

ALTAIR

Altair® FluxMotor® 2022.1

Induction machines – Squirrel cage - Inner & Outer rotor

Motor Factory – Test - Introduction

General user information

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TEST AREA

1.1 Preamble

In this document all the tests are described for both types of machines:

- Induction Machines with Squirrel Cage – Inner Rotor
- Induction Machines with Squirrel Cage – Outer Rotor

When the machines are illustrated with inner rotor, keep in mind that the conditions of test and methods of computation are the same. One test allows to perform thermal computations for Induction Machines with Squirrel Cage – Inner Rotor.

1.2 Overview

Altair® FluxMotor® dedicated test environment (TEST area inside Motor Factory) enables users to assess motor performance. Standard and relevant test portfolios are available. All the predefined tests are ready to be performed.

Relevant input parameters allow users to control test conditions.

Processes are based on optimization technology. All the results are automatically illustrated.

Tests associated with the convention of operating Motor are grouped into packages and classified into test families.

Test family	Topology	Package	Convention	Test
Characterization	IMSQ – IR/OR	Model	Motor	Basic
Characterization	IMSQ – IR/OR	Model	Motor	SSFR
Characterization	IMSQ – IR ⁽¹⁾	Thermal	Motor & Generator	Steady State
Working point	IMSQ – IR/OR ⁽¹⁾	Sine wave	Motor	U-f-N
Performance mapping	IMSQ – IR/OR	Sine wave	Motor	T(slip)
Mechanics	IMSQ – IR ⁽¹⁾⁽²⁾	NVH	Motor	Work. Pt. U-f-N
Mechanics	IMSQ – IR ⁽¹⁾⁽²⁾	NVH	Motor	Work. Pt. I-f-N
Mechanics	IMSQ – IR ⁽¹⁾⁽²⁾	NVH	Motor	Spectrogram - U-f-N
Mechanics	IMSQ – IR ⁽¹⁾⁽²⁾	NVH	Motor	Spectrogram - I-f-N

Notes:

- (1) The test (working point U-f-N, in motor mode is available for both topologies inner and outer rotor. However, the computation in steady state of the thermal behavior is available only for inner rotor topology.
NVH tests are also available only for inner rotor topology.
- (2) In the current version, NVH tests are available only in beta mode user level (See user preferences – Advanced tab)
- (3) The tests are described in documents dedicated to each test family. Here is the list of available documents:
 - MotorFactory_2022.1_IMSQ_IOR_3PH_Test_Characterization
 - MotorFactory_2022.1_IMSQ_IOR_3PH_Test_WorkingPoint
 - MotorFactory_2022.1_IMSQ_IOR_3PH_Test_PerformanceMapping
 - MotorFactory_2022.1_IMSQ_IR_3PH_Test_Mechanics

1.3 Test inputs & settings - Overview

1.3.1 Settings

Settings allow defining the context in which the test is going to be performed. Their definition is specific to each test.

Settings are defined into three main domains:

- Thermal:
 - To make the choice of the thermal solving (when available)
 - To define the active components temperatures (Stator winding and squirrel cage)
- Electronics: To define the power electronics stage feeding the machine
- Mechanics: To define the mechanical loss model parameters

1

2

3

Thermal

Electronics

Mechanics

INPUTS

Line-Line voltage, rms (V)

370.0

Power supply frequency (Hz)

50.0

Operating mode

Motor

User working point - Slip (%)

5.0

+

✓

↺

1	Button to define winding and squirrel cage temperatures to be considered in the test.
2	Button to define the user inputs of the power electronics stage
3	Button to define the parameters of the mechanical loss model

Next sections of this document describe more in-depth of the available settings.

1.3.2 Advanced parameters

In addition to standard parameters, the users can access a list of advanced parameters.

Advanced parameters show additional parameters which helps in fine tuning of the computations in the software (through finite element modeling and simulation parameters) like the number of computations, Mesh order, Rotor initial position mode etc.

Thermal

Electronics

Mechanics

INPUTS

Line-Line voltage, rms (V)

200.0

Power supply frequency (Hz)

50.0

Operating mode

Motor

User working point - Slip (%)

5.0

+

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📄

1

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2

Thermal

Electronics

Mechanics

INPUTS

Line-Line voltage, rms (V)

200.0

Power supply frequency (Hz)

50.0

Operating mode

Motor

User working point - Slip (%)

5.0

Slip distribution mode

Log.

No. comp. in slip range

15

Slip table

-

Rotor initial position (deg)

0.0

Mesh order

2nd

Airgap mesh coefficient

1.5

-

✓

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▶

📄

📄

1	List of standard user input parameters
2	Click on “+” allows to display advanced parameters Once displayed, advanced parameters can be hidden by clicking on “-”
3	List of advanced parameters

2 THERMAL SETTINGS

2.1 Overview

In the thermal settings, depending on the considered test, you have two possible configurations:

- Either, you can define the temperatures of active components (squirrel cage and stator winding) or define the physical properties of the materials needed to run the tests without any thermal computation
- Else you can choose between two other ways to run the test: iterative process until convergence or only one iteration process to perform electromagnetic computation coupled to thermal analysis.

The workflow of all these processes is described here-after.

Edit thermal settings

THERMAL

TEMPERATURE

Winding straight part temperature (°C)	20.0
C.S. end winding temperature (°C)	20.0
O.C.S. end winding temperature (°C)	20.0
Bar temperature (°C)	20.0
C.S. end ring temperature (°C)	20.0
O.C.S. end ring temperature (°C)	20.0

✓

✕

?

1

Edit thermal settings

THERMAL

Thermal solving

⊗

→

↔

TEMPERATURE

Winding straight part temperature (°C)	20.0
C.S. end winding temperature (°C)	20.0
O.C.S. end winding temperature (°C)	20.0
Bar temperature (°C)	20.0
C.S. end ring temperature (°C)	20.0
O.C.S. end ring temperature (°C)	20.0

✓

✕

?

2

1	Default mode of thermal setting for all the tests without thermal analysis
2	Thermal settings with two solving modes for all the tests with thermal analysis

In the current version, the tests which allow using the thermal solving mode are the computations of working points defined by U, f, N with motor convention for Induction Machines with Squirrel cage with inner rotor only.

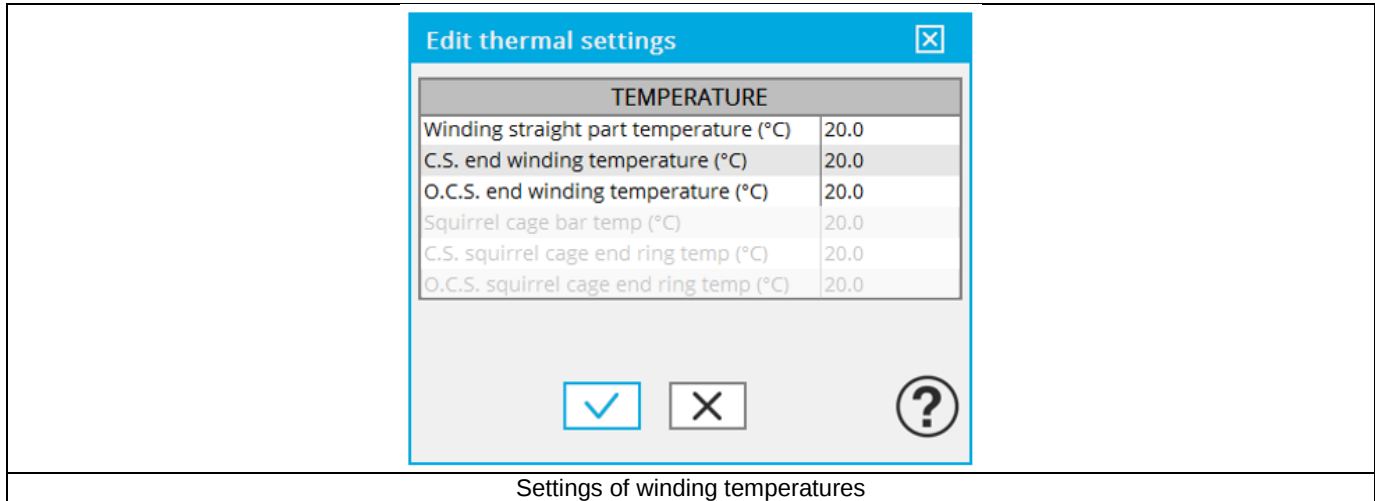
2.2 Thermal settings – Without thermal solving mode

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.

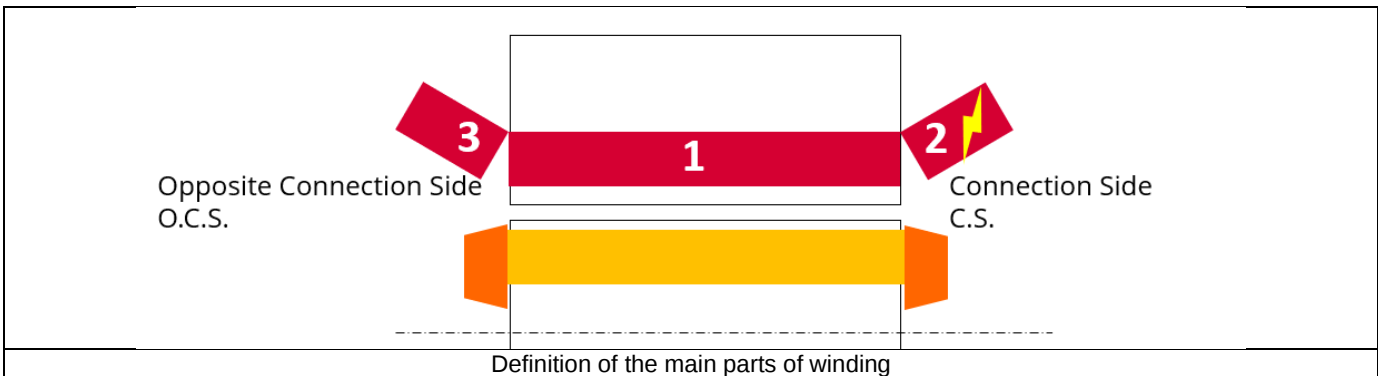
In this case, one must define the temperatures of active components to update the corresponding material physical properties. For Induction Machines with Squirrel cage, stator winding and squirrel cage temperatures must be defined.

2.2.1 Temperature of stator winding



It is possible to define temperature of the three main parts of the stator winding:

- Winding active length temperature (part 1)
- Connection Side (C.S.) end winding temperature (part 2)
- Opposite Connection Side (O.C.S.) end winding temperature (part 3)

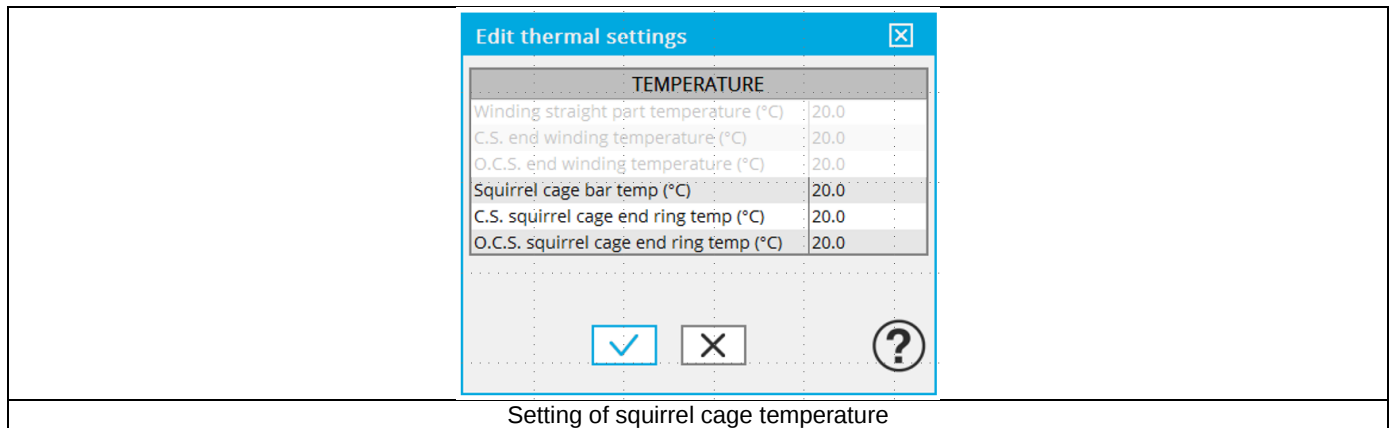


The resulting resistance of each part of the winding is updated according to the temperature:

- Winding straight part resistance (part 1)
- Connection Side (C.S.) end winding resistance (part 2)
- Opposite Connection Side (O.C.S.) end winding resistance (part 3)

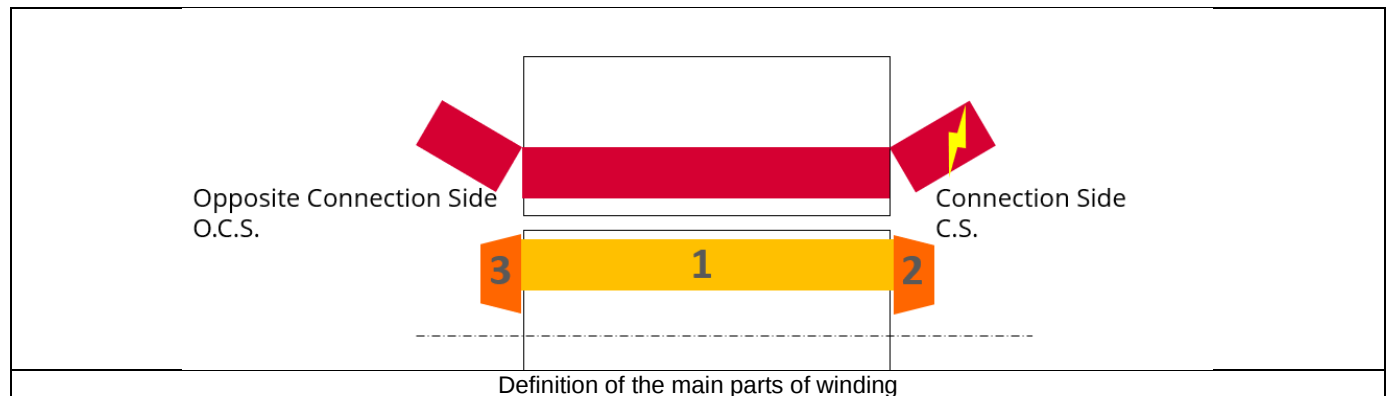
The resulting resistance for the whole winding (considering the three parts described above) is computed as phase resistance and line-line resistance.

2.2.2 Temperature of the squirrel cage



It is possible to define temperature of the three main parts of the squirrel cage:

- Bar temperature (part 1)
- Connection Side (C.S.) end ring temperature (part 2)
- Opposite Connection Side (O.C.S.) end ring temperature (part 3)

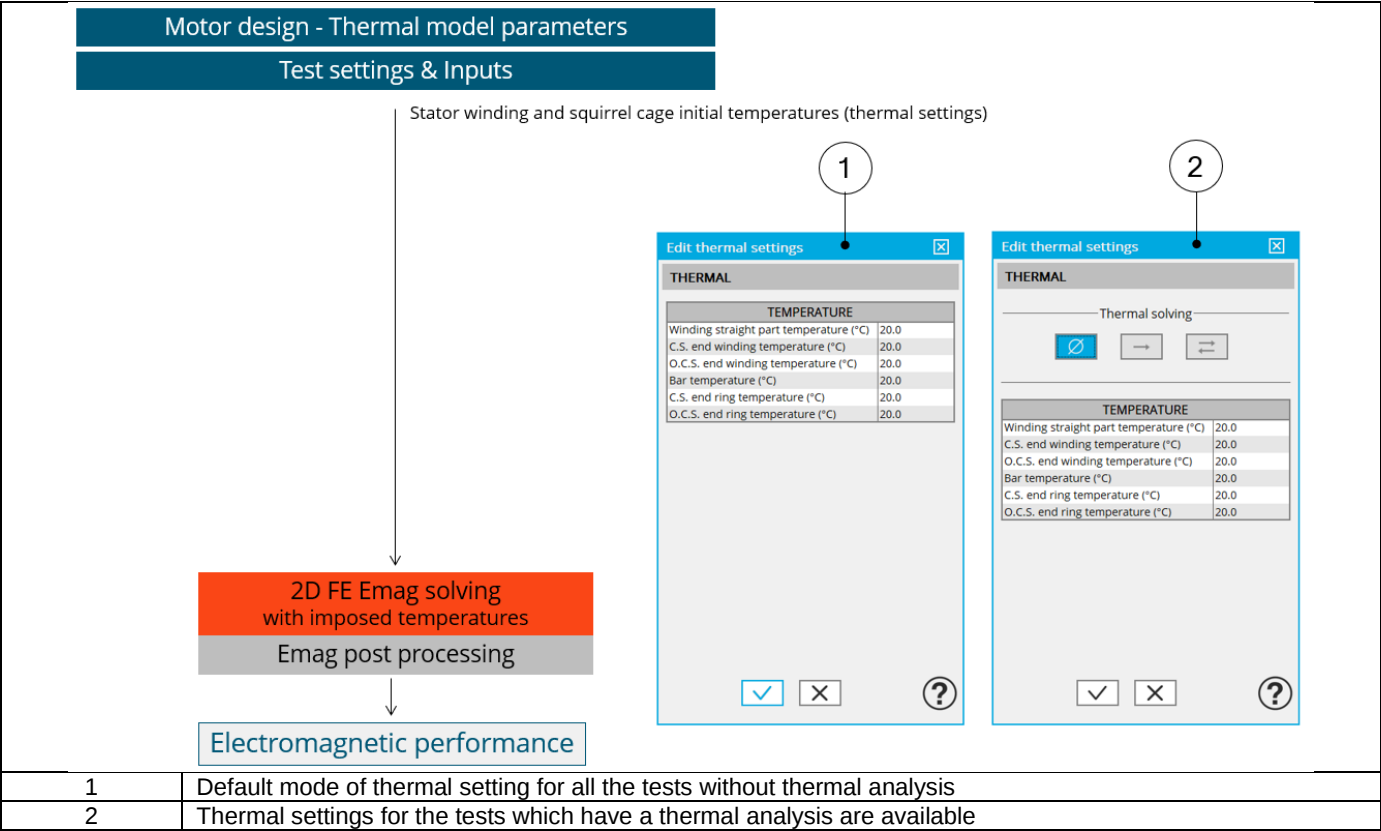


The resulting resistivity and resistance of each part of the squirrel cage is updated according to the temperature:

- Bar DC resistance (part 1)
- Connection Side (C.S.) end ring resistance (part 2)
- Opposite Connection Side (O.C.S.) end ring resistance (part 3)

2.2.3 Flow chart of the tests without thermal solving mode

Below is the flow chart of computation, for test without thermal solving mode, available for all the tests.



2.3 Thermal settings – Thermal solving mode

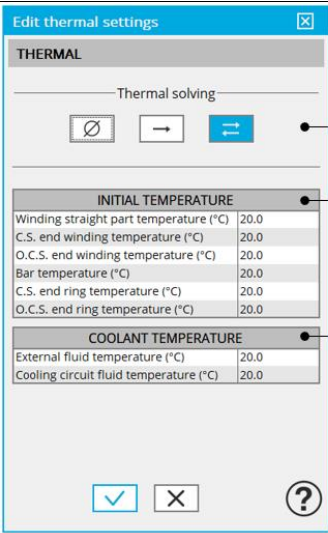
2.3.1 Overview

The choice of thermal solving mode is available for the test dealing with the computation of working point defined by the line-line voltage, power supply frequency and speed. These solving modes involve interactions between electromagnetic and thermal computations.

Two scenarios are available: one with iterative process between electromagnetic and thermal computations until convergence, and the other one with only one iteration between electromagnetic and thermal computations.

2.3.2 Thermal settings to initialize the test

For both scenarios, here is the list of thermal settings needed to initialize the test.



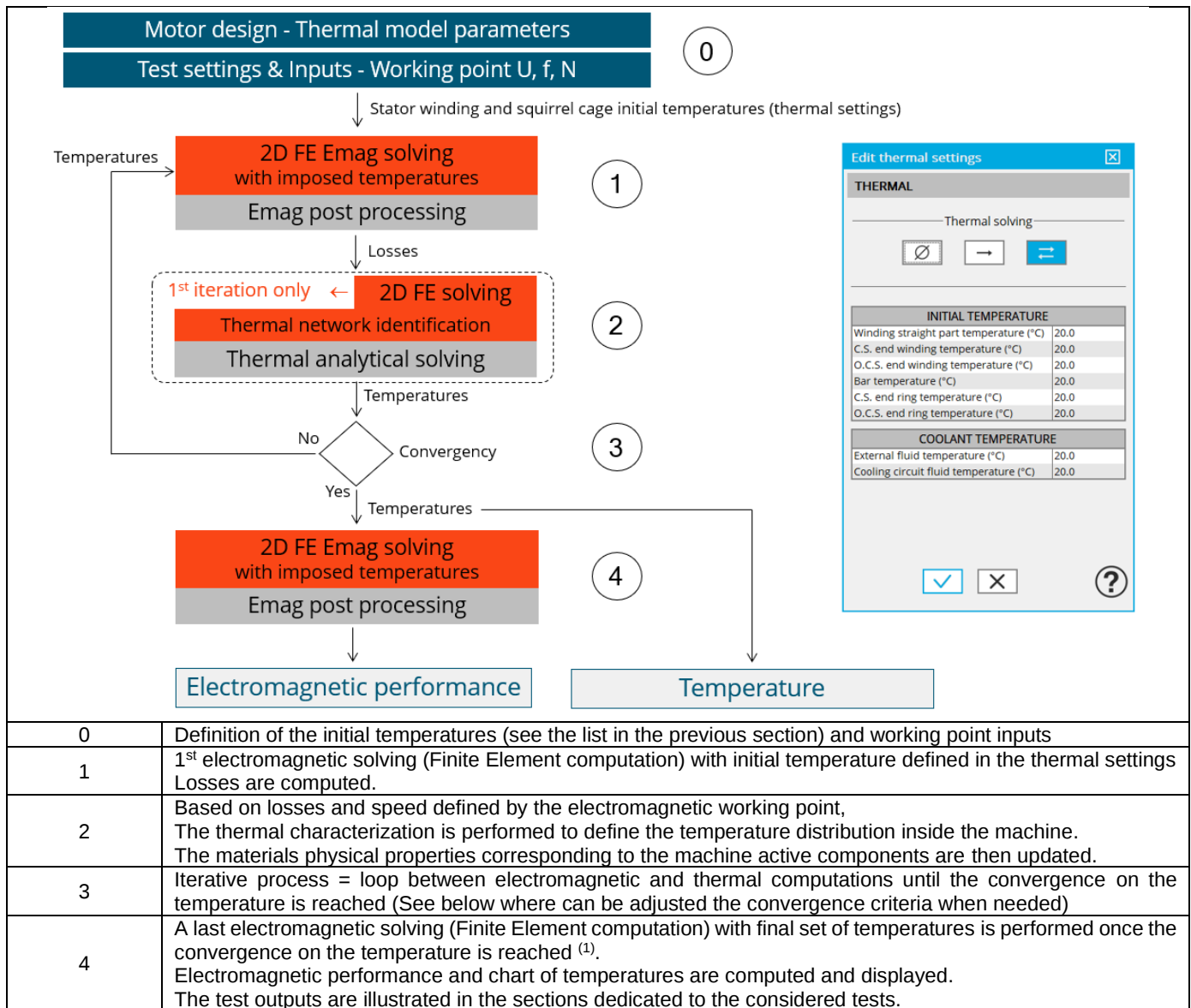
1	Dialog box to define thermal setting. Iterative solving mode is selecting
2	Initial temperatures of the machine active components: Stator winding and squirrel cage. These temperatures are used to initialize the electromagnetic-thermal process of computation.
3	Definition of coolant temperatures to be considered: - External fluid temperature ⁽¹⁾ - Cooling circuit fluid temperature ⁽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 inlet temperature is proposed only when a cooling circuit has been added by the user in the design environment.

2.3.3 Flow chart of thermal solving mode – Iterative process

1) Flow chart for the thermal model solving test with iterative process is given below.



(1) The temperatures which are considered for computed the final machine performance (step 4 in the previous flow chart) can be read in the table dealing with “Winding and Squirrel cage characteristics” of the test configuration at the beginning of result report. See below illustration. The same principle is applied for the squirrel cage temperature. The temperatures are also displayed in the temperature chart and table after electromagnetic results.

Overview	Current				
Settings					
Thermal					
Thermal solving	Iterative				
Winding straight part temperature (°C)	20.0	C.S. end winding temperature (°C)	20.0	O.C.S. end winding temperature (°C)	20.0
Bar temperature (°C)	20.0	C.S. end ring temperature (°C)	20.0	O.C.S. end ring temperature (°C)	20.0
External fluid temperature (°C)	20.0	Cooling circuit fluid temperature (°C)	20.0		
Electronics					
Power electronics stage	Without				
Mechanics					
Mechanical loss computation mode	User				
Reference speed (rpm)	1 000.0	Losses at reference speed (W)	0.0	Speed exponent	0.5

Winding and Squirrel cage characteristics

Winding					
Winding connection	Wye	Winding resistance factor	1.0		
Winding temperature (°C)	59.575				
Phase resistance (Ω)	2.026 E-1	Line-Line resistance (Ω)	4.052 E-1	End winding resistance (Ω)	1.085 E-1
Winding straight part temperature (°C)	54.355	C.S. end winding temperature (°C)	64.881	O.C.S. end winding temperature (°C)	63.586
Winding straight part temperature (°C)	20.0	C.S. end winding temperature (°C)	20.0	O.C.S. end winding temperature (°C)	20.0
Winding straight part resistance (Ω)	9.412 E-2	C.S. end winding resistance (Ω)	5.654 E-2	O.C.S. end winding resistance (Ω)	5.193 E-2
Squirrel cage					
Bar name	Bar	Bar temperature (°C)	82.787		
C.S. end ring (°C)	79.675	O.C.S. end ring (°C)	79.622		
End ring resistance factor	1.0	End ring inductance factor	1.0		
Bar DC resistance (Ω)	6.101 E-4				
AVG end ring resistance (Ω)	5.233 E-7	C.S. end ring resistance (Ω)	5.233 E-7	O.C.S. end ring resistance (Ω)	5.233 E-7
AVG end ring inductance (H)	7.9 E-9	C.S. end ring inductance (H)	7.9 E-9	O.C.S. end ring inductance (H)	7.9 E-9

1

Initial winding temperatures

2

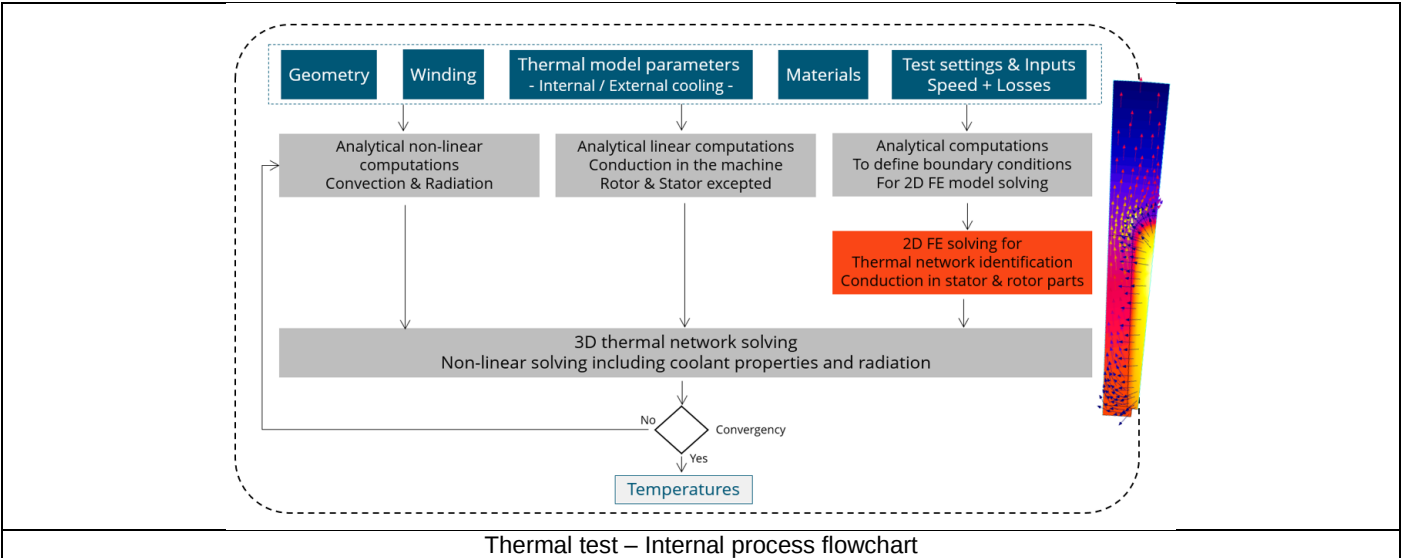
Resulting final temperatures which are considered for computing resulting machine performance

1 Initial winding temperatures

2 Resulting final temperatures which are considered for computing resulting machine performance

2) Thermal characterization in steady state – Flow chart

This section illustrates how the thermal characterization is performed to define the temperature distribution inside the machine from a set of losses and a working point speed
This process corresponds to what is performed to make the thermal characterization of the machine in the test Characterization / Thermal / Steady state
It corresponds to the second step of the previous general flow chart.



The inputs of the internal process are the parameters of: Geometry, Winding, Internal cooling, External cooling, Materials, Test settings and inputs.

Note: 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.

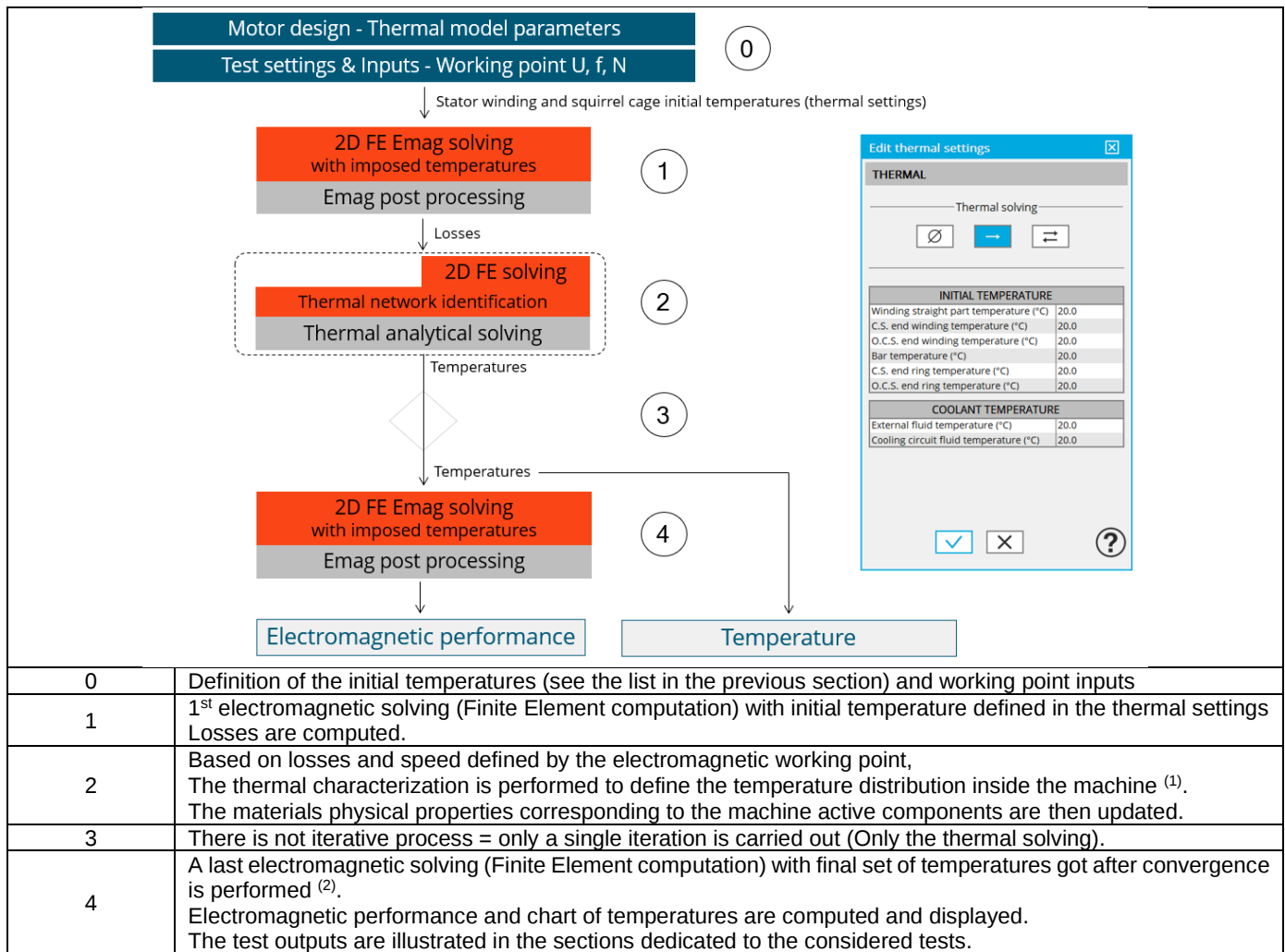
The solving allows to get and to display the whole chart of temperatures of the machines.

3) Iterative process – Adjustment of the convergence criteria

1	Selection of the thermal solving Iterative process in thermal settings
2	Convergence criteria can be adjusted for reaching steady state behavior. The iterative solving is stopped once the temperature variation in the machine between two iterations is lower than the convergence criteria. A percentage close to zero gives more accurate results but takes a higher computation time. A high percentage can make the convergence shorter but decreases the accuracy of the results.

2.3.4 Flow chart of thermal solving mode – “One iteration” process

1) Flow chart of the thermal solving mode test with single iteration is given below.



- (1) It corresponds to what is done to perform the thermal characterization of the machine in the test Characterization / Thermal / Steady state.
- (2) The temperatures which are considered for computed the final machine performance (step 4 in the previous flow chart) can be read in the table dealing with “Winding and Squirrel cage characteristics” of the test configuration at the beginning of result report. See below illustration. The same principle is applied for the squirrel cage temperature.

The temperatures are also displayed in the temperature chart and table after electromagnetic results.

Overview	Current				
Settings					
Thermal					
Thermal solving	Iterative				
Winding straight part temperature (°C)	20.0	C.S. end winding temperature (°C)	20.0	O.C.S. end winding temperature (°C)	20.0
Bar temperature (°C)	20.0	C.S. end ring temperature (°C)	20.0	O.C.S. end ring temperature (°C)	20.0
External fluid temperature (°C)	20.0	Cooling circuit fluid temperature (°C)	20.0		
Electronics					
Power electronics stage	Without				
Mechanics					
Mechanical loss computation mode	User				
Reference speed (rpm)	1 000.0	Losses at reference speed (W)	0.0	Speed exponent	0.5

Winding and Squirrel cage characteristics

Winding					
Winding connection	Wye				
Winding temperature (°C)	59.575	Winding resistance factor	1.0		
Phase resistance (Ω)	2.026 E-1	Line-Line resistance (Ω)	4.052 E-1	End winding resistance (Ω)	1.085 E-1
Winding straight part temperature (°C)	54.355	C.S. end winding temperature (°C)	64.881	O.C.S. end winding temperature (°C)	63.586
Winding straight part temperature (°C)	20.0	C.S. end winding temperature (°C)	20.0	O.C.S. end winding temperature (°C)	20.0
Winding straight part resistance (Ω)	9.412 E-2	C.S. end winding resistance (Ω)	5.654 E-2	O.C.S. end winding resistance (Ω)	5.193 E-2
Squirrel cage					
Bar name	Bar				
C.S. end ring (°C)	79.675	Bar temperature (°C)	82.787		
End ring resistance factor	1.0	O.C.S. end ring (°C)	79.622		
Bar DC resistance (Ω)	6.101 E-4	End ring inductance factor	1.0		
AVG end ring resistance (Ω)	5.233 E-7	C.S. end ring resistance (Ω)	5.233 E-7	O.C.S. end ring resistance (Ω)	5.233 E-7
AVG end ring inductance (H)	7.9 E-9	C.S. end ring inductance (H)	7.9 E-9	O.C.S. end ring inductance (H)	7.9 E-9

1

Initial winding temperatures

2

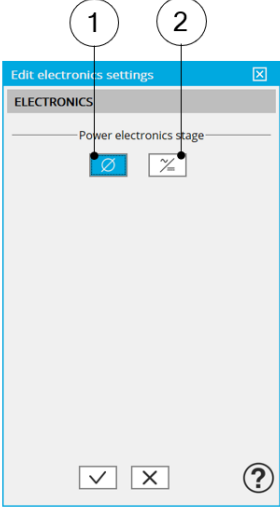
Resulting final temperatures which are considered for computing resulting machine performance

3 POWER ELECTRONICS MODE

3.1 Overview

A dedicated dialog box allows the user to operate the motor with power electronic stage or without power electronic stage. The following tests are concerned by this feature:

- Working point / Sine wave / Motor / U, f, N
- Performance mapping / Sine wave / Motor / T(slip)



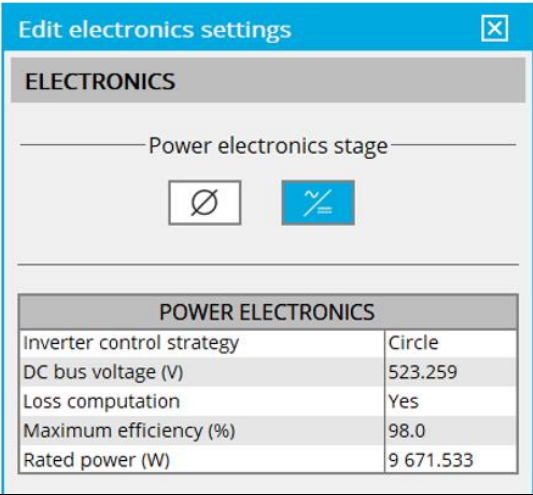
1	Button to not consider power electronics stage (=default mode)
2	Button to define the user parameters of the power electronic mode

3.2 Power electronics parameters

3.2.1 Overview

When available, the selection of the “Power electronics mode” gives access to a dedicated list of user input parameters. The number of user parameters to define depends on the selected test.

The whole list of power electronics parameters is illustrated below.

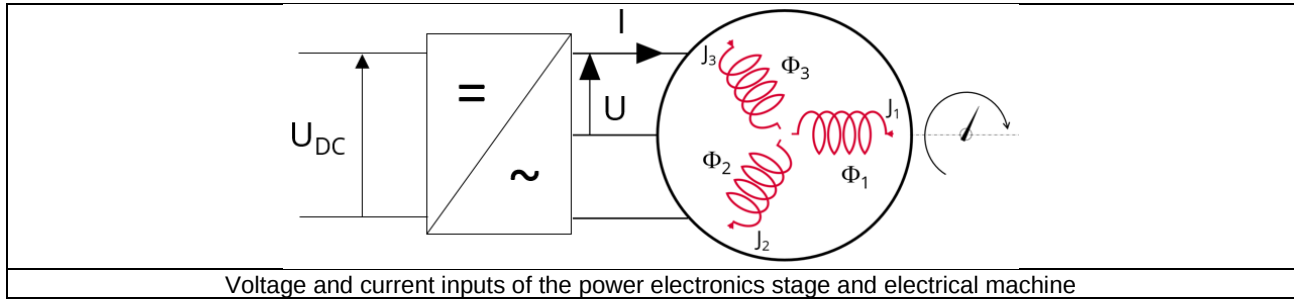


Power electronics mode: whole list of input parameters

3.2.2 DC bus voltage and Inverter control

When the power electronics stage is active, the line-line voltage at the machine terminals required in, inputs of some tests becomes non-accessible. In this case, the line-line voltage is computed from the DC bus voltage (DC bus voltage before inverter UDC) and the Inverter control strategy set in power electronics settings.

The variation range values of DC bus voltage is]0; +inf. [



The chosen inverter control drives the ratio between the DC bus voltage and the line-line voltage seen at the machine terminal. This ratio is defined as:

$$k = \frac{U_{rms}}{U_{DC}}$$

Where U_{DC} is the DC bus voltage before inverter stage and U_{rms} is the rms value of the first harmonic of the line-line voltage at the terminal end of the machine.

The considered inverter control strategies and their corresponding values of k are listed in the table below.

Inverter control strategy	Value of k
Circle tracking	$\frac{1}{\sqrt{2}}$
Hexagon tracking piecewise linear	$\frac{3\sqrt{6}}{\pi^2}$
Hexagon tracking secant	$\frac{0.60573\sqrt{3}}{\sqrt{2}}$
Maximum linear range of triangle/sinus	$\frac{\sqrt{3}}{2\sqrt{2}}$
Six Steps 120°	$\frac{3}{\pi\sqrt{2}}$
Six Steps 180°	$\frac{\sqrt{6}}{\pi}$

3.2.3 Loss computation

An internal process allows evaluating the power dissipated in the power electronics stage and its efficiency.

To get the result of this computation the user input **Loss computation (Power electronics loss computation)** must to be set "Yes". The default value is "No".

When this input is set to "Yes", the computation of power electronics losses and efficiency is performed based on two other parameters to define: The maximum efficiency and the rated active power of the power electronic device to consider.

3.2.4 Max. efficiency (Maximum power electronics efficiency)

This parameter defines the maximal efficiency that the power electronics stage can reach. This efficiency corresponds to the efficiency of an inverter or a variable speed drive.

The losses occurring in the power electronics stage are computed using this parameter and the “Rated power” settings.

Max. efficiency is set to 98% by default.

The variation range of values for this parameter is [10; 100].

3.2.5 Rated power – inverter or variable speed drive

This parameter defines the rated active power of the power electronic stage to consider.

It corresponds to the maximum active power that the power electronics stage (inverter or variable speed drive) can deliver without being overloaded.

The losses occurring in the power electronics stage are computed using this parameter and the parameter “Max. efficiency”.

The rated power default value is defined from the default values of the system (machine and inverter) input voltage and current.

The variation range of values for this parameter is [0; +inf. [

Note 1: The internal process for evaluating the power electronics efficiency versus its rated power is based on analytical empirical formula.

Note 2: Only the first harmonic is considered to compute the behavior of machines. Induced losses due to the switching frequencies are not considered.

3.3 Advice for use

- The internal process defining the power electronics stage gives null efficiency and losses when no power entering the power electronics stage. This is a limit of the used model. Physically, losses are not equal to zero at this point, because switching creates losses even when no power is transmitted.
- For working points above the rated power of the power electronics stage, the model efficiency is decreasing until zero. (Between 120 and 150% of the rated load, depending of the selected inputs). Warning, the given efficiency and losses are not qualified and cannot be guaranteed beyond 100% of the rated electrical active power.
- For a variable speed drive, when the DC bus voltage is not known, set the DC bus voltage to a value slightly lower than the maximum AC voltage provided by the grid.
- **To impose the voltage directly at the machine terminals**, when using the power electronics mode, set the desired peak value voltage at the machine terminals in the field “DC voltage”, and choose the command “circle” on the inverter.

3.4 Dedicated outputs

When power electronics is active, the line-line voltage at the machine terminals and the DC bus voltage are computed/displayed.

Moreover, when the “loss computation” is selected by the user, additional output data are computed and/or displayed.

The losses and the efficiency are computed for the machine, the power electronics stage and the system. The “system” gathers the machine and the power electronics stage.

Then, the electrical power is computed for both the machine and the system.

Power electronics					
Inverter					
Inverter control strategy	Circle	DC bus voltage (V)	551.543	Max. Line-Line voltage, rms (V)	390.0
Working point					
System total losses (W)	2 678.872	Machine total losses (W)	1 230.283	Power electronics losses (W)	1 448.588
System efficiency (%)	95.628	Machine efficiency (%)	97.943	Power electronics efficiency (%)	97.636
System electrical power (W)	61 269.113	Machine electrical power (W)	59 820.524		

Power electronics mode with loss evaluation – Example of dedicated output table

3.5 Power electronic and tests

The available input parameters dedicated to the power electronics mode depend on the considered test.

Below is the table which defined the correspondence between the tests and the input parameters of the power electronics mode.

The whole lists of input parameters are illustrated below.

POWER ELECTRONICS	
Inverter control strategy	Circle
DC bus voltage (V)	551.543
Loss computation	Yes
Maximum efficiency (%)	98.0
Rated power (W)	69 580.766

Whole lists of input parameters dedicated to power electronics

	Inverter Ctrl. strategy	DC bus voltage	Loss computation
Characterization / Model / Motor / Basic	-	-	-
Characterization / Model / Motor / SSFR	-	-	-
Characterization / Model / Thermal / Steady state	-	-	-
Characterization / Model / Thermal / Transient	-	-	-
Working point / Sine wave / Motor / U-f-N	Available	Available	Available
Performance mapping / Sine wave / Motor / T(Slip)	Available	Available	Available
Mechanics / NVH / Working Point / U-f-N	-	-	-
Mechanics / NVH / Working Point / I-f-N	-	-	-
Mechanics / NVH / Spectrogram / U-f-N	-	-	-
Mechanics / NVH / Spectrogram / I-f-N	-	-	-

Notes:

- Loss computation uses Max. efficiency and rated power user inputs
- “-” means the parameter is not used in the considered test

4 MECHANICAL LOSS MODEL PARAMETERS

The definition of mechanical loss computation model is available only for some tests.

MECHANICAL LOSSES	
Ref. speed (rpm)	1 000.0
Losses at ref. speed (W)	0.0
Speed exponent	0.5

User inputs for defining the mechanical losses

Mechanical loss model is considered as:

$$W_{\text{mech}} = W_0 \times \left(\frac{N}{N_0} \right)^{K+1}$$

The following input parameters are needed:

- “**Ref. speed**” (Reference speed) – N_0
- “**Losses at ref. speed**” (mechanical losses at reference speed) – W_0
- “**Exponent**” (Speed exponent) - K
- Current speed “ N ” for which the mechanical losses “ W_{mech} ” must be computed

5 TEST GENERIC INFORMATION

5.1 Electrical machine – Theoretical equations

5.1.1 Electrical induction machines with squirrel cage – Motor convention – Parameters and power balance

The aim of this paragraph is to present all the equations used to compute the power balance of the induction machine with a squirrel cage. As said before, for this purpose, symmetrical components are used, and iron losses are integrated to the power balance.

1) Symmetrical component transformation

The symmetrical component transformation is commonly used to study unbalanced systems. Three phase quantities are transformed by the following matrix into direct component (d), inverse component (i) and homopolar component (0)

$$\begin{aligned} J_N &= J_{N\ Mod} \times e^{jJ_N\ Arg} \\ V_N &= V_{N\ Mod} \times e^{jV_N\ Arg} \end{aligned}$$

$$\begin{bmatrix} J_d \\ J_i \\ J_0 \end{bmatrix} = \frac{1}{3} \times \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} J_a \\ J_b \\ J_c \end{bmatrix} \quad a = e^{\frac{j \times 2 \times \pi}{3}}$$

$$\begin{bmatrix} V_d \\ V_i \\ V_0 \end{bmatrix} = \frac{1}{3} \times \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

Ja: Phase current - Phase A
Jb: Phase current - Phase B
Jc: Phase current - Phase C

Va: Phase voltage - Phase A
Vb: Phase voltage - Phase B
Vc: Phase voltage - Phase C

Jd: Current phase direct component
Ji: Current phase inverse component
J0: Current phase homopolar component

Vd: Voltage phase direct component
Vi: Voltage phase inverse component
V0: Voltage phase homopolar component

Notes:

- In the above formulae the RMS quantities are considered
- The above matrix definition shows that symmetrical components are complex quantities

The case considered by FluxMotor® is a balanced system (alimentation and winding). In this case (balanced system), inverse and homopolar components must be zero, but as previously discussed, they aren't due to various airgap reluctance seen by each phase. So, to obtain a perfect balanced system, only the direct component must be considered. Modulus and phase of electromagnetic quantities (voltage, current...) are deduced from the complex value of the direct component.

2) Phase current, rms value

$$\underline{J_s} = \text{real}(J_d) + j \times \text{imag}(J_d)$$

$$J_s = \sqrt{\text{real}(J_d)^2 + \text{imag}(J_d)^2}$$

3) Phase voltage, rms value

$$\underline{V_s} = \text{real}(V_d) + j \times \text{imag}(V_d)$$

$$V_s = \sqrt{\text{real}(V_d)^2 + \text{imag}(V_d)^2}$$

4) Phase angle

Angle of the phase current vector:

$$J_{S\ phase} = \angle(\underline{J_S})$$

Angle of the phase voltage vector:

$$V_{S\ phase} = \angle(\underline{V_S})$$

Angle between the phase voltage and the phase current vectors:

$$\varphi = (\underline{V_S}, \underline{J_S}) = V_{S\ phase} - J_{S\ phase}$$

5) Power factor

$$PF = \cos(\varphi)$$

Note: All the others electromagnetic quantities are computed from current, voltage and power factor obtained thanks to the symmetrical component transformation except for iron losses which are computed by Flux®.

6) Power supply frequency

" f_S " is the power supply frequency

7) Stator electrical pulsation

$$\omega_S = 2 \times \pi \times f_S$$

8) Stator field speed (stator reference)

$$\Omega_S = \frac{\omega_S}{p}$$

p: Number of pole pairs

9) Slip

The slip (s) corresponds to the difference between the speed of the rotating magnetic field in the stator (Ω_S) and the rotor operating speed (Ω).

$$s = \frac{\Omega_S - \Omega}{\Omega_S}$$

Ω_S : Stator field speed

Ω : Rotor operating speed

10) Rotor electrical frequency

$$f_R = s \times f_S$$

11) Rotor electrical pulsation

$$\omega_R = 2 \times \pi \times f_R$$

12) Rotor field speed (rotor reference)

$$\Omega_R = \frac{\omega_R}{p} = \frac{2 \times \pi \times f_S \times s}{p}$$

p: Number of pole pairs

13) Rotor speed Ω

$$\Omega_R = \frac{\omega_R}{p} = \Omega_S - \Omega$$

$$\Omega = \Omega_S - \Omega_R = \frac{\omega_S}{p} \times (1 - s)$$

ω_S : Stator electrical pulsation
 ω_R : Rotor electrical pulsation
 Ω_S : Stator field speed
 Ω_R : Rotor field speed
 Ω : Rotor operating speed
 p : Number of pole pairs

14) Line current, rms value

. Wye connection

$$I_S = J_S$$

. Delta connection

$$I_S = \sqrt{3} \times J_S$$

J_S : Phase current, rms value
 I_S : Line current, rms value

15) Line-Line voltage, rms value

. Wye connection

$$U_S = \sqrt{3} \times V_S$$

. Delta connection

$$U_S = V_S$$

V_S : Phase voltage, rms value
 U_S : Line-Line voltage, rms value

16) Machine electrical power

$$P_{elec} = \sqrt{3} \times U_S \times I_S \times \cos(\varphi)$$

17) Stator Joule losses

$$P_{JS} = 3 \times R_S \times J_S^2$$

18) Stator Iron losses

$$W_{iron\ stator} = Nb_{Flux\ Pole\ number\ represented} \times W_{Flux\ iron\ stator}$$

19) Rotor Iron losses

$$W_{iron\ rotor} = Nb_{Flux\ Pole\ number\ represented} \times W_{Flux\ iron\ rotor}$$

20) Total Iron losses

$$W_{iron\ tot} = W_{iron\ rotor} + W_{iron\ stator}$$

21) Power crossing the airgap

The transmitted power seen on the stator side is expressed as following:

$$P_{ag} = P_{elec} - W_{joule\ stator} - W_{iron\ stator}$$

Note: the power crossing the airgap P_{ag} includes the electromagnetic power and the rotor electrical losses

22) Torque crossing the airgap

T_{ag} is the torque corresponding to the power crossing the airgap P_{ag}

$$T_{ag} = \frac{P_{ag}}{\Omega_s}$$

Ω_s : Stator field speed

As this torque is applied to the rotor whose velocity is Ω , the resulting power transmitted to the rotor P_{rotor} is defined as below:

$$P_{rotor} = T_{ag} \times \Omega = \left(\frac{P_{ag}}{\Omega_s} \right) \times \Omega = \left(\frac{\Omega}{\Omega_s} \right) \times P_{ag} = (1 - s) \times P_{ag} = P_{rotor}$$

Ω_s : Stator field speed

Ω : Rotor operating speed

p : Number of pole pairs

From the expression of the power received by the rotor, we can express the transmitted power seen on the rotor side:

$$P_{ag} - P_{rotor} = W_{joule\ rotor} + W_{iron\ rotor}$$

$$P_{ag} - (1 - s) \times P_{ag} = W_{joule\ rotor} + W_{iron\ rotor}$$

$$s \times P_{ag} = W_{joule\ rotor} + W_{iron\ rotor}$$

$$P_{ag} = \frac{W_{joule\ rotor} + W_{iron\ rotor}}{s}$$

23) Rotor Joule losses

$$W_{joule\ rotor} = s \times P_{ag} - W_{iron\ rotor}$$

24) Total Joule losses

$$W_{tot} = W_{joule\ stator} + W_{joule\ rotor}$$

25) Electromagnetic torque

$$T_{em} = \frac{P_{em}}{\Omega} = \frac{P_{em}}{(1 - s) \times \Omega_s}$$

$$T_{em} = \frac{W_{joule\ rotor}}{\Omega_R} = \frac{W_{joule\ rotor}}{s \times \Omega_s}$$

Ω_s : Stator field speed

Ω_R : Rotor field speed

Ω : Rotor operating speed

26) Electromagnetic power

$T_{em} = \frac{P_{em}}{\Omega} = \frac{P_{em}}{(1-s) \times \Omega_S}$	$T_{em} = \frac{W_{Joule\ rotor}}{\Omega_R} = \frac{W_{Joule\ rotor}}{s \times \Omega_S}$
---	---

$$\frac{P_{em}}{(1-s) \times \Omega_S} = \frac{W_{Joule\ rotor}}{s \times \Omega_S}$$

$W_{Joule\ rotor} = \frac{(1-s) \times P_{em}}{s}$	$P_{ag} = \frac{W_{Joule\ rotor} + W_{iron\ rotor}}{s}$
--	---

$$P_{em} = \left[P_{ag} - \frac{W_{iron\ rotor}}{s} \right] \times (1-s)$$

Ω_S : Stator field speed
 Ω_R : Rotor field speed
 Ω : Rotor operating speed

27) Mechanical losses

$$W_{mech.} = W_0 \times \left(\frac{N}{N_0} \right)^{K+1}$$

The following input parameters are defined by the user:

"Ref. speed" (Reference speed) – N_0

"Losses at ref. speed" (mechanical losses at reference speed) – W_0

"Exponent" (Speed exponent) - K

Current speed "N" for which the mechanical losses " $W_{mech.}$ " must be computed

Note: for $s = 1$, set $W_{mech.} = 0$

28) Mechanical losses equivalent torque

$$T_{mech. loss.} = \frac{W_{mech.}}{\Omega}$$

29) Mechanical power

$$P_{mech.} = P_{em} - W_{mech.}$$

30) Mechanical torque

$$T_{mech.} = \frac{P_{mech.}}{\Omega}$$

31) Machine total losses

$$W_{tot.} = W_{Joule\ stator} + W_{Joule\ rotor} + W_{iron\ stator} + W_{iron\ rotor} + W_{mech.}$$

32) Power electronics losses (if option selected and/or available)

Refer to "Power Electronic" paragraph which defines the computation method to obtain efficiency " η_{PE} " and losses " P_{PE} " of the power electronics.

- System electrical power

The absorbed power of the global system (machine and power electronics) is defined as:

$$W_{elec\ system} = W_{elec} + W_{PE}$$

- System total losses

$$W_{tot.\ system} = W_{Joule\ stator} + W_{Joule\ rotor} + W_{iron\ stator} + W_{iron\ rotor} + W_{mech.} + W_{PE}$$

33) Machine apparent power

$$\underline{S_n} = \sqrt{3} \times \underline{U_s} \times \underline{I_s}$$

$$S_n = \sqrt{3} \times U_s \times I_s$$

34) Machine reactive electrical power

$$Q_n = Im(\underline{S_n})$$

$$Q_n = \sqrt{3} \times U_s \times I_s \times \sin(\varphi)$$

35) Machine efficiency

- Motor mode

$$\eta = 100 \times \frac{P_{mech.}}{P_{elec}}$$

- Braking mode

$$\eta = 100 \times \frac{abs(P_{mech.})}{P_{elec}}$$

- Generator mode

$$\eta = 100 \times \frac{P_{elec}}{P_{mech.}}$$

36) System efficiency

$$\eta_{system} = \eta \times \eta_{PE}$$

37) Current density in stator conductors, rms value

$$J_{cond} = \frac{I_s}{P_{paths} \times A_{cond}}$$

A_{cond} : Conductor conductive area – See winding section A

P_{paths} : Number of parallel paths

38) Electric loading

This is the ratio between total ampere conductors and airgap circumference

$$A_1 = \frac{2 \times m \times T_{ph} \times J_S}{\pi \times D_{bore}}$$

With:

m : number of phases = 3
 T_{ph} : Number of turns in series per phase
 D_{bore} : Bore diameter
 J_S : phase current, rms value

39) Bar and inter-bar current correction factor

Flux® does not include iron losses in the solving resolution. To compute a correct power balance, FluxMotor® computation process includes iron losses when computing the transmitted power and of rotor Joule losses.

According to this point, a correction factor must be applied on bar and inter-bar current computed by Flux® to propose a current values in agreement with rotor Joule losses evaluated by FluxMotor® computation process.

- Transmitted power without iron losses

$$P_{ag\ Flux} = P_{elec} - W_{Joule\ stator}$$

- Rotor Joule losses without iron losses

$$W_{Joule\ rotor\ Flux} = S \times P_{ag\ Flux}$$

$W_{Joule\ rotor} = A \times J_{R\ model}^2$	$W_{Joule\ rotor\ Flux} = A \times J_{R\ Flux}^2$
--	---

$$J_{R\ model} = J_{R\ Flux} \times \sqrt{\frac{W_{Joule\ rotor}}{W_{Joule\ rotor\ Flux}}}$$

$$J_{R\ model} = J_{R\ Flux} \times X_{Factor\ Jr}$$

$$X_{Factor\ Jr} = \sqrt{\frac{W_{Joule\ rotor}}{W_{Joule\ rotor\ bis}}}$$

40) Bar current

$$J_{bar\ model_n} = X_{Factor\ Jr} \cdot J_{bar\ Flux_n}$$

$J_{bar\ Flux_n}$: Bar currents computed by Flux®

41) Inter-bars current

$$J_{inter-bar\ model_n} = X_{Factor\ Jr} \cdot J_{inter-bar\ Flux_n}$$

$J_{inter-bar\ model_n}$: Inter-bar currents computed by Flux®

42) Current density in rotor bar, rms value

$$J_{bar} = \frac{\max(J_{bar\ model_n})}{S_{bar}}$$

43) Current density in rotor inter-bar, rms value

$$J_{inter-bar} = \frac{\max(J_{inter-bar\ model_n})}{S_{end\ ring}}$$

$S_{end\ ring}$: section of the ring perpendicular to the current flow

5.2 Limitation of thermal computations – Advice for use

5.2.1 General understanding of the results

FluxMotor® thermal model provides the mean temperatures of every component of the machine.

The computation does not consider:

- The hot spots linked to local phenomena, for instance between two conductors in the winding
- The hot spots linked to the machine position (horizontal, or vertical). The motor position set by the user in COOLING subset, EXTERNAL panel, is only considered to compute the external convection occurring on the frame. The temperature difference between the upper components and the lower components of the machine is neglected.
- The machine is assumed to be connected to the external environment only through the frame, itself thereby only extracting the heat to the external fluid and to the cooling circuit fluid. It is assumed that no conduction occurs outside of the represented geometry in FluxMotor®. FluxMotor® model then neglects the following cooling effects:
 - The conduction through the shaft extension until external components, as a load
 - The conduction through the fixation of the machine on the ground, or on a plate.

5.2.2 End winding temperatures

End winding geometry is complex, and many hot spots can exist in this specific part of the machine.

FluxMotor® computes an estimation of the mean temperature occurring on the Connection Side and Opposite Connection Side end windings.

Keep in mind that the real temperatures reached in such non-homogeneous regions can be far from the estimation, depending of the winding manufacturing.

5.2.3 Natural convection on end windings

When choosing to model that the end spaces are cooled with natural convection, FluxMotor® model uses a quite low rotor tip speed ratio (a value of 5) to describe the fluid velocity far from the rotating components.

This can lead to overestimates the cooling of the end winding on high speed machines. This model will be improved for future versions.

When a tip speed ratio of 5 seems to overestimate the end winding cooling, it is advised to switch to forced convection mode.

This mode allows to force some higher tip speed ratios for areas far from the rotor, this reducing the efficiency of the cooling on the end winding.

5.2.4 Bar and end ring temperatures

The bars and end rings are in most of the cases the hottest spots in induction machine with squirrel cages. The temperatures obtained by simulation on these areas are very sensitive, and highly depend on the inputs set by the user. Especially:

- The amount of losses set on the rotor. The user must be specifically careful when dividing the additional losses between the rotor and the stator.
- The axial heat extraction through the shaft and the bearing to the frame. Then the following parameters must be defined carefully: the shaft conductivity, the shaft extension diameters, the interface thickness associated to the bearing, and the bearing lengths.
- The heat extraction from the end rings to the end space fluid, involving exchange areas corresponding to each end ring, possible additional fin areas, and the convection coefficient occurring of each end ring.

5.2.5 Temperatures considered for fluidic computations

Some fluidic computations are based on two different temperatures: the temperature of the fluid, and the temperature of the wall from where the convection occurs.

This explains that the convection results shown in the design environment can be slightly different from the results obtained in the test environment.

In the design environment, the fluid and the wall are at the evaluation temperature, but in the test the wall and the fluid temperatures are evaluated during the solving and are different in most of the cases.

5.2.6 User parts in thermal computations

User parts can be used for thermal computations, as for magnetic computations.

However, a general warning must be kept in mind when building a part to use it for thermal computations.

The thermal computation is based on a finite element thermal project, where a thermal network is identified from the geometry given by the user.

On a user part, every face defined by the user will be a « node » of the thermal mesh that the process identifies on the part.

To have consistent results, be careful when defining the part that:

- There is no face surrounding another one, this giving inconsistent network.
- The faces are as much as possible close to standard shapes, likes rectangles or triangles.

On the other hand, keep in mind that the interface gaps defined in the part are only used for magnetic applications. Only the interface thicknesses defined in the COOLING subset, INTERNAL panel, are considered for thermal computations.

The thermal resistances corresponding to the interface thicknesses are computed considering that the interfaces are made of air at 273.15 Kelvin and at the atmospheric pressure at sea level, 1.013E5 Pa.

5.2.7 Assumption on the geometry of the shaft, the lamination and the frame for thermal computations

The possible air areas existing between the stator lamination and the frame are not considered in FluxMotor® thermal computations. This means that the case of a circular stator lamination, or lamination with chamfer, in contact with a square frame, is not considered.

The assumption is made that there is no gap in the conduction between the stator yoke and the frame: if a square frame is set, the computation considers that the lamination is rectangular as well, without chamfer or fillet.

It is also assumed that there is conduction through each part of the shaft until rear and front bearing (even in the case where the modeled shaft in FluxMotor® is not in contact with the frame).

In addition, the lamination extension, available in previous version, is equal to zero in the thermal computations.