Altair® FluxMotor® 2026

Induction machines – Squirrel cage - Inner & Outer rotor

Motor Factory – Test - Working point

General user information

Contents

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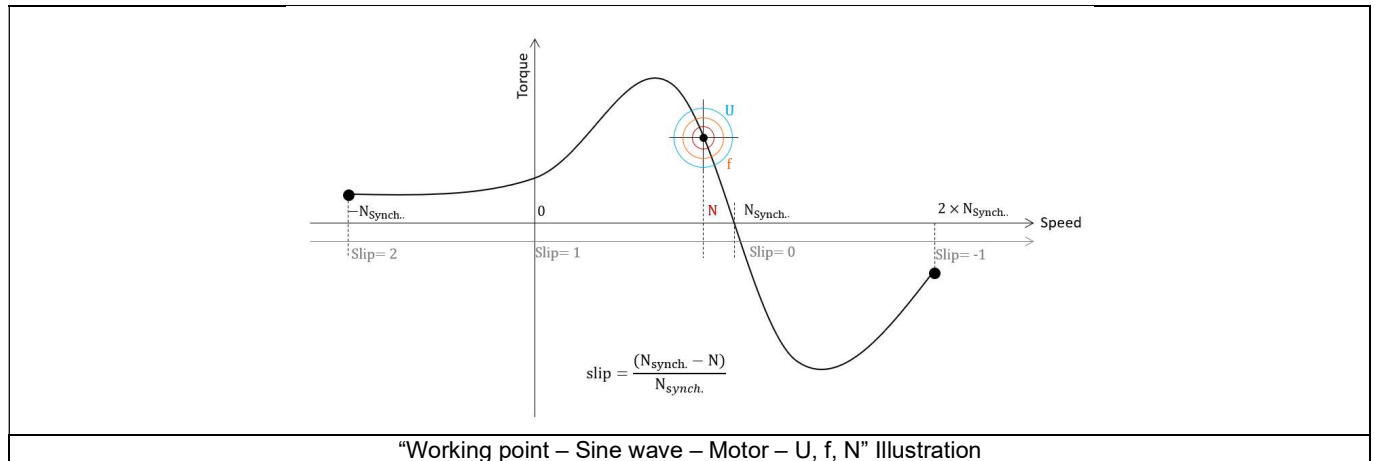
The results of this test give an overview of the electromagnetic analysis of the machine considering its topology.
The general data of the machine, like mechanical torque, current, power factor, efficiency and power balance are computed and displayed. The motor convention is used to build the model.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

1.2   Main principles of computation

1.2.1   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). Indeed, in most cases, "Fast computation mode" provides the same accuracy as the "Accurate computation mode" with a low number of computations per electrical period.
- "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). To significantly increase the accuracy, it is needed to adjust the number of computations per electrical period to catch the rotor current harmonics.

1.2.2   Power balance and iron losses

Whatever the computation mode, "fast or accurate", the iron losses are post-computed, so they must be added to the power balance referring to the following formula:

$$P_{elec} = W_{Joule\ stator} + W_{Joule\ rotor} + W_{iron\ stator} + W_{iron\ rotor} + P_{em}$$

According to the electrical equivalent scheme of a squirrel cage induction machine, the iron losses resistance is considered in parallel to the magnetizing inductance. The magnetizing impedance is in general lower than the iron losses resistance, so the equivalent impedance value is in general close to the magnetizing impedance one as shown in the following example:
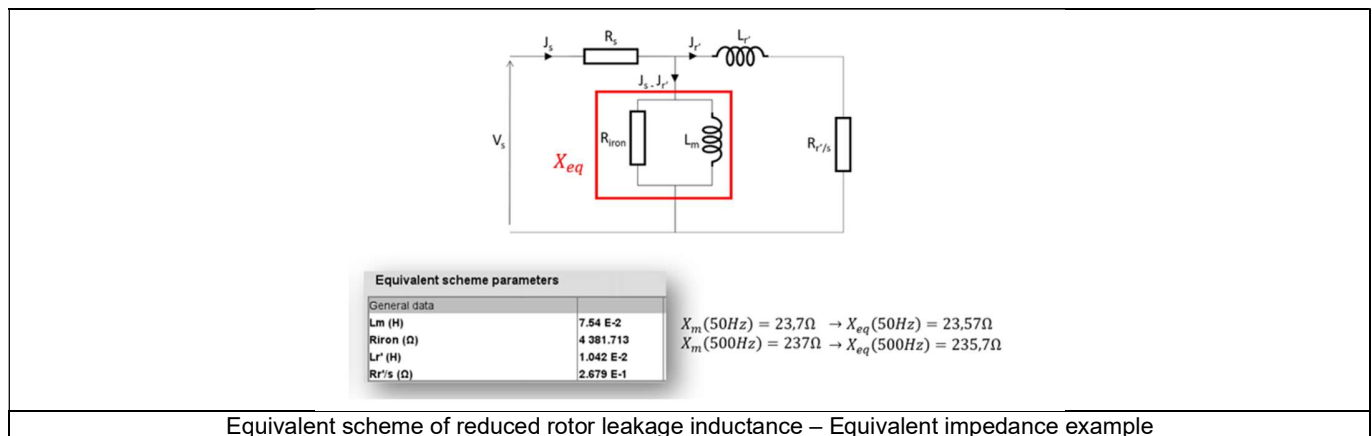
Equivalent scheme of reduced rotor leakage inductance – Equivalent impedance example

V_s: Stator phase voltage at the frequency "f_s"
J_s: Stator phase current at the frequency "f_s"
R_s: Stator phase resistance
L_m: Magnetizing inductance
R_{iron}: Iron losses resistance (stator and rotor)
J'_r: Rotor equivalent phase current bring back to the stator and reduced at the stator frequency "f_s"
L'_r : Leakage inductance total in rotor
R'_r: Rotor equivalent phase resistance brings back to the stator

Following this observation, we can assume that torque is only slightly impacted by the addition of iron losses resistance. This point can also be correlated with the fact that the squirrel cage induction machine has the stator as field, which implies a significant amount of stator current is required to magnetize the machine, which does not directly generate torque. As a result, the consumed current by iron losses is much less significant in terms of torque reduction than for a machine with a rotor as field, such as a synchronous permanent magnet machine.

For this machine, by introducing iron losses into the power balance, we prefer to impact the electrical power (absorbed power) and above all on the power factor.

1.2.3   Fast computation mode

1.2.3.1   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
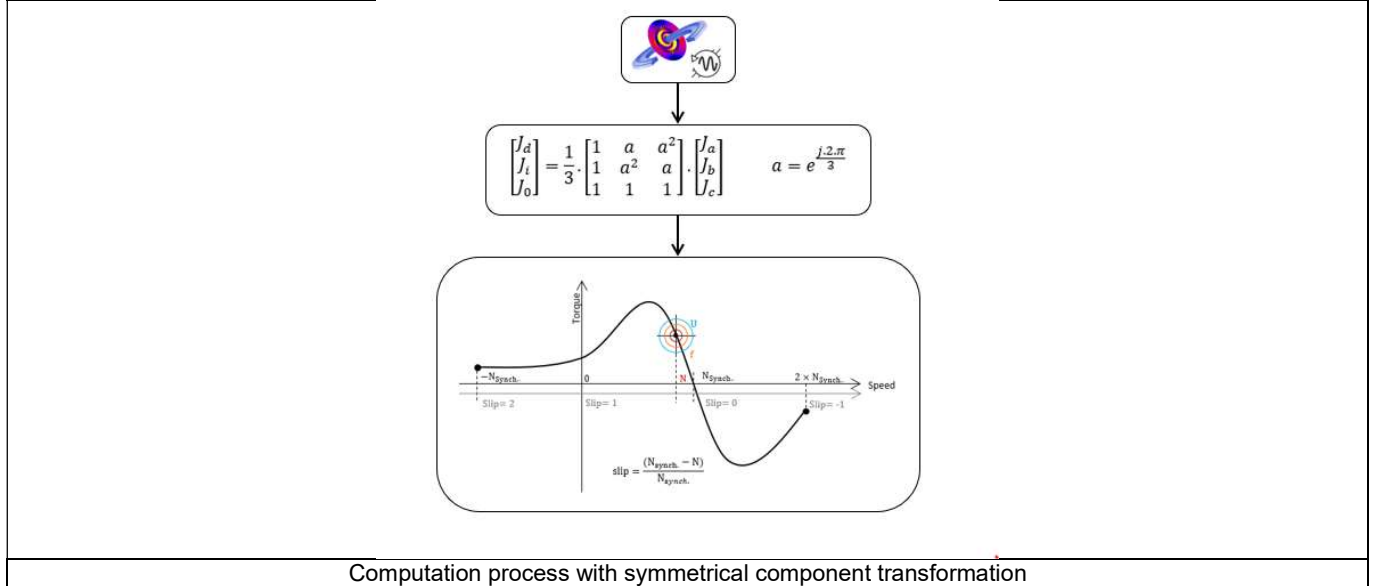
The use of the symmetrical component transformation is a key point.
Indeed, when using finite element modelling with Steady State AC application, each phase of the machine sees different airgap reluctance (due to the fixed rotor position) which generates indirect currents in the stator phases.
It is 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.

1.2.3.2   Power balance with iron losses

According to "1.2.2 Power balance and iron losses", adding iron losses to the power balance results in a power factor correction. The following steps explained the procedure:

- First, the electrical power is computed based on the symmetrical component results to compute the electromagnetic torque and the rotor Joule losses without considering the iron losses.

$$P_{elec\ sc} = \sqrt{3} \times U_S \times I_S \times PF_{sc}$$

U_S : Line-Line voltage, rms value
I_S: : Line current, rms value
PF_{sc} : Power factor without iron losses consideration in the power balance (from symmetrical component)

- Secondly, the electromagnetic power and the rotor Joule losses are computed thanks to the classical induction machine equations:

$$\mathrm{P}_{ag} = \mathrm{P}_{elec} - \mathrm{W}_{Joule\ stator}$$

$$\varGamma_{ag} = \varGamma_{em}$$

$\dfrac{P_{ag}}{\Omega_s} = \dfrac{P_{em}}{\Omega}$	$\Omega_s = \Omega + \Omega_r$ $\Omega_s = \Omega + s \times \Omega_s$

$$P_{em} = P_{ag} \times (1 - s)$$

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$$W_{Joule\ rotor} = s \times P_{ag}$$

- Thirdly, the iron losses are added to the Joule losses and to the electromagnetic power to compute the electrical power of the power balance:

$$P_{elec} = W_{Joule\ stator} + W_{Joule\ rotor} + W_{iron\ stator} + W_{iron\ rotor} + P_{em}$$

- At the end, the power factor is computed considering the RMS values of the phase current and phase voltage equal to those provided by the simulation:

$$PF = \frac{P_{elec}}{3 \times V_S \times J_S}$$

V_S : Phase voltage, rms value
J_S : Phase current, rms value

1.2.3.3   Iron losses

Iron losses (stator and rotor) are computed, thanks to the "AC Bertotti model" in Altair Flux™ software. Note, the more we have a machine with space harmonics, the more those losses are not accurately computed (AC modelling). Fortunately, iron losses are in many cases very small compared to Joule losses, the machine's performance remains well estimated.

1.2.3.4   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.

1.2.3.5   Flux density in iron

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

1.2.4 Accurate computation mode

1.2.4.1 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 considering all the harmonic content.

1.2.4.2 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 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.

1.2.4.3 Power balance with iron losses

According to "1.2.2 Power balance and iron losses", adding iron losses to the power balance results in a power factor correction. The following steps explained the procedure:

- First, the electrical power is obtained thanks to the sum of the electromagnetic power (deduced from the electromagnetic torque and rotating speed) and all the losses.

$$P_{elec} = W_{Joule\ stator} + W_{Joule\ rotor} + W_{iron\ stator} + W_{iron\ rotor} + P_{em}$$

- At the end, the power factor is computed considering the RMS values of the phase current and phase voltage equal to those provided by the simulation:

$$PF = \frac{P_{elec}}{3 \times V_S \times J_S}$$

V_S : Phase voltage, rms value
J_S : Phase current, rms value

1.2.4.4 Iron losses

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

1.2.4.5 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:

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

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

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

1.2.4.6 Rotor Joule winding losses

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

1.2.4.7 Flux density in iron

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

1.2.4.8 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.

1.2.4.9 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.

1.2.4.10 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.

1.2.5 Chart and table of temperatures

Chart and table of temperatures

1.2.6 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.