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Synchronous Machines with Wound Field – Inner Salient Pole – Inner Rotor

Motor Factory – Test – Performance mapping

General user information

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1 PERFORMANCE MAPPING – SINE WAVE – MOTOR – EFFICIENCY MAP

1.1 Overview

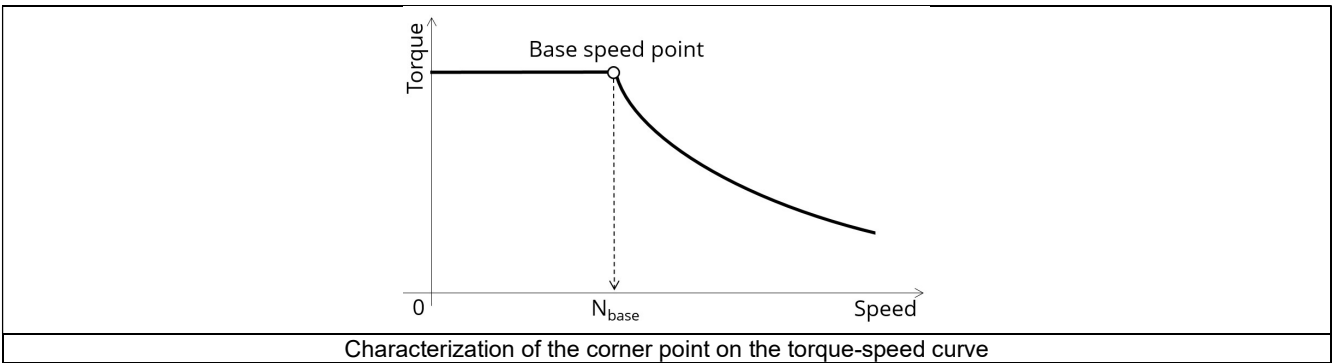
1.1.1 Positioning and objective

The aim of the test “Performance mapping – Sine wave – Motor – Efficiency map” is to characterize the behavior of the machine in the “Torque-Speed” area.

Input parameters like the maximum “Field current”, the maximum “Line current”, maximum “Line-Line voltage”, and the desired “Maximum speed” of the machine are considered.

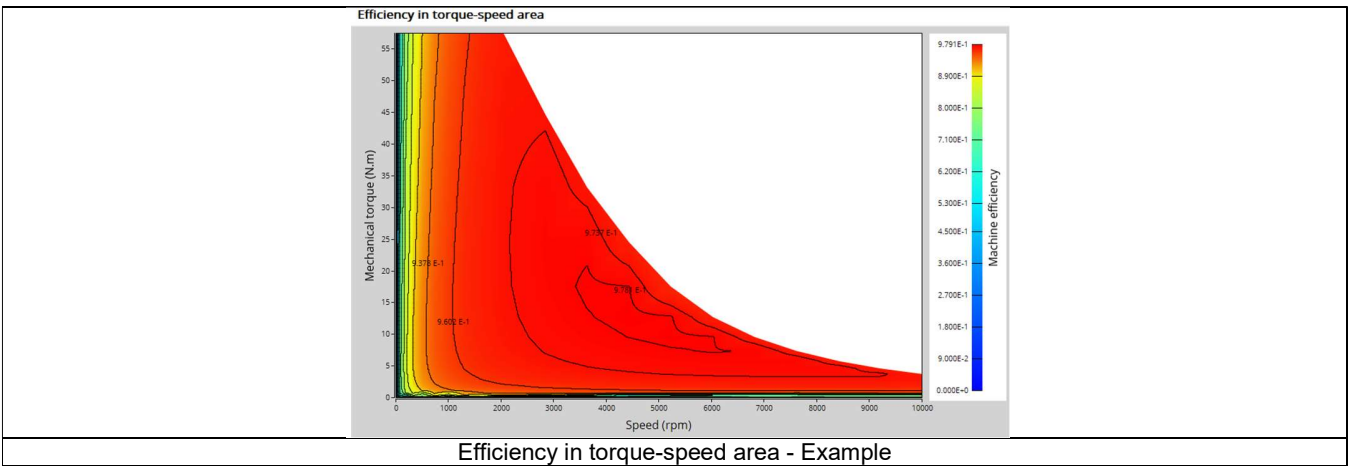
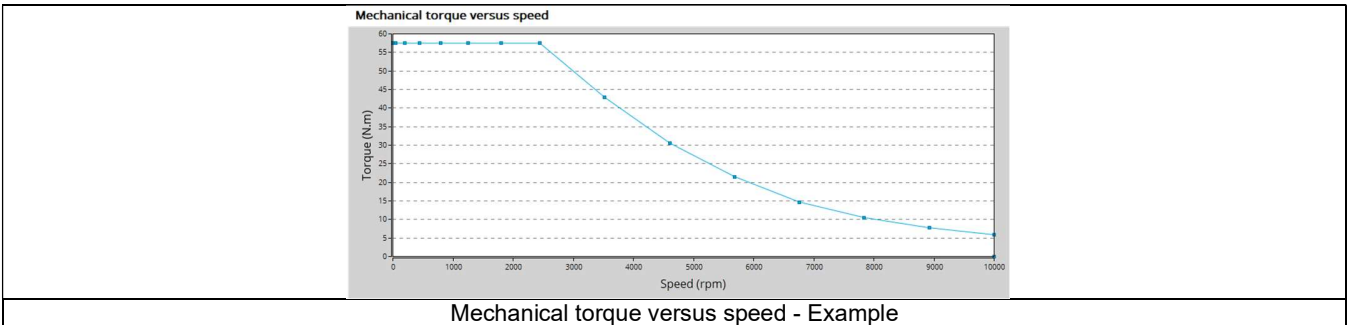
Only The Maximum Torque Per Volt command mode (MTPV) is available in this version. The Maximum Torque Per Amps command mode (MTPA) will be provided in the next releases.

Input parameters define torque-speed area in which the evaluation of the machine behavior is performed.



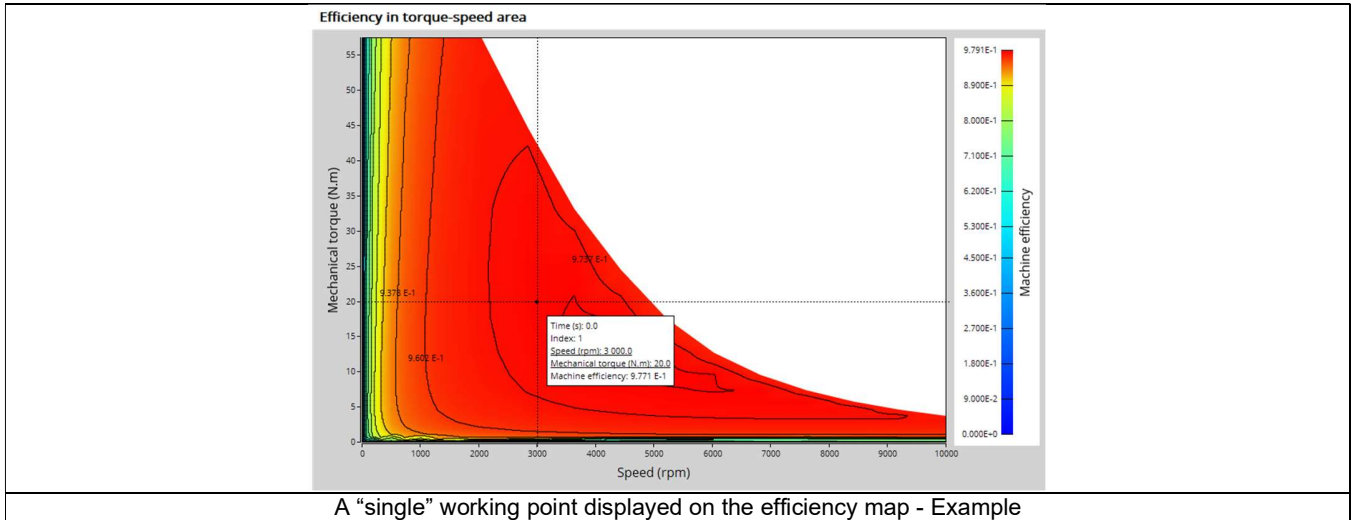
In the results, the performance of the machine at the base point (base speed point) and for the maximum speed set by the user are presented.

A set of curves (like Torque-Speed curve) and maps (like Efficiency map) are computed and displayed.



Two additional features are available in this test. The first one allows extracting one torque-speed point from the efficiency map to get the machine performance, for this specific working point (general data + power balance).

Note: The considered working point is then displayed on all the maps available. The working point can be selected to visualize the corresponding main information.

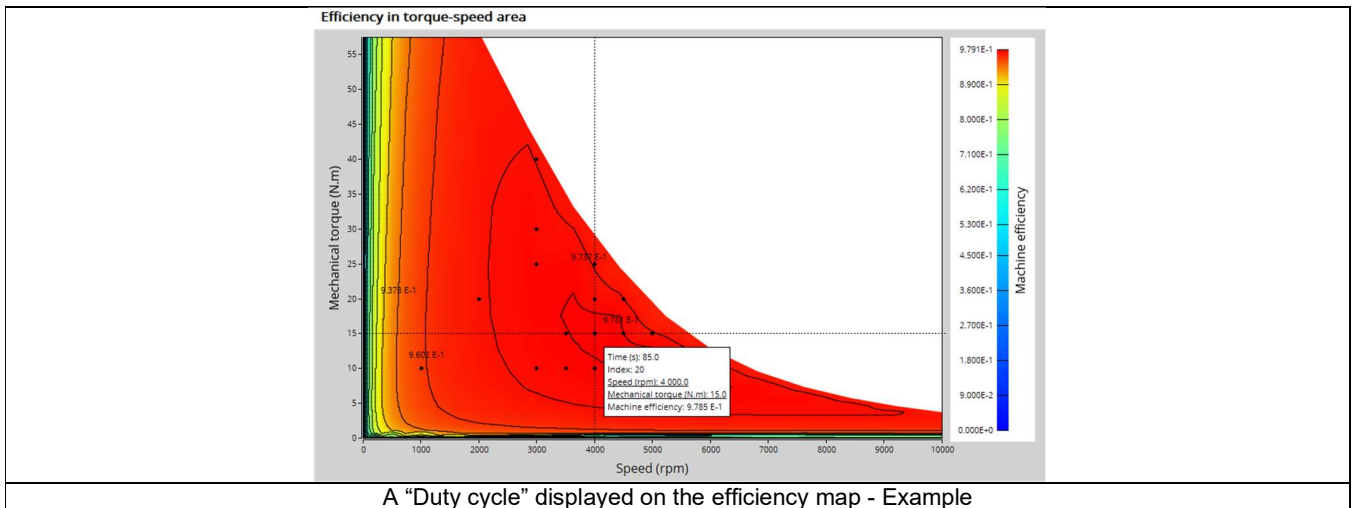


A "single" working point displayed on the efficiency map - Example

The second feature allows the user to define a duty cycle by giving a list of working points (speed, torque) versus the time. The displayed results illustrate the machine performance over the considered duty cycle (mean, min, and max values).

The time variation of the main quantities is also displayed (Mechanical torque, speed, control angle, current, voltage, power, efficiency, losses).

All the corresponding points are displayed on the different provided maps. Each working point can be selected to visualize the corresponding main information.



A "Duty cycle" displayed on the efficiency map - Example

The following table helps to classify the test “Performance mapping – Sine wave – Motor – Efficiency map”.

Family	Performance mapping
Package	Sine wave
Convention	Motor
Test	Efficiency map

Positioning of the test “Performance mapping – Sine wave – Motor – Efficiency map”

1.1.2 User inputs

1.1.2.1 Overview

The main user input parameters needed to perform this test are the maximum allowed supplied, field current, line current, line-line voltage, the targeted maximum speed, and the command mode. Winding temperatures must also be set.

When required, the location of the working points (single point or duty cycle) to be evaluated must be defined as inputs.

Warning! The default values of advanced inputs have been set to get the best compromise between accuracy and computation time. Four advanced user input parameters allow adjusting the compromise between accuracy and computation time: the number of computations for J_d - J_q , the number of computations for I_F , for speed and for torque.

1.1.3 Main outputs

Different kinds of outputs are displayed like data, curves, maps, and tables.

Main test results

- 1) Machine performance - Base speed point
 - General data like torque, speed, electrical powers, control angle, efficiency etc.
 - Power balance
- 2) Machine performance - Maximum speed
 - General data like torque, speed, electrical powers, control angle, efficiency etc.
 - Power balance
- 3) Machine performance - User working point (when requested)
 - General data like torque, speed, electrical powers, control angle, efficiency etc.
 - Power balance
- 4) Machine performance - Duty cycle analysis (when requested)
 - General data like torque, speed, electrical powers, control angle, efficiency etc. (min., mean and max. values)
 - Power balance
 - Energy balance
- 5) Power electronics (when requested by the user)
 - Inverter
 - Base speed point - Power balance
 - Maximum speed point - Power balance
 - User working point – Power balance (when requested)
 - Duty cycle - Power balance (when requested)

- 6) Torque-speed curves
 - Mechanical torque versus speed
 - Current (I_f , J , J_d , J_q) versus speed
 - Voltage (V_f , V , V_d , V_q) versus speed
 - Control angle versus speed
 - Power (machine electrical power, stator electrical power, excitation power, mechanical power, system electrical power) versus speed
 - Power factor versus speed
 - Losses versus speed (Total, Joule, Iron, Mechanical, power electronics, and additional)
- 7) Characteristic curves
 - Electromagnetic torque versus phase current, field current and control angle (Ψ) according to base speed point
 - Characteristic curves in J_d - J_q area - Evolution of the working points in J_d - J_q plane, with iso-torque, iso-current and iso-voltage.
- 8) Torque-Speed maps
 - Efficiency in torque-speed area
 - Current (I_f , J , J_d , J_q) in torque-speed area
 - Voltage (V_f , V , V_d , V_q) in torque-speed area
 - Control angle in torque-speed area
 - Power in torque-speed area (machine electrical power, stator electrical power, excitation power, mechanical power, system electrical power) in the torque-speed plane
 - Power factor in torque-speed area
 - Losses in torque-speed area (Total, Joule, Iron, Mechanical, power electronics, and additional) in the torque-speed plane
- 9) Duty cycle curves (when requested)
 - Speed versus time
 - Mechanical torque versus time
 - Control angle versus time
 - Current (I_f , J , J_d , J_q) versus time
 - Voltage (V_f , V , V_d , V_q) versus time
 - Power factor versus time
 - Power versus time (machine electrical power, stator electrical power, excitation power, mechanical power, system electrical power)
 - Efficiency versus time
 - Losses versus time (Total, Joule, Iron, Mechanical, power electronics, and additional)

Note: When a user working point has been targeted or if a duty cycle is considered, the corresponding working points are displayed on all the maps described above.

1.2 Settings

Four buttons give access to the following setting definition:

- Thermal settings – Definition of the temperature of active components.
For the considered test this concerns the phase winding and field winding temperatures.
- Power electronics settings - Definition of the power electronics parameters
- Mechanics settings - Definition of mechanical loss model parameters
- Import: To import data/setting/input from a “Characterization - Model - Motor - Maps” test, if possible

For more details, please refer to the document: MotorFactory_SMWF_ISP_IR_3PH_Test_Introduction – section “settings”

1.3 Inputs

1.3.1 Introduction

The total number of user inputs is equal to 19.
Among these inputs, 10 are default inputs and 9 are advanced inputs.

1.3.2 Sharing data between tests

An import button is available for allowing sharing the data simulated in Flux between “Characterization / Model / Map” and “Performance mapping / Efficiency map” tests.

Indeed, by implementing the rotor position dependency option for the model map test and efficiency map test of synchronous machines, this update facilitates the seamless transfer of settings, inputs, and crucially, simulated data in Flux between the two tests. As they use the same Flux data in most cases and significant computation time is required to obtain it, users can now accelerate the test resolution and optimize their workflow.

To streamline this process, an import button has been introduced in both the “Characterization / Model / Map” and “Performance mapping / Efficiency map” tests of the following machines:

- Reluctance Synchronous Machines - Inner rotor
- Synchronous Machines with wound field – Inner Salient Pole - Inner rotor

Note: The import button will be added to the tests of Synchronous machines – Permanent magnets - Inner & Outer rotor in the next version.

Upon completing a model map test, users can activate the import button in the efficiency map test GUI. This enables them to effortlessly import the settings and corresponding Flux data from the previous test, eliminating the need to rerun Flux for identical data, a step that typically consumes a substantial portion of computation time during efficiency mapping.

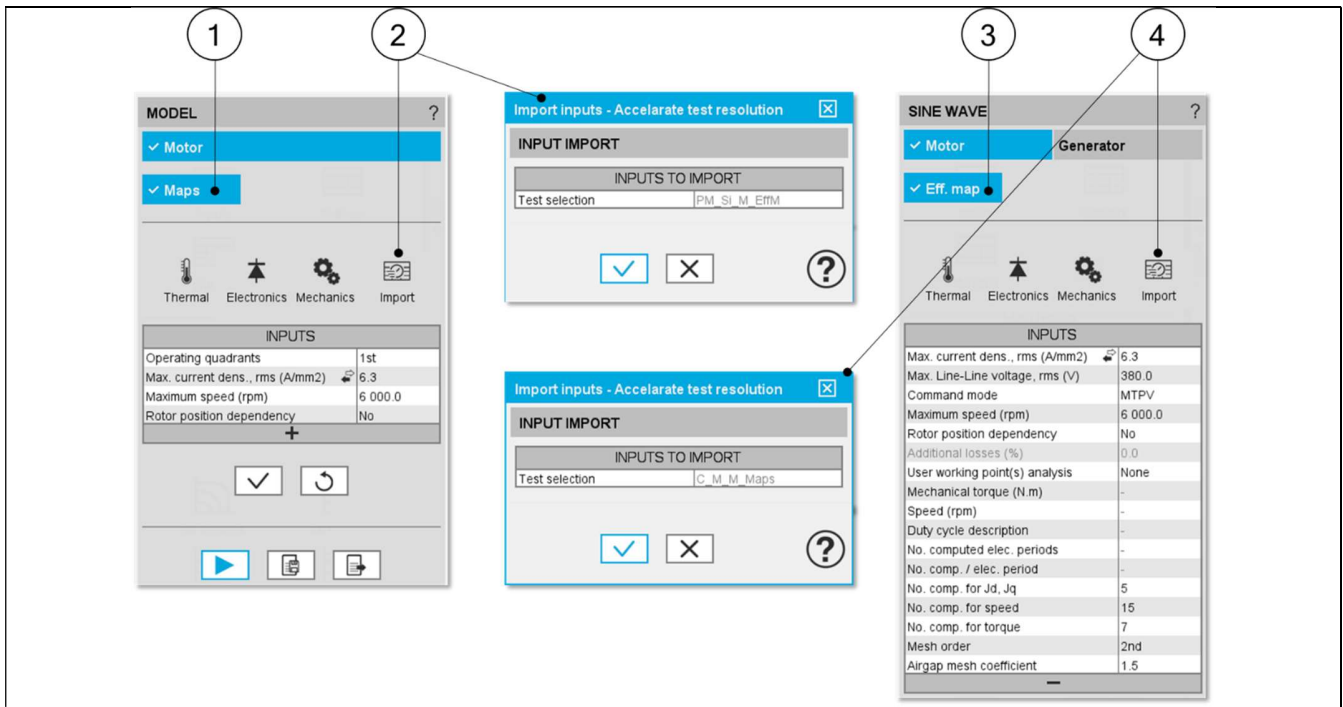
Conversely, upon concluding an efficiency map test, users can use the import button in the efficiency map test GUI to import settings and Flux data from the efficiency map test, further enhancing workflow efficiency.

Note: Only the most recent test results can be imported, saved test results are not yet able to be imported.

Note: While there are shared settings and inputs between the tests, each test may have its own unique settings and inputs. In such cases, the default settings, and inputs of the second test are automatically applied.

Note: When importing from the efficiency map test to the model map test, the quadrant setting defaults to the value specified in the model map test. For certain machine types (SMWF: 2nd quadrant, SM-RSM: 1st quadrant), specific quadrant selections are applied.

Note: In instances where quadrant inputs lead to incompatibility between the model map test and the efficiency map test, only settings and inputs are imported. A warning is issued, and Flux simulation is initiated to rectify the discrepancy.



Import function in Model Map test and Efficiency Map test to accelerate test resolution.
Example for Wound field synchronous machines

1	Open model map test environment when an efficiency map test is available for import
2	Click the import button and import the settings, inputs, and Flux data of the latest efficiency map test
3	Open efficiency map test environment when a model map test is available for import
4	Click the import button and import the settings, inputs, and Flux data of the latest model map test

1.3.3 Standard inputs

1.3.3.1 Field Current and line current definition mode

There are 2 common ways to define the 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) and field current (AC value). In this case, the current definition mode should be « **Current** ».

1.3.3.2 Maximum field current, rms

When the choice of current definition mode is “**Current**”, the maximum DC value of the field current supplied to the machine “**Max. field current, rms**” (*Maximum field current, rms value*) must be provided.

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

1.3.3.3 Maximum field current density, rms

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

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

1.3.3.4 Maximum line current, rms

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

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

1.3.3.5 Maximum Line-Line voltage, rms

The rms value of the maximum line-line voltage supplying to the machine: **“Max. Line-Line voltage, rms”** (*Maximum Line-Line voltage, rms value*) must be provided.

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

1.3.3.6 Maximum speed

The computation and analysis of the torque-speed curves are performed over a given speed range.

The maximum allowed value for the « **Maximum speed** » corresponds to 53000 rad/s - about 506000 rpm.

Notes: As a function of the maximum speed value, following different cases must be considered:

- 1) Case 1: The maximum speed is lower than the base speed N_{base} (corner point speed of the torque-speed curve) $N_{max} < N_{base}$.

In that case, for any command mode (MTPA or MTPV), the behavior of the machine will be studied over the speed range $[0, N_{max}]$.

That allows the user to precisely choose the range of speed to be considered for computing and displaying the torque-speed curve and especially maps like efficiency map.

- 2) Case 2: The maximum speed is greater than the base speed (corner point speed) $N_{max} > N_{base}$.

The relevance of the maximum speed given by the user is analyzed to evaluate if it is reachable by the machine.

If the user maximum speed is unreachable by the machine, the correction of this value is automatically performed.

The resulting new maximum speed is linked to a limit torque. This limit torque is obtained by applying a reduction coefficient to the base point torque.

1.3.3.7 Rotor position dependency

It defines the rotor position dependency of electromagnetic data used for the optimization of the efficiency map such as D-axis magnetic flux, Q-axis magnetic flux, electromagnetic torque, iron losses. By default, the rotor position dependency is set to “No” but it can be set to “Yes”. In this case the computation will be done along the three dimensions $J_d - J_q - I_f$, with an additional fourth axis corresponding to the rotor position θ .

Note: This option allows to have a better accuracy in the evaluation of magnetic flux, electromagnetic torque as well as iron losses. It is worth noting that only with rotor position dependency that the rotor iron losses can be evaluated.

1.3.3.8 Additional losses

Note: “Additional losses” input is not available in the current version (The input label is written in grey).

1.3.3.9 User working point(s) analysis.

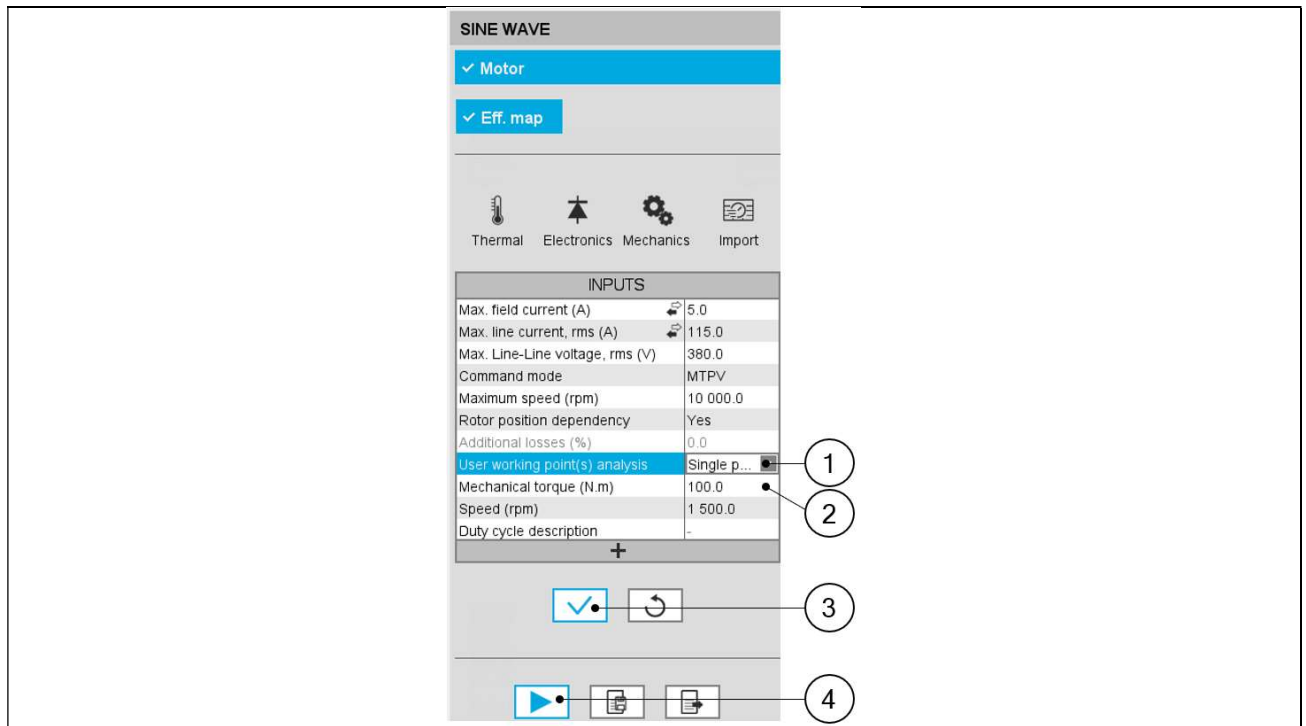
It is possible to perform additional analysis on working point(s) located under the torque-speed curve. The user's input **"User working point(s) analysis"** (*additional analysis on working point(s)*) gives three possibilities to the user:

- 1) User working point(s) analysis = None (=default mode)

This corresponds to the basic configuration of the test, with no additional working point analysis.

- 2) User working point(s) analysis = Single point

This allows computing the machine performance on a working point specified by the user with the targeted speed and torque. In that case the next two fields must be filled with the targeted speed and mechanical torque.



SINE WAVE	
<div style="background-color: #0070C0; color: white; padding: 2px;">Motor</div>	
<div style="background-color: #0070C0; color: white; padding: 2px;">Eff. map</div>	
Thermal Electronics Mechanics Import	
INPUTS	
Max. field current (A)	5.0
Max. line current, rms (A)	115.0
Max. Line-Line voltage, rms (V)	380.0
Command mode	MTPV
Maximum speed (rpm)	10 000.0
Rotor position dependency	Yes
Additional losses (%)	0.0
User working point(s) analysis	Single p... 1
Mechanical torque (N.m)	100.0 2
Speed (rpm)	1 500.0 2
Duty cycle description	-
+	
<div style="display: flex; justify-content: space-around; align-items: center;"> <div style="border: 1px solid #0070C0; padding: 5px; border-radius: 5px; background-color: #0070C0; color: white;">✓</div> <div style="border: 1px solid #0070C0; padding: 5px; border-radius: 5px; background-color: #0070C0; color: white;">↺</div> </div> 3	
<div style="display: flex; justify-content: space-around; align-items: center;"> <div style="border: 1px solid #0070C0; padding: 5px; border-radius: 5px; background-color: #0070C0; color: white;">▶</div> <div style="border: 1px solid #0070C0; padding: 5px; border-radius: 5px; background-color: #0070C0; color: white;">📄</div> <div style="border: 1px solid #0070C0; padding: 5px; border-radius: 5px; background-color: #0070C0; color: white;">📄</div> </div> 4	

User working point analysis = Single point

1	Select the "Single point" option to perform a computation on one working point.
2	Define the targeted working point mechanical torque and speed.
3	Button to validate and consider the user inputs
4	Button to run the computation

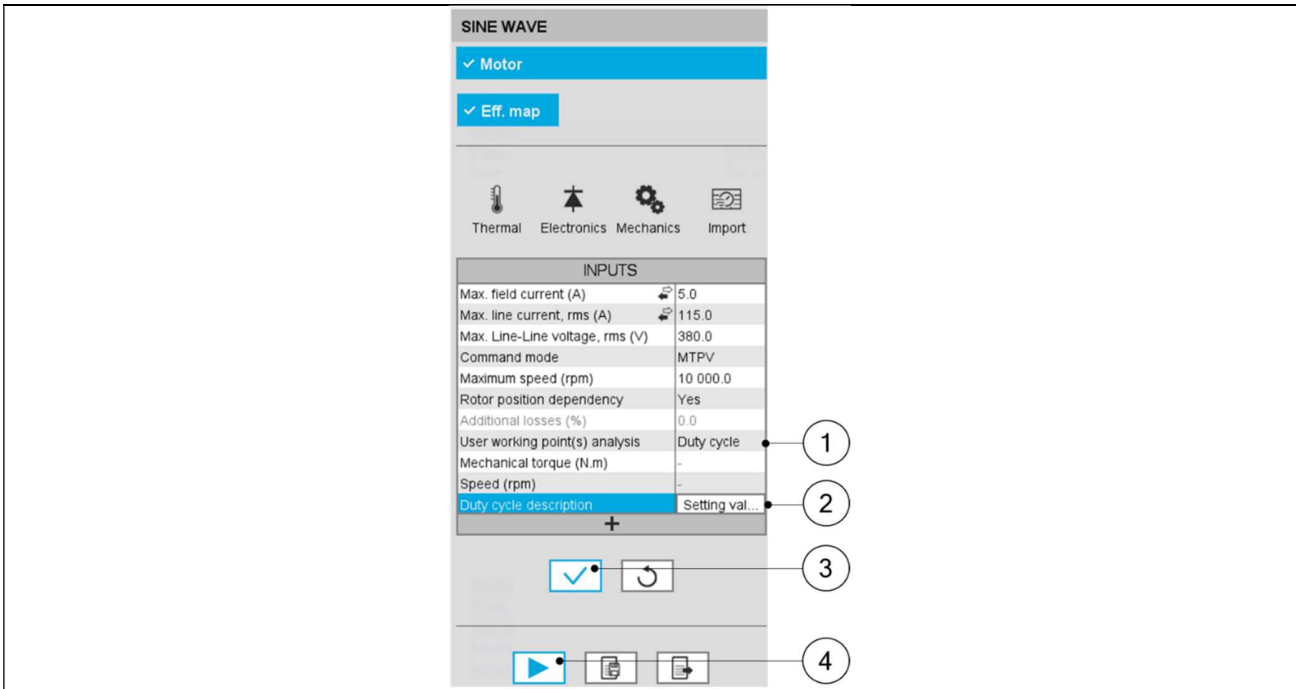
- 3) User working point(s) analysis = Duty cycle

This allows computing the machine performance all over a considered duty cycle.

This duty cycle must be defined by using the next field: "Duty cycle description" and by clicking on the button "Set values".

Two ways are possible to fill in the table: either filling in the table line by line or by importing an excel file which all the working points of the duty cycle are defined.

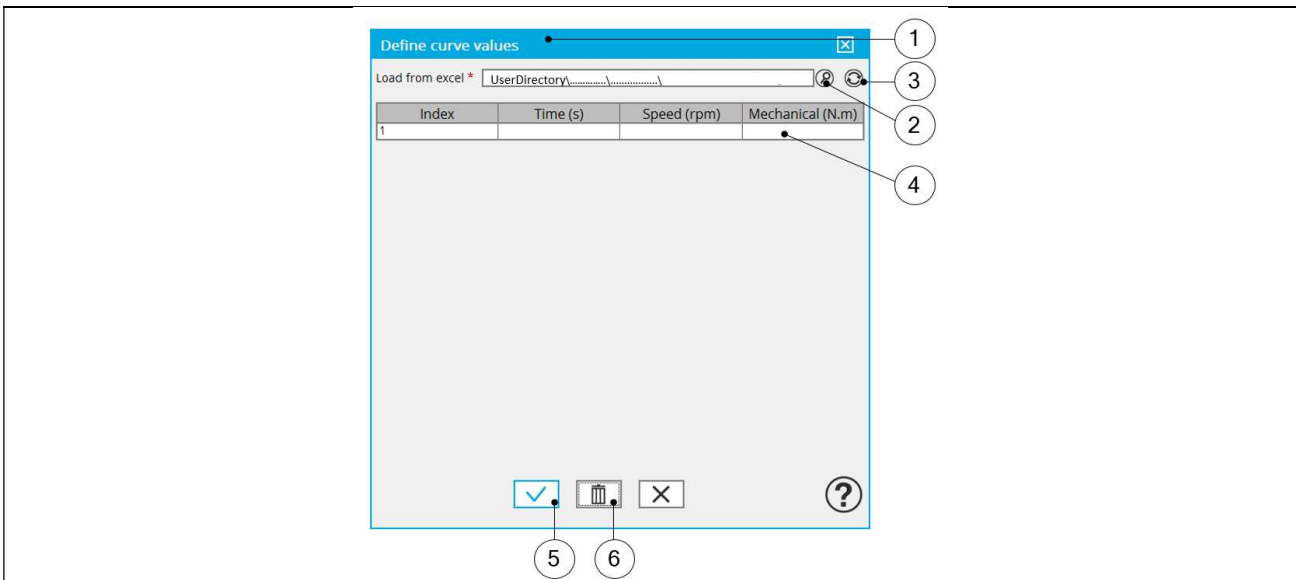
Note: A working point is defined by a time, a speed, and a mechanical torque.



User working point analysis = Duty cycle

1	Select the "Duty cycle" option
2	Click in the button "Set values" of the field "Duty cycle" to open a dialog box to define the duty cycle. Refer to the next illustration which shows how to fill the Duty cycle table.
3	Button to validate the user input data
4	Button to run the computations

Note: Once the test results have been computed, new user working point and duty cycle values can be set, and results will appear instantaneously when relaunching the test.



User working point analysis = Duty cycle – Dialog box to define the duty cycle

1	Dialog box opened after having clicking the button "Set values" in the field "Cycle description"
2	Browse the folder to select an Excel file which is described the duty cycle
3	Button to refresh the table data when the considered Excel file has been modified
4	Fields to be filled with data to describe the duty cycle to be considered

Note: The Excel template used to import a duty cycle is stored in the folder Resource/Template in the installation folder of FluxMotor®. An example of this template is displayed below.

Duty cycle			
Label	Time	Speed	Mech. torque
Units	s	rpm	N.m
Values	0	1000	10
	2	2000	20
	5	3000	30
	10	3000	40
	15	4000	25
	20	4000	20
	22	3500	15
	25	3500	10

Excel file template to define the duty cycle

1.3.4 Advanced inputs

1.3.4.1 Number of computed electrical periods

The user input “**No. computed elec. periods**” (Number of computed electrical periods only required with rotor position dependency set to “Yes”) influences the computation time of the results.

The default value is equal to 0.5. The maximum allowed value is 1 according to the fact that computation is done to characterize steady state behavior based on magnetostatic finite element computation. The default value provides a good compromise between the accuracy of results and computation time.

Note: The outcomes obtained at 0.5 or 1 electrical period are identical across all presented outputs, except for slight variations in rotor iron losses arising from the symmetrical assumption regarding the magnetic flux waveform on the rotor.

1.3.4.2 Number of computations for I_F-axis field current

First, it is needed to compute the D-axis and Q-axis flux linkage in the J_d - J_q planes at various levels of I_F.

To get D-axis and Q-axis flux linkage maps along I_F dimension, the field current is discretized from zero to its maximum value. The number of computation points along the I_F-axis can be defined with the user input « **No. comp. for I_F** » (*Number of computations for I_F-axis field currents*).

The default value is equal to 6. This default value provides a good compromise between the accuracy of results and computation time. The minimum allowed value is 5.

1.3.4.3 Number of computations for J_d, J_q per quadrant

To get D-axis and Q-axis flux linkage maps in the J_d - J_q planes, a grid is defined. The number of computation points along the d-axis and q-axis can be defined with the user input « **No. Comp. for J_d, J_q** » (*Number of computations for D-axis and Q-axis currents per quadrant*). 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.

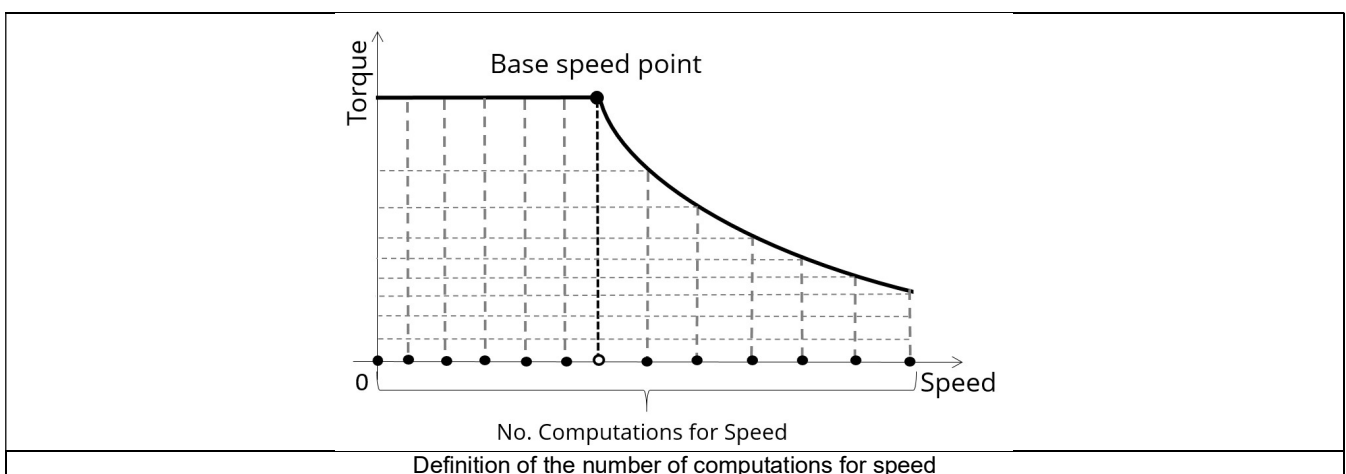
1.3.4.4 Number of computations for speed

The “**No. comp. for speed**” (*Number of computations for speed*) corresponds to the number of points to be considered in the speed range from 0 to the maximum speed.

Half of these points are distributed from 0 to the base speed. The remaining points are distributed from the base speed to the maximum speed.

In both cases, base speed is considered as an additional point.

Note: If the user input parameter “**No. comp. for speed**” is an odd number, one discretization point is automatically removed.



The default value is equal to 15, the minimum allowed value is 5. The maximum recommended value is 40.

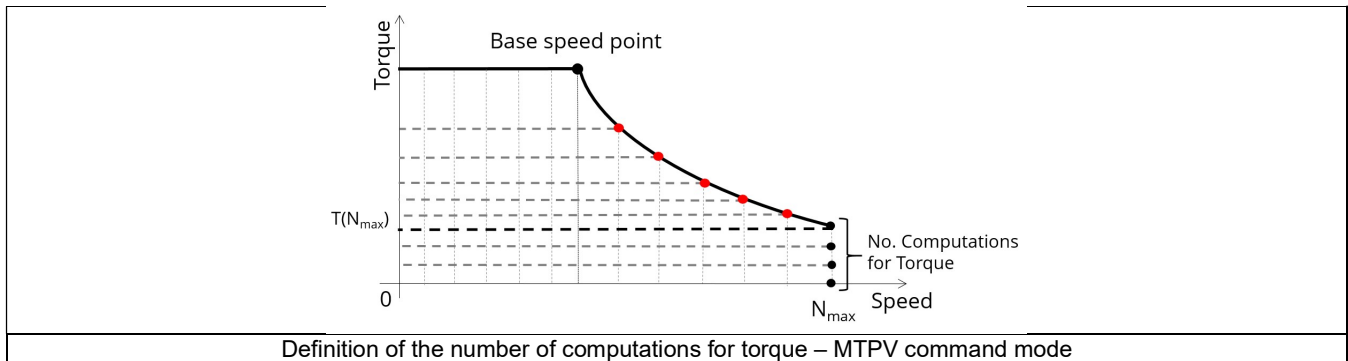
Note: Increasing the number of computations can improve the convergence of the optimization used to define the torque-speed curve and the efficiency map. However, that also means longer computation time.

1.3.4.5 Number of computations for torque

For the speed range $[N_{base}; N_{max}]$, the number of computations for torque is imposed by the number of computations for speed in the speed range $[N_{base}; N_{max}]$ (Red points in the image shown below).

The advanced user input parameter **"No. comp. for torque"** allows finalizing the grid within the torque range $[0, T(N_{max})]$ at the maximum speed (Black points in the image shown below).

The default value is equal to 7. The minimum allowed value is 3. The maximum recommended value is 20.



1.3.4.6 Skew model – Number of layers

When the rotor or the stator 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 modelling the skewing in Flux® Skew environment).

1.3.4.7 Rotor initial position mode

The computations are performed by considering a relative angular position between rotor and stator.

This relative angular position corresponds to the angular distance between the direct axis of the rotor north pole and the axis of the stator phase 1 (reference phase).

The value of the rotor d-axis location, which is automatically defined, for each saliency part, in Part Factory, can be visualized in the output parameters in the saliency area of Motor Factory – Design environment.

1.3.4.8 Airgap mesh coefficient

The advanced user input **"Airgap mesh coefficient"** is a coefficient which adjusts the size of mesh elements inside the airgap. When the value of **"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 points of the geometry), inside the Flux®, is described as:

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

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 a huge number of nodes in the corresponding finite element model. So, it means a need of huge numerical memory and increases the computation time considerably.

1.4 Main principles of computation

1.4.1 Introduction

This paragraph deals with the process to get the torque-speed curves and maps (For example - efficiency map).

The process is separated into the two following parts:

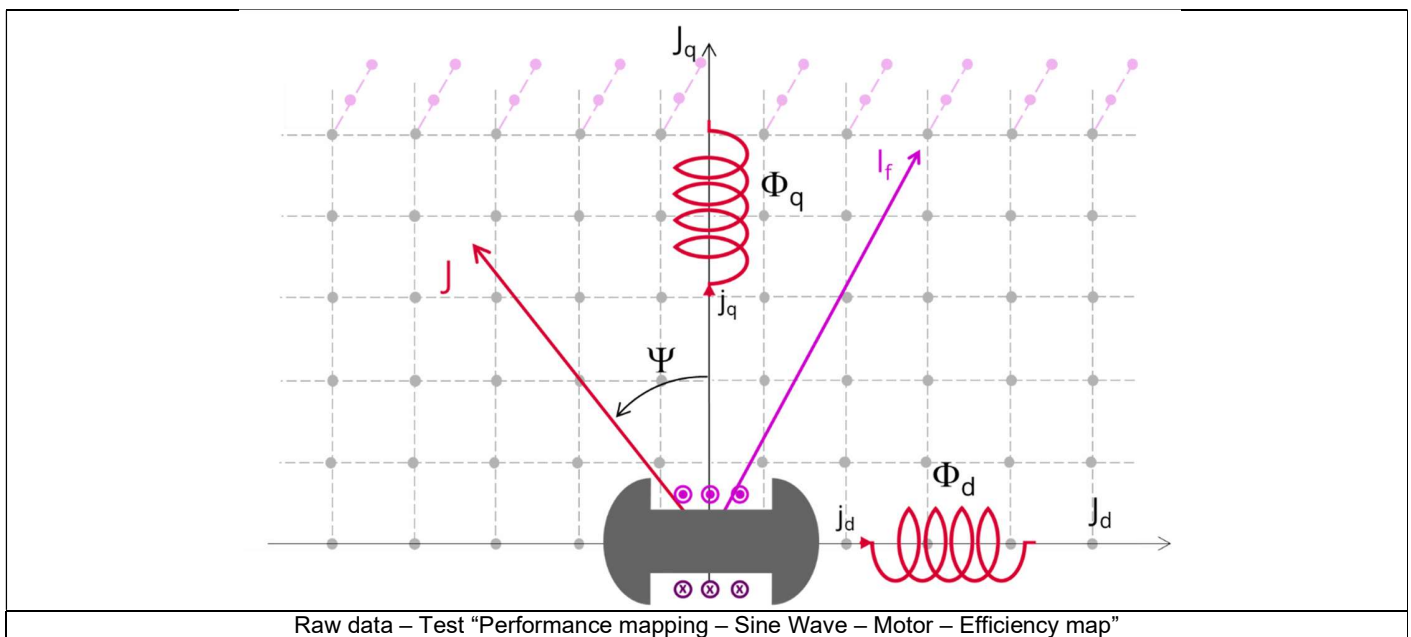
- Raw data and Park model
- Identification of the torque-speed curves and maps – Overview

1.4.2 Raw data and Park's model

The first step consists of computing the raw data which characterize the machine in the three dimensions I_f - J_d - J_q . This is done using Finite Element modelling (Flux® – Magnetostatic application).

To do that, a grid of values (J_d , J_q) is considered for all levels of I_f .

For each node of this grid, the corresponding flux linkage through each phase is extracted (Φ_a , Φ_b , Φ_c). Flux density in regions (teeth and yoke of the machine) are also extracted.



The second step consists of using the raw data with the Park's model.

D-axis flux-linkage component (Φ_d) and Q-axis flux-linkage component (Φ_q) are computed according to the Park's transformation.

The **Electromagnetic torque** T_{em} is computed in different ways in function of the input Rotor position dependency value.

- 1) If rotor position dependency is set to “No”, the flux linkage maps, and the following formula are used:

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

Where m is the number of phases (3) and p is the number of pole pairs. J_d and J_q are the d and q axis peak current.

- 2) If rotor position dependency is set to “Yes”, the Electromagnetic torque T_{em} is computed thanks to finite element computation and virtual work method to get the best evaluation of the ripple torque.

Note: In case the Rotor position dependency is set to “Yes”, **Electromagnetic torque** T_{em} average value computed with the Park's equation or with virtual works are equal.

Note: The computations are the same as those performed in the test “Characterization - Model – Motor - Maps” with or without rotor position dependency.

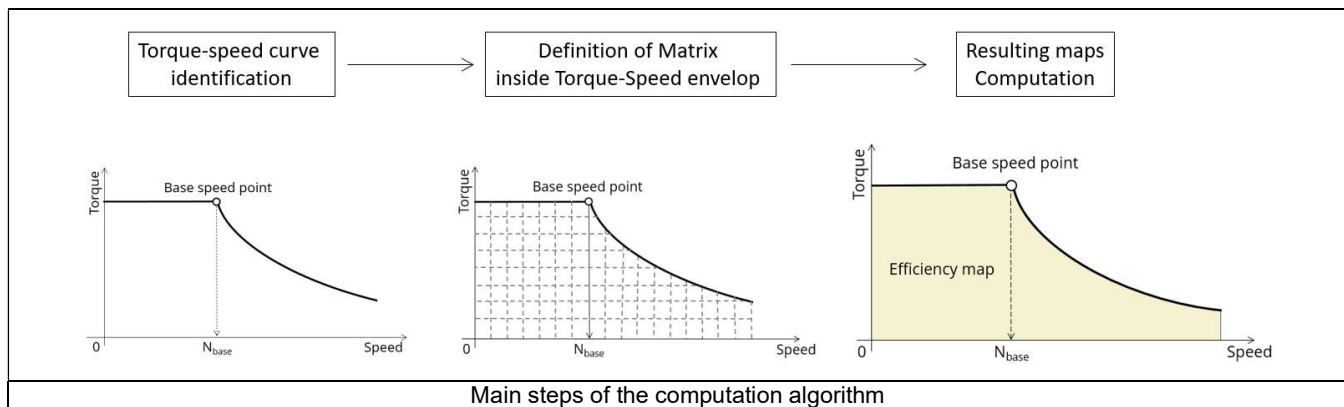
Here are the obtained results which are used to build the next step, that is, curves and maps in the torque-speed area:

- D-axis flux-linkage component - Φ_d
- Q-axis flux-linkage component - Φ_q
- Electromagnetic torque T_{em}
- Stator iron losses $W_{ironStator}$ versus speed
- Rotor iron losses $W_{ironRotor}$ versus speed (only available if rotor position dependency is set to Yes)
- Joule losses in stator winding W_{Cus}
- Joule losses in rotor winding W_{Cur}
- Mechanical losses versus speed
- Amount of total losses W_{total} versus speed

1.4.3 Identification process for the torque-speed curves and maps – Overview

Below presented are the three main steps involved in building the efficiency map and other associated results. These steps are performed by using the computed raw data (see previous section) with optimization processes.

- Building of the torque-speed curve and other associated results
- Define the grid in the area under torque-speed curve
- Building of the efficiency map and other associated results



For more information, please refer to the section 1.5 (Command modes) dealing with the command modes

1.5 Command modes

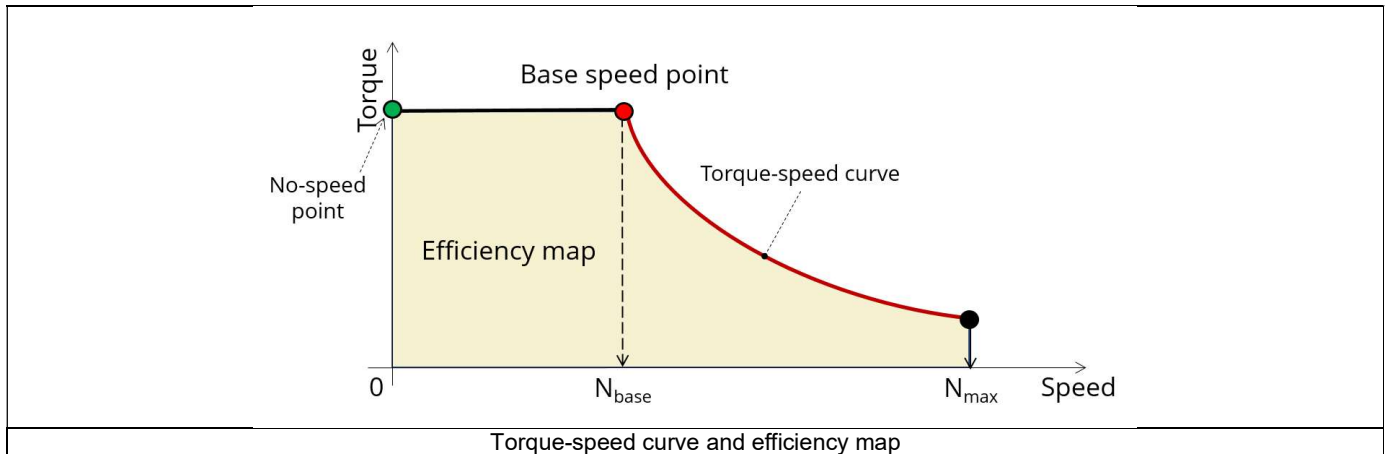
1.5.1 Introduction

The user can choose only one command modes in this version:

- The Maximum Torque Per Voltage (MTPV)

Note: The Maximum Torque Per Amps (MPTA) will be provided in the next releases.

The first step of the process consists of computing the Torque-speed curve (curve which bounded the domain) and the second step is to compute maps bounded by the Torque-speed curve (Efficiency maps, Iron loss maps...).

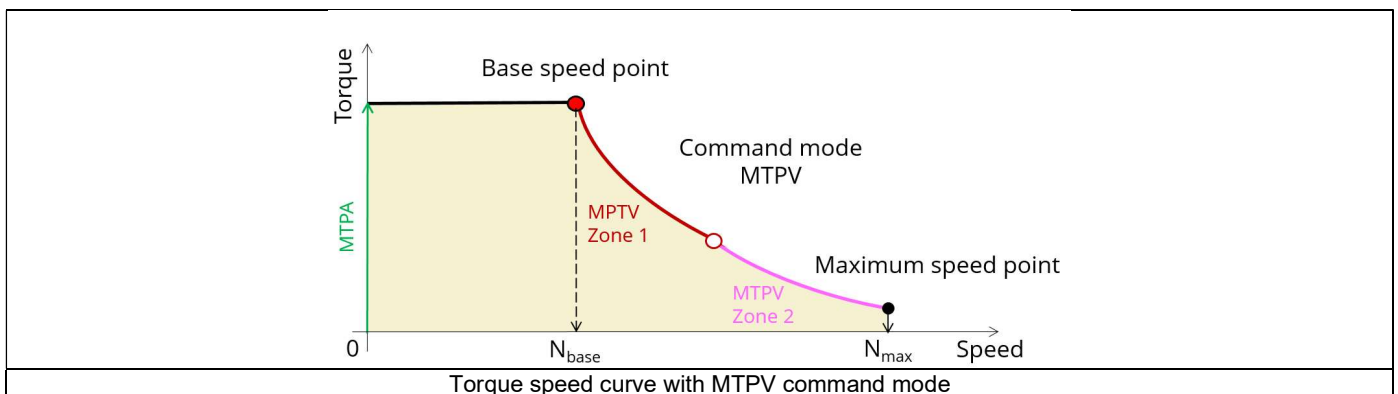


1.5.2 Maximum Torque Per Voltage command mode (MTPV)

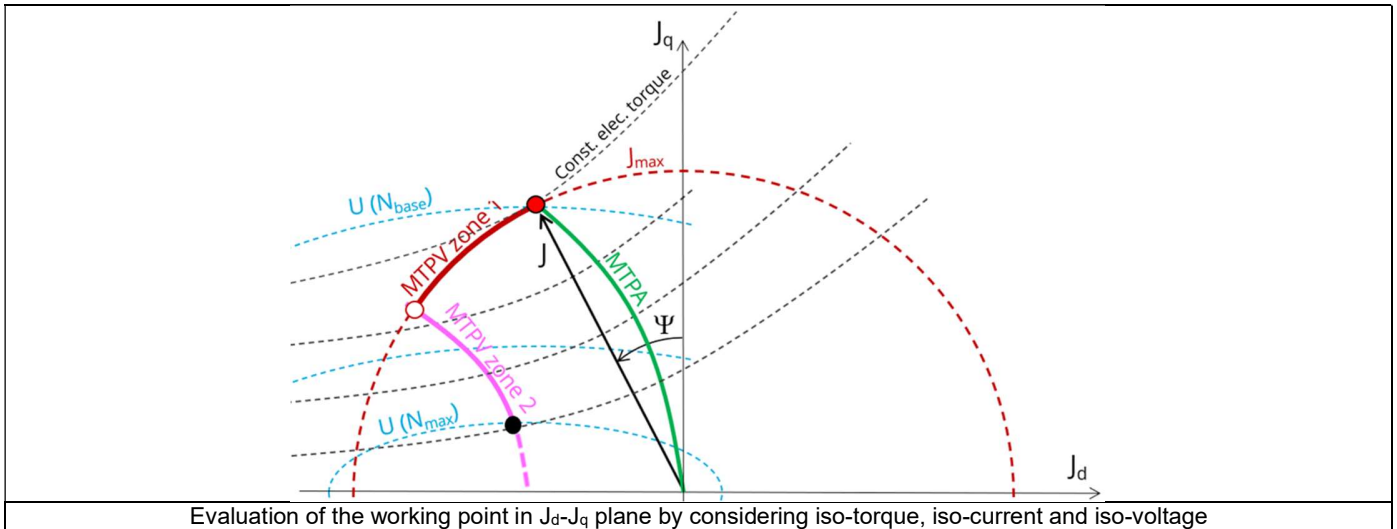
1.5.2.1 Positioning and objective

The Maximum Torque Per Voltage command mode (MTPV) allows to compute the torque-speed curve which corresponds to the maximum potential of mechanical torque (or mechanical power) of a motor from the base speed point to the maximum speed point. This command mode shows the full potential of the machine, but it is also the most difficult command mode to implement in terms of control and drive.

When this command is chosen, it is used to compute the torque speed curve from the base speed point to the maximum speed. Using the base speed point, the torque speed curve is obtained by imposing the useful torque computed at the base speed point and by maximizing the efficiency. The maps bounded by the considered torque-speed curve are computed by maximizing the efficiency for each paired values (Torque, Speed).



Over the speed range $[N_{base}, N_{max}]$ we distinguish two main zones, the Zone 1 commonly called "Flux weakening" and the Zone 2 commonly called "MTPV curve".



In the first zone (MTPV zone 1), the maximization of the mechanical torque for a given speed is reached by keeping the maximum values of voltage and current, and by driving the control angle (Ψ).

$$U = U_{max}$$

$$I = I_{max}$$

In a second zone (MTPV zone 2), the maximization of the mechanical torque is reached by keeping the maximum values of voltage and by decreasing the line current below the maximum allowed value, and by driving the control angle (Ψ).

$$U = U_{max}$$

$$I < I_{max}$$

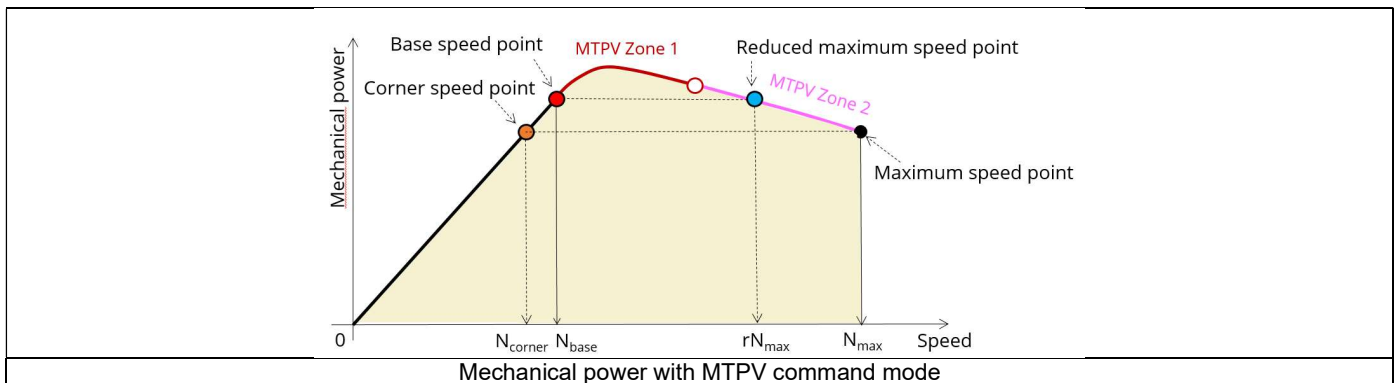
In FluxMotor®, MTPV label is used to mention the combination of these two zones (for both, the maximum torque is computed, at the maximum voltage available. The optimization process automatically deduces the best working zone according to the following constraints:

$$U = U_{max}$$

$$I \leq I_{max}$$

Note: The MTPV zone 2 is available only for motors which have, in D-Q current area, their iso-voltage ellipse center located inside the iso-current circle corresponding to the maximum value of current.

With MTPV command mode the mechanical power is not imposed over the speed range [N_b , N_{max}] as commonly done. In fact, over Zone 1 and Zone 2 the MTPV command mode imposes maximizing the mechanical torque at maximum voltage. Maximizing the mechanical torque at imposed speed is equivalent to maximizing the mechanical power. In conclusion, the MTPV command mode allows to spotlight the potential of mechanical power that the machine can provide over a speed range from the base speed point to the maximum speed point with a given maximum line-line voltage and a maximum line current.



Thanks to the MTPV results we can easily detect the maximum mechanical power that the machine is able to provide over a range of speed.

For examples, referring to the previous figure:

- If we want to impose the mechanical power obtained at the maximum point speed, we can easily deduce the bound at low speed. We called this point as corner speed point (Orange point on the previous figure).
- If we want to impose the mechanical power obtained at the based speed point, we can deduce the bound at high speed. We called this point as reduced maximum speed point (Blue point on the previous figure).

Note: The corner point is equal to the base speed point when the mechanical power at maximum speed is equal to the mechanical power we get for the base speed.

1.5.2.2 Torque-speed curve – Computation and displaying

1) Base speed point

The first step consists of computing the base point (red point on the image shown below).

The target is to find the maximum reachable torque (T_{max}) considering:

- The maximum allowed Line-Line voltage ($U = U_{max}$)
- The maximum allowed line current ($I = I_{max}$)

An optimization process is used, and the variable parameters are the speed (N), the D-axis and the Q-axis components of the phase current (J_d , J_q) and the field current I_f .

2) Maximum speed point

The second step consists of verifying that the maximum speed set by the user is reachable (black point on the image shown below).

The target is to find the maximum reachable torque (T_{max}) considering:

- The maximum allowed Line-Line voltage ($U = U_{max}$)
- Field current less than or equal to the maximum allowed value ($I_f \leq I_{fmax}$)
- Line current less than or equal to the maximum allowed value ($I \leq I_{max}$)
- The maximum speed set by the user ($N=N_{max.}$)

An optimization process is used, and the variable parameters are the D-axis and the Q-axis components of the phase current (J_d , J_q) and the field current I_f .

If the user maximum speed is reachable, the used optimization process reaches convergence and the torque-speed curve identification process continues.

Sometimes, the maximum speed set by the user is not reachable by the machine.

With the MTPV command mode, the maximum speed depends on the characteristics of the motor, and especially on its capabilities for operating in the flux weakening zone. In this case, a computation of a reachable maximum speed is automatically done.

If the maximum speed indicated by the user is not reachable by the machine, an automatic correction is performed.

In that case, the target is to find the maximum reachable speed considering:

- Line-Line voltage equal to the maximum allowed value ($U = U_{max.}$)
- Field current less than or equal to the maximum allowed value ($I_f \leq I_{fmax}$)
- Line current less than or equal to the maximum allowed value ($I \leq I_{max}$)
- The mechanical torque obtained at the base speed divided by ten ($T = T(Nb)/10$)

The variable parameters are the speed (N), the D-axis and the Q-axis components of the phase current (J_d , J_q) and the field current I_f .

3) No speed working point

The third step consists of computing the no-speed working point (Green point in the image shown below).

The target is to find the maximum reachable efficiency for the machine by considering:

- Line-Line voltage less than or equal to the maximum allowed value ($U \leq U_{max}$)
- Field current less than or equal to the maximum allowed value ($I_f \leq I_{fmax}$)
- Line current less than or equal to the maximum allowed value ($I \leq I_{max}$)
- A null speed
- Imposed torque equal to the base speed torque ($T=T(Nb)$) if $Nb < N_{max.}$ or equal to the maximum speed torque ($T = T(N_{max.})$) if $Nb > N_{max.}$

An optimization process is used, and the variable parameters are the D-axis and the Q-axis component of the phase current (J_d , J_q) and the field current I_f .

Note: At zero speed, losses match exactly with Joule losses. In that case, one can consider that MTPA is applied (Green point in the image shown below).

4) Torque-speed curve in the range $]0, N_b[$

The base speed, the maximum speed and the no-speed working points being fixed, the fourth step consists of computing the part of the torque-speed curve where the torque is constant (Black line in the image shown below).

The target is to find the maximum reachable efficiency for the machine by considering:

- Imposed torque equal to the base speed torque $T=T(N_b)$.
- Imposed speed with $N \in]0, N_b[$
- Line-Line voltage less than or equal to the maximum allowed value ($U \leq U_{max}$)
- Field current less than or equal to the maximum allowed value ($I_f \leq I_{fmax}$)
- Line current less than or equal to the maximum allowed value ($I \leq I_{max}$)

The variable parameters are the D-axis and the Q-axis components of the phase current (j_d , j_q) and the field current I_f .

5) Torque speed curve in the range $]N_b, N_{max} [$

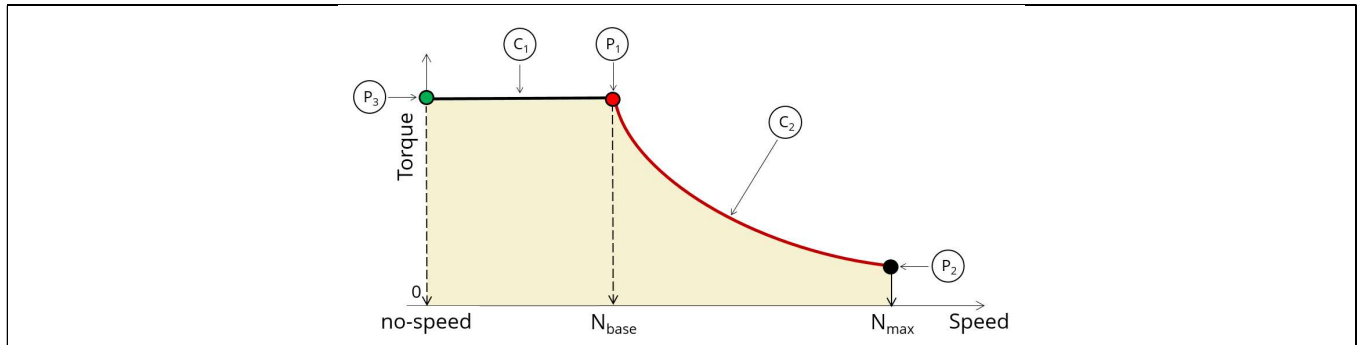
Then, the last step consists of computing the torque-speed curve over the speed range $]N_b, N_{max} [$ (red curve in the image shown below).

This step is done only when $N_b < N_{max}$.

The target is to find the Maximum reachable torque by considering:

- Imposed speed with $N \in]N_b, N_{max} [$
- Line-Line voltage equal to the maximum allowed value ($U = U_{max}$)
- Field current less than or equal to the maximum allowed value ($I_f \leq I_{fmax}$)
- Line current less than or equal to the maximum allowed value ($I \leq I_{max}$)

An optimization process is used, and the variable parameters are the D-axis and the Q-axis components of the phase current (J_d , J_q) and the field current I_f .



MTPV command modes – Torque-speed curve computation process

P₁	Base speed point	Target: Maximum torque (T_{max})
	Constraints	$I = I_{max}$, $U = U_{max}$,
	Variable parameters	J_d , J_q , I_f , Speed (N)
P₂	Max. speed point	Target: Maximum torque (T_{max})
	Constraints	$I_f \leq I_{fmax}$ $I \leq I_{max}$ $U = U_{max}$ Speed = Maximum speed (N_{max} .)
	Variable parameters	J_d , J_q , I_f
P₃	Null speed point	Target: maximum efficiency
	Constraints	$I_f \leq I_{fmax}$ $I \leq I_{max}$ $U \leq U_{max}$ Speed = $N = 0$ Torque = base speed torque ($T(N_b)$)
	Variable parameters	J_d , J_q , I_f
C₁	Low speed zone	Target: maximum efficiency
	Constraints	$I_f \leq I_{fmax}$ $I \leq I_{max}$ $U \leq U_{max}$ Speed $\in]0, N_b[$ Torque = base speed torque ($T(N_b)$)
	Variable parameters	J_d , J_q , I_f
C₂	High speed zone	Target: maximum torque (T_{max})
	Constraints	$I_f \leq I_{fmax}$ $I \leq I_{max}$ $U = U_{max}$ Speed $N \in]N_b, N_{max}[$
	Variable parameters	J_d , J_q , I_f

1.5.2.3 Computation and displaying maps

Evaluating the maps for all the electromagnetic quantities consists of computing the machine performance for each node of a grid bounded by the torque-speed curve (Yellow part in the image shown below).

1) Maps at no-speed

At no-speed losses match exactly with Joule Losses. One can consider that MTPA command is applied. In that case, the target is to minimize the Joule losses by considering:

- Line-Line voltage less than or equal to the maximum allowed value ($U \leq U_{\max}$)
- Field current less than or equal to the maximum allowed value ($I_f \leq I_{f\max}$)
- Line current less than or equal to the maximum allowed value ($I \leq I_{\max}$)
- Speed = 0
- Imposed torque by the user discretization

An optimization process is used and the variable parameters are the D-axis and the Q-axis components of the phase current (J_d , J_q) and the field current I_f .

2) Maps at no torque

At zero torque, only iron losses and mechanical losses, which depend on the speed, are computed. All other electromagnetic quantities are set to 0 (including efficiency).

3) Maps at no-speed and no-torque

When speed and torque are null all the quantities are equal to 0.

4) Maps in the range $]0, N_{\max}]$

For each paired (torque, speed) working points, the target is to find the maximum reachable efficiency for the machine by considering:

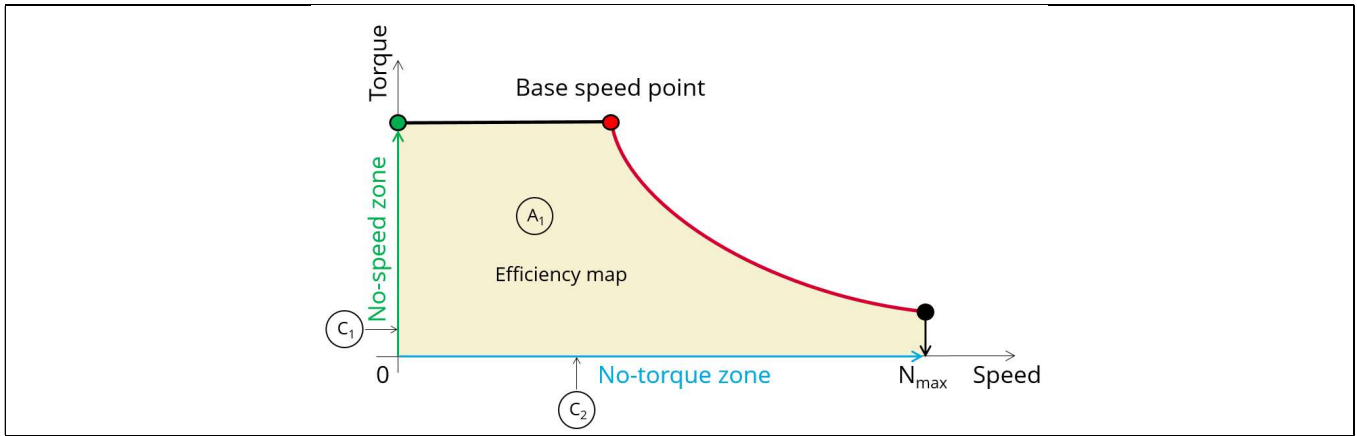
- Imposed speed with $N \in [0, N_{\max}]$
- Imposed torque with $T \in [0, T_b]$
- Line-Line voltage less than or equal to the maximum allowed value ($U \leq U_{\max}$)
- Field current less than or equal to the maximum allowed value ($I_f \leq I_{f\max}$)
- Line current less than or equal to the maximum allowed value ($I \leq I_{\max}$)

An optimization process is used, and variable parameters are the D-axis and the Q-axis components of the current (J_d , J_q).

Note: The computation of efficiency integrates the Joule losses, iron losses, mechanical losses, and additional losses (if used).

Note: Usually, at low speed, the Joule losses dominate other types of losses.

Considering this, at low-speed results obtained with this process can be very close to results obtained with an MTPA command mode.



MTPV command modes – Efficiency map computation process

C ₁	Null speed zone	Target: Minimum Joule losses
	Constraints	$I_f \leq I_{fmax}$ $I \leq I_{max}$ $U \leq U_{max}$ Speed $N = 0$ User torque (got by user's discretization)
	Variable parameters	J_d, J_q, I_f
C ₂	Null torque zone	
	Only iron losses and mechanical losses are computed All other quantities are set to 0, even the efficiency.	
A ₁	Efficiency map	Target: Maximum efficiency
	Constraints	$I_f \leq I_{fmax}$ $I \leq I_{max}$ $U \leq U_{max}$ Targeted speed (got by user's discretization) Targeted torque (got by user's discretization)
	Variable parameters	J_d, J_q, I_f

1.6 Test results

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

1.6.1 Test conditions

1.6.1.1 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).

1.6.1.2 Settings

All the settings dedicated to the test and dealing with the thermal are displayed in this section.

Here is the displayed subsection:

- Thermal
- Electronics
- Mechanics

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

1.6.1.3 Winding characteristics

The winding characteristics are displayed into three locations

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

1.6.2 Main results

1.6.2.1 Machine performance – Base speed point

All the machine main electromagnetic data computed for the based speed point are presented in this table with the following subsections:

- General data
- Power balance

For more details, please refer to the document: MotorFactory_SMWF_IR_3PH_Test_Introduction – section “Test generic information”.

1.6.2.2 Machine performance – Maximum Speed point

All the machine main electromagnetic data computed for the maximum speed point are presented in this table with the following subsections:

- General data
- Power balance

For more details, please refer to the document: MotorFactory_SMWF_IR_3PH_Test_Introduction – section “Test generic information”.

1.6.2.3 Machine performance – User working point

All the machine main electromagnetic data computed for a user working point are presented in this table with the following subsections:

- General data
- Power balance

For more details, please refer to the document: MotorFactory_SMWF_ISP_IR_3PH_Test_Introduction – section “Test generic information”.

1.6.2.4 Machine performance – Duty cycle data

This section is displayed when the user wants to perform additional analysis on working points before running the test. User input parameter “User working point(s) analysis” = Duty cycle.

The following subsections are displayed:

- General data
- Power balance
- Energy balance

Mean values as well as minimum and maximum values of general data, power balance and energy balance are computed and displayed.

Notes:

The mean value of a quantity “Qty” is computed as:

$$\frac{1}{T_{\text{Duty cycle}}} \times \int_0^{T_{\text{Duty cycle}}} \text{Qty} dt$$

The minimum and maximum values are defined over the duty cycle.

1.6.2.5 Power electronics

This section is displayed when the user, before running the test, has selected “With power electronics stage” for “Electronics” settings.

All the main power electronics data computed for the user working point are presented in the table “Power electronics” with the following subsections:

- Inverter
- Base speed point
- Maximum speed point
- User working point (if set be the user)
- Duty cycle (if set be the user)

1.6.3 Curves

1.6.3.1 Torque-speed curves

List of torque-speed curves computed and displayed:

- Mechanical torque versus speed
- Phase current and field current versus speed
- Phase voltage and field current versus speed
- Control angle (Ψ) versus speed
- Powers versus speed
- Power factor versus speed
- Losses versus speed

1.6.4 Torque-speed Maps

List of torque-speed maps computed and displayed:

- Efficiency in torque-speed area
- Electrical current (Phase, D-axis, Q-axis, Field)
- Phase voltage (Phase, D-axis, Q-axis, Field)
- Control angle (Ψ) in torque-speed area
- Power (System electrical, machine electrical, mechanical)
- Power factor in torque-speed area
- Losses (System total, machine total, Joule, iron, mechanical, power electronics, additional) in torque-speed area

Note: When a user's working point has been targeted or if a duty cycle is considered, the corresponding working points are displayed on all the maps described above.

1.6.5 Duty cycle curves

List of curves dealing with the duty cycle when expected:

- Speed versus time
- Mechanical torque versus time
- Control angle versus time
- Current versus time (Phase, D-axis, Q-axis)
- Voltage versus time (Phase, D-axis, Q-axis)
- Power factor versus time
- Power versus time (system electrical, machine electrical and mechanical)
- Efficiency versus time
- Losses versus time (System total, machine total, Joule, Iron, mechanical, power electronics and additional)