



ALTAIR

Altair[®] FluxMotor[®] 2025.1

Synchronous machines with wound field – Inner salient pole - Inner rotor

Motor Factory – Test - Working point

General user information

Contents

1	Working point – Sine wave – Motor – I_f, I, Ψ, N	5
1.1	Overview	5
1.1.1	Positioning and objective	5
1.1.2	User inputs	6
1.1.3	Main outputs	6
1.1.3.1	Main results	6
1.1.3.2	Curves – in the “Fast computation modes”	6
1.1.3.3	Curves – in the “Accurate computation modes”	6
1.1.3.4	Graphics	6
1.2	Settings	7
1.2.1	Thermal settings	7
1.2.2	Power electronics parameters	7
1.2.3	Mechanical loss model parameters	7
1.3	Inputs	8
1.3.1	Standard inputs	8
1.3.1.1	Modes of computation	8
1.3.1.2	Field current definition mode	8
1.3.1.3	Field current	8
1.3.1.4	Field current density	8
1.3.1.5	Line current definition mode	8
1.3.1.6	Line current, rms	8
1.3.1.7	Current density, rms	8
1.3.1.8	Control angle	8
1.3.1.9	Speed	9
1.3.1.10	Rotor position dependency	9
1.3.1.11	AC losses analysis - Fast	9
1.3.1.12	AC losses analysis - Accurate	10
1.3.2	Advanced inputs	10
1.3.2.1	Number of computed electrical periods	10
1.3.2.2	Number of computations per electrical period	10
1.3.2.3	Rotor initial position	11
1.3.2.4	Skew model – Number of layers	11
1.3.2.5	Mesh order	11
1.3.2.6	Airgap mesh coefficient	11
1.4	Main principles of computation	12
1.4.1	Introduction	12
1.4.2	Fast computation mode	12
1.4.2.1	Working point - Definition	12
1.4.2.2	Electromagnetic behavior – General information	12
1.4.2.3	Flux in airgap	12
1.4.2.4	Flux density in iron	13
1.4.2.5	Ripple torque	13
1.4.3	Accurate computation mode	14
1.4.3.1	Working point - Definition	14
1.4.3.2	Electromagnetic behavior – General information	14
1.4.3.3	Iron losses	14
1.4.3.4	Joule losses - armature and field windings	14
1.4.3.5	Flux density in iron	15
1.4.3.6	Torque	15
1.4.3.7	Flux in airgap	15

1.4.3.8	Field voltage	15
1.4.3.9	Field current	15
1.4.3.10	Phase voltage	15
1.4.3.11	Phase current	15
1.5	Test results	16
1.5.1	Test conditions	16
1.5.1.1	Inputs	16
1.5.1.2	Settings	16
1.5.1.3	Windings characteristics	16
1.5.2	Main results	16
1.5.2.1	Machine performance – Working point	16
1.5.2.2	Power electronics	16
1.5.2.3	Ripple mechanical torque	17
1.5.3	Curves – Without rotor position dependency (Fast mode)	17
1.5.4	Curves - With rotor position dependency (Fast mode + Rotor position dependency and Accurate mode)	17
1.5.5	Isovalues and isolines	17
2	Working point – Sine wave – Motor & GENERATOR – P, Pf, U, N	18
2.1	Overview	18
2.1.1	Positioning and objective	18
2.1.2	User inputs	19
2.1.3	Main outputs	19
2.1.3.1	Main results	19
2.1.3.2	Curves	19
2.1.3.3	Graphics	19
2.2	Settings	20
2.2.1	Thermal settings	20
2.2.2	Mechanical loss model parameters	20
2.3	Inputs	21
2.3.1	Introduction	21
2.3.2	Standard inputs	21
2.3.2.1	Convention	21
2.3.2.2	Operating mode	21
2.3.2.3	Power definition mode	21
2.3.2.4	Output power	21
2.3.2.5	Apparent power	21
2.3.2.6	Power factor definition mode	22
2.3.2.7	Power factor lag	22
2.3.2.8	Power factor lead	22
2.3.2.9	Field current definition mode	22
2.3.2.10	Maximum Field current	22
2.3.2.11	Maximum Field current density	22
2.3.2.12	Speed	22
2.3.2.13	Line-line voltage, rms	23
2.3.2.14	Ripple torque analysis	23
2.3.3	Advanced inputs	23
2.3.3.1	Number of computations for J_d , J_q per quadrant	23
2.3.3.2	Number of computations for field current	23
2.3.3.3	Number of computations for control angle	23
2.3.3.4	Number of computations per ripple torque period	24
2.3.3.5	Skew model – Number of layers	24
2.3.3.6	Rotor initial position	24
2.3.3.7	Mesh order	24
2.3.3.8	Airgap mesh coefficient	24

2.4	Main principles of computation	26
2.4.1	Introduction	26
2.4.1.1	Generator operating mode	26
2.4.1.2	Motor operating mode	27
2.4.2	P-Pf-U-N Working point search for the generator operating mode	27
2.4.2.1	Identify the research zone and the target performance	28
2.4.2.2	If-I-Psi-N Working point test in the research zone	29
2.4.2.3	Performance matching to search for (If, ψ)	30
2.4.2.4	Final If-I-Psi-N	30
2.4.3	P-Pf-U-N Working point search for the motor operating mode	30
2.4.3.1	Identify the research zone and the target performance	31
2.4.3.2	Model map test to derive the research zone	31
2.4.3.3	Performance matching to search for (If, I_d , I_q)	32
2.4.3.4	Final If-I-Psi-N	32
2.4.3.5	Feasibility diagram and color meaning of outputs in the working point table	32
2.4.4	Computing principles of other terms in the result tables	34
2.4.4.1	Electromagnetic behavior – General information	34
2.4.4.2	Flux in airgap	34
2.4.4.3	Flux density in iron	34
2.4.4.4	Ripple torque	34
2.5	Test results	36
2.5.1	Test conditions	36
2.5.1.1	Inputs	36
2.5.1.2	Settings	36
2.5.1.3	Windings characteristics	36
2.5.2	Main results	36
2.5.2.1	Machine performance – Working point	36
2.5.2.2	Power electronics	36
2.5.2.3	Ripple mechanical torque	37
2.5.3	Curves	37
2.5.4	Isovalues and isolines	37

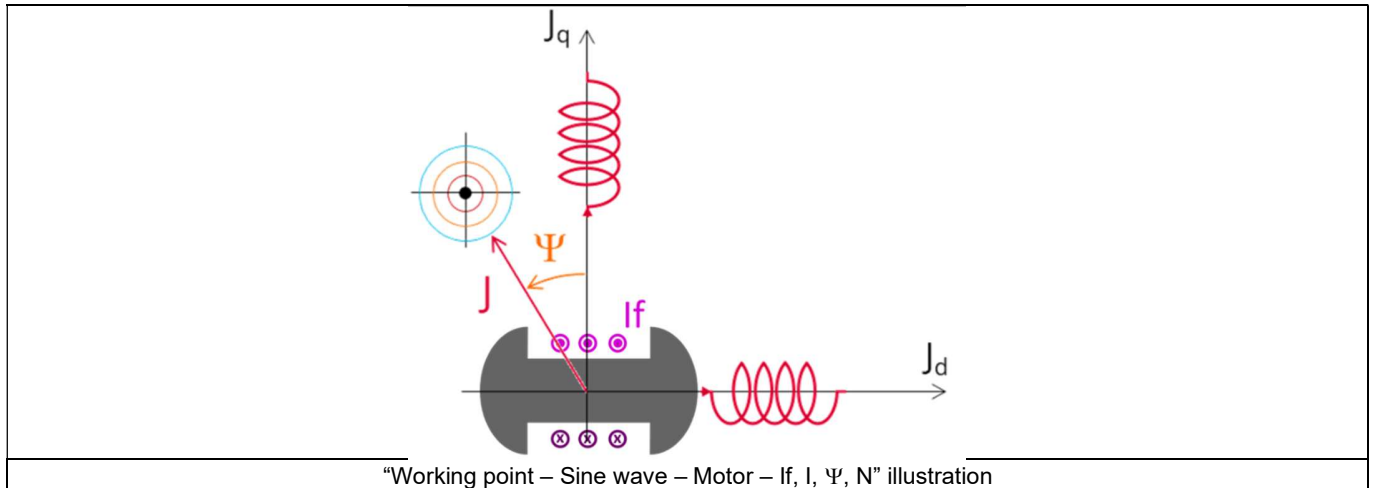
1 WORKING POINT – SINE WAVE – MOTOR – I_f , I , Ψ , N

1.1 Overview

1.1.1 Positioning and objective

The aim of the test “**Working point – Sine wave – Motor – I_f , I , Ψ , N** ” is to characterize the behavior of the machine when operating at the targeted input values I_f , I , Ψ , N (Magnitude of field current, magnitude of current, Control angle, Speed). These four inputs are enough to impose a precise working point.

For instance, a working point can be chosen on the efficiency map, by identifying the field current, current, the control angle, and the speed with different curves or maps displayed in the “Performance mapping / Sine wave / Motor / Efficiency map” test. Then, the “Working point – Sine wave – Motor – I_f , I , Ψ , N ” test allows to compute the performance for this working point.



The results of this test give an overview of the electromagnetic analysis of the machine, considering its topology.

The general data of the machine, like the machine constant and power balance, are computed and displayed. The motor convention is used to build the model.

The magnetic flux density is also computed in every region of the machine’s magnetic circuit to evaluate the design.

Two computation modes are available:

- “Fast computation mode” is perfectly suited for the pre-design step (Hybrid model based on Magneto-Static Finite Element computations and Park transformation theory).
- “Accurate computation mode” is perfectly suited for the final design step (Pure Finite Element modeling based on transient computations).

It also gives the capability to make comparisons between the results obtained from the measurements and those obtained with Altair® FluxMotor®.

The following table helps to classify the test “Working point – Sine wave – Motor – I_f , I , Ψ , N ”.

Family	Working point
Package	Sine wave
Convention	Motor
Test	I_f , I , Ψ , N

Positioning of the test “Working point – Sine wave – Motor – I_f , I , Ψ , N ”

1.1.2 User inputs

The four main user input parameters are the field current, supply line current, control angle, speed, and computation mode. In addition, the winding temperatures must be set.

1.1.3 Main outputs

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

1.1.3.1 Main results

- 1) Machine performance – Base speed point
 - General data
 - Machine constants
 - Power balance
 - Flux in airgap
 - Flux density in iron
- 2) Power electronics
 - Inverter
 - Working point
- 3) Ripple mechanical torque
 - Working point

1.1.3.2 Curves – in the “Fast computation modes”

- 1) Ripple mechanical torque versus rotor angular position
- 2) Flux density in airgap versus rotor angular position

1.1.3.3 Curves – in the “Accurate computation modes”

- 1) Mechanical torque versus rotor angular position
- 2) Mechanical torque harmonic analysis
- 3) Flux density in airgap versus rotor angular position
- 4) Flux density in airgap harmonic analysis
- 5) Field voltage versus rotor angular position
- 6) Field current versus rotor angular position
- 7) Phase voltage versus rotor angular position
- 8) Phase voltage harmonic analysis
- 9) Phase current versus rotor angular position
- 10) Phase current harmonic analysis

1.1.3.4 Graphics

- 1) Isovalues

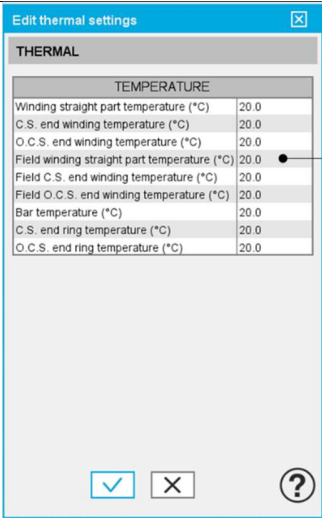
1.2 Settings

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

Additional information can be read in the document: MotorFactory_SMWF_IR_3PH_Test_Introduction – sections dealing with settings.

1.2.1 Thermal settings

One can define the temperatures of active components (windings and dampers (bars + end ring)) to define the physical properties of the materials needed to directly run the tests.



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
Field winding straight part temperature (*C)	20.0
Field C.S. end winding temperature (*C)	20.0
Field 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

Temperatures of the machine active components to be considered for characterizing the physical properties of the associated materials.

For more details, please refer to the document: MotorFactory_SMWF_IR_3PH_Test_Introduction – section “thermal settings”.

1.2.2 Power electronics parameters

Dialog box to define the power electronics parameters:

- Inverter control strategy
- Inputs for evaluating the power electronics stage losses.

For more details, please refer to the document: MotorFactory_SMWF_IR_3PH_Test_Introduction – sections dealing with “Power electronics mode settings”.

1.2.3 Mechanical loss model parameters

A dialog box allows for defining the mechanical loss computation model.
For more details, please refer to the document: MotorFactory_SMWF_IR_3PH_Test_Introduction – section “Mechanical loss model settings”.

1.3 Inputs

1.3.1 Standard inputs

1.3.1.1 Modes of computation

There are two modes of computation.

The “**Fast**” computation mode is the default one. It corresponds to a hybrid model, which is perfectly suited for the pre-design step. Indeed, all the computations in the back end are based on magnetostatic finite element computations associated with Park’s transformation. It evaluates the electromagnetic quantities with the best compromise between accuracy and computation time to explore the space of solutions quickly and easily.

The “**Accurate**” computation mode allows solving the computation with transient magnetic finite element modeling. This mode of computation is perfectly suited to the final design step because it allows getting more accurate results. It also computes additional quantities like the AC losses in winding and rotor iron losses.

1.3.1.2 Field current definition mode

There are two common ways to define electrical current.

Electrical current can be defined by the current density in electric conductors.
In this case, the current definition mode should be « **Density** ».

Electrical current can be defined directly by indicating the value of the field current.
In this case, the current definition mode should be « **Current** ».

1.3.1.3 Field current

When the choice of current definition mode is “**Current**”, the DC value of the current supplied to the field winding: “**Field current**” (*Current in Field conductors*) must be provided.

1.3.1.4 Field current density

When the choice of current definition mode is “**Density**”, the DC value of the current density in electric conductors “**Field current density**” (*Current density in Field conductors*) must be provided.

Note: The number of parallel paths is automatically considered in the results.

1.3.1.5 Line current definition mode

There are two common ways to define electrical current.

Electrical current can be defined by the current density in electric conductors.
In this case, the current definition mode should be « **Density** ».

Electrical current can be defined directly by indicating the value of the line current (the rms value is required).
In this case, the current definition mode should be « **Current** ».

1.3.1.6 Line current, rms

When the choice of current definition mode is “**Current**”, the rms value of the line current supplied to the machine: “**Line current, rms**” (*Line current, rms value*) must be provided.

1.3.1.7 Current density, rms

When the choice of current definition mode is “**Density**”, the rms value of the current density in electric conductors “**Current density, rms**” (*Current density in conductors, rms value*) must be provided.

Note: The number of parallel paths and the winding connection are automatically considered in the results.

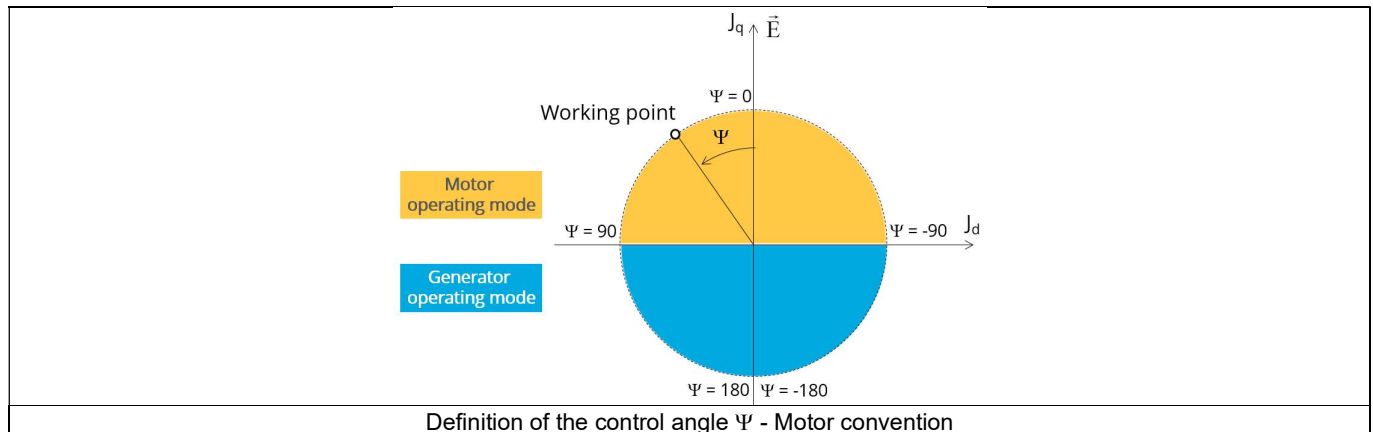
1.3.1.8 Control angle

Considering the vector diagram shown below, the “**Control angle**” is the angle between the electromotive force (E) and the electrical current (J) ($\Psi = \text{angle}(E, J)$).

The default value is 45 degrees. It is an electrical angle. It must be set in a range of -180 to 180 degrees.

This range of values covers all the possible working points in the motor convention. The operating mode is displayed at the head of the results.

Note: The sign of results like power depends on both the convention and the operating mode.



1.3.1.9 Speed

The imposed **"Speed"** (*Speed*) of the machine must be set.

1.3.1.10 Rotor position dependency

This input is enabled only if the "Fast" mode is selected. By default, the rotor position dependency is set to "No", but it can be set to "Yes". When selected, this option allows the user to carry out the test by considering the rotor position. Hence, the computation will be done with rotor position θ , varying within the "No. computed elec. periods", providing a better estimate of machine performance while maintaining a relatively low computation time compared with "Accurate mode".

Note: In "Fast" mode, the ripple torque is analyzed only if the "Rotor position dependency" is Yes.

1.3.1.11 AC losses analysis - Fast

The **"AC losses analysis - Fast"** (AC losses analysis required only while "Fast" computation mode and Rotor position dependency are selected) allows computing or not AC losses in stator winding. There are two available options:

None: AC losses are not computed. However, as the computation mode is "Fast" with rotor position dependency, a multi-static computation is performed without representing the solid conductors (wires) inside the slots. Phases are modeled with coil regions. Thus, the mesh density (number of nodes) is lower which leads to a lower computation time.

FE-Hybrid: AC losses in winding are computed without representing the wires (strands, solid conductors) inside the slots.

Since the location of each wire is accurately defined in the winding environment, sensors evaluate the evolution of the flux density close each wire. Then, a postprocessing based on analytical approaches computes the resulting current density inside the conductors and the corresponding Joule losses.

The wire topology can be "Circular" or "Rectangular".

There can be one or several wires in parallel (in hand) in a conductor (per turn).

This method leads to quite accurate results with lower computation time. This is a good compromise between accuracy and computation time.

Warning: With the "FE-Hybrid" option the accuracy of results is good especially when the wire size is small (let's say wire diameter lower than 2.5 mm). However, this can have a little impact on the accuracy of results because we have supposed that the magnetic field is not impacted by the modeling assumption.

Note: With FE-Hybrid option the recommended "Number of computed electrical periods" is equal to "1/2".

Note: When the winding is built with hairpin technology the FE-Hybrid mode is not available because it is not relevant for computations with such kind of winding/conductors.

1.3.1.12 AC losses analysis - Accurate

The “**AC losses analysis - Accurate**” (AC losses analysis required only while “Accurate” computation mode is selected) allows computing or not AC losses in stator winding. There are three options available:

None: AC losses are not computed. However, as the computation mode is “Accurate”, a transient computation is performed without representing the solid conductors (wires) inside the slots. Phases are modeled with coil regions. Thus, the mesh density (number of nodes) is lower which leads to a lower computation time.

FE-One phase: AC losses are computed with only one phase modeled with solid conductors (wires) inside the slots. The other two phases are modeled with coil regions. Thus, AC losses in winding are computed with a lower computation time than if all the phases were modeled with solid conductors. However, this can have a little impact on the accuracy of results because we have supposed that the magnetic field is not impacted by the modeling assumption.

FE-All phase: AC losses are computed, with all phases modeled with solid conductors (wires) inside the slots. This computation method gives the best results in terms of accuracy, but with a higher computation time.

FE-Hybrid: AC losses in winding are computed without representing the wires (strands, solid conductors) inside the slots. Since the location of each wire is accurately defined in the winding environment, sensors evaluate the evolution of the flux density close each wire. Then, a postprocessing based on analytical approaches computes the resulting current density inside the conductors and the corresponding Joule losses.

The wire topology can be “Circular” or “Rectangular”.

There can be one or several wires in parallel (in hand) in a conductor (per turn).

This method leads to quite accurate results with lower computation time. This is a good compromise between accuracy and computation time.

Warning: With the “FE-Hybrid” option the accuracy of results is good especially when the wire size is small (let’s say wire diameter lower than 2.5 mm). However, this can have a little impact on the accuracy of results because we have supposed that the magnetic field is not impacted by the modeling assumption.

Note: With FE-Hybrid option the recommended “Number of computed electrical periods” is equal to “1/2” whereas 2 computed electrical periods are needed for “FE-One phase” and for “FE-All phase” options.

Indeed, when solid conductors are represented in the Finite Element model (like with FE-One phase and FE-All phase options), there are transient phenomena to consider which leads to increase the “Number of computed electrical periods” to reach the steady state.

With the “FE-Hybrid option”, the transient phenomena are handled by the analytical model, so, it is not necessary to increase the “Number of computed electrical periods” compared to a study with “None” options (without AC losses computation).

Note: When the winding is built with a hairpin technology the FE-Hybrid mode is not available because it is not relevant for computations with such kind of winding/conductors.

1.3.2 Advanced inputs

1.3.2.1 Number of computed electrical periods

The user input “**No. computed elec. periods**” (Number of computed electrical periods only required with “Accurate” computation mode or “Fast” computation mode with rotor position dependency activated) influences the accuracy of results, especially in the case of AC losses computation. Indeed, with represented conductors (AC losses analysis set to “FE - One phase” or “FE - All phase”), the computation may lead to have transient current evolution in wires requiring more than an electrical period of simulation to reach the steady state over an electrical period.

The default value is equal to 2. The minimum allowed value is 0.5 (recommended in “Accurate” mode with AC losses analysis set to “None” or “Hybrid” and “Fast” mode with rotor position dependency). The default value provides a good compromise between the accuracy of results and computation time.

1.3.2.2 Number of computations per electrical period

The user input “**No. comp / electrical period**” (Number of computations per electrical period required only with “Accurate” computation mode or “Fast” computation mode with rotor position dependency activated) influences the accuracy of results (computation of the peak-peak ripple torque, iron losses, AC losses...) and the computation time.

The default value is equal to 40. The minimum recommended value is 20. The default value provides a good balance between accuracy of results and computation time.

1.3.2.3 Rotor initial position

By default, the “**Rotor initial position**” is set to “**Auto**”.

When the “**Rotor initial position mode**” is set to “**Auto**”, the initial position of the rotor is automatically defined by an internal process of FluxMotor®. The resulting relative angular position corresponds to the alignment between the axis of armature phase 1 (reference phase) and the direct axis of the salient pole.

When the “**Rotor initial position**” is set to “User input” (i.e., the toggle button on the right), the initial position of the rotor to be considered for computation must be set by the user in the field « **Rotor initial position** ». The default value is equal to 0. The range of possible values is [-360, 360]. For more details, please refer to the document: MotorFactory_SMWF_ISP_IR_3PH_Test_Introduction – section “Rotor and armature relative position”.

1.3.2.4 Skew model – Number of layers

When the rotor magnets or the armature slots are skewed, the number of layers used in Flux® Skew environment to model the machine can be modified: “**Skew model - No. of layers**” (*Number of layers for modeling the skewing in Flux® Skew environment*).

1.3.2.5 Mesh order

To get the results, the original computation is performed using a Finite Element Modeling.

Two levels of meshing can be considered for this finite element calculation: first order and second order.

This parameter influences the accuracy of results and the computation time.

By default, a second order mesh is used.

1.3.2.6 Airgap mesh coefficient

The advanced user input “**Airgap mesh coefficient**” is a coefficient that adjusts the size of mesh elements inside the airgap. When the value of the “**Airgap mesh coefficient**” decreases, the mesh elements get smaller, leading to a higher mesh density inside the airgap and increasing the computation accuracy.

The imposed Mesh Point (size of mesh elements touching the points of the geometry), inside the Flux® software, is described as:

$$\text{Mesh Point} = (\text{airgap}) \times (\text{airgap mesh coefficient})$$

Airgap mesh coefficient is set to 1.5 by default.

The variation range of values for this parameter is [0.05; 2].

0.05 gives a very high mesh density and 2 gives a very coarse mesh density.

Caution:

Be aware, a very high mesh density does not always mean a better result quality. However, this always leads to the formation of a huge number of nodes in the corresponding finite element model. So, it means a need for huge numerical memory and increases the computation time considerably.

1.4 Main principles of computation

1.4.1 Introduction

The aim of this test in motor convention is to give a good overview of the electromagnetic potential of the machine by characterizing the working point according to the field current, line current, control angle, and speed set by the user. In addition, ripple torque at the working point is also computed.

Two computation modes are available:

- “Fast computation mode” is perfectly suited for the pre-design step to explore the space of solutions quickly and easily (Hybrid model based on magnetostatic FE computations and Park transformation).
- “Accurate computation mode” is perfectly suited for the final design step because it allows getting more accurate results and computing additional quantities like the AC losses in winding and rotor iron losses (Pure FE model based on transient computations).

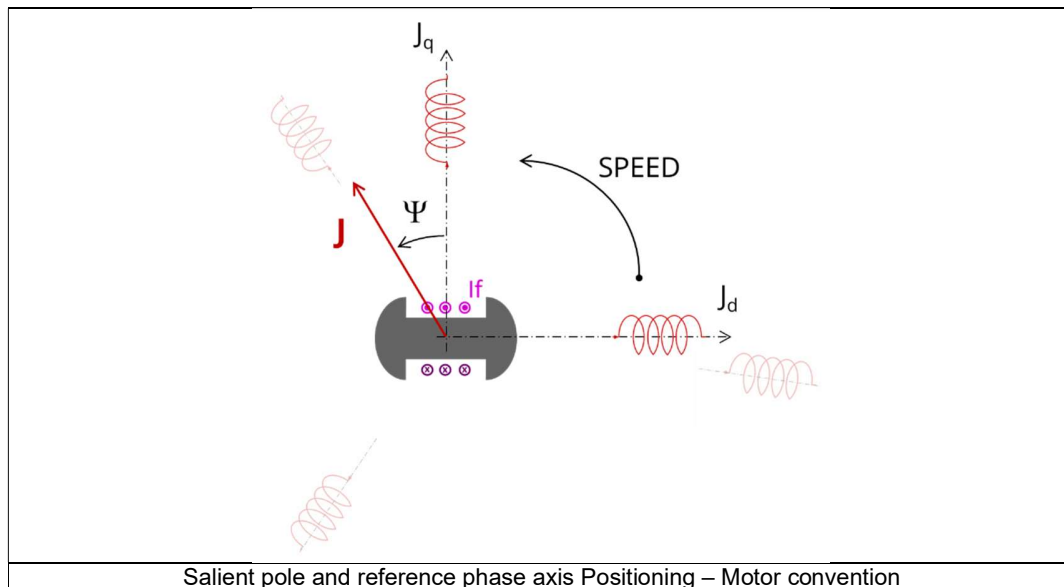
1.4.2 Fast computation mode

1.4.2.1 Working point - Definition

To compute the working point, the principle consists of positioning the salient pole towards the reference phase axis by considering the targeted control angle.

At the same time, the targeted field current, line current, and speed are imposed.

Then, the resulting behavior of the machine can be simulated, and all the main electromagnetic characteristics of the machine can be deduced by using Park's transformation and associated electric equations.



1.4.2.2 Electromagnetic behavior – General information

The method used for computing the electromagnetic behavior depends on the choice made (“Yes” or “No”) for the user “rotor position dependency”.

- “Yes” is selected: The analysis of the electromagnetic behavior is done over the number of computed electrical periods defined by users.
- “No” is selected: The analysis of the electromagnetic behavior is done through a dedicated static computation (1 rotor position to be considered) for the computed working point (with line current, control angle and speed obtained for the working point).

1.4.2.3 Flux in airgap

The flux in the airgap is always computed thanks to the dedicated static computation of the working point.

The airgap flux density is computed along a path in the airgap in Flux® software. The resulting signal is obtained for at least an electric period. The average and the peak value of the flux density are also computed. The harmonic analysis of the flux density in airgap versus rotor position is done to compute the magnitude of the first harmonic of the flux density.

1.4.2.4 Flux density in iron

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

1.4.2.5 Ripple torque

A specific computation is performed to precisely determine the rate of ripple torque.

Considering J_d and J_q at the base speed point, a computation is performed over one ripple torque period by using Finite Element modelling (Flux® software – Magnetostatic application).

Many computation points are considered over the ripple torque period (advanced user input: **No. comp. / ripple period**).

The following steps are performed to determinate the mechanical torque.

2) Original computation of the electromagnetic torque

The electromagnetic torque exerted on a non-deformable part of the domain is computed by the virtual work method. The torque in a direction is obtained by deriving the system energy with respect to a virtual displacement of the part in this direction.

The electromagnetic torque T_{em} is given by the following derivative:

$$T_{em} = - \frac{\partial W_m}{\partial \theta}$$

$\partial \theta$ = elementary angular displacement,

W_m = magnetic energy in the regional volume

The electromagnetic ripple torque is computed over the ripple torque period with respect to the rotor angular position $T_{em,\theta}$. The mean value " $T_{em, mean}$ " can also be computed.

3) Mechanical ripple torque based on Park's model

The mechanical ripple torque must be computed at the base speed.

First, we compute the electromagnetic torque " $T_{em, Park}$ " with Park's model:

$$T_{em, Park} = \frac{m}{2} \times p \times (\Phi_d \times J_q - \Phi_q \times J_d)$$

Then, the iron loss torque, the mechanical loss torque, and the additional loss torque are subtracted from " $T_{em, Park}$ " to get the corresponding mean value of the mechanical torque " $T_{mech, Park}$ ".

4) Resulting mechanical torque versus rotor angular position

To compute the resulting mechanical ripple torque, the original electromagnetic torque computed previously is weighted by the ratio of the mean value of the mechanical torque based on Park's model ($T_{mech, Park}$) and of the mean value of the original electromagnetic ripple torque ($T_{em, mean}$).

$$T_{mech,\theta} = T_{em,\theta} \times \frac{T_{mech, Park}}{T_{em, mean}}$$

The peak-peak value of the mechanical torque is then computed. The rate of ripple torque is deduced as a percentage or per unit of the nominal torque.

Warning: When the ripple torque computation is not requested, the computation of the working point is performed by considering only one position within the electrical period. It means that all the data characterizing the behavior of the machine can change based on the selection of ripple torque (Yes/No).

Flux density in a magnetic circuit will be more accurately computed when the computation of the ripple torque is requested.

1.4.3 Accurate computation mode

1.4.3.1 Working point - Definition

Working point computation is based on a transient magnetic finite element simulation over a half, one, or several electrical periods for a given set of inputs: field current, line current, control angle, and speed defined as for the Fast computation mode. Thus, all the main electromagnetic characteristics of the machine can be deduced accurately.

1.4.3.2 Electromagnetic behavior – General information

All the main quantities are directly computed from the Flux® software in the framework of a transient magnetic finite element simulation.

1.4.3.3 Iron losses

Iron losses (stator and rotor) are computed thanks to the “transient modified Bertotti model” in Flux® software.

1.4.3.4 Joule losses - armature and field windings

The armature and field windings DC Joule losses are always computed.

However, if AC losses analysis is set to “FE-One phase” or “FE-all phase”, armature AC Joule losses are computed in addition to the armature’s DC Joule losses.

FE-One phase: AC losses are computed with only one phase modeled for solid conductors (wires) inside the slots. The two other ones are modeled with coil regions. Thus, AC losses in winding are computed with a lower computation time than if all the phases were modeled with solid conductors. However, this can have a little impact on the accuracy of the results because we have supposed that the magnetic field is not impacted by the modeling assumption.

FE-All phase: AC losses are computed, with all phases modeled with solid conductors (wires) inside the slots. This computation method gives the best results in terms of accuracy, but with a higher computation time.

FE-Hybrid: AC losses in winding are computed without representing the wires (strands, solid conductors) inside the slots.

Since the location of each wire is accurately defined in the winding environment, sensors evaluate the evolution of the flux density close to each wire. Then, a postprocessing based on analytical approaches computes the resulting current density inside the conductors and the corresponding Joule losses.

With the “FE-Hybrid” option, the accuracy of results is good, especially when the wire size is small (let’s say a wire diameter lower than 2.5 mm). However, this can have a little impact on the accuracy of the results because we have supposed that the magnetic field is not impacted by the modeling assumption.

In FluxMotor®, armature AC Joule losses correspond to the additional losses induced by fields and skin effects in the conductors (wires) at high speed. Circulating current between parallel path or/and conductor wires are also considered in the modeling. In the case of AC losses, the total armature Joule losses ($W_{\text{Armature Joule Tot.}}$) is given by:

$$W_{\text{Armature Joule Tot.}} = W_{\text{Armature DC Joule Tot.}} + W_{\text{Armature AC Joule Tot.}}$$

Each term “AC and DC” is itself divided into two parts: the “winding active length part” (lamination part) and the “end winding part”.

$$W_{\text{Armature DC Joule Tot.}} = W_{\text{Armature DC Joule W.A.L.}} + W_{\text{Armature DC Joule E.W.}}$$

$$W_{\text{Armature AC Joule Tot.}} = W_{\text{Armature AC Joule W.A.L.}} + W_{\text{Armature AC Joule E.W.}}$$

In the winding active length part (W.A.L.), field effect, skin effect, and circulating current are considered.

In the end winding part (E.W.), field effect and skin effect are neglected; only circulating current is considered. This allows us to identify the amount of AC losses induced by circulating current between wires of conductors (Circulating current is induced by the unbalance of impedance of wires of a conductor itself, induced by the field variation in conjunction with each wire position in a conductor).

Thanks to AC losses computation, the “armature winding resistance ratio” is computed for the “total resistance”, the “Winding Active Length resistance” and the “End Winding resistance”. Ratios are computed by following the below equations:

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

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

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

1.4.3.5 Flux density in iron

The Mean and maximum values of the flux density of each iron region are computed with the help of sensors in Flux® software.

1.4.3.6 Torque

The electromagnetic torque exerted on a non-deformable part of the domain is computed by the virtual work method. The torque in a direction is obtained by deriving the system energy with respect to a virtual displacement of the part in this direction.

The electromagnetic torque T_{em} is given by the following derivative:

$$T_{em} = - \frac{\partial W_m}{\partial \theta}$$

$\partial \theta$ = elementary angular displacement,

W_m = magnetic energy in the regional volume

The electromagnetic torque is computed over the electrical period with respect to the rotor angular position $T_{em,\theta}$.

Then, the mean value of the electromagnetic torque is computed as " $T_{em, mean}$ ".

The iron loss torque, the mechanical loss torque, and the additional loss torque are subtracted from " $T_{em, mean}$ " to get the corresponding mean value of the mechanical torque, " $T_{mech, mean}$ ". To compute the resulting mechanical ripple torque, the mean electromagnetic torque previously computed is weighted by the ratio of the mean value of the mechanical torque ($T_{mech, mean}$) and the mean value of the original electromagnetic torque ($T_{em, mean}$).

$$T_{mech,\theta} = T_{em,\theta} \times \frac{T_{mech,mean}}{T_{em,mean}}$$

The peak-peak value of the mechanical torque is then computed. The rate of ripple torque is deduced as a percentage or per unit of the nominal torque.

1.4.3.7 Flux in airgap

The airgap flux density is computed with a sensor, which is defined in the static part of the airgap under a tooth in Flux® software. The resulting signal is obtained over an electric period. The average and the peak value of the flux density are also computed. The harmonic analysis of the phase voltage is done to evaluate the harmonics content.

1.4.3.8 Field voltage

The field voltage is computed with a sensor defined in the electrical circuit in Flux® software. The resulting signal is obtained over an electric period. The harmonic analysis of the phase voltage is done to evaluate the harmonics content.

1.4.3.9 Field current

The field current is computed with a sensor defined in the electrical circuit in Flux® software. The resulting signal is obtained over an electric period.

1.4.3.10 Phase voltage

The phase voltage is computed with a sensor defined in the electrical circuit in Flux® software. The resulting signal is obtained over an electric period. The harmonic analysis of the phase voltage is done to evaluate the harmonics content.

1.4.3.11 Phase current

The phase current is computed with a sensor defined in the electrical circuit in Flux® software. The resulting signal is obtained over an electric period. The harmonic analysis of the phase voltage is done to evaluate the harmonics content, which is very useful in the case of delta winding coupling.

1.5 Test results

Once a test is finished, the corresponding results are automatically displayed in the central window.

1.5.1 Test conditions

1.5.1.1 Inputs

All the parameter values belonging to standard inputs or advanced inputs are described in this section.

It shows the initial conditions considered for the test.

Here are the displayed subsections:

- Context
- Standard parameters
- Advanced parameters

For more information refer to the section 1.3 (Inputs).

1.5.1.2 Settings

All the settings dedicated to the test, along with the thermal characteristics, are displayed in this section.

Here are the displayed subsections:

- Thermal
- Electronics
- Mechanics

1.5.1.3 Windings characteristics

All windings' characteristics are displayed in the following subsections:

- Armature Winding characteristics
- Field Winding characteristics

For more details, please refer to the document: MotorFactory_SMWF_ISP_IR_3PH_Test_Introduction – section “Machine characteristics”.

1.5.2 Main results

1.5.2.1 Machine performance – Working point

Output data displayed in the following subsections is described in the section Working point – Sine wave –Motor.

Here are the displayed subsections:

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

Output data displayed in the following area list is described in the document: MotorFactory_SMWF_ISP_IR_3PH_Test_Introduction – section Working point – Sine wave – Display of results.

1.5.2.2 Power electronics

- Inverter

When power electronics stage is selected by the user, the inverter control strategy and the DC bus voltage are reminded. For information, the corresponding maximum line-line voltage, rms value is computed and displayed.

- Working point

The power balance and the corresponding efficiencies are computed and displayed for the machine, the power electronics stage and the system (i.e., the machine + power electronics stage).

For more details, please refer to the document: MotorFactory_SMWF_ISP_IR_3PH_Test_Introduction – sections dealing with “Power electronics mode settings”.

1.5.2.3 Ripple mechanical torque

The analysis of the ripple torque is presented in the table “Ripple mechanical torque” with the following subsections:

- Working point

For more details, please refer to the document: MotorFactory_SMWF_ISP_IR_3PH_Test_Introduction – sections dealing with “Working point – Sine wave – Display of results”.

1.5.3 Curves – Without rotor position dependency (Fast mode)

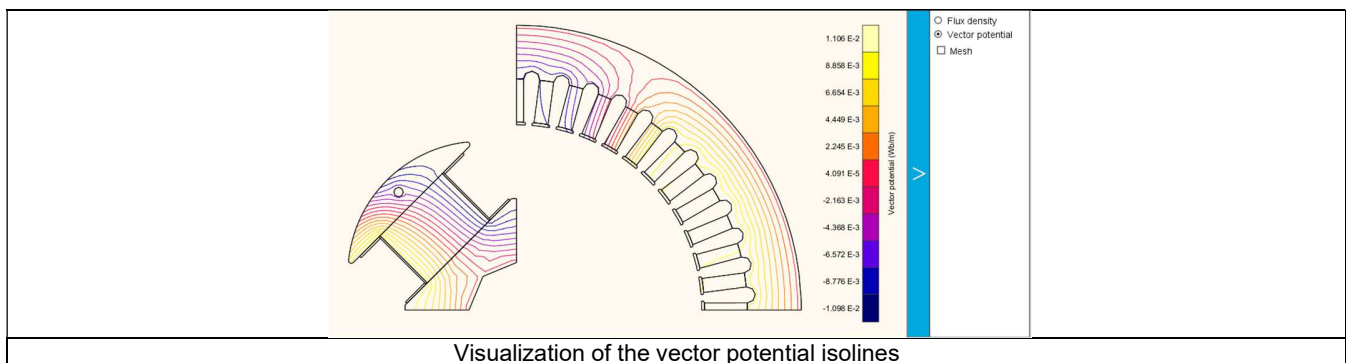
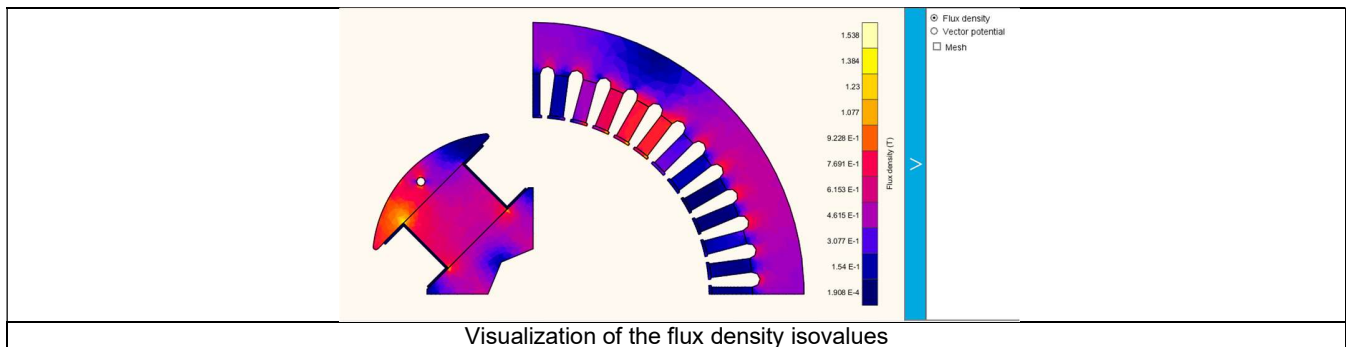
- Flux density in airgap versus rotor angular position
- Chart of temperature (radial and axial views)

1.5.4 Curves - With rotor position dependency (Fast mode + Rotor position dependency and Accurate mode)

- Mechanical torque versus rotor angular position
- Mechanical torque harmonic analysis
- Flux density in airgap versus rotor angular position
- Flux density in airgap harmonic analysis
- Field voltage versus rotor angular position
- Field current versus rotor angular position
- Phase voltage versus rotor angular position
- Phase voltage harmonic analysis
- Phase current versus rotor angular position
- Phase current harmonic analysis

1.5.5 Isovalues and isolines

The flux density isovalues and the vector potential isolines can be displayed.



Note: The visualization of the meshing of the model can also be displayed.

2 WORKING POINT – SINE WAVE – MOTOR & GENERATOR – P, PF, U, N

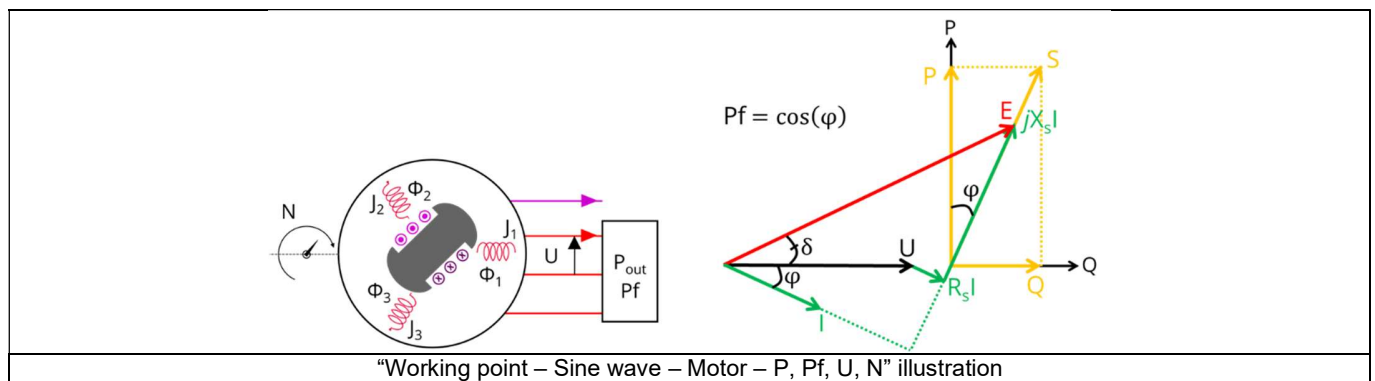
2.1 Overview

2.1.1 Positioning and objective

The aim of the test “**Working point – Sine wave – Motor & Generator – P, Pf, U, N**” is to characterize the behavior of the machine when operating at the working point that is targeted by the user. This point is defined by:

- The output power, which can be either the electrical power transmitted to the stator winding if the machine is in generator operating mode or the mechanical power exerted on the shaft if the machine is in motor operation. If the generator operation is targeted, the output power can be replaced by the apparent power.
- The power factor,
- The line-line voltage,
- and the rotating speed.

Through this test, the user can also verify whether the desired operating point is compatible with the machine. Additionally, the user can identify the appropriate reference values for the field current and the control angle needed to achieve this operating point.



The results of this test give an overview of the electromagnetic analysis of the machine, considering its topology.

The general data of the machine, like the machine constant and power balance, are computed and displayed. The user can choose between motor and generator conventions to build the model.

The magnetic flux density is also computed in every region of the machine’s magnetic circuit to evaluate the design.

It also gives the capability to make comparisons between the results obtained from the measurements and those obtained with FluxMotor.

The following table helps to classify the test: “Working point – Sine wave – Motor & Generator – P, Pf, U, N”.

Family	Working point
Package	Sine wave
Convention	Motor & Generator
Test	P, Pf, U, N

Positioning of the test “Working point – Sine wave – Motor & Generator – P, Pf, U, N”

2.1.2 User inputs

The main user input parameters are the choice of the convention and the operating mode, then the output power/apparent power, the power factor (lead/lag), the speed and the line-line voltage. In addition, the temperatures of the windings must be set.

2.1.3 Main outputs

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

2.1.3.1 Main results

- 1) Machine performance – Base speed point
 - General data
 - Machine constants
 - Power balance
 - Flux in airgap
 - Flux density in iron
- 2) Ripple mechanical torque
 - Working point

2.1.3.2 Curves

- 1) Ripple mechanical torque versus rotor angular position and its harmonic analysis
- 2) Flux density in airgap versus rotor angular position
- 3) Feasibility diagram

2.1.3.3 Graphics

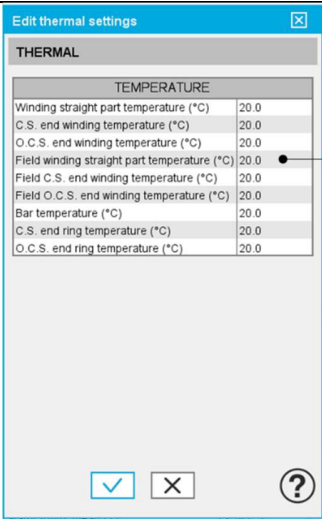
- 1) Isovalues

2.2 Settings

Two buttons give access to the following setting definitions: Thermal and Mechanics. Each kind of setting is briefly defined here. Additional information can be read in the document: MotorFactory_SMWF_IR_3PH_Test_Introduction – sections dealing with settings.

2.2.1 Thermal settings

In the thermal settings, one can define the temperatures of active components (windings and dampers (bars + end ring)) to define the physical properties of the materials needed to directly run the tests.



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
Field winding straight part temperature (*C)	20.0
Field C.S. end winding temperature (*C)	20.0
Field 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

Temperatures of the machine’s active components to be considered for characterizing the physical properties of the associated materials.

For more details, please refer to the document: MotorFactory_SMWF_IR_3PH_Test_Introduction – section “thermal settings”.

2.2.2 Mechanical loss model parameters

A dialog box allows for defining the mechanical loss computation model.
For more details, please refer to the document: MotorFactory_SMWF_IR_3PH_Test_Introduction – section “Mechanical loss model settings”.

2.3 Inputs

2.3.1 Introduction

The total number of user inputs is equal to 15 for a machine without skew and 16 for a skewed machine. Among these inputs, 8 are standard inputs and 8 or 7 are advanced inputs, depending on whether a machine is skewed or not.

2.3.2 Standard inputs

2.3.2.1 Convention

There are two conventions to choose from: “**generator**” and “**motor**”.

The “**generator**” convention is considered the default. In this convention, the machine operates as a generator from an electrical perspective. It receives mechanical power through the shaft (input) and outputs electrical power via the stator winding.

The “**motor**” convention is used when viewing the machine as a motor from an electrical perspective. It receives electrical power through the stator winding (input) and outputs mechanical power via the shaft.

Note: The sign of the power terms will vary based on the chosen convention and the machine's operating mode. For further details, refer to the document: MotorFactory_SMWF_ISP_IR_3PH_Test_Introduction – section “Test generic information”.

2.3.2.2 Operating mode

There are two operating modes to choose from: “**generator**” and “**motor**”.

It is intuitive to say that an electrical machine operates as a motor in the motor convention and vice versa as a generator in the generator convention. However, in any convention, an electrical machine can be regulated to operate in both generator and motor modes. This is because the machine can function in all four quadrants of the d-q plane.

Note: It is advised to choose the “**motor**” operating mode when the “**motor**” convention has been selected previously. And vice versa, the “**generator**” operating mode should be chosen for the “**generator**” convention. The other couple of selections are less common but very useful for applications in which the machine can switch between the two operating modes, such as in the traction application.

2.3.2.3 Power definition mode

Depending on the user's habit, the working point can be defined either by the output power of the machine or by its apparent electrical power.

Note: When the generator mode is selected, both apparent power and output power options are available for defining the working point. When the motor mode is selected, only the output power option is available. Defining the working point using apparent power is not applicable for motor operation.

2.3.2.4 Output power

If the generator operating mode is selected, the output power corresponds to the machine's active power, labeled “Stator Electrical Power” in the “Machine Performance – Working Point” result table.

If the motor operating mode is selected, the output power refers to the mechanical power exerted on the machine's shaft, labeled “Mechanical Power” in the “Machine Performance – Working Point” result table.

Note: The output is constrained by the selected convention and operating mode as follows:

1. **Same Convention and Operating Mode** (either motor or generator):
 - Power output is a positive value.
2. **Mixed Convention and Operating Mode** (motor convention with generator operating mode, or generator convention with motor operating mode):
 - Power output is a negative value.

If an incorrect value is entered, an error message will appear when the user clicks the “Run” button.

2.3.2.5 Apparent power

This option is only available if the generator operating mode is selected. It is also the default selection for the user. The apparent power is labeled “Apparent power” in the “Machine Performance – Working Point” result table.

Note: It is recommended to use apparent power to define the test if the user intends to evaluate different power factors at the same apparent power value. This approach allows the backend of FluxMotor to run the Finite Element simulation only once for the initial power

factor value and then use the simulated data for subsequent power factor values. Since the Finite Element simulation constitutes most of the computing time for the test, this method can significantly reduce the computing time for evaluating later power factor values.

2.3.2.6 Power factor definition mode

The power factor itself is not sufficient to determine if a machine supplies or consumes reactive power from the electrical network. Therefore, the user is provided with two options for the power factor.

The **power factor lag** means that the phase current vector is behind the phase voltage vector and the reactive power is positive, or the machine supplies reactive power in the generator convention and consumes reactive power in the motor convention.

The **power factor lead** means that the phase current vector is in advance compared to the phase voltage vector and the reactive power is negative, or the machine consumes reactive power in the generator convention and supplies reactive power in the motor convention.

2.3.2.7 Power factor lag

The **“power factor lag”** takes values from -1 to 1. If the user chooses this option, the phase current vector is behind the phase voltage vector. Hence, the phase angle and reactive power must be positive in the “Machine Performance – Working Point” result table.

Note: The power factor lag is constrained by the selected convention and operating mode as follows:

1. **Same Convention and Operating Mode** (either motor or generator):
 - Power factor lag varies between 0 and 1.
2. **Mixed Convention and Operating Mode** (motor convention with generator operating mode, or generator convention with motor operating mode):
 - Power factor lag varies between -1 and 0.

If an incorrect value is entered, an error message will appear when the user clicks the "Run" button.

2.3.2.8 Power factor lead

The **“power factor lead”** takes values from -1 to 1. If the user chooses this option, the phase current vector is in advance compared to the phase voltage vector. Hence, the phase angle and reactive power must be negative in the “Machine Performance – Working Point” result table.

Note: The “power factor lead” is constrained by the selected convention and operating mode as follows:

1. **Same Convention and Operating Mode** (either motor or generator):
 - “Power factor lead” varies between 0 and 1.
2. **Mixed Convention and Operating Mode** (motor convention with generator operating mode, or generator convention with motor operating mode):
 - “Power factor lead” varies between -1 and 0.

If an incorrect value is entered, an error message will appear when the user clicks the "Run" button.

2.3.2.9 Field current definition mode

In the backend of FluxMotor, machine performance is analyzed within a research zone defined by the field current and the control angle. The goal is to identify the combination of field current and control angle that allows achieving the desired working point characterized by P-Pf-U-N. The maximum field current sets the upper limit for the field current.

There are two common ways to define the maximum field current:

- by the current density in electric conductors, in this case, the field current definition mode should be « **Density** ».
- by indicating the value of the field current (DC value), in this case, the field current definition mode should be « **Current** ».

2.3.2.10 Maximum Field current

When the choice of current definition mode is **“Current”**, the DC value of the maximum current supplied to the field winding: **“Maximum Field current”** (*Current in Field conductors*), must be provided.

2.3.2.11 Maximum Field current density

When the choice of current definition mode is **“Density”**, the DC value of the maximum current density in electric conductors, **“Maximum Field current density”** (*Current density in Field conductors*), must be provided.

Note: The number of parallel paths is automatically considered in the results.

2.3.2.12 Speed

The imposed **“Speed”** (*Speed*) of the machine must be set.

2.3.2.13 Line-line voltage, rms

The imposed “**Line-line voltage**” (*Line-line voltage, rms*) of the machine must be set.

2.3.2.14 Ripple torque analysis

The “**Ripple torque analysis**” (Additional analysis on ripple torque period: Yes / No) allows to compute or not the value of the ripple torque and to display the corresponding torque versus the angular position over the ripple torque period.

The default value is “No”.

Notes:

- This choice influences the accuracy of results and the computation time. The magnitude of the ripple torque is calculated. This additional computation needs additional computation time.
- In the case of “Yes”, the ripple torque is computed. Then, the flux density in regions is evaluated through the ripple torque computation.
- In the case of “No”, the ripple torque is not computed. Then, the flux density in regions is evaluated by considering the Park’s model computation.

2.3.3 Advanced inputs

2.3.3.1 Number of computations for J_d , J_q per quadrant

This input is available only if the motor operating mode is selected. It defines how finely the response surfaces of machine performance in the J_d - J_q planes are discretized. In other words, it defines the number of computation points along the d-axis and q-axis. The default value is equal to 6. This default value provides a good compromise between accuracy and computation time. The minimum allowed value is 5.

Note: As a synchronous machine with wound field machine operates in both 1st and 2nd quadrants, the total number of computations for the D-axis is twice the number entered for « **No. Comp. for J_d , J_q** » minus one, as the zero value is shared between the two quadrants. For example, if « **No. Comp. for J_d , J_q** » is 6, there will be 11 computations for the D-axis.

2.3.3.2 Number of computations for field current

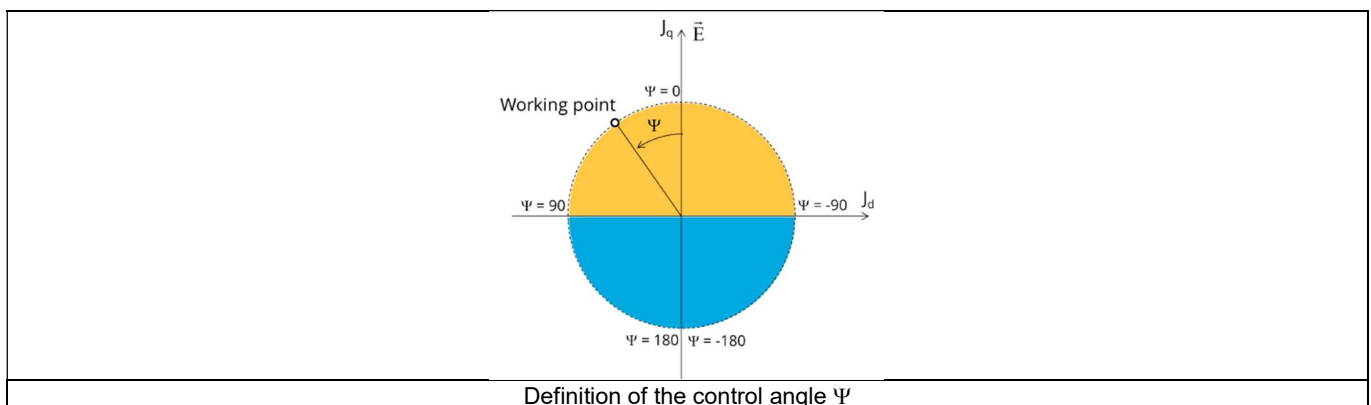
In the backend of FluxMotor, the field current is varied within a research zone from 0 to the maximum field current defined previously to find the value allows achieving the desired working point P-Pf-U-N. This research zone is discretized linearly based on the “**Number of computations for field current.**”

The machine's performance is represented by the response surfaces of field current and control angle. An optimization algorithm uses these response surfaces to determine the field current and control angle that provide the required P-Pf-U-N performance. Thus, the “**Number of computations for field current**” is crucial for the optimizer's accuracy.

Note: For the best compromise between computing time and accuracy, set the “**Number of computations for field current**” to 6. If higher accuracy is needed, increase this value accordingly, keeping in mind that higher values will require more computing time.

2.3.3.3 Number of computations for control angle

This input is available only if the generator operating mode is selected. Considering the vector diagram shown below, the “**Control angle**” is the angle between the electromotive force (E) and the electrical current (J) ($\Psi = \text{angle}(E, J)$).



In the backend of FluxMotor, the control angle is varied within a research zone to find the value allows achieving the desired working point P-Pf-U-N. This research zone is discretized linearly based on the **“Number of computations for control angle.”**

The machine's performance is represented by the response surfaces of field current and control angle. An optimization algorithm uses these response surfaces to determine the field current and control angle that provide the required P-Pf-U-N performance. Thus, the **“Number of computations for control angle”** is crucial for the optimizer's accuracy.

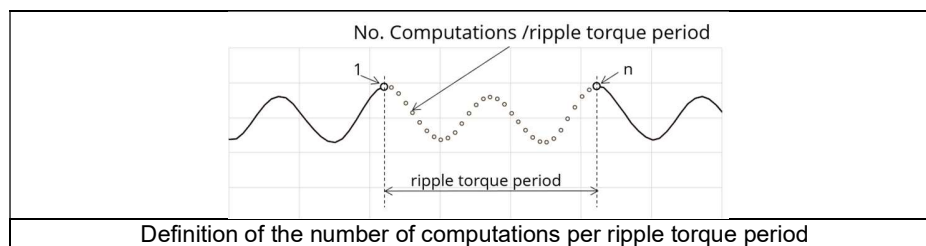
Note: For the best compromise between computing time and accuracy, set the **“Number of computations for control angle”** to 13. If higher accuracy is needed, increase this value accordingly, keeping in mind that higher values will require more computing time.

2.3.3.4 Number of computations per ripple torque period

The number of computations per ripple torque period is considered when the user has chosen to perform a “Ripple torque analysis” (i.e., answered “Yes” to the standard input “Ripple torque analysis” required only with “Fast” computation mode).

The user input **“No. comp. / ripple period”** (Number of computations per ripple torque period) influences the accuracy of the results (computation of the peak-peak ripple torque) and the computation time.

The default value is equal to 30. The minimum allowed value is 25. The default value provides a good balance between the accuracy of results and computation time.



2.3.3.5 Skew model – Number of layers

When the rotor magnets or the armature slots are skewed, the number of layers used in Flux® Skew environment to model the machine can be modified: **“Skew model - No. of layers”** (Number of layers for modeling the skewing in Flux® Skew environment).

2.3.3.6 Rotor initial position

By default, the **“Rotor initial position”** is set to **“Auto”**.

When the **“Rotor initial position mode”** is set to **“Auto”**, the initial position of the rotor is automatically defined by an internal process of FluxMotor®. The resulting relative angular position corresponds to the alignment between the axis of armature phase 1 (reference phase) and the direct axis of the salient pole.

When the **“Rotor initial position”** is set to “User input” (i.e., the toggle button on the right), the initial position of the rotor to be considered for computation must be set by the user in the field **« Rotor initial position »**. The default value is equal to 0. The range of possible values is [-360, 360]. For more details, please refer to the document: MotorFactory_SMWF_IR_3PH_Test_Introduction – section “Rotor and armature relative position”.

2.3.3.7 Mesh order

To get the results, the original computation is performed using a Finite Element Modeling.

Two levels of meshing can be considered for this finite element calculation: first order and second order.

This parameter influences the accuracy of results and the computation time.

By default, a second order mesh is used.

2.3.3.8 Airgap mesh coefficient

The advanced user input **“Airgap mesh coefficient”** is a coefficient that adjusts the size of mesh elements inside the airgap. When the value of the **“Airgap mesh coefficient”** decreases, the mesh elements get smaller, leading to a higher mesh density inside the airgap and increasing the computation accuracy.

The imposed Mesh Point (size of mesh elements touching the points of the geometry) inside the Flux® software is described as:

$$\text{Mesh Point} = (\text{airgap}) \times (\text{airgap mesh coefficient})$$

Airgap mesh coefficient is set to 1.5 by default.
The variation range of values for this parameter is [0.05; 2].
0.05 gives a very high mesh density and 2 gives a very coarse mesh density.

Caution:

Be aware, a very high mesh density does not always mean a better result quality. However, this always leads to the formation of a huge number of nodes in the corresponding finite element model. So, it means a need for huge numerical memory and increases the computation time considerably.

2.4 Main principles of computation

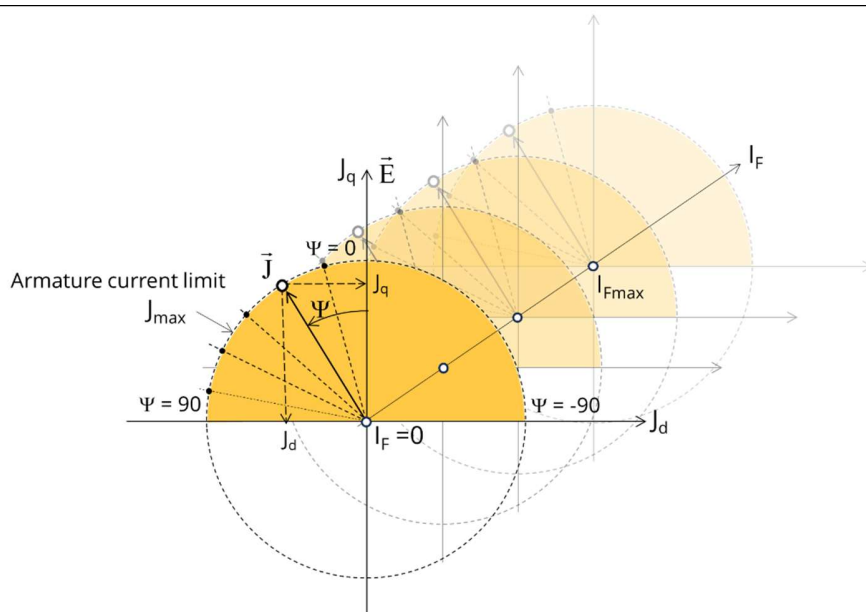
2.4.1 Introduction

The aim of this test in motor / generator convention is to give a good overview of the electromagnetic potential of the machine by characterizing the working point according to the output power / apparent power, power factor, speed and voltage set by the user. In addition, ripple torque at the working point is also computed.

To achieve such an objective, in the back end of FluxMotor, an automatic search is performed to identify the line current I , the field current I_f and control angle ψ providing the performance defined by the user.

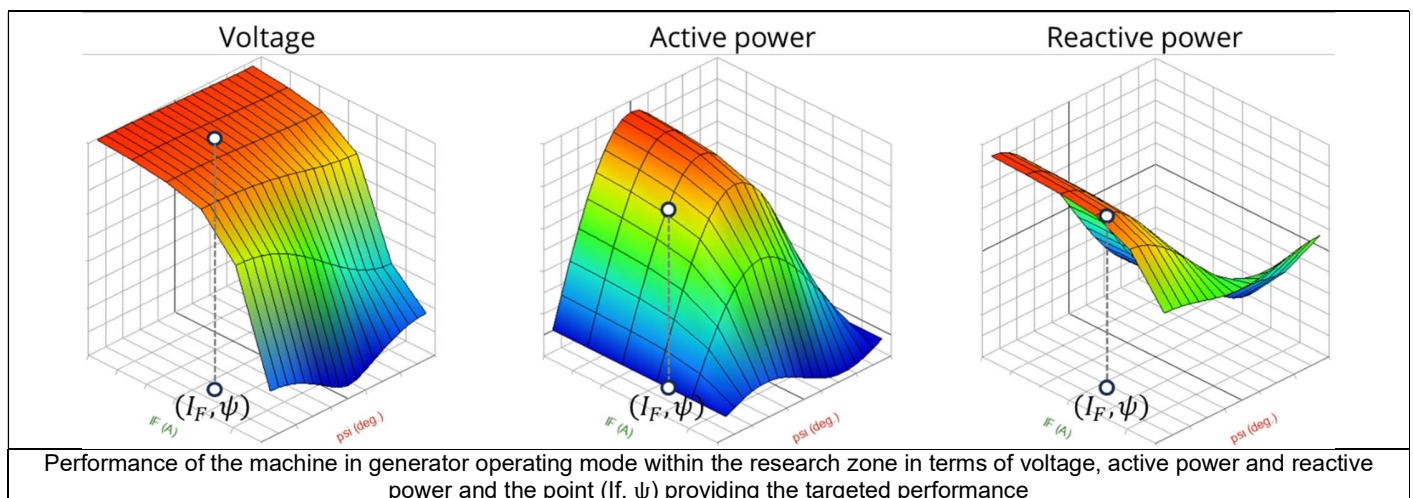
2.4.1.1 Generator operating mode

In the generator operating mode, the line current can be deduced directly from the user input (output power / apparent power, power factor and line-line voltage). The research zone comprises thus two dimensions: field current and control angle. It is defined by the maximum field current, the number of computations along the field current axis and the control angle axis, all of which can be adjusted by the user in the inputs of the test.



Research zone of the P-Pf-U-N for the generator operating mode defined by maximum field current and number of computations along the field current axis and control angle axis

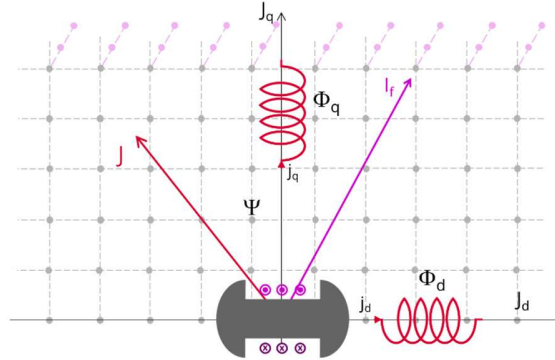
Within the research zone, the I_f - I - Ψ - N test will be executed at all points (I_f, ψ) to determine the performance response surfaces of the machine. Then an optimizer is used to search for the point (I_f, ψ) providing the match with the targeted performance.



Performance of the machine in generator operating mode within the research zone in terms of voltage, active power and reactive power and the point (I_f, ψ) providing the targeted performance

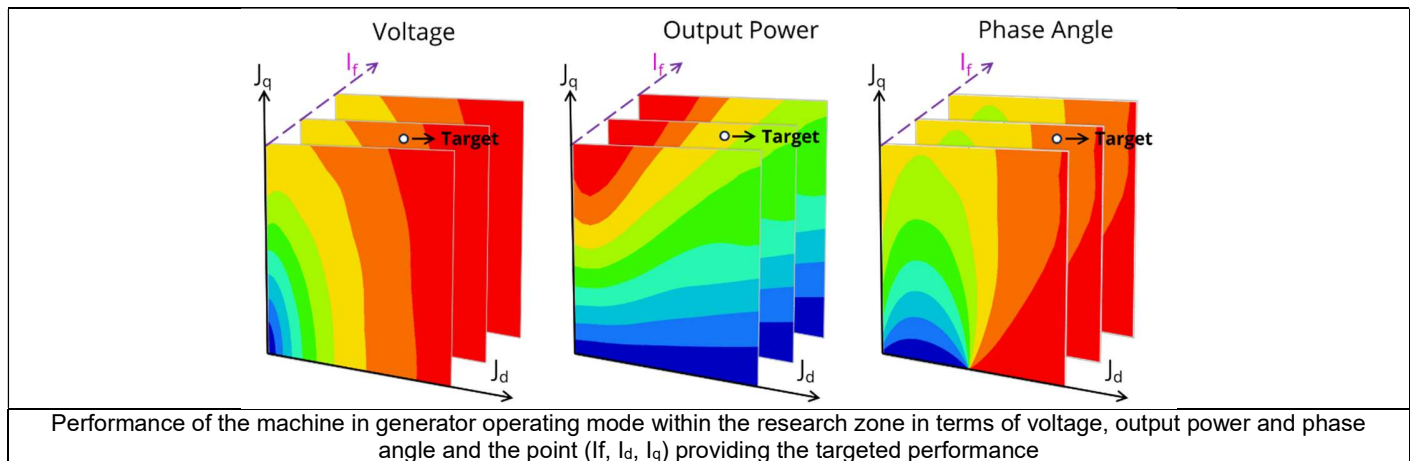
2.4.1.2 Motor operating mode

In the motor operating mode, the line current cannot be deduced directly from the user input (output power, power factor and line-line voltage) as the output power is related to on-shaft mechanical power without any knowledge of efficiency. The research zone comprises thus three dimensions: field current, armature current and control angle, or field current, d-axis armature current and q-axis armature current. It is defined by the maximum field current, the number of computations along the field current axis and the number of computations along the d-axis and q-axis of the armature current, all of which can be adjusted by the user in the inputs of the test.



Research zone of the P-Pf-U-N for the motor operating mode defined by maximum field current and number of computations along the field current axis and the number of computations along the d and q axis of stator current

Within the research zone, the If-I-Psi-N test will be executed at all points (I_f , I_d , I_q) to determine the performance response surfaces of the machine. Then an optimizer is used to search for the point (I_f , I_d , I_q) providing the match with the targeted performance.

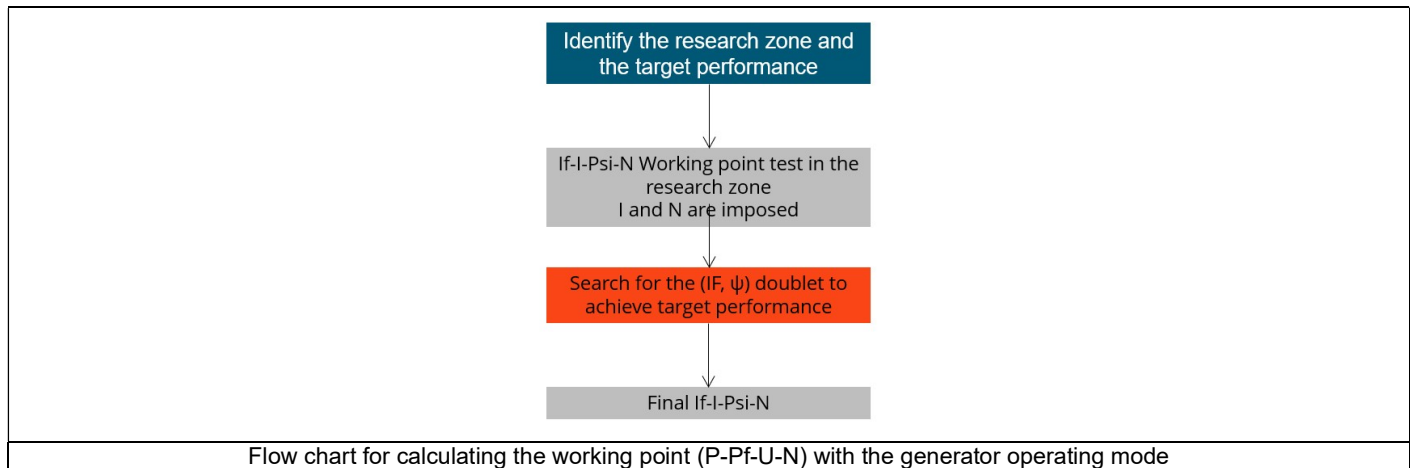


Performance of the machine in generator operating mode within the research zone in terms of voltage, output power and phase angle and the point (I_f , I_d , I_q) providing the targeted performance

2.4.2 P-Pf-U-N Working point search for the generator operating mode

The search process can be summarized by the following diagram. There are 4 main steps:

- Step 1: Identify the research zone and the target performance from the user's inputs.
- Step 2: Run If-I-Psi-N at all points of the research zone to determine the performance response surfaces of the machine (I and N are imposed).
- Step 3: Search for the point (I_f , ψ) providing the targeted performance by using an optimization algorithm.
- Step 4: Compute the working point If-I-Psi-N with the resulting values of (I_f , Ψ) and the imposed values of I and N by the user's inputs to deduce the real performance of the machine at the identified working point.



2.4.2.1 Identify the research zone and the target performance

From the output power / apparent power, power factor and voltage, the armature current limit is deduced, which is required for the If-I-Psi-N test within the research zone.

If one chooses to provide apparent power S_{target} , power factor $P_{f,target}$, and line-line voltage U_{target} , then we have:

Parameter labels	Definition and formula
Power factor lead/lag, target	$P_{f,target}$
Apparent power, target	S_{target}
Output power / Active power, target	$P_{target} = P_{f,target} \times S_{target}$
Reactive power, target	$Q = s \times S_{target} \times \sqrt{1 - P_{f,target}^2}$ $\text{with } s = \begin{cases} 1 & \text{if power factor lag} \\ -1 & \text{if power factor lead} \end{cases}$
Armature current	$J = \frac{S_{target}}{k \times U_{target}}$ $\text{with } k = \begin{cases} \sqrt{3} & \text{for Wye connection} \\ 3 & \text{for Delta connection} \end{cases}$

If one targets the output power P_{target} , the power factor P_{ftarget} , and the line-line voltage U_{target} , then we have:

Parameter labels	Definition and formula
Power factor lead/lag, target	P_{ftarget}
Apparent power, target	$S_{\text{target}} = \frac{P_{\text{target}}}{P_{\text{ftarget}}}$
Output power / Active power, target	P_{target}
Reactive power, target	$Q = s \times S_{\text{target}} \times \sqrt{1 - P_{\text{ftarget}}^2},$ with $s = \begin{cases} 1 & \text{if power factor lag} \\ -1 & \text{if power factor lead} \end{cases}$
Armature current	$J = \frac{S_{\text{target}}}{k \times U_{\text{target}}},$ with $k = \begin{cases} \sqrt{3} & \text{for Wye connection} \\ 3 & \text{for Delta connection} \end{cases}$

For both cases of inputs, the research zone is defined by the armature current limit J , maximum field current I_{fmax} , the number of computations along the field current axis and the control angle axis and the target performance can be reduced to the couple of active power P_{target} and reactive power Q_{target} .

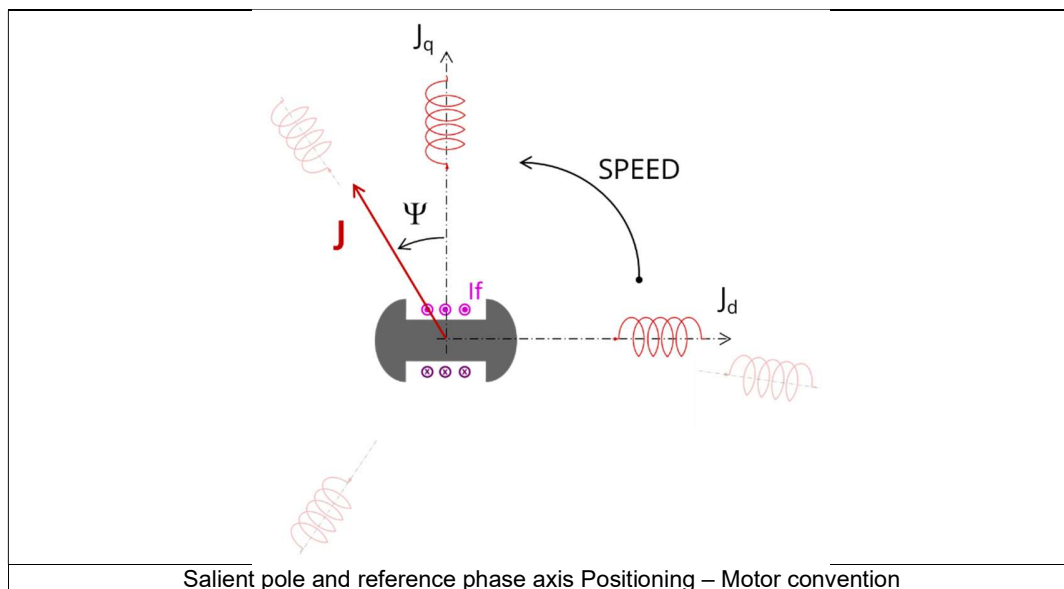
2.4.2.2 If-I-Psi-N Working point test in the research zone

The field current varies from zero to the maximum field current I_{fmax} and the control angle varies from $[-90^\circ \text{ to } 90^\circ]$ in the generator convention (quadrants 1 and 2) and $[90^\circ \text{ to } 180^\circ] + [-180^\circ \text{ to } -90^\circ]$ in the motor convention (quadrants 3 and 4). Then at each value of field current and control angle, the If-I-Psi-N in Fast Mode is executed. Please see the previous section of If-I-Psi-N test for more details.

To compute the working point If-I-Psi-N, the principle consists of positioning the salient pole towards the reference phase axis by considering the targeted control angle.

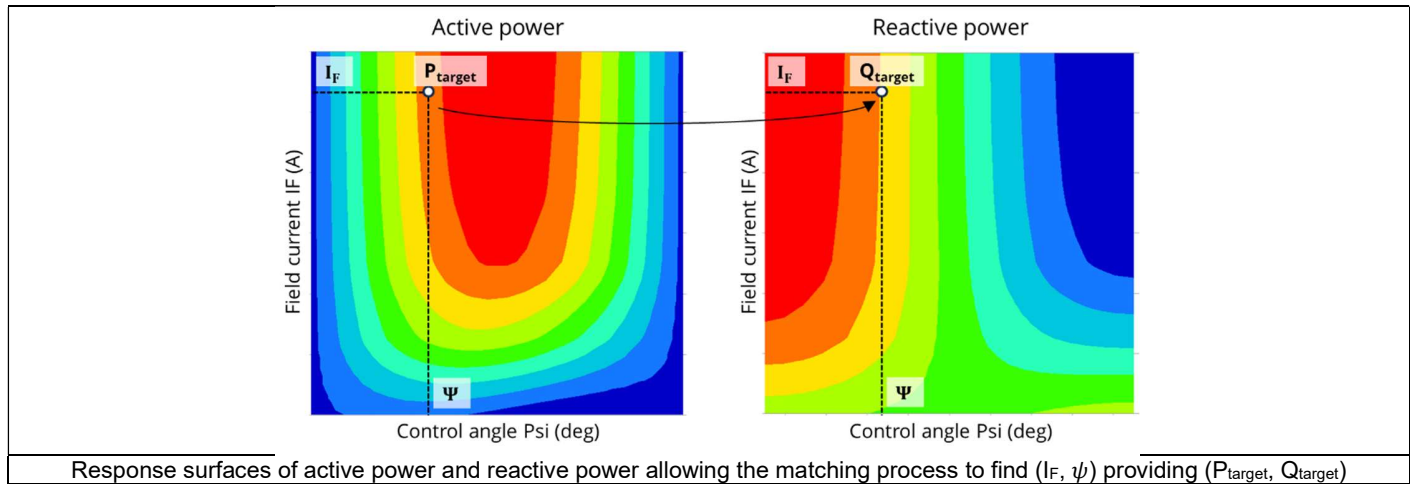
At the same time, the targeted field current, line current, and speed are imposed.

Then, the resulting behavior of the machine can be simulated, and all the main electromagnetic characteristics of the machine can be deduced by using Park's transformation and associated electric equations.



2.4.2.3 Performance matching to search for (I_f , ψ)

Response surfaces of active power and reactive power are built, and an optimizer is used to search for the point (I_f , ψ) providing P_{target} and Q_{target} .



2.4.2.4 Final If-I-Psi-N

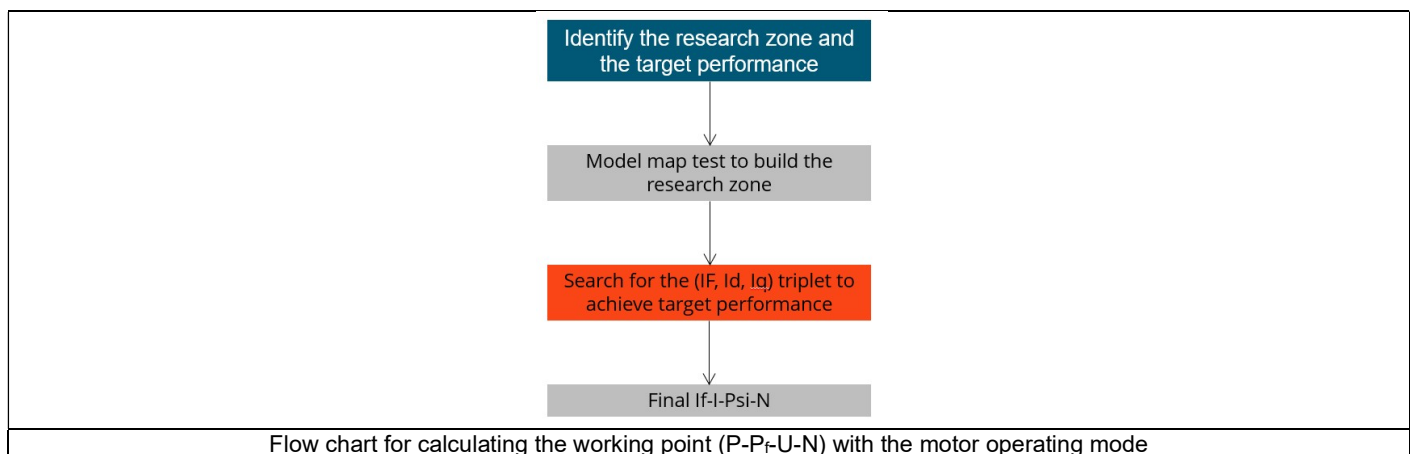
The found field current and control angle are combined with the imposed line current and speed for a final If-I-Psi-N test to identify the real performance of the machine.

Note: The field current and control angle are determined using an interpolation approach based on response surfaces. As a result, the active power, reactive power, and line-line voltage values presented in the “Machine Performance – Working Point” table may slightly differ from the targeted values. The extent of this difference depends on the number of computations used for the field current and control angle. A higher number of computations will result in more finely discretized response surfaces, thereby reducing the differences. For improved accuracy, consider increasing the number of computations if necessary.

2.4.3 P-Pf-U-N Working point search for the motor operating mode

The search process can be summarized by the following diagram. There are 4 main steps:

- Step 1: Identify the research zone and the target performance from the user's inputs.
- Step 2: Run a model map test to determine the performance response surfaces of the machine.
- Step 3: Search for the triplet (I_f , I_d , I_q) providing the targeted performance (Voltage, output power and phase angle) by using an optimization algorithm.
- Step 4: Run an If-I-Psi-N with the resulting values of (I_f , I_d , I_q) and the value of N (user input) and I resulting from the voltage + output power + phase angle to deduce the performance of the machine corresponding to the identified working point.



2.4.3.1 Identify the research zone and the target performance

From the output power, power factor and voltage, the armature current limit is deduced, which is required for the If-I-Psi-N test within the research zone.

If one chooses to provide output power P_{target} , power factor $P_{f_{target}}$, and line-line voltage U_{target} , then we have:

Parameter labels	Definition and formula
Power factor lead/lag, target	$P_{f_{target}}$
Output power / Active power, target	P_{target}
Phase angle, target	$\varphi_{target} = s \times \arccos(P_{f_{target}})$ $\text{with } s = \begin{cases} 1 & \text{if power factor lag} \\ -1 & \text{if power factor lead} \end{cases}$
Armature current limit ensures that, under all circumstances, the target operating point remains within the designated operating range	$J_{max} = \frac{2P_{target}}{k \times P_{f_{target}} \times U_{target}}$ $\text{with } k = \begin{cases} \sqrt{3} & \text{for Wye connection} \\ 3 & \text{for Delta connection} \end{cases}$

The research zone is defined by the armature current limit J_{max} , maximum field current $I_{f_{max}}$, the number of computations along the field current axis and the d-axis and q-axis of the armature current. And the target performance can be reduced to the couple of active power P_{target} and phase angle φ_{target} .

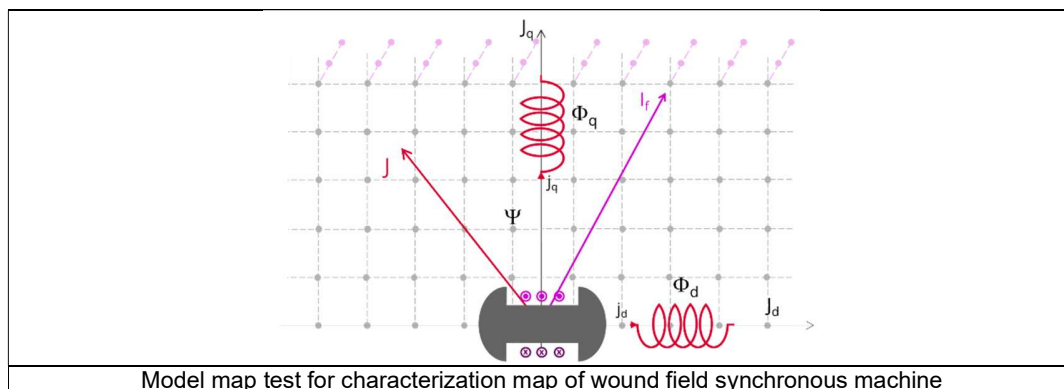
Note: In generator operating mode, the armature current is set directly by the user's input. However, in motor operating mode, the exact value of the armature current is not predefined and can vary between 0 and J_{max} . This ensures that the target operating point remains within the designated operating range.

2.4.3.2 Model map test to derive the research zone

The model map of wound field synchronous machine is performed in this step with the following inputs.

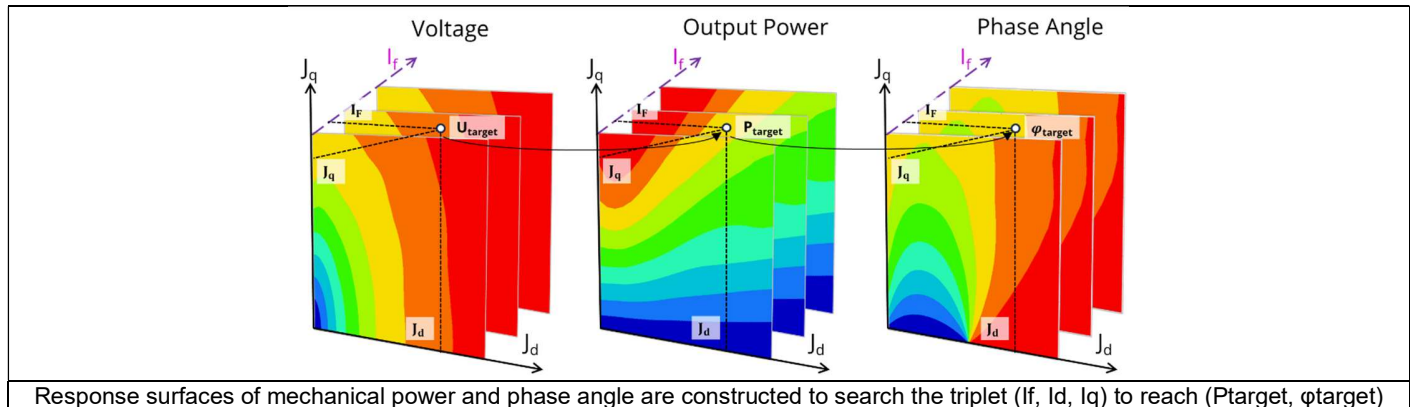
- Operating quadrants: 1st & 2nd
- Max. field current (A): $I_{f_{max}}$
- Max. current density, rms: J_{max}
- Maximum speed: N
- Rotor position dependency: No
- No. comp. for I_f : defined by user inputs in 1.3
- No. comp. for J_d , J_q : defined by user inputs in 1.3

For more information about the principle of the model map test, please refer to the dedicated document of the test.



2.4.3.3 Performance matching to search for (I_f , I_d , I_q)

Response surfaces of mechanical power, phase angle and voltage are built, and an optimizer is used to search for the point (I_f , I_d , I_q) providing P_{target} and ϕ_{target} and U_{target} .



2.4.3.4 Final If-I-Psi-N

The found field current and control angle are combined with the imposed line current and speed for a final If-I-Psi-N test to identify the real performance of the machine.

Note: The field current and d-axis + q-axis armature current are determined using an interpolation approach based on response surfaces. As a result, the active power, reactive power, and line-line voltage values presented in the "Machine Performance – Working Point" table may slightly differ from the targeted values. The extent of this difference depends on the number of computations used for the field current and control angle. A higher number of computations will result in more finely discretized response surfaces, thereby reducing the differences. For improved accuracy, consider increasing the number of computations if necessary.

2.4.3.5 Feasibility diagram and color meaning of outputs in the working point table

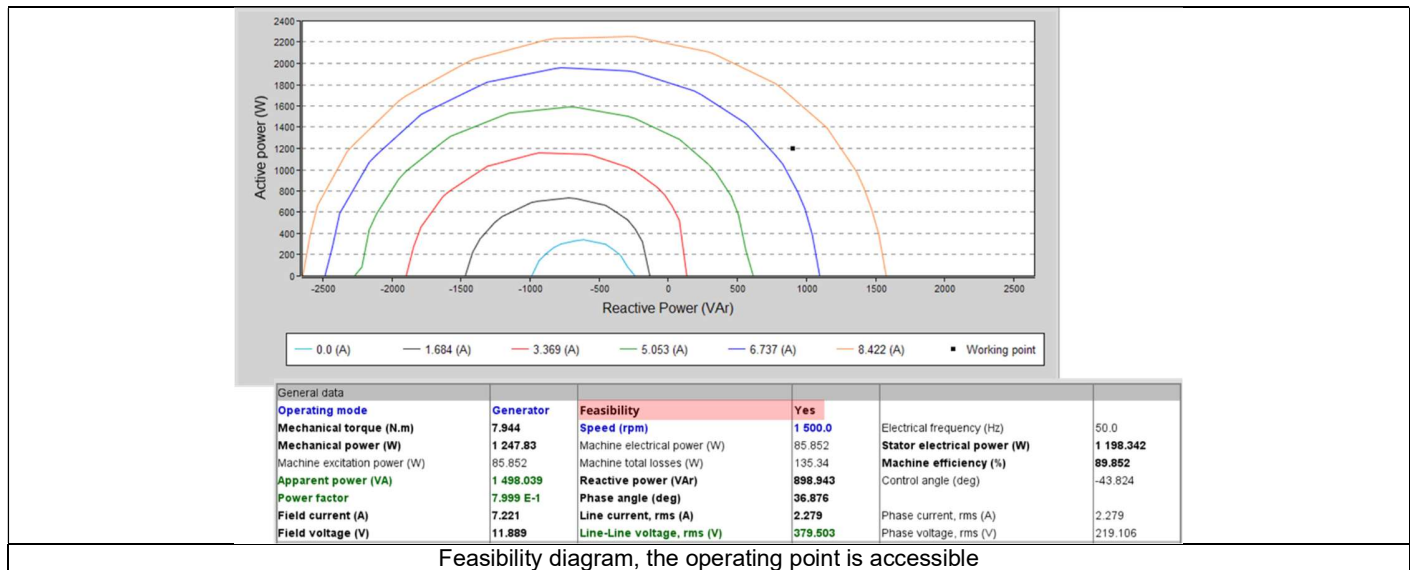
In this test, one can set any combination of power, power factor, voltage, and speed. However, not all the combinations are feasible for a given synchronous machine. To help users detect unfeasible operating points, a powerful tool called the Feasibility Diagram is provided.

The concept is like the P-Q diagram used by generator designers. In the P-Q plane, curves corresponding to different field current (I_f) values are plotted. Each point on these curves represents a combination of field current, armature current magnitude, and control angle. The curves range from $I_f = 0$ to I_{fmax} , and while the armature current remains constant (determined by the apparent power and voltage targets), each point on a curve corresponds to a different control angle.

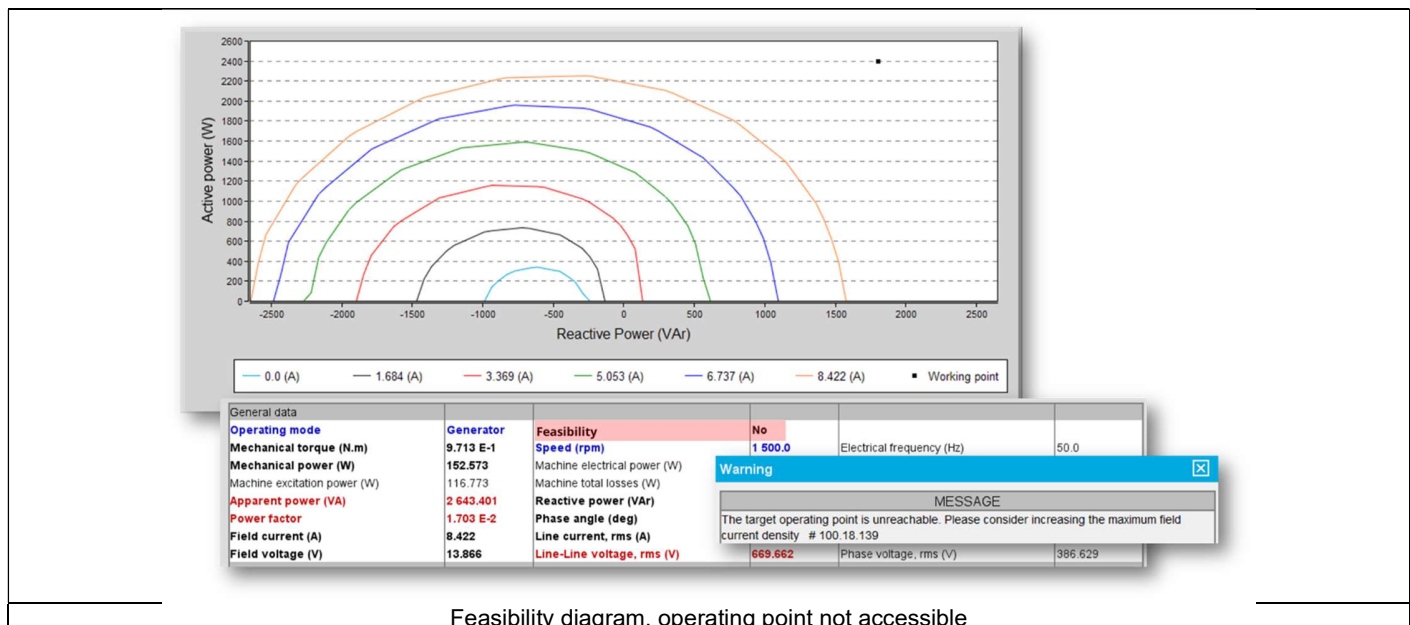
The target operating point is also plotted on this diagram.

1. **Feasible Working Point:** If the target point lies within the curve defined by I_{fmax} , the operating point is feasible. The required field current and control angle are interpolated between the two curves surrounding the target point. The accuracy of these values depends on the number of points plotted on each curve. The more points, the more precise the field current, control angle, and corresponding values of power, power factor, and voltage will be.
2. **Unfeasible Working Point:** If the target point falls outside the curve defined by I_{fmax} , it is not achievable with the current settings. Users can try increasing I_{fmax} to reach the desired point. However, if the target power is too high and the machine is saturated, increasing I_{fmax} may still not make the point reachable.

The **Feasibility** output in the working point table will display "Yes" if the target point is feasible, or "No" if it is not, based on the position of the working point relative to the feasible area.



Feasibility diagram, the operating point is accessible



Feasibility diagram, operating point not accessible

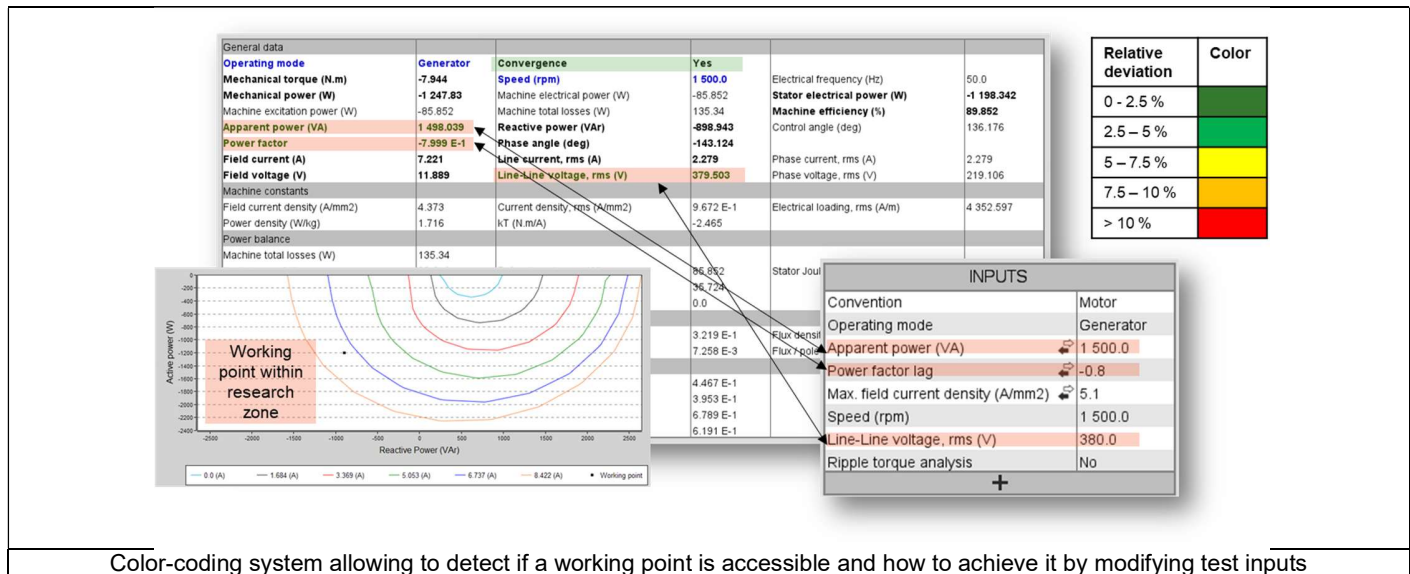
Even if the working point is not feasible, the optimizer in the backend of FluxMotor still provides a combination of field current, armature current, and control angle. This combination allows the machine to operate, but the resulting power, power factor, and voltage might be close to the target values—or far from them. We provide these results regardless, as they might still be helpful to the user.

To visually indicate how close the found working point is to the target, we use a color-coding system in the working point table. This system highlights key quantities:

- **Generator operating mode:** Apparent power, stator electrical power (active power), reactive power, power factor, and voltage.
- **Motor operating mode:** Mechanical power, power factor, and voltage.

Each color corresponds to a specific range of deviation between the found values and the target values:

- Dark green: 0% – 2.5% deviation
- Light green: 2.5% – 5% deviation
- Yellow: 5% – 7.5% deviation
- Orange: 7.5% – 10% deviation
- Red: Greater than 10% deviation



Color-coding system allowing to detect if a working point is accessible and how to achieve it by modifying test inputs

Note: If **Feasibility** is marked as "No" and the colors are not green, users may choose to increase the maximum field current to bring the working point closer to the target. Additionally, if the system does not compute enough points for field current or control angle, the color might appear yellow, orange, or red as the interpolation works badly with a **poorly discretized response surface**. In such cases, users can increase the number of computations for **If**, **Jd**, **Jq**, or control angle to improve accuracy.

2.4.4 Computing principles of other terms in the result tables

2.4.4.1 Electromagnetic behavior – General information

The method used for the computation of electromagnetic behavior depends on whether ripple torque analysis is set to "Yes" or "No":

- "Yes" is selected: The analysis of the electromagnetic behavior is done over one ripple torque period.
- "No" is selected: The analysis of the electromagnetic behavior is done through a dedicated static computation (1 rotor position to be considered) for the computed working point (with field current, line current, control angle, and speed obtained for the working point).

2.4.4.2 Flux in airgap

The flux in the airgap is always computed thanks to the dedicated static computation of the working point.

The airgap flux density is computed along a path in the airgap in Flux® software. The resulting signal is obtained for at least an electric period. The average and the peak value of the flux density are also computed. The harmonic analysis of the flux density in airgap versus rotor position is done to compute the magnitude of the first harmonic of the flux density.

2.4.4.3 Flux density in iron

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

2.4.4.4 Ripple torque

A specific computation is performed to precisely determine the rate of ripple torque.

Considering J_d and J_q at the base speed point, a computation is performed over one ripple torque period by using Finite Element modelling (Flux® software – Magnetostatic application).

Many computation points are considered over the ripple torque period (advanced user input: **No. comp. / ripple period**).

The following steps are performed to determine the mechanical torque.

1) Original computation of the electromagnetic torque

The electromagnetic torque exerted on a non-deformable part of the domain is computed by the virtual work method. The torque in a direction is obtained by deriving the system energy with respect to a virtual displacement of the part in this direction.

The electromagnetic torque T_{em} is given by the following derivative:

$$T_{em} = - \frac{\partial W_m}{\partial \theta}$$

$\partial\theta$ = elementary angular displacement,
 W_m = magnetic energy in the regional volume

The electromagnetic ripple torque is computed over the ripple torque period with respect to the rotor angular position $T_{em,\theta}$. The mean value " $T_{em, mean}$ " can also be computed.

2) Mechanical ripple torque based on Park's model

The mechanical ripple torque must be computed at the base speed.

First, we compute the electromagnetic torque " $T_{em, Park}$ " with Park's model:

$$T_{em, Park} = \frac{m}{2} \times p \times (\Phi_d \times J_q - \Phi_q \times J_d)$$

Then, the iron loss torque, the mechanical loss torque, and the additional loss torque are subtracted from " $T_{em, Park}$ " to get the corresponding mean value of the mechanical torque " $T_{mech, Park}$ ".

3) Resulting mechanical torque versus rotor angular position

To compute the resulting mechanical ripple torque, the original electromagnetic torque computed previously is weighted by the ratio of the mean value of the mechanical torque based on Park's model ($T_{mech, Park}$) and of the mean value of the original electromagnetic ripple torque ($T_{em, mean}$).

$$T_{mech,\theta} = T_{em,\theta} \times \frac{T_{mech, Park}}{T_{em, mean}}$$

The peak-peak value of the mechanical torque is then computed. The rate of ripple torque is deduced as a percentage or per unit of the nominal torque.

Warning: When the ripple torque computation is not requested, the computation of the working point is performed by considering only one position within the electrical period. It means that all the data characterizing the behavior of the machine can change based on the selection of ripple torque (Yes/No).

Flux density in a magnetic circuit will be more accurately computed when the computation of the ripple torque is requested.

2.5 Test results

Once a test is finished, the corresponding results are automatically displayed in the central window.

2.5.1 Test conditions

2.5.1.1 Inputs

All the parameter values belonging to standard inputs or advanced inputs are described in this section. It shows the initial conditions considered for the test. Here are the displayed subsections:

- Context
- Standard parameters
- Advanced parameters

For more information refer to the section 1.3 (Inputs).

2.5.1.2 Settings

All the settings dedicated to the test along with the thermal characteristics are displayed in this section. Here are the displayed subsections:

- Thermal
- Electronics
- Mechanics

2.5.1.3 Windings characteristics

All windings and damper characteristics are displayed in the following subsections:

- Armature Winding
- Field Winding
- Damper

For more details, please refer to the document: MotorFactory_SMWF_IR_3PH_Test_Introduction – section “Machine characteristics”.

2.5.2 Main results

2.5.2.1 Machine performance – Working point

Output data displayed in the following subsections is described in the section Working point – Sine wave – Motor. Here are the displayed subsections:

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

Output data displayed in the following area list is described in the document: MotorFactory_SMWF_IR_3PH_Test_Introduction – section Working point – Sine wave – Display of results.

2.5.2.2 Power electronics

- Inverter

When the power electronics stage is selected by the user, the inverter control strategy and the DC bus voltage are reminded. For information, the corresponding maximum line-line voltage rms value is computed and displayed.

- Working point

The power balance and the corresponding efficiencies are computed and displayed for the machine, the power electronics stage and the system (i.e., the machine + power electronics stage).

For more details, please refer to the document: MotorFactory_SMWF_IR_3PH_Test_Introduction – sections dealing with “Power electronics mode settings”.

2.5.2.3 Ripple mechanical torque

The analysis of the ripple torque is presented in the table “Ripple mechanical torque” with the following subsections:

- Working point

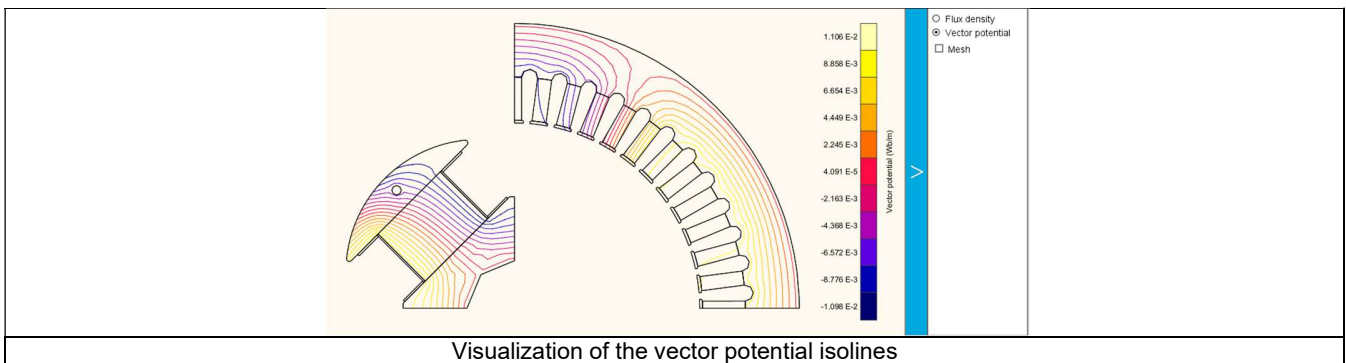
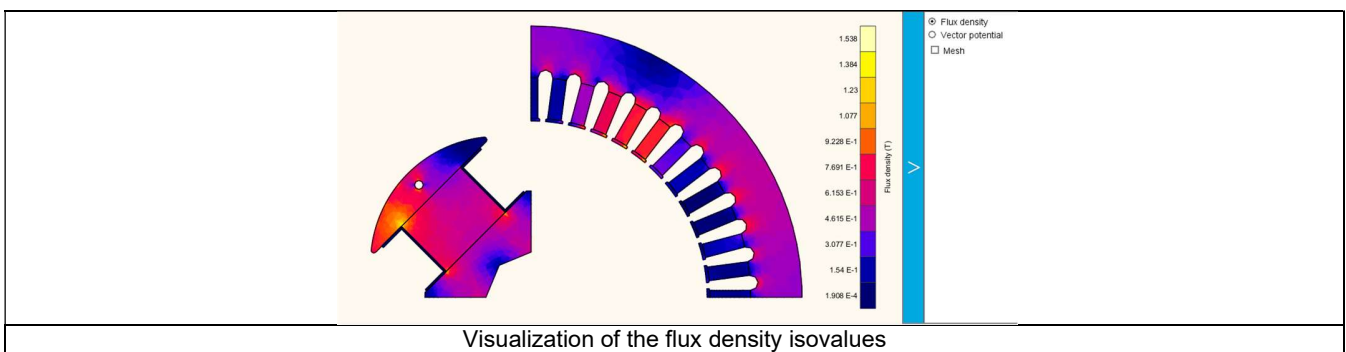
For more details, please refer to the document: MotorFactory_SMWF_ISP_IR_3PH_Test_Introduction – sections dealing with “Working point – Sine wave – Display of results”.

2.5.3 Curves

- Ripple mechanical torque versus rotor angular position and its harmonic analysis
- Flux density in airgap versus rotor angular position
- Feasibility diagram

2.5.4 Isovalues and isolines

The flux density isovalues and the vector potential isolines can be displayed.



Note: The visualization of the meshing of the model can also be displayed.