Altair® FluxMotor® 2022.1

Reluctance Synchronous Machines - Inner rotor

Motor Factory - Test - Characterization

General user information

Contents

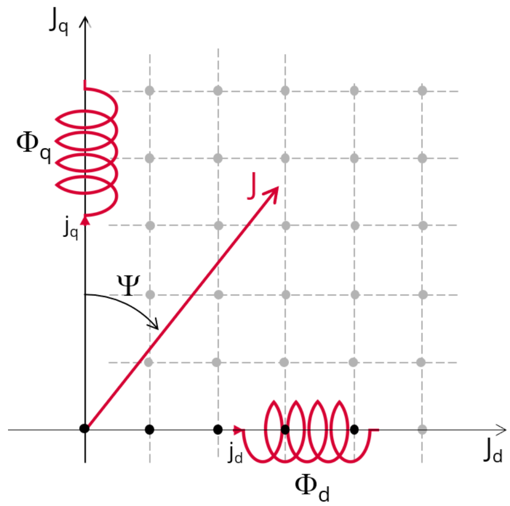
1 CHARACTERIZATION – MODEL – MOTOR – MAPS

1.1 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 reluctance synchronous machines.

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.



“Characterization - Model - Motor - Maps” illustration

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”

1.1.1 User inputs

Maps are mainly function of the following user inputs: the maximum value of the electrical current and the speed.

1.1.2 Main outputs

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

Table of results

1) Machine performance – Open circuit
- Results

Maps in J_d-J_q plane

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

2) Inductance
- D-axis inductance (dynamic and static)
- Q-axis inductance (dynamic and static)

3) Saliency in J_d-J_q area

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) Mechanical losses versus speed

1.2 Settings

Three buttons give access to the following setting definition:

- Thermal settings – Definition of the temperature of the winding.
- 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_2022.1_SMRSM_IR_3PH_Test_Introduction – sections dealing with settings.

1.3 Inputs

1.3.1 Introduction

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

1.3.2 Standard inputs

1.3.2.1 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** ».

1.3.2.2 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.

1.3.2.3 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.

1.3.2.4 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*).

1.3.3 Advanced inputs

1.3.3.1 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.

1.3.3.2 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.

1.3.3.3 Skew model – Number of layers

When the rotor 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*).

1.3.3.4 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.

1.3.3.5 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.

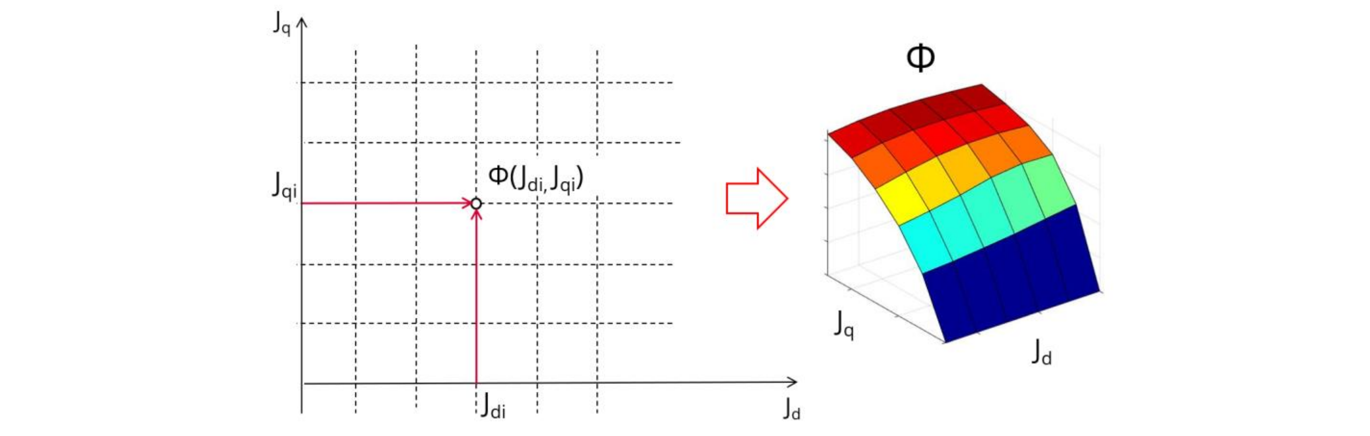
1.3.3.6 Rotor initial position mode - Note

The computations are performed by considering a relative angular position between rotor and stator.
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 value of the rotor d-axis location, which is automatically defined, for each saliency part, in Part Factory, can be visualized in the output parameters in the saliency area of Motor Factory – Design environment.

1.4 Main principles of computation

1.4.1 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 -** $\boldsymbol{\Phi_q}$ 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.

1.4.2 Dynamic inductances

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

$$\mathrm{L_{d-dynamic}} = \frac{\Delta\Phi_\mathrm{d}}{\Delta \mathrm{J_d}} + L_{endW} \qquad \mathrm{L_{q-dynamic}} = \frac{\Delta\Phi_\mathrm{q}}{\Delta \mathrm{J_q}} + L_{endW}$$

Note 1: The end-winding leakage inductance L_{endw}, computed in the winding area, is added to the previous expression to get the final values of the dynamic inductances $L_{d\text{–dynamic}}$ and $L_{q\text{-dynamic}}$.

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

1.4.3 Static inductances

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

$$\mathrm{L_{d-static}} = \frac{(\Phi_d)}{\sqrt{2}\times J_d} + L_{endW} \qquad \mathrm{L_{q-static}} = \frac{\Phi_q}{\sqrt{2}\times J_q} + L_{endW}$$

Note 1: The end-winding leakage inductance L_{endw}, computed in the winding area, is added to the previous expression to get the final values of the dynamic inductances $L_{d\text{–dynamic}}$ and $L_{q\text{-dynamic}}$.

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

1.4.4 Saliency

The saliency in Jd-Jq area is computed and displayed as a map in J_d, J_q plane.This value corresponds to the ratio between q-axis and d-axis static inductances.

$$Saliency = \frac{L_{q-static}}{L_{d-static}}$$

1.4.5 Electromagnetic torque

Electromagnetic torque is computed from the flux linkage maps and using the following formula:

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

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

1.4.6 Iron loss computation

A dedicated process has been developed to compute the stator iron losses.
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.

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

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

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: 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).

1.4.7 Joule losses

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

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

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

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

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

1.4.8 Mechanical losses

The mechanical losses are computed as a function of the speed.
For more details, please refer to the document: MotorFactory_2020.1_SMPM_IOR_3PH_Test_Introduction – section “Mechanical loss model settings”

1.4.9 Total losses

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

1.5 Test results

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

1.5.1 Test conditions

1.5.1.1 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 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
- Electronics
- Mechanics

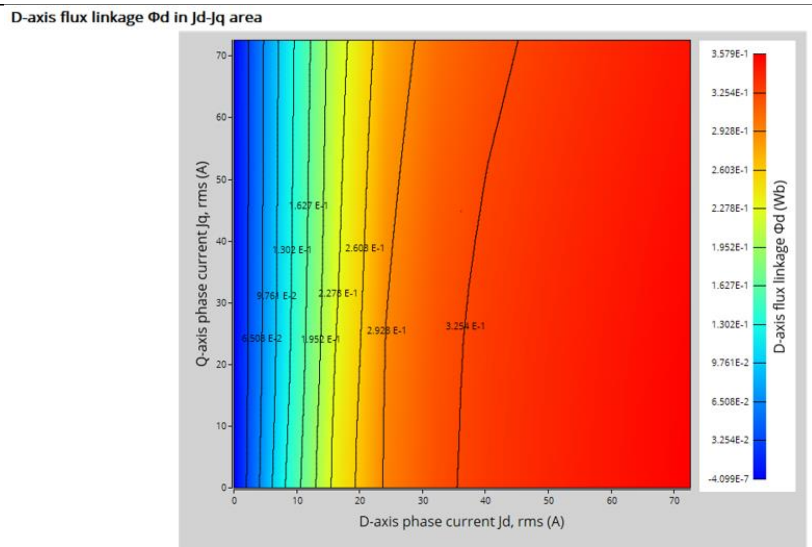
1.5.1.3 Winding characteristics

All the winding characteristics are displayed (for all the winding, end-windings, and straight parts)

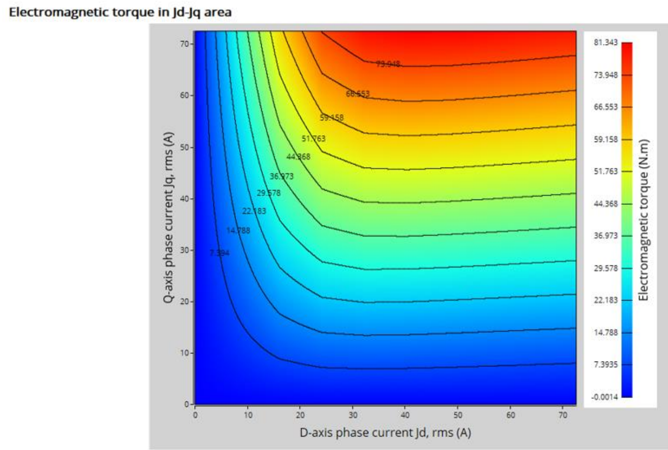
For more details, please refer to the document: MotorFactory_2022.1_SMPM_IOR_3PH_Test_Introduction – sections dealing with settings.

1.5.2 Maps

Maps illustrating the following quantities, Φ_d, Φ_q, $L_{d\text{-dynamic}}$, $L_{q\text{-dynamic}}$, , $L_{d\text{-static}}$, $L_{q\text{-static}}$, saliency, electromagnetic torque, Joule losses, are displayed in the J_d-J_q plane.

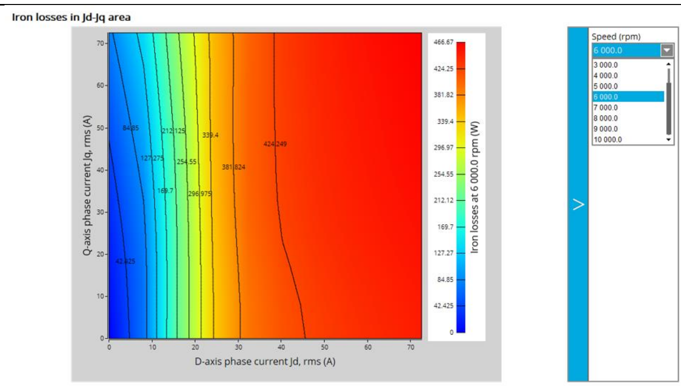


D-axis inductance L_d in J_d - J_q area - Selection of speed in the drop-down menu



Electromagnetic torque in J_d - J_q area

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. The desired speed can be chosen in the drop-down menu on the right of the graph (close to the legend).

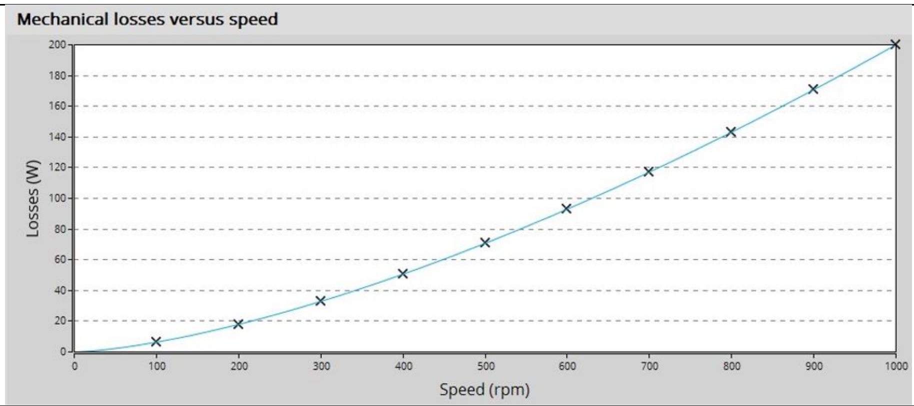


Iron losses in J_d - J_q area - Selection of speed in the drop-down menu

1.5.3 Curves

1.5.3.1 Mechanical losses

A curve showing the evolution of mechanical losses versus speed is displayed.
The maximum speed considered is the one defined in the test input parameters.



Mechanical losses versus speed - Visualization of the mechanical loss curve

2 CHARACTERIZATION – THERMAL – MOTOR & GENERATOR – STEADY STATE

2.1 Overview

2.1.1 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”.

2.1.2 User inputs

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

2.1.3 Main outputs

Here are the main results available:

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

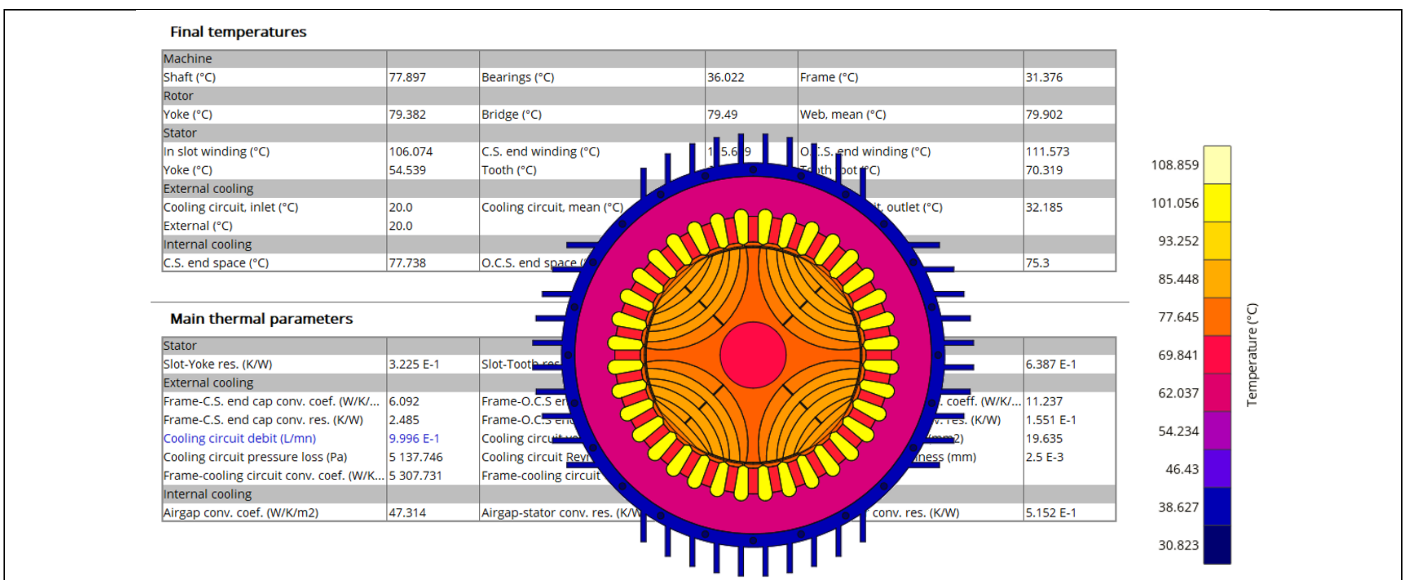


Illustration of results - Overview

2.2 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.

2.3 Inputs

2.3.1 Introduction

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

2.3.2 Standard inputs

2.3.2.1 Speed

The speed of the machine to be considered.

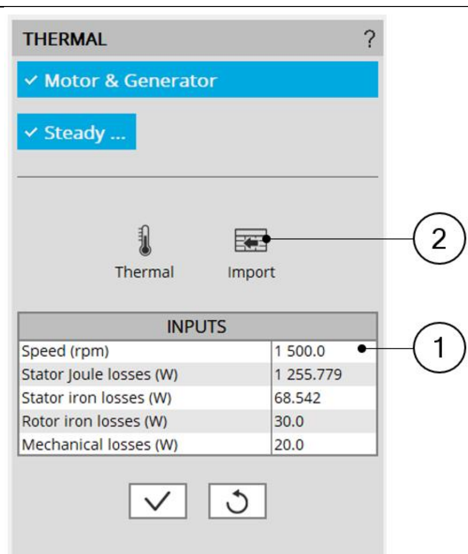
2.3.2.2 Set of losses

The losses to be defined are the following ones:

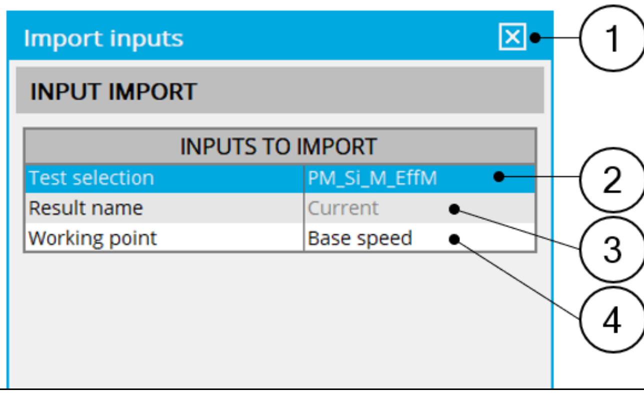
- Stator Joule losses
- Stator iron losses
- Rotor iron losses
- Mechanical losses

2.3.2.3 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.



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.



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.

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 rotor iron losses). In that case, the corresponding values are set to 0 in the thermal characterization input table.

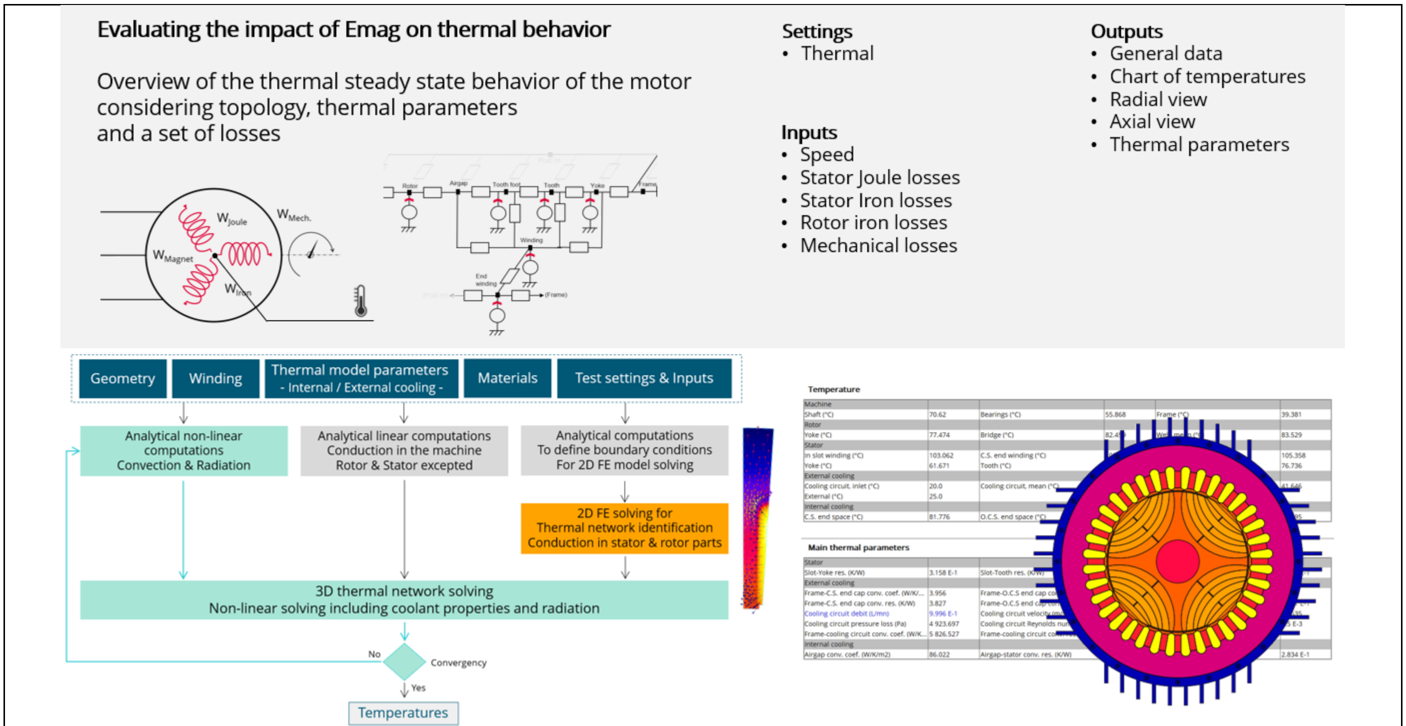
2.3.3 Advanced input

There are no advanced inputs required for this test.

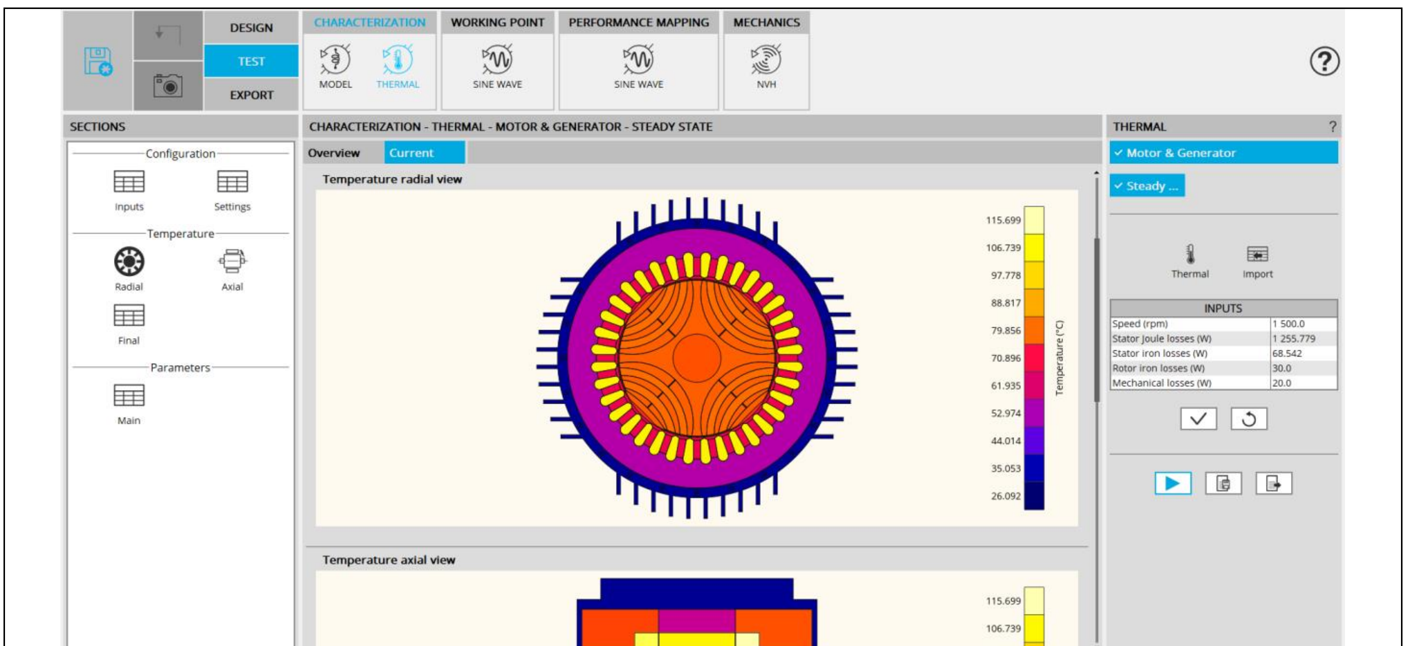
2.4 Main principles of computation

2.4.1 Introduction

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



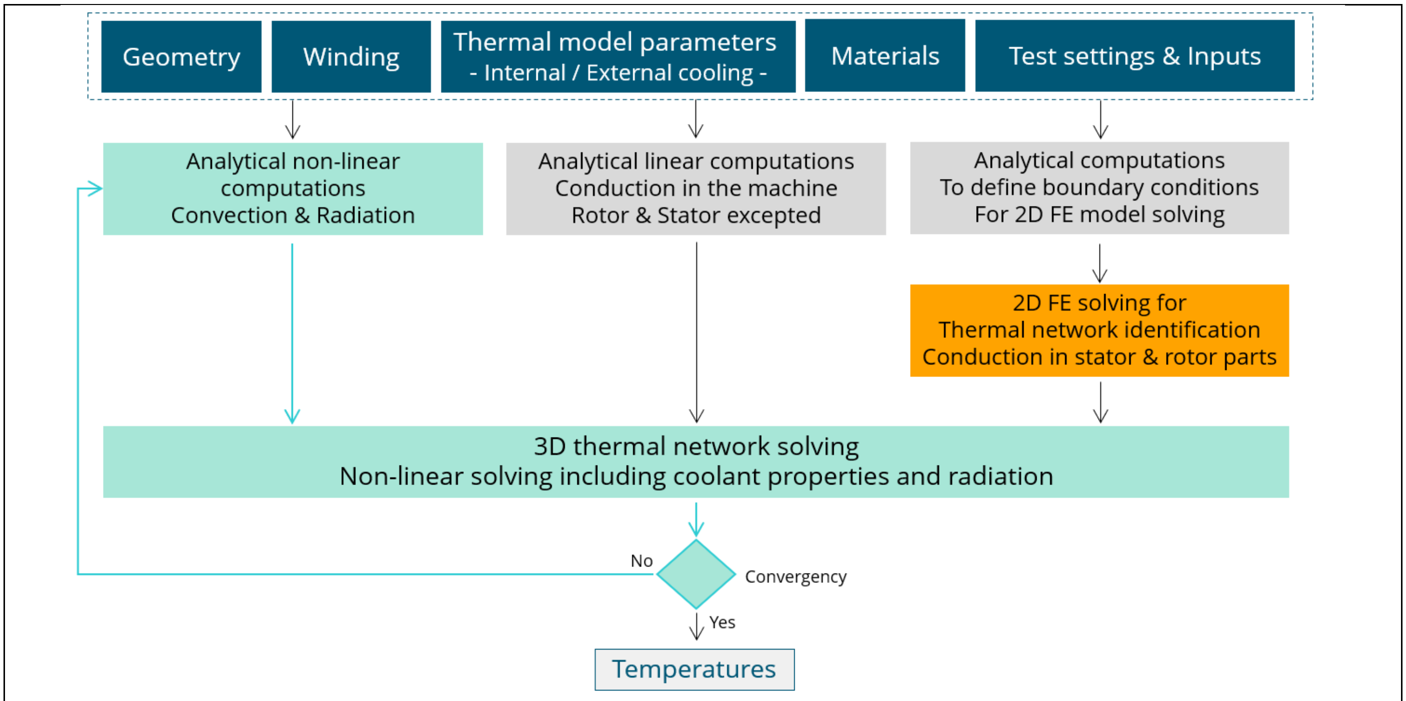
Characterization – Thermal – Steady state – Reluctance Synchronous Machine - Overview



Characterization – Thermal – Steady state – Reluctance Synchronous Machine – Test results

2.4.2 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.

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

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

2.5.1.2 Settings

The thermal settings are reminded:

- External fluid temperature
- Cooling circuit temperature

2.5.2 Main results

- Temperature radial and axial views
- Temperature table

2.5.2.1 Main thermal parameters 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

2.5.2.2 Main thermal parameters 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

2.5.2.3 Main thermal parameters 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

2.6 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_2022.1_SMPM_IOR_3PH_Test_Introduction – section "Limitation of thermal computations – Advice for use"