Altair® FluxMotor® 2026

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

Motor Factory – Test - Working point

General user information

Altairhyperworks.com

Contents

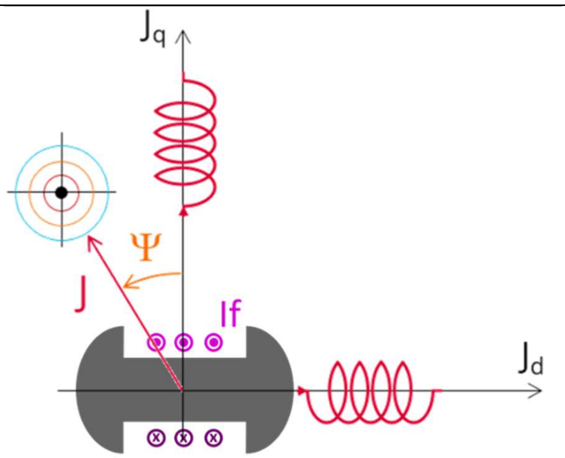
1 WORKING POINT – SINE WAVE – MOTOR – If, I, Ψ, N

1.1 Overview

1.1.1 Positioning and objective

The aim of the test "**Working point – Sine wave – Motor – If, I, Ψ, N"** is to characterize the behavior of the machine when operating at the targeted input values If, 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 – If, I, Ψ, N" test allows to compute the performance for this working point.



"Working point – Sine wave – Motor – If, I, Ψ, N" illustration

The results of this test give an overview of the electromagnetic analysis of the machine, considering its topology.
The general data of the machine, like 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 – If, I, Ψ, N".

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

Positioning of the test "Working point – Sine wave – Motor – If, I, Ψ, N"

1.2 Main principles of computation

1.2.1 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.

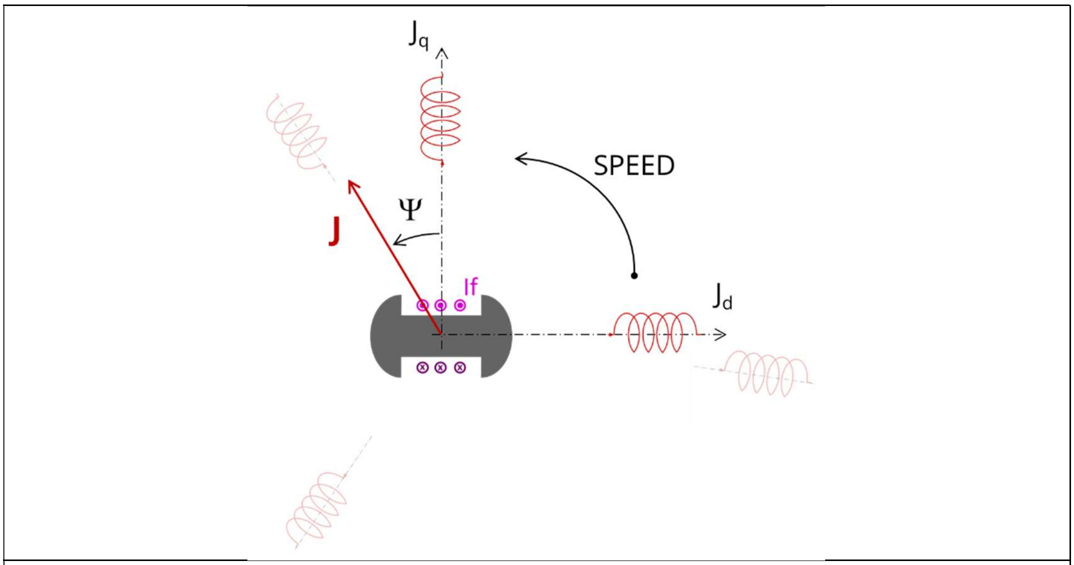
Two computation modes are available:

- “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).

1.2.2 Fast computation mode

1.2.2.1 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.



Salient pole and reference phase axis Positioning – Motor convention

1.2.2.2 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).

1.2.2.3 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.

1.2.2.4 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.

1.2.2.5 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.

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.

1.2.3 Accurate computation mode

1.2.3.1 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.

1.2.3.2 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.

1.2.3.3 Iron losses

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

1.2.3.4 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 themself 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:

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

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

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

1.2.3.5 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.

1.2.3.6 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.

1.2.3.7 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.

1.2.3.8 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.

1.2.3.9 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.

1.2.3.10 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.

1.2.3.11 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.

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

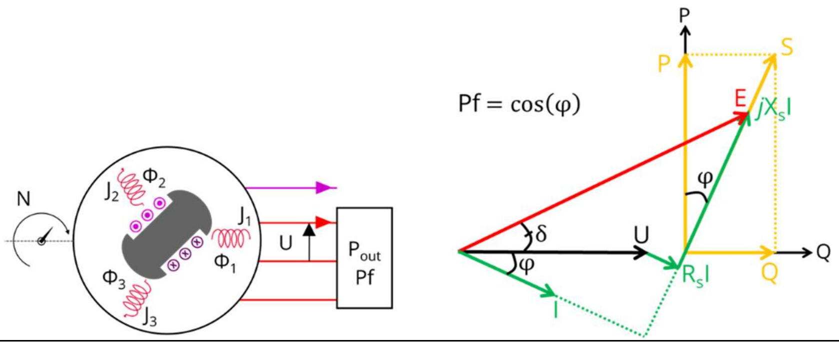
2.1 Overview

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.



“Working point – Sine wave – Motor – P, Pf, U, N” illustration

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

The general data of the machine, like 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”

2.2 Main principles of computation

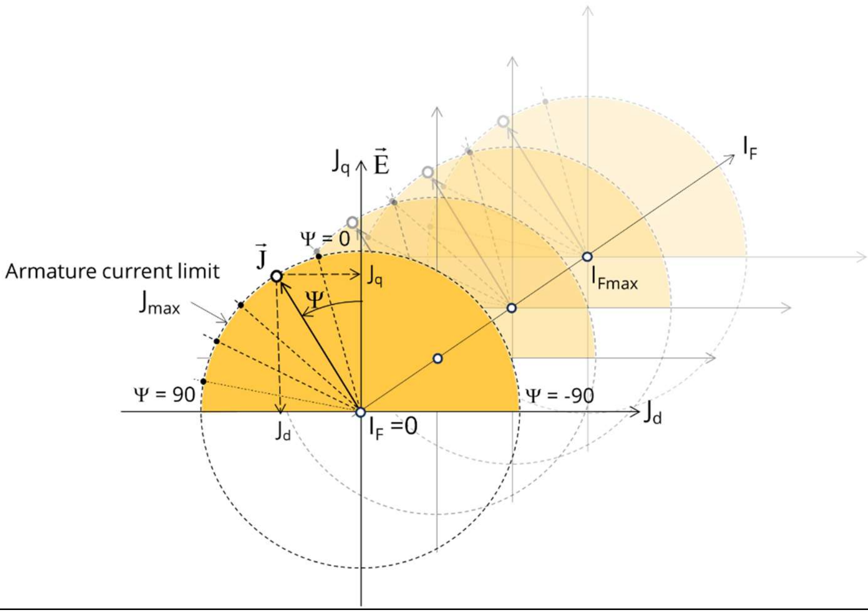
2.2.1 Introduction

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 If and control angle ψ providing the performance defined by the user.

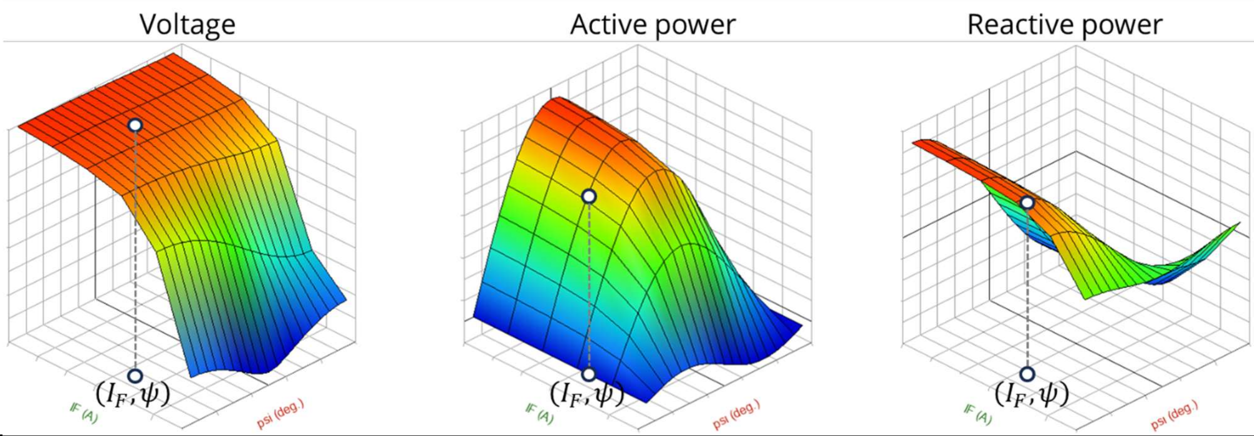
2.2.1.1 Generator operating mode

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

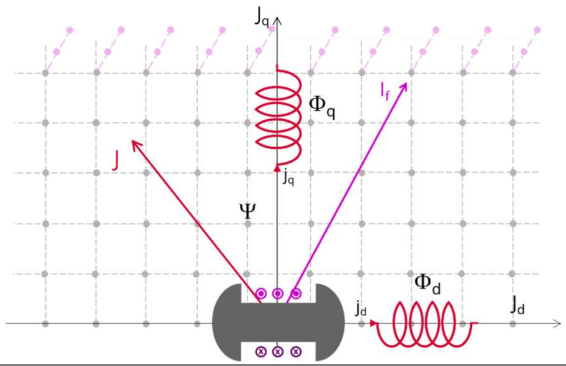
Within the research zone, the If-I-Psi-N test will be executed at all points (If, ψ) to determine the performance response surfaces of the machine. Then an optimizer is used to search for the point (If, ψ) providing the match with the targeted performance.



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

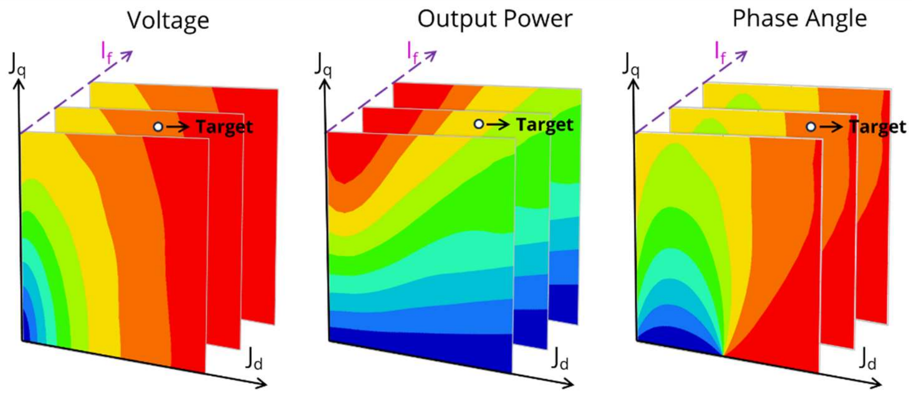
2.2.1.2 Motor operating mode

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 (If, I_d, I_q) to determine the performance response surfaces of the machine. Then an optimizer is used to search for the point (If, I_d, I_q) providing the match with the targeted performance.

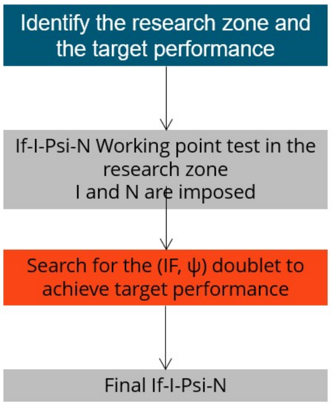


Performance of the machine in generator operating mode within the research zone in terms of voltage, output power and phase angle and the point (If, I_d, I_q) providing the targeted performance

2.2.2 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 (If, 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 (If, 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.



Flow chart for calculating the working point (P-Pf-U-N) with the generator operating mode

2.2.2.1 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 $P_{ftarget}$, and line-line voltage U_{target}, then we have:

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

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

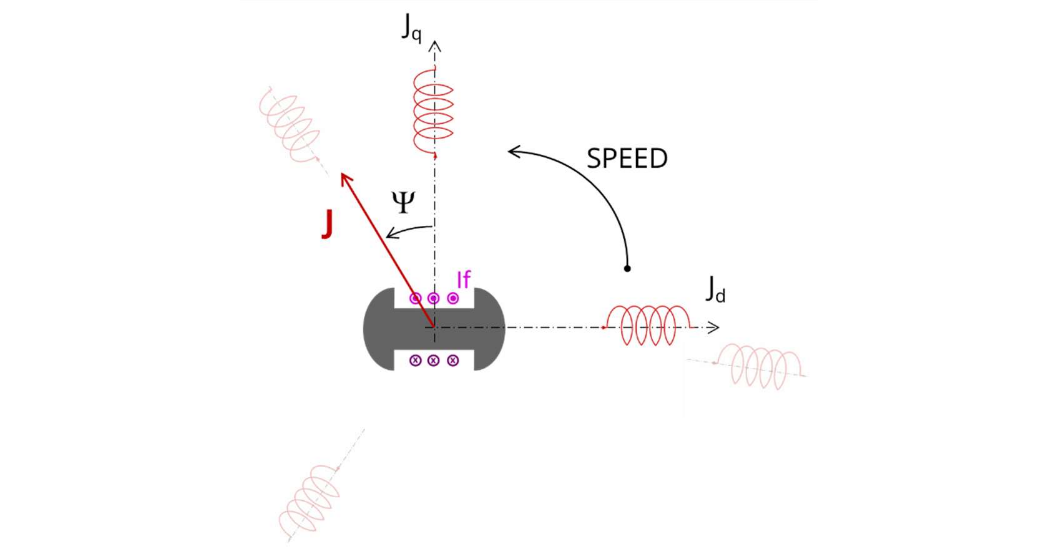
Parameter labels	Definition and formula
Power factor lead/lag, target	$P_{ftarget}$
Apparent power, target	$S_{target} = \frac{P_{target}}{P_{ftarget}}$
Output power / Active power, target	P_{target}
Reactive power, target	$Q = s \times S_{target} \times \sqrt{1 - P_{ftarget}}$, $with\ s = \begin{cases}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

For both cases of inputs, the research zone is defined by the armature current limit J, maximum field current Ifmax, 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 Ptarget and reactive power Qtarget.

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

The field current varies from zero to the maximum field current Ifmax and the control angle varies from [-90° to 90°] in the generator convention (quadrants 1 and 2) and [90° to 180°] + [-180° to -90°] 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.

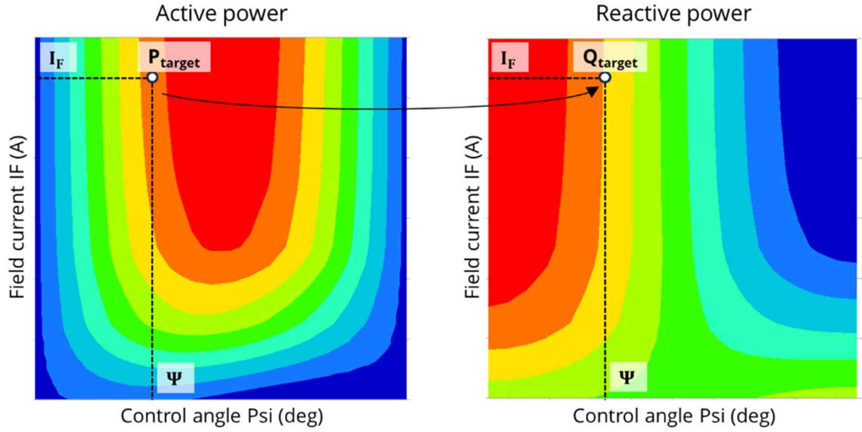
To compute the working point If-I-Psi-N, the principle consists of positioning the salient pole towards the reference phase axis by considering the targeted control angle.
At the same time, the targeted field current, line current, and speed are imposed.
Then, the resulting behavior of the machine can be simulated, and all the main electromagnetic characteristics of the machine can be deduced by using Park's transformation and associated electric equations.



Salient pole and reference phase axis Positioning – Motor convention

2.2.2.3 Performance matching to search for (If, ψ)

Response surfaces of active power and reactive power are built, and an optimizer is used to search for the point (If, ψ) providing Ptarget and Qtarget.



Response surfaces of active power and reactive power allowing the matching process to find (I_F, ψ) providing (P_{target}, Q_{target})

2.2.2.4 Final If-I-Psi-N

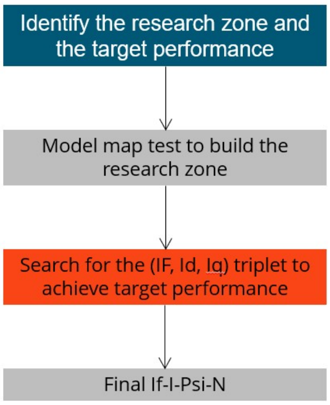
The found field current and control angle are combined with the imposed line current and speed for a final If-I-Psi-N test to identify the real performance of the machine.

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.

2.2.3 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 (If, Id, Iq) 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 (If, Id, Iq) 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.



Flow chart for calculating the working point (P-P_f-U-N) with the motor operating mode

2.2.3.1 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 $P_{ftarget}$, and line-line voltage U_{target}, then we have:

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

The research zone is defined by the armature current limit Jmax, maximum field current Ifmax, 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 Ptarget and phase angle φtarget.

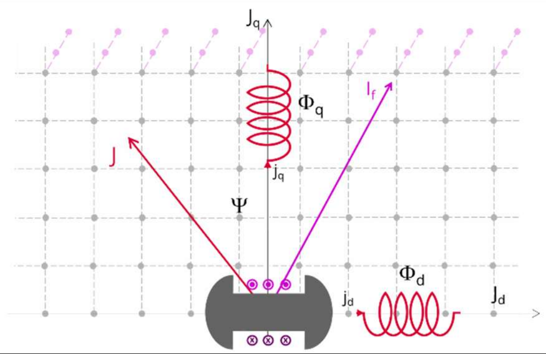
Note: In generator operating mode, the armature current is set directly by the user's input. However, in motor operating mode, the exact value of the armature current is not predefined and can vary between 0 and Jmax. This ensures that the target operating point remains within the designated operating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

2.2.3.2 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): If_{max}
- Max. current density, rms: J_{max}
- Maximum speed: N
- Rotor position dependency: No
- No. comp. for If: defined by user inputs in 1.3
- No. comp. for Jd, Jq: defined by user inputs in 1.3

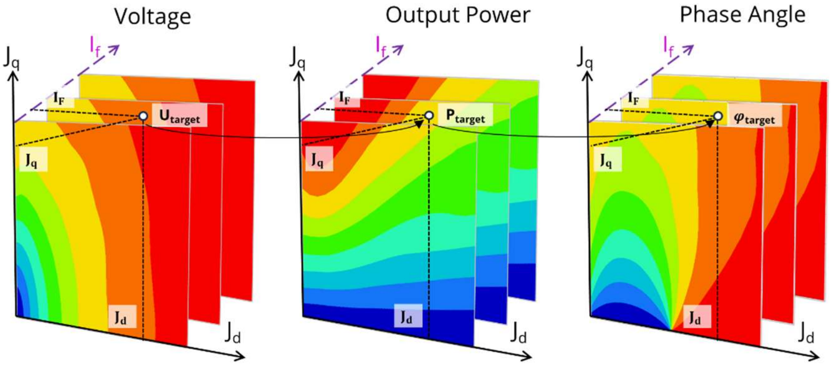
For more information about the principle of the model map test, please refer to the dedicated document of the test.



Model map test for characterization map of wound field synchronous machine

2.2.3.3 Performance matching to search for (If, 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 (If, Id, Iq) providing Ptarget and φtarget and Utarget.



Response surfaces of mechanical power and phase angle are constructed to search the triplet (If, Id, Iq) to reach (Ptarget, φtarget)

2.2.3.4 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.

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

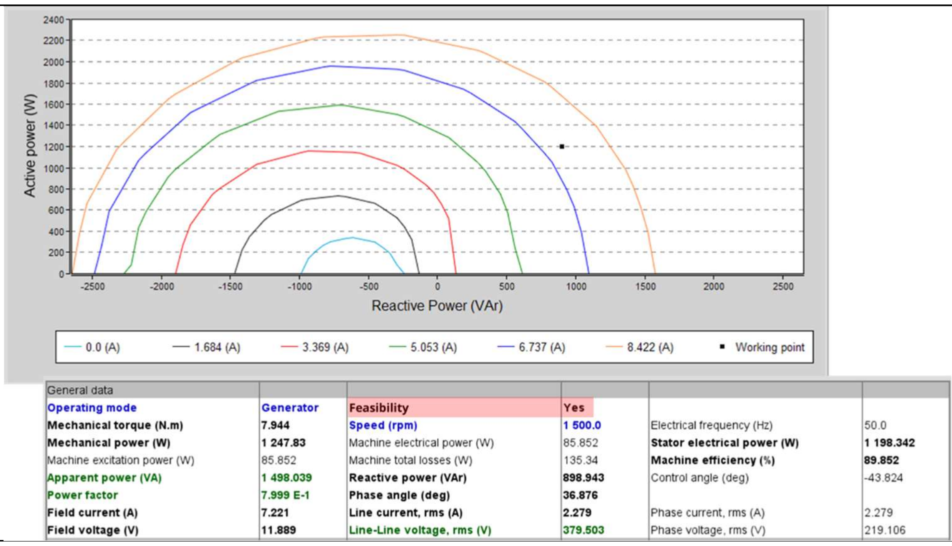
In this test, one can set any combination of power, power factor, voltage, and speed. However, not all the combinations are feasible for a given synchronous machine. To help users detect unfeasible operating points, a powerful tool called the Feasibility Diagram is provided.

The concept is like the P-Q diagram used by generator designers. In the P-Q plane, curves corresponding to different field current (IF) values are plotted. Each point on these curves represents a combination of field current, armature current magnitude, and control angle. The curves range from If = 0 to Ifmax, 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.

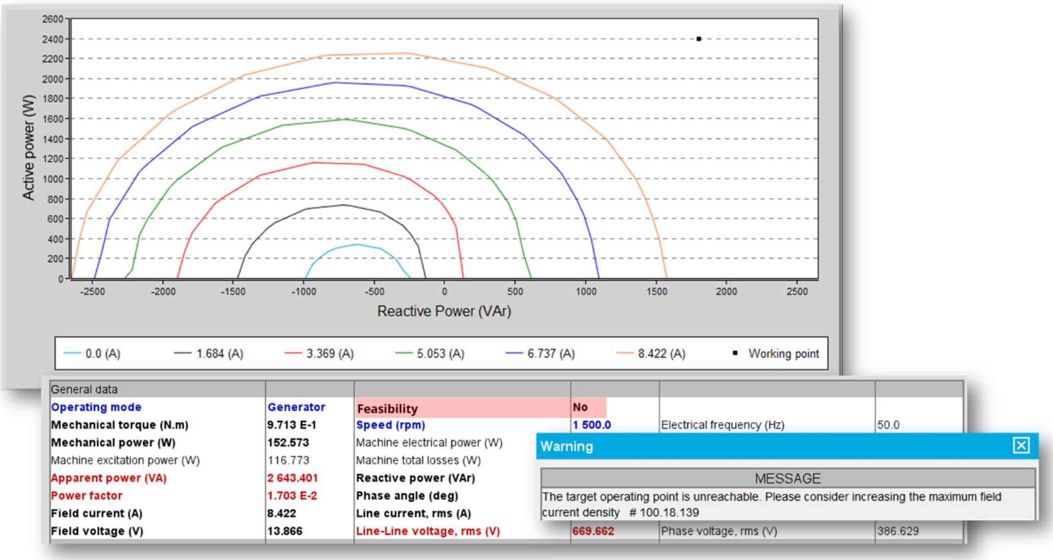
1. **Feasible Working Point**: If the target point lies within the curve defined by Ifmax, the operating point is feasible. The required field current and control angle are interpolated between the two curves surrounding the target point. The accuracy of these values depends on the number of points plotted 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 Ifmax, it is not achievable with the current settings. Users can try increasing Ifmax to reach the desired point. However, if the target power is too high and the machine is saturated, increasing Ifmax 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.



General data					
Operating mode	Generator	Feasibility	Yes		
Mechanical torque (N.m)	7.944	Speed (rpm)	1 500.0	Electrical frequency (Hz)	50.0
Mechanical power (W)	1 247.83	Machine electrical power (W)	85.852	Stator electrical power (W)	1 198.342
Machine excitation power (W)	85.852	Machine total losses (W)	135.34	Machine efficiency (%)	89.852
Apparent power (VA)	1 498.039	Reactive power (VAr)	898.943	Control angle (deg)	-43.824
Power factor	7.999 E-1	Phase angle (deg)	36.876		
Field current (A)	7.221	Line current, rms (A)	2.279	Phase current, rms (A)	2.279
Field voltage (V)	11.889	Line-Line voltage, rms (V)	379.503	Phase voltage, rms (V)	219.106

Feasibility diagram, the operating point is accessible



General data					
Operating mode	Generator	Feasibility	No		
Mechanical torque (N.m)	9.713 E-1	Speed (rpm)	1 500.0	Electrical frequency (Hz)	50.0
Mechanical power (W)	152.573	Machine electrical power (W)			
Machine excitation power (W)	116.773	Machine total losses (W)			
Apparent power (VA)	2 643.401	Reactive power (VAr)			
Power factor	1.703 E-2	Phase angle (deg)			
Field current (A)	8.422	Line current, rms (A)			
Field voltage (V)	13.866	Line-Line voltage, rms (V)	669.662	Phase voltage, rms (V)	386.629

Feasibility diagram, operating point not accessible

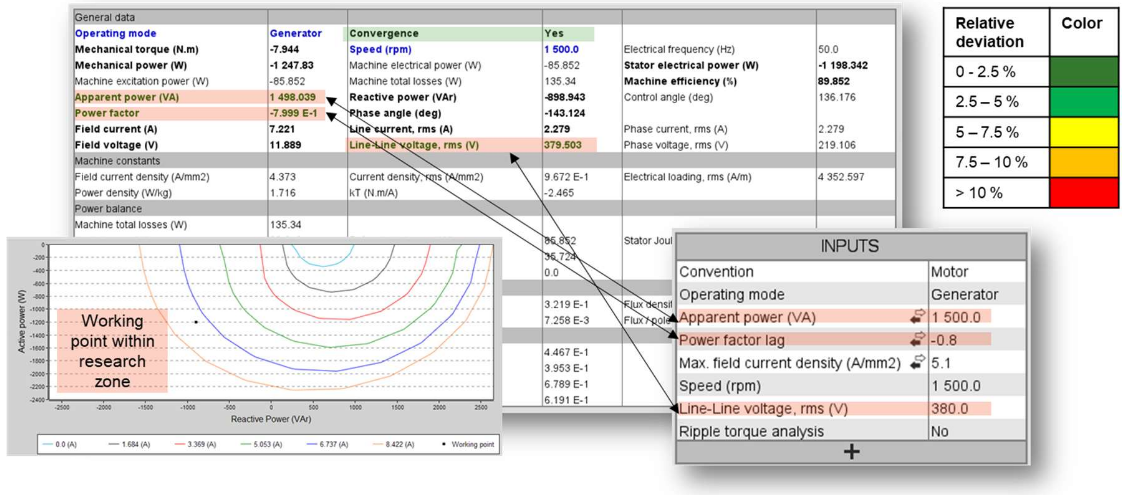
Even if the working point is not feasible, the optimizer in the backend of FluxMotor still provides a combination of field current, armature current, and control angle. This combination allows the machine to operate, but the resulting power, power factor, and voltage might be close to the target values—or 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.

2.2.4 Computing principles of other terms in the result tables

2.2.4.1 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).

2.2.4.2 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.

2.2.4.3 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.

2.2.4.4 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:

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

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.