Altair® FluxMotor® 2026

Synchronous machines – Permanent magnets - Inner & Outer rotor

Motor Factory – Test – Performance mapping

General user information

Altairhyperworks.com

Contents

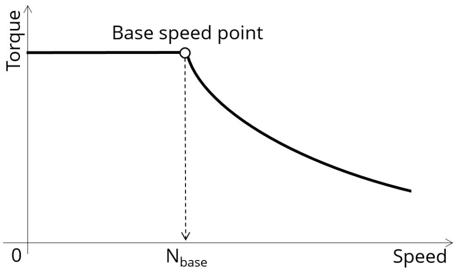
1 PERFORMANCE MAPPING – SINE WAVE – MOTOR – EFFICIENCY MAP

1.1 Overview

1.1.1 Positioning and objective

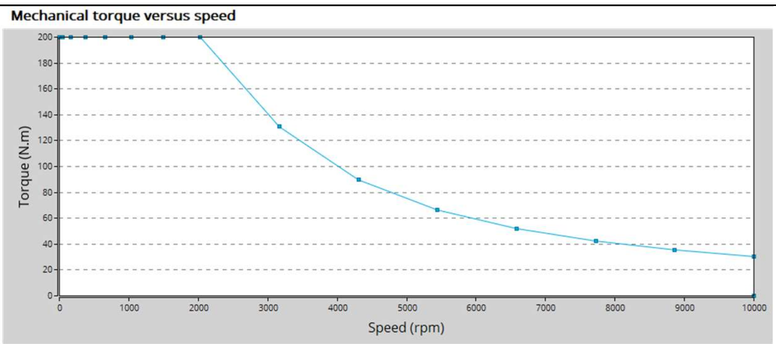
The aim of the test "**Performance mapping – Sine wave – Motor – Efficiency map**" is to characterize the behavior of the machine in the "Torque-Speed" area.
Input parameters like the maximum "Line-Line voltage", the maximum "line current" and the desired "Maximum speed" of the machine are considered.

Two types of command modes are available: The Maximum Torque Per Volt command mode (MTPV) and the Maximum Torque Per Amps command mode (MTPA).
Input parameters define torque-speed area in which the evaluation of the machine behavior is performed.

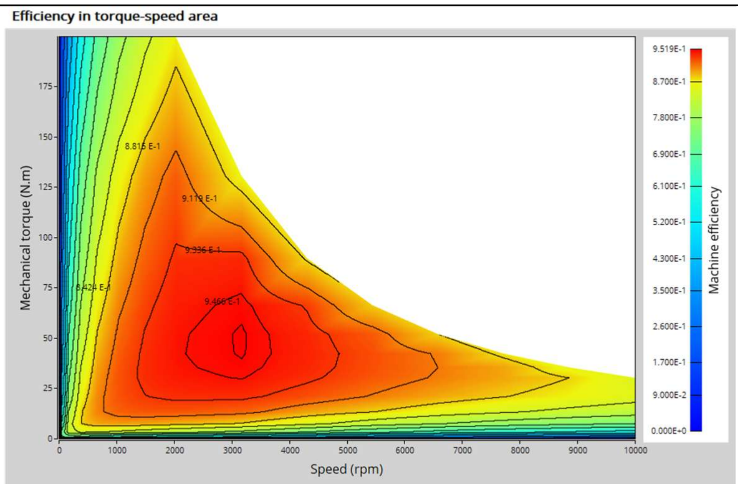


Characterization of the corner point on the torque-speed curve

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.

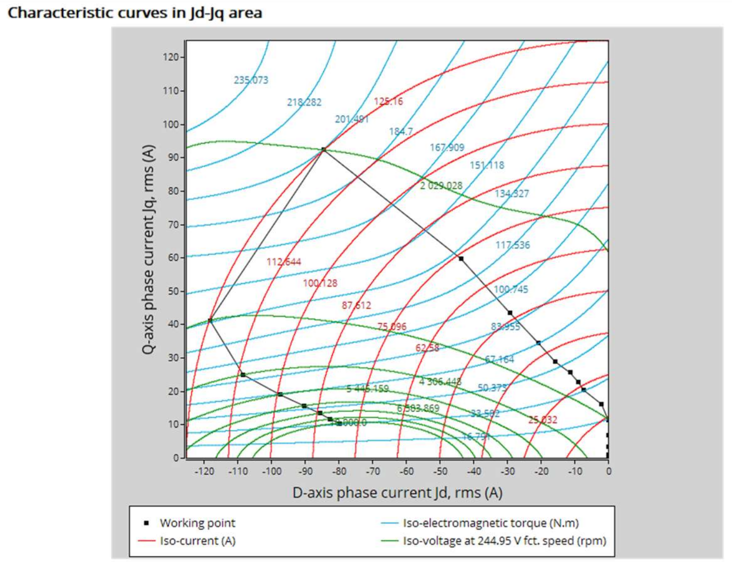


Mechanical torque versus speed - Example



Efficiency in torque-speed area - Example

Note: In addition, in J_d-J_q plane, a graph shows the computed working points for the torque speed curve. The iso-electromagnetic torque, the iso-current and the iso-voltage are also displayed in J_d-J_q plane.
These results help the user to understand the possible performance of the machine in its electric environment.



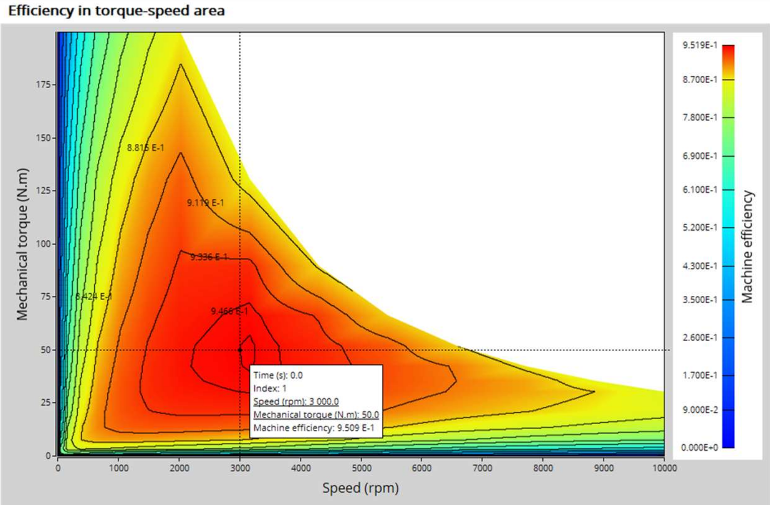
Characteristics curves in J_d-J_q area - Example

1.1.2 Driving cycle with or without thermal solving

1.1.2.1 Basic driving cycle

Two 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.

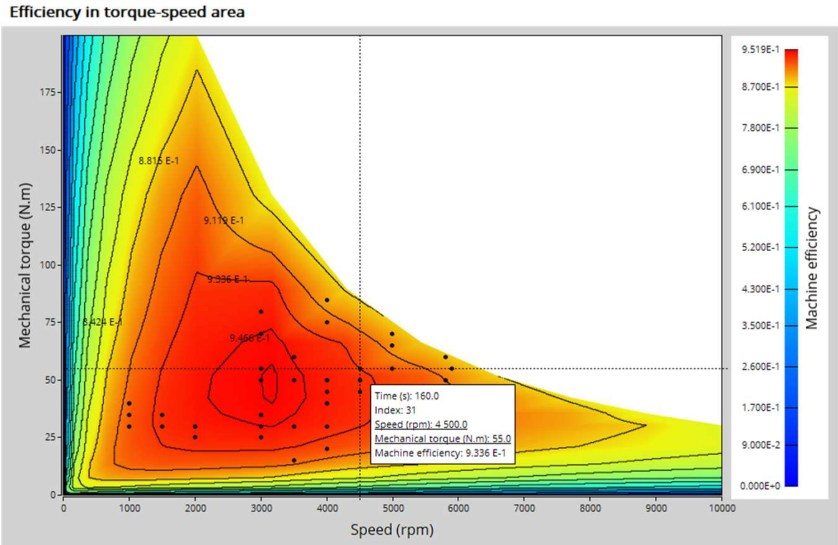


A “single” working point displayed on the efficiency map - Example

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).

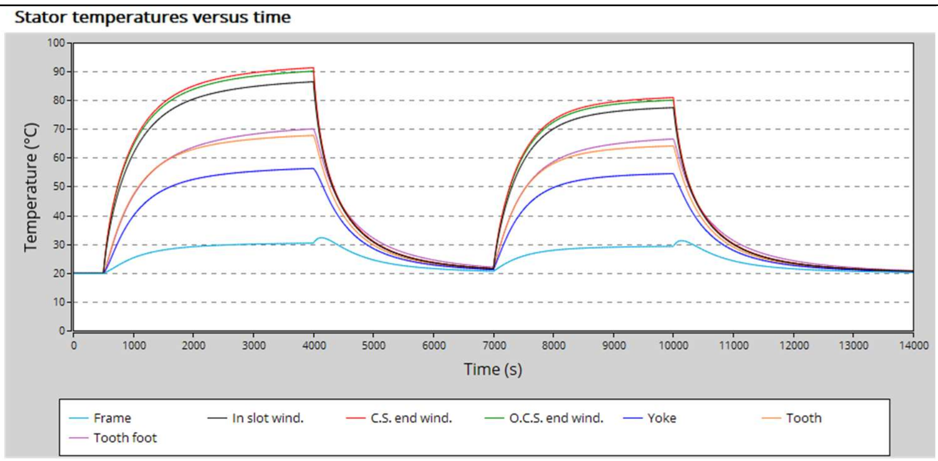
All the corresponding points are displayed on the different provided maps.



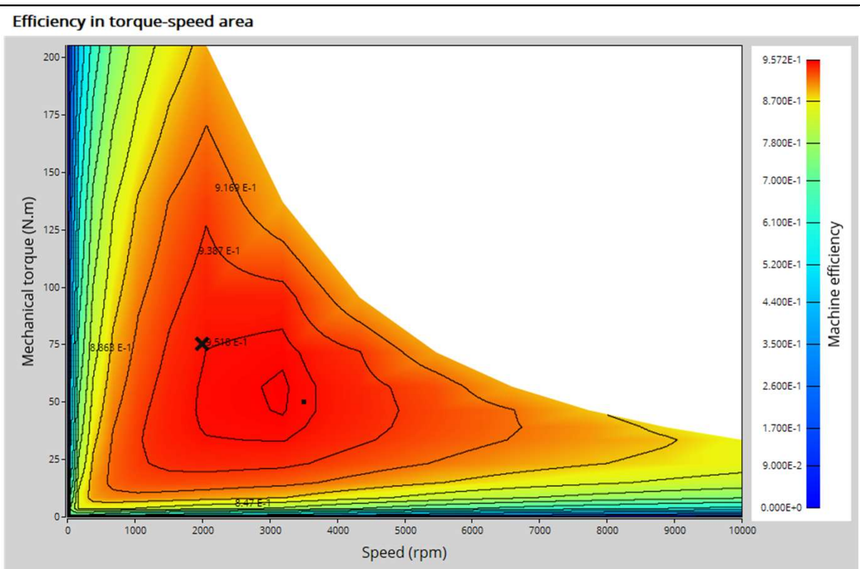
A “Driving cycle” displayed on the efficiency map - Example

1.1.2.2 Driving cycle with thermal solving

When the "thermal solving" is selected in the settings, the machine temperatures are computed over the driving cycle.
The variation of the machine performance are computed and displayed over all the driving cycle time.



The machine temperature variations can be evaluated all along the driving cycle



A working point of the driving cycle can be selected for displaying the corresponding machine electromagnetic performance

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”

1.2 Main principles of computation

1.2.1 Introduction

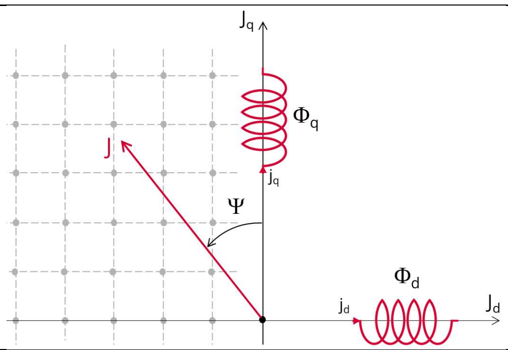
This paragraph deals with the process to get the torque-speed curves and maps (For example - efficiency map).

The process is separated into the two following parts:

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

1.2.2 Raw data and Park's model

The first step consists of computing the raw data which characterize the machine in the J_d-J_q plane. This is done using Finite Element modelling (Flux® – Magnetostatic application).
To do that, a grid of (J_d, J_q) values is considered.
Flux linkage through each phase (Φ_a, Φ_b, Φ_c) and flux density in regions (teeth and yoke of the machine) are computed and extracted as a function of (J_d, J_q).



Raw data – Test "Performance mapping – Sine Wave – Motor – Efficiency map"

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:

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

Park's model - Motor convention - Torque equation

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:

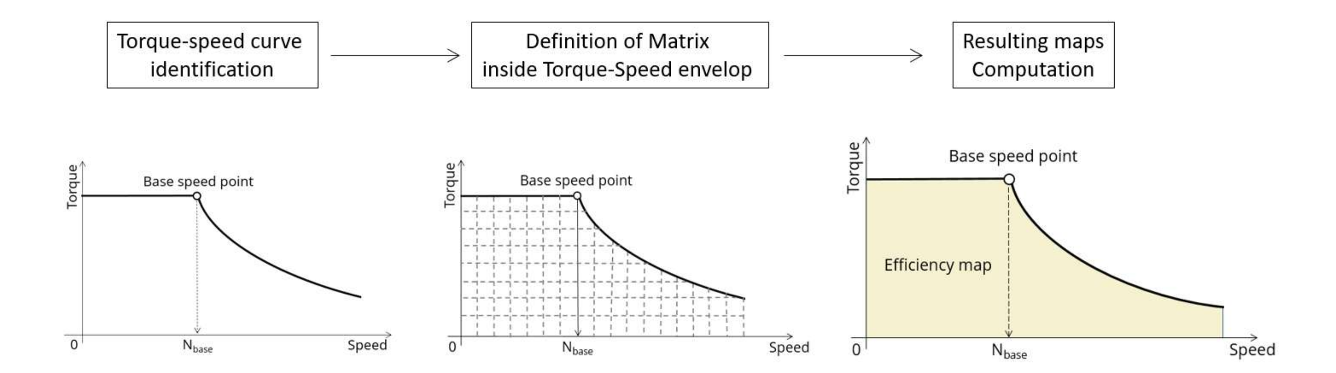
- D-axis flux-linkage component - Φ_d
- Q-axis flux-linkage component - Φ_q
- Electromagnetic torque T_{em}
- Stator iron losses W_{iron} versus speed
- Joule losses in stator winding W_{Cus}
- Mechanical losses versus speed
- Amount of total losses W_{total} versus speed

1.2.3 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 similar for all the command modes with only some specifications.

These steps are performed by using the computed raw data (see previous section) with optimization processes associated with the considered command mode functions like MTPA curves.

- 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



Main steps of the computation algorithm

For more information, please refer to the section 1.3 (Command modes) dealing with the command modes

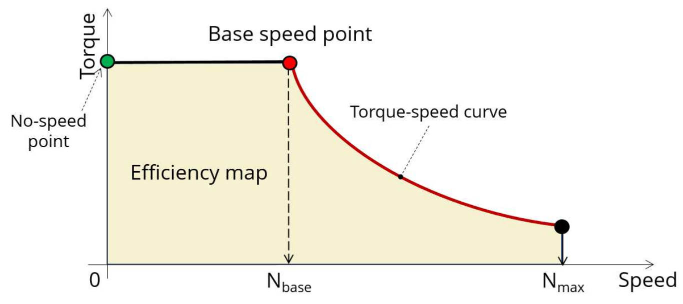
1.3 Command modes

1.3.1 Introduction

The user can choose between two types of command modes:

- The Maximum Torque Per Voltage (MTPV)
- The Maximum Torque Per Amps (MPTA)

Whatever is the command mode applied, 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…).



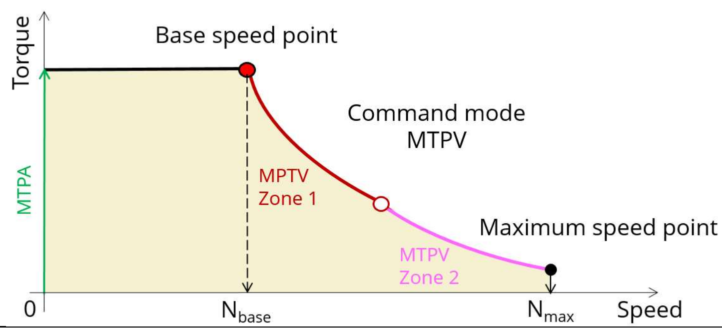
Torque-speed curve and efficiency map

1.3.2 Maximum Torque Per Voltage command mode (MTPV)

1.3.2.1 Positioning and objective

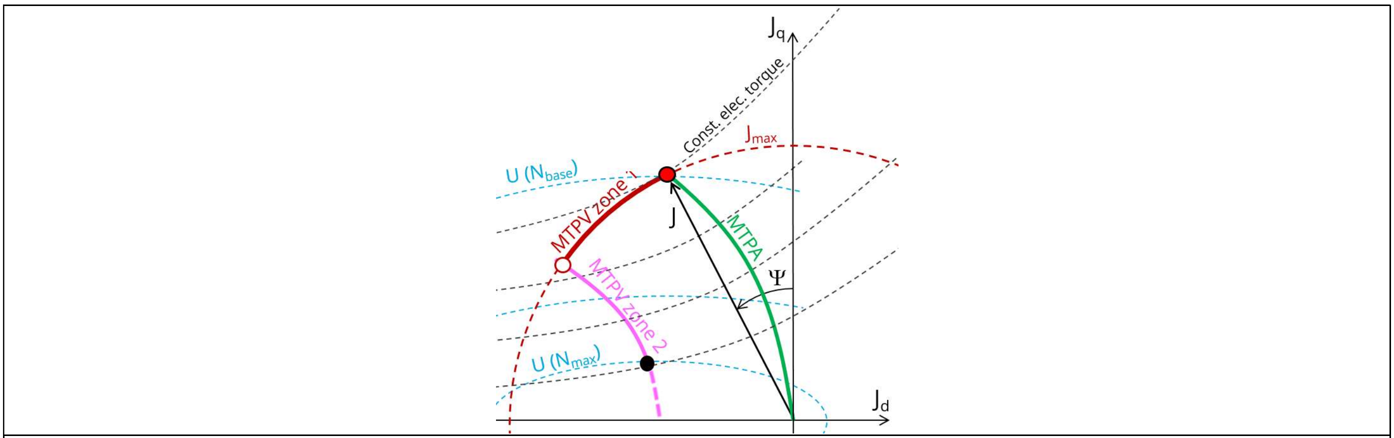
The Maximum Torque Per Voltage command mode (MTPV) allows to compute the torque-speed curve which corresponds to the maximum potential of mechanical torque (or mechanical power) of a motor from the base speed point to the maximum speed point.
This command mode shows the full potential of the machine, 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.
Upstream 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).



Torque speed curve with MTPV command mode

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”.



Evaluation of the working point in J_d-J_q plane by considering iso-torque, iso-current and iso-voltage

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).

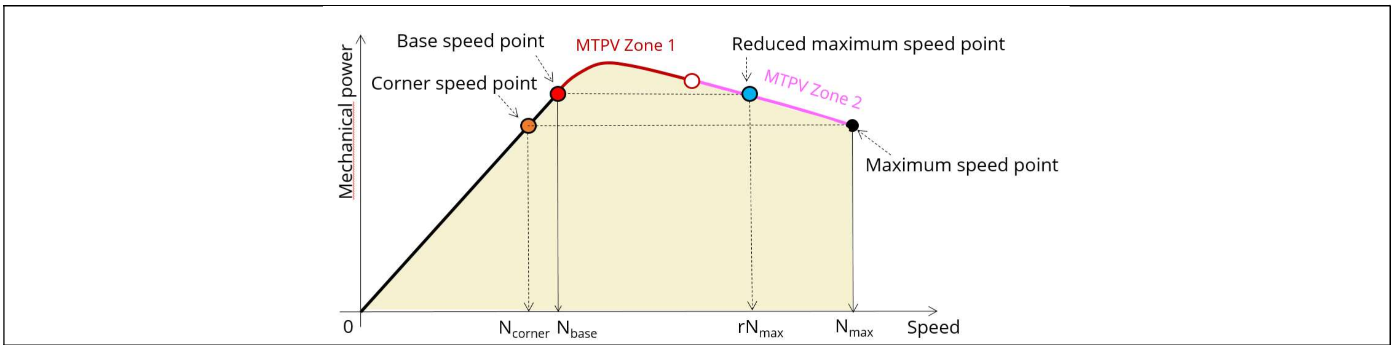
$$U = U_{max}$$
$$I < I_{max}$$

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 to maximize 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.



Mechanical power with MTPV command mode

Thanks to the MTPV results we can easily deduce 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 are able to 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.

1.3.2.2 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 = Imax)

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).

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)
- Line current less than or equal to the maximum allowed value (I ≤ Imax)
- The maximum speed set by the user (N=Nmax.)

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).

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 = Umax.)
- Line current less than or equal to the maximum allowed value (I ≤ Imax.)
- 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).

3) No speed working point

The third step consists to compute 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 ≤ U max)
- Line current less than or equal to the maximum allowed value (I ≤ Imax)
- A null speed
- Imposed torque equal to the base speed torque (T=T(Nb)) if Nb < Nmax. or equal to the maximum speed torque (T = T(Nmax.)) if Nb > Nmax.

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).
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(Nb) if Nb < Nmax. or T = T(Nmax.) if Nb > Nmax.
- Imposed speed with N ∈]0, Nb[
- Line-Line voltage less than or equal to the maximum allowed value (U ≤ U max)
- Line current less than or equal to the maximum allowed value (I ≤ Imax)

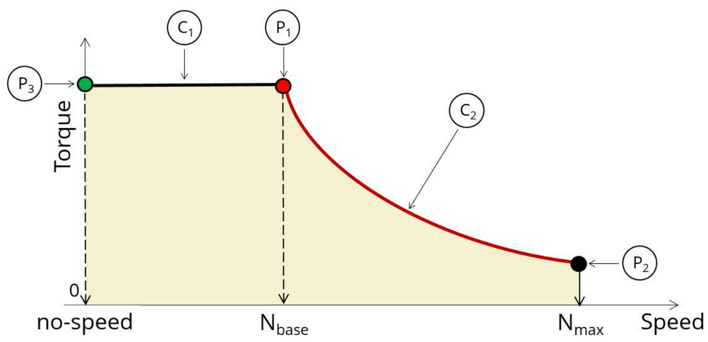
The variable parameters are the D-axis and the Q-axis components of the phase current (j_d, j_q).

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

Then, the last step consists of computing the torque-speed curve over the speed range] Nb, 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∈]Nb , Nmax [
- Line-Line voltage equal to the maximum allowed value (U = Umax)
- Line current less than or equal to the maximum allowed value (I ≤ Imax)

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).



MTPV command modes – Torque-speed curve computation process

P_1	**Base speed point**	Target: Maximum torque (T_{max})
	Constraints	I = I_{max}, U=U_{max},
	Variable parameters	J_d, J_q, Speed (N)
P_2	**Max. speed point**	Target: Maximum torque (T_{max})
	Constraints	I ≤ I_{max} U=U_{max} Speed = Maximum speed ($N_{max.}$)
	Variable parameters	J_d, J_q
P_3	**Null speed point**	Target: maximum efficiency
	Constraints	I ≤ I_{max} U ≤ U_{max} Speed = N = 0 Torque = base speed torque (T(N_b))
	Variable parameters	J_d, J_q
C_1	**Low speed zone**	Target: maximum efficiency
	Constraints	I ≤ I_{max} U ≤ U_{max} Speed ∈]0, N_b[Torque = base speed torque (T(N_b))
	Variable parameters	J_d, J_q
C_2	**High speed zone**	Target: maximum torque (T_{max})
	Constraints	I ≤ I_{max} U = U_{max} Speed N ∈]N_b, $N_{max.}$[
	Variable parameters	J_d, J_q

1.3.2.3 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 ≤ U max)
- Line current less than or equal to the maximum allowed value (I ≤ Imax)
- 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).

2) Maps at no torque

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

3) Maps at no-speed and no-torque

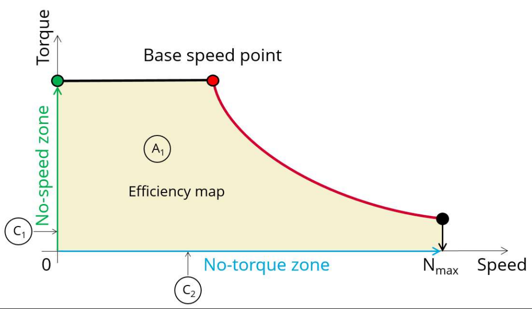
When speed and torque are null all the quantities are equal to 0.

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 ∈[0, Nmax]
- Imposed torque with T ∈[0, Tb]
- Line-Line voltage less than or equal to the maximum allowed value (U ≤ U max)
- Line current less than or equal to the maximum allowed value (I ≤ 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

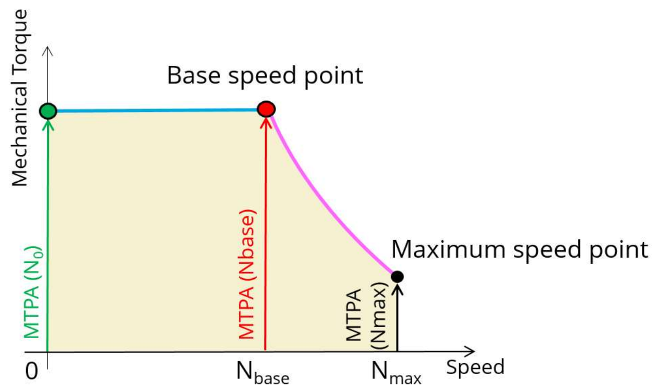
C_1	**Null speed zone**	Target: Minimum Joule losses
	Constraints	$I \leq I_{max}$, $U \leq U_{max}$, Speed N = 0 User torque (got by user’s discretization)
	Variable parameters	J_d, J_q
C_2	**Null torque zone**	
	Only iron losses and mechanical losses are computed All other quantities are set to 0, even the efficiency.	
A_1	**Efficiency map**	Target: Maximum efficiency
	Constraints	$I \leq I_{max}$ $U \leq U_{max}$ Targeted speed (got by user’s discretization) Targeted torque (got by user’s discretization)
	Variable parameters	J_d, J_q

1.3.3 Maximum Torque Per Amps command mode – MTPA

1.3.3.1 Positioning and objective

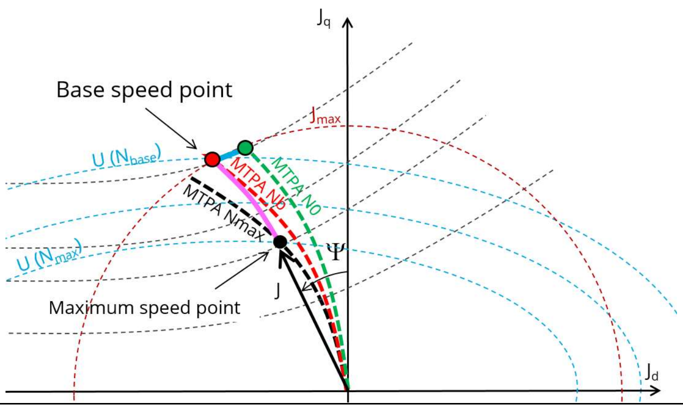
The Maximum Torque Per Ampere command mode "MTPA" is one of the easiest to implement in terms of drive and control. That is why this command mode is still frequently used, especially for low-cost applications.

In FluxMotor®, the "MTPA" command mode is applied to compute the torque-speed curve and maps mainly thanks to MTPA curves function of the speed. More details on the global process of computation are presented in the next section.



Torque speed curve with MTPA command mode

In FluxMotor®, we consider not just one MTPA curve but as many MTPA curves as speed discretization imposed by the user.
In fact, mechanical torque is function of the current magnitude but also of the speed according to iron losses, mechanical losses, magnet losses (neglected in FluxMotor®) etc.
So, it is more rigorous to consider one MTPA curve for each speed.



Evaluation of the working point in Jd-Jq plane
by considering iso-torque, iso-current and iso-voltage

In most of the case, losses function of current and speed (iron losses, magnet losses…) are just some percent of total losses. For such cases, MTPA curves are very close each other.
For some cases, losses function of current and speed dominate, so, MTPA curves present significant variations each other as in the figure above.

1.3.3.2 Torque-speed curve – Computation and displaying

1) Base speed point

The first step consists of computing the base speed point (Red point in the next image shown below).
The computation method is the same as the one which described for the MTPV command. In fact, the base speed point is the same in both the command: MTPV or MTPA.

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 (integrating MTPA curves) and the variable parameters are the speed N, the D-axis and the Q-axis component of the phase current (J_d, J_q).

2) Maximum speed point

The second step consists in verifying that the maximum speed set by the user ($N_{max.}$) is reachable (black point in 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 ≤ Imax)
- The maximum speed set by the user (N = Nmax)

An MTPA curve is used, and variable parameters are the D-axis and the Q-axis components of the phase current (j_d, j_q). The identification is done by interpolation of data on MTPA curves.

When the user maximum speed is reachable, a working point will be found on the MTPA curve and the torque-speed curve identification process continues.
Sometimes, the maximum speed set by the user is unreachable by the machine according to its own limitation. In this case, a computation of a reachable maximum speed is automatically done.
A correction of the maximum speed could be performed if needed.
The target is to find the maximum reachable speed (N_{max}) considering:

- Line-Line voltage equal to the maximum allowed value (U = Umax)
- Line current less than or equal to the maximum allowed value (I ≤ Imax)
- The useful torque obtained at the base speed divided by ten (T = T(Nb)/10)

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

3) Torque-speed curve in the range [0, N_b[

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

The computation of operating points is done over [0, N_b] when $N_b < N_{max.}$ and over [0, $N_{max.}$] when $N_b > N_{max.}$

The target is to find the mechanical torque corresponding to the base speed T(Nb) on the different MTPA curves which are depending on the speed.

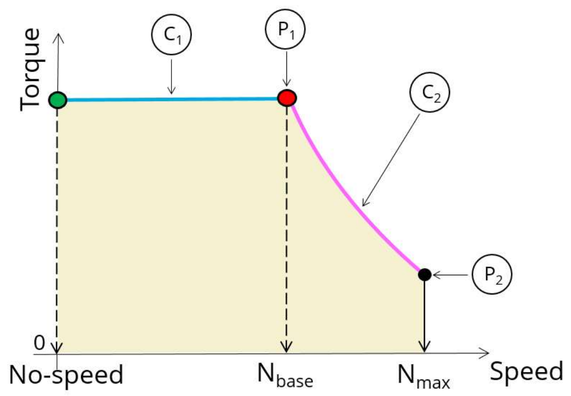
MTPA curves are used, and variable parameters are the D-axis and the Q-axis components of the phase current (J_d, J_q). The identification is done by interpolation of data on MTPA curves (which are depending on the speed).

4) Torque-speed curve in the range]Nb, N_{max} [

Then, the last step consists of computing the torque-speed curve over the speed range]N_b, N_{max}[(Pink line on the picture shown below).
This step is done only if $N_b < N_{max.}$
The target is to find the maximum reachable mechanical torque (T_{max}) considering:

- Imposed speed with N∈]Nb, Nmax [
- Line-line voltage equal to the maximum allowed value (U = Umax)
- Line current less than or equal to the maximum allowed value (I ≤ Imax)

MTPA curves are used, and variable parameters are the D-axis and the Q-axis components of the phase current (J_d, J_q). The identification is done by interpolation of data on MTPA curves (which are depending on the speed).



MTPA command modes – Torque-speed curve computation process

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

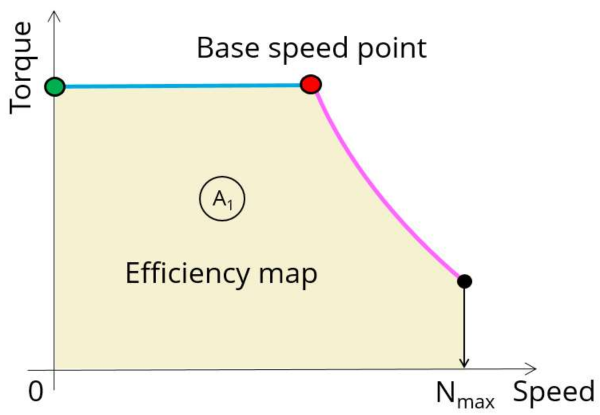
1.3.3.3 Computation and displaying of the efficiency map

Evaluating maps for all the electromagnetic quantities consists of computing the machine performances for each node of a grid bounded by the torque-speed curve. All working points defined by a value of torque and a value of speed are computed over [0, T_b] and [0, N_{max}]. (Yellow part in the image shown below).

For each pair of "Torque - Speed" point, the target is to find the corresponding point on the corresponding MTPA curve:

- 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 ($U \leq U_{max}$)
- Line current less than or equal to the maximum allowed value ($I \leq I_{max}$)

MTPA curves are used, and variable parameters are the D-axis and the Q-axis components of the phase current (J_d, J_q). The identification is done by interpolation of data on MTPA curves.



MTPA command modes – Efficiency map computation process

A_1	**Efficiency map**	Target: MTPA process
	Constraints	$I \leq I_{max}$ $U \leq U_{max}$ $T = T_{target}$ (got by user's discretization) $N = N_{target}$ (got by user's discretization)
	Variable parameters	J_d, J_q

2 PERFORMANCE MAPPING – SINE WAVE – GENERATOR – EFFICIENCY MAP

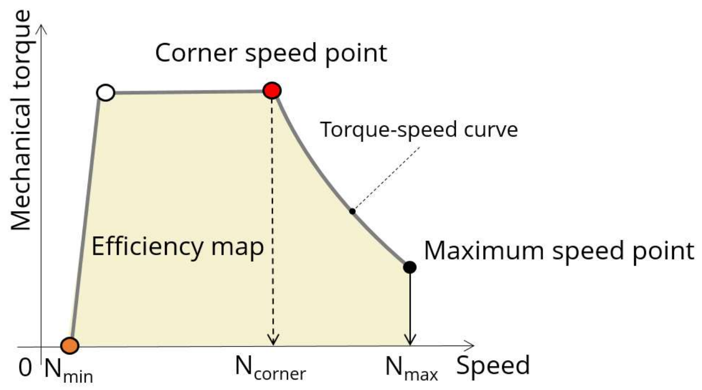
2.1 Overview

2.1.1 Positioning and objective

The aim of the test "**Performance mapping – Sine wave – Generator – Efficiency map**" is to characterize the behavior of the machine in the "Torque-Speed" area.

This test gives an overview of the electromagnetic behavior of the generator as a function of its speed.
Electrical power, mechanical torque, output voltage, electrical current, power balance, power factor and control angle are plotted versus speed.

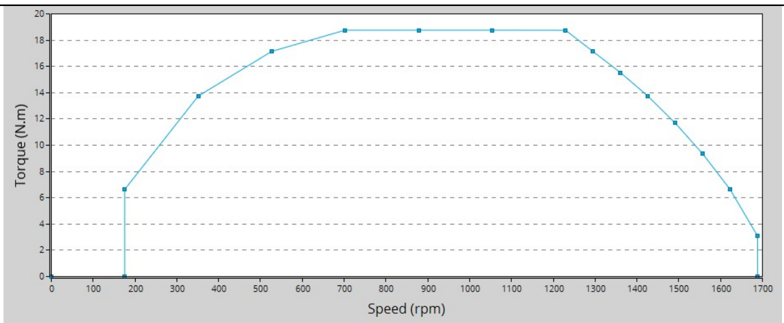
Input parameters define the zone in which the evaluation of the machine behavior is performed.
Input parameters like the "maximum Line-Line voltage", the "maximum line current" and the targeted "Maximum speed" of the machine are considered.
One type of command mode is available: The Maximum Torque Per Amps command mode (MTPA).



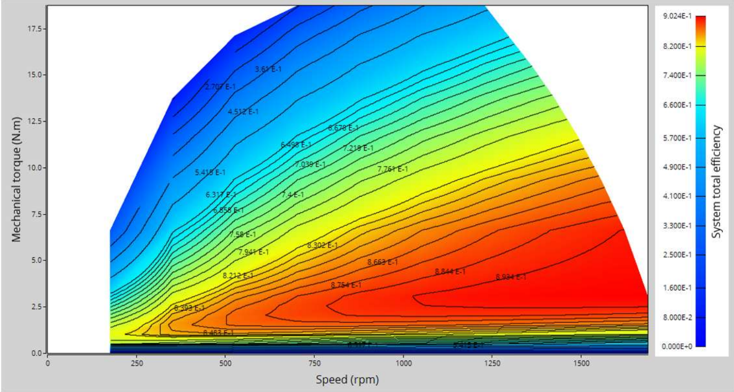
Characterization of the corner speed point on the torque-speed curve

In the results, the performance of the machine at the corner 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.

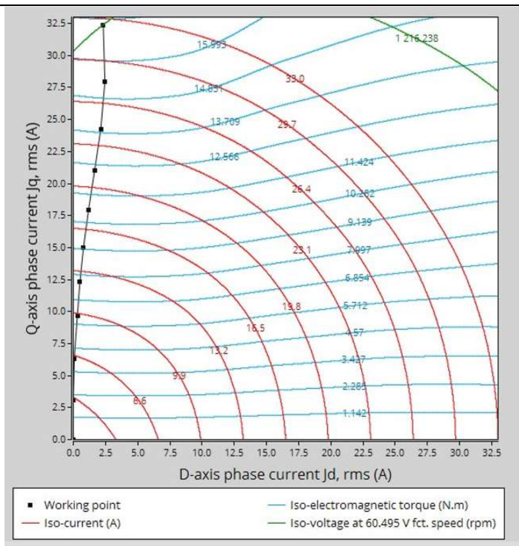


Mechanical torque versus speed - Example



Efficiency in torque-speed area - Example

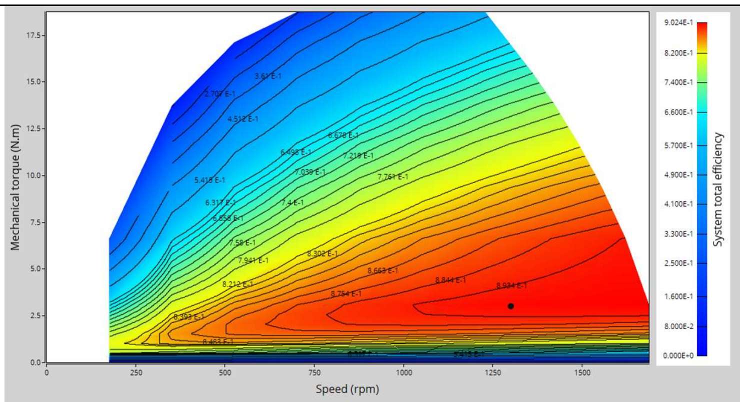
Note In addition, in J_d-J_q plane, a graph shows the working points computed for the torque speed curve. The iso-electromagnetic torque, the iso-current and the iso-voltage are also displayed in J_d-J_q plane.
These results help the user to understand the possible performance of the machine in its electric environment.



Characteristics curves in J_d-J_q area - Example

Moreover, two additional features are available in this test.
The first one allows extracting one 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.

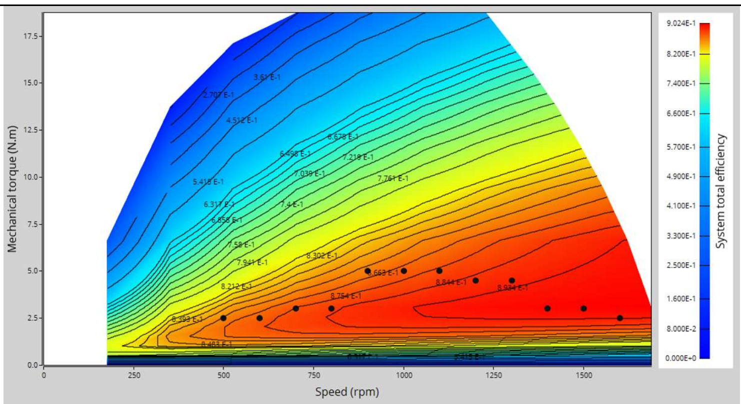


A “single” working point displayed on the efficiency map - Example

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 provided maps.



A “Duty cycle” displayed on the efficiency map - Example

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

Family	Performance mapping
Package	Sine wave
Convention	Generator
Test	Efficiency map

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

2.2 Main principles of computation

2.2.1 Introduction

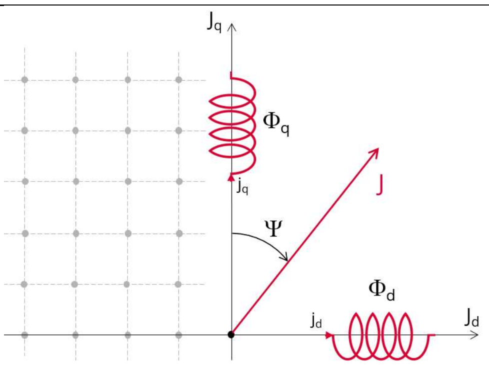
This paragraph deals with the process to get the torque-speed curves and maps (For example - efficiency map).

The process is separated into the two following parts:

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

2.2.2 Raw data and Park's model

The first step consists of computing the raw data which characterize the machine in the J_d-J_q plane. This is done using Finite Element modelling (Flux® – Magnetostatic application).
To do that, a grid of (J_d, J_q) values is considered.
Flux linkage through each phase (Φ_a, Φ_b, Φ_c) and flux density in regions (teeth and yoke of the machine) are computed and extracted as a function of (J_d, J_q).



Raw data – Test "Performance mapping – Sine Wave – Generator – Efficiency map"

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:

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

Park model - Generator convention - Torque equation

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:

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

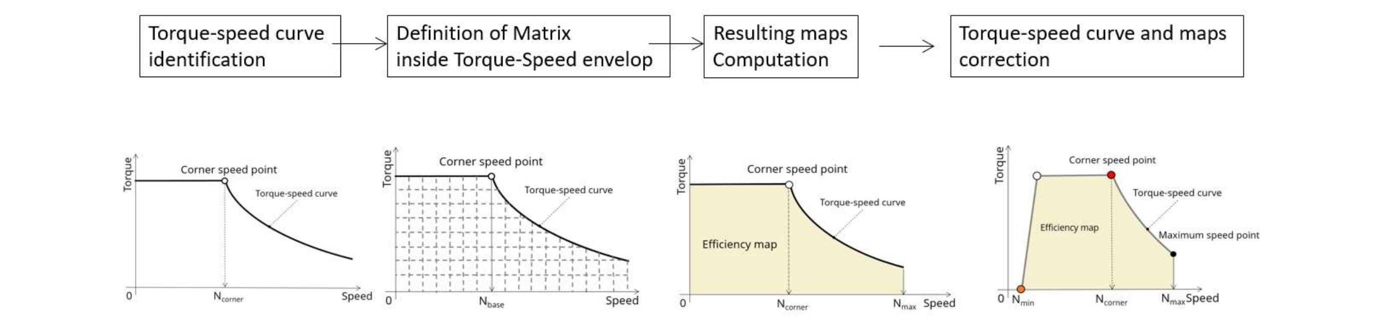
- D-axis flux-linkage component - Φ_d
- Q-axis flux-linkage component - Φ_q
- Electromagnetic torque T_{em}
- Stator iron losses W_{iron} versus speed
- Joule losses in stator winding W_{Cus}

- Mechanical losses versus speed
- Total losses W_{total} versus speed

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

Below are presented the fourth main steps involved in building the efficiency map and other associated results. These steps are similar for all the command modes with only some specifications (for more information, refer to command mode paragraphs).
These steps are performed by using the computed raw data (see previous section) with optimization functions or dedicated functions like MTPA curves (for more information, refer to command mode paragraphs).

- Building of the Torque-speed curve and other associated results
- Define the grid of the torque speed maps
- Building of the maps in torque-speed area
- Torque-speed curves and maps correction



Main steps of the computation algorithm

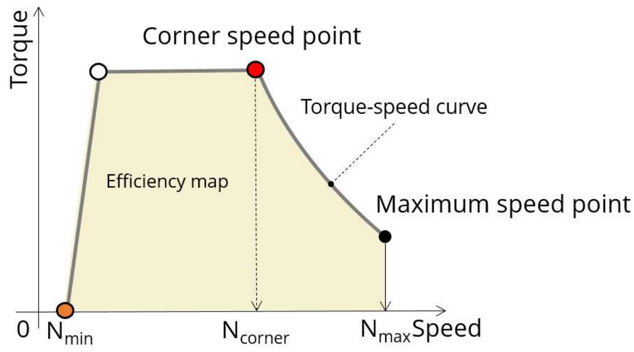
2.3 Command modes

2.3.1 Introduction

The user can choose one type of command mode:

- The Maximum Torque Per Amps (MPTA)

Whatever is the command mode applied, 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…).



Torque-speed curve and efficiency map - Generator operating mode

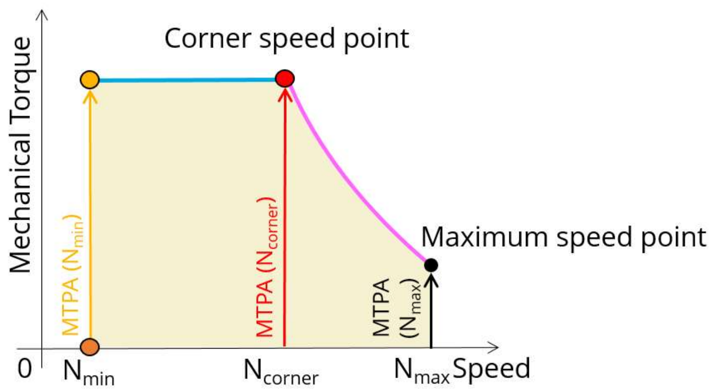
2.3.2 Maximum Torque Per Amps – MTPA

2.3.2.1 Positioning and objective

1) Main concept

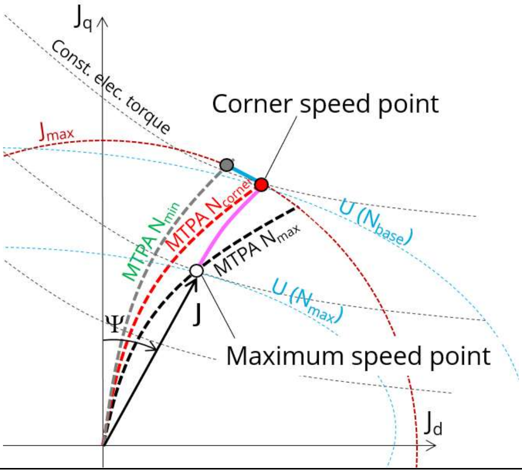
The maximum torque per amps command mode "MTPA" in terms of drive and control, is one of the easiest to implement. That is why this command mode is still used frequently, especially for low cost applications.

In FluxMotor®, the "MTPA" command mode is applied to compute the torque-speed curve and maps mainly thanks to MTPA curves function of the speed (more details on the global process of computation are presented in the next section).



Torque speed curve with MTPA command mode – Generator operating mode

In FluxMotor®, we consider not just one MTPA curve but as many MTPA curves as speed discretization imposed by the user.
In fact, the mechanical torque is function of current magnitude but also of the speed according to iron losses, magnet losses (neglected in FluxMotor®).
So, it is more rigorous to consider one MTPA curve for each speed.



Evaluation of the working point in Jd-Jq plane
by considering iso-torque, iso-current and iso-voltage

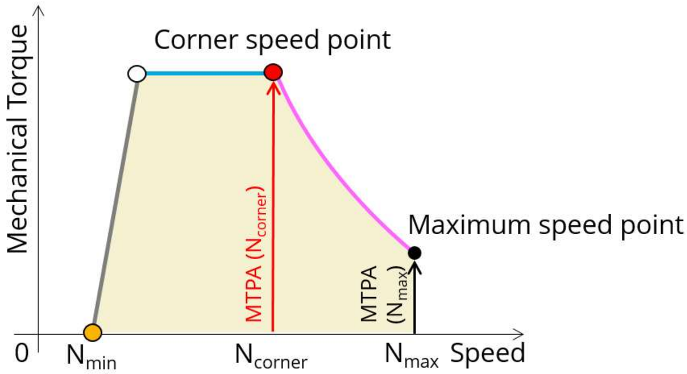
In the most of case, losses function of current and speed (iron losses, magnet losses etc) are just some percent of total losses. For such cases, MTPA curves are very close to each other.
For some cases, losses function of current and speed dominate, so, MTPA curves present significant variations each other as in the figure above.

2) Minimum speed point

Note that, in generator operating mode, a minimum speed is needed to be able to supply electrical current.

In fact, mechanical power provided on the shaft must be higher than losses otherwise the electrical power is negative and no current can be supplied by the generator

This aspect is considered in FluxMotor® process and according to the discretization in speed imposed by the user, a minimum speed able to supply electrical current is deduced.
Higher is the discretization of speed, more accurate is the computed “minimum speed” but higher is the computation time.
With a high discretization we get results as presented below:

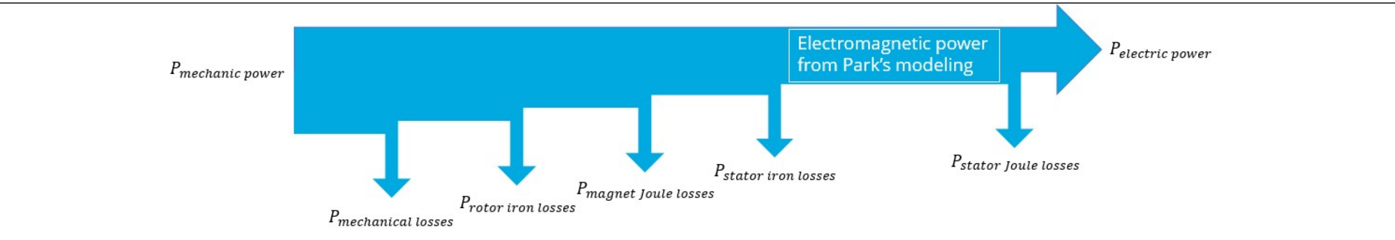


Torque speed curve with MTPA command mode – Generator operating mode
High discretization of speed

3) Corner speed point and constant mechanical torque part

In generator operating mode, we speak about “Corner speed point” while in motor operating mode, we speak about “Based speed point”. In FluxMotor® terminology, the last working point of the constant torque part of the torque-speed curve is called “Base speed point” only if it is obtained for the maximum allowed line-line voltage and maximum line current. If it is not in the case, we called as “Corner speed point”.

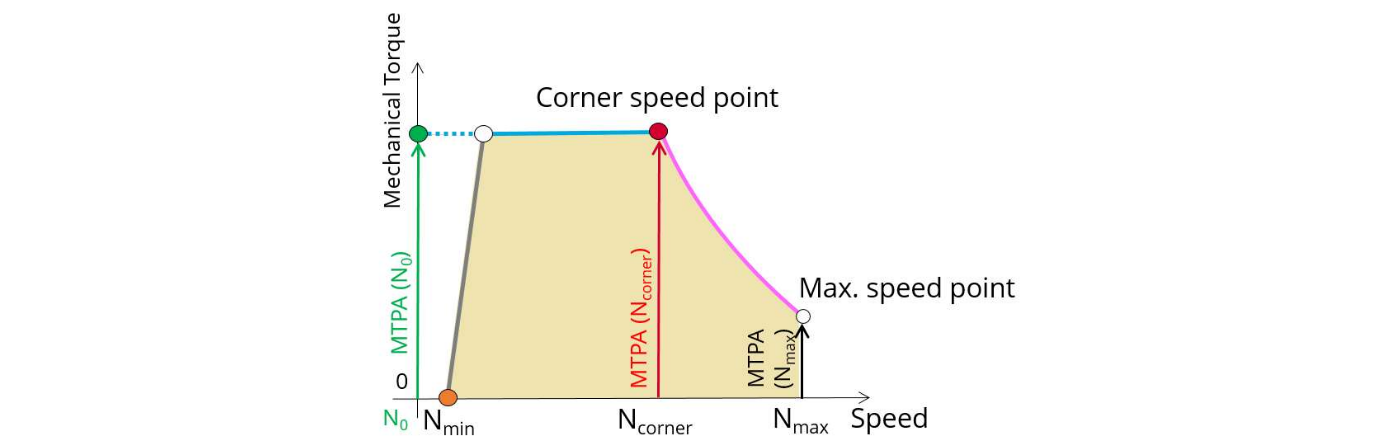
In generator operating mode, with FluxMotor® process, the mechanical power and the electric power are computed from the electromagnetic power (obtained with Park’s model) following the power balance presented by the figure below.



Power balance in generator operating mode – FluxMotor® process

When we work with a maximum current and with a control angle for maximizing the electromagnetic torque (maximize the electromagnetic power obtained with Park’s model), the mechanical torque will increase with the speed because some losses (like iron and mechanical losses) increase with the speed.

According to this point, it can provide a torque-speed curve with a reachable constant mechanical torque part at low speed, the process of computation imposed us to reach the value of no-speed mechanical torque at the corner speed point.



Torque speed curve with MTPA command mode – Generator operating mode – Corner speed point and constant torque part

Note: The computed torque at no-speed corresponds to an unavailable working point in generator operating mode, it is just used in the process for computing the corner speed point and the constant mechanical torque part.

2.3.2.2 Torque-speed curve – Computation and displaying

1) No-speed point

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

The target is to find the maximum reachable mechanical torque (T_{max}) considering:
- Line-line voltage less than or equal to the maximum allowed value (U ≤ U max)
- The maximum allowed line current (I = Imax)

MTPA curve at no-speed is used, and variable parameters are the D-axis and the Q-axis components of the phase current (J_d, J_q). The identification is done by interpolation of data on MTPA curves.

Note: The computed torque at no-speed corresponds to an unavailable working point in generator operating mode, it is just used for the process of computation of the corner speed point and of the constant mechanical torque part.

2) Corner speed point

The second step consists of computing the corner speed point (Red point in the next image shown below).

The target is to find the maximum reachable speed (N_{max}) considering:
- Line-Line voltage equal to the maximum allowed value (U = Umax)
- Line current less than or equal to the maximum allowed value (I ≤ Imax)
- The Mechanical torque obtain at no-speed (T = T(N0))

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

3) Maximum speed point

The third step consists of verifying that the maximum speed set by the user (N_{max}) is reachable (Black point in the image shown below).

The target is to find the maximum reachable torque (T_{max}) considering:
- The maximum allowed Line-Line voltage (U = Umax)
- The maximum allowed line current (I ≤ Imax)
- The maximum speed set by the user (N = Nmax)

An MTPA curve is used, and variable parameters are the D-axis and the Q-axis components of the phase current (J_d, J_q). The identification is done by interpolation of data on MTPA curves.

If the user maximum speed is reachable, it will be found on the MTPA curve and the Torque-speed curve identification process continues. Sometimes, the maximum speed set by the user is unreachable by the machine. In this case, a computation of a reachable maximum speed is automatically done.

The second step can include the correction of the maximum speed if needed as previously explained.

The target is to find the maximum reachable speed (N_{max}) considering:
- Line-line voltage equal to the maximum allowed value (U = Umax)
- Line current less than or equal to the maximum allowed value (I ≤ Imax)
- The mechanical torque obtained at the corner speed point divided by ten (T = T(Nc)/10)

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

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

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

The computation of operating points is done over]0, N_c[if «$N_c < N_{max}$» but over]0,N_{max}[if «$N_c > N_{max}$».

The target is to find the corner speed mechanical torque (T_c) on MTPA curves for each speed.

MTPA curves are used, and variable parameters are the D-axis and the Q-axis components of the phase current (J_d, J_q). The identification is done by interpolation of data on MTPA curves.

Note: At low speed, some computed working points can be unreachable in generator operating mode, (resulting negative electrical power). In this case, a correction is done, see the last subsection 2.3.2.4 (Torque-speed curves and maps correction).

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

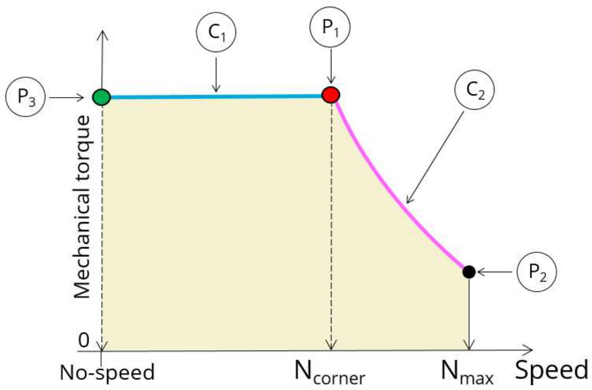
Then, the last step consists of computing the torque-speed curve over the speed range $]N_c, N_{max}[$ (Pink line in the image shown below). This step is done only if $N_c < N_{max}$.

The target is to find the maximum reachable torque (Tmax) considering:

- Imposed speed with N∈]Nc, Nmax [
- Line-Line voltage equal to the maximum allowed value (U = Umax)
- Line current less than or equal to the maximum allowed value (I ≤ Imax)

MTPA curves are used, and variable parameters are the D-axis and the Q-axis components of the phase current (J_d, J_q). The identification is done by interpolation of data on MTPA curves.

Note: At high speed, some computed working points can be unreachable in generator operating mode, (resulting negative electrical power). In this case, a correction is done, see the last subsection 2.3.2.4 (Torque-speed curves and maps correction).



MTPA command modes – Torque-speed curve computation process

P_3	**No-speed point**	Target: Maximum mechanical torque ($T_{max.}$)
	Constraints	$I = I_{max}$ $U \leq U_{max}$
	Variable parameters	J_d, J_q
P_1	**Corner speed point**	Target: Maximum speed (N_{max})
	Constraints	$I \leq I_{max}$ $U = U_{max}$ $T = T(N_0)$
	Variable parameters	J_d, J_q, Speed
P_2	**Max. speed point**	Target: Maximum mechanical torque ($T_{max.}$)T)
	Constraints	$I \leq I_{max}$ $U = U_{max}$ $N = N_{max}$
	Variable parameters	J_d, J_q
C_1	**Low speed zone**	Target: $T = T_b$
	Constraints	$I \leq I_{max}$ $U \leq U_{max}$ $N \in [0, N_b[$
	Variable parameters	J_d, J_q
C_2	**High speed zone**	Target: Maximum mechanical torque ($T_{max.}$)
	Constraints	$I \leq I_{max}$ $U = U_{max}$ $N \in]N_b, N_{max}[$
	Variable parameters	J_d, J_q

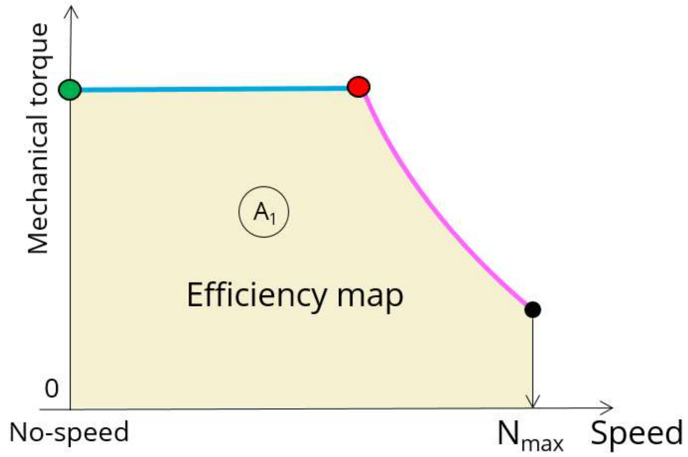
2.3.2.3 Efficiency map – Computation and displaying

Evaluating maps for all the electromagnetic quantities consists of computing the machine performance for each node of a grid bounded by the torque-speed curve. All working points defined by a value of torque and speed are computed over [0, T_c] and [0, N_{max}]. (Yellow part in the image shown below).

For each pair of “Torque - Speed” point, the target is to find the corresponding point on the corresponding MTPA curve:

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

MTPA curves are used, and variable parameters are the D-axis and the Q-axis components of the phase current (J_d, J_q). The identification is done by interpolation of data on MTPA curves.

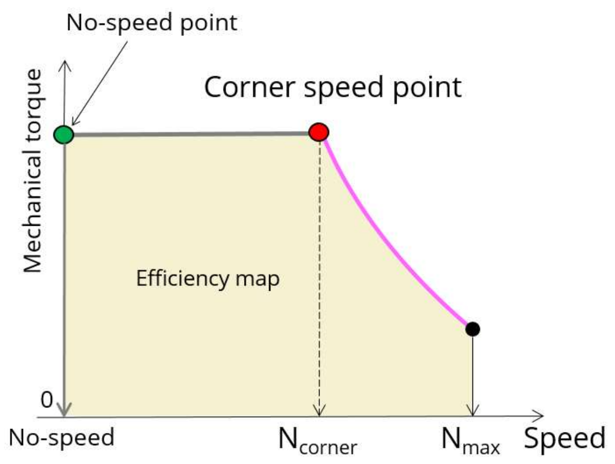


MTPA command modes – Efficiency map computation process		
A1	**Efficiency map**	Target: MTPA process
	Constraints	$I \leq I_{max}$ $U \leq U_{max}$ $T = T_{target}$ (got by user discretization) $N = N_{target}$ (got by user discretization)
	Variable parameters	J_d, J_q

Note: At low and high speed, some computed working points can be unreachable in generator operating mode, (resulting negative electrical power). In this case, a correction is done, see the last subsection 2.3.2.4 (Torque-speed curves and maps correction).

2.3.2.4 Torque-speed curves and maps correction

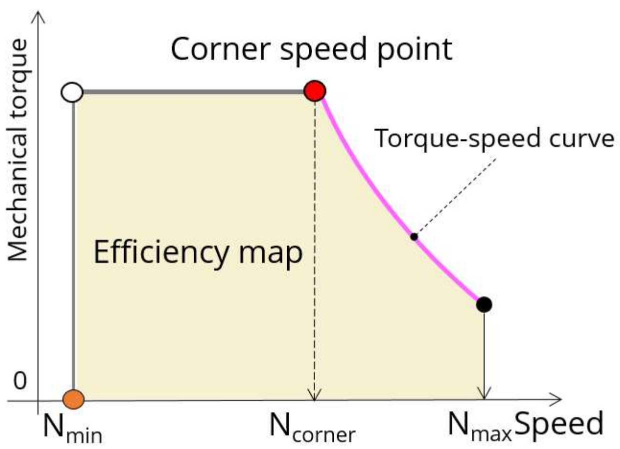
As seen in the two previous subsections, the torque-speed curves and maps are computing in all the torque and speed ranges as show bellow:



Torque speed curves and maps with MTPA command mode before correction of unreachable generator working points

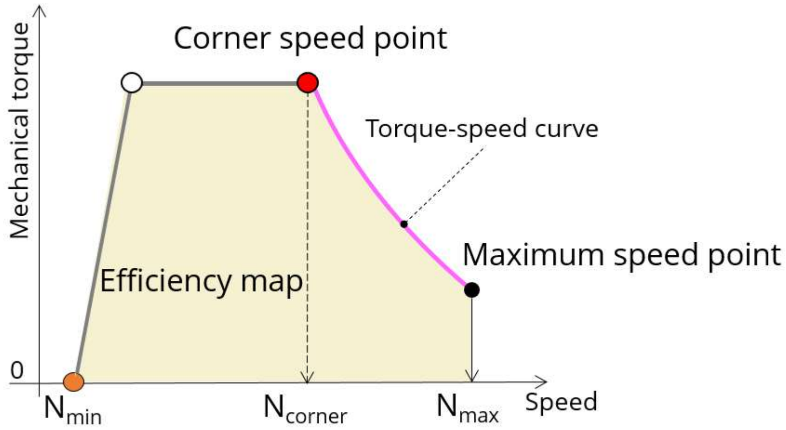
As seen previously, in generator operating mode, a minimum speed is needed to make the generator able to supply an electrical current. Mechanical power (i.e. mechanical torque and speed) must be higher than losses otherwise the electrical power is negative and no electrical current is supplied.
At low speed, a minimum speed limit always exists to make the generator able to supply electrical current. In FluxMotor® this limit is called "Minimum speed point".

So, after the computation of the overall torque speed curves and maps a correction is done by detecting all the working points with negative electrical power. These points are considered as unreachable, and the resulting torque-speed curves and maps look like as the following figure:



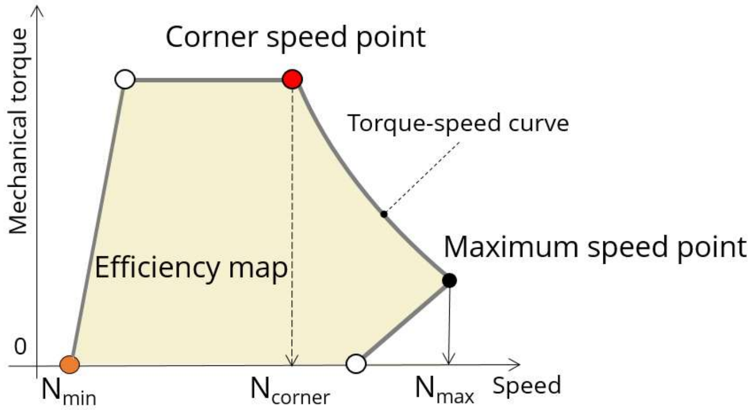
Torque speed curves and maps with MTPA command mode after correction of unavailable generator working points

Higher is the discretization of speed, more accurate is the computed "minimum speed" but higher is the computation time.
With a high discretization we obtain results as presented below:



Torque speed curves and maps with MTPA command mode after correction of unavailable working points

Additional unreachable working points can exist. In this case, the resulting torque speed curves and maps look as the following figure:



Machine with high losses at high speed
Torque speed curves and maps with MTPA command mode after correction of unavailable working points