Altair® FluxMotor® 2024.1

Induction machines – Squirrel cage - Inner & Outer rotor

Motor Factory – Test - Working point

General user information

Contents

△ ALTAIR

1   WORKING POINT – SINE WAVE – MOTOR – U, f, N

1.1   Overview

1.1.1   Positioning and objective

The aim of the test "**Working point – Sine wave – Motor – U, f, N"** is to characterize the behavior of the machine when operating at the targeted input values U, f, N (Magnitude of line-line voltage, Power supply frequency, Speed).
These three inputs are enough to impose a precise working point.

For instance, a working point can be chosen on a torque slip curve, by identifying the voltage, the power supply frequency and the speed with different curves displayed in the "Performance mapping / Sine wave / Motor / T-S" test. Then, the "Working point – Sine wave – Motor – U, f, N" test allows to compute the motor performance for this chosen working point.

"Working point – Sine wave – Motor – U, f, N" Illustration
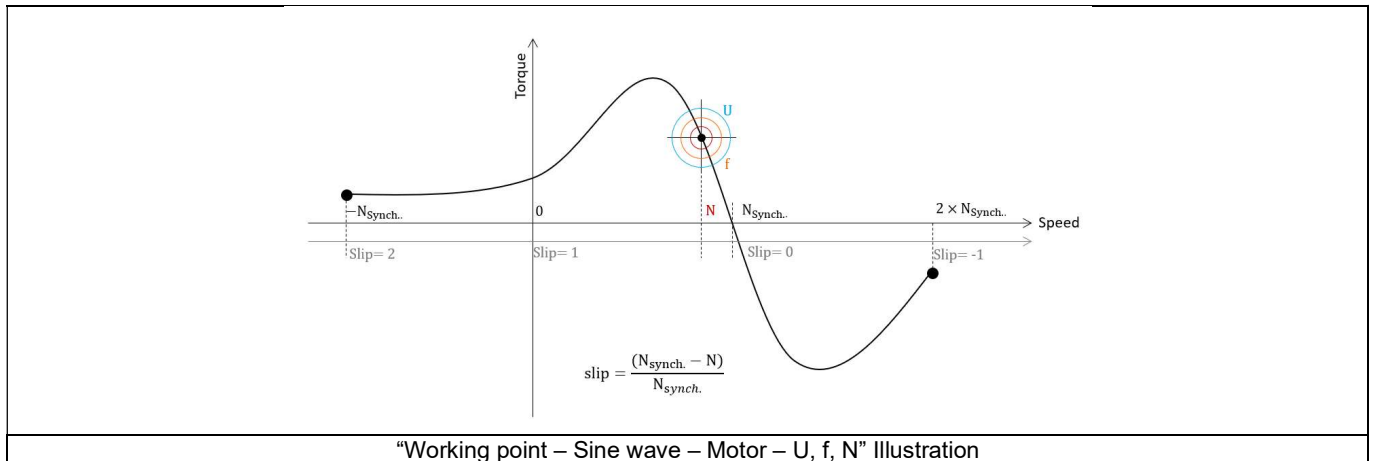
The results of this test give an overview of the electromagnetic analysis of the machine considering its topology.
The general data of the machine, like mechanical torque, current, power factor, efficiency and power balance are computed and displayed. The motor convention is used to build the model.
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 AC finite element computations and symmetrical component transformation)
- "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 the 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 Induction Machines with Squirrel cage with Inner rotor
- One of the two following thermal solving modes is selected: One iteration or iterative solving mode

It also gives the capability to make comparisons between the results got from measurements and those got with the FluxMotor®.
The following table helps to classify the test "Working point – Sine wave – Motor – U, f, N".

Family	Working point
Package	Sine wave
Convention	Motor
Test	U, f, N

Positioning of the test "Working point – Sine wave – Motor – U, f, N"

1.1.2   User inputs

The four main user input parameters are the supply Line-Line voltage, power supply frequency, speed (or the slip) and the computation mode. In addition, temperatures of winding and squirrel cage must be set.

1.1.3   Main outputs

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

1.1.3.1   Main 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) 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

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
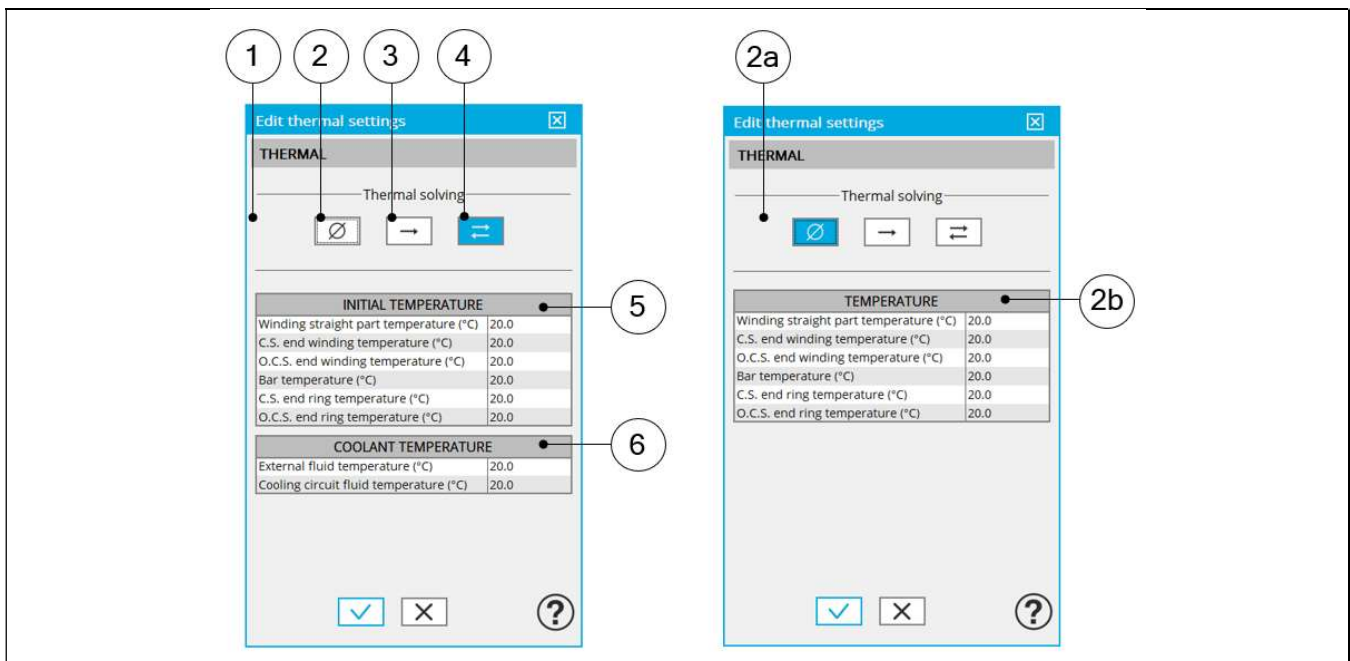
1.2   Settings

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

For more details, please refer to the document: MotorFactory_IMSQ_IOR_3PH_Test_Introduction.

1.2.1   Thermal settings

In the thermal settings you have two main possible choices:

- Either you can define the temperatures of active components (Magnet and winding) to define the physical properties of the materials needed to directly run the tests without any thermal computation.

- Or you can choose between two other ways to run the test: iterative process or one 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 active components winding and magnets temperatures to run test without any thermal analysis.
2b	Temperatures of the machine active components to be considered for characterizing the physical properties of the associated materials.
3	Thermal solving mode with only one iteration between electromagnetic and thermal computations.
4	Thermal solving mode with iterative process between electromagnetic and thermal computations till the convergency.
5	Initial temperatures of the machine active components stator winding and squirrel cage. These temperatures are used to initialize the electromagnetic-thermal process of computation
6	Definition of coolant temperatures to be considered: • External fluid temperature [1] • Cooling circuit inlet fluid 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.

1.2.2   Power electronics parameters

Dialog box to define the power electronics parameters:

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

For more details, please refer to the document: MotorFactory_IMSQ_IOR_3PH_Test_Introduction.

1.2.3   Mechanical loss model parameters

A dialog box allows defining the mechanical loss computation model.

For more details, please refer to the document: MotorFactory_IMSQ_IOR_3PH_Test_Introduction.

1.3   Inputs

1.3.1   Introduction

The total number of user inputs is equal to 9.
Among these inputs, 5 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 AC finite element computations associated to symmetrical component 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.

1.3.2.2   Line-Line voltage, rms

The rms value of the Line-Line voltage supplying the machine: "**Line-Line voltage, rms"** (*Line-Line voltage, rms value*) must be provided.
Note: The number of parallel paths and the winding connections are automatically considered in the results.

1.3.2.3   Power supply frequency

The value of the power supply frequency of the machine: "**Power supply frequency**" (*Power supply frequency*) must be provided.
The power supply frequency is the electrical frequency applied at the terminals of the machine.

1.3.2.4   Definition mode

There are 2 common ways to define the working point. It can be defined by indicating the slip "**Slip**" or by defining the operating speed of the machine "**Speed**".

1.3.2.5   AC losses analysis

The "**AC losses analysis**" (AC losses analysis required only with "Accurate" computation mode) allows to compute or not AC losses in stator winding. There are three options available:

None: AC losses are not computed. However, as the computation mode is "Accurate", a transient computation is performed but without representing the solid conductors (wires) inside the slots. Phases are modeled with coil regions. Thanks to that, the mesh density is lower which results in a lower number of nodes and a lower computation time.

FE-One phase: AC losses are computed but only one phase is modeled with solid conductors (wires) inside the slots. The other two phases are modeled with coil regions. 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, and all phases are 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.

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.

1.3.2.6 Slip

When the choice of definition mode is "**Slip**", the value of machine's slip "**Slip**" (*Slip*) must be provided.
Note: The slip (s) corresponds to the difference between the speed of the rotating magnetic field in the stator (Ns = Synchronous speed) and the rotor operating speed (N).

$$s = \frac{N_S - N}{N_S}$$

Unit can be % or PU.

1.3.2.7 Speed

When the choice of definition mode is "**Speed**", the value of operating speed "**Speed**" (*Speed*) must be provided.

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. Indeed, the computation often leads to have transient current evolution which 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. 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 the computation time.

1.3.3.3 Skew model – No. of layers

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

1.3.3.4 Rotor initial position

The initial position of the rotor considered for computation can be set by the user in the field « **Rotor initial position** » (*Rotor initial position*).
The default value is equal to 0. The range of possible values is [-360, 360].

The rotor initial position has an impact only on the induction curve in the air gap.

1.3.3.5 Mesh order

To get the results, the original computation is performed by using a Finite Element Modeling. The geometry of the machine is automatically meshed.
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 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:

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

Airgap mesh coefficient is set to 1.5 by default.
The variation range of values for this parameter is [0.05; 2].
0.05 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 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 Induction Machines with Squirrel cage with Inner rotor (Thermal computations are available only for inner rotor machine)
- One of the two following thermal solving modes is selected: One iteration or iterative solving mode.

1.4 Main principles of computation

1.4.1 Introduction

The aim of this test is to give a good overview of the electromagnetic potential of the machine (in motor convention) by characterizing the working point according to the line-line voltage, the power supply frequency and the speed (or the slip) set by the user.

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 AC FE computations and symmetrical components)
- "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… (Pure FE model based on transient computations)

1.4.2 Fast computation mode

1.4.2.1 Working point characteristics

The computation process considers the complex values of current and voltage. Moreover, these quantities are computed by considering the symmetrical component transformation.
Then, the power balance which includes stator and rotor iron losses are computed.

Computation process with symmetrical component transformation
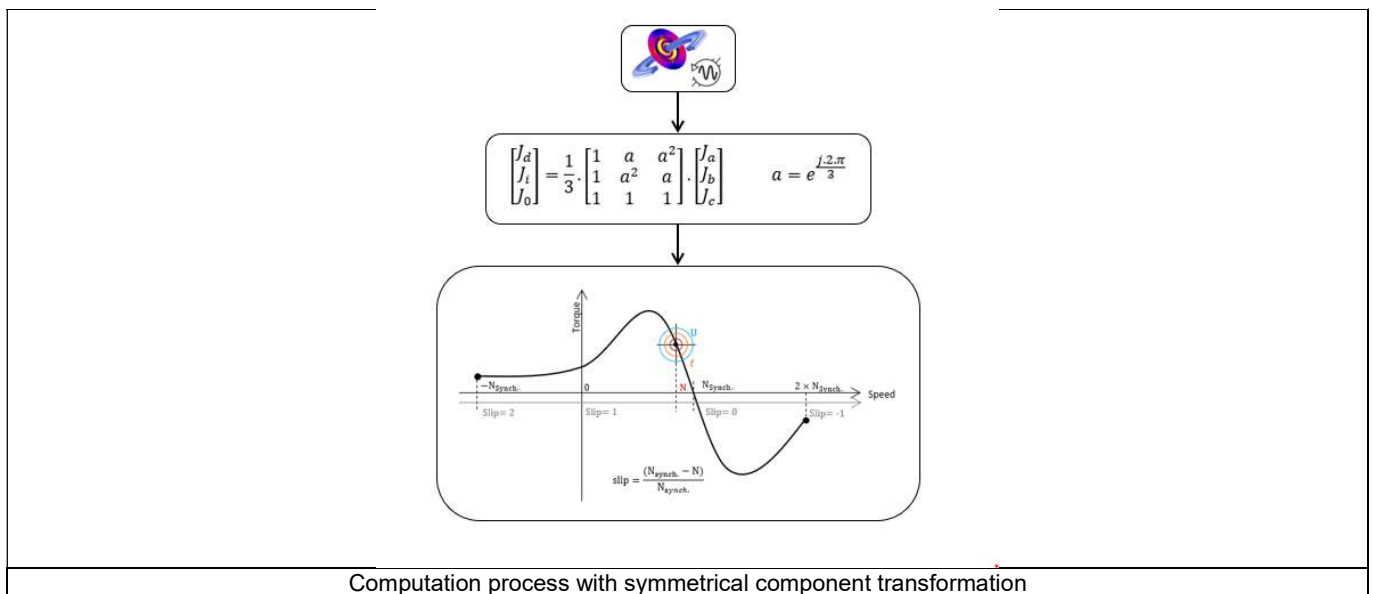
The use of the symmetrical component transformation is a key point.
Indeed, when using finite element modelling with Steady State AC application, each phase of the machine sees different airgap reluctance (due to the fixed rotor position) which generates indirect currents in the stator phases.
It is not a physical phenomenon because, over an electrical period, each phase sees the same air gap reluctance variation.
So, a correction must be done by using symmetrical component transformation which allows to get the only direct component of current and voltage.
Then, the power balance and all electromagnetic quantities can be calculated accurately.

1.4.2.2 Flux in airgap

The flux in the airgap is always computed by the dedicated magneto-harmonic computation at the working point.

The airgap flux density is computed along a path in the airgap in Flux® software. The resulting signal is obtained for 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.

1.4.2.3 Flux density in iron

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

1.4.3   Accurate computation mode

1.4.3.1   Warning about power balance

The computation of power balance for IMSQ in "accurate mode" is not well balanced.
In the test "working point – sine wave – motor – U, f, N", while computing the power balance with the accurate mode (i.e., with the transient application) the results are not well balanced. Indeed, the difference between the electrical power and the power on the shaft is not exactly equal to the total amount of losses.
Depending on the considered slip the difference can be about a few percent (ref.: FXM-16121).
Note: The number of computation points per electrical period and the number of considered electrical periods (user's inputs) have an impact on the accuracy of the results.
Note: The displayed value (in FluxMotor) of the mechanical torque is based on the Finite Element computations and considers the iron losses and the mechanical losses.
Note: The rotor Joule losses (squirrel cage) result from the Finite Element computations.

1.4.3.2   Working point characteristics

Working point computation is based on a transient magnetic finite element simulation over one or more electrical periods for a given voltage, power supply frequency and speed or slip.
All the main electromagnetic characteristics of the machine can be deduced accurately.

1.4.3.3   Iron losses

Iron losses (stator and rotor) are computed, thanks to the "transient modified Bertotti model" in Altair Flux^{TM} software.

1.4.3.4   Stator Joule winding losses

Stator 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 with solid conductors (wires) inside of 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.
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 following the below equations:

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

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

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

1.4.3.5 Rotor Joule winding losses

Rotor Joule losses are computed with the help of sensors defined for each corresponding region in Flux® software.

1.4.3.6 Flux density in iron

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

1.4.3.7 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 with respect to the electrical period versus 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.

1.4.3.8 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.

1.4.3.9 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.

1.4.3.10 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 test along with the thermal characteristics are displayed in this section.
Here is the displayed subsection:

- Thermal
- Electronics
- Mechanics

1.5.1.3   Winding and squirrel cage characteristics

All winding and squirrel cage characteristics are displayed in the following subsections:

- Winding characteristics
- Squirrel cage characteristics

1.5.2   Main results

1.5.2.1   Machine performance – Working point

Here are the displayed subsections:

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

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_IMSQ_IOR_3PH_Test_Introduction.

1.5.3   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

1.5.4   Isovalues and isolines

The flux density isovalues, the vector potential isolines and the rotor bars current density isovalues can be displayed.

Visualization of the flux density isovalues

Visualization of the vector potential isolines

Visualization of the rotor bars current density isovalues
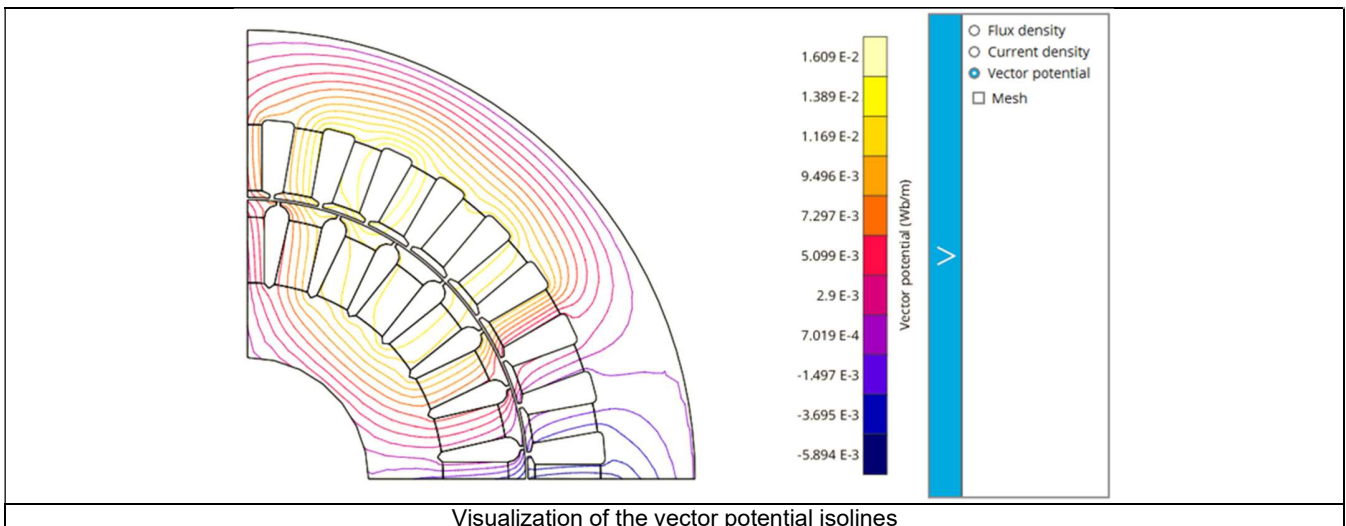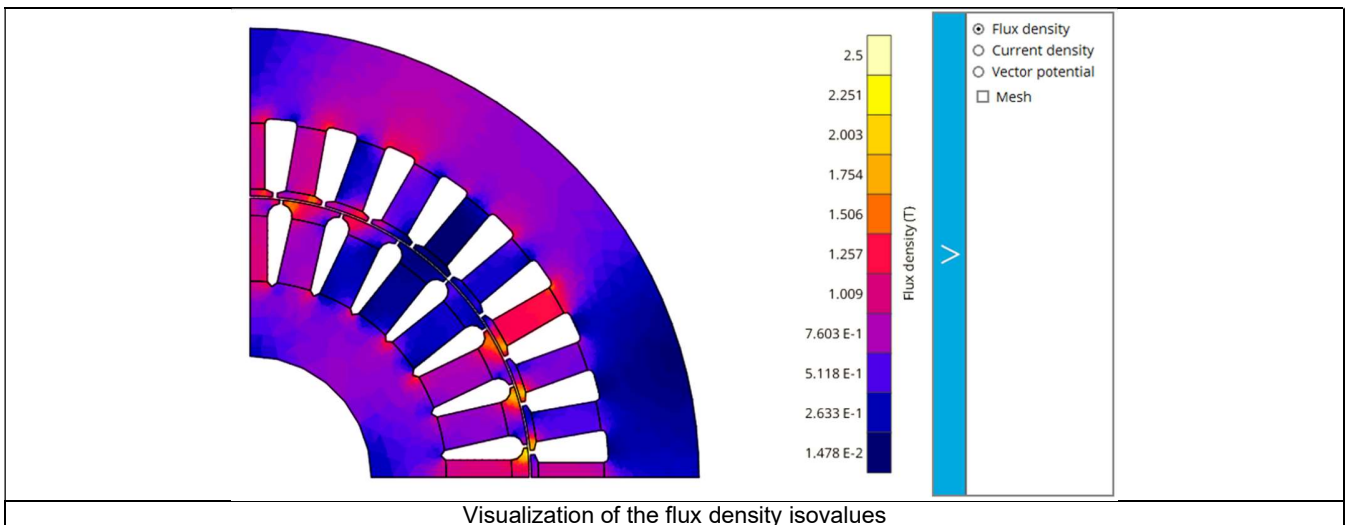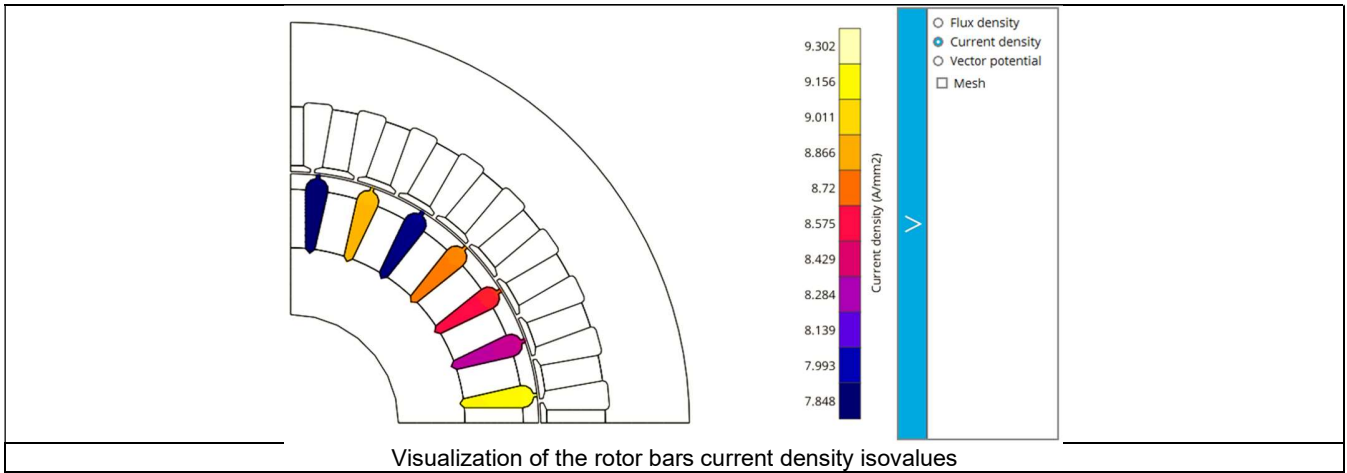
Note: The visualization of the meshing of the model can also be displayed.

1.5.5 Chart and table of temperatures

Chart and table of temperatures
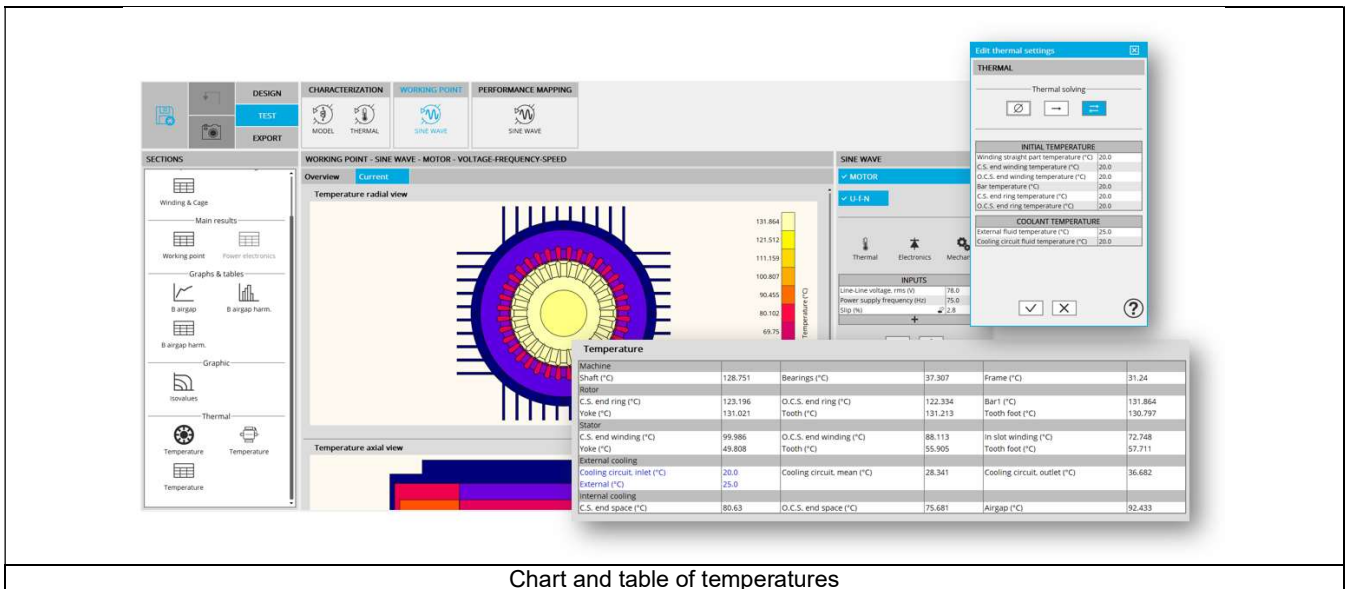
1.5.6 Limitation of thermal computations - Advice for use

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 on 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 more details, please refer to the document: MotorFactory_IMSQ_IOR_3PH_Test_Introduction.