Altair® FluxMotor® 2026

Induction machines – Squirrel cage - Inner & Outer rotor

Motor Factory – Test - Characterization

General user information

Altairhyperworks.com

Contents

1 CHARACTERIZATION – MODEL – MOTOR – BASIC

1.1 Overview

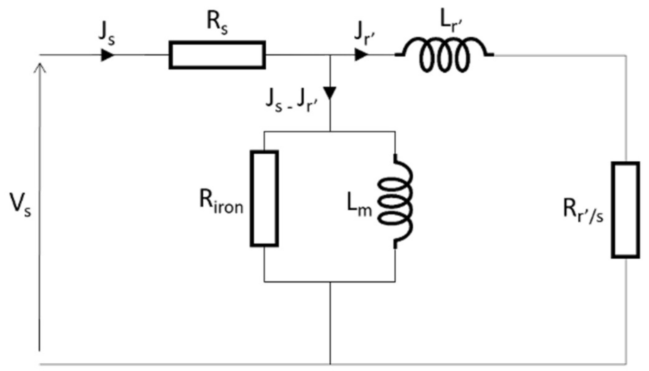
1.1.1 Positioning and objective

The aim of the test “Characterization – Model – Motor – Basic” is to identify the parameters of an electrical equivalent scheme of the 3-Phase induction machine with squirrel cage according to targeted input values U and f (Magnitude of line-line voltage and Power supply frequency).

This test can be described into three main steps:

- First, the equivalent scheme called “Original Model” is characterized by performing the two following classical tests: The No-load test and the locked-rotor test.
- Then, it is possible to improve the accuracy of the “Original model” by using refinement process to obtain a “Refined Model”.
- And lastly, once the model identification is done, it is possible to evaluate machine behavior by considering various working point defined by the magnitude of “Operating line-line voltage” and “Operating power supply frequency”.

Note: At any time, the relevance of the model parameters can be checked by comparing the results got with this model and those got with the Finite Element computations.



“Characterization – Model – Motor – Basic” – Illustration of the model

Warnings! The resulting model is a linear one, so it cannot provide accurate results on the whole ranges of operating voltages and frequencies.
To get a good accuracy of results, it is highly recommended to use the model with a Line-Line voltage and even more a Power supply frequency close to those used for its identification.

Based on the resulting electrical equivalent scheme, results are computed and displayed to give an overview of the electromagnetic analysis of the machine. General data of the machine, like mechanical torque, currents, power factor and power balance are computed and displayed as curves.

System integrators and / or control-command engineers will find a tool adapted to their needs. Indeed, the resulting equivalent scheme can be used into a system simulation software for evaluating the interaction between the machine and the system in which it is integrated.
The following table helps to classify the test “Characterization – Model – Motor – Basic”.

Family	Characterization
Package	Model
Convention	Motor
Test	Basic

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

1.2 Main principles of computation

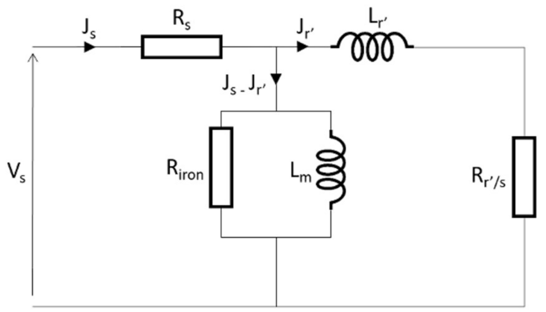
1.2.1 Introduction

As said previously, the aim of the test "Characterization – Model – Motor – Linear" is to identify the parameters of an electrical equivalent scheme of the 3-Phase induction machine with squirrel cage according to targeted input values U and f (Magnitude of line-line voltage and Power supply frequency).

The "Original model" used is based on a classical equivalent scheme with leakage inductance totaled in rotor. The identification of the model is performed considering the two following classical tests: The No-load test and the locked-rotor test. The corresponding computations are performed with a Finite Element modelling using a Steady State AC application.
Then, the accuracy improvement of the original model can be operate using refinement processes like a "Fitting" or "X-Factor" to obtain a "Refined Model".
Lastly, once the equivalent model is available, it is possible to evaluate its behavior by considering various working point defined by the magnitude of "Operating line-line voltage" and "Operating power supply frequency".

1.2.2 Electrical equivalent scheme with leakage inductance totaled in rotor

We have chosen to identify the electrical equivalent scheme with totalized leakage inductance at the rotor. Because it's one of the easiest to use and to apply a "V/f scalar control command mode".



"Characterization – Model – Motor – Linear" – Equivalent scheme of reduced rotor leakage inductance

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 totaled in rotor
R_r': Rotor equivalent phase resistance brings back to the stator

All the equivalent scheme parameters are defined in the following subsection. Then, the computations carried out to identify the model are presented with the no-load and the locked-rotor computations.

1.2.3 Model parameters

1.2.3.1 Equivalent scheme coefficients

An equivalent scheme corresponds to a specific value of the coefficient "m". There are as many equivalent schemes as there are coefficient values "m". This equivalent scheme above is characterized by a coefficient "m" defined such as:

$m = \frac{L_s}{\frac{3}{2} \times M_{rs}}$	$L_s = l_s - m_s$

L_s: Stator cyclic inductance (Cyclic means that the contribution of the 3 phases is considered)
l_s: Stator self-inductance
m_s: Stator mutual inductance (between 2 stator phases)
M_{rs}: Mutual inductance magnitude between a stator phase and a rotor phase (when the position of the rotor corresponds to a stator phase opposite a rotor phase)

1.2.3.2 Transformation ratio and equivalent scheme coefficient

When we make the analogy with a wound rotor, the transformation ratio is defined such as:

$$\frac{V_1^0}{V_s^0} = \frac{\frac{3}{2} \times M_{rs}}{L_s} = \frac{1}{m}$$

V_1^0: No-load rotor phase voltage
V_s^0: No-load stator phase voltage
L_s: Stator cyclic inductance (Cyclic means that the contribution of the 3 phases is considered)
M_{rs}: Mutual inductance magnitude between a stator phase and a rotor phase (when the position of the rotor corresponds to a stator phase opposite a rotor phase)
m: Equivalent scheme coefficient

The transformation ratio "$\frac{V_1^0}{V_a^0}$" is the inverse of the equivalent scheme coefficient "m".

1.2.3.3 Rotor equivalent phase current bring back to the stator and reduced at the stator frequency

The rotor equivalent phase current "J_r'" brings back to the stator and reduced at the stator frequency "f_s" is defined such as:

$J_r' = -\frac{J_r}{m}$	$J_r' = -J_r \times \frac{\frac{3}{2} \times M_{rs}}{L_s}$

J_r: Rotor equivalent phase current at the frequency "$g \times f_s$"
J_r': Rotor equivalent phase current bring back to the stator and reduced at the stator frequency "f_s"
m: Equivalent scheme coefficient

1.2.3.4 Magnetizing inductance

The magnetizing inductance is defined such as:

$L_m = m \times \frac{3}{2} \times M_{rs}$	$L_m = L_s$

1.2.3.5 Iron loss resistance

The iron loss resistance "R_{iron}" is added to the equivalent scheme in parallel with of the magnetizing inductance to be able to consider the stator and rotor iron losses in the power balance during the solving of the circuit.

1.2.3.6 Leakage inductance totaled in rotor

The total leakage inductance totalized to the rotor "L_r'" is defined such as:

$L_r' = m^2 \times \sigma \times L_r = m^2 \times N_r$	$L_r' = \left(\frac{L_s}{\frac{3}{2} \times M_{rs}}\right)^2 \times \sigma \times L_r = \left(\frac{L_s}{\frac{3}{2} \times M_{rs}}\right)^2 \times N_r$

L_r: Rotor cyclic inductance (Cyclic means that the contribution of the 3 phases is considered, which is a vision of the mind in the case of a squirrel cage machine)
σ: Blondel leakage coefficient
N_r: Boucherot's total leakage inductance

Boucherot's total leakage inductance "N_r" is defined such as:

$$N_r = \sigma \times L_r$$

Blondel leakage coefficient "σ" is defined such as:

$$\sigma = 1 - \frac{\left(\frac{3}{2} \times M_{rs}\right)^2}{L_s \times L_r}$$

L_r: Rotor cyclic inductance (Cyclic means that the contribution of the 3 phases is considered, which is a vision of the mind in the case of a squirrel cage machine)
L_s: Stator cyclic inductance (Cyclic means that the contribution of the 3 phases is considered)
M_{rs}: Mutual inductance magnitude between a stator phase and a rotor phase (when the position of the rotor corresponds to a stator phase opposite a rotor phase)

Note, for a perfect electromagnetic coupling, we have "$\left(\frac{3}{2} \times M_{rs}\right)^2 = L_s \times L_r$" so "$\sigma = 0$" which means no flux leakage between stator and rotor. Commonly the order of magnitude is "$\sigma < 10\%$"

1.2.3.7 Rotor equivalent phase resistance brings back to the stator

The rotor equivalent phase resistance "R_r'" brings back to the stator is defined such as:

$R_r' = m^2 \times R_r$	$R_r' = \left(\frac{L_s}{\frac{3}{2} \times M_{rs}}\right)^2 \times R_r$

J_r: Rotor equivalent phase current at the frequency "$s \times f_s$"
J_r': Rotor equivalent phase current bring back to the stator and reduced at the stator frequency "f_s"
m: Equivalent scheme coefficient

The resistance "R_r'" is not the rotor phase resistance. However, rotor Joule losses stay equivalent:

$$R_r' \times {J_r'}^2 = m^2 \times R_r \times \left(-\frac{J_r}{m}\right)^2 = R_r \times (J_r)^2$$

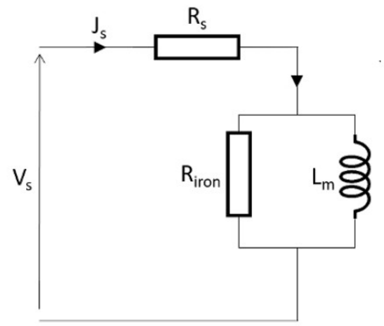
"$R_r' \times {J_r'}^2$" is representative of rotor Joule losses.
"$\frac{(1-s)}{s} \times R_r' \times {J_r'}^2$" is representative of electromagnetic torque.

1.2.4 Computations for model identification

1.2.4.1 No load computation

The no load computation is done for a very small value of slip “0.1 %” to be close to the synchronous speed at the rated voltage and the rated power supply frequency.

The equivalent scheme corresponding to the no-load computation is shown in the following picture.



“Characterization – Model – Motor – Linear” – Equivalent scheme – No load computation

“ R_{iron} ” and “ L_m ” are deduced from computation results according to the following equations:

$$L_m = \frac{1}{2 \times \pi \times f_s} \times \frac{3 \times \left(abs(V_{s0} - R_s.J_{s0})\right)^2}{Q_0}$$

$$X_m = L_m \times 2 \times \pi \times f_s$$

$$R_{iron} = \frac{3 \times \left(abs(V_{s0} - R_s.J_{s0})\right)^2}{W_{iron\,tot.\;0}}$$

J_{s0}:	Phase current at no load
V_{s0}:	Phase voltage at no load
Q_0:	Reactive electrical power at no load
f_s:	Power supply frequency
$W_{iron\,tot.\;0}$:	Total iron losses at no load
L_m :	Magnetizing inductance
X_m :	Magnetizing reactance

Note: Stator leakage inductance is neglected because it is considered small compared with the magnetizing inductance and the stator resistance.

1.2.4.2 Locked rotor computation

The locked rotor computation is done with a slip equal to “100 %” (to be at zero speed) and for the “Locked-rotor line current” and the “Locked rotor slip red. freq.”.
The “Locked rotor slip red. freq.” allows to compute the “Reduced power supply frequency” which corresponds to the power supply frequency of the computation:

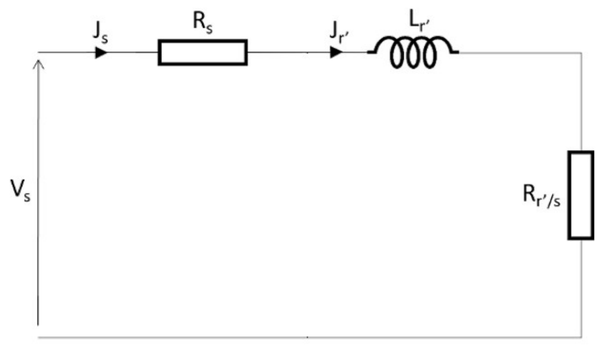
$$f_{s\,red.\,freq.} = s_{red.\,freq.} \times f_s$$

f_s: Power supply frequency
$f_{s\,red.freq.}$: Reduced power supply frequency
$s_{red.\,freq.}$: Slip to be considered when computing the reduced power supply frequency

When “Model computation mode” is set to “Auto.”, “Locked-rotor line current” and the “Locked-rotor slip red. freq.” are automatically set by an internal process.
In this case, a Steady state AC computation is done over the motor slip range (considering the “Line-Line voltage” and the “Power supply frequency” as inputs).
Then, the “Locked-rotor line current” and the “Locked-rotor slip red. freq.” are got from the values obtained at the maximum torque over the slip range.
When “Model computation mode” is set to “User”, “Locked-rotor line current” and the “Locked-rotor slip red. freq.” must be provided by the user to define the targeted working point for identifying the linear model.
Then, the “Reduce power supply frequency” can be computed.

For the locked-rotor computation, a “Reduce power supply frequency” is used to be as close as possible to the real operating conditions and more precisely as close as possible to the rotor real operating conditions (according to the targeted working point for identifying the model).
To obtain a linear model with a good accuracy in the T(Slip) curve linear part, it is recommended to use the breakdown torque in motor mode as the targeted working point (automatic methods).

The equivalent scheme corresponding to the no-load computation is shown in the following figure.



“Characterization – Model – Motor – Linear” – Equivalent scheme – Locked-rotor computation

" R_r' " and " N_r " are deduced from results according to the following equations:

$$N_r = \frac{1}{2 \times \pi \times f_{s\,red.freq.}} \times \frac{3 \times \left(abs(V_s - R_s.J_{s\,LR})\right)^2}{Q_{LR}}$$

$$X_r = N_r \times 2 \times \pi \times f_s$$

$$\mathrm{P}_{elec.} = \sqrt{3} \times U_s \times I_{s\,LR} \times PF_{LR}$$

$$W_{Jr\,LR} = s \times (P_{elec.\ LR} - W_{Js\ LR} - W_{LR\,iron\,stat.\ LR}) - W_{LR\,iron\,rot.\ LR}$$

$$R_r' = \frac{W_{Jr\ LR}}{3 \times J_{s\,LR}^{\ 2}}$$

s:	Slip
$J_{s\,\mathrm{LR}}$:	Phase current at locked-rotor
$I_{s\,LR}$:	Line current at locked-rotor
V_s:	Phase voltage
U_s:	Line-Line voltage
Q_{LR}:	Reactive electrical power at locked rotor
f_s:	Power supply frequency
$f_{s\,red.freq.}$:	Reduced power supply frequency
$W_{iron\,stat.\ \mathrm{LR}}$:	Stator iron losses at locked rotor
$W_{iron\,rot.\ \mathrm{LR}}$:	Rotor iron losses at locked rotor
PF_{LR}:	Power factor at locked rotor
$W_{Jr\,LR}$:	Rotor Joule losses at locked rotor
$W_{Js\ LR}$:	Stator Joule losses at locked rotor
N_r:	Leakage inductance totaled in rotor
X_r:	Leakage reactance totaled in rotor
R_r':	Rotor equivalent phase resistance brings back to the stator

Notes:

The magnetizing current "$J_s - J_r'$" is neglected because it's considered small in front of "J_r'" current.

" L'_r " is computed at " $f_{s\,red.freq.}$ " but " X'_r " is computed at " f_s "

All iron losses are considered to compute " R_r' ", so iron losses are considered in the power balance to identify the linear model in the same way for the test "T(Slip)"

1.2.5 Model refinement

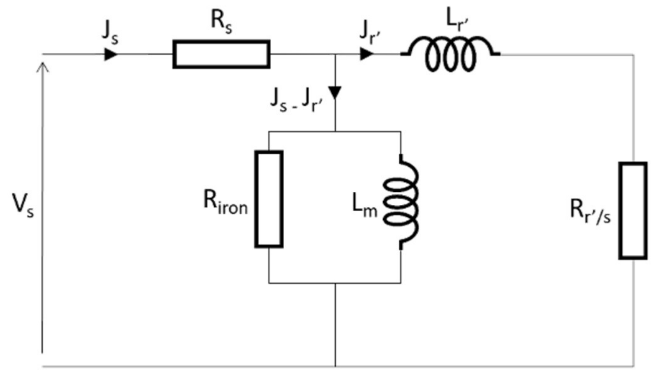
Whatever is the chosen model refinement method, Fitting or X-Factor, the principle is the same, X-Factors which are automatically or manually defined are applied to the four equivalent scheme parameters to get new equivalent scheme behavior.
The four considered X-Factors are the following ones:

- $XF_{R_{iron}}$: Magnetizing inductance factor
- XF_{L_m}: Iron losses resistance factor
- XF_{N_r}: Leakage inductance factor
- $XF_{R_{r'}}$: Rotor Joule losses resistance factor

Warning! Increase the accuracy of the model for a set of input data "Line-Line voltage" and "Power supply frequency" does not ensure the model improvement over a full range of operating working points

1.2.6 Model evaluation

The evaluation of the accuracy of the linear model is based on the resulting equivalent scheme with the considered "Op. Line – Line voltage, rms" and "Op. power supply freq." set by the user.



"Characterization – Model – Motor – Linear" – Equivalent scheme evaluation

The resulting equivalent scheme corresponds to the original model or the refined one according to whether a refinement has been performed or not.

Note 1: In addition, a Finite Element computation can be done considering the same input data ("Operating Line - Line voltage and the "Operating power supply frequency" to precisely determine the validity range the model.

Note 2: The only operating mode addressed by this test is "Motor".
In motor mode, the torque is positive « $\Gamma > 0$ » and the speed is positive « $N > 0$ », so, the resulting mechanical power is also positive « $P_{mech.} > 0$ ». As the motor convention is used, the electrical power is regarded to be positive « $P_{elec.} > 0$ ». According to the power flow, the electrical power is greater than the mechanical power « $P_{elec.} > P_{mech.}$ ».

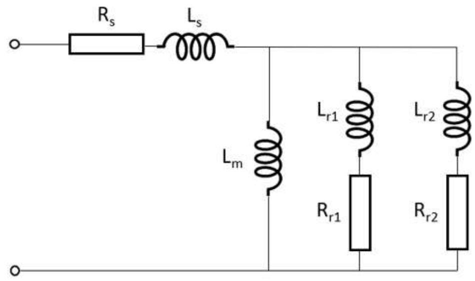
Note 3: The integration of iron losses into the power balance as well as the consideration of mechanical losses can lead to a negative mechanical power. In this case, there are too many losses to provide mechanical power, so, the operating points involved are assumed physically unreachable and therefore not displayed.

2 CHARACTERIZATION – MODEL – MOTOR – SSFR

2.1 Overview

2.1.1 Positioning and objective

The aim of the test “**Characterization – Model – Motor – SSFR**” is to characterize all the parameters of the equivalent scheme by performing a frequency analysis.
Then, the resulting equivalent scheme can be evaluated by simulating the starting of the considered induction machine. The speed, torque and absorbed current versus time are computed and displayed.



Parameters of the equivalent circuit

Parameters					
Ls (H)	9.836 E-4	Lsw (H)	4.753 E-4	Lss (H)	5.082 E-4
Rs (Ω)	1.753 E-1	Lm (H)	6.014 E-2		
Rr1 (Ω)	8.571 E-2	Lr1 (H)	4.637 E-3		
Rr2 (Ω)	2.47	Lr2 (H)	9.146 E-3		

“Characterization – Model – Motor – SSFR” – Characterization of all the equivalent scheme parameters

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

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

Family	Characterization
Package	Model
Convention	Motor
Test	SSFR

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

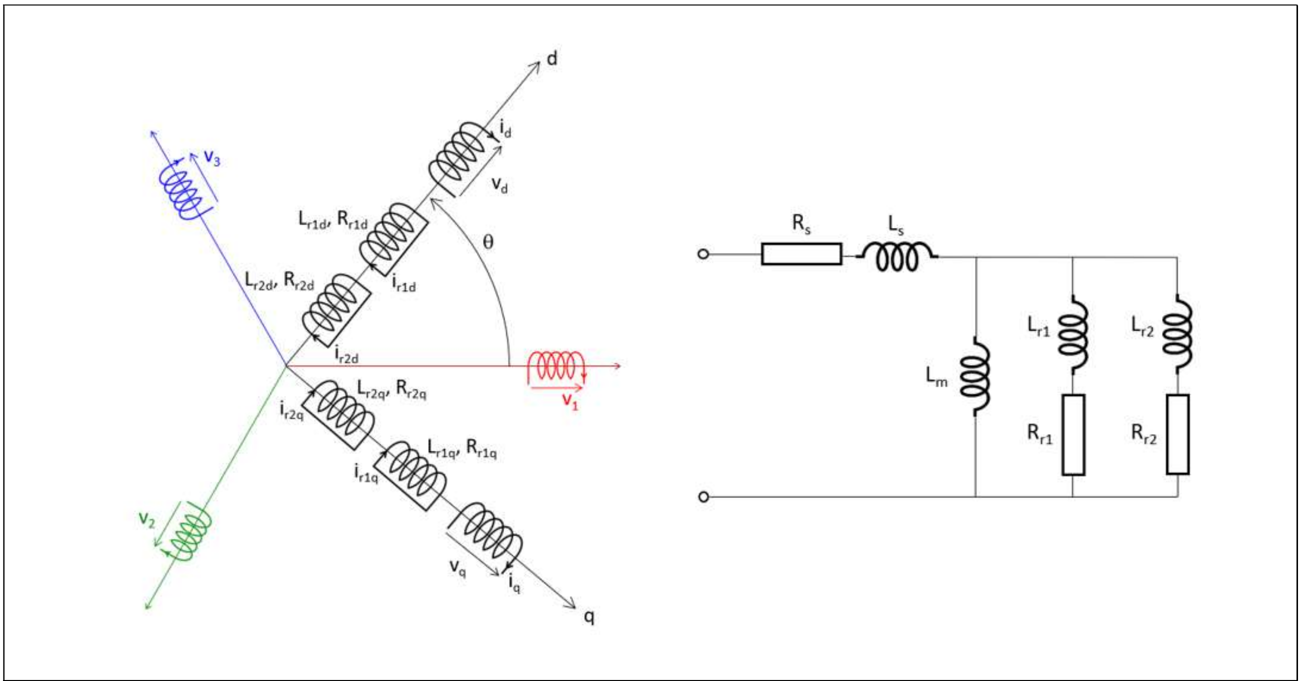
2.2 Main principles of computation

2.2.1 Introduction

As said previously, the aim of the test “Characterization – Model – Motor – SSFR” is to identify all the parameters of the electrical equivalent scheme of a 3-Phase squirrel cage induction machine by considering either a first order or a second order for the operational inductance transfer function L(p).

2.2.2 Model representation

2.2.2.1 Second order model



2[nd] order equivalent scheme of induction machine with squirrel cage

Notes:

Considering the topology of squirrel cage induction machines, the assumption considered is that there is no variation (or very low) of magnetic reluctance inside the airgap versus the rotor angular position.
The consequence is that both d-axis equivalent scheme and q-axis equivalent scheme are the same, hence:

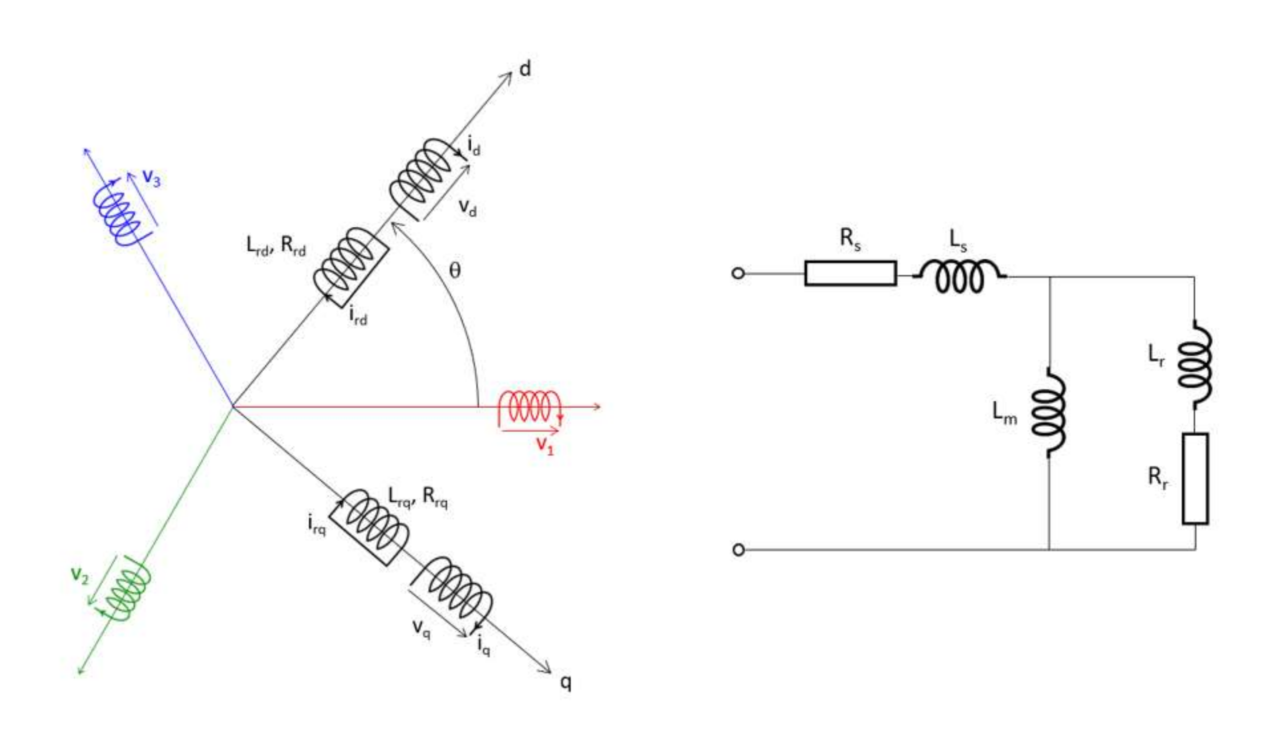
$L_{r1d} = L_{r1q} = L_{r1}$
$L_{r2d} = L_{r2q} = L_{r2}$
$R_{r1d} = R_{r1q} = R_{r1}$
$R_{r2d} = R_{r2q} = R_{r2}$

On the previous graph, θ represents the relative position between the first stator winding phase and the d-axis of the machine model.

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

R_s: Stator phase resistance
L_s: Stator phase leakage inductance = ($L_{sw} + L_{ss}$)
L_{sw}: Stator end winding leakage inductance (included in L_s)
L_{ss}: Stator straight part leakage inductance (included in L_s)
Rr1: Rotor squirrel cage resistance – 1st branch
Lr1: Rotor squirrel cage inductance – 1st branch
Rr2: Rotor squirrel cage resistance – 2nd branch
Lr2: Rotor squirrel cage inductance – 2nd branch

2.2.2.2 First order model



1st order equivalent scheme of induction machine with squirrel cage

Notes:

Considering the topology of squirrel cage induction machines, the assumption considered is that there is no variation (or very low) of magnetic reluctance inside the airgap versus the rotor angular position.
The consequence is that both d-axis equivalent scheme and q-axis equivalent scheme are the same, hence:

$L_{rd} = L_{rq} = L_r$
$R_{rd} = R_{rq} = R_r$

On the previous graph, θ represents the relative position between the first stator winding phase and the d-axis of the machine model.

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

R_s: Stator phase resistance
L_s: Stator phase leakage inductance = (L_{sw} + L_{ss})
L_{sw}: Stator end winding leakage inductance (included in L_s)
L_{ss}: Stator straight part leakage inductance (included in L_s)
Rr: Rotor squirrel cage resistance
Lr: Rotor squirrel cage inductance

2.2.3 Test procedure

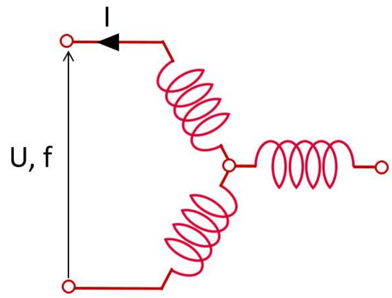
2.2.3.1 Short description

The rotor of the machine does not rotate. The rotor angular position has no importance on the test results.

By considering a 3-Phase induction machine, a voltage U is applied between two phases like illustrated below to compute the impedance Z(p).

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

As a result, the induction machine is characterized by its frequency response which is the magnitude and the phase angle of the operational inductance transfer function versus the frequency.



A voltage U is applied between two phases

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

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

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

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

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

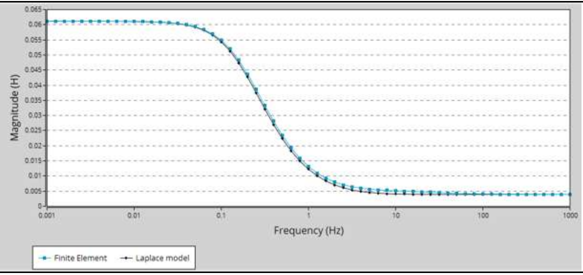
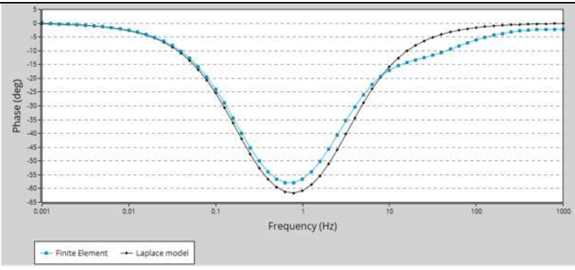
Theoretical analytical formulas allow deducing all the equivalent scheme parameters from operational inductance transfer function coefficients.

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

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

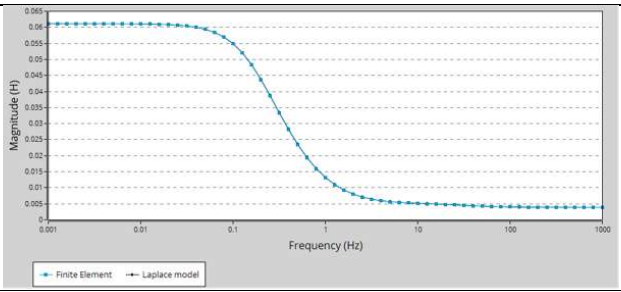
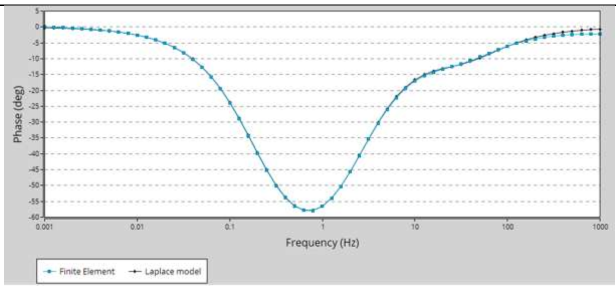
The aim of the internal optimization process is to make these two resulting curves as close as possible from each other by taking action on the L(p) parameters.

Modeling of an induction machine with squirrel cage - using a first order operational inductance

<table>
<tr><td>
</td><td>
</td></tr>
<tr><td>Magnitude of L(p) vs frequency</td><td>Phase angle of L(p) vs frequency</td></tr>
</table>

In this case, the first order is not enough accurate to make the resulting model correspond to the considered motor frequency-response.

Modeling of an induction machine with squirrel cage - using a second order operational inductance

<table>
<tr><td>
</td><td>
</td></tr>
<tr><td>Magnitude of L(p) vs frequency</td><td>Magnitude of L(p) vs frequency</td></tr>
</table>

In this case, the second order allows to make the resulting model correspond to the considered motor frequency-response.

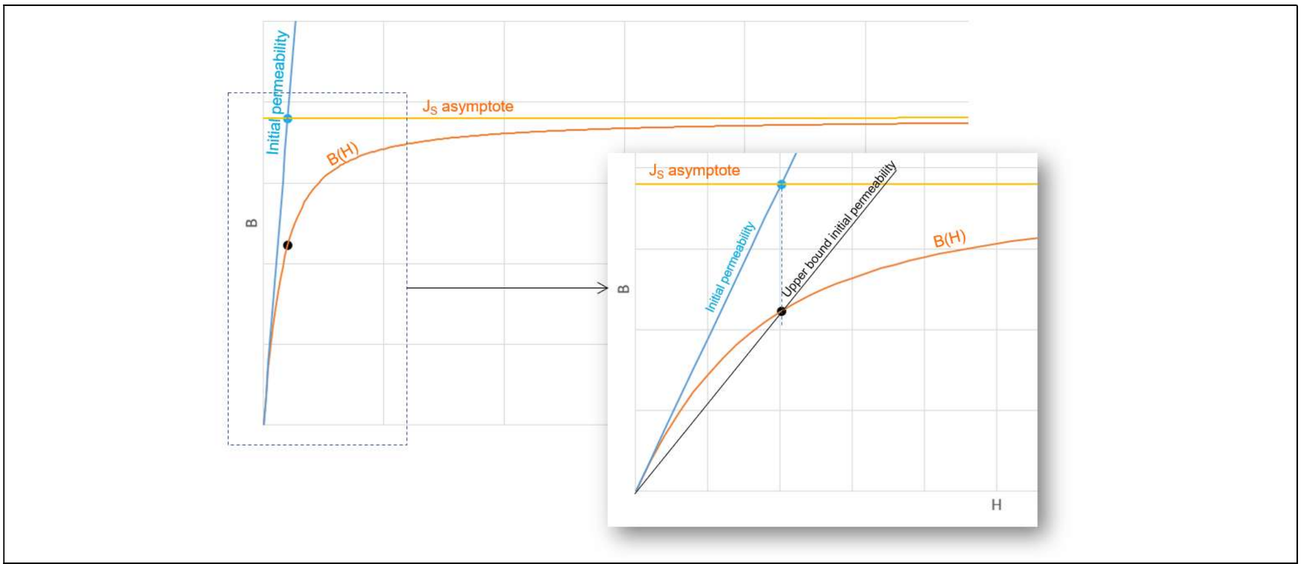
2.2.3.2 Additional information

1) Materials magnetic properties

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

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

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



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

2) Stator phase leakage inductance computation

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

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

The stator straight part leakage (L_{ss}) is computed from the magnetic energy stored in the slots along the half part of the airgap close to the stator bore diameter.
The total value of the stator phase leakage inductance (L_s) is computed as follows:

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

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

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

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

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

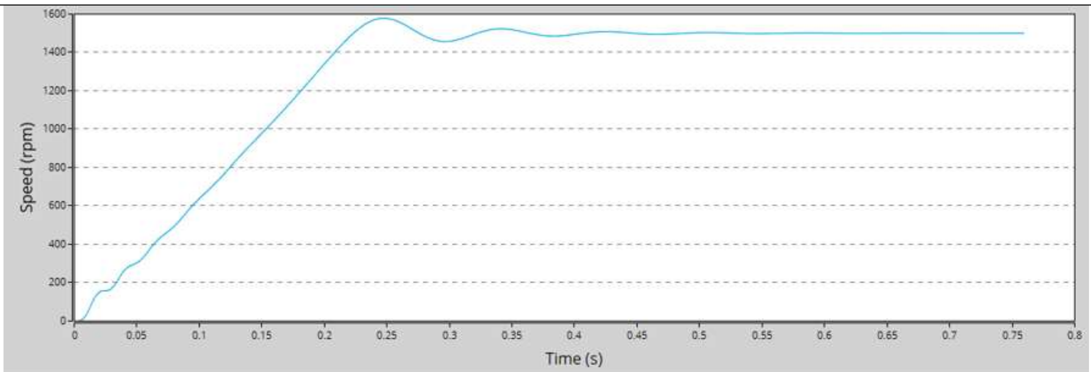
Considering the topology of induction machines with squirrel cage, one can assume that there is no variation (or very low) of magnetic reluctance inside the airgap versus the rotor angular position.
Therefore, both d-axis equivalent scheme and q-axis equivalent scheme are the same, hence: $L_d = L_q$

2.2.3.3 Model evaluation

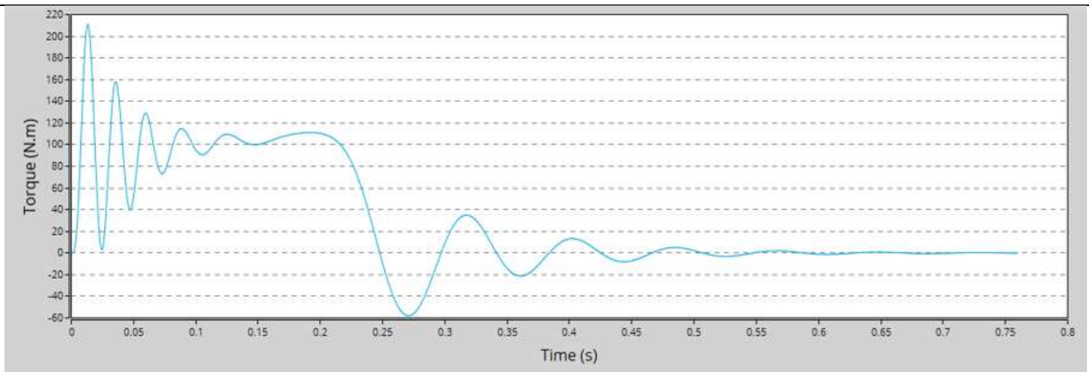
Based on the equivalent scheme parameters obtained in the characterization part, the voltage, and magnetic equations of the induction machine alongside with its mechanical equation are written and solved to simulate the behavior of the motor during a starting.

Thus, speed, electromagnetic torque and current versus time are computed and displayed.
Synthesis of start-up characteristic are computed and displayed.

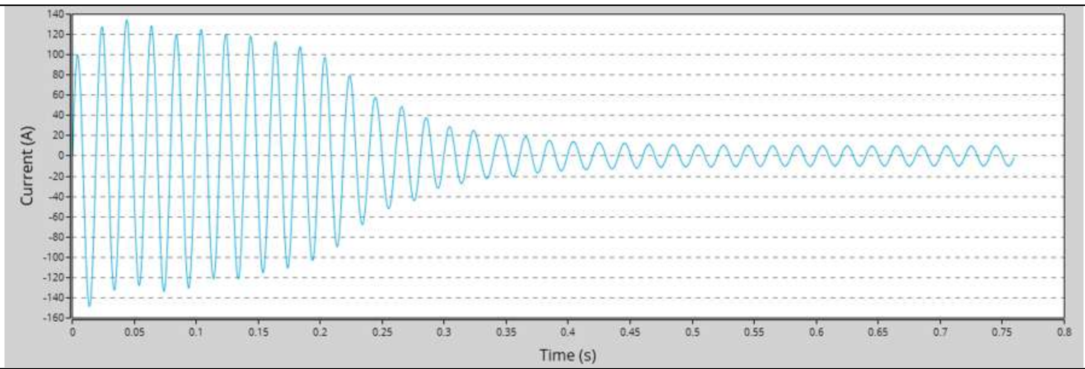
Here are illustrations of these outputs:



Speed versus time



Electromagnetic torque versus time



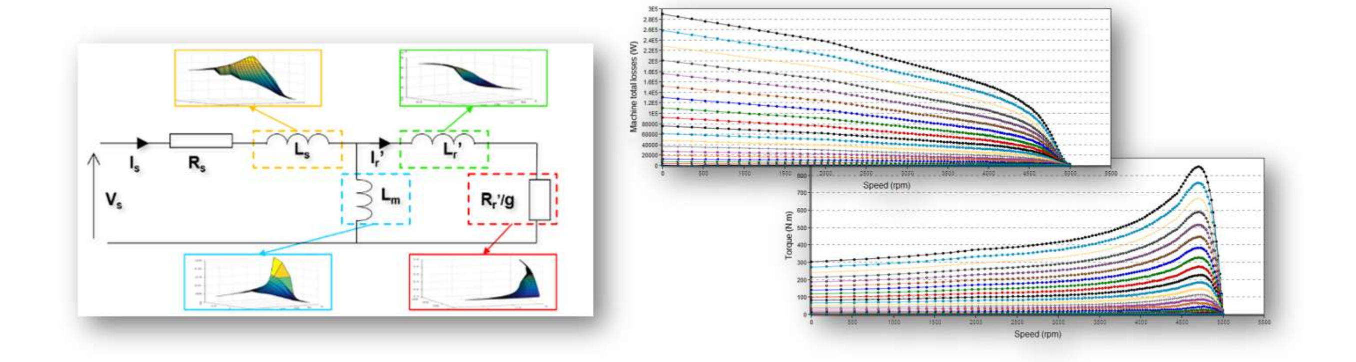
Speed versus time

3 CHARACTERIZATION – MODEL – MOTOR – SCALAR

3.1 Overview

3.1.1 Positioning and objective

The aim of the test “**Characterization – Model – Motor – Scalar**” is to characterize the behavior of the machine in function of a set of Line-Line voltage (U) and a set of power supply frequency (f) (only motor operating mode available). Those computations are based on the identification and the solving of a non-linear model considering the cross saturation and the eddy current effects. All the main electromagnetic quantities are computed and displayed as curves in function of speed for a given power supply frequency and a set of Line-Line voltages.



“Characterization – Model – Motor – Scalar” Illustration

The results of this test give an overview of the electromagnetic behavior of the machine considering its topology. For a set of Line-Line voltages (U) and a set of power supply frequencies (f), the general parameters of the machine like, mechanical torque, currents, power factor and power balance are computed and displayed as curves.
This gives the capability to make comparisons between the results obtained from the measurements and those with the Altair® FluxMotor®.

In this test, system engineers will find a characterization tool adapted to their needs and able to provide accurate curves ready to be used in system simulation software like, Activate or PSIM. Indeed, from results obtained in this test, a scalar drive and control can be applied.

Note: We consider the motor convention.

The following table classifies the test “Characterization – Model – Motor – Scalar

Family	Characterization
Package	Model
Convention	Motor
Test	Scalar

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

3.2 Main principles of computation

The documentation is under construction.

4 CHARACTERIZATION – THERMAL – MOTOR & GENERATOR – STEADY STATE

4.1 Overview

4.1.1 Positioning and objective

The aim of the test "Characterization – Thermal – Motor & Generator – Steady state" is to evaluate the impact of electromagnetic performance on the thermal behavior of the machine.
A thermal working point defined by a speed and a set of losses can be considered to compute the temperature charts and the main thermal parameters. The inputs describing the thermal working point can be set manually or imported from some electromagnetic tests previously solved.

This test helps to answer the following questions:

- Can the machine operate at the targeted working point without any overheating? Yes / No
- Can the different kinds of proposed cooling help to reach good performance? Yes / No

The following table helps to classify the test "Characterization – Thermal – Motor & Generator – Steady state".

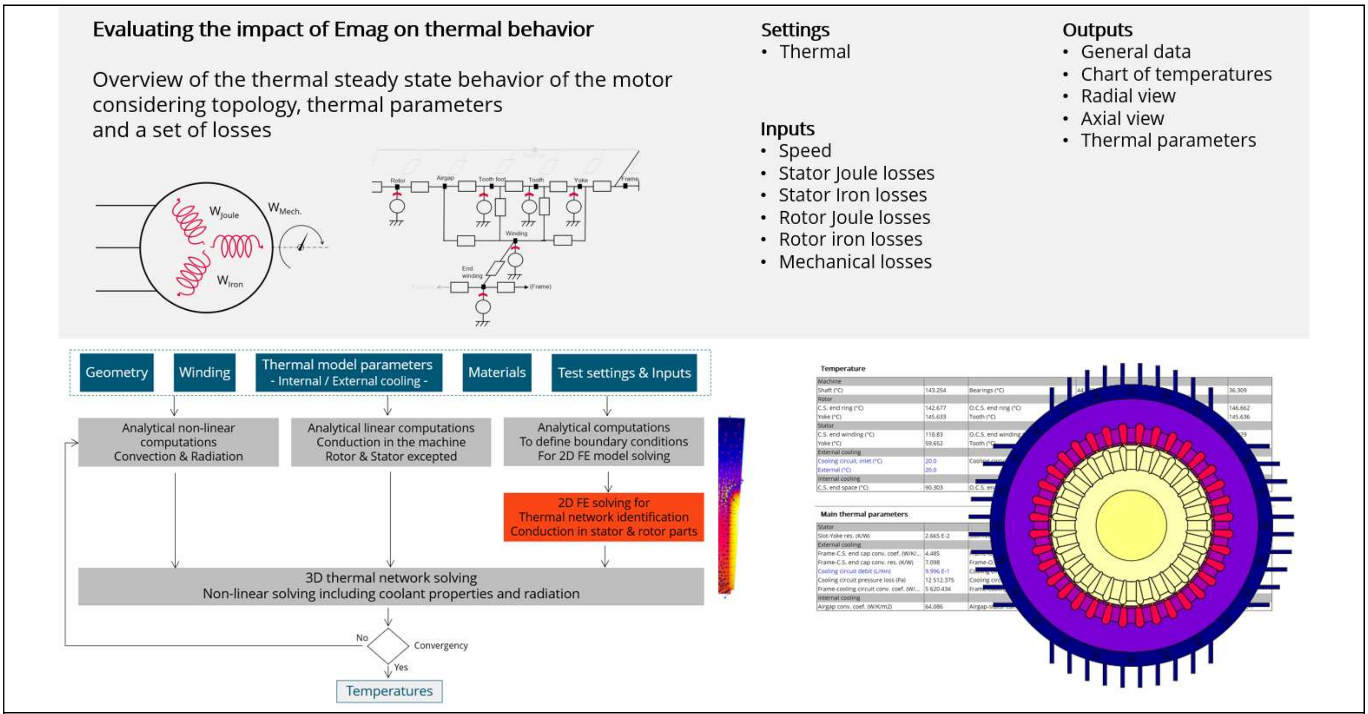
Family	Characterization
Package	Thermal
Convention	Motor & Generator
Test	Steady state

Positioning of the test "Characterization – Thermal – Motor & Generator – Steady state".

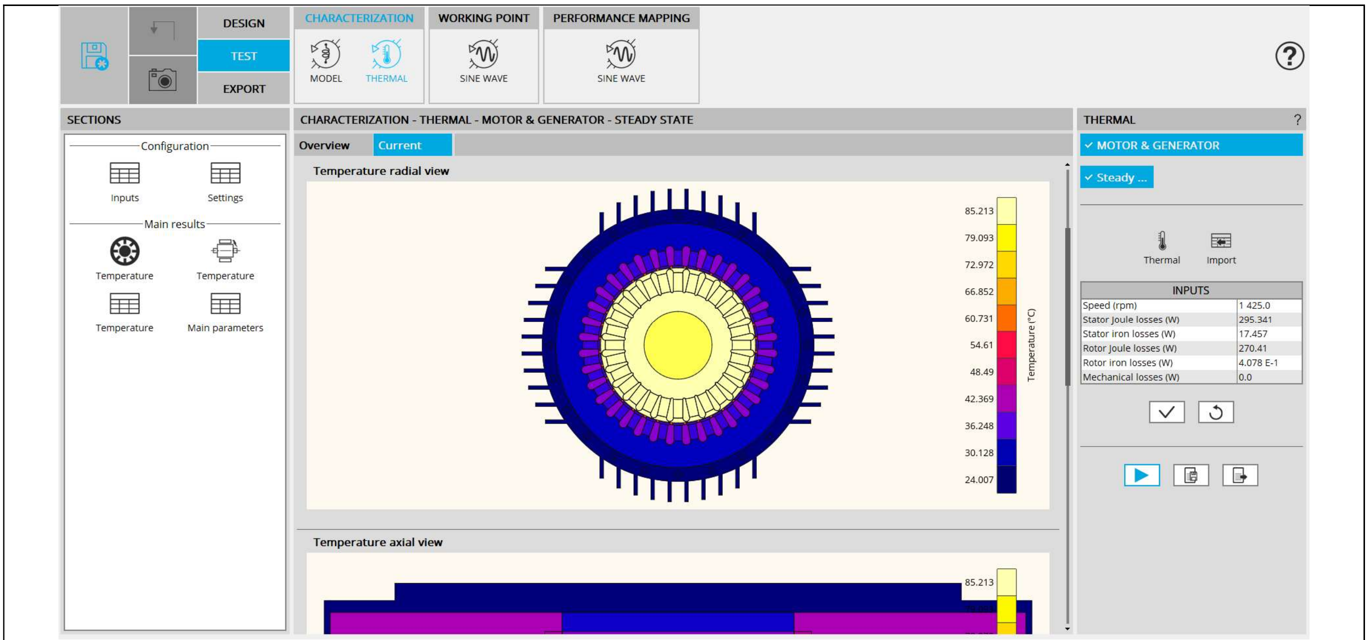
4.2 Main principles of computation

4.2.1 Introduction

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



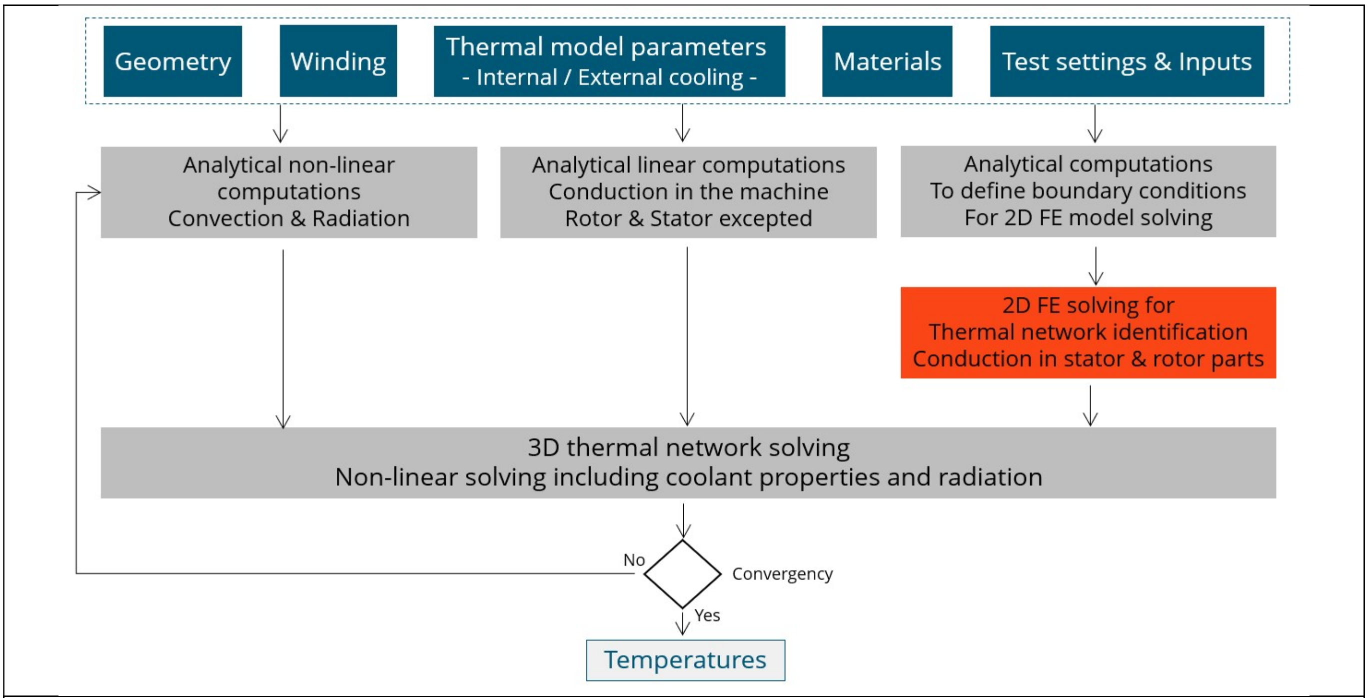
Characterization – Thermal – Steady state – Synchronous machine - Overview



Characterization – Thermal – Steady state – Synchronous machine – Test results

4.2.2 Flow chart

Here is the flowchart illustrating the internal process of the thermal test.



Thermal test – Internal process flowchart

The inputs of the internal process are the parameters of:

- Geometry
- Winding
- Internal cooling
- External cooling
- Materials
- Test settings and inputs

To be underlined that a 2D Finite Elements model is solved to identify a thermal network which corresponds accurately to any kind of rotor or stator parts, including user parts.

Then, the resulting network is extended with analytical computations to consider the 3D effect of the geometry.

The solving allows to get and to display the whole chart of temperatures of the machines.

4.2.3 Limitation of thermal computations – Advice for use

Please refer to the document: MotorFactory_IMSQ_IOR_3PH_Test_Introduction – section “Limitation of thermal computations – Advice for use”

5 CHARACTERIZATION – THERMAL – MOTOR & GENERATOR – TRANSIENT

5.1 Overview

5.1.1 Positioning and objective

The aim of “Characterization – Thermal – Motor & Generator – Transient” test is to evaluate the impact of electromagnetic performance on thermal behavior of the machine in a transient mode.
A thermal working point defined by a speed and a set of losses can be considered to compute the temperature charts and the main thermal parameters. The inputs describing the thermal working point can be set manually or imported from electromagnetic tests that were previously solved.
In addition to that, a maximum evaluation duration and a time step are added as inputs to set the transient mode.

This test helps to answer the following questions:

- Can the machine operate at the targeted working point without any overheating? Yes / No
- Can the different kinds of proposed cooling help to reach good performance? Yes / No
- How long does it take to reach the thermal steady state and what are the thermal time constants of the machine?

The following table helps to classify the test “Characterization – Thermal – Motor & Generator – Steady state”.

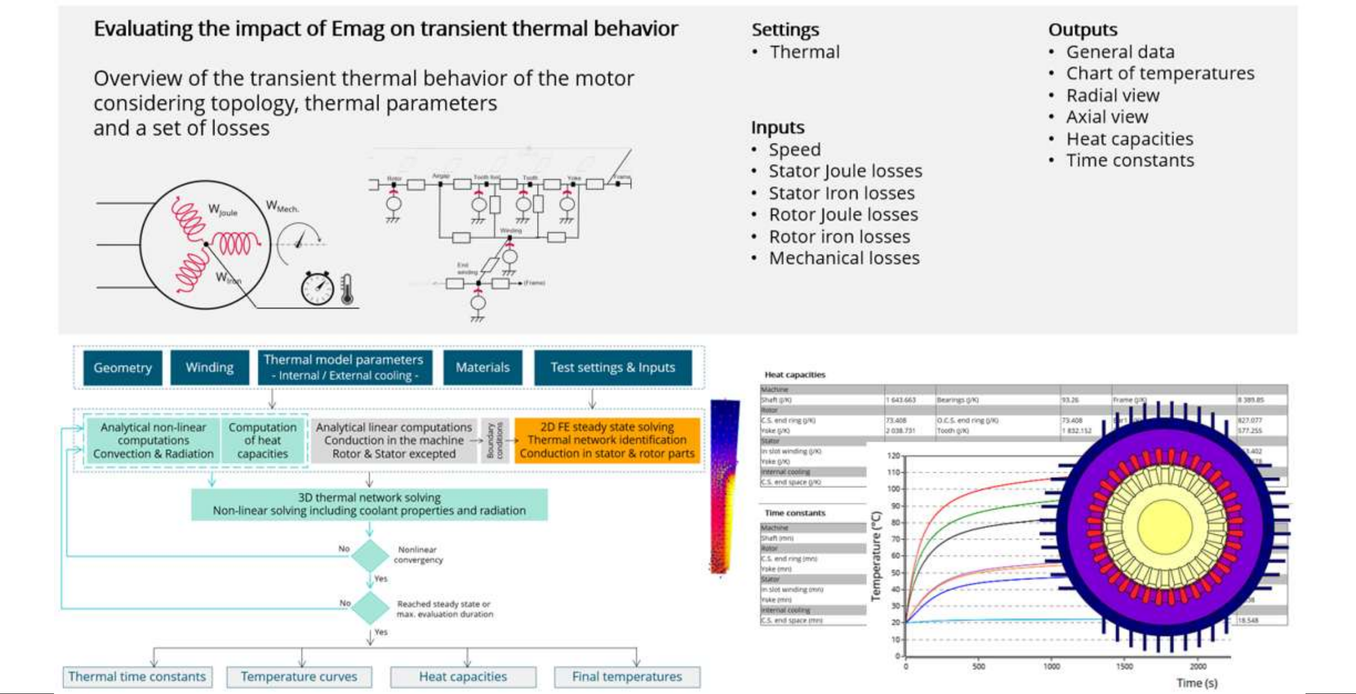
Family	Characterization
Package	Thermal
Convention	Motor & Generator
Test	Transient

Positioning of the test “Characterization – Thermal – Motor & Generator – Transient”

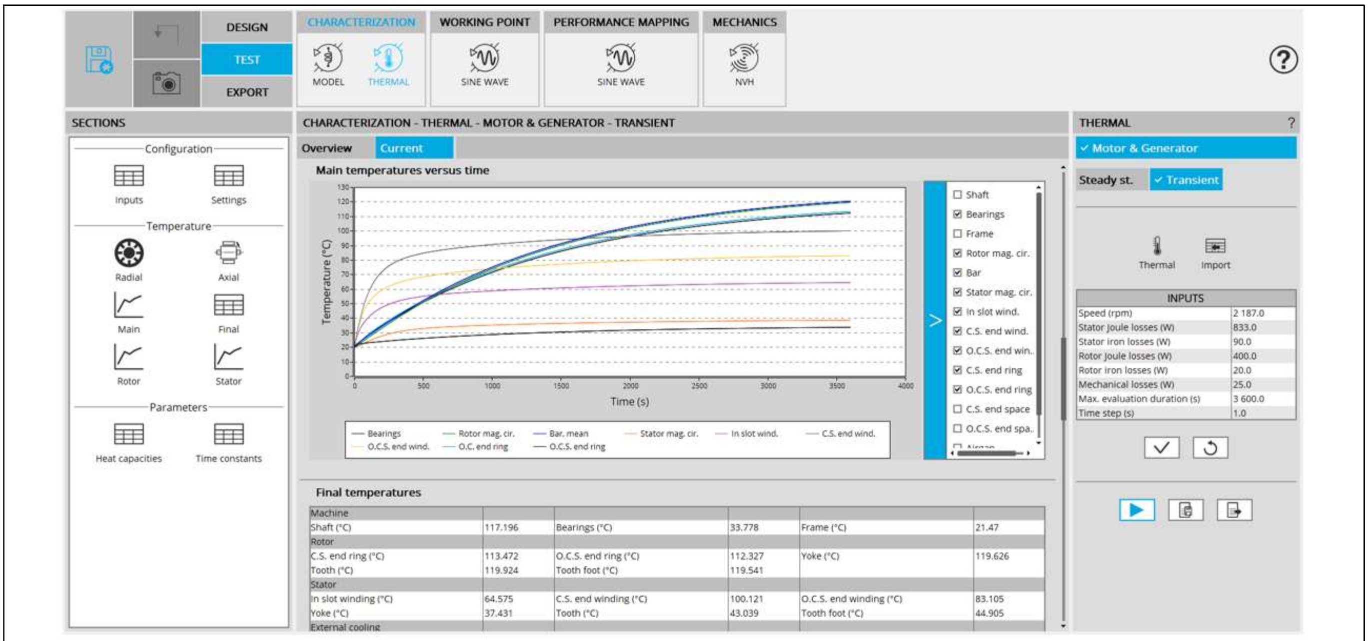
5.2 Main principles of computation

5.2.1 Introduction

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



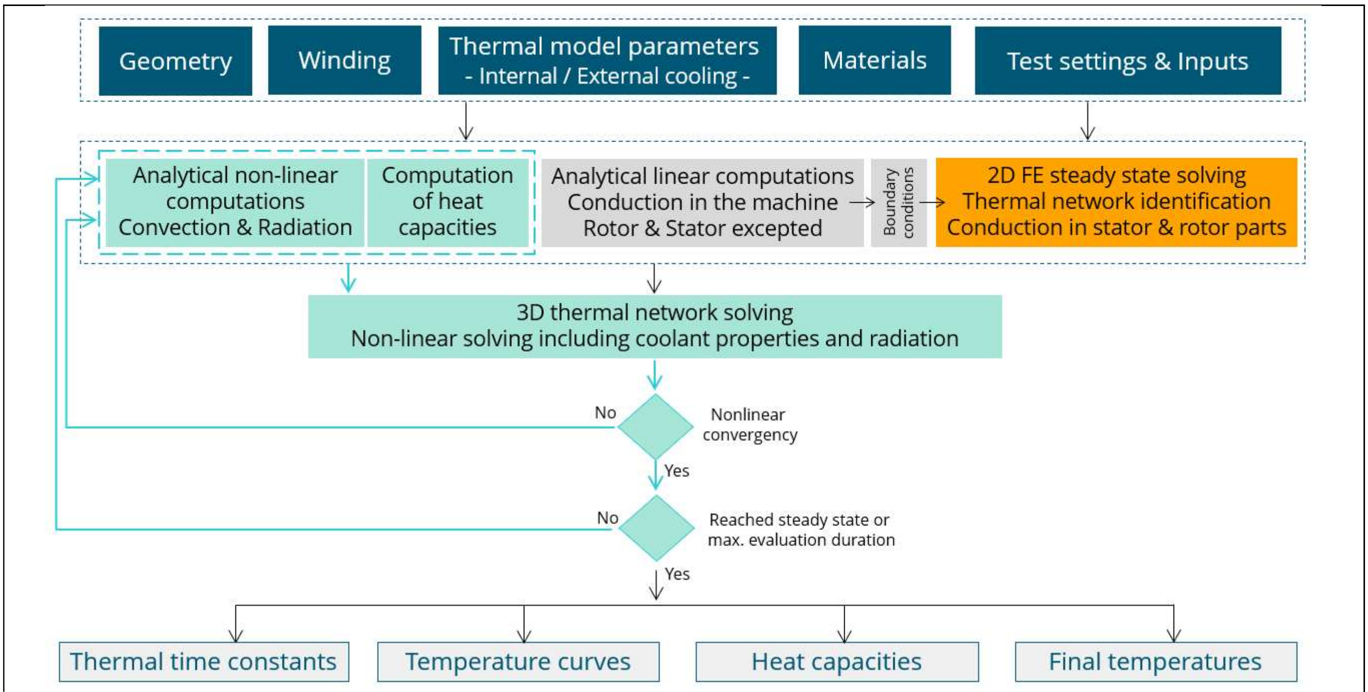
Characterization – Thermal – Transient – Synchronous machine - Overview



Characterization – Thermal – Transient– Synchronous machine – Test results

5.2.2 Flow chart

Here is the flowchart illustrating the internal process of the thermal transient test.



Thermal transient test – Internal process flow chart

The inputs of the internal process are the parameters of:

- Geometry
- Winding
- Internal cooling
- External cooling
- Materials
- Test settings and inputs

A 2D Finite Element model is solved to identify a thermal network which corresponds accurately to any kind of rotor or stator parts, including user parts.
Then, the resulting network is extended with analytical computations to consider the 3D effect of the geometry at each time step. For that, a non-linear computation is performed in the solving of the transient thermal test.
Each thermal node of the machine is associated to a thermal capacitance, depending on the specific heat and density of the material(s) composing the node, and the associated volume.
Thus, the main provided outputs are the whole chart of temperatures of the machines versus time, the heat capacities, and the time constants.

Note: What are the criteria that allow to see if the steady state is reached while thermal transient solving?
First, from the thermal steady state computation, one gets a good estimation of the final temperature (θ_f).
From the thermal transient computation, variation of the temperature versus the time, one deduces the inverse function, i.e. the variation of the time versus the temperature.
Knowing that the time constant to reach 63% of a temperature step is equal to:

$$\theta_\tau = \theta_0 + (1- e^{-1}) \times (\theta_f - \theta_0).$$

We are looking for the time t that corresponds to θ_τ. If found, it corresponds to tau.
If the evaluation time t considered is lower than τ ($t < \tau$), there is no convergency yet.
If $\tau < t < 5\tau$, there is no convergency, the thermal steady state is not reached yet, but an estimation of time needed to converge can be estimated and given to the user.
If $t > \tau$ The solving has converged, and the steady state is reached.

5.3 Limitation of computations - Advice for use

Notes:

1) The resistance network identification of a machine is always done without any skew angle.
   This can bring some inaccuracy in the results for highly skewed machines.

2) Please refer to the document: MotorFactory_IMSQ_IOR_3PH_Test_Introduction – section “Limitation of thermal computations – Advice for use”