# Altair® FluxMotor® 2024

Reluctance Synchronous Machines - Inner rotor

Motor Factory - Test - Characterization

General user information

# Contents

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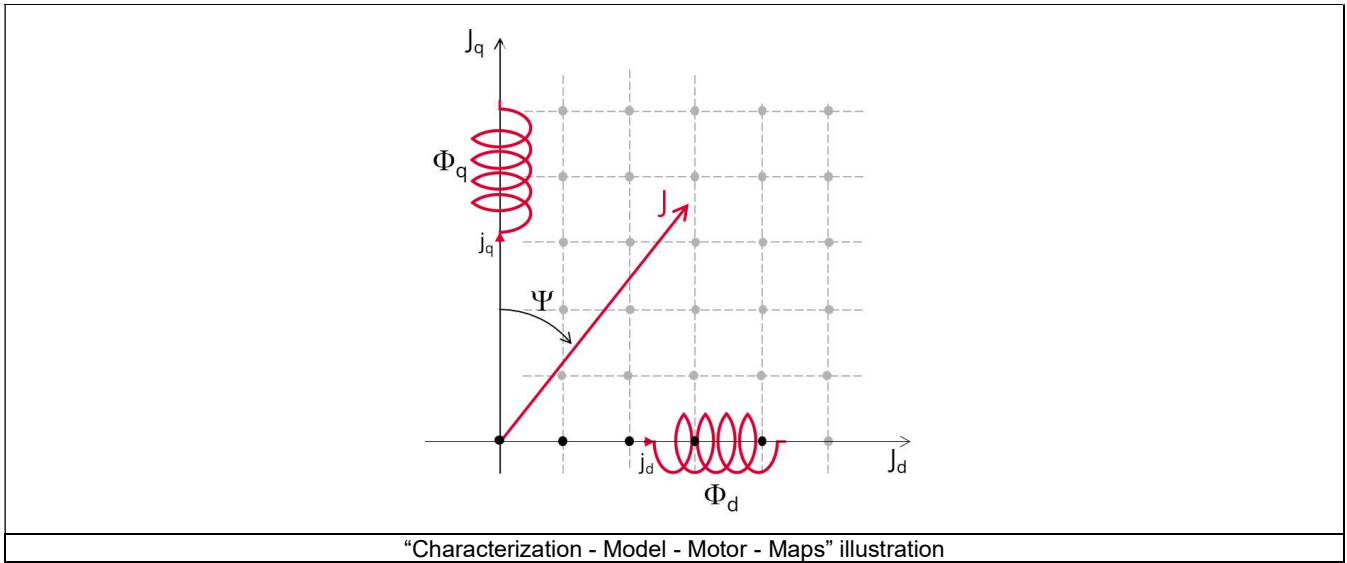
Performance of the machine in steady state can be deduced from the results obtained in this test in association with the drive and control mode to be considered.

The following table helps to classify the test:

| Family | Characterization |
|---|---|
| Package | Model |
| Convention | Motor |
| Test | Maps |

Positioning of the test "Characterization - Model - Motor - Maps"

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### 1.1.1   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.

### 1.1.2   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 $\Phi_d$
- Q-axis flux-linkage $\Phi_q$

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) Saliency in $J_d$-$J_q$ area

5) Torque
- Electromagnetic torque $T_{em}$

6) 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 winding temperature.
- 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_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    Sharing data between tests

An import button is available for allowing sharing the data simulated in Flux between "Characterization / Model / Map" and "Performance mapping / Efficiency map" tests.

Indeed, by implementing the rotor position dependency option for the model map test and efficiency map test of synchronous machines, this update facilitates the seamless transfer of settings, inputs, and crucially, simulated data in Flux between the two tests. As they use the same Flux data in most cases and significant computation time is required to obtain it, users can now accelerate the test resolution and optimize their workflow.

To streamline this process, an import button has been introduced in both the "Characterization / Model / Map" and "Performance mapping / Efficiency map" tests of the following machines:

- Reluctance Synchronous Machines - Inner rotor
- Synchronous Machines with wound field – Inner Salient Pole - Inner rotor

Note: The import button will be added to the tests of Synchronous machines – Permanent magnets - Inner & Outer rotor in the next version.

Upon completing a model map test, users can activate the import button in the efficiency map test GUI. This enables them to effortlessly import the settings and corresponding Flux data from the previous test, eliminating the need to rerun Flux for identical data, a step that typically consumes a substantial portion of computation time during efficiency mapping.

Conversely, upon concluding an efficiency map test, users can use the import button in the efficiency map test GUI to import settings and Flux data from the efficiency map test, further enhancing workflow efficiency.

Note: Only the most recent test results can be imported, saved test results are not yet able to be imported.

Note: While there are shared settings and inputs between the tests, each test may have its own unique settings and inputs. In such cases, the default settings, and inputs of the second test are automatically applied.

Note: When importing from the efficiency map test to the model map test, the quadrant setting defaults to the value specified in the model map test. For certain machine types (SMWF: 2nd quadrant, SM-RSM: 1st quadrant), specific quadrant selections are applied.

Note: In instances where quadrant inputs lead to incompatibility between the model map test and the efficiency map test, only settings and inputs are imported. A warning is issued, and Flux simulation is initiated to rectify the discrepancy.
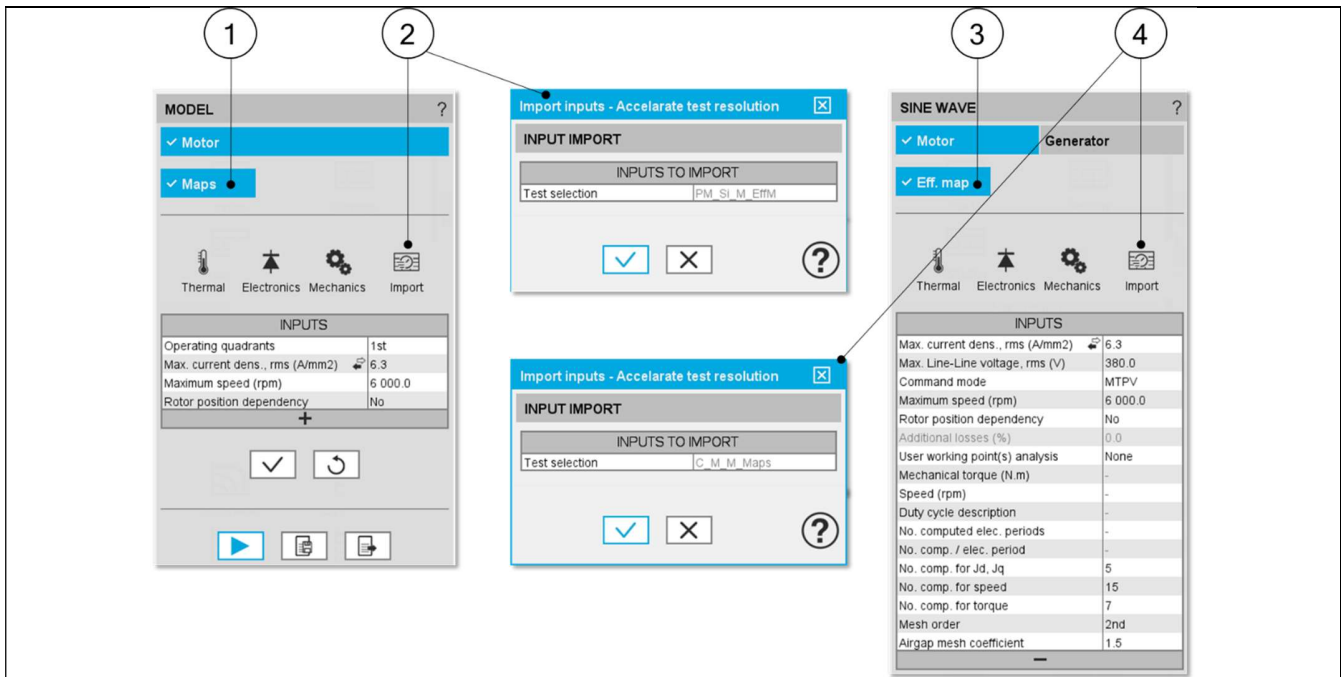
| | Import function in Model Map test and Efficiency Map test to accelerate test resolution. Example for Wound field synchronous machines |
|---|---|
| 1 | Open model map test environment when an efficiency map test is available for import |
| 2 | Click the import button and import the settings, inputs, and Flux data of the latest efficiency map test |
| 3 | Open efficiency map test environment when a model map test is available for import |
| 4 | Click the import button and import the settings, inputs, and Flux data of the latest model map test |

### 1.3.3  Standard inputs

#### 1.3.3.1  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.

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".

#### 1.3.3.2  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** ».

#### 1.3.3.3  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.

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### 1.3.3.4    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.

### 1.3.3.5    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*).

### 1.3.3.6    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 $\theta_r$.

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).

### 1.3.4   Advanced inputs

#### 1.3.4.1   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 are 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.

#### 1.3.4.2   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.

#### 1.3.4.3   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.

#### 1.3.4.4   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.

#### 1.3.4.5   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*).

#### 1.3.4.6   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.

#### 1.3.4.7   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:

$$MeshPoint = (airgap) \times (airgap \ mesh \ coefficient)$$

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.

1.3.4.8   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 ($\Phi_a$, $\Phi_b$, $\Phi_c$) through corresponding phases a, b, c). This is done using Finite Element modelling (Flux® software – Magnetostatic application).
**D-axis flux-linkage component - $\Phi_d$** and **Q-axis flux-linkage component - $\Phi_q$** are deduced according to Park's transformation.


Computation on a grid in $J_d$, $J_q$ plane
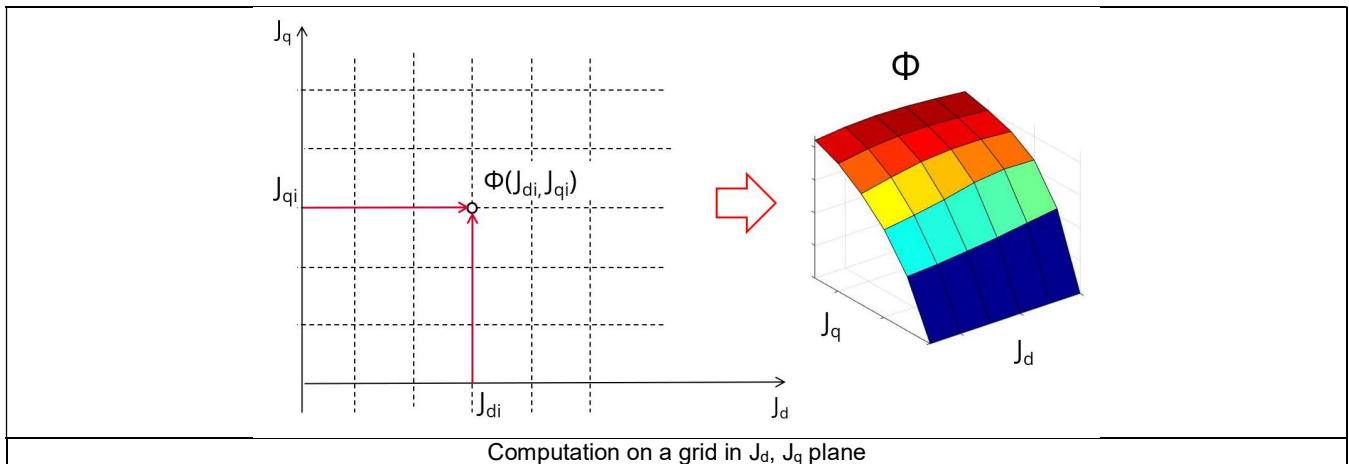
Our modeling considers cross-saturation. However, neither winding harmonics nor the variation of reluctance as a function of angular position of the rotor are considered.

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.*

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 $\theta_r$.

### 1.4.2 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 $\theta_r$.

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.

### 1.4.3    Dynamic inductances

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

$$L_{d-dynamic} = \frac{\Delta\Phi_d}{\Delta J_d} \qquad L_{q-dynami} = \frac{\Delta\Phi_q}{\Delta J_q}$$

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 dynamic inductances L$_{d-dynamic}$ and L$_{q-dynamic}$ 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$_r$.

### 1.4.4    Dynamic cross inductances

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

$$L_{dq-dynamic} = \frac{\Delta\Phi_d}{\Delta J_q} \qquad L_{qd-dynamic} = \frac{\Delta\Phi_q}{\Delta J_d}$$

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$_r$.

### 1.4.5    Static inductances

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

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

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$_{d-static}$ and L$_{q-static}$ 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$_r$.

### 1.4.6    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.

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

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$_r$.

### 1.4.7    Electromagnetic torque

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

#### 1.4.7.1    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.

#### 1.4.7.2    Rotor position dependency set to "Yes"

The **Electromagnetic torque 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 T_{em}** average value computed with the Park's equation or with virtual works are equal.

### 1.4.8    Iron loss computation

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

#### 1.4.8.1    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.

#### 1.4.8.2    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.

1.4.8.3   Model used to compute iron losses

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

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

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).

1.4.9   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 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 $\theta_r$.

1.4.10   Mechanical losses

The mechanical losses are computed as a function of the speed.
For more details, please refer to the document: MotorFactory_2020.2_SMPM_IOR_3PH_Test_Introduction – section "Mechanical loss model settings"

1.4.11   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.

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 $\theta_r$.

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## 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:
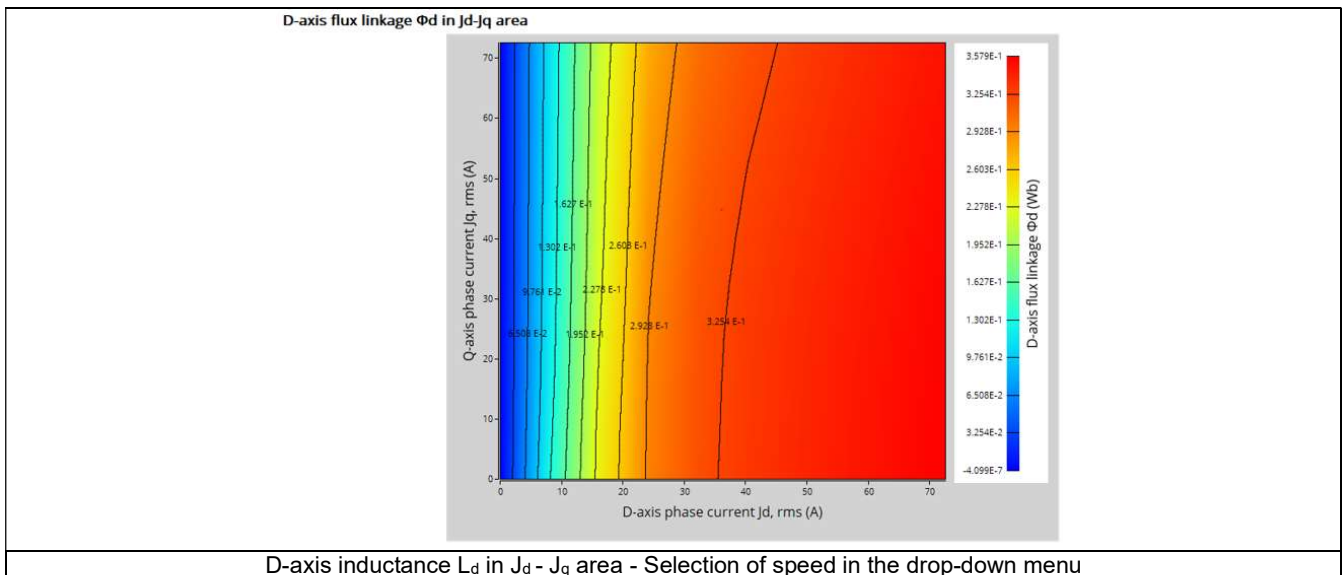
- Thermal
- Electronics
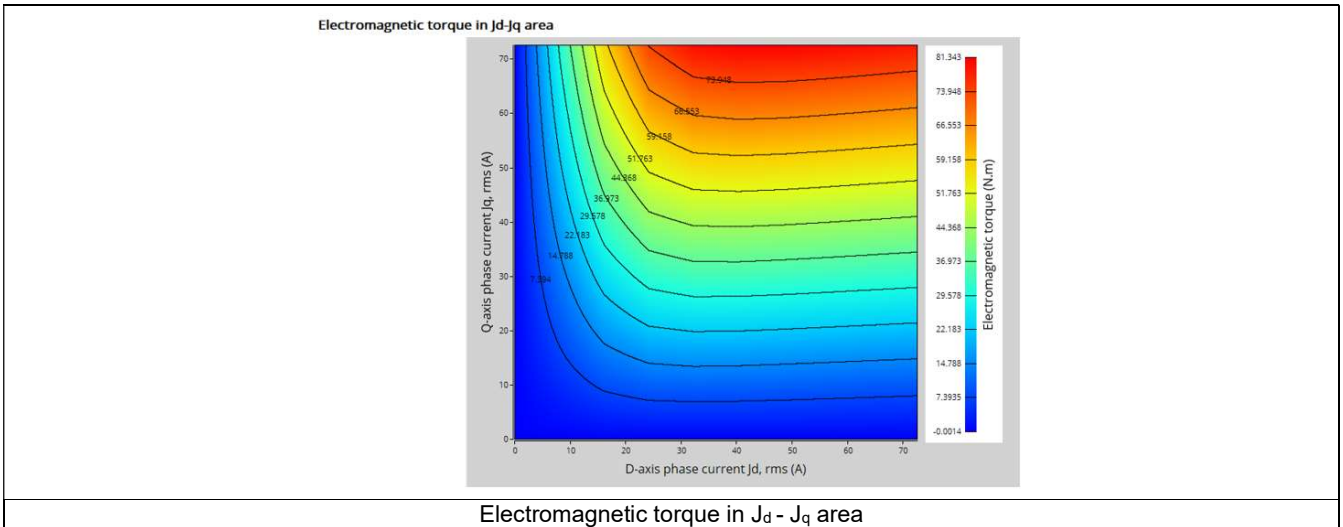- Mechanics

#### 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_SMPM_IOR_3PH_Test_Introduction – sections dealing with settings.

### 1.5.2    Maps

Maps illustrating the following quantities ($\Phi_d$, $\Phi_q$, $\Phi_d/d\theta_r$, $\Phi_q/d\theta_r$, $L_{d\text{-dynamic}}$, $L_{q\ dynamic}$, $L_{dq\text{-dynamic}}$, $L_{qd\ dynamic}$, $L_{d\text{-static}}$, $L_{q\ static}$, torque) 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
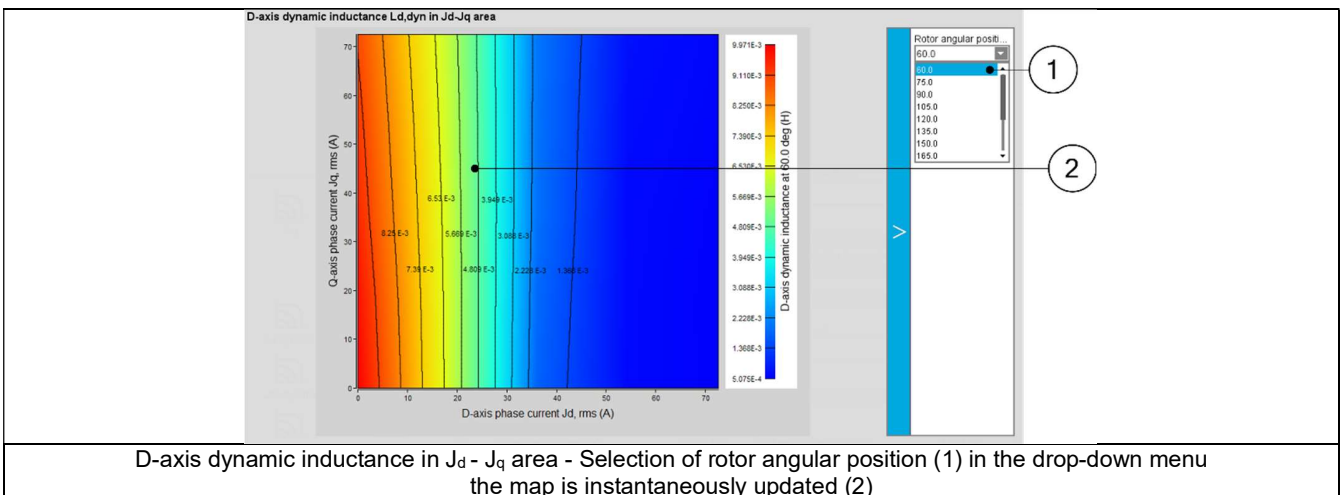
Electromagnetic torque in $J_d$ - $J_q$ area

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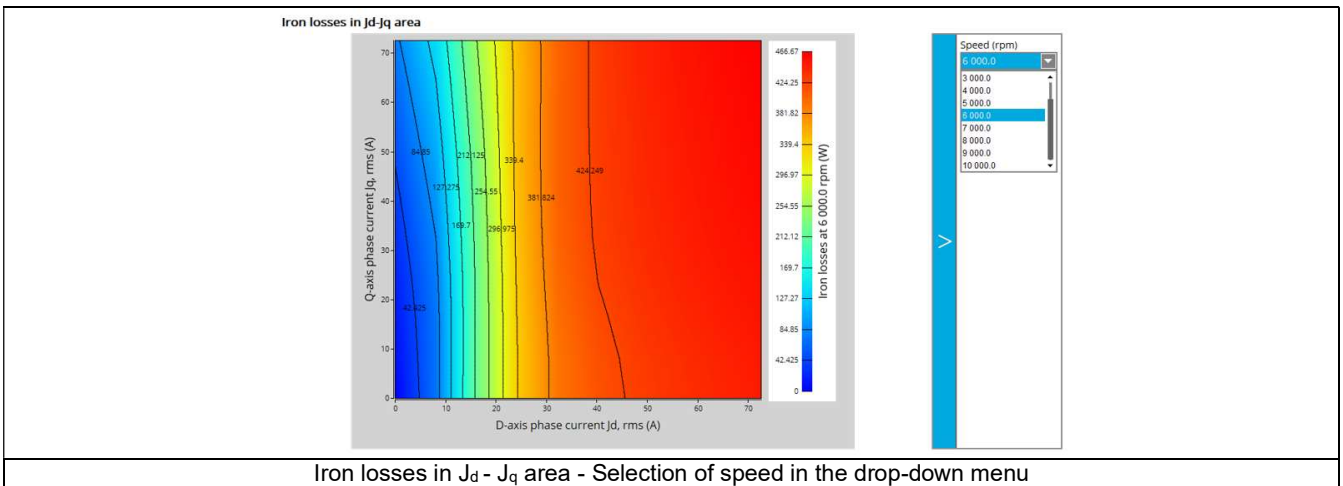
Illustrations of results depending on the user's inputs dealing with the Rotor position dependency ("Yes" or "No"). In case the Rotor position dependency is set to "Yes", computations are done in the $J_d$ - $J_q$ plane with an additional third axis corresponding to the rotor position $\theta_r$.



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)

The results depend on the selected operating quadrants ("2nd and 3rd ", "1st and 2nd "or "all"). An example is presented below.



Iron losses in $J_d$ - $J_q$ area - Selection of speed and rotor position in the drop-down menu
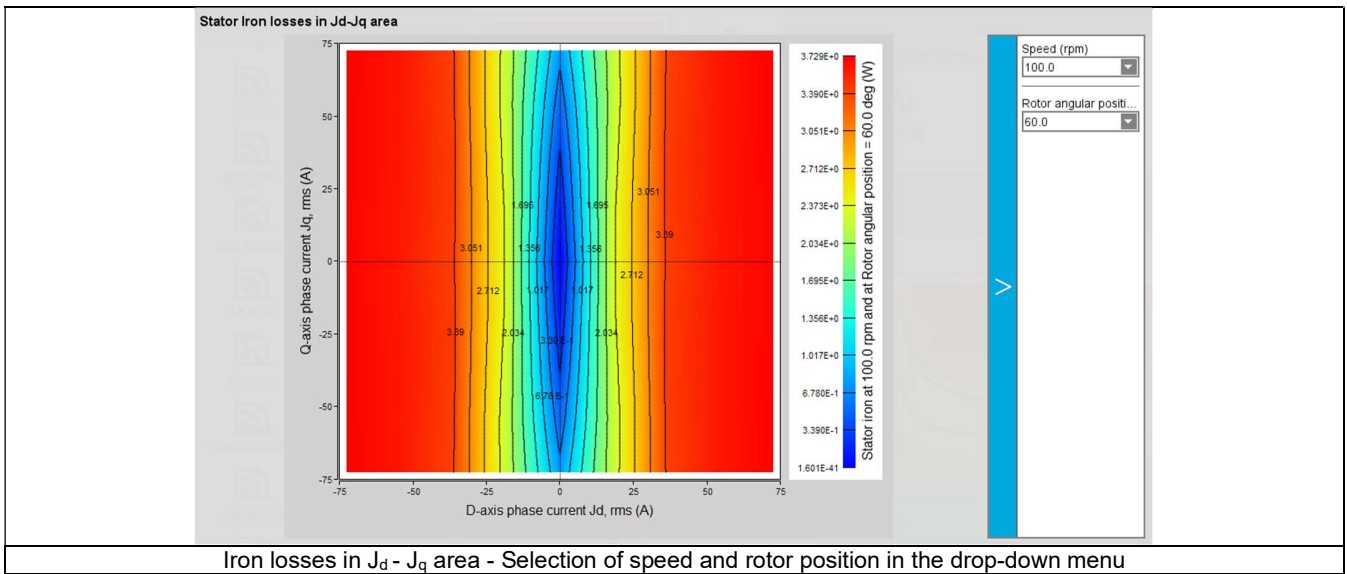
### 1.5.3    Curves

#### 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
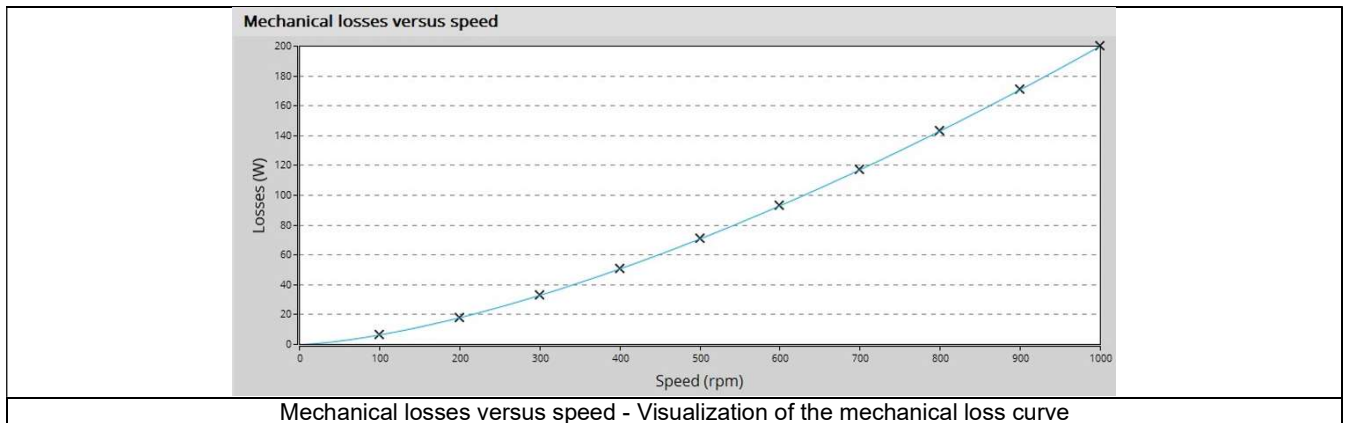
# 2    CHARACTERIZATION – THERMAL – MOTOR & GENERATOR – STEADY STATE

## 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
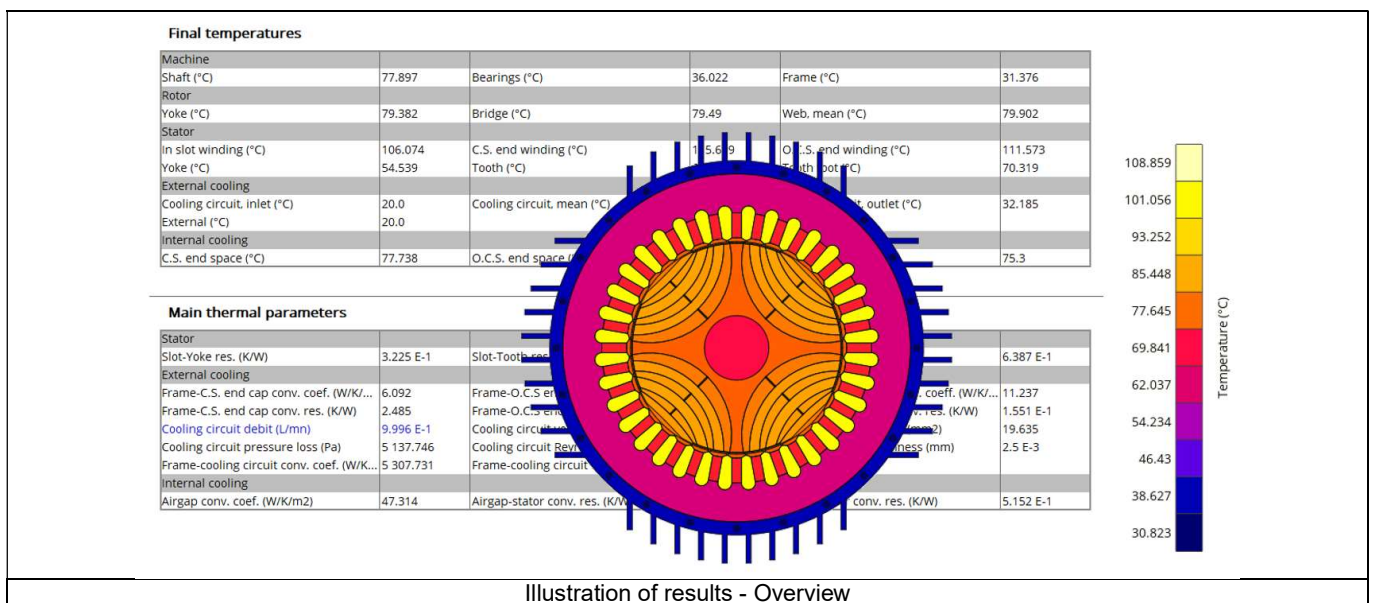
## 2.2    Settings

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
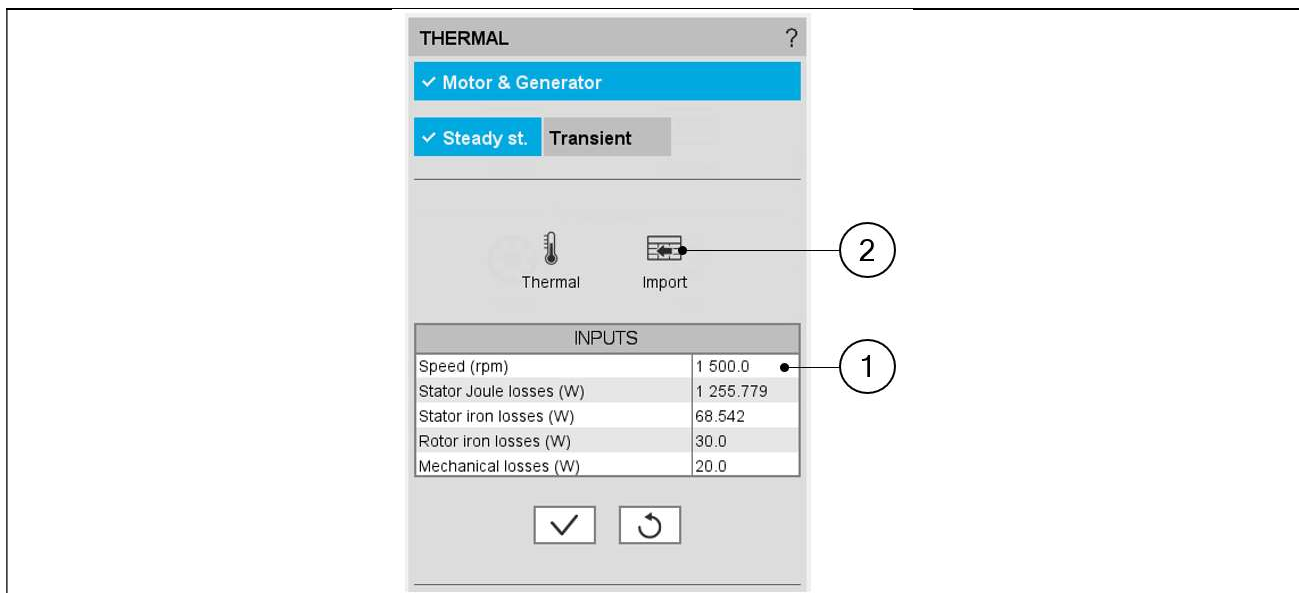
The speed of the machine to be considered.

#### 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
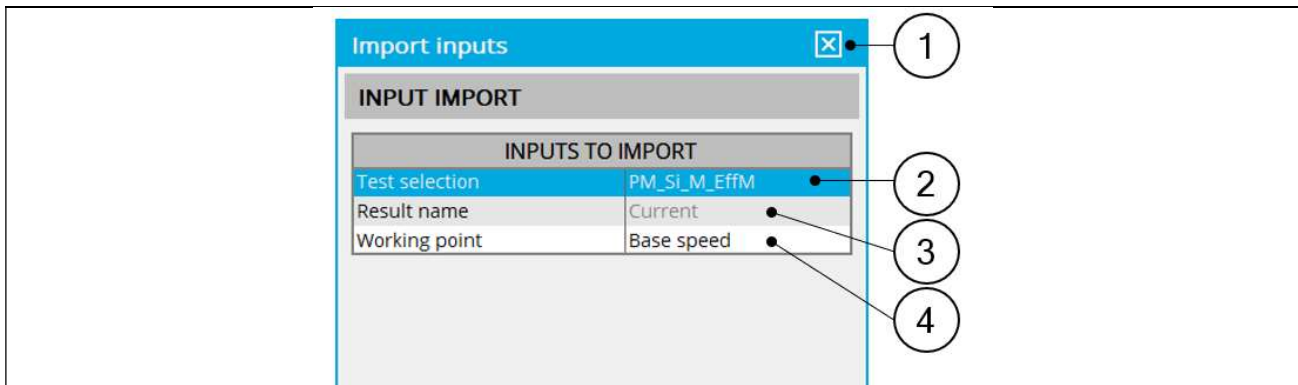- Mechanical losses

#### 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.
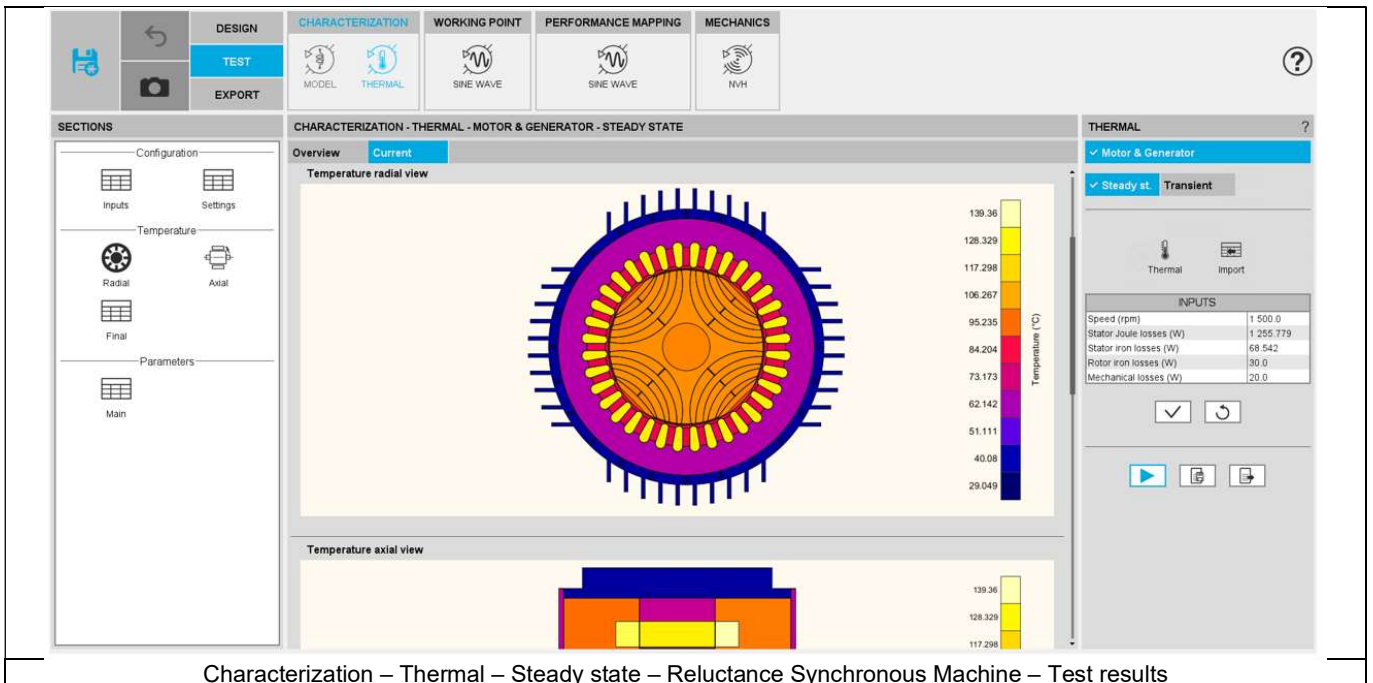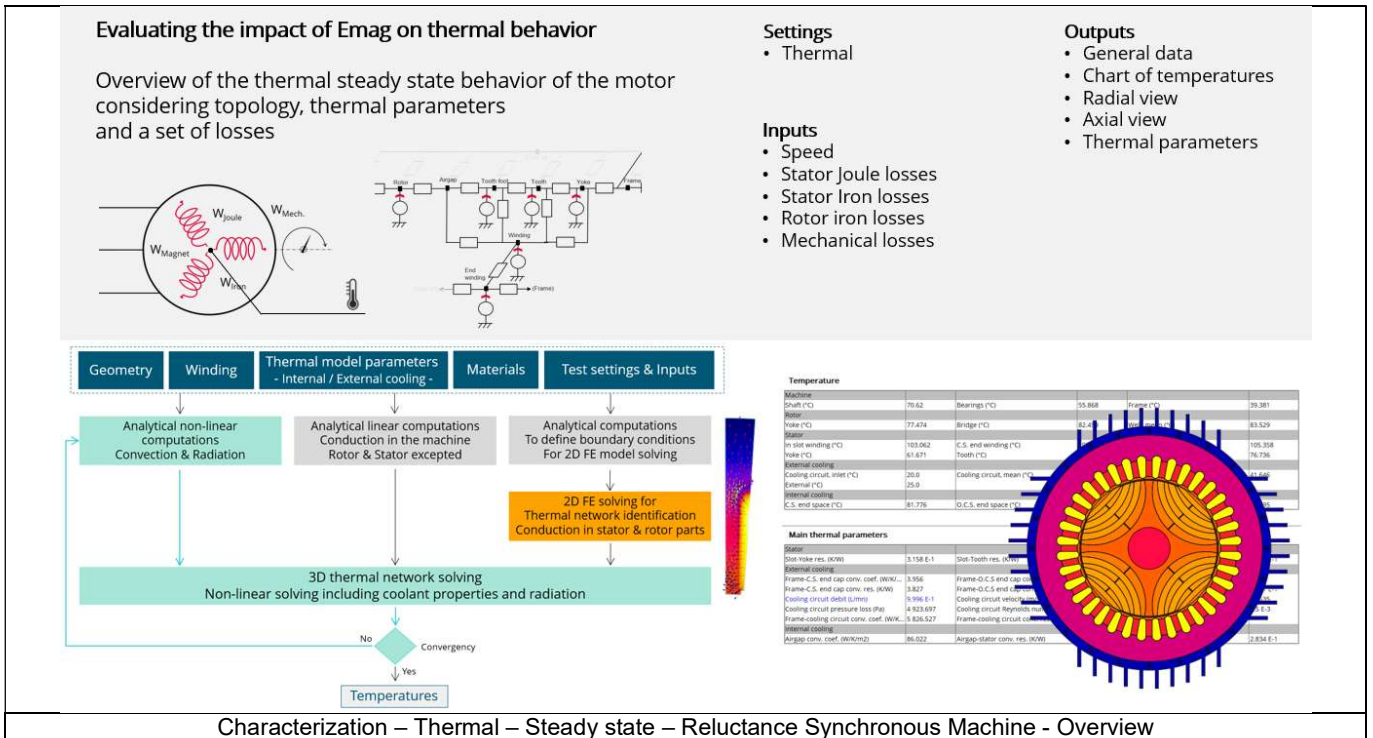
### 2.3.3 Advanced input

There are no advanced inputs required for this test.

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## 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
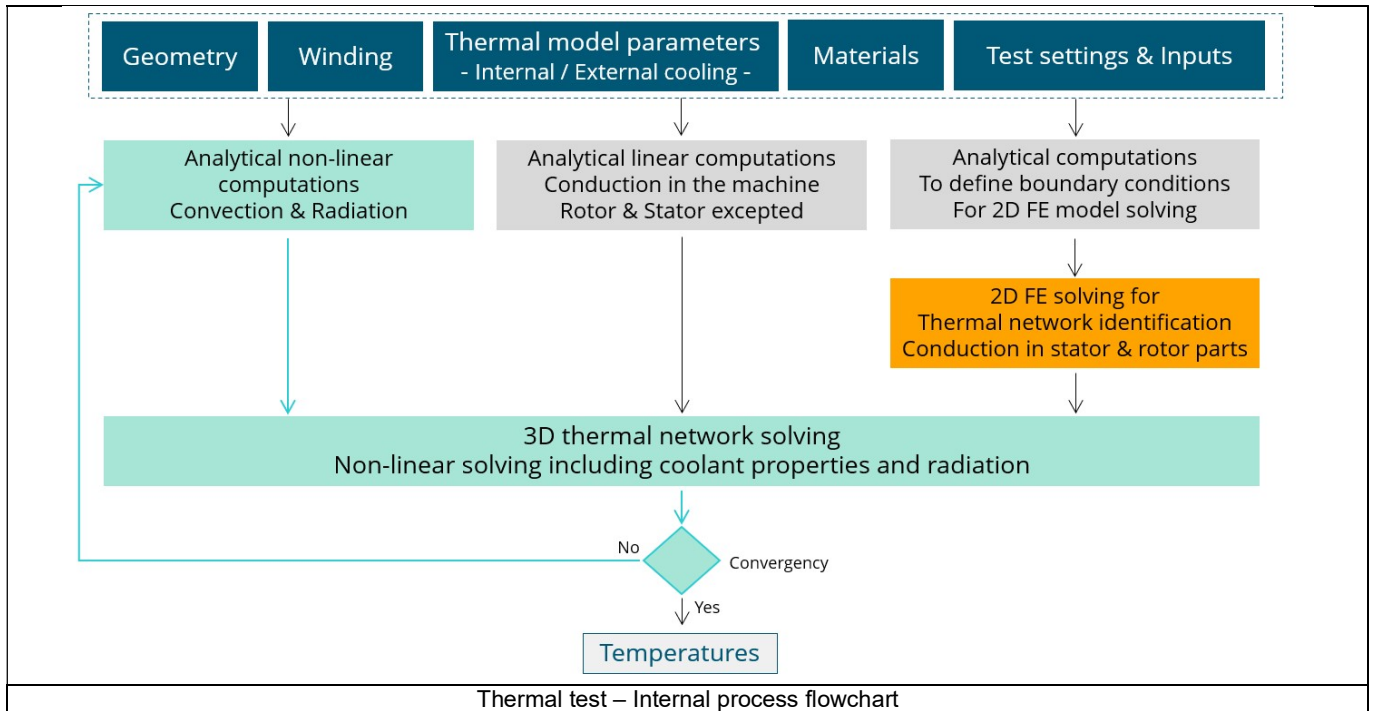
The inputs of the internal process are the parameters of:

- 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<br>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<br>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<br>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<br>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<br>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<br>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<br>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_SMRSM_IR_3PH_Test_Introduction – section "Limitation of thermal computations – Advice for use"

# 3    CHARACTERIZATION – THERMAL – MOTOR & GENERATOR – TRANSIENT

## 3.1    Overview

### 3.1.1    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"

### 3.1.2    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.

### 3.1.3    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
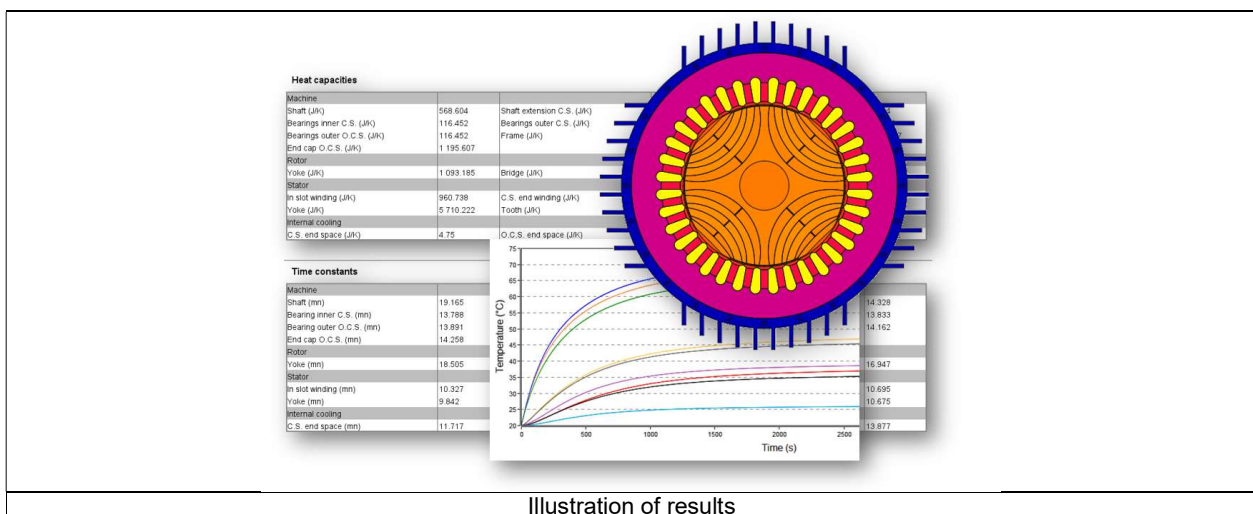- Heat capacity and time constant table



Illustration of results

## 3.2    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.

## 3.3    Inputs

### 3.3.1    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.

### 3.3.2    Standard inputs

#### 3.3.2.1   Speed

The speed of the machine to be considered.

#### 3.3.2.2   Set of losses

The losses to be defined are the following ones:

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

#### 3.3.2.3   Time definition

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

- Maximum evaluation duration
- Time step

#### 3.3.2.4   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.
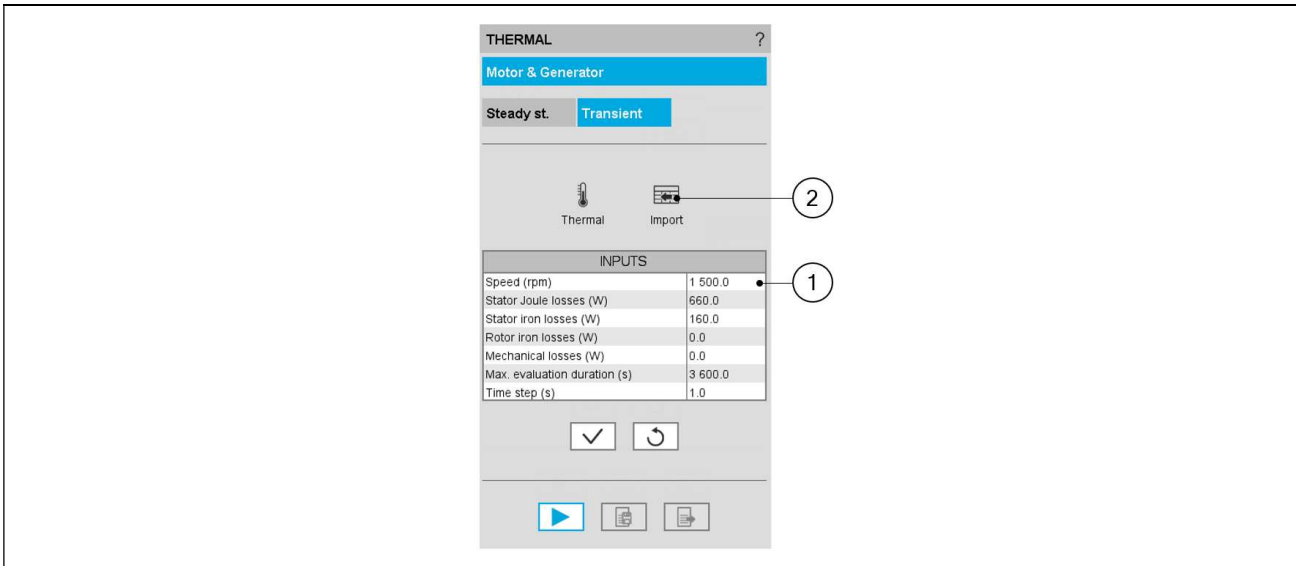
| | How to define the inputs |
|---|---|
| 1 | Fill in the table to define the speed, all the losses to be considered, the max evaluation duration and the time step. |
| 2 | Click on the button "import" to import inputs corresponding to a solved test. All existing data of the selected test will be imported into the inputs of the thermal characterization. The data which does not exist in the outputs of the selected test are set to 0. |



| | 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 rotor iron losses). In that case, the corresponding input in transient thermal test will remain at the value existing before the import.

### 3.3.3    Advanced input

There are no advanced inputs required for this test.

## 3.4    Main principles of computation

### 3.4.1    Introduction

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



Characterization – Thermal – Transient – Synchronous machine - Overview



Characterization – Thermal – Transient– Synchronous machine – Test results

## 3.4.2    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 ($\theta_f$).
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 $\theta\tau$. If found, it corresponds to tau.
If the evaluation time t considered is lower than $\tau$ (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.

## 3.5     Test results

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

### 3.5.1     Test conditions

#### 3.5.1.1   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

#### 3.5.1.2   Settings
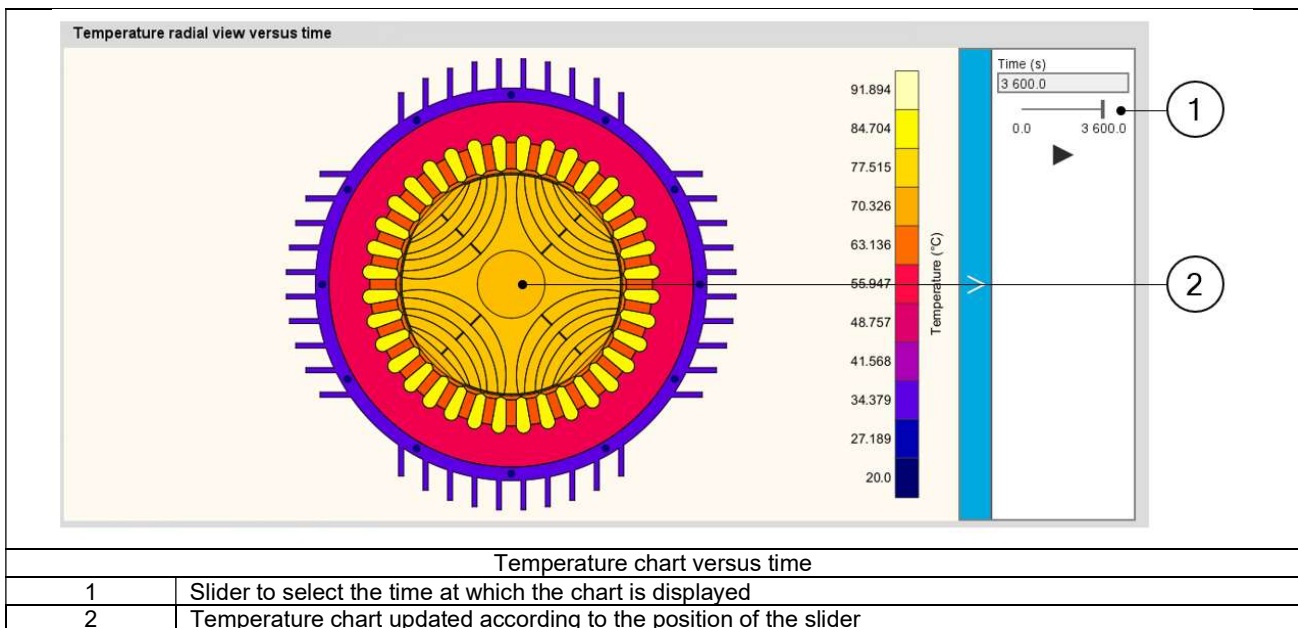
The thermal settings are reminded:
- External fluid temperature
- Cooling circuit temperature

### 3.5.2     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

### 3.5.3     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 |

## 3.6     Limitation of computations - Advice for use

Notes:

3) 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.

4) Please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – section "Limitation of thermal computations – Advice for use"