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Altair[®] FluxMotor[®] 2024

Reluctance Synchronous Machines - Inner rotor

Motor Factory - Test - Working point

General user information

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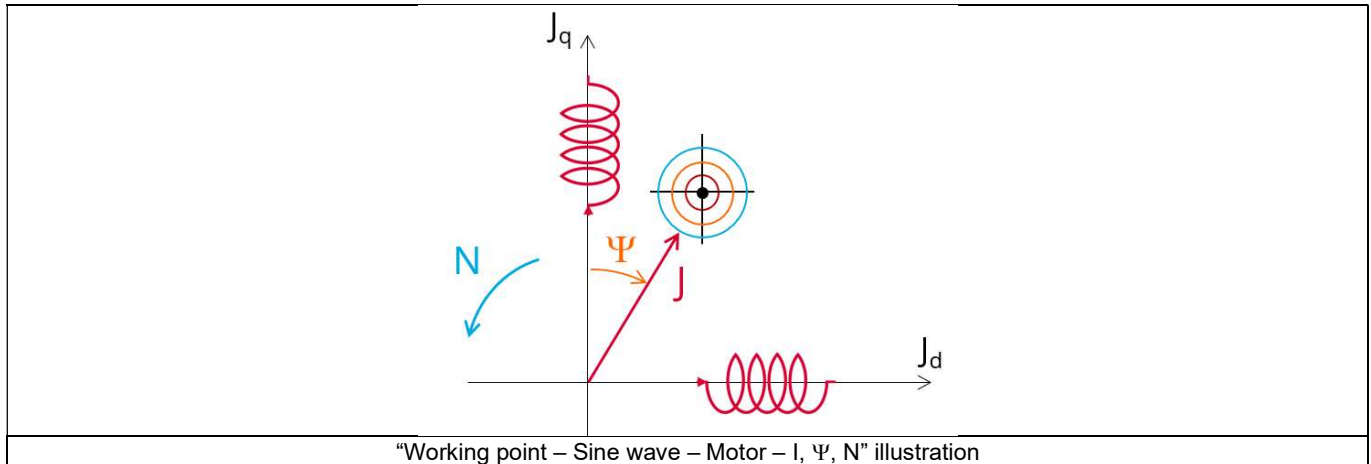
1 WORKING POINT – SINE WAVE – MOTOR – I, Ψ , N

1.1 Overview

1.1.1 Positioning and objective

The aim of the test **“Working point – Sine wave – Motor – I, Ψ , N”** is to characterize the behavior of the machine when operating at the targeted input values I, Ψ , N (Magnitude of current, Control angle, Speed). These three inputs are enough to impose a precise working point.

For instance, a working point can be chosen on the efficiency map, by identifying the current, the control angle and the speed with different curves or maps displayed in the “Performance mapping / Sine wave / Motor / Efficiency map” test. Then, the “Working point – Sine wave – Motor – I, Ψ , N” test allows to compute the performance for this working point.



The results of this test give an overview of the electromagnetic analysis of the machine considering its topology. The general data of the machine, like machine constants and power balance are computed and displayed. The motor convention is used to build the model.

The magnetic flux density is also computed in every region of the machine’s magnetic circuit to evaluate the design.

Two computation modes are available:

- “Fast computation mode” is perfectly suited for the pre-design step (Hybrid model based on Magneto-Static Finite Element computations and Park transformation theory)
- “Accurate computation mode” is perfectly suited for the final design step (Pure Finite Element modeling based on transient computations)

It also gives the capability to make comparisons between the results obtained from the measurements and those evaluated with Altair® FluxMotor®.

When both the following conditions are met, this test allows to perform electromagnetic computations with coupled thermal analysis:

- The type of machine is Reluctance Synchronous Machine with Inner rotor
- One of the two following thermal solving modes is selected: One iteration or iterative solving mode

The following table helps to classify the test “Working point – Sine wave – Motor – I, Ψ , N”.

| | |
|------------|---------------|
| Family | Working point |
| Package | Sine wave |
| Convention | Motor |
| Test | I, Ψ , N |

Positioning of the test “Working point – Sine wave – Motor – I, Ψ , N”

1.1.2 User inputs

The three main user input parameters are the supply line current, control angle and speed. In addition, temperatures of winding must be set.

1.1.3 Main outputs

Test results are illustrated with data, graphs, and tables

1.1.3.1 Tables of results

- 1) Machine performance – Working point
 - General data
 - Machine constants
 - Power balance
 - Flux in airgap
 - Flux density in iron
- 2) Power electronics
 - Inverter
 - Working point
- 3) Inductances
 - Working point
 - D-Q model representation
- 4) Ripple mechanical torque
 - Working point
- 5) Thermal data
 - Table of temperatures

1.1.3.2 Curves – in the “Fast computation modes”

- 1) Ripple mechanical torque versus rotor angular position
- 2) Flux density in airgap versus rotor angular position
- 3) Chart of temperature (radial and axial views)

1.1.3.3 Curves – in the “Accurate computation modes”

- 1) Mechanical torque versus rotor angular position
- 2) Mechanical torque harmonic analysis
- 3) Flux density in airgap versus rotor angular position
- 4) Flux density in airgap harmonic analysis
- 5) Phase voltage versus rotor angular position
- 6) Phase voltage harmonic analysis
- 7) Phase current versus rotor angular position
- 8) Phase current harmonic analysis

1.1.3.4 Graphics

- 1) Isovalues

1.1.3.5 Temperatures

- 1) Chart of temperature (radial and axial views)
- 2) Thermal data
 - Table of temperatures

1.2 Settings

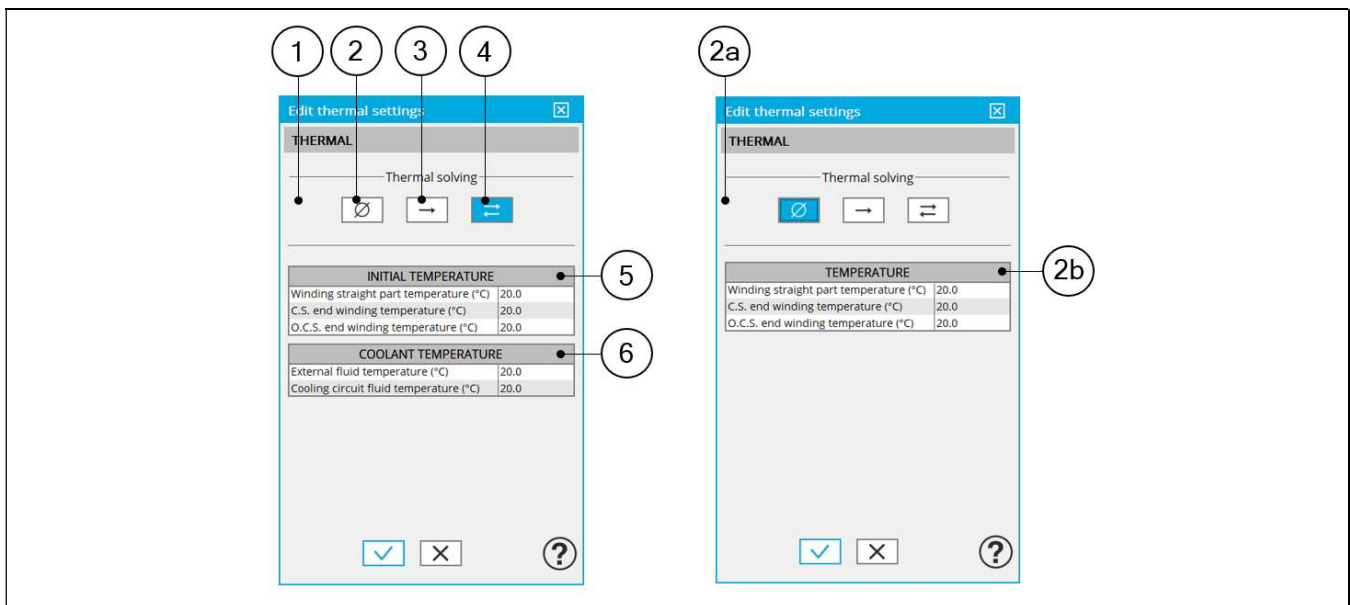
Three buttons give access to the following setting definition: Thermal, Electronics and Mechanics. Each kind of settings is briefly defined here.

Additional information can be read in the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – sections dealing with settings.

1.2.1 Thermal settings

In the thermal settings you have two main possible choices:

- You can define the temperatures of the winding to define the physical properties of the materials needed to run directly the tests without any thermal computation.
- Or you can choose between two other ways to run the test: iterative process until convergence or a single iteration process to perform electromagnetic computation coupled to thermal analysis.



| | |
|----|---|
| 1 | Dialog box to define the thermal settings. Buttons allow to choose one of the three thermal solving modes |
| 2 | The first option of thermal setting is to run the test with only electromagnetic computation without any thermal analysis. This option is the default one available for all the tests. |
| 2a | Dialog box that allows to define the winding temperatures to run the test without any thermal analysis. |
| 2b | Temperatures of the winding (in three locations) to be considered for characterizing the physical properties of the associated materials. |
| 3 | Thermal solving mode with a single iteration between electromagnetic and thermal computations. |
| 4 | Thermal solving mode with iterative process between electromagnetic and thermal computations till the convergence. |
| 5 | Initial temperatures of the machine winding (in three locations). These temperatures are used to initialize the electromagnetic-thermal process of computation. |
| 6 | Definition of coolant temperatures to be considered: <ul style="list-style-type: none"> External fluid temperature ⁽¹⁾ Cooling circuit fluid inlet temperature (when a cooling circuit is defined on the design side ⁽²⁾) |

Notes

(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”.

(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.

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

1.2.2 Power electronics parameters

A dialog box allows defining the power electronics parameters:

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

For more details, please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – sections dealing with “Power electronics mode settings”.

1.2.3 Mechanical loss model parameters

Dialog box to define mechanical loss computation model.

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

1.3 Inputs

1.3.1 Introduction

The total number of user inputs is equal to 8.
Among these inputs, 4 are standard inputs and 4 are advanced inputs.

1.3.2 Standard inputs

1.3.2.1 Modes of computation

There are 2 modes of computation.

The **“Fast”** computation mode is the default one. It corresponds to a hybrid model which is perfectly suited for the pre-design step. Indeed, all the computations in the back end are based on magnetostatic finite element computations (Altair® Flux® software) associated to Park transformation. It evaluates the electromagnetic quantities with the best compromise between accuracy and computation time to explore the space of solutions quickly and easily.

The **“Accurate”** computation mode allows solving the computation with transient magnetic finite element modelling (Flux® software). This mode of computation is perfectly suited to the final design step because it allows getting more accurate results. It also computes additional quantities like the AC losses in winding, rotor iron losses and Joule losses in magnets.

1.3.2.2 Current definition mode

There are 2 common ways to define the electrical current.

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

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

1.3.2.3 Line current, rms

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

1.3.2.4 Current density, rms

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

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

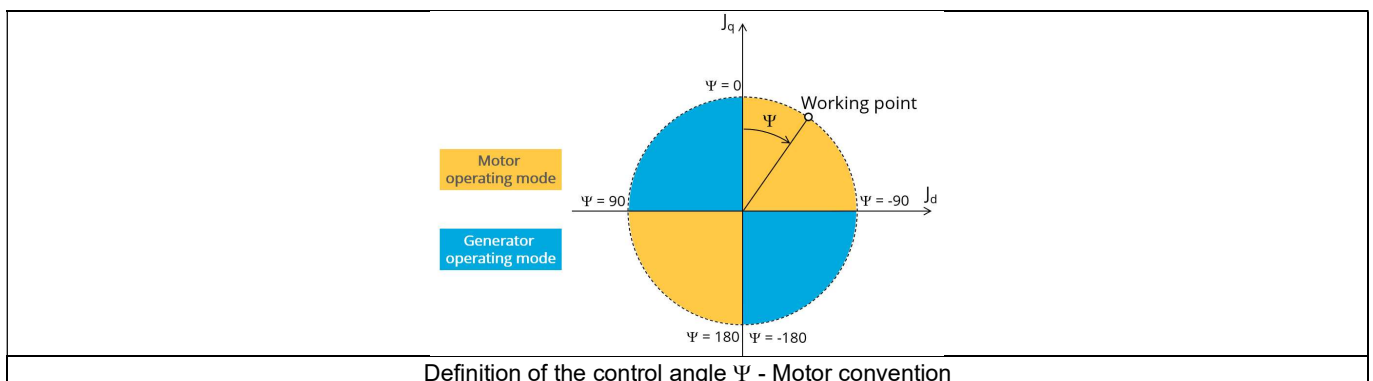
1.3.2.5 Control angle

Considering the vector diagram shown below, the **“Control angle”** is the angle between the Q-axis and the electrical current (J) i.e. ($\Psi = (J_q, J)$).

The default value is 45 degrees. It is an electrical angle. It must be set in a range of -90 to 90 degrees.

This range of values covers all the possible working points in motor and generator operating mode with motor convention. The operating mode is displayed at the head of results.

Note: The sign of results like power depends on both the convention and the operating mode.



1.3.2.6 AC losses analysis

The “**AC losses analysis**” (AC losses analysis required only while “Accurate” computation mode is selected) allows computing or not AC losses in stator winding. There are three available options:

None: AC losses are not computed. However, as the computation mode is “Accurate”, a transient computation is performed without representing the solid conductors (wires) inside the slots. Phases are modeled with coil regions. Thus, the mesh density (number of nodes) is lower which leads to a lower computation time.

FE-One phase: AC losses are computed with only one phase modeled with solid conductors (wires) inside the slots. The other two phases are modeled with coil regions. Thus, AC losses in winding are computed with a lower computation time than if all the phases were modeled with solid conductors. However, this can have a little impact on the accuracy of results because we have supposed that the magnetic field is not impacted by the modeling assumption.

FE-All phase: AC losses are computed, with all phases modeled with solid conductors (wires) inside the slots. This computation method gives the best results in terms of accuracy, but with a higher computation time.

FE-Hybrid: AC losses in winding are computed without representing the wires (strands, solid conductors) inside the slots. Since the location of each wire is accurately defined in the winding environment, sensors evaluate the evolution of the flux density close each wire. Then, a postprocessing based on analytical approaches computes the resulting current density inside the conductors and the corresponding Joule losses.

The wire topology can be “Circular” or “Rectangular”.

There can be one or several wires in parallel (in hand) in a conductor (per turn).

This method leads to quite accurate results with lower computation time. This is a good compromise between accuracy and computation time.

Warning: With the “FE-Hybrid” option the accuracy of results is good especially when the wire size is small (let’s say wire diameter lower than 2.5 mm). However, this can have a little impact on the accuracy of results because we have supposed that the magnetic field is not impacted by the modeling assumption.

Note: With FE-Hybrid option the recommended “Number of computed electrical periods” is equal to “1/2” whereas 2 computed electrical periods are needed for “FE-One phase” and for “FE-All phase” options.

Indeed, when solid conductors are represented in the Finite Element model (like with FE-One phase and FE-All phase options), there are transient phenomena to consider which leads to increase the “Number of computed electrical periods” to reach the steady state.

With the “FE-Hybrid option”, the transient phenomena are handled by the analytical model, so, it is not necessary to increase the “Number of computed electrical periods” compared to a study with “None” options (without AC losses computation).

Note: When the winding is built with a hairpin technology the FE-Hybrid mode is not available because it is not relevant for computations with such kind of winding/conductors.

1.3.2.7 Speed

The imposed “**Speed**” (*Speed*) of the machine must be set.

1.3.2.8 Ripple torque analysis

The “**Ripple torque analysis**” (Additional analysis on ripple torque period: Yes / No) allows to compute or not compute the value of the ripple torque and to display the corresponding torque versus the angular position over the ripple torque period.

The default value is “No”.

Notes:

- This choice influences the accuracy of results and the computation time. The peak-peak ripple torque is calculated. This additional computation needs addition computation time.
- In case of “Yes”, the ripple torque is computed. Then, the flux density in regions is evaluated through the ripple torque computation.
- In case of “No”, the ripple torque is not computed. Then, the flux density in regions is evaluated by considering one dedicated static computation (1 rotor position to be considered) for the computed working point.

1.3.2.9 Additional losses

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

1.3.3 Advanced inputs

1.3.3.1 Number of computed electrical periods

The user input **"No. computed elec. periods"** (Number of computed electrical periods only required with "Accurate" computation mode) influences the accuracy of results especially in case of AC losses computation. Indeed, with represented conductors (AC losses analysis set to "FE - One phase" or "FE - All phase") the computation may lead to have transient current evolution in wires requiring more than an electrical period of simulation to reach the steady state over an electrical period.

The default value is equal to 2. The minimum allowed value is 0.5 (recommended with AC losses analysis set to "None"). The default value provides a good compromise between the accuracy of results and computation time.

1.3.3.2 Number of points per electrical period

The user input **"No. points / electrical period"** (Number of points per electrical period required only with "Accurate" computation mode) influences the accuracy of results (computation of the peak-peak ripple torque, iron losses, AC losses...) and the computation time.

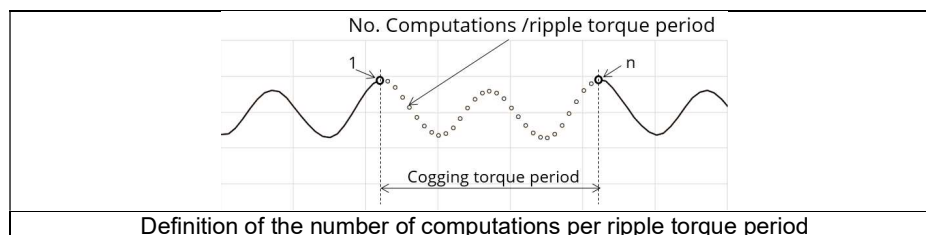
The default value is equal to 40. The minimum recommended value is 20. The default value provides a good balance between accuracy of results and computation time.

1.3.3.3 Number of computations per ripple torque period

The number of computations per ripple torque period is considered when the user has chosen to perform a "Ripple torque analysis" (i.e. answered "Yes" to the standard input "Ripple torque analysis" required only with "Fast" computation mode).

The user input **"No. comp. / ripple period"** (Number of computations per ripple torque period) influences the accuracy of results (computation of the peak-peak ripple torque) and the computation time.

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



1.3.3.4 Skew model – Number of layers

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

1.3.3.5 Mesh order

To get the results, the original computation is performed using a Finite Element Modeling.

Two levels of meshing can be considered for this finite element calculation: first order and second order.

This parameter influences the accuracy of results and the computation time.

By default, second order mesh is used.

1.3.3.6 Airgap mesh coefficient

The advanced user input **"Airgap mesh coefficient"** is a coefficient which adjusts the size of mesh elements inside the airgap. When 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 the points of the geometry), inside the Flux® software, is described as:

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

Airgap mesh coefficient is set to 1.5 by default.

The variation range of values for this parameter is [0.05; 2].

0.05 gives a very high mesh density and 2 gives 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 the formation of a huge number of nodes in the corresponding finite element model. So, it means a need of huge numerical memory and increases the computation time considerably.

1.3.3.7 Convergence criteria on temperature

The advanced user input “**Converg. Criteria on temperature**” (*Convergence criteria on temperature*) is a percentage driving the convergence of the computation.

This advanced user input is available when the iterative thermal solving mode is selected in the thermal settings.

The iterative process (loop between electromagnetic and thermal computations) must run until the convergence criteria has been reached leading to the electromagnetic-thermal steady state. The convergence process is completed when the variation of temperature between two iterations gets lower than the ratio “**Converg. Criteria on temperature**” set in input.

Convergence criteria on temperature is set to 1.0 % by default.

The variation range of values for this percentage is]0;10].

A percentage close to zero gives more accurate results, but a longer computation time. A high percentage can make the convergence shorter but decreases the accuracy of the results. The default value of 1.0% gives a good balance between the accuracy and computation time on most of the computations, but a smaller value can also be used to increase the computation accuracy on some working points.

Note: Two conditions are required to make the “Convergence criteria” available:

- The type of machine is Reluctance Synchronous Machine with Inner rotor (Thermal computations are available only for inner rotor machines)
- One of the two following thermal solving modes is selected: One iteration or iterative computation until convergence mode.

1.3.3.8 Rotor d-axis location

The computations are performed by considering a relative angular position between rotor and stator.

For the reluctance synchronous machines, the rotor d-axis location is defined and automatically used to perform computations. This value is characterized by the saliency topology. This is important to keep in mind this information it.

For more details, please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – section “Rotor and stator relative position”.

1.4 Main principles of computation

1.4.1 Introduction

The aim of this test in motor convention is to give a good overview of the electromagnetic potential of the machine by characterizing the working point according to the line current, control angle and speed set by the user. In addition, ripple torque at the working point is also computed.

Two computation modes are available:

- “Fast computation mode” is perfectly suited for the pre-design step to explore the space of solutions quickly and easily (Hybrid model based on magnetostatic FE computations and Park transformation)
- “Accurate computation mode” is perfectly suited for the final design step because it allows getting more accurate results and to compute additional quantities like the AC losses in winding, rotor iron losses and Joule losses in magnets (Pure FE model based on transient computations)

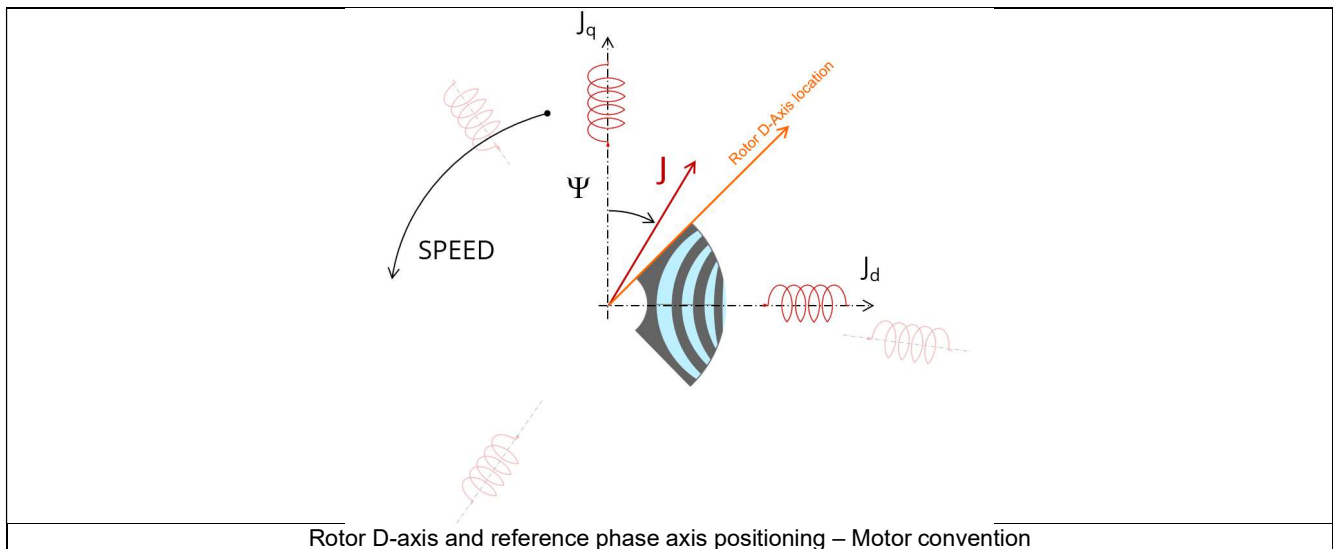
1.4.2 Fast computation mode

1.4.2.1 Working point - Definition

To compute the working point, the principle consists of positioning the rotor d-axis towards the reference phase axis by considering the targeted control angle.

At the same time, the targeted line current and speed are imposed.

Then, the resulting behavior of the machine can be simulated, and all the main electromagnetic characteristics of the machine can be deduced by using Park’s transformation and associated electric equations.



1.4.2.2 Electromagnetic behavior – General information

The method used for computation of electromagnetic behavior computation depends on if ripple torque analysis is set to “Yes” or “No”:

- “Yes” is selected: The analysis of the electromagnetic behavior is done over one ripple torque period (when torque ripple computation is not performed).
- “No” is selected: The analysis of the electromagnetic behavior is done through a dedicated static computation (1 rotor position to be considered) for the computed working point (with line current, control angle and speed obtained for the working point).

1.4.2.3 Flux in airgap

The flux in the airgap is always computed thanks to the dedicated static computation of the working point.

The airgap flux density is computed along a path in the airgap in Flux® software. The resulting signal is obtained for at least an electric period. The average and the peak value of the flux density are also computed. The harmonic analysis of the flux density in airgap versus rotor position is done to compute the magnitude of the first harmonic of the flux density.

1.4.2.4 Flux density in iron

Mean and maximum values of flux density of each iron region are computed with the help of sensors in Flux® software.

1.4.2.5 Ripple torque

A specific computation is performed to precisely determine the rate of ripple torque.

Considering J_d and J_q at the base speed point, a computation is performed over one ripple torque period by using Finite Element modelling (Flux® software – Magnetostatic application).

Many computation points are considered over the ripple torque period (advanced user input: **No. comp. / ripple period**).

The following steps are performed to determinate the mechanical torque.

1) Original computation of the electromagnetic torque

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

The magnetic torque T_{em} is given by the following derivative:

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

$\partial \theta$ = elementary angular displacement,

W_m = magnetic energy in the regional volume

The electromagnetic ripple torque is computed over the ripple torque period with respect to the rotor angular position $T_{em,\theta}$. The mean value " $T_{em,mean}$ " can also be computed.

2) Mechanical ripple torque based on Park's model

The mechanical ripple torque must be computed at the base speed.

First, we compute the electromagnetic torque " $T_{em, Park}$ " with Park's model:

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

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

3) Resulting mechanical torque versus rotor angular position

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

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

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

Warning: When the ripple torque computation is not requested, the computation of the working point is performed by considering only one position within the electrical period. It means that all the data characterizing the behavior of the machine can change based on the selection of ripple torque (Yes/No).

Flux density in magnetic circuit will be more accurately computed when the computation of the ripple torque will be requested.

1.4.3 Accurate computation mode

1.4.3.1 Working point - Definition

Working point computation is based on a transient magnetic finite element simulation over a half, one or several electrical periods for a given set of inputs: control angle, line current and speed defined as for the Fast computation mode.

Thus, all the main electromagnetic characteristics of the machine can be deduced accurately.

1.4.3.2 Electromagnetic behavior – General information

All the main quantities are directly computed from the Flux® software in the framework of a transient magnetic finite element simulation.

1.4.3.3 Iron losses

Iron losses (stator and rotor) are computed, thanks to the “transient modified Bertotti model” in Flux® software.

1.4.3.4 Stator Joule winding losses

The stator’s DC Joule losses are always computed.

However, if AC losses analysis is set to “FE-One phase” or “FE-all phase” stator AC Joule losses are computed in addition to stator’s DC Joule losses.

FE-One phase: AC losses are computed with only one phase modeled for solid conductors (wires) inside the slots. The two other ones are modeled with coil regions. Thus, AC losses in winding are computed with a lower computation time than if all the phases were modeled with solid conductors. However, this can have a little impact on the accuracy of results because we have supposed that the magnetic field is not impacted by the modeling assumption.

FE-All phase: AC losses are computed, with all phases modeled with solid conductors (wires) inside the slots. This computation method gives the best results in terms of accuracy, but with a higher computation time.

FE-Hybrid: AC losses in winding are computed without representing the wires (strands, solid conductors) inside the slots. Since the location of each wire is accurately defined in the winding environment, sensors evaluate the evolution of the flux density close each wire. Then, a postprocessing based on analytical approaches computes the resulting current density inside the conductors and the corresponding Joule losses.

With the “FE-Hybrid” option the accuracy of results is good especially when the wire size is small (let’s say wire diameter lower than 2.5 mm). However, this can have a little impact on the accuracy of results because we have supposed that the magnetic field is not impacted by the modeling assumption.

In FluxMotor®, stator AC Joule losses corresponds to the additional losses induced by fields and skin effects in the conductors (wires) at high speed. The circulating current between parallel path or/and conductor wires are also considered in the modeling. In case of AC losses, the total stator Joule losses ($W_{\text{Stator Joule Tot.}}$) is given by:

$$W_{\text{Stator Joule Tot.}} = W_{\text{Stator DC Joule Tot.}} + W_{\text{Stator AC Joule Tot.}}$$

Each term “AC and DC” are themselves divided in two parts: the “winding active length part” (lamination part) and the “end winding part”.

$$W_{\text{Stator DC Joule Tot.}} = W_{\text{Stator DC Joule W.A.L.}} + W_{\text{Stator DC Joule E.W.}}$$

$$W_{\text{Stator AC Joule Tot.}} = W_{\text{Stator AC Joule W.A.L.}} + W_{\text{Stator AC Joule E.W.}}$$

In the winding active length part (W.A.L), field effect, skin effect and circulating current are considered.

In the end ring part (E.W), field effect and skin effect are neglected, only circulating current are considered. This allows to identify the amount of AC losses induced by circulating current between wires of conductors (Circulating current are induced by the unbalance of impedance of wires of a conductor itself induced by the field variation in conjunction of each wire position in a conductor).

Thanks to AC losses computation, “stator winding resistance ratio” are computed for the “total resistance”, the “Winding Active Length resistance” and the “End Winding resistance”. Ratios are computed by following the below equations:

$$R_{s \text{ AC/DC}} = \frac{W_{\text{Stator DC Joule Tot.}} + W_{\text{Stator AC Joule Tot.}}}{W_{\text{Stator DC Joule Tot.}}}$$

$$R_{s \text{ w.a.l. AC/DC}} = \frac{W_{\text{Stator DC Joule W.A.L.}} + W_{\text{Stator AC Joule W.A.L.}}}{W_{\text{Stator DC Joule W.A.L.}}}$$

$$R_{s \text{ e.w. AC/DC}} = \frac{W_{\text{Stator DC Joule E.W.}} + W_{\text{Stator AC Joule E.W.}}}{W_{\text{Stator DC Joule E.W.}}}$$

1.4.3.5 Flux density in iron

Mean and maximum values of flux density of each iron region are computed with the help of sensors in Flux® software.

1.4.3.6 Torque

The magnetic torque exerted on a non-deformable part of the domain is computed by the virtual work method. The torque in a direction is obtained by deriving the system energy with respect to a virtual displacement of the part in this direction.

The magnetic torque T_{em} is given by the following derivative:

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

$\partial \theta$ = elementary angular displacement,

W_m = magnetic energy in the regional volume

The electromagnetic torque is computed over the electrical period with respect to the rotor angular position $T_{em,\theta}$.

Then, the mean value of the electromagnetic torque is computed “ $T_{em, mean}$ ”. The iron loss torque, the mechanical loss torque and the additional loss torque are subtracted from “ $T_{em, mean}$,” to get the corresponding mean value of the mechanical torque “ $T_{mech, mean}$ ”. To compute the resulting mechanical ripple torque, the mean electromagnetic torque previously computed is weighted by the ratio of the mean value of the mechanical torque ($T_{mech, mean}$) and the mean value of the original electromagnetic torque ($T_{em, mean}$).

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

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

1.4.3.7 Flux in airgap

The airgap flux density is computed with a sensor which is defined in the static part of the airgap under a tooth in Flux® software. The resulting signal is obtained over an electric period. The average and the peak value of the flux density are also computed. The harmonic analysis of the phase voltage is done to evaluate the harmonics content.

1.4.3.8 Phase voltage

The phase voltage is computed with a sensor defined in the electrical circuit in Flux® software. The resulting signal is obtained over an electric period. The harmonic analysis of the phase voltage is done to evaluate the harmonics content.

1.4.3.9 Phase current

The phase current is computed with a sensor defined in the electrical circuit in Flux® software. The resulting signal is obtained over an electric period. The harmonic analysis of the phase voltage is done to evaluate the harmonics content very useful in case of delta winding coupling.

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 along with the thermal characteristics are displayed in this section.

Here is the displayed subsection:

- Thermal
- Electronics
- Mechanics

1.5.1.3 Winding characteristics

The winding characteristics (in three locations) are displayed.

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

1.5.2 Main results

1.5.2.1 Machine performance – Working point

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

Here are the displayed subsections:

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

Output data displayed in the following area list are described in the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – section Working point – Sine wave – Display of results.

1.5.2.2 Power electronics

- Inverter

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

- Working point

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

For more details, please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – sections dealing with “Power electronics mode settings”.

1.5.2.3 Inductances

- Working point
- D-Q model representation

1.5.2.4 Ripple mechanical torque

The analysis of the ripple torque is presented in the table “Ripple mechanical torque” with the following subsections:

- Working point

For more details, please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – sections dealing with “Working point – Sine wave – Display of results”.

1.5.3 Curves - Fast

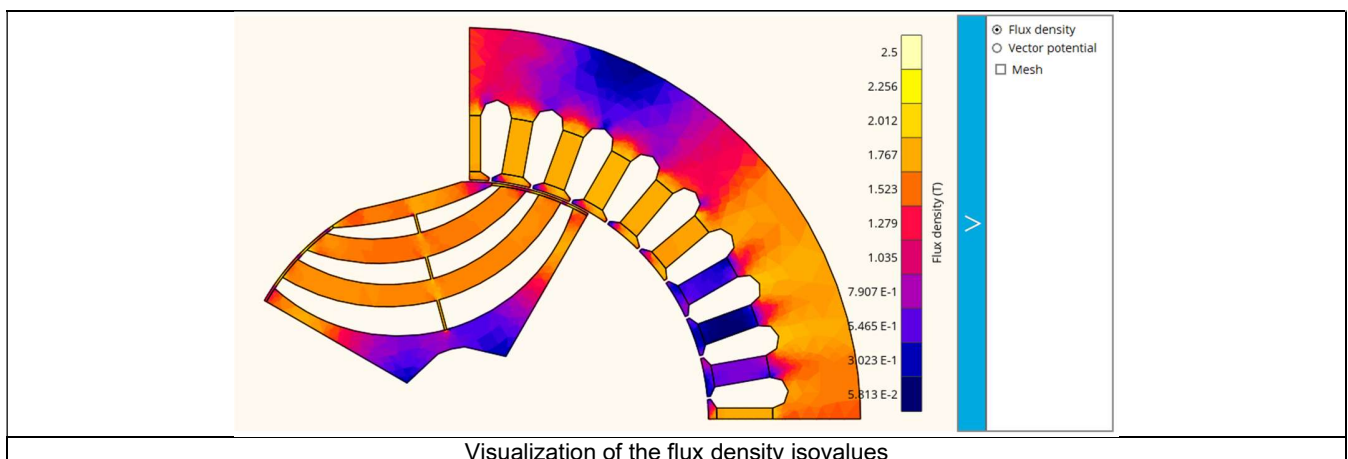
- Ripple mechanical torque versus rotor angular position
- Flux density in airgap versus rotor angular position
- Chart of temperature (radial and axial views)

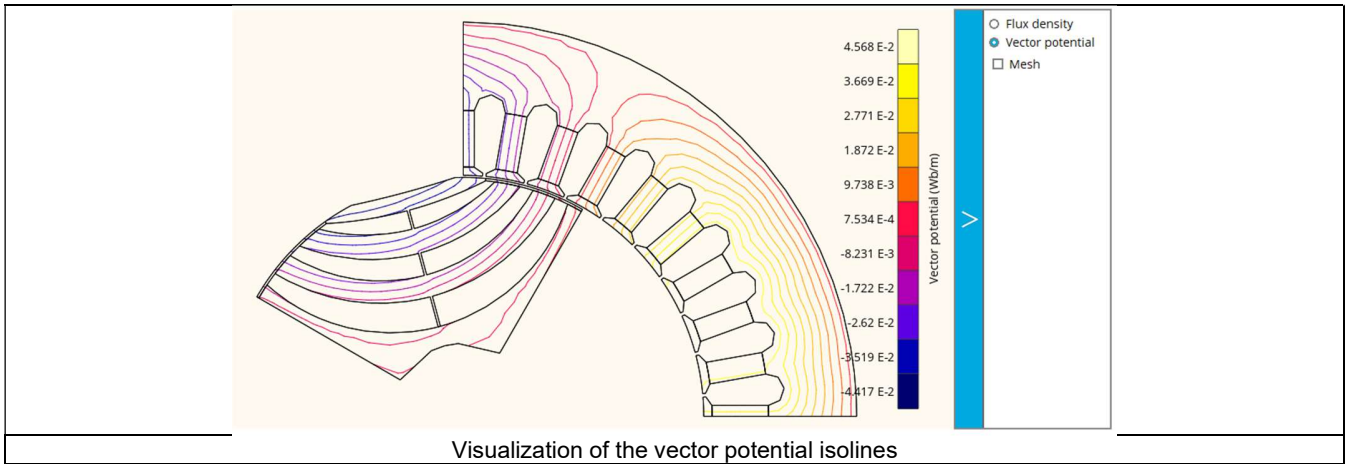
1.5.4 Curves - Accurate

- Mechanical torque versus rotor angular position
- Mechanical torque harmonic analysis
- Flux density in airgap versus rotor angular position
- Flux density in airgap harmonic analysis
- Phase voltage versus rotor angular position
- Phase voltage harmonic analysis
- Phase current versus rotor angular position
- Phase current harmonic analysis

1.5.5 Isovalues and isolines

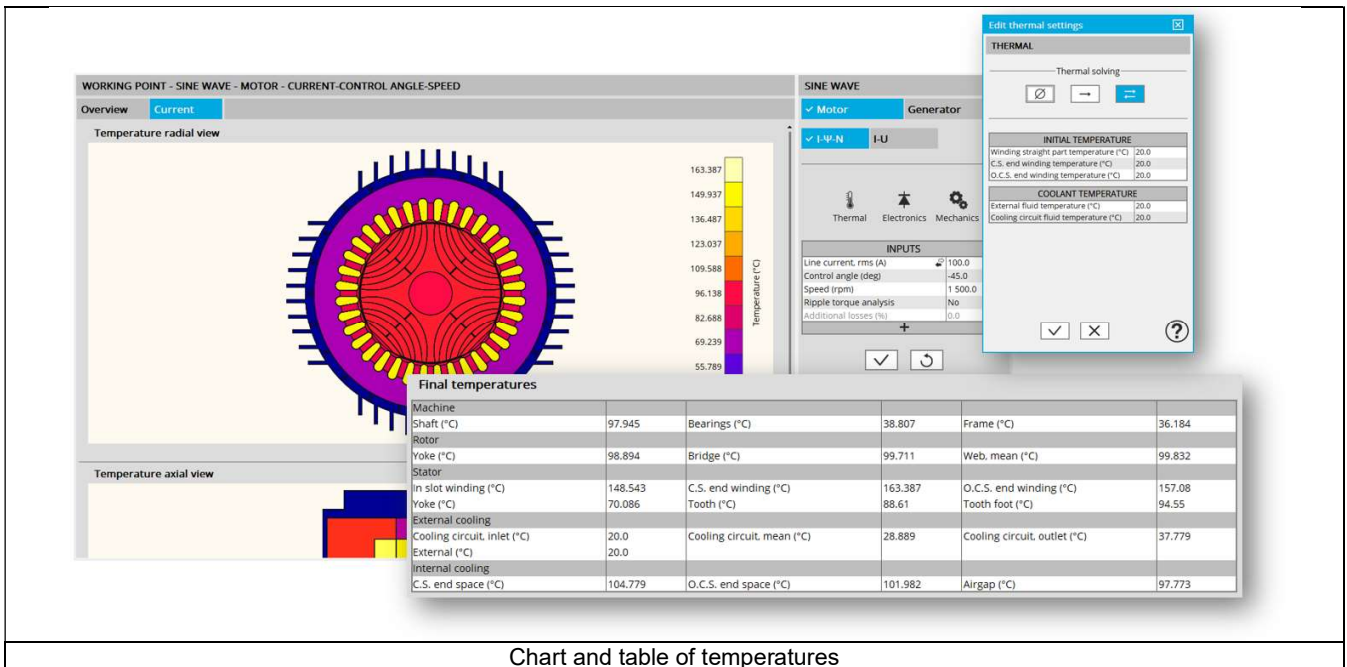
The flux density isovalues and the vector potential isolines can be displayed.





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

1.5.6 Chart and table of temperatures



1.5.7 Limitation of thermal computations - Advices for use

Notes:

- 1) Setting a skew angle modifies the electromagnetic performance of the machine, including the losses. For electromagnetic/thermal iterative solving, the losses are then considered as inputs of the thermal computation. This means that in "One iteration" or "Iterative" solving modes, the temperatures reached in the machine will change depending of the skew angle in input.
- 2) 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.
- 3) For additional information, please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – section "Limitation of thermal computations – Advices for use"

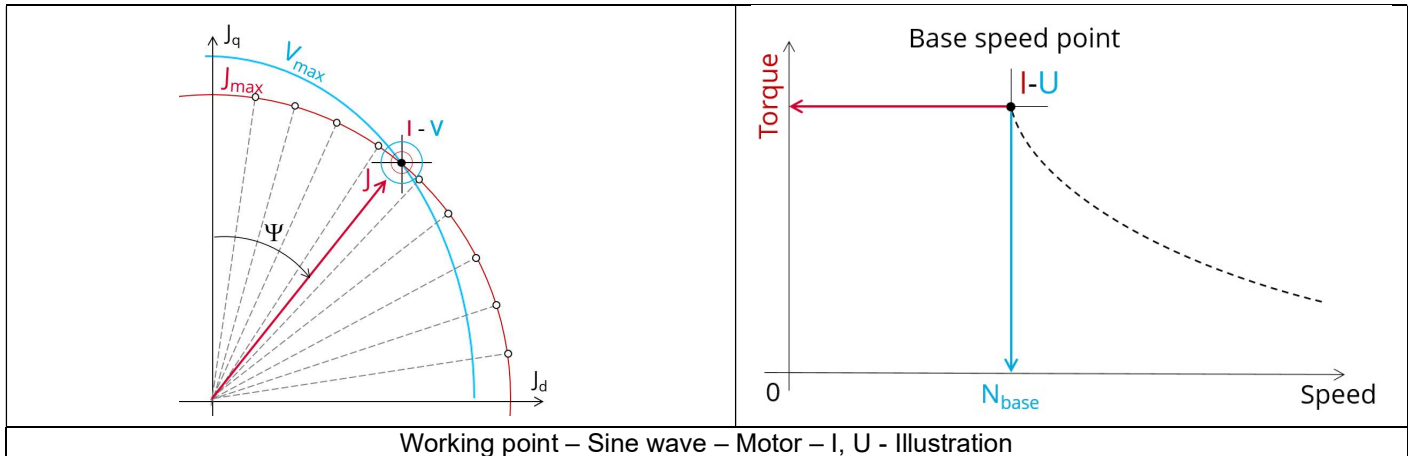
2 WORKING POINT – SINE WAVE – MOTOR – I, U

2.1 Overview,

2.1.1 Positioning and objective

The aim of the test **“Working point – Sine wave – Motor – I, U”** is to characterize the behavior of the machine when operating at the working point which is targeted by the user. It corresponds to the base point at the imposed maximum line current and maximum Line-Line voltage.

The base point of the torque-speed curve is defined by considering the targeted input values I, U (Voltage, current). Then, this test allows deducing the performance for this working point.



The results of this test give an overview of the electromagnetic analysis of the motor considering the machine topology. The general data of the machine, like machine constants and the power balance are computed and displayed. The magnetic flux density is also computed in every region of the machine’s magnetic circuit to evaluate the design. In addition, ripple torque at the base speed point is computed.

The following table helps to classify the test “Working point – Sine wave – Motor – I, U”.

| | |
|------------|---------------|
| Family | Working point |
| Package | Sine wave |
| Convention | Motor |
| Test | I, U |

Positioning of the test “Working point – Sine wave – Motor – I, U”

2.1.2 User inputs

The main user input parameters are the maximum allowed supplied Line-Line voltage and line current. In addition, temperatures of winding must be set.

2.1.3 Main outputs

Test results are illustrated with data, graphs, and tables

2.1.3.1 Tables of results

1) Machine performance – Base speed point

- General data
- Machine constants
- Power balance
- Flux in airgap
- Flux density in iron
- Maximum speed estimation

2) Power electronics

- Inverter
- Working point

3) Inductances

- Working point
- D-Q model representation

4) Ripple mechanical torque

- Working point

2.1.3.2 Curves

- 1) Ripple mechanical torque versus rotor angular position
- 2) Mechanical torque versus current and control angle
- 3) Flux density in airgap versus rotor angular position

2.2 Settings

Three buttons give access to the following setting definition:

- Temperatures of winding (into three locations)
- Definition of the power electronics parameters
 - Inverter control strategy
 - DC bus voltage before inverter stage
 - Inputs for evaluating the power electronics stage losses
- Definition of mechanical loss model parameters

For more details, please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – sections dealing with settings.

2.3 Inputs

2.3.1 Introduction

The total number of user inputs is equal to 8. Among these inputs, 4 are standard inputs and 4 are advanced inputs.

2.3.2 Standard inputs

2.3.2.1 Current definition mode

There are 2 common ways to define the electrical current.

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

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

2.3.2.2 Maximum line current, rms

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

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

2.3.2.3 Maximum current density, rms

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

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

2.3.2.4 Command mode

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

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

2.3.2.5 Ripple torque analysis

The “**Ripple torque analysis**” (Additional analysis on ripple torque period: Yes / No) allows to compute or not to compute the value of the ripple torque and to display the corresponding torque versus the angular position over the corresponding ripple torque period. The default value is “No”.

Notes:

- This choice influences the accuracy of results and on the computation time. The peak-peak ripple torque is calculated. This additional computation needs addition computation time.
- In case of “Yes”, the ripple torque is computed. Then, the flux density in regions is evaluated through the ripple torque computation.
- In case of “No”, the ripple torque is not computed. Then, the flux density in regions is evaluated by considering one dedicated static computation (1 rotor position to be considered) for the computed working point.

2.3.2.6 Additional losses

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

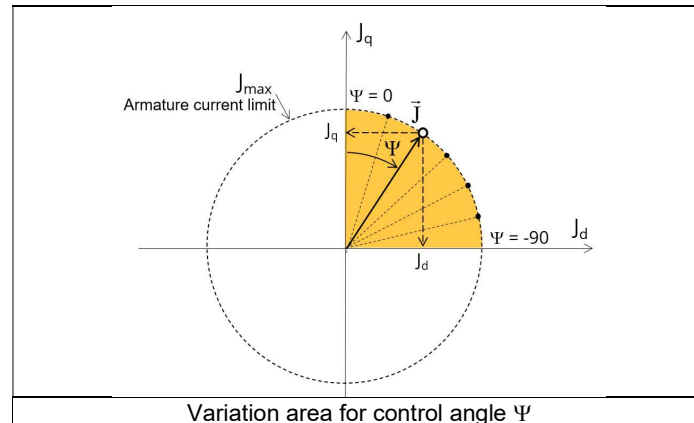
2.3.3 Advanced inputs

2.3.3.1 Number of computations for control angle

Considering the vector diagram shown below, the control angle Ψ is the angle between the Q-axis and the electrical current (J) ($\Psi = (J_q, J)$).

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

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

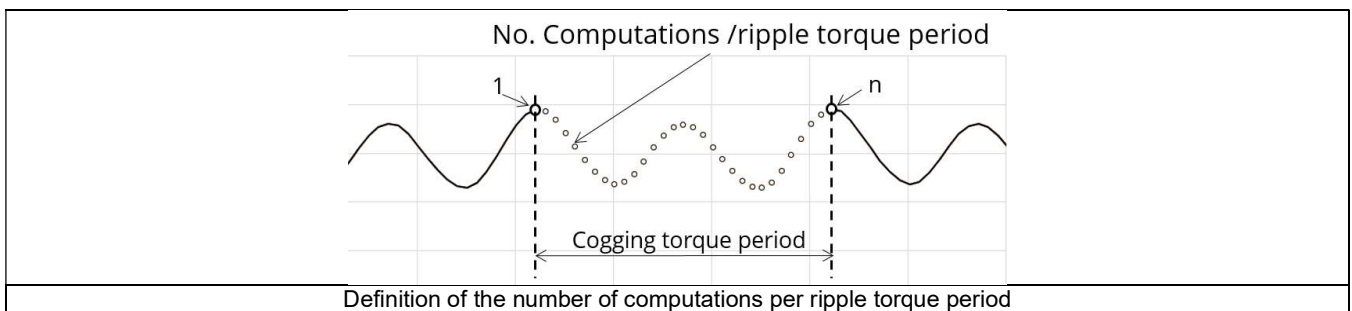


2.3.3.2 Number of computations per ripple torque period

The number of computations per ripple torque period is considered when the user chooses to perform a "Ripple torque analysis" (i.e. answered "Yes" to the standard input "Ripple torque analysis").

The user input **"No. comp. / ripple period"** (*Number of computations per ripple torque period*) influences the accuracy of results (computation of the peak-peak ripple torque) and the computation time.

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



2.3.3.3 Skew model – Number of layers

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

2.3.3.4 Mesh order

To get the results, the original computation is performed using a Finite Element Modeling.

Two levels of meshing can be considered for this finite element calculation: first order and second order.

This parameter influences the accuracy of results and the computation time.

By default, second order mesh is used.

2.3.3.5 Airgap mesh coefficient

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

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

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

Airgap mesh coefficient is set to 1.5 by default.

The variation range of values for this parameter is [0.05; 2].

0.05 gives a very high mesh density and 2 gives 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.

2.3.3.6 Rotor d-axis location

The computations are performed by considering a relative angular position between rotor and stator.

For the reluctance synchronous machines, the rotor d-axis location is defined and automatically used to perform computations. This value is characterized by the saliency topology. This is important to keep in mind this information it.

For more details, please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – section “Rotor and stator relative position”.

2.4 Main principles of computation

2.4.1 Introduction

The aim of this test is to give an overview of the electromagnetic potential of the machine by characterizing the base speed point according to the maximum Line-Line voltage and the maximum line current set by the user. In addition, ripple torque at the base speed point is computed.

For this purpose, several computation processes are involved:

- Base speed point
- Electromagnetic behavior
- Ripple torque
- Maximum speed estimation

2.4.2 Base speed point

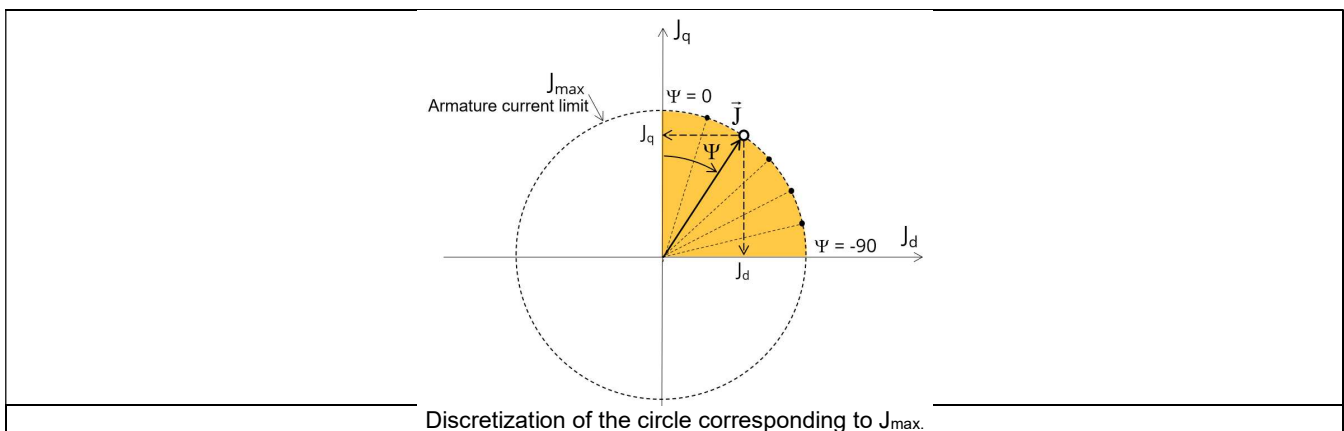
The base speed point of the torque speed curve corresponds to the obtained working point by considering the maximum allowed values of line current and line-line voltage (I_{max} and U_{max}).

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

Several quantities, like the flux in the coils and flux density in regions (teeth and yoke to be able to compute iron losses) are computed as a function of the control angle Ψ .

These computations are done by using Finite Element Modelling (Flux® software – Magnetostatic application).

- $\Phi_d = f(\Psi)$
- $\Phi_q = f(\Psi)$
- $B = f(\Psi)$



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

The resulting data are called “general data” and include:

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

In addition, the power balance is done and machine constant for the base speed point “kT” is computed.

For more details, please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – section dealing with “Electrical machine – Theoretical equations”.

2.4.3 Electromagnetic behavior

2.4.3.1 Introduction

Used method of electromagnetic behavior computation depends on if ripple torque analysis is set to “Yes” or to “No”:

- “Yes” is selected; analysis of the electromagnetic behavior is done over one ripple torque period (when torque ripple computation is not performed).
- “No” is selected; analysis of the electromagnetic behavior is done with a dedicated static computation (1 rotor position to be considered) done for the working point computed (with line current, control angle and speed obtained for the working point).

2.4.3.2 Flux in airgap

The flux in the airgap is always computed thanks to the dedicated static computation of the working point.

The airgap flux density is computed along a path in the airgap in Flux® software. The resulting signal is obtained over at least an electric period. The average and the peak value of the flux density are also computed. A harmonic analysis of the flux density in airgap versus rotor position is done to compute the magnitude of the first harmonic of the flux density.

2.4.3.3 Flux density in iron

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

2.4.4 Ripple torque

A specific computation is performed to determine the rate of ripple torque precisely.

Considering J_d and J_q at the base speed point, a computation is performed over one ripple torque period by using Finite Element modelling (Flux® software – Magnetostatic application).

Many computation points are considered over the ripple torque period (advanced user input: **No. comp. / ripple period**).

The following steps are performed to determinate the mechanical torque.

2.4.4.1 Original computation of the electromagnetic torque

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

The magnetic torque T_{em} is given by the following derivative:

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

$\partial \theta$ = elementary angular displacement,

W_m = magnetic energy in a volume region

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

2.4.4.2 Mechanical ripple torque based on Park’s model

The mechanical ripple torque must be computed at the base speed.

First, we compute the electromagnetic torque “ $T_{em, Park}$ ” with Park’s model:

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

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

2.4.4.3 Resulting mechanical torque versus rotor angular position

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

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

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

Warning: When the ripple torque computation is not requested, the computation of the working point is performed by considering only one position within the electrical period. It means that all the data characterizing the behavior of the machine can change based on the selection of ripple torque (Yes/No).

Flux density in magnetic circuit will be more accurately computed when the computation of the ripple torque will be requested.

2.4.5 Maximum speed estimation

The maximum speed estimation is based on results obtain at the base speed point. Thanks to Park model voltage equations (phase resistance neglected but End winding inductance considered) and flux linkage computed at the base speed point, a linear assumption is done on the flux to estimate the maximum speed. Then, a reduction factor is applied to minimize the linear assumption impact. This computation is performed by considering the command mode (MTPV, MTPA...).

According to assumptions, the aim is just to give the order of magnitude of the maximum speed reachable by the motor.

2.5 Test results

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

2.5.1 Test conditions

2.5.1.1 Inputs

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

Here are the displayed subsections:

- Context
- Standard parameters
- Advanced parameters

For more information refer to the section 2.3 (Inputs).

2.5.1.2 Settings

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

Here is the displayed subsection:

- Thermal
- Electronics
- Mechanics

For more details, please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – sections dealing with settings.

2.5.1.3 Winding characteristics

The winding characteristics (into three locations) are displayed.

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

2.5.2 Main results

2.5.2.1 Machine performance – Working point

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

Here are the displayed subsections:

- General data
- Machine constants
- Power balance
- Flux in airgap
- Flux density in iron
- Maximum speed estimation

2.5.2.2 Power electronics

- Inverter

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

- Working point

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

For more details, please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – sections dealing with “Power electronics mode settings”.

2.5.2.3 Inductances

- Working point
- D-Q model representation

2.5.2.4 Ripple mechanical torque

The analysis of the ripple torque is presented in the table “Ripple mechanical torque” with the following subsections:

For more details, please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – sections dealing with “Working point – Sine wave – Display of results”.

2.5.3 Curves

- Ripple mechanical torque versus rotor angular position
- Mechanical torque versus current and control angle
- Flux density in airgap versus rotor angular position

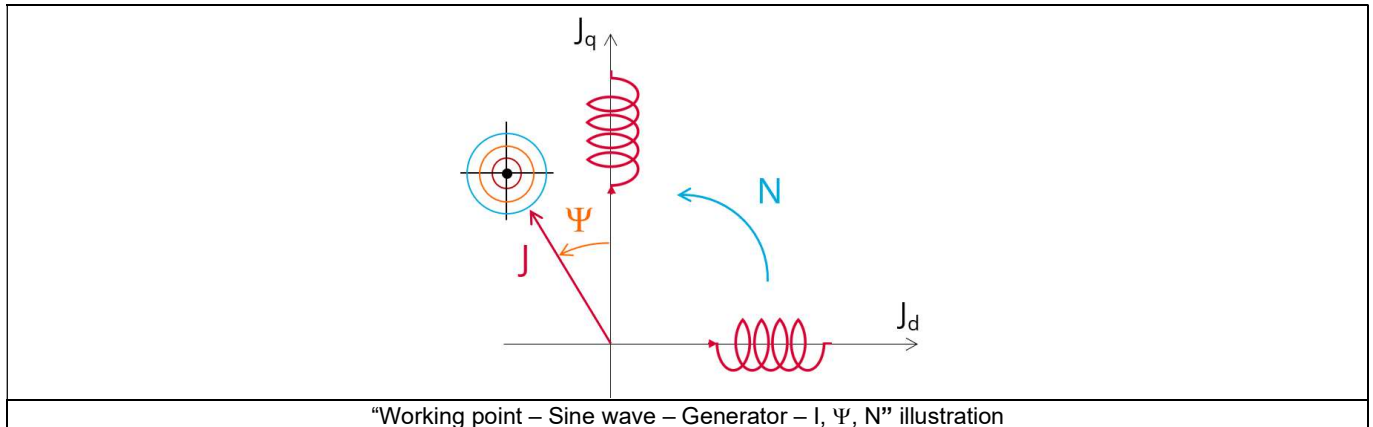
3 WORKING POINT – SINE WAVE – GENERATOR – I, Ψ , N

3.1 Overview

3.1.1 Positioning and objective

The aim of the test “**Working point – Sine wave – Generator – I, Ψ , N**” is to characterize the behavior of the machine when operating at the targeted input values I, Ψ , N (Magnitude of current, Control angle, Speed). These three inputs are enough to impose a precise working point.

For instance, a working point on the efficiency map can be chosen, by identifying the current, the control angle and the speed with different curves or maps displayed in the “Performance mapping / Sine wave / Generator / Efficiency map” test. Then, the “Working point – Sine wave – Generator – I, Ψ , N” test allows to compute the performance for this working point.



The results of this test give an overview of the electromagnetic analysis of the machine considering its topology. The general data of the machine, like machine constants and power balance are computed and displayed. The generator convention is used to build the model.

The magnetic flux density is also computed in every region of the machine magnetic circuit to evaluate the design.

When both the following conditions are met this test allows performing electromagnetic computations with coupled thermal analysis.:

- The type of machine is Reluctance Synchronous Machine with Inner rotor
- One of the two following thermal solving modes is selected: One iteration or iterative solving mode.

Two computation modes are available:

- “Fast computation mode” is perfectly suited for the pre-design step (Hybrid model based on Magneto-Static Finite Element computations and Park transformation theory)
- “Accurate computation mode” is perfectly suited for the final design step (Pure Finite Element modeling based on transient computations)

It also gives the capability to make comparisons between the results obtained from measurements and those evaluated with FluxMotor®.

The following table helps to classify the test “Working point – Sine wave – Generator – I, Ψ , N”.

| | |
|------------|---------------|
| Family | Working point |
| Package | Sine wave |
| Convention | Generator |
| Test | I, Ψ , N |

Positioning of the test “Working point – Sine wave – Generator – I, Ψ , N”

3.1.2 User inputs

The three main user input parameters are the supply line current, control angle and speed. In addition, temperatures of winding must be set.

3.1.3 Main outputs

Test results are illustrated with data, graphs, and tables

3.1.3.1 Tables of results

- 1) Machine performance – Base speed point
 - General data
 - Machine constants
 - Power balance
 - Flux in airgap
 - Flux density in iron
- 2) Power electronics
 - Inverter
 - Working point
- 3) Inductances
 - Working point
 - D-Q model representation
- 4) Ripple mechanical torque
 - Working point
- 5) Thermal data
 - Table of temperatures

3.1.3.2 Curves – in the “Fast computation modes”

- 1) Ripple mechanical torque versus rotor angular position
- 2) Flux density in airgap versus rotor angular position
- 3) Chart of temperature (radial and axial views)

3.1.3.3 Curves – in the “Accurate computation modes”

- 1) Mechanical torque versus rotor angular position
- 2) Mechanical torque harmonic analysis
- 3) Flux density in airgap versus rotor angular position
- 4) Flux density in airgap harmonic analysis
- 5) Phase voltage versus rotor angular position
- 6) Phase voltage harmonic analysis
- 7) Phase current versus rotor angular position
- 8) Phase current harmonic analysis

3.1.3.4 Graphics

- 1) Isovalues

3.1.3.5 Temperatures

- 1) Chart of temperature (radial and axial views)
- 2) Thermal data

- Table of temperatures

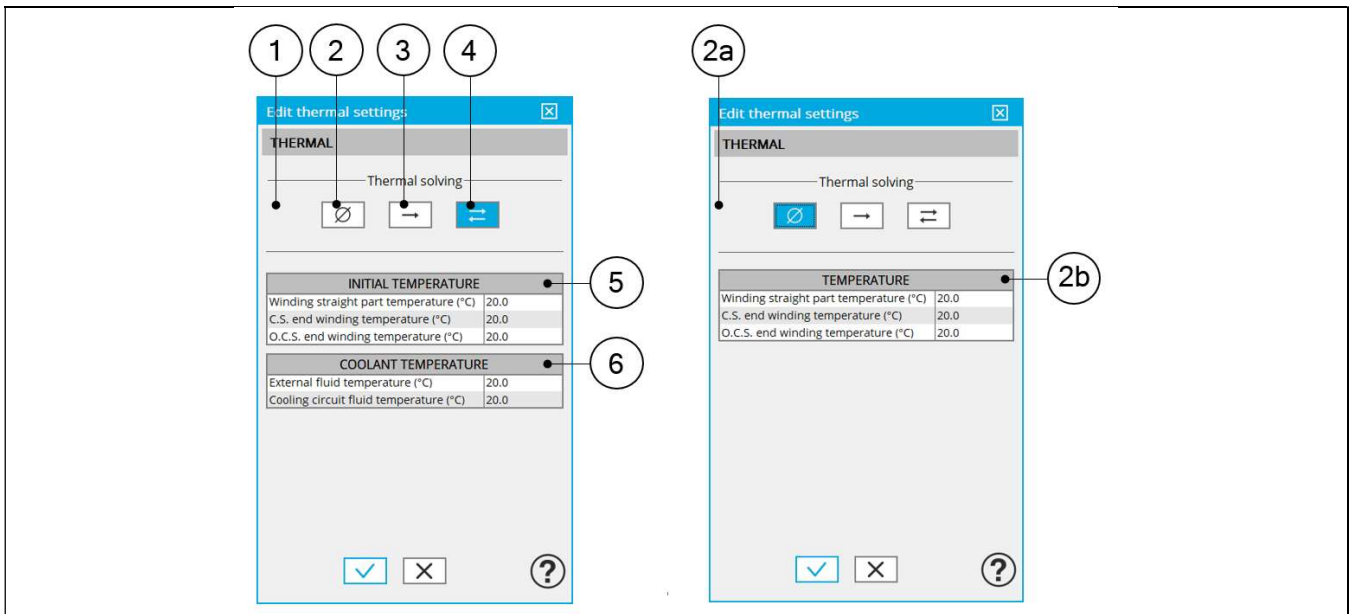
3.2 Settings

Two buttons give access to the following setting definition: Thermal and Mechanics. Each kind of settings is briefly defined here. For more details, please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – sections dealing with settings.

3.2.1 Thermal settings

In the thermal settings you have two main possible choices:

- You can define the temperatures of the winding (into three locations) to define the physical properties of the materials needed to run directly the test without any thermal computation.
- Or you can choose between two other ways to run the test: iterative process until convergence or a single iteration process to perform electromagnetic computation coupled to thermal analysis.



| | |
|----|---|
| 1 | Dialog box to define the thermal settings. Buttons allow to choose one of the three thermal solving modes |
| 2 | The first option of thermal setting is to run the test with only electromagnetic computation without any thermal analysis. This option is the default one available for all the tests. |
| 2a | Dialog box that allows to define the machine winding temperatures to run test without any thermal analysis. |
| 2b | Temperatures of the machine winding to be considered for characterizing the physical properties of the associated materials. |
| 3 | Thermal solving mode with a single iteration between electromagnetic and thermal computations. |
| 4 | Thermal solving mode with iterative process between electromagnetic and thermal computations till the convergence. |
| 5 | Initial temperatures of the machine winding into three locations. These temperatures are used to initialize the electromagnetic-thermal process of computation |
| 6 | Definition of coolant temperatures to be considered: <ul style="list-style-type: none"> • External fluid temperature ⁽¹⁾ • Cooling circuit fluid inlet temperature (when a cooling circuit is defined on the design side ⁽²⁾) |

Notes

(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”.

(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.

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

3.2.2 Mechanical loss model parameters

A dialog box allows defining mechanical loss computation model.

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

3.3 Inputs

3.3.1 Introduction

The total number of user inputs is equal to 13.
Among these inputs, 7 are standard inputs and 6 are advanced inputs.

3.3.2 Standard inputs

3.3.2.1 Computation modes

There are 2 modes of computation.

The “**Fast**” computation mode is the default one. It corresponds to a hybrid model which is perfectly suited for the pre-design step. Indeed, all the computations in the back end are based on magnetostatic finite element computations associated to Park transformation. It evaluates the electromagnetic quantities with the best compromise between accuracy and computation time to explore the space of solutions quickly and easily.

The “**Accurate**” computation mode allows solving the computation with transient magnetic finite element modelling. This mode of computation is perfectly suited to the final design step because it allows getting more accurate results. It also computes additional quantities like the AC losses in winding, rotor iron losses and Joule losses in magnets.

3.3.2.2 Current definition mode

There are 2 common ways to define the electrical current.

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

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

3.3.2.3 Line current, rms

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

3.3.2.4 Current density, rms

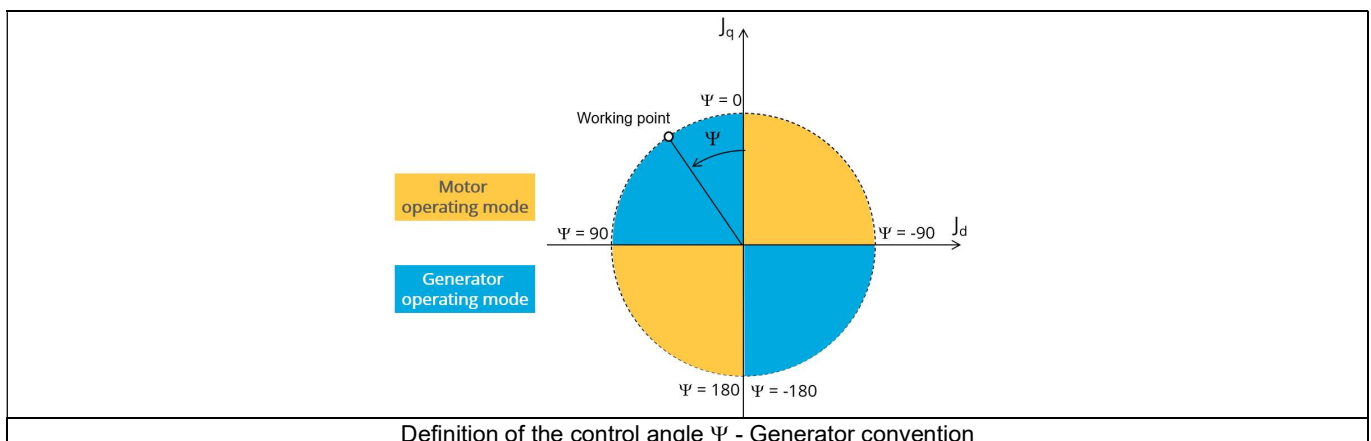
When the choice of current definition mode is “**Density**”, the rms value of the current density in electric conductors “**Current density, rms**” (*Current density in conductors, rms value*) must be provided.

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

3.3.2.5 Control angle

Considering the vector diagram shown below, the “**Control angle**” is the angle between the Q-axis and the electrical current (J) i.e. ($\Psi = (J_q, J)$).

The default value is 45 degrees. It is an electrical angle. It must be set in a range of -90 to 90 degrees.



3.3.2.6 AC losses analysis

The “**AC losses analysis**” (AC losses analysis required only while “Accurate” computation mode is selected) allows computing or not AC losses in stator winding. There are three available options:

None: AC losses are not computed. However, as the computation mode is “Accurate”, a transient computation is performed without representing the solid conductors (wires) inside the slots. Phases are modeled with coil regions. Thus, the mesh density (number of nodes) is lower which leads to a lower computation time.

FE-One phase: AC losses are computed with only one phase modeled with solid conductors (wires) inside the slots. The other two phases are modeled with coil regions. Thus, AC losses in winding are computed with a lower computation time than if all the phases were modeled with solid conductors. However, this can have a little impact on the accuracy of results because we have supposed that the magnetic field is not impacted by the modeling assumption.

FE-All phase: AC losses are computed, with all phases modeled with solid conductors (wires) inside the slots. This computation method gives the best results in terms of accuracy, but with a higher computation time.

FE-Hybrid: AC losses in winding are computed without representing the wires (strands, solid conductors) inside the slots. Since the location of each wire is accurately defined in the winding environment, sensors evaluate the evolution of the flux density close each wire. Then, a postprocessing based on analytical approaches computes the resulting current density inside the conductors and the corresponding Joule losses.

The wire topology can be “Circular” or “Rectangular”.

There can be one or several wires in parallel (in hand) in a conductor (per turn).

This method leads to quite accurate results with lower computation time. This is a good compromise between accuracy and computation time.

Warning: With the “FE-Hybrid” option the accuracy of results is good especially when the wire size is small (let’s say wire diameter lower than 2.5 mm). However, this can have a little impact on the accuracy of results because we have supposed that the magnetic field is not impacted by the modeling assumption.

Note: With FE-Hybrid option the recommended “Number of computed electrical periods” is equal to “1/2” whereas 2 computed electrical periods are needed for “FE-One phase” and for “FE-All phase” options.

Indeed, when solid conductors are represented in the Finite Element model (like with FE-One phase and FE-All phase options), there are transient phenomena to consider which leads to increase the “Number of computed electrical periods” to reach the steady state.

With the “FE-Hybrid option”, the transient phenomena are handled by the analytical model, so, it is not necessary to increase the “Number of computed electrical periods” compared to a study with “None” options (without AC losses computation).

Note: When the winding is built with a hairpin technology the FE-Hybrid mode is not available because it is not relevant for computations with such kind of winding/conductors.

3.3.2.7 Speed

The imposed “**Speed**” (*Speed*) of the machine must be set.

3.3.2.8 Ripple torque analysis

The “**Ripple torque analysis**” (Additional analysis on ripple torque period: Yes / No) allows to compute or not to compute the value of the ripple torque and to display the corresponding torque versus the angular position over the ripple torque period.

The default value is “No”.

Notes:

- This choice influences the accuracy of results and on the computation time. The peak-peak ripple torque is calculated. This additional computation needs addition computation time.
- In case of “Yes”; the ripple torque is computed. Then, the flux density in regions is evaluated through the ripple torque computation.
- In case of “No”; the ripple torque is not computed. Then, the flux density in regions is evaluated by considering one dedicated static computation (1 rotor position to be considered) for the computed working point.

3.3.2.9 Additional losses

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

3.3.3 Advanced inputs

3.3.3.1 Number of computed electrical periods

The user input "**No. computed elec. periods**" (Number of computed electrical periods only required with "Accurate" computation mode) influences the accuracy of results especially in case of AC losses computation. Indeed, with represented conductors (AC losses analysis set to "FE - One phase" or "FE - All phase") the computation may lead to have transient current evolution in wires requiring more than an electrical period of simulation to reach the steady state over an electrical period.

The default value is equal to 2. The minimum allowed value is 0.5 (recommended with AC losses analysis set to "None"). The default value provides a good compromise between the accuracy of results and computation time.

3.3.3.2 Number of points per electrical period

The user input "**No. points / electrical period**" (Number of points per electrical period required only with "Accurate" computation mode) influences the accuracy of results (computation of the peak-peak ripple torque, iron losses, AC losses...) and the computation time.

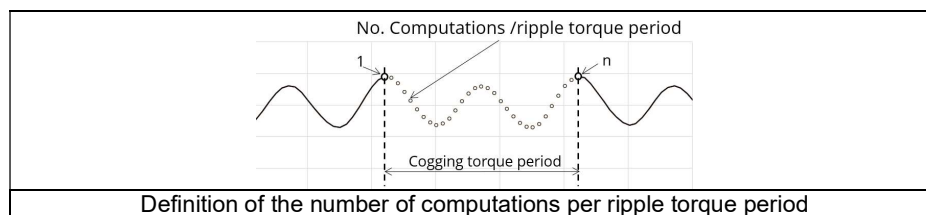
The default value is equal to 40. The minimum recommended value is 20. The default value provides a good balance between accuracy of results and computation time.

3.3.3.3 Number of computations per ripple torque period

The number of computations per ripple torque period is considered when the user has chosen to perform a "Ripple torque analysis" (i.e. answered "Yes" to the standard input "Ripple torque analysis" required only with "Fast" computation mode).

The user input "**No. comp. / ripple period**" (Number of computations per ripple torque period) influences the accuracy of results (computation of the peak-peak ripple torque) and the computation time.

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



3.3.3.4 Rotor initial position mode

The computation is 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).

According to the input "**Rotor initial position mode**", the angular position can be defined either automatically using an internal process of FluxMotor® « **Auto** » (Automatic) or specified by the user « **User** » (User).

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

3.3.3.5 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).

3.3.3.6 Mesh order

To get the results, the original computation is performed using a Finite Element Modeling.

Two levels of meshing can be considered for this finite element calculation: first order and second order.

This parameter influences the accuracy of results and the computation time.

By default, second order mesh is used.

3.3.3.7 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 the points of the geometry), inside the Flux® software, is described as:

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

Airgap mesh coefficient is set to 1.5 by default.

The variation range of values for this parameter is [0.05; 2].

0.05 gives a very high mesh density and 2 gives 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 the formation of a huge number of nodes in the corresponding finite element model. So, it means a need of huge numerical memory and increases the computation time considerably.

3.3.3.8 Convergence criteria on temperature

The advanced user input “**Converg. Criteria on temperature**” (*Convergence criteria on temperature*) is a percentage driving the convergence of the computation.

This advanced user input is available when the iterative thermal solving mode is selected in the thermal settings.

The iterative process (loop between electromagnetic and thermal computations) must run until the convergence criterion has been reached leading to the electromagnetic-thermal steady state. The convergence process is completed when the variation of temperature between two iterations gets lower than the ratio “**Converg. Criteria on temperature**” set in input.

Convergence criterion on temperature is set to 1.0 % by default.

The variation range of values for this percentage is]0;10].

A percentage close to zero gives more accurate results, but a longer computation time. A high percentage can make the convergence shorter but decreases the accuracy of the results. The default value of 1.0% gives a good balance between accuracy and computation time on most of the computations, but a smaller value can also be used to increase the computation accuracy on some working points.

Note: Two conditions are required to make the “Convergence criteria” available:

- The type of machine is Reluctance Synchronous Machine with Inner rotor (Thermal computations are available only for inner rotor machines)
- One of the two following thermal solving modes is selected: One iteration or iterative computation until convergence mode.

3.3.3.9 Rotor d-axis location

The computations are performed by considering a relative angular position between rotor and stator.

For the reluctance synchronous machines, the rotor d-axis location is defined and automatically used to perform computations. This value is characterized by the saliency topology. This is an important information to keep in mind.

For more details, please refer to the document: MotorFactory_SM RMSM_IR_3PH_Test_Introduction – section “Rotor and stator relative position”.

3.4 Main principles of computation

3.4.1 Introduction

The aim of this test in generator convention is to give a good overview of the electromagnetic potential of the machine by characterizing the working point according to the line current, control angle and speed set by the user. In addition, ripple torque at the working point is also computed.

Two computation modes are available:

- “Fast computation mode” is perfectly suited for the pre-design step to explore the space of solutions quickly and easily (Hybrid model based on magnetostatic FE computations and Park transformation)
- “Accurate computation mode” is perfectly suited for the final design step because it allows getting more accurate results and to compute additional quantities like the AC losses in winding, rotor iron losses and Joule losses in magnets (Pure FE model based on transient computations)

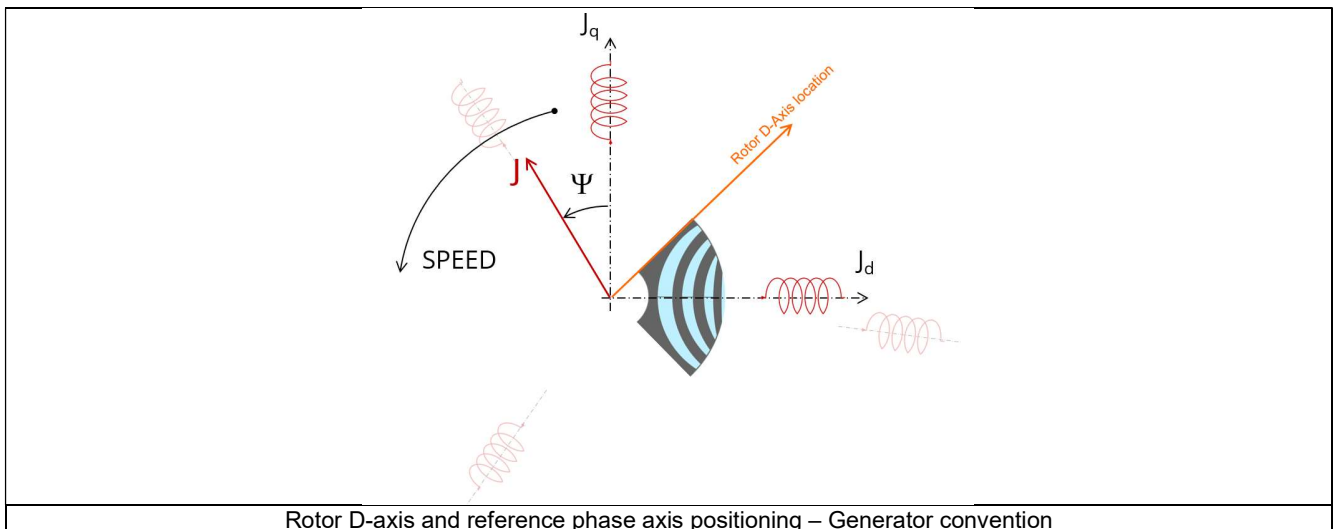
3.4.2 Fast computation mode

3.4.2.1 Working point - Definition

To compute the working point, the principle consists of positioning the rotor D-axis and the reference phase axis by considering the targeted control angle.

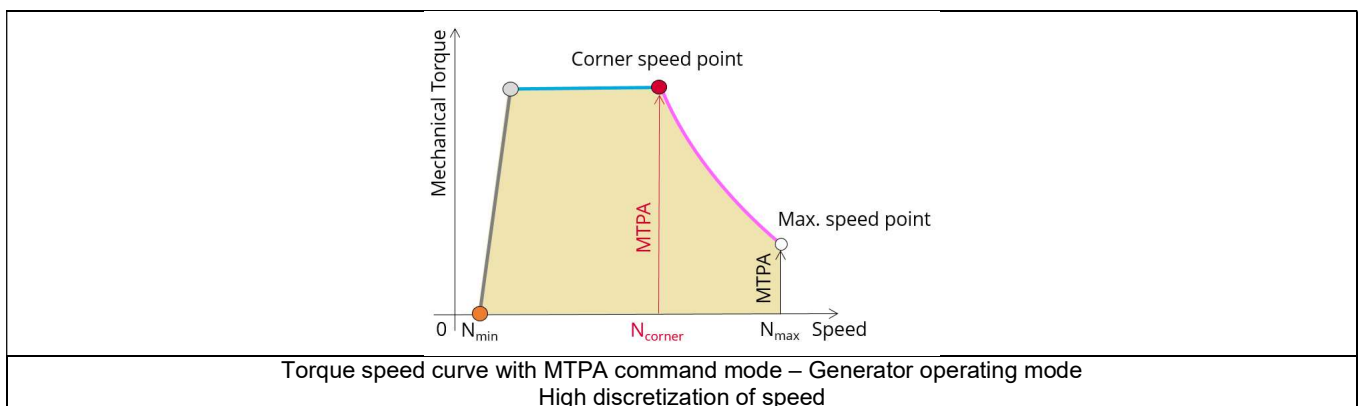
At the same time, the targeted line current and speed are imposed.

Then, the resulting behavior of the machine can be simulated, and all the main electromagnetic characteristics of the machine can be deduced by using Park's transformation and associated electric equations.

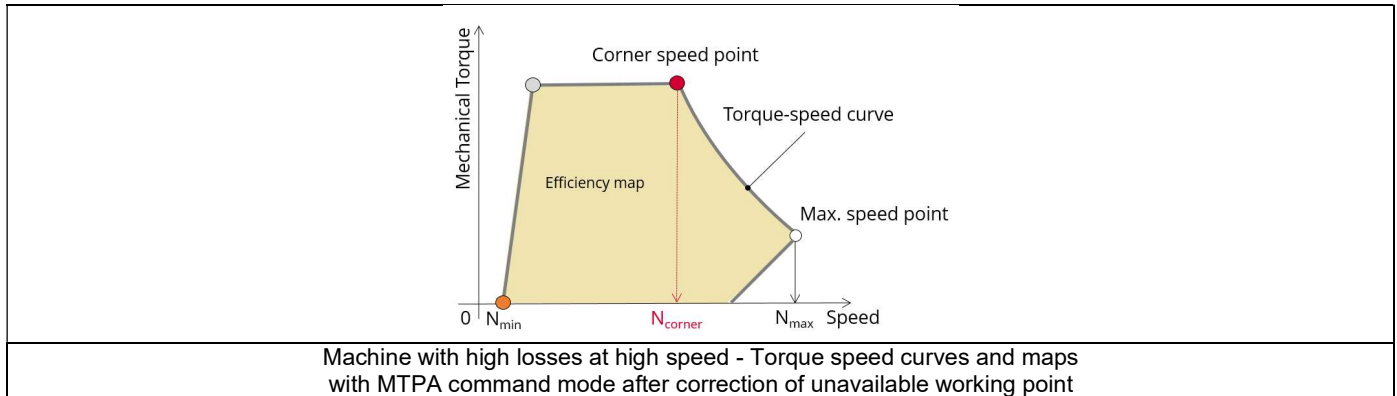


Note: In generator operating mode, mechanical power provided on the shaft must be higher than losses otherwise the electrical power is negative, and no current can be supplied by the generator.

It is why, at low speed, for each value of mechanical torque, a minimum speed always exists to be able to supply electrical current. In FluxMotor®, this limit at no-speed is called “Minimum speed point”.



Note: When the machine has high losses at high speed some working points can be unreachable. Resulting torque-speed curves and maps look like as the following figure:



So, when the targeted working point is in an unreachable zone (left or right white area of the figure above), a warning message is issued by FluxMotor® and the efficiency is set at “-”. All other computed results are available and can be analyzed (power balance) for targeting a reachable working point.

3.4.2.2 Electromagnetic behavior – General information

The method used for computation of electromagnetic behavior depends on if ripple torque analysis is set to “Yes” or to “No”:

- “Yes” is selected: The analysis of the electromagnetic behavior is done over one ripple torque period (when torque ripple computation is not performed).
- “No” is selected: The analysis of the electromagnetic behavior is done with a dedicated static computation (1 rotor position to be considered) done for the working point computed (with line current, control angle and speed obtained for the working point).

3.4.2.3 Flux in airgap

The flux in the airgap is always computed thanks to the dedicated static computation of the working point.

The airgap flux density is computed along an airgap path in Flux® software. The resulting signal is obtained for at least an electric period. The average and the peak value of the flux density are also computed. The harmonic analysis of the flux density in airgap versus rotor position is done to compute the magnitude of the first harmonic of the flux density.

3.4.2.4 Flux density in iron

Mean and maximum values of flux density of each iron region are computed with the help of sensors in Flux® software.

3.4.2.5 Ripple torque

A specific computation is performed to determine the rate of ripple torque precisely.

Considering J_d and J_q at the base speed point, a computation is performed over one ripple torque period by using Finite Element modelling (Flux® software – Magnetostatic application).

Many computation points are considered over the ripple torque period (advanced user input: **No. comp. / ripple period**).

The following steps are performed to determinate the mechanical torque.

1) Original computation of the electromagnetic torque

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

The magnetic torque T_{em} is given by the following derivative:

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

$\partial \theta$ = elementary angular displacement,

W_m = magnetic energy in the regional volume

The electromagnetic ripple torque is computed over the ripple torque period with respect to the rotor angular position $T_{em,\theta}$. The mean value " $T_{em,mean}$ " can also be computed.

2) Mechanical ripple torque based on Park's model

The mechanical ripple torque must be computed at the base speed.

First, we compute the electromagnetic torque " $T_{em, Park}$ " with Park's model:

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

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

3) Resulting mechanical torque versus rotor angular position

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

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

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

Warning: When the ripple torque computation is not requested, the computation of the working point is performed by considering only one position within the electrical period. It means that all the data characterizing the behavior of the machine can change based on the selection of ripple torque (Yes/No).

Flux density in magnetic circuit will be more accurately computed when the computation of the ripple torque will be requested.

3.4.3 Accurate computation mode

3.4.3.1 Working point - Definition

Working point computation is based on a transient magnetic finite element simulation over a half, one or several electrical periods for a given set of inputs: control angle, line current and speed defined as for the Fast computation mode.

Thus, all the main electromagnetic characteristics of the machine can be deduced accurately.

3.4.3.2 Electromagnetic behavior – General information

All the main quantities are directly computed from the Flux® software in the framework of a transient magnetic finite element simulation.

3.4.3.3 Iron losses

Iron losses (stator and rotor) are computed, thanks to the "transient modified Bertotti model" in Flux® software.

3.4.3.4 Stator Joule winding losses

The stator's DC Joule losses are always computed.

However, if AC losses analysis is set to "FE-One phase" or "FE-all phase" stator AC Joule losses are computed in addition to stator's DC Joule losses.

FE-One phase: AC losses are computed with only one phase modeled for solid conductors (wires) inside the slots. The two other ones are modeled with coil regions. Thus, AC losses in winding are computed with a lower computation time than if all the phases were modeled with solid conductors. However, this can have a little impact on the accuracy of results because we have supposed that the magnetic field is not impacted by the modeling assumption.

FE-All phase: AC losses are computed, with all phases modeled with solid conductors (wires) inside the slots. This computation method gives the best results in terms of accuracy, but with a higher computation time.

FE-Hybrid: AC losses in winding are computed without representing the wires (strands, solid conductors) inside the slots.

Since the location of each wire is accurately defined in the winding environment, sensors evaluate the evolution of the flux density close each wire. Then, a postprocessing based on analytical approaches computes the resulting current density inside the conductors and the corresponding Joule losses.

With the “FE-Hybrid” option the accuracy of results is good especially when the wire size is small (let’s say wire diameter lower than 2.5 mm). However, this can have a little impact on the accuracy of results because we have supposed that the magnetic field is not impacted by the modeling assumption.

In FluxMotor®, stator AC Joule losses corresponds to the additional losses induced by fields and skin effects in the conductors (wires) at high speed. Circulating current between parallel path or/and conductor wires are also considered in the modeling. In case of AC losses, the total stator Joule losses ($W_{\text{Stator Joule Tot.}}$) is given by:

$$W_{\text{Stator Joule Tot.}} = W_{\text{Stator DC Joule Tot.}} + W_{\text{Stator AC Joule Tot.}}$$

Each term “AC and DC” are themselves divided in two parts: the “winding active length part” (lamination part) and the “end winding part”.

$$W_{\text{Stator DC Joule Tot.}} = W_{\text{Stator DC Joule W.A.L.}} + W_{\text{Stator DC Joule E.W.}}$$

$$W_{\text{Stator AC Joule Tot.}} = W_{\text{Stator AC Joule W.A.L.}} + W_{\text{Stator AC Joule E.W.}}$$

In the winding active length part (W.A.L), field effect, skin effect and circulating current are considered.

In the end ring part (E.W), field effect and skin effect are neglected, only circulating current are considered. This allows to identify the amount of AC losses induced by circulating current between wires of conductors (Circulating current are induced by the unbalance of impedance of wires of a conductor itself induced by the field variation in conjunction of each wire position in a conductor).

Thanks to AC losses computation, “stator winding resistance ratio” are computed for the “total resistance”, the “Winding Active Length resistance” and the “End Winding resistance”. Ratios are computed following the below equations:

$$R_{s \text{ AC/DC}} = \frac{W_{\text{Stator DC Joule Tot.}} + W_{\text{Stator AC Joule Tot.}}}{W_{\text{Stator DC Joule Tot.}}}$$

$$R_{s \text{ w.a.l. AC/DC}} = \frac{W_{\text{Stator DC Joule W.A.L.}} + W_{\text{Stator AC Joule W.A.L.}}}{W_{\text{Stator DC Joule W.A.L.}}}$$

$$R_{s \text{ e.w. AC/DC}} = \frac{W_{\text{Stator DC Joule E.W.}} + W_{\text{Stator AC Joule E.W.}}}{W_{\text{Stator DC Joule E.W.}}}$$

3.4.3.5 Flux density in iron

Mean and maximum values of flux density of each iron region are computed with the help of sensors in Flux® software.

3.4.3.6 Torque

The magnetic torque exerted on a non-deformable part of the domain is computed by the virtual work method. The torque in a direction is obtained by deriving the system energy with respect to a virtual displacement of the part in this direction.

The magnetic torque T_{em} is given by the following derivative:

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

$\partial \theta$ = elementary angular displacement,

W_m = magnetic energy in the regional volume

The electromagnetic torque is computed over the electrical period with respect to the rotor angular position $T_{em,\theta}$.

Then, the mean value of the electromagnetic torque is computed “ $T_{em, \text{mean}}$ ”. The iron loss torque, the mechanical loss torque and the additional loss torque are subtracted from “ $T_{em, \text{mean}}$ ” to get the corresponding mean value of the mechanical torque “ $T_{mech, \text{mean}}$ ”. To compute the resulting mechanical ripple torque, the mean electromagnetic torque previously computed is weighted by the ratio of the mean value of the mechanical torque ($T_{mech, \text{mean}}$) and the mean value of the original electromagnetic torque ($T_{em, \text{mean}}$).

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

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

3.4.3.7 Flux in airgap

The airgap flux density is computed with a sensor which is defined in the static part of the airgap under a tooth in Flux® software. The resulting signal is obtained over an electric period. The average and the peak value of the flux density are also computed. A harmonic analysis of the phase voltage is done to evaluate harmonics content.

3.4.3.8 Phase voltage

The phase voltage is computed with a sensor defined in the electrical circuit in Flux® software. The resulting signal is obtained over an electric period. The harmonic analysis of the phase voltage is done to evaluate the harmonics content.

3.4.3.9 Phase current

The phase current is computed with a sensor defined in the electrical circuit in Flux® software. The resulting signal is obtained over an electric period. The harmonic analysis of the phase voltage is done to evaluate the harmonics content very useful in case of delta winding coupling.

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

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 3.3 (Inputs).

3.5.1.2 Settings

All the settings dedicated to the test along with the thermal characteristics are displayed in this section.

- Thermal
- Mechanics

3.5.1.3 Winding characteristics

The winding characteristics (into three locations) are displayed.

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

3.5.2 Main results

3.5.2.1 Machine performance – Working point

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

Here are the displayed subsections:

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

Output data displayed in the following area list are described in the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – section Working point - Sine wave - Display of results.

3.5.2.2 Inductances

- Working point
- D-Q model representation

3.5.2.3 Ripple mechanical torque

The analysis of the ripple torque is presented in the table “Ripple mechanical torque” with the following subsections:

- Working point

For more details, please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – sections dealing with “Power electronics mode settings”.

3.5.3 Curves - Fast

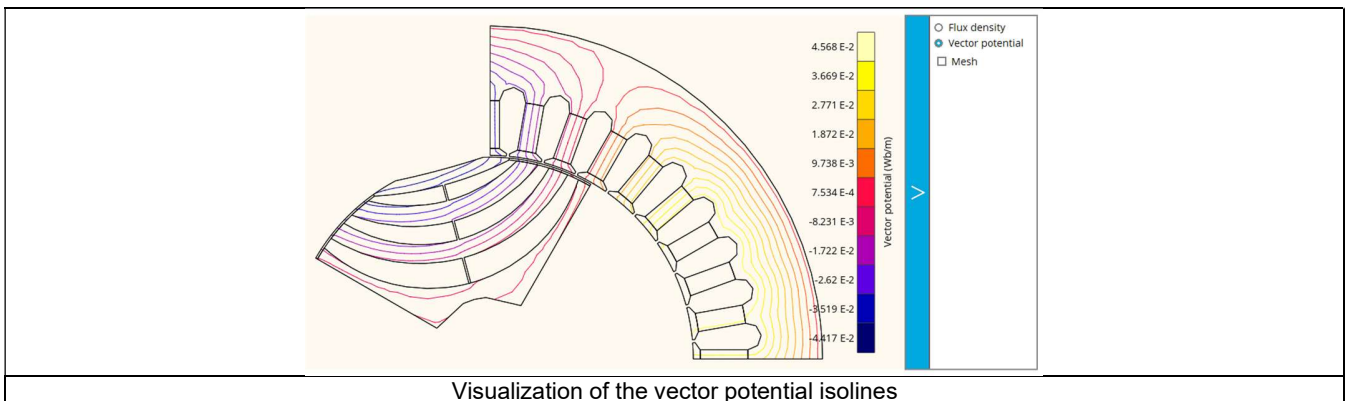
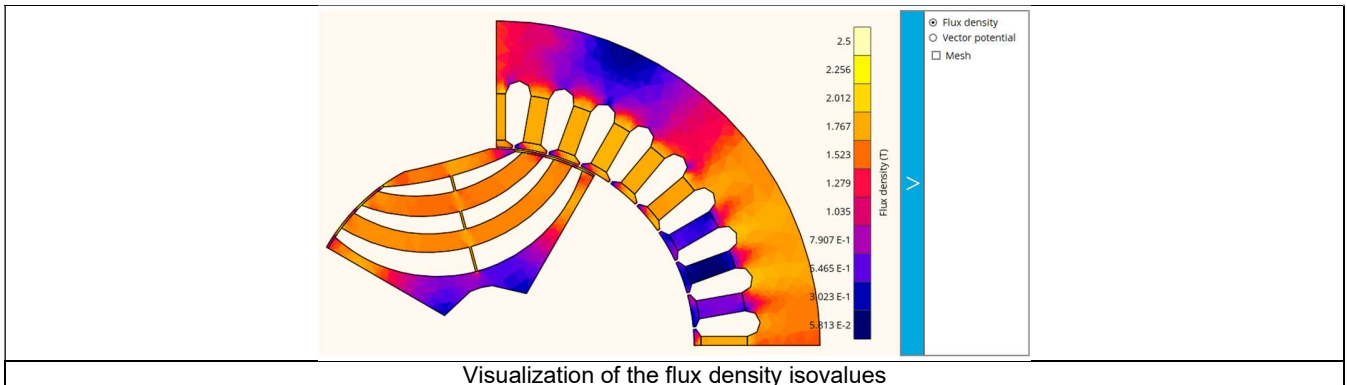
- Ripple mechanical torque versus rotor angular position
- Flux density in airgap versus rotor angular position
- Chart of temperature (radial and axial views)

3.5.4 Curves - Accurate

- Mechanical torque versus rotor angular position
- Mechanical torque harmonic analysis
- Flux density in airgap versus rotor angular position
- Flux density in airgap harmonic analysis
- Phase voltage versus rotor angular position
- Phase voltage harmonic analysis
- Phase current versus rotor angular position
- Phase current harmonic analysis

3.5.5 Isovalues and isolines

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



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

3.5.6 Chart and table of temperatures

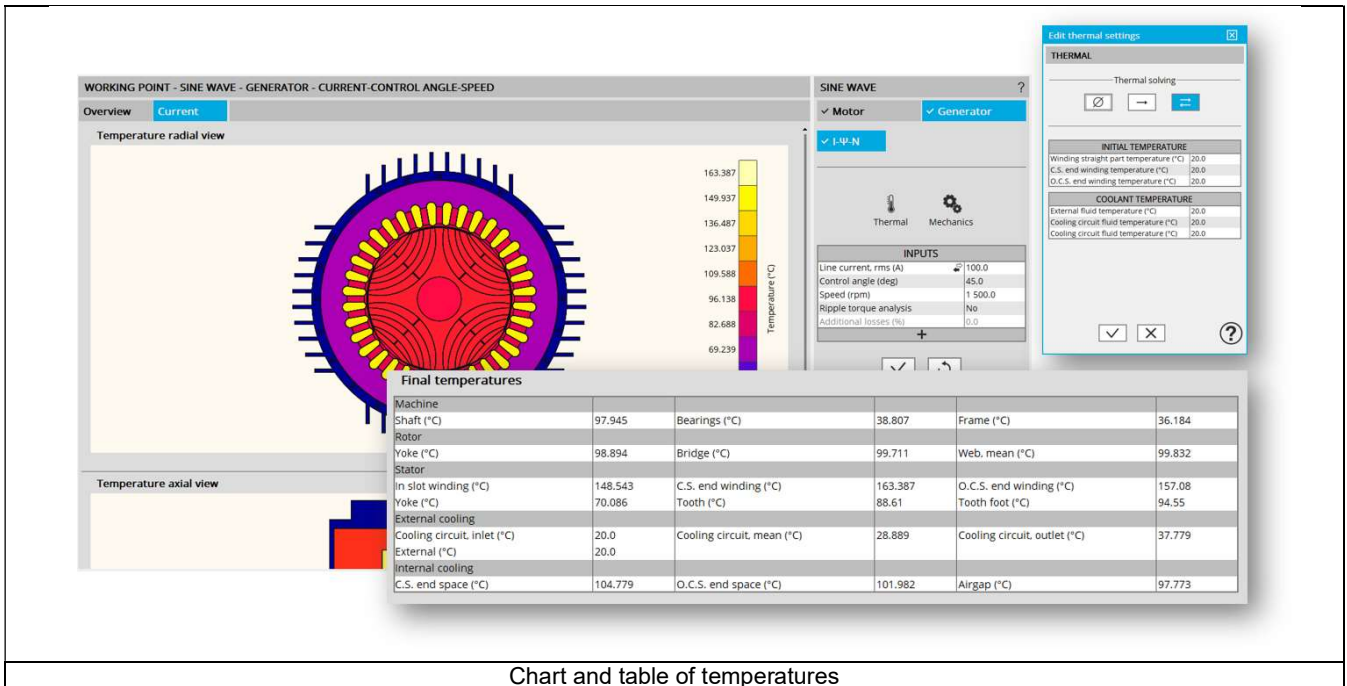


Chart and table of temperatures

3.5.7 Limitation of thermal computations - Advice for use

Notes:

- 1) Setting a skew angle modifies the electromagnetic performance of the machine, including the losses. For electromagnetic/thermal iterative solving, the losses are then considered as inputs of the thermal computation. This means that in "One iteration" or "Iterative" solving modes, the temperatures reached in the machine will change depending of the skew angle in input.
- 2) 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.
- 3) For additional information, please refer to the document: MotorFactory_SMRSM_IR_3PH_Test_Introduction – section "Limitation of thermal computations – Advice for use"