Altair® FluxMotor® 2022.2

Synchronous machines – Permanent magnets - Inner & Outer rotor

Motor Factory – Test - Introduction

General user information

Altairhyperworks.com

Contents

1   TEST AREA

1.1   Preamble

This document concerns both types of machines:

- Synchronous Machines with Permanent Magnets – Inner Rotor
- Synchronous Machines with Permanent Magnets – Outer Rotor

When machines with inner rotor are illustrated, keep in mind that the conditions of tests and methods of computation are the same.

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 results are automatically illustrated.

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

Here is the list of tests for Synchronous machines with Permanent Magnets – Inner rotor and outer rotor

Test family	Topology	Package	Convention	Test
Characterization	SMPM – IR/OR	Open circuit	Motor & Generator	Cogging torque
	SMPM – IR/OR	Open circuit	Motor & Generator	Back emf
	SMPM – IR/OR	Model	Motor	Maps
	SMPM – IR/OR	Datasheet	Motor	I-U
	SMPM – IR [1]	Thermal	Motor & Generator	Steady State
	SMPM – IR [1]	Thermal	Motor & Generator	Transient
Working point	SMPM – IR/OR [1]	Sine wave	Motor	I-Ψ-N
	SMPM – IR/OR	Sine wave	Motor	T-N
	SMPM – IR/OR	Sine wave	Motor	I-U
	SMPM – IR/OR [1]	Sine wave	Generator	I-Ψ-N
	SMPM – IR/OR	Sine wave	Generator	R-L-N
	SMPM – IR/OR	Square wave	Motor	Forced I
Performance mapping	SMPM – IR/OR	Sine wave	Motor	Efficiency map
	SMPM – IR/OR	Sine wave	Generator	Efficiency map
Mechanics	SMPM – IR [1]	NVH	Motor & Generator	Work. Pt. I-Ψ-N
	SMPM – IR [1]	NVH	Motor & Generator	Spectrogram WP I-Ψ-N
	SMPM – IR [1]	NVH	Motor	Spectrogram T-N

Notes:

(1) The test (working point I-Ψ-N, in both motor and generator modes are available for both topologies inner and outer rotor. However, the computation in steady state and transient of the thermal behavior is available only for inner rotor topology.
   NVH tests are also available only for inner rotor topology.

(2) The tests are described in documents dedicated to each test family. Here is the list of available documents:

- MotorFactory_2022.2_SMPM_IOR_3PH_Test_Characterization
- MotorFactory_2022.2_ SMPM_IOR_3PH_Test_WorkingPoint
- MotorFactory_2022.2_ SMPM_IOR_3PH_Test_PerformanceMapping
- MotorFactory_2022.2_ SMPM_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 (magnets and winding)

- Electronics: To define the power electronics stage feeding the machine

- Mechanics: To define the mechanical loss model parameters

1	Button to define the thermal inputs (Solving mode or active components temperatures)
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 to a list of advanced parameters.

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

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 (Magnet and 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 workflows of all these processes are described here-after.

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 I, Ψ, N with motor or generator convention for Synchronous Machines with Permanent Magnets 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 make the corresponding material physical properties updated.
For Synchronous Machines with Permanent Magnets, winding and magnet temperatures must be defined.

2.2.1   Temperature of winding

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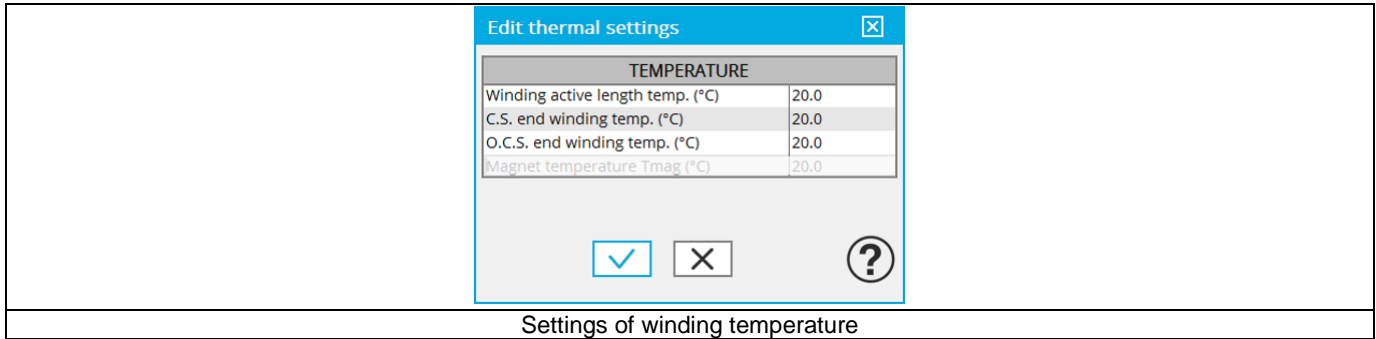
It is possible to define temperature of the three main parts of the stator winding:

- 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)

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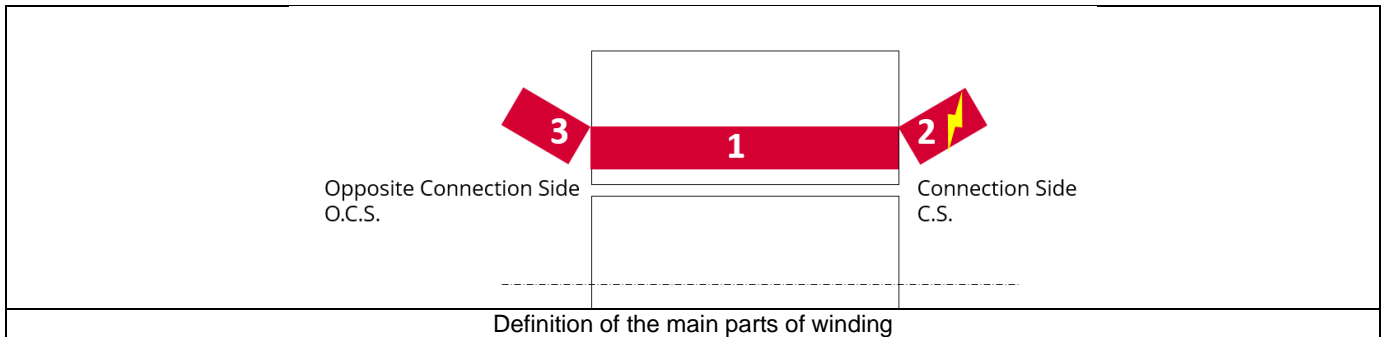
The resulting resistance of each part of the winding is updated according to the temperature:

- 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 magnets

The physical properties of magnets are updated considering the temperature set in this field.
The physical properties which are affected by this temperature are: the residual flux density (remanence) Br, the intrinsic coercivity (HcJ), the normal coercivity (HcB) and the resistivity.

Setting of magnet temperature
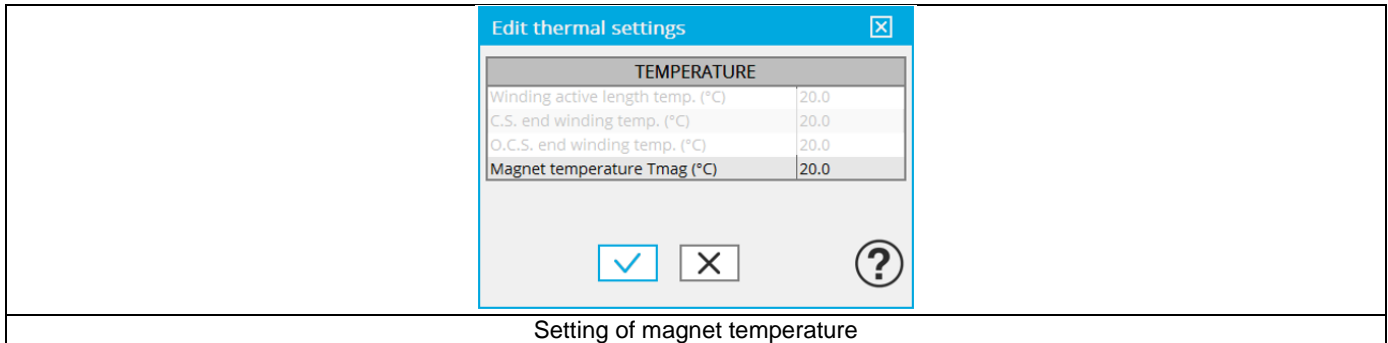
2.2.3 Flow chart of the tests without thermal solving mode

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

1	Default mode of thermal setting for all the tests without thermal analysis
2	Thermal settings for the tests which have a thermal analysis are available
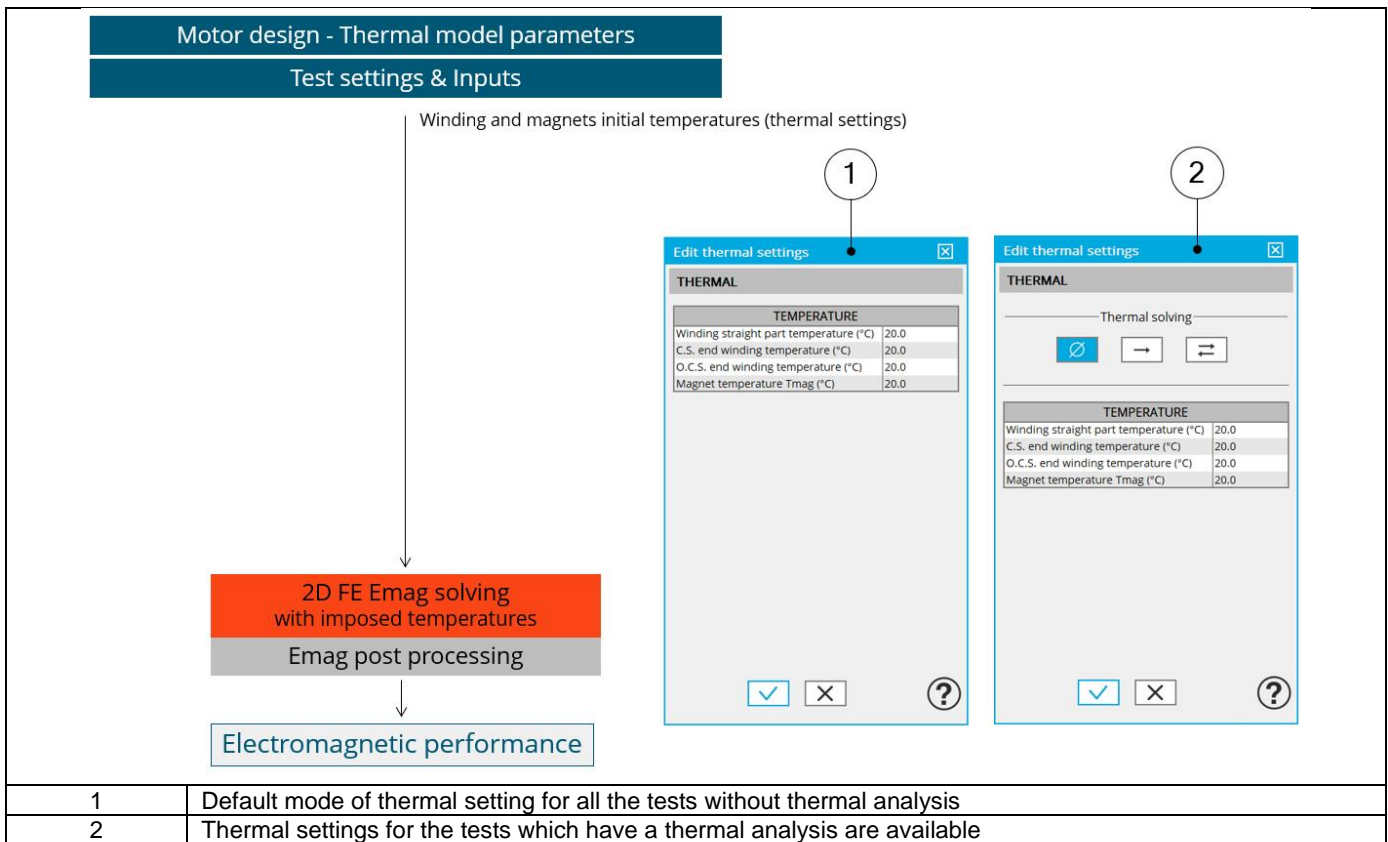
2.3   Thermal settings – Thermal solving mode
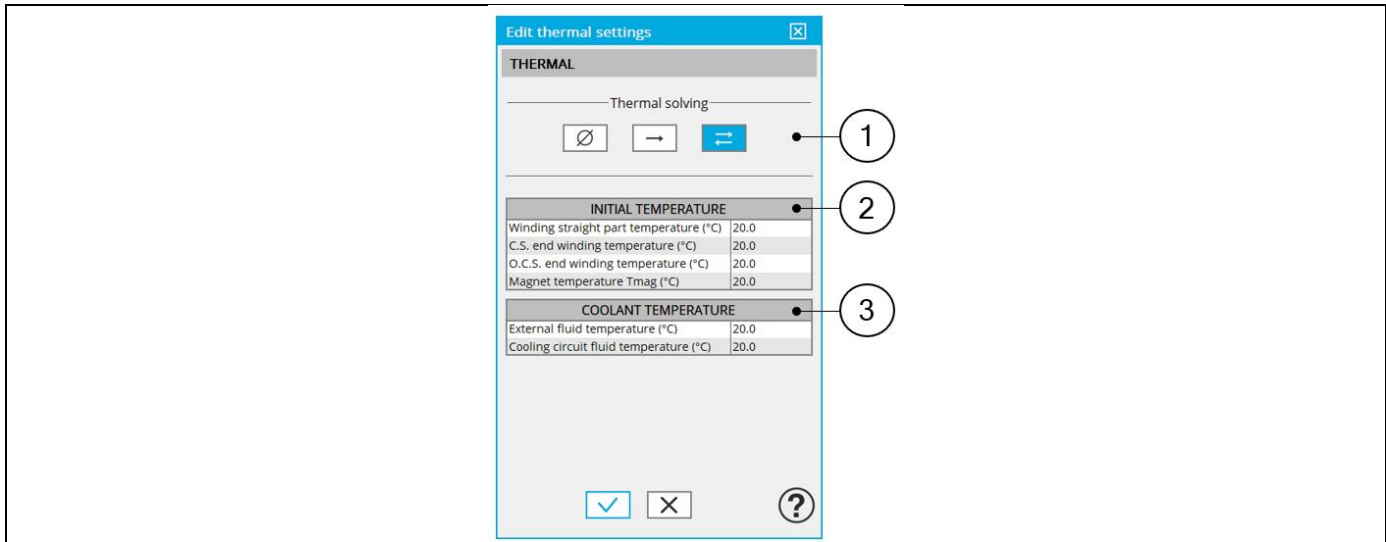
2.3.1   Overview

The choice of thermal solving mode is available for the test dealing with the computation of working point defined by the current, control angle 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 convergency, 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 magnets. 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.

△ ALTAIR

2.3.3   Flow chart of thermal solving mode – "Iterative" process

1)   Flow chart of the thermal solving mode test with iterative process.

0	Definition of the initial temperatures (see the list in the previous section) and working point inputs
1	1st electromagnetic solving (Finite Element computation) with initial temperature defined in the thermal settings Losses are computed.
2	Based on losses and speed defined by the electromagnetic working point, The thermal characterization is performed to define the temperature distribution inside the machine. The materials physical properties corresponding to the machine active components are then updated.
3	Iterative process = loop between electromagnetic and thermal computations until the convergence on the temperature is reached (See below where can be adjusted the convergency criteria when needed)
4	A last electromagnetic solving (Finite Element computation) with final set of temperatures is performed once the convergence on the temperature is reached [1]. Electromagnetic performance and chart of temperatures are computed and displayed. The test outputs are illustrated in the sections dedicated to the considered tests.

(1)   The temperatures which are considered for computing the final machine performance (step 4 in the previous flow chart) can be read in the table dealing with "Winding and Magnet characteristics" of the test configuration at the beginning of result report. See below illustration.

The temperatures are also displayed in the chart of temperature and table after the 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
Magnet temperature Tmag (°C)	20.0	External fluid temperature (°C)	25.0	Cooling circuit fluid temperature (°C)	22.0
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

   ● ——— ① *(Winding straight part temperature row highlighted)*

Winding and Magnet characteristics

Winding					
Winding connection	Wye	Winding resistance factor	1.113		
Winding temperature (°C)	106.386				
Phase resistance (Ω)	1.065 E-1	Line-Line resistance (Ω)	2.13 E-1	End winding resistance (Ω)	7.062 E-2
Winding straight part temperature (°C)	99.787	C.S. end winding temperature (°C)	111.442	O.C.S. end winding temperature (°C)	107.878
Winding straight part resistance (Ω)	3.59 E-2	C.S. end winding resistance (Ω)	3.91 E-2	O.C.S. end winding resistance (Ω)	3.152 E-2
Magnets					
Magnet name	Magnet	Material name	REF.NdFeB_1...	Material reference temp. Tref (°C)	20.0
Remanent induction at Tref (T)	1.23	Intrinsic coercive field at Tref (A/m)	1.4 E6	Relative permeability at Tref	1.1
Magnet temperature Tmag (°C)	73.914				
Remanent induction at Tmag (T)	1.164	Intrinsic coercive field at Tmag (A/m)	9.471 E5	Relative permeability at Tmag	1.1

   ● ——— ② *(Winding straight part temperature row highlighted)*

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

△ ALTAIR

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.

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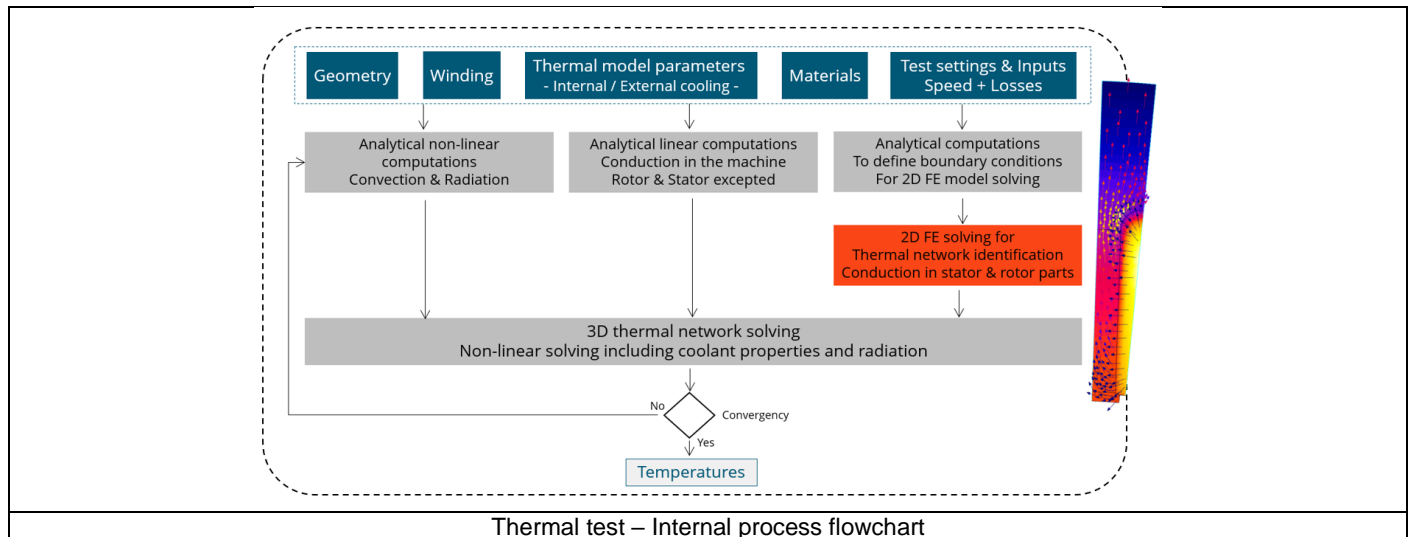
The inputs of the internal process are the parameters of: Geometry, Winding, Internal cooling, External cooling, Materials, Test settings and inputs.

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 one iteration.

0	Definition of the initial temperatures (see the list in the previous section) and working point inputs
1	1st electromagnetic solving (Finite Element computation) with initial temperature defined in the thermal settings Losses are computed.
2	Based on losses and speed defined by the electromagnetic working point, The thermal characterization is performed to define the temperature distribution inside the machine (1). The materials physical properties corresponding to the machine active components are then updated.
3	There is not iterative process = only one iteration is carried out.
4	A last electromagnetic solving (Finite Element computation) with final set of temperatures got after convergence is performed (2). Electromagnetic performance and chart of temperatures are computed and displayed. The test outputs are illustrated in the sections dedicated to the considered tests.

(1)   It corresponds to what is performed to make the thermal characterization of the machine in the test Characterization / Thermal / Steady state

(2)   The temperatures which are considered for computing the final machine performance (step 4 in the previous flow chart) can be read in the table dealing with "Winding and Magnet characteristics" of the test configuration at the beginning of result report. See below illustration.

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

Overview | **Current**

Settings

Thermal

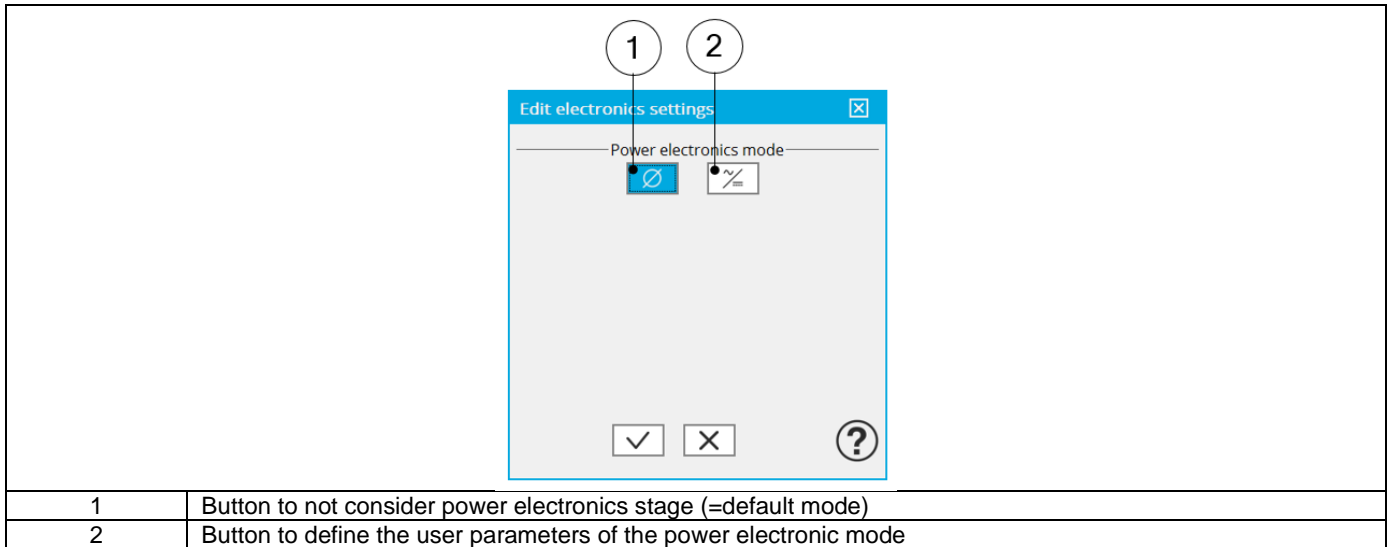|					
Thermal solving	Iterative				
Winding straight part temperature (°C)	20.0	C.S. end winding temperature (°C)	20.0	O.C.S. end winding temperature (°C)	20.0
Magnet temperature Tmag (°C)	20.0	External fluid temperature (°C)	25.0	Cooling circuit fluid temperature (°C)	22.0

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 Magnet characteristics

Winding

Winding connection	Wye	Winding resistance factor	1.113		
Winding temperature (°C)	106.386				
Phase resistance (Ω)	1.065 E-1	Line-Line resistance (Ω)	2.13 E-1	End winding resistance (Ω)	7.062 E-2
Winding straight part temperature (°C)	99.787	C.S. end winding temperature (°C)	111.442	O.C.S. end winding temperature (°C)	107.878
Winding straight part resistance (Ω)	3.59 E-2	C.S. end winding resistance (Ω)	3.91 E-2	O.C.S. end winding resistance (Ω)	3.152 E-2

Magnets

Magnet name	Magnet	Material name	REF.NdFeB_1...	Material reference temp. Tref (°C)	20.0
Remanent induction at Tref (T)	1.23	Intrinsic coercive field at Tref (A/m)	1.4 E6	Relative permeability at Tref	1.1
Magnet temperature Tmag (°C)	73.914				
Remanent induction at Tmag (T)	1.164	Intrinsic coercive field at Tmag (A/m)	9.471 E5	Relative permeability at Tmag	1.1

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

3   POWER ELECTRONICS MODE SETTINGS

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:

- Characterization / Model / Motor / Maps
- Characterization / Datasheet / Motor / I, U

- Working point / Sine wave / Motor / I, U
- Working point / Sine wave / Motor / T, N
- Working point / Sine wave / Motor / I, Ψ, N

- Performance mapping / Sine wave / Motor / Efficiency map

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. (refer to the section 3.5 - Power electronic and tests)

The whole list of power electronics parameters is illustrated below.

Power electronics mode: whole list of input parameters

△ ALTAIR
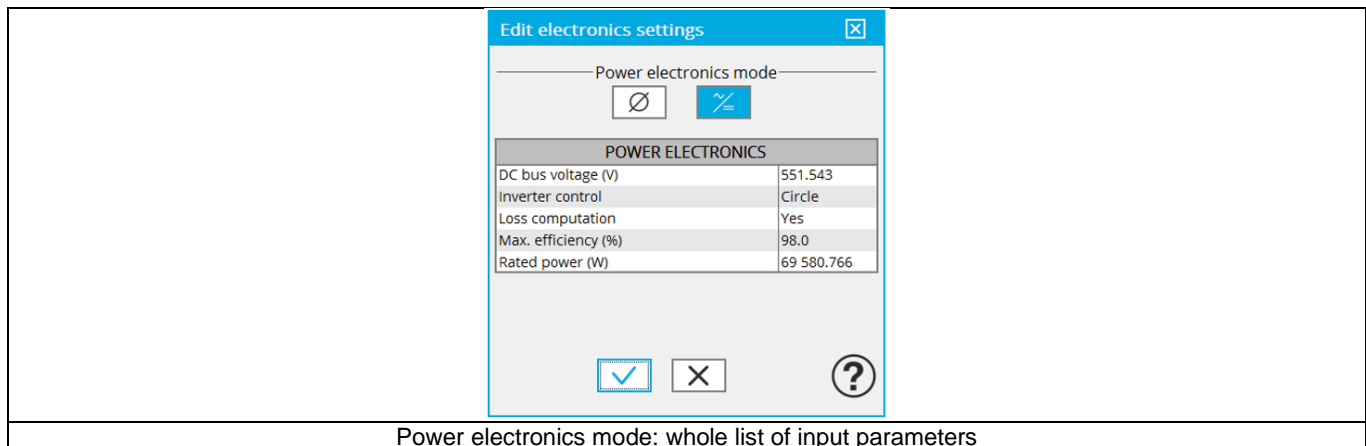
3.2.2 DC bus voltage and Inverter control

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

Voltage and current inputs of the power electronics stage and electrical machine
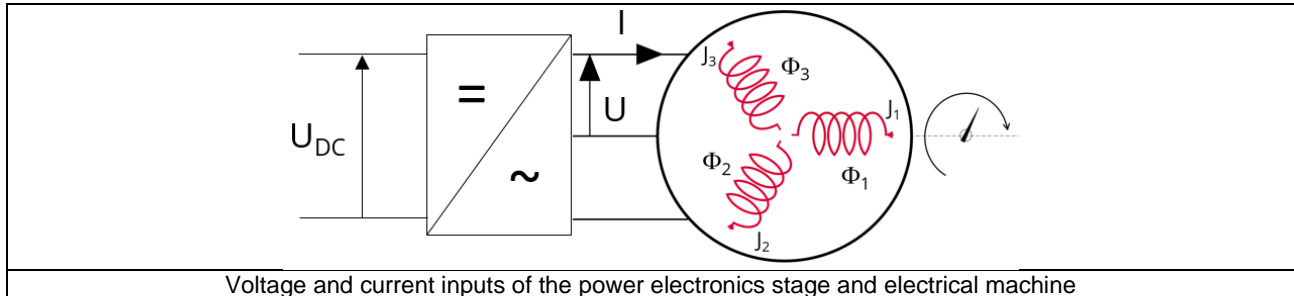
The chosen inverter control drives the ratio between the DC bus voltage and the line-line voltage seen at the machine terminal. This ratio is defined as:

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

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 ends 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	$\dfrac{1}{\sqrt{2}}$
Hexagon tracking piecewise linear	$\dfrac{3\sqrt{6}}{\pi^2}$
Hexagon tracking secant	$\dfrac{0.60573\sqrt{3}}{\sqrt{2}}$
Maximum linear range of triangle/sinus	$\dfrac{\sqrt{3}}{2\sqrt{2}}$
Six Steps 120°	$\dfrac{3}{\pi\sqrt{2}}$
Six Steps 180°	$\dfrac{\sqrt{6}}{\pi}$

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 be set to "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 can correspond 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 into 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 on 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

ALTAIR

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 in which are defined the correspondence between the tests and the input parameters of the power electronics mode.
The whole list of input parameters is illustrated below.

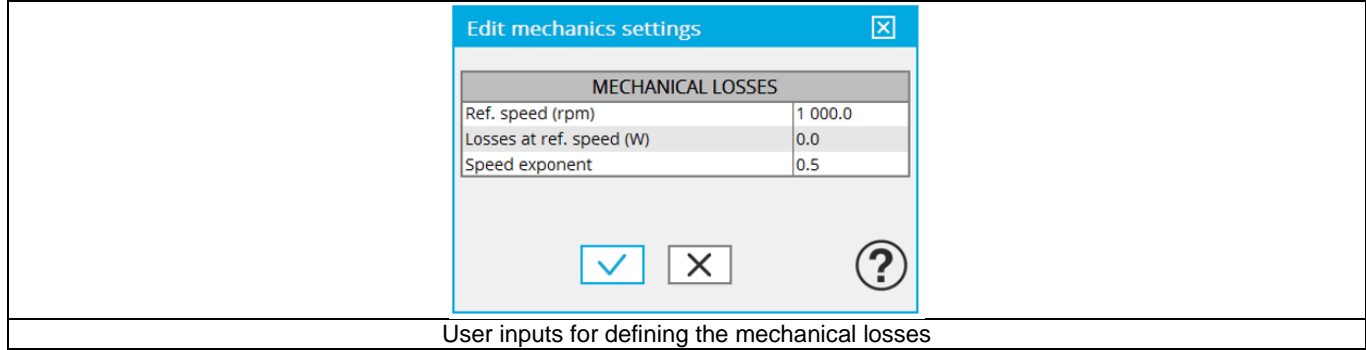| POWER ELECTRONICS	
Inverter control strategy	Circle
DC bus voltage (V)	551.543
Loss computation	Yes
Maximum efficiency (%)	98.0
Rated power (W)	69 580.766

Whole list of input parameters dedicated to power electronics

	Inverter Ctrl. strategy	DC bus voltage	Loss computation
Characterization / Open circuit / Motor & Generator / Cogging	-	-	-
Characterization / Open circuit / Motor & Generator / back emf	-	-	-
Characterization / Model / Motor / Maps	-	-	Available
Characterization / Datasheet / Motor / I-U	Available	Available	Available
Characterization / Thermal / Motor & Generator / Steady state	-	-	-
Characterization / Thermal / Motor & Generator / Transient	-	-	-
Working point / Sine wave / Motor / I-Ψ-N	Available	-	Available
Working point / Sine wave / Motor / T-N	Available	-	Available
Working point / Sine wave / Motor / I-U	Available	Available	Available
Working point / Sine wave / Generator / I-Ψ-N	-	-	-
Working point / Sine wave / Generator / R-L-N	-	-	-
Working point / Square wave / Motor / Forced I	-	-	-
Performance mapping / Sine wave / Motor / Efficiency map	Available	Available	Available
Performance mapping / Sine wave / Generator / Efficiency map	-	-	-
Mechanics / NVH / Working Point / I-Ψ-N	-	-	-
Mechanics / NVH / Spectrogram / I-Ψ-N	-	-	-
Mechanics / NVH / Spectrogram / T-N	Available	Available	Available

Notes:

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

ALTAIR

4   MECHANICAL LOSS MODEL SETTINGS

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

Edit mechanics settings ⊠

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:

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

The following input parameters are needed:

- "Ref. speed" (Reference speed) – N0
- "Losses at ref. speed" (mechanical losses at reference speed) – W0
- "Exponent" (Speed exponent) - k
- Current speed "N" for which the mechanical losses "Wmech" must be computed

5   TEST GENERIC INFORMATION

5.1   Machine characteristics

In this section, active parts (magnet and winding) of the machine are characterized by considering the operating temperatures described in the section "Settings". In addition, the mechanical loss model used in FluxMotor® is described.

5.1.1   Magnet characteristics

Magnet temperature during the test ("**Magnet temperature – T$_{mag}$**"). The physical properties of magnets are defined by considering this temperature.
Magnet name, defined in the design environment of Motor Factory.
Material name defined in the material database.
Database Reference temperature ("**Reference temp. Tref"**), defined in the material database.

Remanent induction (residual flux, intrinsic coercivity (H$_{cJ}$) and normal coercivity (H$_{cb}$) and relative permeability are given for both database reference temperature (T$_{ref}$) and magnet temperature (T$_{mag}$) during the test.
Results are presented together so that they can be compared with each other.

5.1.2   Winding characteristics

It is possible to define the temperature for 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)

Definition of the main parts of winding
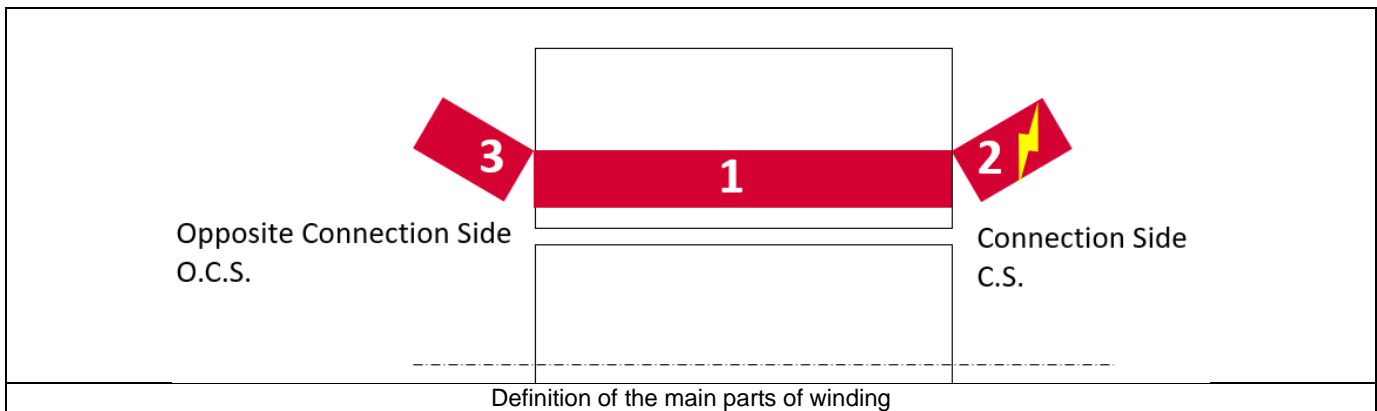
The resulting resistance of each part of the winding is computed as:
Winding straight part resistance (part 1)
Connection Side (C.S.) end winding resistance (part 2)
Opposite Connection Side (O.C.S.) end winding resistance (part 3)

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

The **resistance factor** and the **winding connection** are listed here (see definitions in winding documentation).

5.1.3   Mechanical losses

The mechanical loss model considered is described in the related test settings section as:

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

Information about the mechanical loss computation is listed in the result table. It includes:

"**Ref. speed**" (Reference speed) – N_0
"**Losses at ref. speed**" (mechanical losses at reference speed) – W_0
"**Exponent**" (Speed exponent) - k

5.1.4   Rotor and stator phase relative position

The relative angular position between the axis of the stator phase 1 (reference phase) and the direct axis of the rotor north pole must be controlled to perform the tests. See the picture below. That allows defining the working point of the machine.

Definition of rotor initial position – Rules for direction
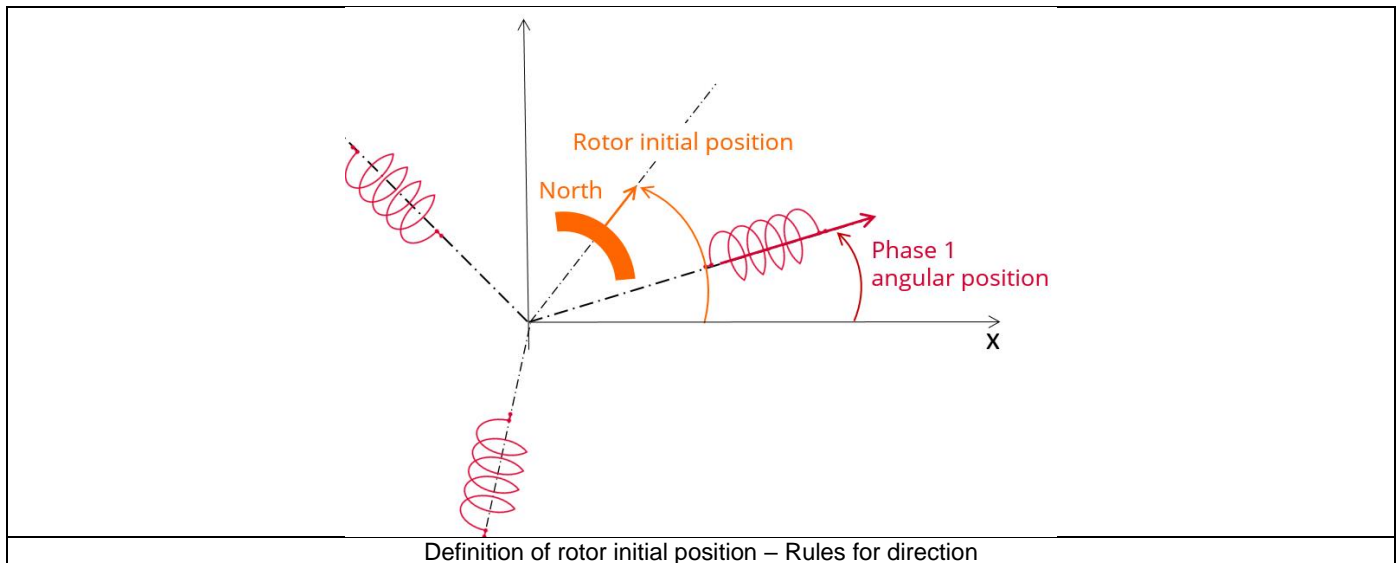
The winding axis of the reference phase is defined from the phase shift of the first electrical harmonic of the magneto motive force (M.M.F.).
By convention, a field pole "North" corresponds to a magnetic flux density vector oriented towards exterior of the rotor.

5.2 Electrical machine – Theoretical equations

5.2.1 Electrical synchronous machines – General parameters and equations

Note: All the following electrical quantities are expressed by considering rms values.

Parameter labels	Definition and formula
Formulae for Current quantities, rms value	$J_d = -J_{ph} \times \sin \psi$ $J_q = -J_{ph} \times \cos \psi$
Current expressed as a complex number, rms value	$J_{ph} = J_d + j \times J_q$
Magnitude of current, rms value	$\lvert J_{ph} \rvert = \sqrt{J_d^2 + J_q^2}$
Angular speed	$\Omega = \dfrac{N \times \pi}{30} =$ angular speed in rad/sec
Phase resistance	R_{phase}: Computed in Winding area of Motor Factory.
End-winding inductance, in Henry	L_{endw}: Computed in Winding area of Motor Factory.
Voltage expressed as a complex number, rms value	$\underline{V_{Ph}} = V_d + jV_q$
Magnitude of voltage, rms value	$\lvert \underline{V_{Ph}} \rvert = V_{Ph} = \sqrt{V_d^2 + V_q^2}$
Apparent power	$\underline{S_n} = 3 \times V_{ph} \times \overline{J_{ph}}$
Active power	$\underline{P_n} = \mathrm{Re}\left(\underline{S_n}\right)$
Reactive power	$\underline{Q_n} = \mathrm{Im}\left(\underline{S_n}\right)$
Power factor	$\mathrm{Cos}(\phi) = \mathrm{Cos}\left(\mathrm{Angle}\left(\underline{S_n}\right)\right)$
N	Speed in rpm
p	Number of pole pairs
m	Number of phases (3)

5.2.2   Electrical synchronous machines – Motor convention – Parameters and equations

Note: Since the motor is a receptor, we speak about "motor convention" instead of receptor convention. However, the theoretical definition of these two expressions is the same.

Parameter labels	Definition and formula
Voltage computations, rms value	$V_d = J_d \times R_{phase} - \left(\left(\Phi_q + J_q \times L_{endw} \right) \times \Omega \times p \right)$ $V_q = J_q \times R_{phase} + \left(\left(\Phi_d + J_d \times L_{endw} \right) \times \Omega \times p \right)$
Electromagnetic torque T$_{em}$	$T_{em} = \dfrac{m}{2} \times p \times \left(\Phi_d \times J_q - \Phi_q \times J_d \right)$
$\Sigma(losses)$ = Total losses	$\Sigma(losses) = \left(W_{Iron} + W_{Joule} + W_{Mechanical} + W_{Additional} \right)_{Losses}$
P$_{elec}$ = electrical power	$P_{abs} = \dfrac{m}{2} \times \left(V_d \times J_d + V_q \times J_q \right)$
Q = Reactive power	$Q = \dfrac{m}{2} \left(V_q . J_d - V_d . J_q \right)$
P$_{mech.}$ = mechanical power	$P_{mech.} = P_{elec} - \Sigma(losses)$
Efficiency Operating mode: motor	$\eta = 100 \times \dfrac{P_u}{P_{elec}}$
Efficiency Operating mode: generator	$\eta = 100 \times \dfrac{P_{elec}}{P_u}$

5.2.3   Electrical synchronous machines – Generator convention – Parameters and equations

Parameter labels	Definition and formula
Voltage computations, rms value	$V_d = -J_d \times R_{phase} + \left(\left(\Phi_q + J_q \times L_{endw} \right) \times \Omega \times p \right)$ $V_q = -J_q \times R_{phase} - \left(\left(\Phi_d + J_d \times L_{endw} \right) \times \Omega \times p \right)$
Electromagnetic torque T$_{em}$	$T_{em} = \dfrac{m}{2} \times p \times \left(\Phi_q \times J_d - \Phi_d \times J_q \right)$
$\Sigma(losses)$ = Total losses	$\Sigma(losses) = \left(W_{Iron} + W_{Joule} + W_{Mechanical} + W_{Additional} \right)_{Losses}$
P$_{elec}$ = electrical power	$P_{elec} = \dfrac{m}{2} \times \left(V_d \times J_d + V_q \times J_q \right)$
Q = Reactive power	$Q = \dfrac{m}{2} \left(V_q . J_d - V_d . J_q \right)$
P$_{mech.}$ = mechanical power	$P_{mech.} = P_{elec} + \Sigma(losses)$
Efficiency Operating mode: motor	$\eta = 100 \times \dfrac{P_u}{P_{elec}}$
Efficiency Operating mode: generator	$\eta = 100 \times \dfrac{P_{elec}}{P_u}$

ALTAIR

5.3   Working point – Sine wave – Motor – Display of results

5.3.1   Working point performance – General data

Label	Symbol	Tooltip, note, formula
Operating mode	OP_{mode}	Motor or generator operating mode are available according to the considered working point
Mechanical torque	T	$T_{mech.} = T_{em} - \dfrac{\Sigma(losses)_{post}}{\Omega_{mech.}}$ $\Sigma(losses)_{post} = (W_{Iron} + W_{Mechanical} + W_{Additional})_{Losses}$ $\Omega_{mech.}$ = mechanical speed of rotation T_{em} = Electromagnetic torque given by the export of electromagnetic torque given by FLUX T_{em} = mean value of electromagnetic torque over an electric period.
Speed	N	User input data defined by using the unit chosen by the user ("Units" application). Note: In documentation, the "speed" notation is given as Ω and is defined in rad/s.
Electrical frequency	f_{elec}	$f_{elec} = \dfrac{p \times N}{60}$ with p = number of pole pairs
Mechanical power	$P_{mech.}$	Refer to the section dealing with the chosen convention: motor or generator
Machine electrical power	P_{elec}	P_{elec} or P_{abs} according chosen convention. Refer to the section dealing with conventions: motor or generator
Machine total losses	$\Sigma(losses)$	$\Sigma(losses) = (W_{Iron} + W_{Joule} + W_{Mechanical} + W_{Additional})_{Losses}$ See definitions in power balance section
Machine efficiency	η	Refer to the section dealing with the chosen convention: motor or generator
Apparent power	S	$\underline{S} = 3 \times \underline{V_{Ph}} \times \overline{\underline{J}_{Ph}}$
Reactive power	Q	$\underline{Q} = Im(\underline{S})$
Control angle	Ψ	

Label	Symbol	Tooltip, note, formula
Power factor	$Cos(\phi)$	$Cos(\phi) = Cos\left(Angle(\underline{S})\right)$
Phase angle	φ	$\varphi = (V, J)$ Angle between the phase voltage and the phase current vectors
Line current, rms	$I_{L,rms}$	Line current, rms value
Phase current, rms	$J_{Ph,rms}$	Phase current, rms value
Line-Line voltage, rms	$U_{LL,rms}$	Maximum Line-Line voltage, rms value
Phase voltage, rms	$V_{Ph,rms}$	Phase voltage, rms value

5.3.2   Working point performance – Machine constants – Part 1

Label	Symbol	Tooltip, note, formula
Max. current density, rms	J	Maximum current density in conductors, rms value $$J = \frac{\left(\dfrac{J_{Ph,rms}}{P_{paths}}\right)}{A_{Cond}}$$ A_{Cond} = Conductor conductive area – See winding section P_{paths} = number of parallel paths
Electrical loading, rms	A₁	Electrical loading, rms value $$A_1 = \frac{2 \times m \times T_{ph} \times J_{Ph,rms}}{\pi \times D_{bore}}$$ Ratio between total ampere conductors and airgap circumference. m = number of phases = 3 T_{ph} = Number of turns per phase D_{bore} = bore diameter $J_{Ph,rms}$ = phase current, rms value
Power density	δPᵤ	Power density $$\delta P_{u1} = \frac{P_u}{\Sigma M_{ap}}$$ ΣM_{ap} = Summation of active part masses = rotor and stator magnetic materials, electrical conductor materials, magnets and shaft. Housing is not taken into account.

5.3.3   Working point performance – Machine constants – Part 2

Label	Symbol	Tooltip, note, formula
kT	kT	Torque constant, kT $$KT = \frac{Mechanical\ torque}{I_{L,peak}}$$ $I_{L,peak}$ = Line current, peak value
kE, peak	kE	Voltage constant kE , $kE = \frac{U0_{LL,peak}}{\Omega}$ with Ω = speed in rad/s $U0_{LL,peak}$ = No load Line-Line voltage, peak value. No load Line-Line voltage, peak value considering at the speed Ω (No load voltage computed from the back-emf voltage).

Note 1: The No-load Line-Line voltage peak value is not displayed in the result panel for the tests concerning Working points. It is computed and used in our internal processes to deduce kE.

Note 2: Concerning the sine wave drive, the voltage constant is displayed only in the two following tests:
• Characterization/Open circuit/Motor & Generator/back-emf
• Characterization/Datasheet/Motor/I, U

5.3.4 Working point performance – power balance

Label	Symbol	Tooltip, note, formula
Machine total losses	$\Sigma(losses)$	$\Sigma(losses) = \left(W_{Iron} + W_{Joule} + W_{Mechanical} + W_{Additional}\right)_{Losses}$
Joule losses	W_{Cus}	$W_{Cus} = m \times R_{phase} \times \left(J_{Ph1,rms}\right)^2$ m = number of phases = 3
Mechanical losses	$W_{mech.}$	Function of speed, see the test settings.
Iron losses	W_{Iron}	Dedicated internal process. See test Characterization – Model – Maps.
Additional losses	$W_{add.}$	$W_{add.} = K_{AddLoss} \times (W_{Cus} + W_{Fe})$ $K_{AddLoss}$= additional loss percentage of electric losses = standard user input parameter.

5.3.5 Working point performance – Flux in airgap

Label	Symbol	Tooltip, note, formula
Flux density, ARV	$B_{o\,ARV}$	Flux density, Average Rectified Value. $B_{o\,ARV} = \dfrac{\sum_k |B_o(\theta_k)|}{k}$
Flux density, 1st harm., rms	$B_{o1,rms}$	Flux density, 1st harmonic, rms value.
Flux density, peak	$B_{o\,peak}$	Flux density, peak value.
Flux / pole, ARV	$\Phi_{p,ARV}$	Flux per pole, Average Rectified Value. $\Phi_{p\,ARV} = \dfrac{\sum_k |\Phi_p(\theta_k)|}{k}$
Flux / pole, 1st harm., rms	$\Phi_{p1,rms}$	Flux per pole, 1st harmonic, rms value.
Flux / pole, Peak	$\Phi_{p,peak}$	Flux per pole, peak value.

5.3.6 Working point performance – Flux density in iron

Label	Symbol	Tooltip, note, formula
Stator tooth, max.	$B_{Sth_{max.}}$	Magnetic flux density in stator tooth, max. value.
Stator foot tooth, max.	$B_{Sfth_{max.}}$	Magnetic flux density in stator tooth foot, max. value.
Stator yoke, max.	$B_{Sy_{max.}}$	Magnetic flux density in stator yoke, max. value.
Stator tooth, mean	$B_{Sth_{mean.}}$	Magnetic flux density in stator tooth, mean value.
Stator foot tooth, mean	$B_{Sfth_{mean.}}$	Magnetic flux density in stator tooth foot, mean value.
Stator yoke, mean	$B_{Sy_{mean.}}$	Magnetic flux density in stator yoke, mean value.
Rotor yoke, max	$B_{Ry_{max.}}$	Magnetic flux density in rotor yoke, max. value.
Rotor yoke, mean	$B_{Ry_{mean.}}$	Magnetic flux density in rotor yoke, mean value.

Note 1: The sub-regions of the "Inner magnet" part are the sub-regions defined in the part used in the motor.
Here is the list of possible sub-region labels: Yoke, Web, Bridge, Pole core, Pole shoe, Interpole, Hub, Mechanical device, ferromagnetic wedge.
The levels of flux density are defined for each sub-region described in the part.

Note 2: Using Finite Element modeling, the magnetic flux density quantities are computed from dedicated regional sensors.
Note: Flux density is also given in all the rotor regions.

Shown below is an example of region definition. The respective region is highlighted in yellow.

Stator foot tooth	Stator tooth	Stator yoke
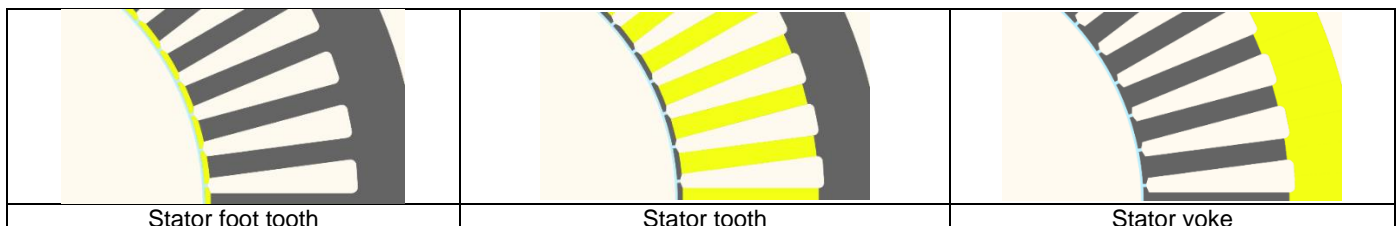
5.3.7   Working point performance – Magnet behavior

Label	Symbol	Tooltip, note, formula
Magnet name	-	Magnet name
Material name	-	When several kinds of magnet materials are considered, the magnet behavior is defined for each kind of magnet material
Flux density, mean	B_{magnet}	Flux density, mean value. Mean value of flux density computed in all the magnets.
Magnetic field strength, mean	H_{magnet}	Magnetic field strength, mean value. Mean value of the magnetic field computed in all the magnets.
Coerc.Field 50%	50%HcJ	Coercive field 50%. $50\%\,\mathrm{HcJ} = 0.5 \times \mathrm{HcJ}$ = limit to define Zone 1 for demagnetization analysis.
Coerc.Field 90%	90%HcJ	Coercive field 90%. $90\%\,\mathrm{HcJ} = 0.9 \times \mathrm{HcJ}$ = limit to define Zone 2 for demagnetization analysis.
Demag. rate < CF50	$D_{emag}50$	Percentage of magnet area in Zone 1 (where maximum magnetic field, absolute value, is lower than $50\%\,\mathrm{HcJ} = 0.5 \times \mathrm{HcJ}$)
Demag. rate > CF90	$D_{emag}90$	Percentage of magnet area in Zone 2 (where maximum magnetic field, absolute value, is greater than $90\%\,\mathrm{HcJ} = 0.9 \times \mathrm{HcJ}$)

Additional information:

The J(H) curve of magnets illustrates the capability of magnets to polarize their associated magnetic circuit. Two zones are defined, based on the intrinsic coercivity field of magnet HcJ.

The first zone corresponds to magnetic fields lower than $0.5 \times \mathrm{HcJ}$. That means the zone in which there is no risk of demagnetization.

The second zone corresponds to magnetic fields greater than $0.9 \times \mathrm{HcJ}$. That means the zone in which there is a very high risk of demagnetization.


Demagnetization rate zones
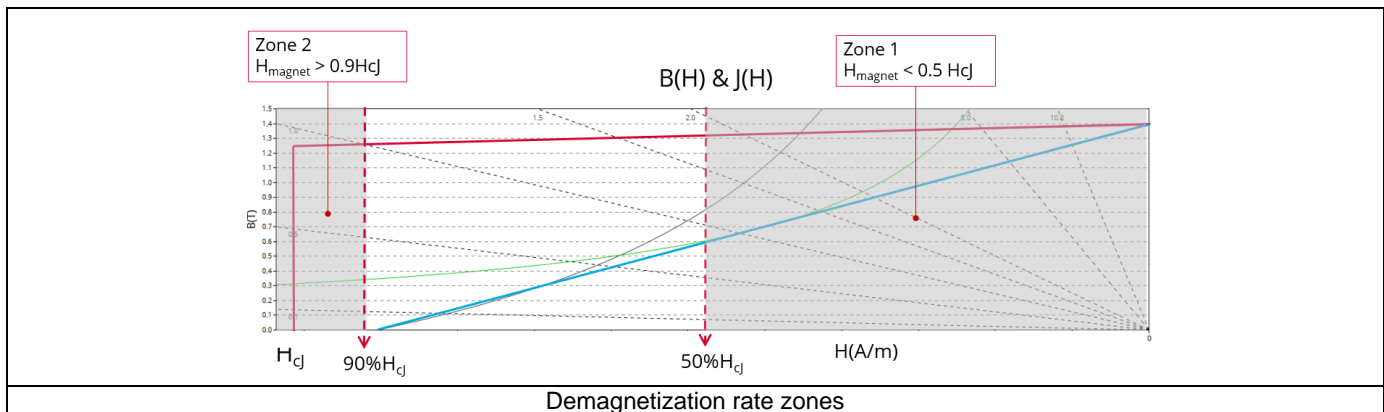
During the analysis of the machine behavior over one electrical period, sensors compute the levels of magnetic fields in all the magnets.
The **Demag. Rate** (demagnetization rate) < CF50 (in % or P.U.) gives the percentage of magnet area where the maximum computed magnetic field is below fifty percent of intrinsic coercivity (HcJ).
It corresponds to the area of magnet in Zone 1

The **Demag. Rate** (demagnetization rate) > CF90 (in % or P.U.) gives the percentage of magnet area where the maximum computed magnetic field is beyond ninety percent of intrinsic coercivity (HcJ).
It corresponds to the area of magnet in the zone 2.

These two results allow evaluating the relevance of the design at the working point, in term of demagnetization.
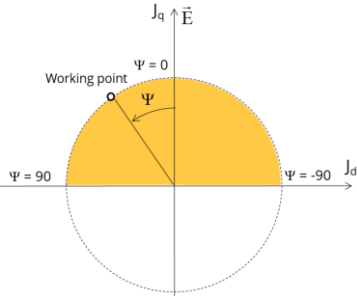
5.3.8   Working point performance – Torque and ripple torque

Label	Symbol	Tooltip, note, formula
Mechanical torque	T_{mean}	Mean value of the mechanical torque over a ripple torque period.
Ripple mech. torque, pk-pk	ΔT T_{max}-T_{min}	Ripple mechanical torque, peak-peak value
Ripple mech. Torque +- vs avg.	$\Delta T_{\%}$	Ripple mechanical torque magnitude versus average value
Ripple torque period	T_ripple	Ripple torque period

Computation of ripple mechanical torque characteristics
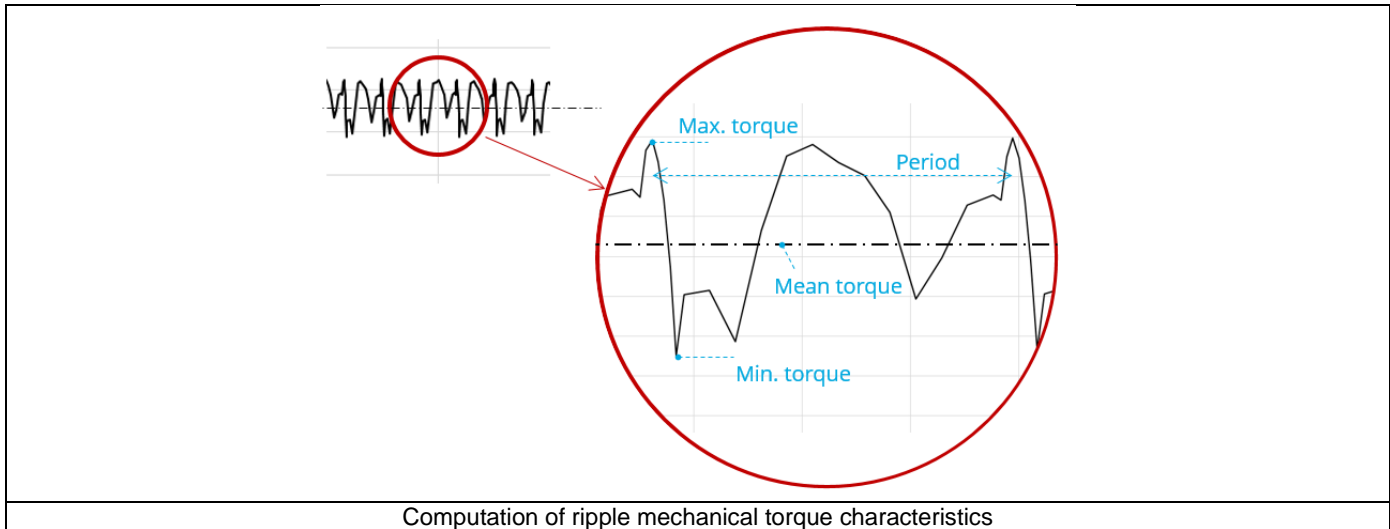
5.4   Working point – Square wave – Motor: Display of results

5.4.1   Working point performance – General data

Label	Symbol	Tooltip, note, formula
Operating mode	OP_{mode}	Only Motor mode is available with current version of FluxMotor® when square wave drive is considered.
Mechanical torque	T	$T_{mech.} = T_{em} - \dfrac{\Sigma(losses)_{post}}{\Omega_{mech.}}$ $\Sigma(losses)_{post} = (W_{Iron} + W_{Mechanical} + W_{Additional})_{Losses}$ $\Omega_{mech.}$ = mechanical speed of rotation T_{em} = Electromagnetic torque given by the export of electromagnetic torque given by FLUX T_{em} = mean value of electromagnetic torque over an electric period.
Speed	N	User input data defined by using the unit chosen by the user ("Units" application) Note: In documentation, the "speed" notation is given as Ω and is defined in rad/s.
Electrical frequency	f_{elec}	$f_{elec} = \dfrac{p \times N}{60}$ with p = number of pole pairs
Mechanical power	P_{mech}	Mechanical power = (Mechanical torque) x Ω
Machine electrical power	P_{elec}	Electrical power = Electromagnetic power + Joule losses in coils + Joule losses in magnets. Where Electromagnetic power = Tem x Ω
Machine total losses	$\Sigma(losses)$	$\Sigma(losses) = (W_{Iron} + W_{Joule} + W_{Magnets} + W_{Mechanical} + W_{Additional})_{Losses}$ See definitions in power balance section
Efficiency	η	$\eta = 100 \times \dfrac{Mechanical\ power}{Machine\ electrical\ power}$
Apparent power	S	Apparent power = 3*(Phase voltage, rms) x (Phase current, rms)
Control angle	Ψ	Angle between the electromotive force E and the electrical current (J) (Ψ = (E, J)).
Power factor	PF	$PF = \dfrac{Machine\ electrical\ power}{Apparent\ power}$

Label	Symbol	Tooltip, note, formula
Line current, rms	$I_{L,rms}$	rms value got from the associated curve analysis
Phase current, rms	$J_{Ph,rms}$	rms value got from the associated curve analysis
Line current, peak	$I_{L,pk}$	Peak value got from the associated curve analysis
Line-Line voltage, rms	$U_{LL,rms}$	rms value got from the associated curve analysis
Phase voltage, rms	$V_{Ph,rms}$	rms value got from the associated curve analysis
Line-Line voltage, peak	$U_{LL,pk}$	Peak value got from the associated curve analysis

5.4.2 Working point performance – Machine constants – Part 1

Label	Symbol	Tooltip, note, formula
Max. current density, rms	J	Maximum current density in conductors, rms value $J = \dfrac{\left(\dfrac{I_{Ph,rms}}{P_{paths}}\right)}{A_{Cond}}$ A_{Cond} = Conductor active area – See winding section P_{paths} = number of parallel paths
Electrical loading, rms	A₁	Electrical loading, rms value $A_1 = \dfrac{2 \times m \times T_{Ph} \times J_{Ph,rms}}{\pi \times D_{bore}}$ Ratio between total ampere conductors and airgap circumference. m = number of phases = 3 T_{ph} = Number of turns per phase D_{bore} = bore diameter $J_{Ph,rms}$ = phase current, rms value
Power density	δPu	Power density $\delta P_{u1} = \dfrac{P_u}{\Sigma M_{ap}}$ ΣM_{ap} = Summation of active part masses = rotor and stator magnetic materials, electrical conductor materials, magnets and shaft. Housing is not taken into account.

5.4.3 Working point performance – Machine constants – Part 2

Label	Symbol	Tooltip, note, formula
kT	kT	Torque constant, kT $KT = \dfrac{Mechanical\ torque}{I_{L,peak}}$ $I_{L,peak}$ = Line current, peak value
kE, peak	kE	Voltage constant kE , $kE = \dfrac{U0_{LL,peak}}{\Omega}$ with Ω = speed in rad/s $U0_{LL,peak}$ = No load Line-Line voltage, peak value considering at the speed Ω (No load voltage computed from the back emf voltage)

Note: The No-load Line-Line voltage peak value is not displayed in the result panel for the tests concerning Working points. It is computed and used in our internal processes to deduce kE.

5.4.4   Working point performance – Power balance

Note: In the table below, the mean values of losses are displayed

Label	Symbol	Tooltip, note, formula
Machine total losses	$\Sigma(losses)$	$\Sigma(losses) = \left(W_{Iron} + W_{Joule} + W_{Magnets} + W_{Mechanical} + W_{Additional}\right)_{Losses}$
Joule losses	W$_{Cus}$	Average value of the following result over an electrical period. $W_{Cus} = R_{phase} \times \left[\left(J_{Ph1,rms}\right)^2 + \left(J_{Ph2,rms}\right)^2 + \left(J_{Ph3,rms}\right)^2\right]$
Losses in magnets,	W$_{Magnets}$	The computation of losses in magnets is performed over half electrical period by using Finite Element modelling
Iron losses	W$_{Iron}$	The calculation of the iron losses is based on the Steinmetz' model, by considering transient analysis
Additional losses,	W$_{add}$	$W_{add.} = K_{AddLoss} \times \left(W_{Cus} + W_{Fe} + W_{Magnets}\right)$ K$_{AddLoss}$= additional loss percentage of electric losses = standard user input parameter.
Mech. losses	W$_{mech.}$	Function of speed, see the test settings.
Total iron losses,	W$_{iron}$T	Iron losses = W$_{Iron}$
Stator iron losses,	W$_{iron}$S	The calculation of the stator iron losses is based on the Steinmetz' model, by considering transient analysis
Rotor iron losses,	W$_{iron}$R	The calculation of the rotor iron losses is based on the Steinmetz' model, by considering transient analysis

5.4.5   Working point performance – Flux in airgap

Label	Symbol	Tooltip, note, formula
Flux density, ARV	$B_{o\,ARV}$	Flux density, Average Rectified Value. $B_{o\,ARV} = \dfrac{\sum_k |B_o(\theta_k)|}{k}$
Flux density, 1st harm. rms	$B_{o1,rms}$	Flux density 1st harmonic, rms value.
Flux density, peak	$B_{o\,peak}$	Flux density, peak value.
Flux / pole, ARV	$\Phi_{p1,ARV}$	Flux per pole, Average Rectified Value. $\Phi_{p\,ARV} = \dfrac{\sum_k \left|\Phi_{p_1}(\theta_k)\right|}{k}$
Flux / pole, 1st harm. rms	$\Phi_{p1,rms}$	Flux per pole 1st harmonic, rms value.
Flux / pole, 1st harm. Peak	$\Phi_{p1,peak}$	Flux per pole 1st harmonic, peak value.

5.4.6   Working point performance – Flux density in iron

Label	Symbol	Tooltip, note, formula
Stator tooth, max.	$B_{Sth_{max.}}$	Magnetic flux density in stator tooth, max. value.
Stator foot tooth, max.	$B_{Sfth_{max.}}$	Magnetic flux density in stator foot tooth, max. value.
Stator yoke, max.	$B_{Sy_{max.}}$	Magnetic flux density in stator yoke, max. value.
Stator tooth, mean	$B_{Sth_{mean.}}$	Magnetic flux density in stator tooth, mean value.
Stator foot tooth, mean	$B_{Sfth_{mean.}}$	Magnetic flux density in stator foot tooth, mean value.
Stator yoke, mean	$B_{Sy_{mean.}}$	Magnetic flux density in stator yoke, mean value.
Rotor yoke, max	$B_{Ry_{max.}}$	Magnetic flux density in rotor yoke, max. value.
Rotor yoke, mean	$B_{Ry_{mean.}}$	Magnetic flux density in rotor yoke, mean value.

Note: The sub-regions of the "Inner magnet" part are the sub-regions defined in the part used in the motor.
Here is the list of possible sub-region labels: Yoke, Web, Bridge, Pole core, Pole shoe, Interpole, Hub, Mechanical device, ferromagnetic wedge.
The levels of flux density are defined for each sub-region described in the part.

ALTAIR

5.4.7   Working point performance – Magnet behavior

Label	Symbol	Tooltip, note, formula
Magnet name	-	
Material name	-	When several kinds of magnet materials are considered, the magnet behavior is defined for each kind of magnet material
Flux density, mean	B_{magnet}	Flux density, mean value. Mean value of flux density computed in all the magnets.
Magnetic field strength, mean	H_{magnet}	Magnetic field strength, mean value. Mean value of the magnetic field computed in all the magnets.
Coerc.Field 50%	50%HcJ	Coercive field 50%. $50\%\,\mathrm{HcJ} = 0.5 \times \mathrm{HcJ}$ = limit to define Zone 1 for demagnetization analysis.
Coerc.Field 90%	90%HcJ	Coercive field 90%. $90\%\,\mathrm{HcJ} = 0.9 \times \mathrm{HcJ}$ = limit to define Zone 2 for demagnetization analysis
Demag. rate < CF50	$D_{emag}50$	Percentage of magnet area in Zone 1 (where maximum magnetic field, absolute value, is lower than $50\%\,\mathrm{HcJ} = 0.5 \times \mathrm{HcJ}$)
Demag. rate > CF90	$D_{emag}90$	Percentage of magnet area in Zone 2 (where maximum magnetic field, absolute value, is greater than $90\%\,\mathrm{HcJ} = 0.9 \times \mathrm{HcJ}$

Note 1: When several kinds of magnet materials are considered, the magnet behavior is defined for each kind of magnet material.
Note 2: Refer to the section Test generic information - Magnet behavior – Rate of demagnetization for more details on data listed in the previous table.

Demagnetization rate zones
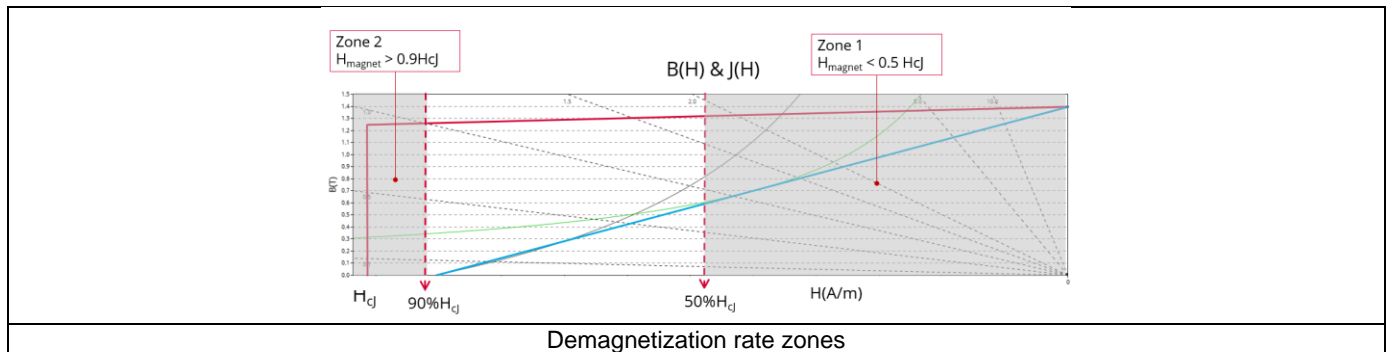
5.4.8   Working point performance – Ripple torque data

The analysis of the ripple torque is applied on the mechanical torque.

Label	Symbol	Tooltip, note, formula
Mechanical torque	T_{mean}	Mean value of the mechanical torque over a ripple torque period.
Ripple mech. torque, pk-pk	ΔT T_{max}-T_{min}	Ripple mechanical torque, peak-peak value = Max. torque – Min. torque
Ripple mech. torque +- vs avg.	$\Delta T_\%$	Ripple mechanical torque magnitude versus average value (Max. torque – Min. torque) / (Mean torque) x 100
Ripple torque period	T_ripple	Ripple torque period

Computation of ripple mechanical torque characteristics
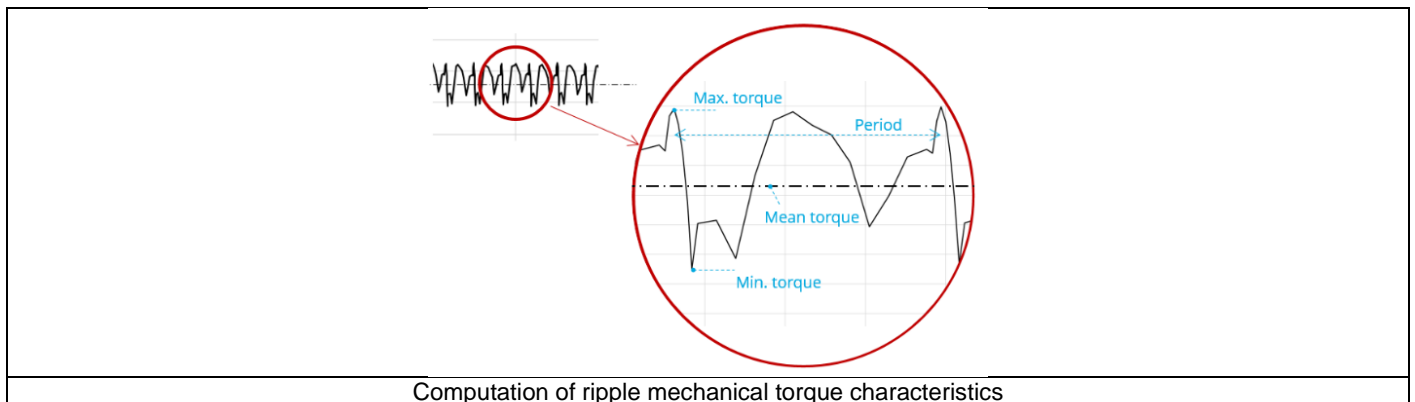
5.5   Open circuit test: Display of results

5.5.1   Open circuit – back-emf characteristics

Note: All results described below are obtained from signal analysis performed over one electrical period.

Label	Symbol	Tooltip, note, formula
kE, peak	kE	Voltage constant kE. $kE = \frac{U0_{LL,peak}}{\Omega}$ with Ω = speed in rad/s $U0_{LL\,,peak}$ = no load line-line voltage, peak value. No load Line-Line voltage, peak value considering at the speed Ω (No load voltage computed from the back emf voltage)
Phase volt. 1st harm., peak	$E_{1,peak}$	Phase voltage 1st. harmonic, peak value.
Phase volt. 1st harm., rms	$E_{1,rms}$	Phase voltage 1st. harmonic, rms value.
Phase volt., THD	$E_{1,THD}$	Phase voltage, THD. $E_{1,THD} = \dfrac{\sqrt{\sum_{k \neq 1}\left(E_{k,peak}\right)^2}}{E_1^{peak}}$
Line-Line volt. 1st harm., peak	$U_{1,peak}$	Line-Line voltage 1st. harmonic, peak value.
Line-Line volt. 1st harm., rms	$U_{1,rms}$	Line-Line voltage 1st. harmonic, rms value.
Line-Line volt., THD	$U_{1,THD}$	Line-Line voltage, THD. $U_{1,THD} = \dfrac{\sqrt{\sum_{k \neq 1}\left(U_{k,peak}\right)^2}}{U_1^{peak}}$

Note: The No-load Line-Line voltage peak value is not displayed in the result panel for the tests concerning Working points. It is computed and used in our internal processes to deduce kE.

△ ALTAIR

5.5.2   Open circuit – Flux linkage

Label	Symbol	Tooltip, note, formula
Phase 1 - 1st harm., Peak	$\Phi 1_{1,peak}$	Magnetic flux through Phase 1 - 1st harmonic, peak value.
Phase 2 - 1st harm., Peak	$\Phi 2_{1,peak}$	Magnetic flux through Phase 2 - 1st harmonic, peak value.
Phase 3 - 1st harm., Peak	$\Phi 3_{1,peak}$	Magnetic flux through Phase 3 - 1st harmonic, peak value.
Phase 1 - 1st harm., rms	$\Phi 1_{1,rms}$	Magnetic flux through Phase 1 - 1st harmonic, rms value.
Phase 1, peak	$\Phi 1_{peak}$	Magnetic flux through Phase 1, peak value.
Phase 1, ARV	$\Phi 1_{ARV}$	Magnetic flux through Phase 1, Average Rectified Value. $\Phi 1_{ARV} = \dfrac{\sum_k |\Phi(\theta_k)|}{k}$
D-axis, peak	$\Phi_{d,peak}$	D-axis magnetic flux, peak value. $\Phi_{d,peak} = \dfrac{\Phi_{d,\max} - \Phi_{d,\min}}{2}$
D-axis, mean	$\Phi_{d,mean}$	D-axis magnetic flux, mean value. $\Phi_{d,mean} = \dfrac{\sum_k |\Phi_d(\theta_k)|}{k}$
Q-axis, peak	$\Phi_{q,peak}$	Q-axis magnetic flux, peak value. $\Phi_{q,peak} = \dfrac{\Phi_{q,\max} - \Phi_{q,\min}}{2}$
Q-axis, mean	$\Phi_{q,mean}$	Q-axis magnetic flux, mean value. $\Phi_{q,mean} = \dfrac{\sum_k |\Phi_q(\theta_k)|}{k}$

Note:

Φ_d and Φ_q the D-axis and Q-axis flux linkage computed from flux through each phase of the machine by using Park's transformation.
Here are formulae used to convert the three-axis system to two axis systems:

$$\Phi_d = \frac{2}{3} \times \left(\Phi 1 \times \mathrm{Cos}(\theta) + \Phi 2 \times \mathrm{Cos}\left(\theta - \frac{2\pi}{3}\right) + \Phi 3 \times \mathrm{Cos}\left(\theta - \frac{4\pi}{3}\right) \right)$$

$$\Phi_q = \frac{2}{3} \times \left(\Phi 1 \times \mathrm{Sin}(\theta) - \Phi 2 \times \mathrm{Sin}\left(\theta - \frac{2\pi}{3}\right) - \Phi 3 \times \mathrm{Sin}\left(\theta - \frac{4\pi}{3}\right) \right)$$

5.5.3   Open circuit – Flux in airgap

| Label	Symbol	Tooltip, note, formula
Flux density, ARV	Bo_{ARV}	Flux density, Average Rectified Value. $Bo_{ARV} = \dfrac{\sum_k |Bo(\theta_k)|}{k}$
Flux density 1st harm., rms	$Bo_{1,rms}$	Flux density 1st harmonic, rms value.
Flux density, peak	Bo_{peak}	Flux density, peak value.
Flux / pole, ARV	$\Phi_{p,1,ARV}$	Flux per pole, Average Rectified Value. $\Phi_{p,1,ARV} = \dfrac{\sum_k |\Phi_{p1}(\theta_k)|}{k}$
Flux / pole 1st harm., rms	$\Phi_{p,1,rms}$	Flux per pole 1st harmonic, rms value.
Flux / pole, Peak	$\Phi_{p,1,peak}$	Flux per pole, peak value.

△ ALTAIR

5.5.4   Open circuit – Flux density in iron

Label	Symbol	Tooltip, note, formula
Stator tooth, max.	$BSth_{max.}$	Magnetic flux density in stator tooth, max. value.
Stator foot tooth, max.	$BSfth_{max.}$	Magnetic flux density in stator foot tooth, max. value.
Stator yoke, max.	$BSy_{max.}$	Magnetic flux density in stator yoke, max. value.
Stator tooth, mean	$BSth_{mean.}$	Magnetic flux density in stator tooth, mean value.
Stator foot tooth, mean	$BSfth_{mean.}$	Magnetic flux density in stator foot tooth, mean value.
Stator yoke, mean	$BSy_{mean.}$	Magnetic flux density in stator yoke, mean value.
Rotor yoke, max	$BRy_{max.}$	Magnetic flux density in rotor yoke, max. value.
Rotor yoke, mean	$BRy_{mean.}$	Magnetic flux density in rotor yoke, mean value.

Note: Using Finite Element modeling, the magnetic flux density quantities are computed from dedicated regional sensors. Shown below is an example of region definition. The respective region is highlighted in yellow.

Stator foot tooth	Stator tooth	Stator yoke
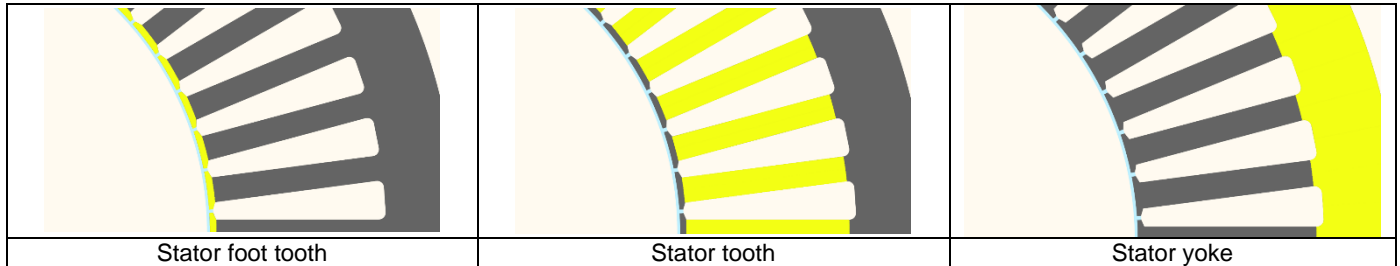
Here is a tip to visualize region
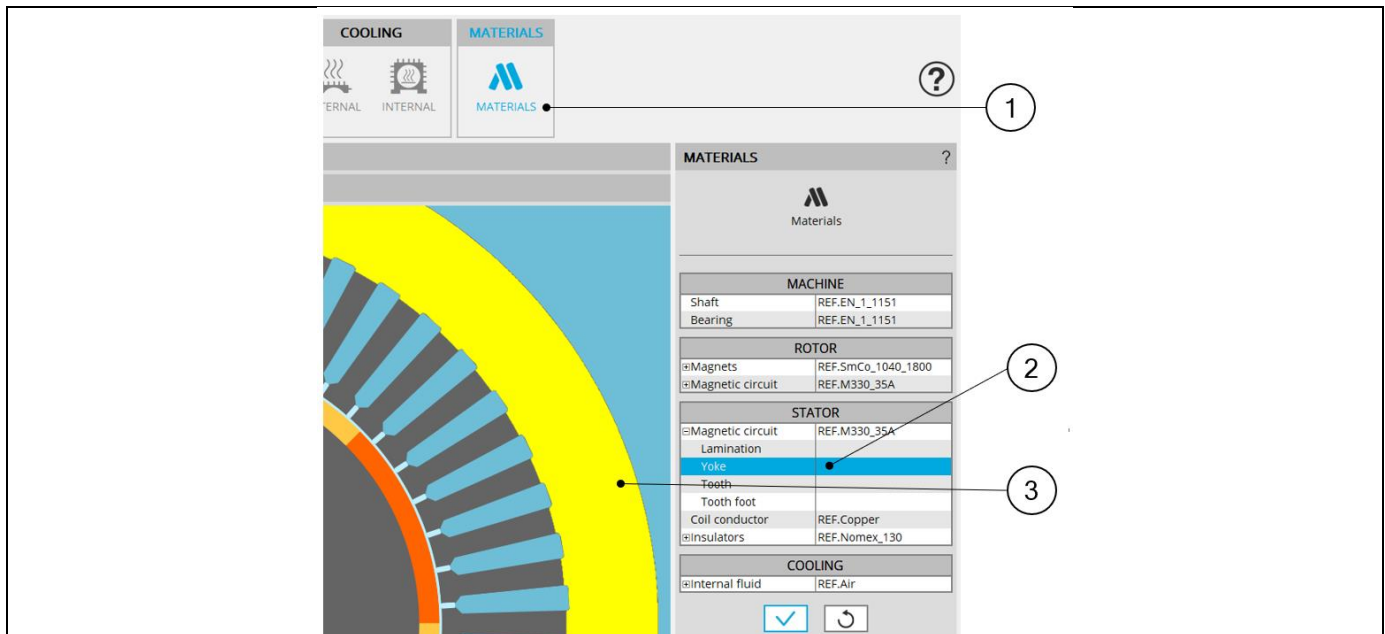
1	In DESIGN environment of Motor Factory, select MATERIALS area (STATOR or ROTOR).
2	Expand "Magnetic circuit" to see the list of regions.
3	By selecting a region name (Yoke for example) the corresponding face region is highlighted.

5.5.5   Open circuit – Magnet behavior

Label	Symbol	tooltip
Magnet name	-	
Material name	-	When several kinds of magnet materials are considered, the magnet behavior is defined for each kind of magnet material
Flux density, mean	$Bmag_{mean}$	Flux density, mean value.
Energy product, mean	BH_{mean}	Energy product, mean value. $BH_{mean} = \dfrac{Bmag_{mean} \times Hmag_{mean}}{2}$
Magnetic field strength, mean	$Hmag_{mean}$	Magnetic field strength, mean value.
Load factor	LF_{mag}	Load factor. $LFmag = \dfrac{Bmag_{mean}}{\mu_0 \times Hmag_{mean}}$

5.6   Limitation of thermal computations – Advice for use

5.6.1   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.

5.6.2   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.

5.6.3   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.

5.6.4   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.

5.6.5   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.

△ ALTAIR

5.6.6   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.