Altair® FluxMotor® 2024.1

Synchronous Machines with wound field – Inner salient pole - Inner rotor

Motor Factory - Test - Characterization

General user information

Contents

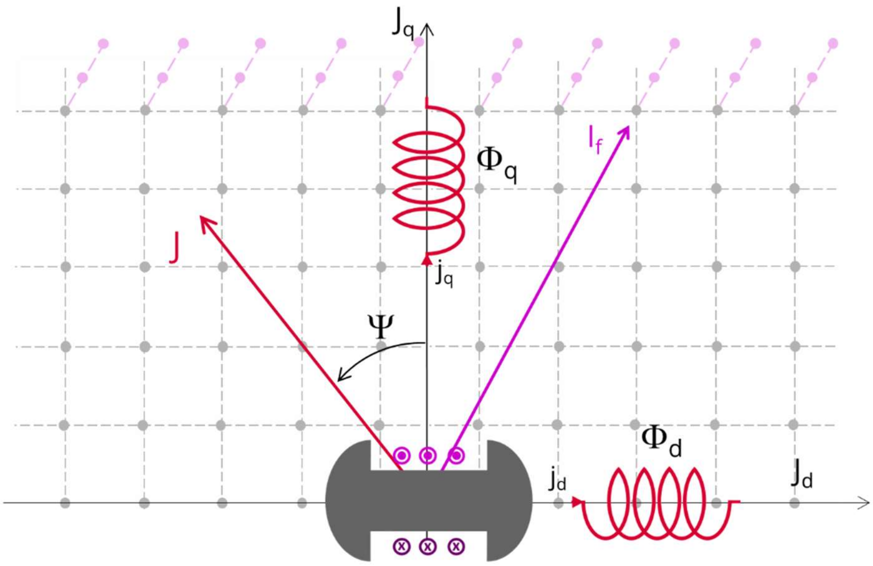
1 CHARACTERIZATION – MODEL – MOTOR – MAPS

1.1 Positioning and objective

The aim of the test "Characterization - Model - Motor - Maps" is to give maps along the three dimensions, I_f-J_d-J_q, for characterizing the 3-Phase synchronous machines with wound field.

These maps allow for 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. Example for a second quadrant calculus.

The 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

1.1.1.1 Overview

Maps are mainly function of the following user inputs: the maximum value of the field current, the maximum value of the line current, the speed, 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 the three dimensions I_f - J_d - J_q

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

2) Flux linkage derivative (only when the rotor position dependency is considered)
- D-axis flux-linkage derivative with respect to the rotor position $\Phi_d/d\theta_r$
- Q-axis flux-linkage derivative with respect to the rotor position $\Phi_q/d\theta_r$

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

4) Saliency

5) Torque
- Electromagnetic torque T_{em}

6) Losses
- Stator iron losses $W_{ironStator}$ versus speed
- Rotor iron losses $W_{ironRotor}$ versus speed (only when the rotor position dependency is considered)
- Total losses W_{total} versus speed

Maps in the two dimensions Jd - Jq

1) Losses
- Joule losses W_{Cus} in stator winding
- Power electronics losses

Curves

1) Field current flux and cross effect flux curve versus J_q
2) Joule losses W_{Cur} in rotor winding versus field current
3) Mechanical losses versus speed versus speed

1.2 Settings

Three buttons give access to the following setting definition:

- Thermal settings – Definition of the phase winding and field 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_SMWF_ISP_IR_3PH_Test_Introduction – sections dealing with settings.

1.3 Inputs

1.3.1 Introduction

The total number of user inputs is equal to 13.
Among these inputs, 5 are standard inputs and 8 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.

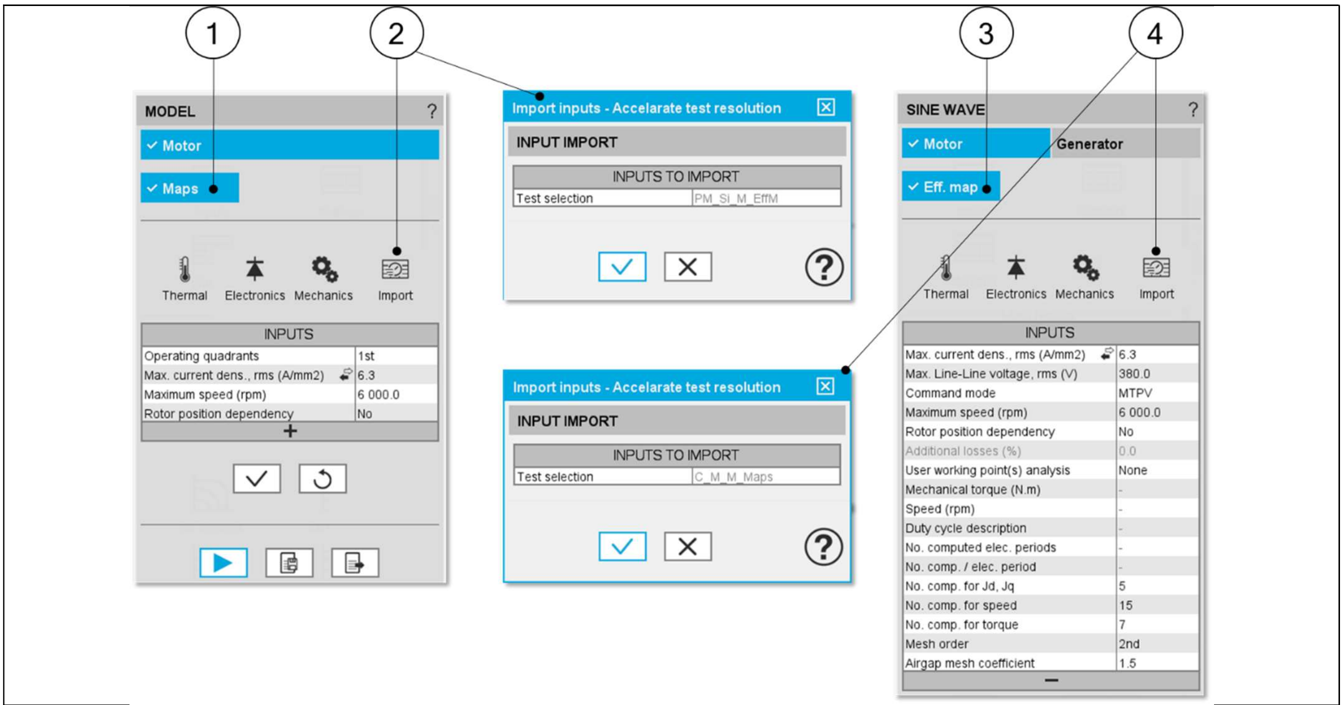
Conversely, upon concluding an efficiency map test, users can use the import button in the efficiency map test GUI to import settings and Flux data from the efficiency map test, further enhancing workflow efficiency.

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. Options allow computing and displaying 1, 2 or 4 quadrants.

By default, the considered quadrants are the "1st and 2nd" (i.e., the grid is defined for both negative and positive values of the current in the d axis and positive ones in the q axis). This option is chosen as default because the Synchronous Machine with wound field heritages the characteristic of both Synchronous Machine with Permanent Magnets and Reluctance Synchronous Machines which work respectively in the second and the first quadrant in the motor operating mode.

The other possible values for this input are "2nd", "2nd and 3rd", and "all".

1.3.3.2 Field Current and line current definition mode

There are two common ways to define 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) and field current (AC value).
In this case, the current definition mode should be « **Current** ».

1.3.3.3 Maximum field current, rms

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

Note: The number of parallel paths is automatically considered in the results.

1.3.3.4 Maximum field current density, rms

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

Note: The number of parallel paths is automatically considered in the results.

1.3.3.5 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.

1.3.3.6 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 line conductors, rms value*) must be provided.

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

1.3.3.7 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*).

1.3.3.8 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 along the three dimensions I_f - J_d - J_q, with an additional fourth 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).

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 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.

Note: The outcomes obtained at 0.5 or 1 electrical period are identical across all presented outputs, except for slight variations in rotor iron losses arising from the symmetrical assumption regarding the magnetic flux waveform on the rotor.

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, and the minimum allowed is 13. The default value provides a good balance between the accuracy of the results and the computation time.

1.3.4.3 Number of computations per quadrant for D-axis and Q-axis phase currents

To get maps in the J_d - J_q plane, a grid is defined. The number of computation points per quadrant 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 6. 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 I_f - axis field current

To get maps along the I_f dimension, the field current is discretized from zero to its maximum value. The number of computation points along the I_f - axis can be defined with the user input « **No. comp. for I_f** » *(Number of computations for I_f - axis field currents)*.
The default value is equal to 6. This default value provides a good compromise between the accuracy of results and computation time.
The minimum allowed value is 5.

Note: If one uses more than one quadrant, the total number of computations for J_d and J_q will be calculated based on the **No. comp. for current J_d, J_q** input and the number of quadrants. For example, if **No. comp. for current J_d, J_q** is set to 10 and the quadrant is set to "1st and 2nd ", then the total number of computations for J_d is 10, but 19 for J_q considering J_d = 0 is shared between both quadrants.

1.3.4.5 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.

1.3.4.6 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 modeling the skewing in Flux® Skew environment*).

1.3.4.7 Mesh order

To get results, Finite Element Modeling 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.

1.3.4.8 Airgap mesh coefficient

The advanced user input "**Airgap mesh coefficient**" is a coefficient that 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 and 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.

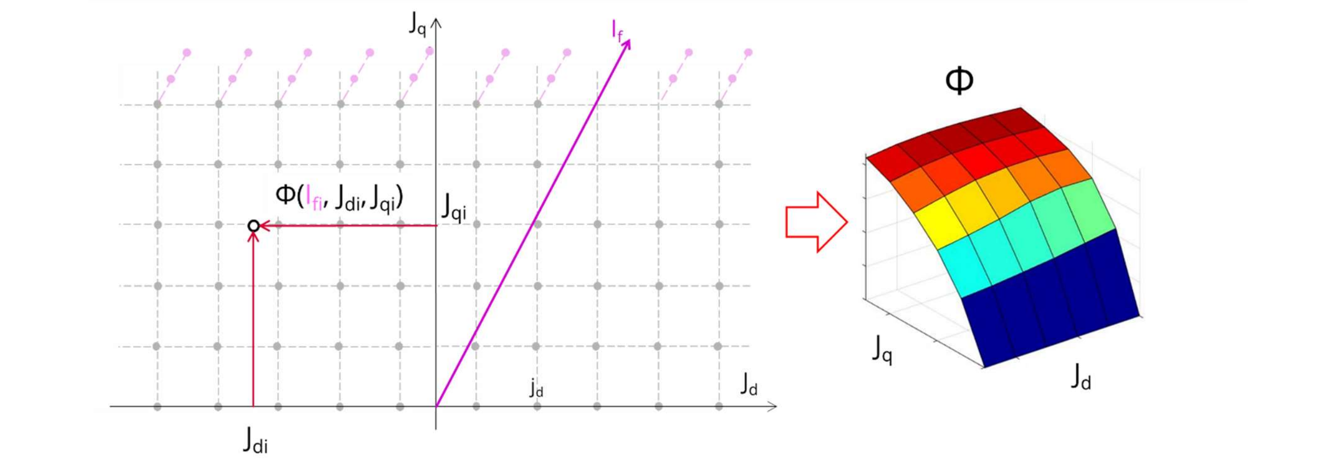
1.3.4.9 Rotor initial position mode - Note

The computations are performed by considering the relative angular position between the 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.

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 planes at different levels of I_f between zero and the maximum value of I_f.
To do that, a grid of values (J_d, J_q) is considered for all levels of I_f.
For each node of this grid, the corresponding flux linkage through each phase is extracted (Φ_a, Φ_b, Φ_c) through the corresponding phases (a, b, c). This is done using Finite Element modeling (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 at a level of I_f

Our modeling considers cross-saturation. However, winding harmonics and the variation of reluctance as a function of the angular position of the rotor are only considered if the "Rotor position dependency" input is "Yes".

Note: The impact on accuracy will be more important for machines with high level of saturation.

When the "Rotor position dependency" input is "No", i*ron loss computations are based on both Finite Element modeling and 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 the field is weakening.*

When the "Rotor position dependency" input is "Yes", i*ron loss computations are based on Finite Element modeling with all considerations for flux leakage.*

Note: In the examples shown in the images, negative value of J_d and positive value of J_q are considered as the 2nd quadrant is chosen as example. 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 ones, 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 three dimensions I_f - J_d - J_q with an additional fourth axis corresponding to the rotor position θ_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 formula:

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

These maps are available only when the input Rotor position dependency is set to "Yes". The computation is done in the three dimensions I_f - J_d - J_q with an additional fourth 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.

1.4.3 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 formulas:

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

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 $L_{d\text{–dynamic}}$ and $L_{q\text{-dynamic}}$ consider the value of the end-winding inductance.

Note 2: In the previous formula, 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 three dimensions I_f - J_d - J_q with an additional fourth axis corresponding to the rotor position θ_r.

1.4.4 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 formula:

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

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. However, the values of the dynamic cross inductances $L_{dq\text{–dynamic}}$ and $L_{qd\text{-dynamic}}$ are not impacted by the end-winding inductance value since they are obtained with the derivative of the 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 formula, 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 three dimensions I_f - J_d - J_q with an additional fourth axis corresponding to the rotor position θ_r.

1.4.5 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 formula:

$$L_{d-\text{static}} = \frac{(\Phi_d - \phi_0)}{\sqrt{2} \times J_d} \qquad L_{q-\text{static}} = \frac{\Phi_q}{\sqrt{2} \times J_q}$$

ϕ_0 is the D-axis magnetic flux linkage component when J_d equals zero. This term corresponds to the magnetic flux linkage created by the field current I_f added to the flux created by the cross effect of J_q along the q-axis. Its value is a function of J_q and I_f.

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: In the previous formula, 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 three dimensions I_f - J_d - J_q with an additional fourth axis corresponding to the rotor position θ_r.

1.4.6 Saliency

The saliency in the J_d-J_q area is computed and displayed as a map in J_d- J_q plane for all levels of I_f. This value corresponds to the ratio between q-axis and d-axis static inductances.

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

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

1.4.7 Electromagnetic torque

The **Electromagnetic torque T_{em}** is computed in different ways as a 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:

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

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

1.4.7.2 Rotor position dependency set to "Yes"

The **Electromagnetic torque T_{em}** is computed thanks to finite element computation and the 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 is equal.

1.4.8 Iron loss computation

The **iron losses** are computed in a different way as a 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 are 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 for 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 three dimensions J_d-J_q-I_f 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:

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

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: In case the "Rotor position dependency" input is set to "No", the impact on accuracy will be more important for a machine with a high level of saturation. In fact, the semi-numerical method used to compute the 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 Stator Joule losses

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

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

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

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

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).

1.4.10 Rotor Joule losses

Joule losses in rotor winding W_{Cur} are computed using the following formula:

$$W_{Cur} = R_r \times I_f^2$$

I_f is the DC value of the field current,
R_r is the field resistance computed according to the temperatures defined by user in the test settings.

Note 1: R_r considers the resistance factor defined in the winding settings (DESIGN area of Motor Factory).

1.4.11 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."

1.4.12 Total losses

For each considered value of speed and currents J_d, J_q, I_f 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 three dimensions I_f - J_d - J_q with an additional fourth axis corresponding to the rotor position θ_r.

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 are the displayed subsections:

- Thermal
- Electronics
- Mechanics

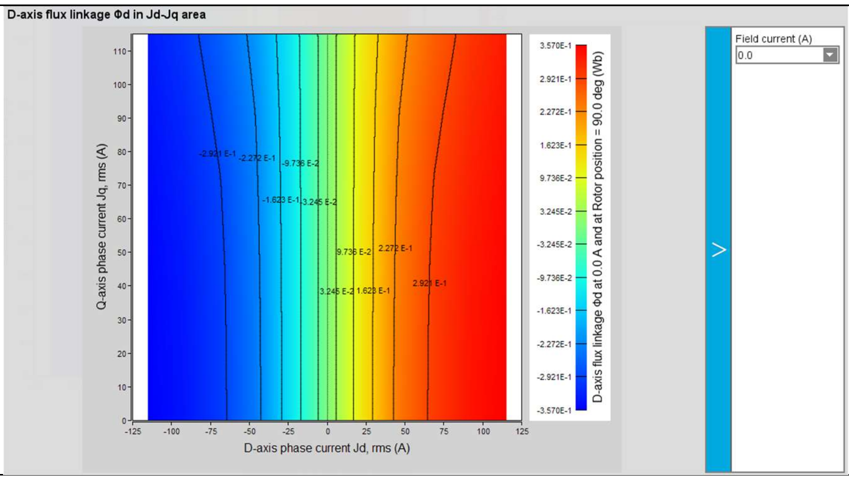
1.5.1.3 Winding characteristics

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

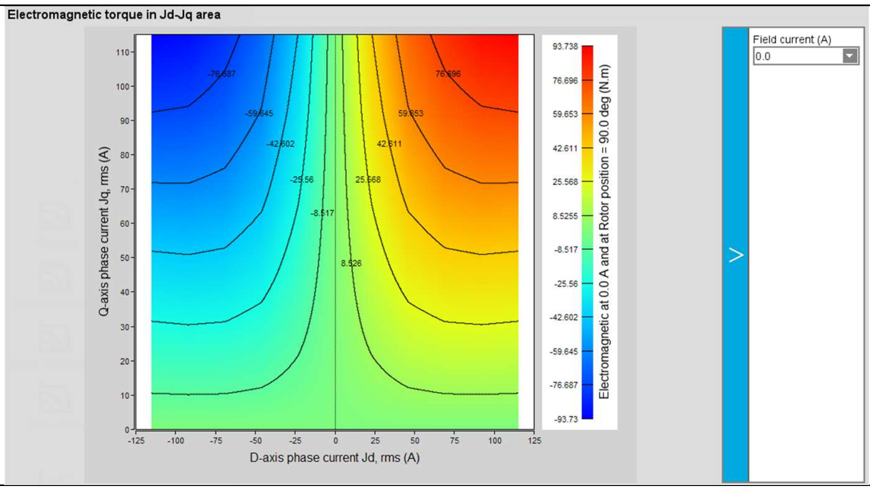
For more details, please refer to the document: MotorFactory_SMPM_IOR_3PH_Test_Introduction – sections dealing with settings.

1.5.2 Maps

Maps illustrating the following quantities (Φ_d, Φ_q, $\Phi_d/d\theta_r$, $\Phi_q/d\theta_r$, $L_{d\text{-dynamic}}$, $L_{q\ dynamic}$, $L_{dq\text{-dynamic}}$, $L_{qd\ dynamic}$, $L_{d\text{-static}}$, $L_{q\ static}$, saliency, torque) are displayed in the J_d-J_q plane with a drop-down menu allowing to pick the desired value of I_f field current.

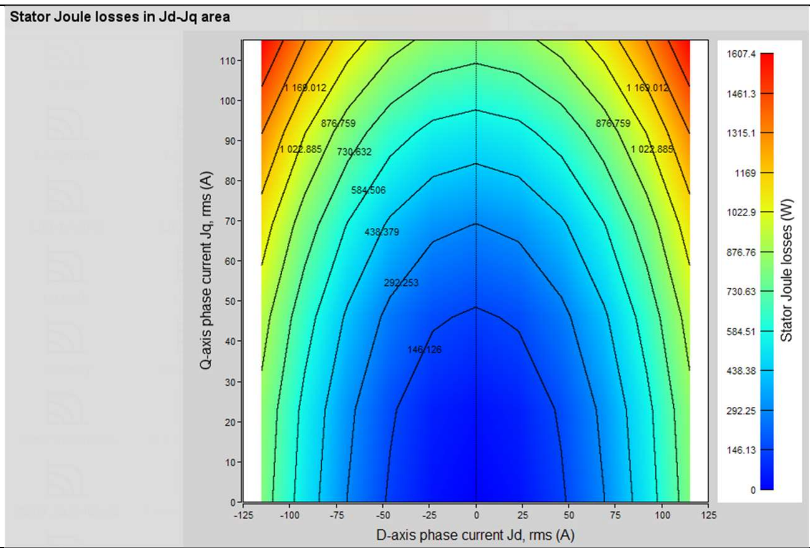


D-axis inductance L_d in J_d - J_q area - Selection of field current in the drop-down menu



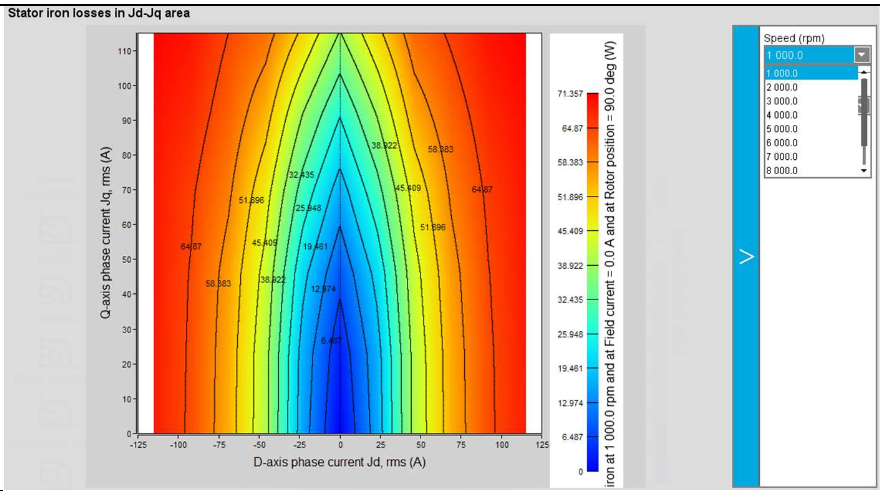
Electromagnetic torque in J_d - J_q area - Selection of field current in the drop-down menu

Joule loss maps and power electronic loss maps are displayed in the J_d-J_q plane without the selection of field current because they are independent of field current.



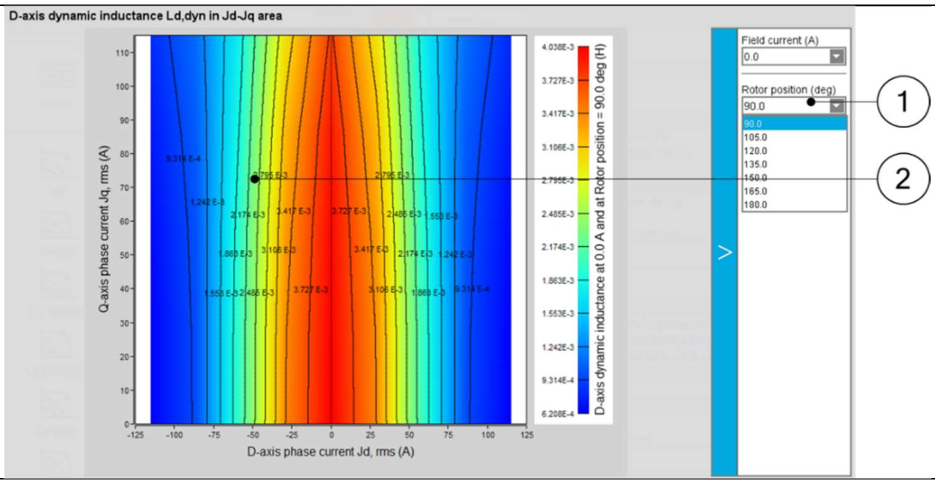
Stator Joule losses in J_d - J_q area

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



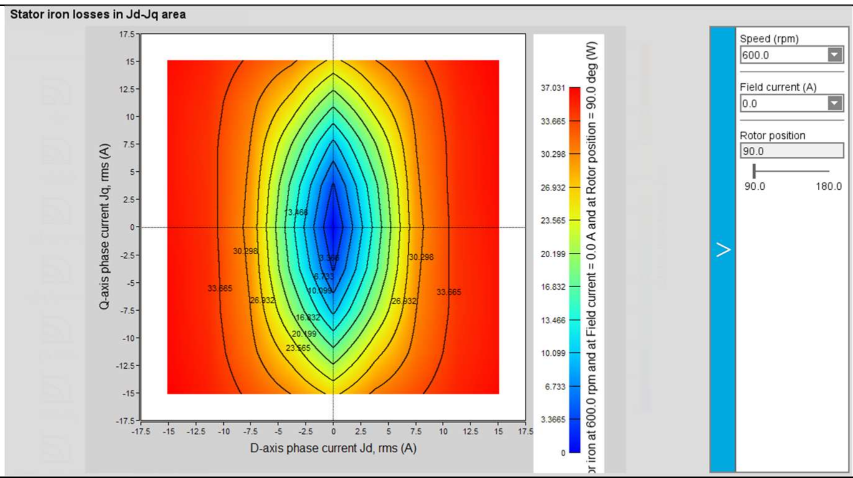
Iron losses in J_d - J_q area - Selection of speed in the drop-down menu

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 three dimensions J_d - J_q – I_f with an additional fourth axis corresponding to the rotor position θ_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.

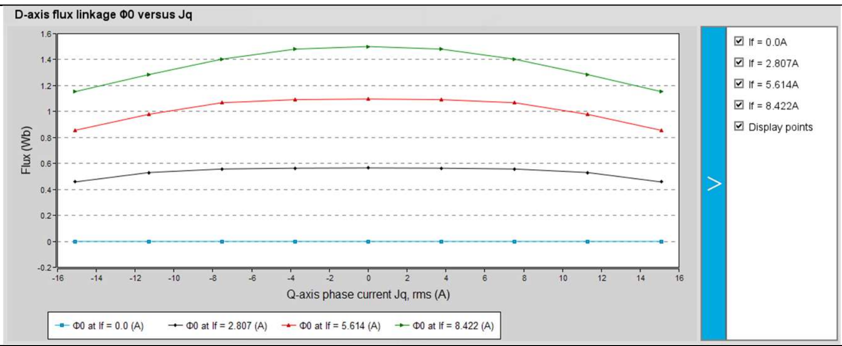


Stator Iron losses in J_d - J_q area - Selection of speed and rotor position in the drop-down menu

1.5.3 Curves

1.5.3.1 Field current flux and cross effect flux curve

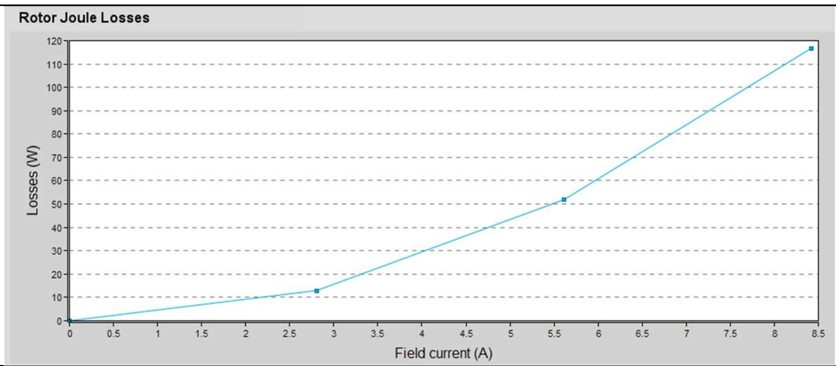
Curves showing the evolution of field current flux added by magnetic flux provided by J_d along the q-axis at different levels of field current I_f are displayed.
The maximum line current and field current considered are the ones defined in the test input parameters.
One can choose to display curves corresponding to the levels of field current I_f by checking the desired value of I_f.



Field current flux & cross effect flux versus J_d - Visualization of the ϕ_{d0} curve

1.5.3.2 Rotor Joule losses

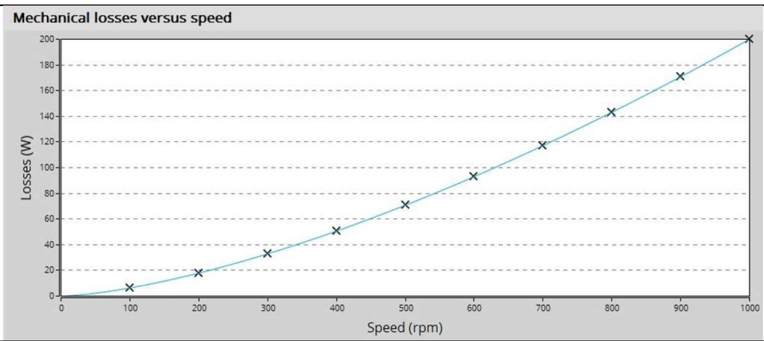
A curve showing the evolution of rotor Joule losses versus field current is displayed.
The maximum field current considered is the one defined in the test input parameters.



Rotor Joule losses versus field current - Visualization of the Rotor Joule loss curve

1.5.3.3 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.



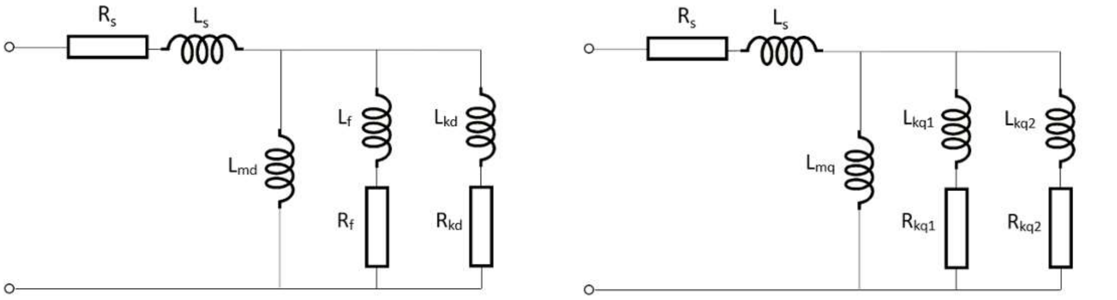
Mechanical losses versus speed - Visualization of the mechanical loss curve

2 CHARACTERIZATION – MODEL – MOTOR – SSFR

2.1 Overview

2.1.1 Positioning and objective

The aim of the test “**Characterization – Model – Motor – SSFR**” dedicated to the wound field synchronous machine is to characterize all the parameters of the D-axis and Q-axis equivalent schemes by performing a frequency analysis.



D-axis parameters of the equivalent circuit

Parameters					
Ls (H)	3.458 E-4	Lsw (H)	2.399 E-4	Lss (H)	1.059 E-4
Rs (Ω)	1.085 E-2	Lmd (H)	1.528 E-2		
Rf (Ω)	2.301 E-3	Lf (H)	1.823 E-3		
Rkd (Ω)	1.931 E-2	Lkd (H)	1.069 E-3		

Q-axis parameters of the equivalent circuit

Parameters					
Ls (H)	3.475 E-4	Lsw (H)	2.399 E-4	Lss (H)	1.076 E-4
Rs (Ω)	1.085 E-2	Lmq (H)	6.989 E-3		
Rkq1 (Ω)	1.762 E-2	Lkq1 (H)	1.029 E-3		
Rkq2 (Ω)	5.182 E-2	Lkq2 (H)	1.168 E-3		

Characterization – Model – Motor – SSFR” – Characterization of all the equivalent scheme parameters
D-axis and Q-axis equivalent scheme data – 2nd order is considered in the example above.

These results are based on the magnitude and the phase of the operational inductance transfer function which are computed with Finite Element software Flux® 2D.

The resulting reactances and time constants of the machines are also provided. Hence, such data can be used in system modeling tools like Altair® PSIM™ to evaluate the behavior of the machine with its drive and control system.

Reactances

Reactances					
Xd (Ω)	5.892	Xd' (Ω)	7.444 E-1	Xd" (Ω)	3.736 E-1
Xq (Ω)	2.766	Xq' (Ω)	4.692 E-1	Xq" (Ω)	3.223 E-1
Xs (Ω)	1.304 E-1	Xmd (Ω)	5.762	Xmq (Ω)	2.635
Reactances in per-unit system					
Reference impedance (Ω)	2.564				
Xd (%)	229.799	Xd' (%)	29.032	Xd" (%)	14.572
Xq (%)	107.865	Xq' (%)	18.298	Xq" (%)	12.571
Xs (%)	5.084	Xmd (%)	224.715	Xmq (%)	102.756

Time constants

Time constants					
Td' (s)	9.393 E-1	Td" (s)	7.012 E-2	Td0' (s)	7.435
Td0" (s)	1.397 E-1				
Tq' (s)	7.719 E-2	Tq" (s)	2.738 E-2	Tq0' (s)	4.551 E-1
Tq0" (s)	3.986 E-2				

Reactances and time constants of the machine are computed

The following table helps to classify the test “Characterization – Model – Motor – SSFR”.

Family	Characterization
Package	Model
Convention	Motor
Test	SSFR

Positioning of the test “Characterization – Model – Motor – SSFR”

2.1.2 User inputs

The main user input parameters are the order of the operational inductance transfer function to be considered for the D-axis and the Q-axis of the machine. 1st and 2nd order are considered depending not only on the presence or absence of dampers in the rotor pole shoes, but also on the accuracy of the results obtained with the 1st order model. For the Q-axis, it is also possible to consider a zero order model since machines without dampers normally present a quasi-constant response for the Q-axis.
Then, the reference frequency and the reference impedance for the per-unit system computation are needed to compute the resulting machine reactances.
In addition, the temperatures of the stator and rotor windings and dampers must be set.

2.1.3 Main outputs

The main outputs are all the computed parameters of the equivalent scheme (Zero, 1st or 2nd).
The quality of results is also illustrated with the superimposition of the magnitude and phase of the operational inductance is computed either with Finite Element software Flux® 2D (Steady State AC application) or analytically by considering the resulting operational inductance.

2.1.3.1 Table or results

1) D-axis and Q-axis equivalent scheme parameters
   - Operational inductance Laplace function with the corresponding computed parameters
   - Wound field synchronous machine equivalent scheme, D-axis and Q-axis (Zero, 1st or 2nd) with its associated computed parameters
   - Reactances and time constants

2.1.3.2 Curves

1) Magnitude of the operational inductance versus frequency – D-axis and Q-axis
2) Phase of the operational inductance versus frequency – D-axis and Q-axis

2.2 Settings

One button gives access to the following setting definition:

- Temperature of active components: stator and rotor windings and dampers

For more details, please refer to the document: MotorFactory_SMWF_ISP_IR_3PH_Test_Introduction.

2.3 Inputs

2.3.1 Introduction

The total number of user inputs is equal to 13.
Among these inputs, 4 are standard inputs and 9 are advanced inputs.

2.3.2 Standard inputs

2.3.2.1 D-axis operational inductance order

The **D-axis operational inductance order** (D-axis operational inductance order) can be either "1st" order or "2nd" order.
This choice depends not only on the presence or absence of dampers in the rotor pole shoes but also on the results obtained with the "1st" order model. When the first order model doesn't allow getting good fitting between computation results from Finite Elements computations of the operational inductance and those got with the resulting analytical model, the 2nd order is needed.
By default, this input is set to "2nd" order.

2.3.2.2 Q-axis operational inductance order

The **Q-axis operational inductance order** (Q-axis operational inductance order) can be either "Zero", "1st" order or "2nd" order.
This choice depends not only on the presence or absence of dampers in the rotor pole shoes but also on the results obtained with the selected model order. When the selected model order doesn't allow getting good fitting between computation results from Finite Elements computations of the operational inductance and those got with the resulting analytical model, a higher order is needed. The "Zero" order model is available for the Q-axis because for a machine without dampers the frequency response tends to be quasi-constant.
By default, this input is set to "2nd" order.

2.3.2.3 Reference frequency

To compute machine reactances, an electrical frequency f_0 must be provided to define the electrical pulsation ω_0, in which $\omega_0 = 2 \cdot \pi \cdot f_0$.
By default, this input is set to 50 Hz, providing an electrical pulsation of 314.159.. radians per second.

2.3.2.4 Reference impedance

To compute machine reactances in the per-unit system, a reference impedance Z_b must be provided to normalize the reactances values by dividing the calculated ones by Z_b.
By default, this input is set to 1 Ω.

2.3.3 Advanced inputs

2.3.3.1 Linear permeability distribution

Two methods allow defining the permeability in the magnetic circuit of the machine; either the magnetic permeability is constant in the stator, rotor and shaft or the magnetic permeability is linked to the magnetic state of the machine when running at a working point.

When the "Linear permeability distribution" mode is "**Constant**", the relative magnetic permeability must be defined for the stator, the rotor, and the shaft.
When the "Linear permeability distribution" mode is "**Working point**" the characteristics of the working point must be defined with the field current If, the stator current I and the control angle Ψ.
Then, the magnetic permeability mapping of a motor is done at the selected working point (If, I, Ψ). Even though the working-point If-I-Ψ-N will be used in this process, the rotor speed N only impacts post-processing computations but has no impact on the permeability distribution, reason why it is not required as input for the SSFR test.
The resulting map of permeability is then applied to the model while performing the frequency analysis. This is what we call the frozen permeability method.

2.3.3.2 Stator permeability

This input allows to set the value of the magnetic permeabilities for the stator. To meet the requirements of the test assumptions, the computations with Finite Elements are operated by considering linear ferromagnetic materials.

The relative permeability of the stator **"Stator permeability"** (*stator magnetic relative permeability)* is by default set to Auto. In this auto mode, the applied stator relative permeability is computed by an internal process (see illustration in below section) in case of a nonlinear magnetic material since the SSFR test is based on the principle that magnetic materials need to be linear.
In case of a linear magnetic material, the stator permeability is the one defined in the material properties (no internal computation is necessary).
The user can enter his own stator permeability by using the toggle button added for this purpose.
This value allows to perform the SSFR test.

2.3.3.3 Rotor permeability

This input allows to set the value of the magnetic permeabilities for the rotor. To meet the requirements of the test assumptions, the computations with Finite Elements are operated by considering linear ferromagnetic materials

The relative permeability of the rotor **"Rotor permeability"** (*rotor magnetic relative permeability)* is defined as the stator permeability by two modes. An auto mode and a user mode. By default, it is set to Auto.
This value allows to perform the SSFR test.

2.3.3.4 Shaft permeability

This input allows to set the value of the magnetic permeabilities for the shaft. To meet the requirements of the test assumptions, the computations with Finite Elements are operated by considering linear ferromagnetic materials.

The relative permeability of the shaft **"Shaft permeability"** (*shaft magnetic relative permeability)* is defined as the stator and rotor permeabilities in case of the existence of a shaft. By default, the relative permeability of the shaft is set to Auto.

Note that, if a shaft is added to a motor, the default value of the shaft permeability is equal to the rotor permeability for the wound field synchronous machine.

2.3.3.5 Working point characteristics

When the "Linear permeability distribution" mode is "Working point", it means that the frequency analysis to compute the operational inductance - L(p) – is based on a working point defined with the field current I_f, the stator current I and the control angle Ψ.
Hence, these three data must be defined:

- **WP- Field current density** (*Working point – Current density in Field conductors)* or **WP- Field current** (*Working point – Field current)*
- **WP- Current density, rms** (*Working point – Current density in conductors, rms value)* or **WP- Line current, rms** (*Working point – Line current, rms value)*
- **WP- Control angle** (*Working point – Control angle)*

Note: currently, if the designed machine has either stator slots or rotor salient poles skewed, the "Working point" mode for the "Linear permeability distribution" is not available.

2.3.3.6 SSFR voltage, rms

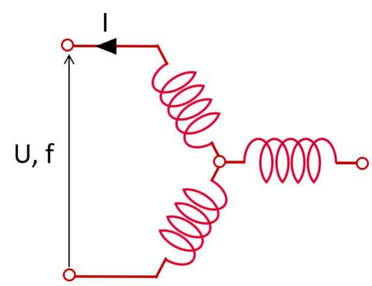
The rms value of the SSFR voltage "**SSFR voltage, rms**" (*Voltage between two terminals during SSFR test, rms value)* must be provided. This value allows to perform the SSFR test.

Notes:
- The number of parallel paths is automatically considered in the results.
- The test is always operated by considering a star winding connection.

By default, this input is equal to 0.2 V.

The test procedure for performing the SSFR test consists in applying a fixed low voltage source between two terminals of the machine armature winding (Star winding connection) over a range of frequencies. SSFR voltage corresponds to the voltage source (U) applied.

For additional information please refer to the main principles of computation section.



SSFR voltage (U) applied between two terminals of the machine armature winding

2.3.3.7 Skew model – Number of layers

When the stator slots or the rotor salient poles 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*).

2.3.3.8 Rotor initial position

The computations are performed by considering the relative angular position between the 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.

Note: for the SSFR test, the rotor initial position corresponds to the position in which the Q-axis characteristics will be measured, following the SSFR test standard if referring to the winding connection as described in the scheme above. The D-axis characteristics will always be measured in the following rotor position (in degrees):

$$\theta_{Daxis} = \theta_{Qaxis} - \frac{1}{2} \cdot \frac{180}{p}$$

With p = number of pole pairs of the machine.

2.3.3.9 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:

Mesh Point = (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].
Giving 0.05 produces a very high mesh density and giving 2 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.

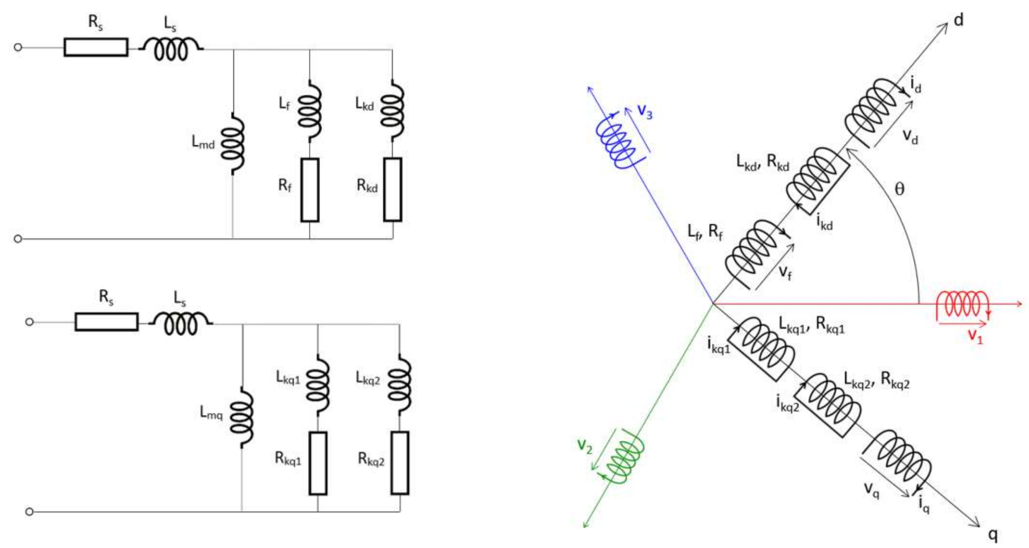
2.4 Main principles of computation

2.4.1 Introduction

As said previously, the aim of the test "Characterization – Model – Motor – SSFR" is to identify all the parameters of the electrical equivalent scheme of a 3-Phase wound field synchronous machine by considering either a first order or a second order for the D-axis and Q-axis operational inductance transfer function L(p).

2.4.2 Model representation

2.4.2.1 Second order D-Axis and Q-Axis model



2^{nd} order equivalent scheme of the wound field synchronous machine with dampers

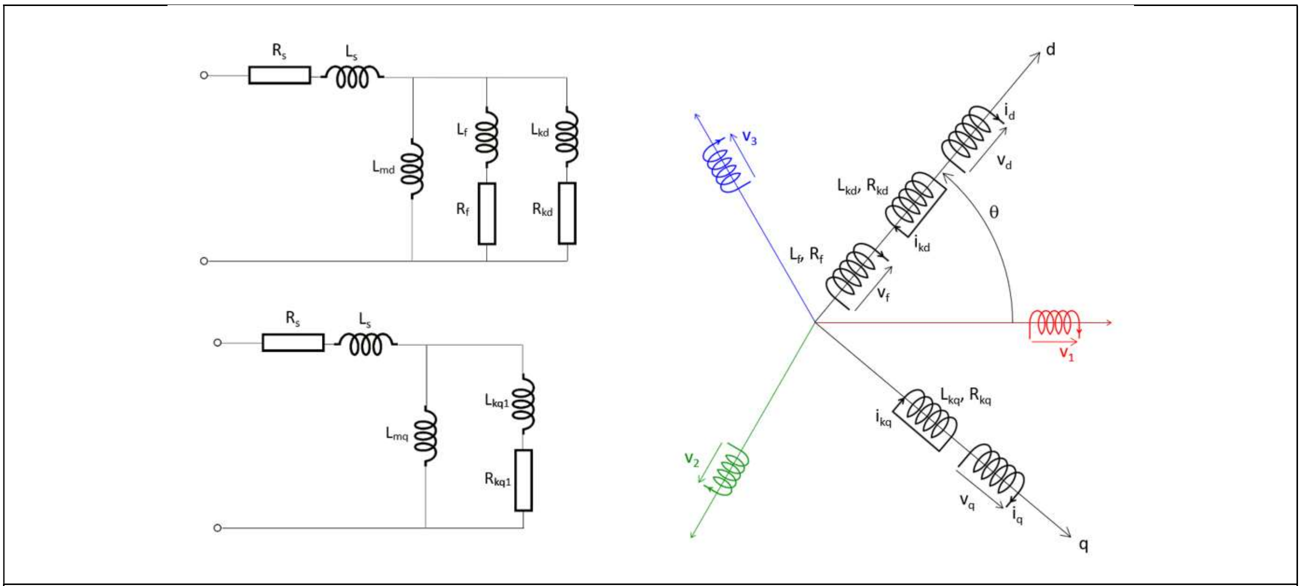
Notes:

On the previous and following graphs, θ represents the relative position between the first stator winding phase and the d-axis of the machine model.
All the components displayed in the picture correspond to the equivalent scheme parameters. For more information, please refer to the user help guides.

Here is the list of the second order equivalent scheme parameters:

R_s: Stator phase resistance
L_s: Stator phase leakage inductance = (L_{sw} + L_{ss})
L_{sw}: Stator end winding leakage inductance (included in L_s)
L_{ss}: Stator straight part leakage inductance (included in L_s)
L_{md}: D-axis magnetizing inductance
R_f: Field resistance
L_f: Field inductance
R_{kd}: D-axis damper resistance
L_{kd}: D-axis damper inductance
L_{mq}: Q-axis magnetizing inductance
R_{kq1}: Q-axis damper resistance – 1^{st} branch
L_{kq1}: Q-axis damper inductance – 1^{st} branch
R_{kq2}: Q-axis damper resistance – 2^{nd} branch
L_{kq2}: Q-axis damper inductance – 2^{nd} branch

2.4.2.2 Second order D-Axis and first order Q-Axis model

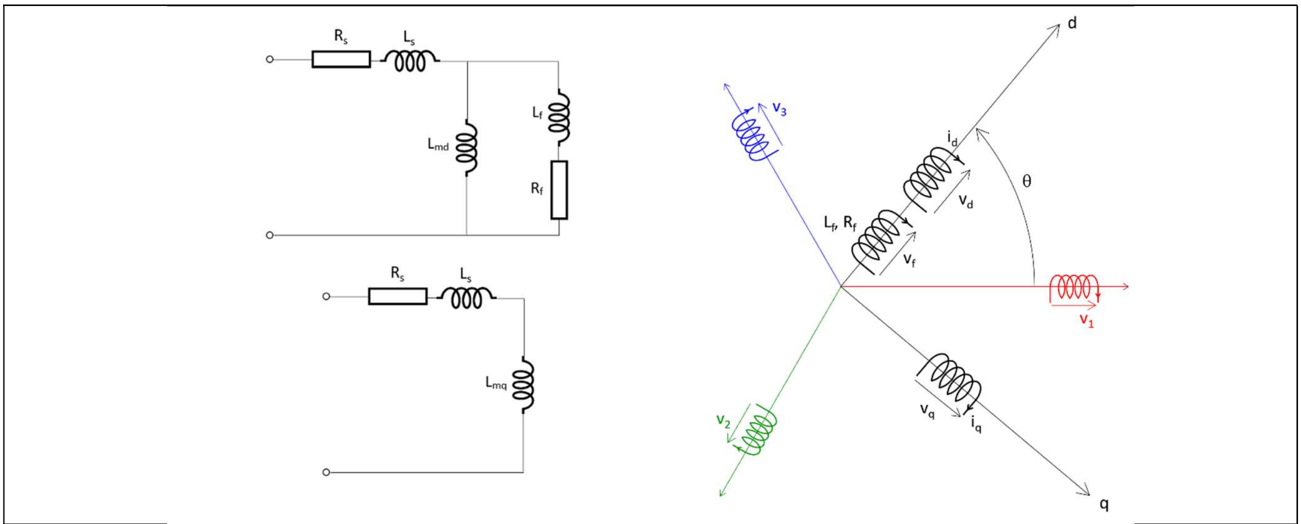


D-Axis 2nd order equivalent scheme and Q-Axis 1st order equivalent scheme
of the wound field synchronous machine with dampers

Here is the list of the first order equivalent scheme parameters:

R_s: Stator phase resistance
L_s: Stator phase leakage inductance = (L_{sw} + L_{ss})
L_{sw}: Stator end winding leakage inductance (included in L_s)
L_{ss}: Stator straight part leakage inductance (included in L_s)
L_{md}: D-axis magnetizing inductance
R_f: Field resistance
L_f: Field inductance
R_{kd}: D-axis damper resistance
L_{kd}: D-axis damper inductance
L_{mq}: Q-axis magnetizing inductance
R_{kq1}: Q-axis damper resistance – 1st branch
L_{kq1}: Q-axis damper inductance – 1st branch

2.4.2.3 First order D-Axis and zero order Q-Axis model



D-Axis 1st order equivalent scheme and Q-Axis Zero order equivalent scheme
of the wound field synchronous machine without dampers

Here is the list of the first order equivalent scheme parameters:

R_s: Stator phase resistance
L_s: Stator phase leakage inductance = (L_{sw} + L_{ss})
L_{sw}: Stator end winding leakage inductance (included in L_s)
L_{ss}: Stator straight part leakage inductance (included in L_s)
L_{md}: D-axis magnetizing inductance
R_f: Field resistance
L_f: Field inductance
L_{mq}: Q-axis magnetizing inductance

2.4.3 Test procedure

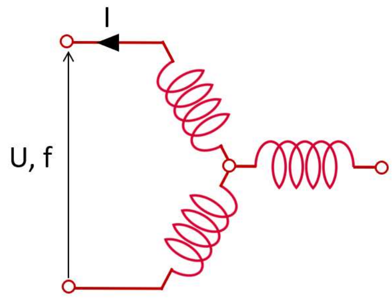
2.4.3.1 Short description

The rotor of the machine does not rotate. Two positions are considered for the rotor angular position, one to characterize the D-axis parameters and another one to characterize the Q-axis parameters. Hence, the following process is performed twice, once for each rotor angular position.

By considering a 3-Phase wound field synchronous machine, the magnitude and a phase angle of the machine's operational inductance L(p) are computed versus the frequency for the D-axis and the Q-axis.

The operational inductance L(p) is deduced from the impedance Z(p) as a magnitude and a phase angle, then formulated as a transfer function.
To perform these computations, a frequency analysis is carried out over a range of frequencies between 1 mHz and 1 kHz, considering 10 frequency values per decade. These computations are performed with Finite Element tool Flux® 2D – Steady state AC application.

As a result, the wound field synchronous machine is characterized on both D-axis and Q-axis by its frequency response, which is the magnitude and phase angle of the operational inductance transfer function versus the frequency.



A voltage U is applied between two phases

The operational inductance transfer function is deduced from the applied voltage and frequency as follow:

$$\frac{U}{I} = Z(p) = -2 \times [R_S + p \times L(p)]$$

Depending on the operational inductance transfer function order, the corresponding analytical formula of L(p) is represented as illustrated below:

$L(p) = A\frac{1 + Bp}{1 + Cp}$	$L(p) = A\frac{1 + Bp + Cp^2}{1 + Dp + Ep^2}$
1st order operational inductance transfer function	2nd order operational inductance transfer function

Then, an internal optimization process computes for each axis all the corresponding parameters (A, B, C, D, and E) to make both results from the analytical approach and Finite Element tool computation as close as possible.

For the Q-axis zero order operational inductance, the only parameter for the transfer function is A, and no optimization process is run, since it will be equal to the magnitude of the first point provided by the Finite Element tool computation with a zero degree of phase, i.e., a constant real value.

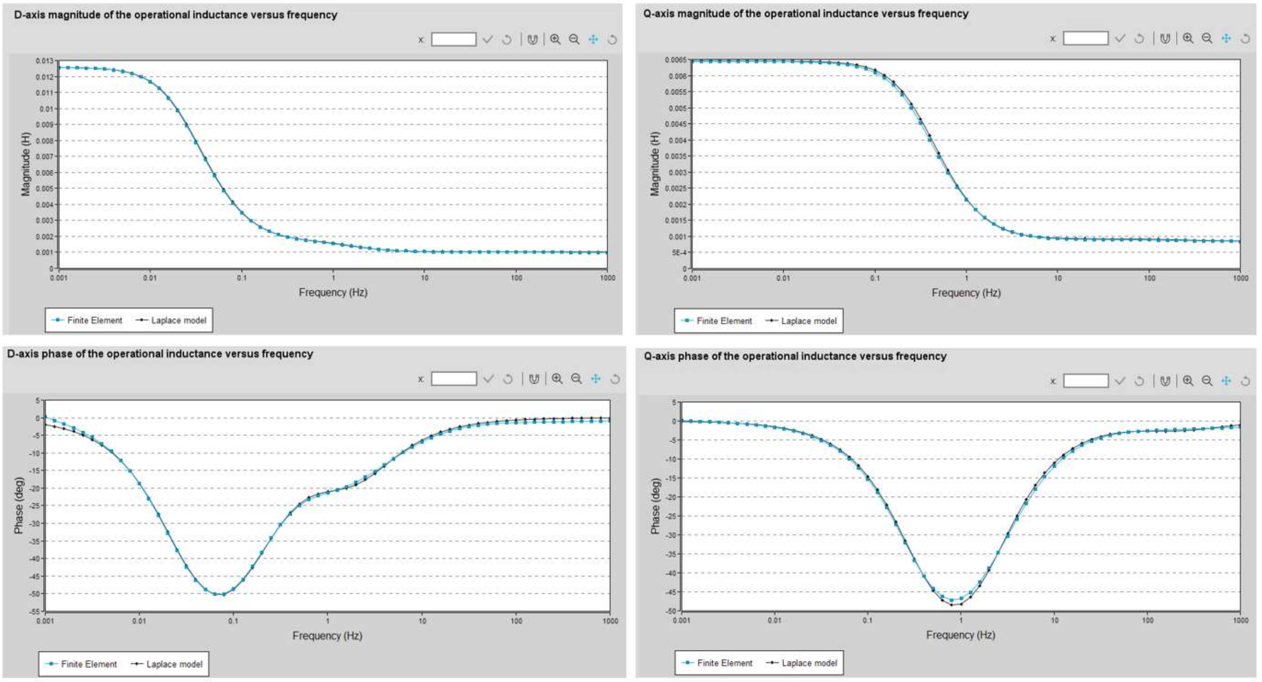
Theoretical analytical formulas allow deducing all the D-axis and Q-axis equivalent scheme parameters from operational inductance transfer function coefficients.

Here are results to illustrate this comparison in the test area.

Blue points (curves) correspond to Finite Element computation results.
Black points (curves) correspond to analytical computations based on equivalent operational inductance transfer function.

The aim of the internal optimization process is to make these two resulting curves as close as possible to each other by acting on the L(p) parameters.

Modeling of a wound field synchronous machine with dampers - using a second order operational inductance for both the D-axis and Q-axis.



Magnitude and a phase of the D-Axis and Q-Axis operational inductance L(p) vs frequency

For additional information regarding D-axis and Q-axis operational inductance model order selection, please refer to the Best Practices document: MotorFactory_Test_BestPractices.

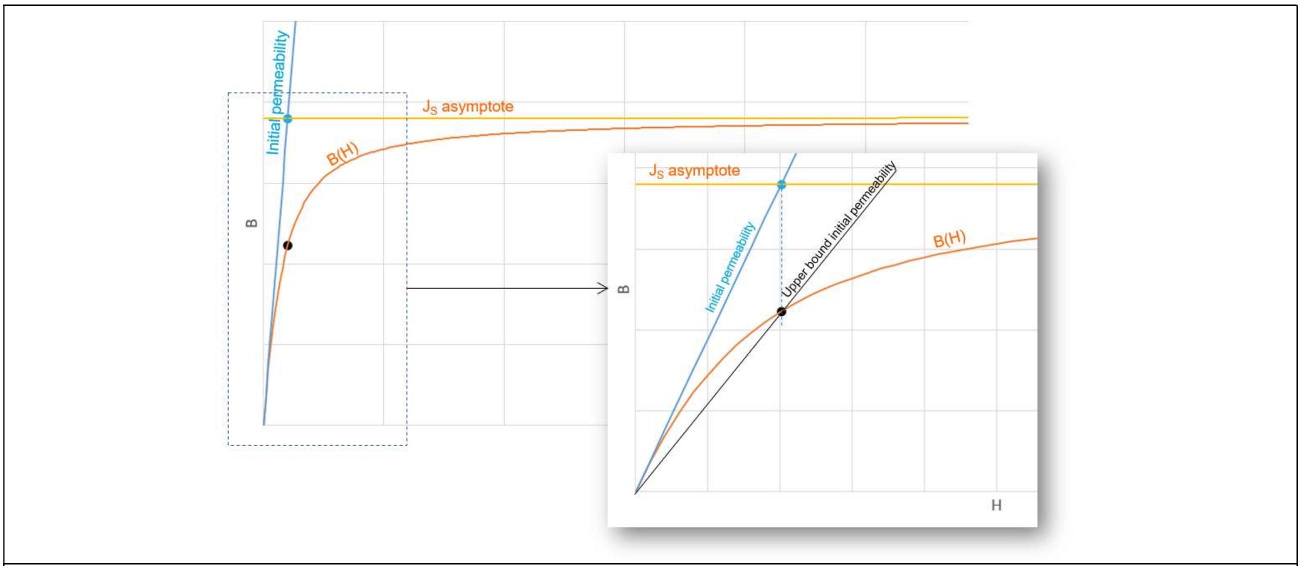
2.4.3.2 Additional information

1) Materials magnetic properties

To meet the requirements of the test assumptions, the computations with Finite Elements are operated by considering linear ferromagnetic materials.

The constant value of each material magnetic permeability is computed by considering a mean value in the very first part of the considered B(H) curve.

From a practical point of view, the constant magnetic permeability used in the computation is the average value of initial and the upper bound permeability defined as below illustrated.



Definition of constant magnetic permeability used for computations with Finite Elements software

2) Stator phase leakage inductance computation

L_s is the stator phase leakage inductance.
L_{sw} is the stator end winding leakage inductance.
L_{ss} is the stator straight part leakage inductance (including slot leakage inductance)

L_{sw} corresponds to the total end winding inductance (including the two sides of the machine). It is computed in the winding area environment with analytical method of computation.

The stator straight part leakage (L_{ss}) 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 stator phase leakage inductance (L_s) is computed as follows:

$$L_s = (L_{sw} + L_{ss})$$

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

$$L_{md} = L_d - L_s$$
$$L_{mq} = L_q - L_s$$

Where L_d is the D-axis phase winding inductance, which corresponds to the A parameter of the D-axis operational inductance, which corresponds to the inductance at low frequency.
L_q is the Q-axis phase winding inductance, which corresponds to the A parameter of the Q-axis operational inductance, which corresponds to the inductance at low frequency.

$L(p) = A\frac{1 + Bp}{1 + Cp}$	$L(p) = A\frac{1 + Bp + Cp^2}{1 + Dp + Ep^2}$
1st order operational inductance transfer function	2nd order operational inductance transfer function

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 that belong 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

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

2.5.1.3 Windings & Damper characteristics

The stator and field windings and damper characteristics are displayed in the following subsections:

- Stator winding characteristics
- Field winding characteristics
- Damper characteristics

2.5.2 Main results

2.5.2.1 D-axis operational inductance

Whatever the considered D-axis operational inductance order, the corresponding theoretical transfer function is displayed.
All the related coefficients of the D-axis operational inductance model are displayed.

Then, the magnitude and the phase angle of the D-axis operational inductance transfer function versus the frequency are displayed.

2.5.2.2 D-axis equivalent circuit

Whatever the considered D-axis operational inductance order, the corresponding equivalent scheme is displayed.
All the related equivalent scheme parameters are displayed.

2.5.2.3 Q-axis operational inductance

Whatever the considered Q-axis operational inductance order, the corresponding theoretical transfer function is displayed.
All the related coefficients of the Q-axis operational inductance model are displayed.

Then, the magnitude and the phase angle of the Q-axis operational inductance transfer function versus the frequency are displayed.

2.5.2.4 Q-axis equivalent circuit

Whatever the considered Q-axis operational inductance order, the corresponding equivalent scheme is displayed.
All the related equivalent scheme parameters are displayed.

2.5.2.5 Reactances

Considering the D-axis and Q-axis operational inductance orders, the corresponding reactances are displayed, according to the input reference frequency. The per-unit system values are also displayed, according to the input reference impedance.

2.5.2.6 Time constants

Considering the D-axis and Q-axis operational inductance orders, the corresponding time constants are displayed.