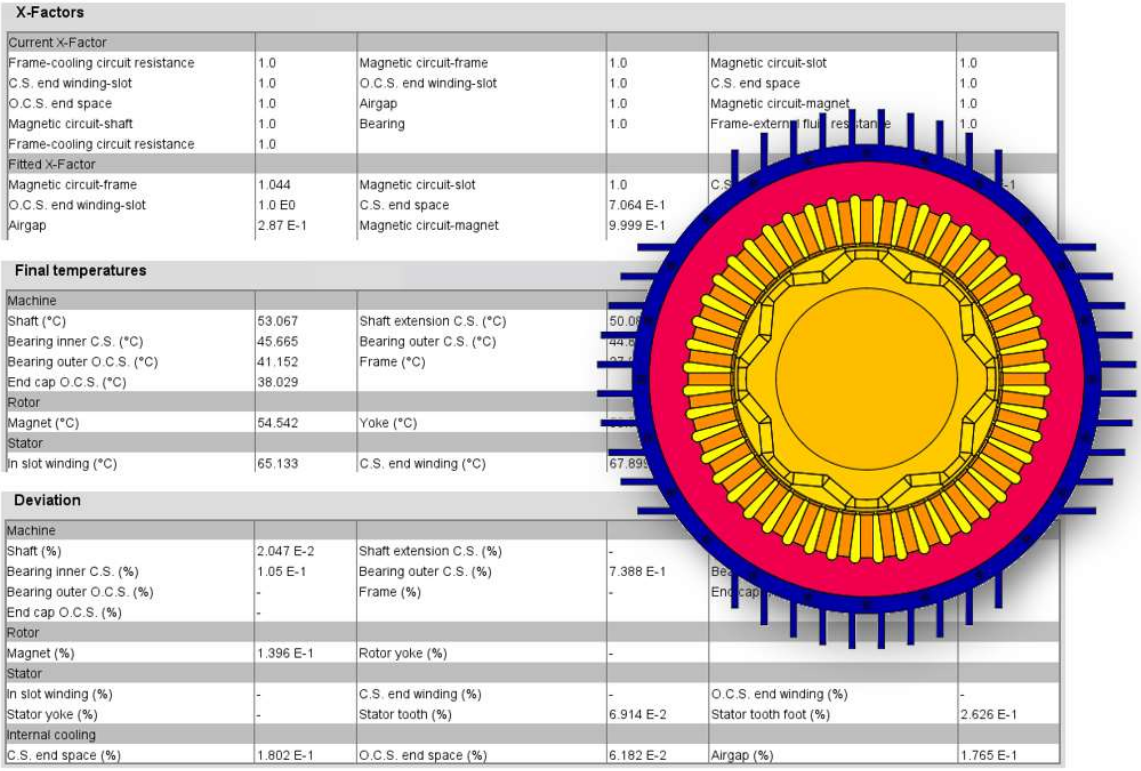
- External fluid temperature
- Cooling circuit temperature

Target temperature and X-factors are to be considered.

7.5.2 Main results

- X-Factors (Current values, fitted values, and the deviations between both values for each considered resistance).
- Temperature charts – radial and axial view

- Final temperatures table
- Table of deviations between initial and final temperature at each considered node of the thermal network.
- Main thermal parameters – Thermal resistance, convection coefficients, cooling circuit debit, and regular pressure loss.



X-Factors

Current X-Factor					
Frame-cooling circuit resistance	1.0	Magnetic circuit-frame	1.0	Magnetic circuit-slot	1.0
C.S. end winding-slot	1.0	O.C.S. end winding-slot	1.0	C.S. end space	1.0
O.C.S. end space	1.0	Airgap	1.0	Magnetic circuit-magnet	1.0
Magnetic circuit-shaft	1.0	Bearing	1.0	Frame-extern flu res tan e	1.0
Frame-cooling circuit resistance	1.0				
Fitted X-Factor					
Magnetic circuit-frame	1.044	Magnetic circuit-slot	1.0	C.S	-1
O.C.S. end winding-slot	1.0 E0	C.S. end space	7.064 E-1		
Airgap	2.87 E-1	Magnetic circuit-magnet	9.999 E-1		

Final temperatures

Machine					
Shaft (°C)	53.067	Shaft extension C.S. (°C)	50.08		
Bearing inner C.S. (°C)	45.665	Bearing outer C.S. (°C)	44.6		
Bearing outer O.C.S. (°C)	41.152	Frame (°C)			
End cap O.C.S. (°C)	38.029				
Rotor					
Magnet (°C)	54.542	Yoke (°C)			
Stator					
In slot winding (°C)	65.133	C.S. end winding (°C)	67.89		

Deviation

Machine					
Shaft (%)	2.047 E-2	Shaft extension C.S. (%)	-		
Bearing inner C.S. (%)	1.05 E-1	Bearing outer C.S. (%)	7.388 E-1	Be	
Bearing outer O.C.S. (%)	-	Frame (%)	-	End cap	
End cap O.C.S. (%)	-				
Rotor					
Magnet (%)	1.396 E-1	Rotor yoke (%)	-		
Stator					
In slot winding (%)	-	C.S. end winding (%)	-	O.C.S. end winding (%)	-
Stator yoke (%)	-	Stator tooth (%)	6.914 E-2	Stator tooth foot (%)	2.626 E-1
Internal cooling					
C.S. end space (%)	1.802 E-1	O.C.S. end space (%)	6.182 E-2	Airgap (%)	1.765 E-1

Illustration of results

7.6 Limitation of computations - Advice for use

Notes:

1) The resistance network identification of a machine is always done without any skew angle.
   This can cause some inaccuracy in the results for highly skewed machines.

2) Please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – section “Limitation of thermal computations – Advice for use”