SERVO MOTORS AND MOTION CONTROL SYSTEMS
(Electrical Machine and Load Characteristics, Stable Operating Points and Motor Selection-Lecture 3)

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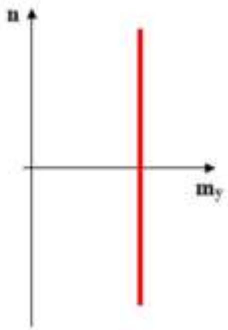
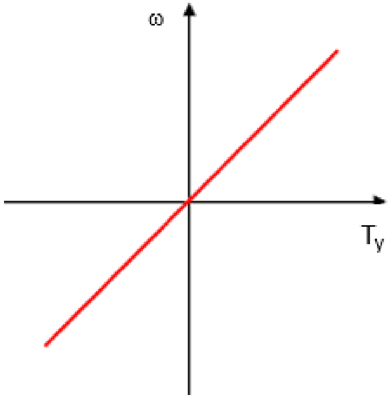
LOAD TYPES AND TORQUE-SPEED CHARACTERISTICS

Gravity



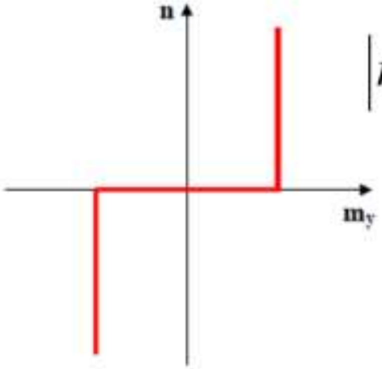
$$m_y = const.$$

Viscous Friction



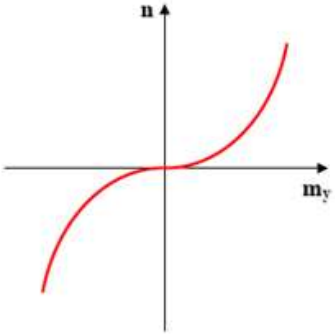
$$T_y \sim \omega$$

Dry Friction



$$|m_y| = const.$$

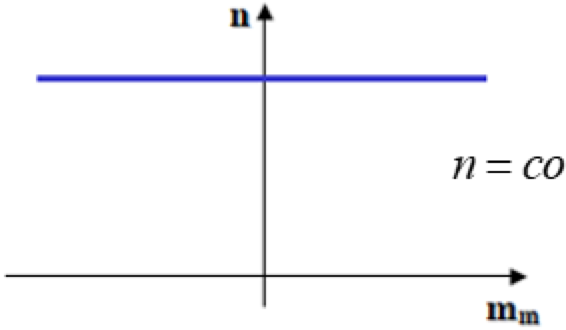
Turbulence



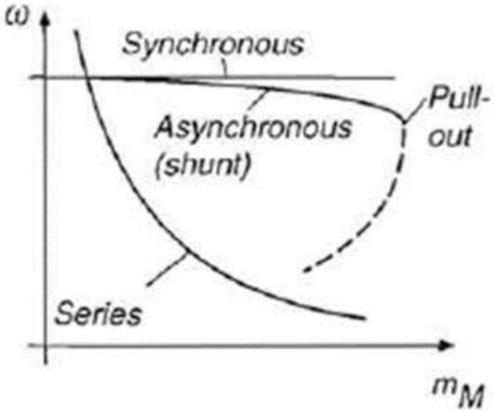
$$m_y \sim n^2$$

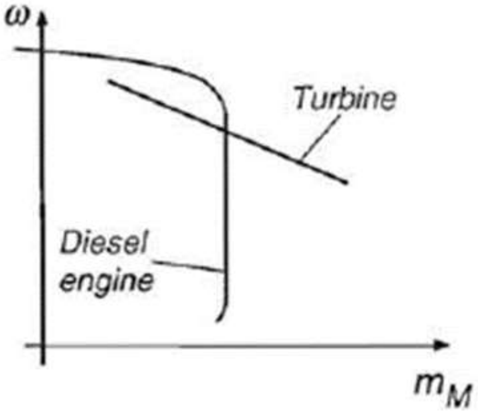
MOTOR TORQUE CHARACTERISTICS

Synchronous

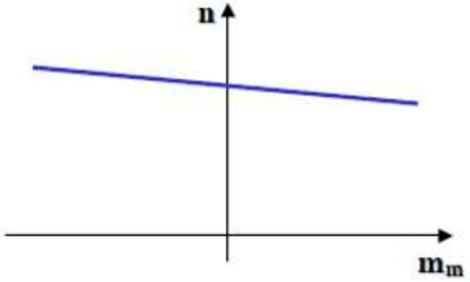


$$n = const.$$



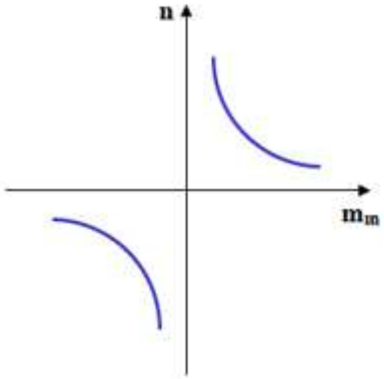


Shunt



$$n = -k \cdot m_m + n_0$$

Serial

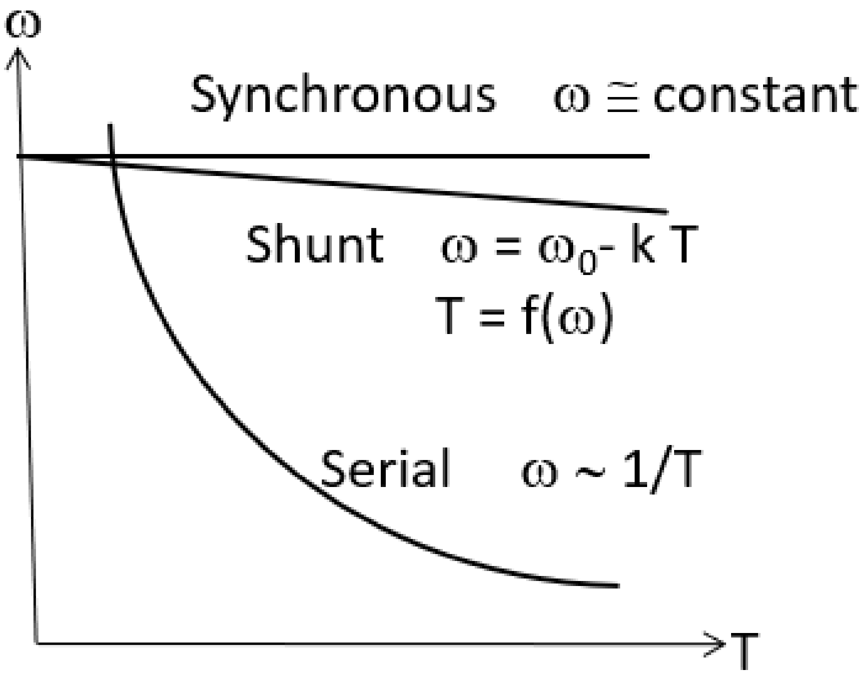


$$n \sim \frac{1}{m_m}$$

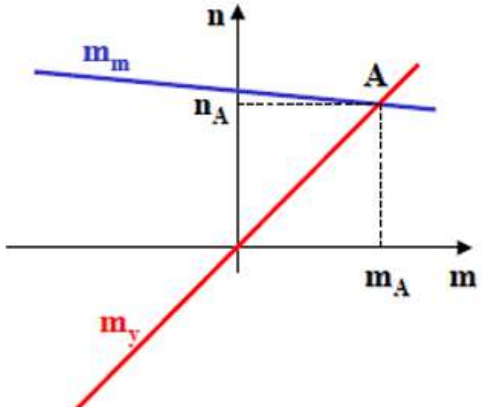
Operating Point

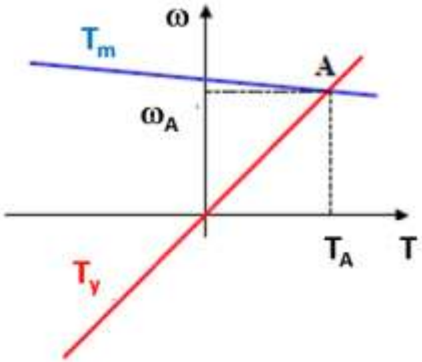
The point in the speed-torque curve where a motor operates in a continuous regime at a **constant speed** with a motor torque equal to all mechanical load effects on the mechanism connected to it is the operating point.

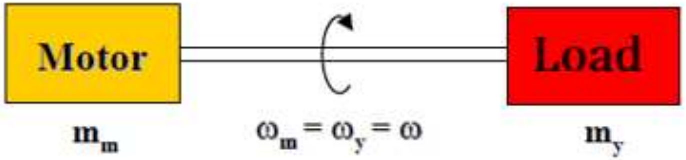
The operating point is the intersection point of the motor and load curves drawn on the speed-torque characteristic.



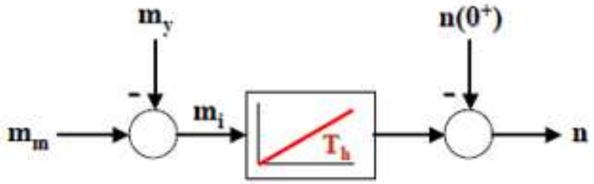
The steady-state operating point of the system, which consists of a viscous friction load and a shunt characteristic motor that moves it, is point A.

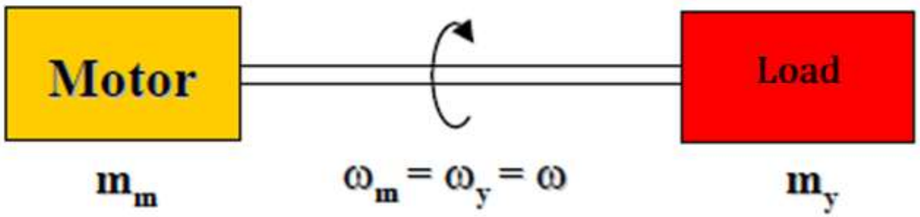




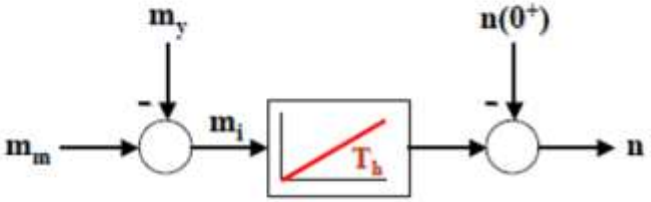


$$\boxed{m_m - m_y = m_i = J\frac{d\omega}{dt} = \frac{2\pi \cdot J}{60}\frac{dn}{dt}}$$





$$\boxed{m_m - m_y = m_i = 0 \rightarrow m_m = m_y \rightarrow n = const.}$$



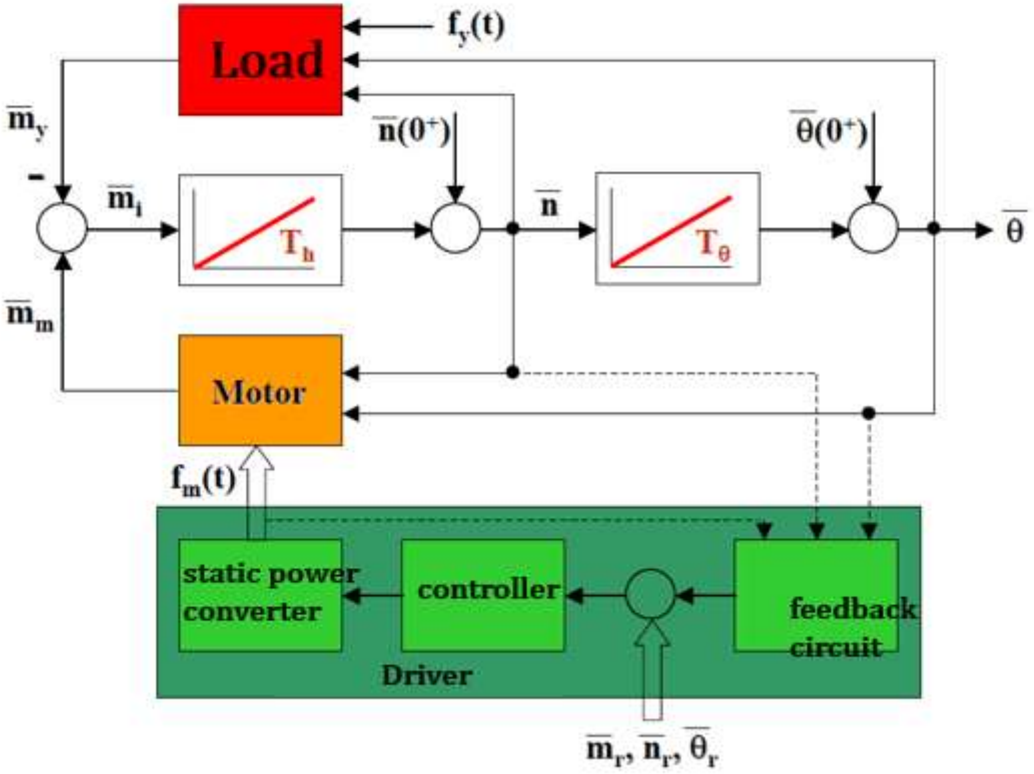
$$m_m - m_y = J\frac{d\omega}{dt} \quad \Big|:M_n$$

$$\frac{m_m}{M_n} - \frac{m_y}{M_n} = \frac{2\pi \cdot J \cdot N_{0n}}{60 \cdot M_n}\frac{d}{dt}\left(\frac{n}{N_{0n}}\right)$$

$$\overline{m}_m - \overline{m}_y = \frac{2\pi \cdot J \cdot N_{0n}}{60 \cdot M_n}\frac{d\overline{n}}{dt} = T_h\frac{d\overline{n}}{dt}$$

acceleration time constant

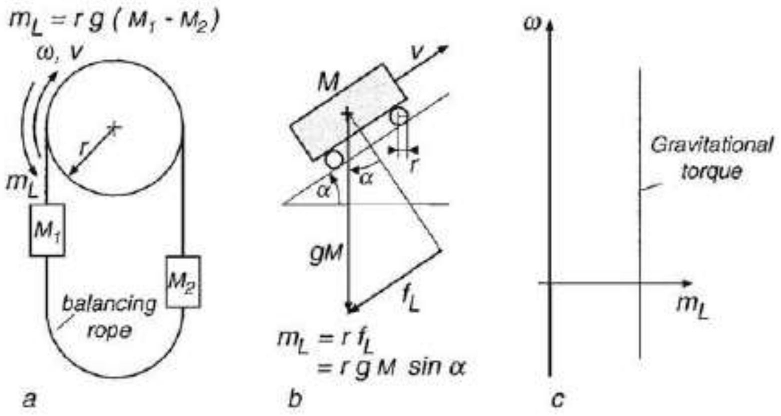
$$T_h = \frac{2\pi \cdot J \cdot N_{0n}}{60 \cdot M_n}\ [s]$$

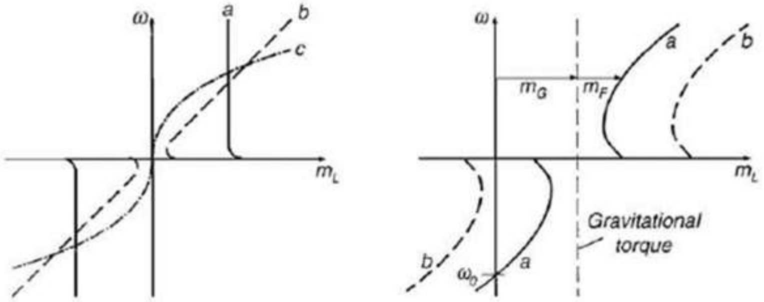


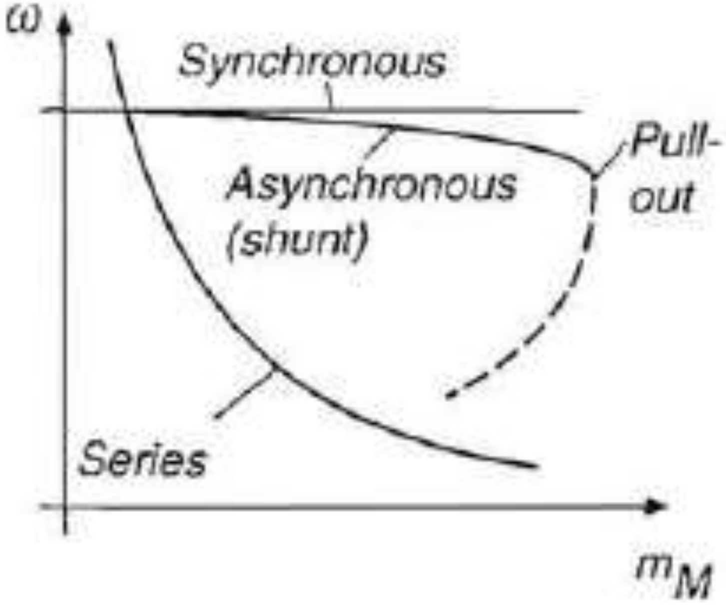
$$T_h = \frac{2\pi \cdot J \cdot N_{0n}}{60 \cdot M_n} \quad [s]$$

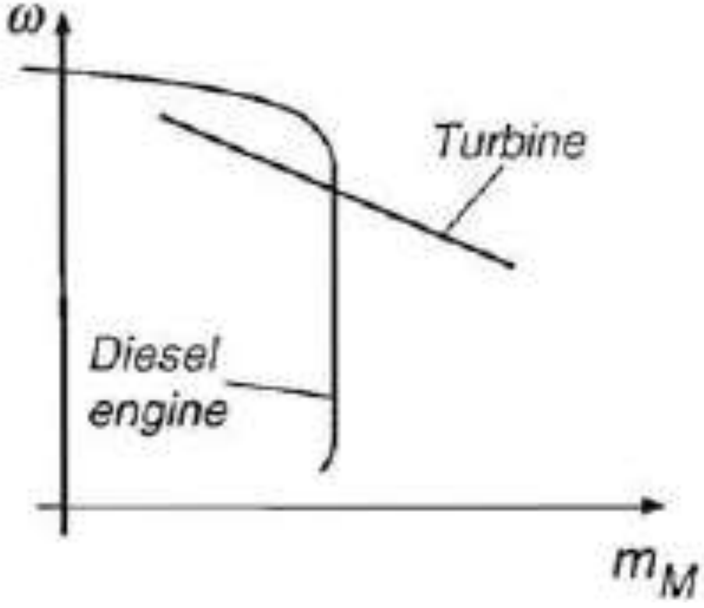
Objective: To reduce the acceleration time constant

J / M_n ↓


m_L = r g (M_1 - M_2)
ω, v
r
m_L
M_1
M_2
balancing rope
a
M
v
r
α
α
gM
f_L
m_L = r f_L
= r g M sin α
b
ω
Gravitational torque
m_L
c


ω
a
b
c
m_L
ω
a
b
m_G
m_F
m_L
Gravitational torque
b
ω_0
a





$$T_m(\omega) - T_y(\omega) = J\frac{d\omega}{dt}$$

Stable and Unstable Operating Points

System dynamic equation in the servo system where all load effects are collected as Ty:

$$T_m(\omega) - T_y(\omega) = J\frac{d\omega}{dt}$$

Steady-State Condition

$$T_m(\omega) = T_y(\omega) \qquad T_m(\omega_1) = T_y(\omega_1); \quad \omega = \omega_1$$

<u>Stability test of operating point:</u>

If $\omega=\omega 1+\Delta\omega$ deviation occurs in the speed of the engine operating at point $\omega 1$

$$T_m(\omega_1 + \Delta\omega) - T_y(\omega_1 + \Delta\omega) = J\frac{d(\omega_1 + \Delta\omega)}{dt} = J\frac{d\,\Delta\omega}{dt}$$

If it is linearized around $\omega = \omega_1$
and the first terms are taken into account:

$$J\frac{d(\omega_1+\Delta\omega)}{dt} = \left.\frac{\partial T_m}{\partial \omega}\right|_{\omega=\omega_1}\Delta\omega - \left.\frac{\partial T_y}{\partial \omega}\right|_{\omega=\omega_1}\Delta\omega$$

Taylor Series Expansion (First Order Approximation)

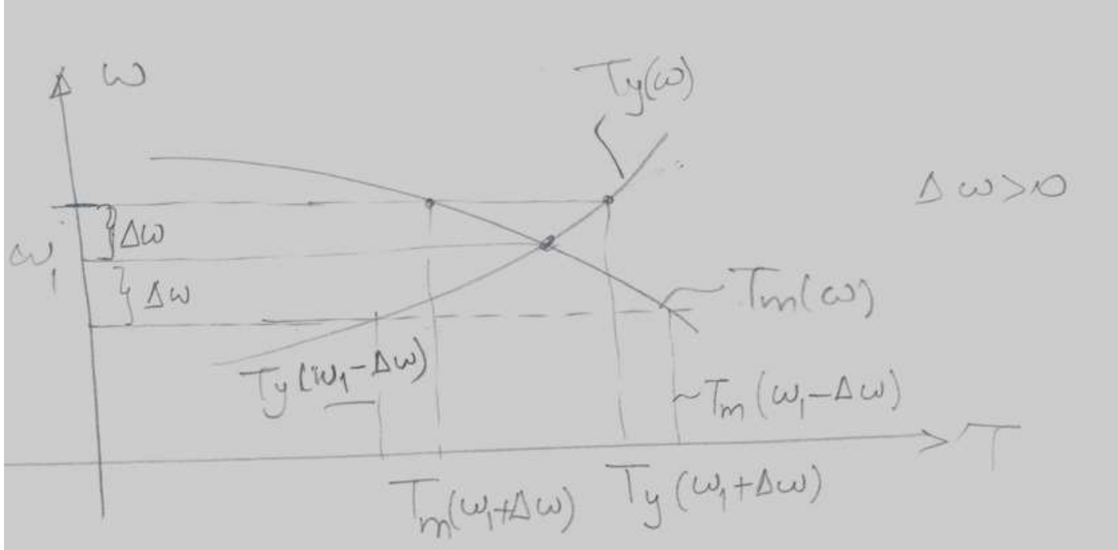
$$J\frac{d\Delta\omega}{dt} = \Delta\omega \left.\underbrace{\left[\frac{\partial T_m}{\partial \omega} - \frac{\partial T_y}{\partial \omega}\right]}_{-k}\right|_{\omega=\omega_1}$$

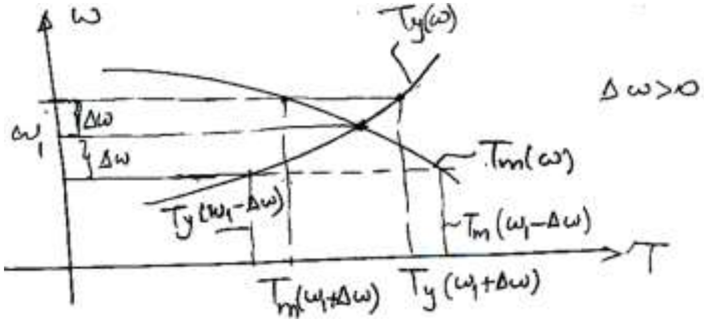
$$J\frac{d\Delta\omega}{dt} + k\Delta\omega = 0$$

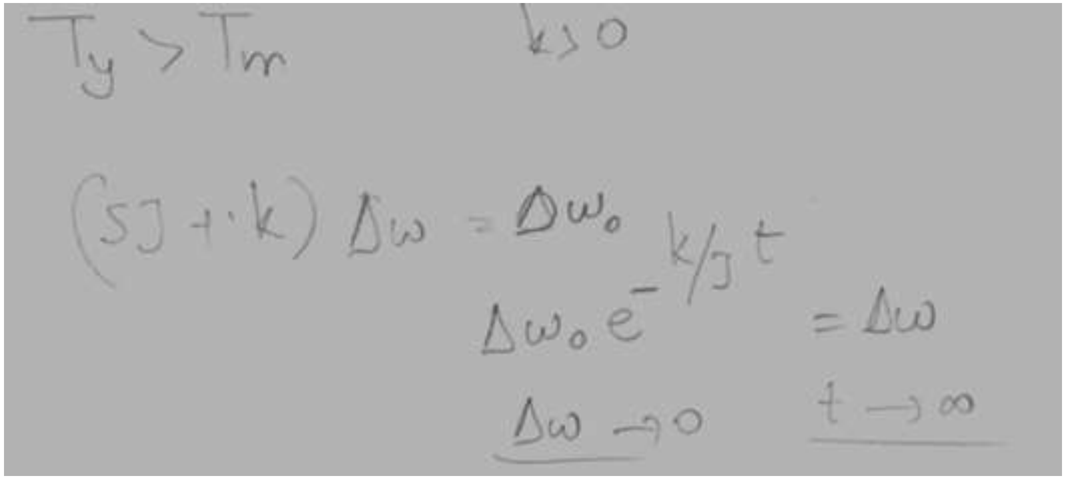
$$k \succ 0 \Rightarrow \omega_1\_is\_stable\_po\mathrm{int}$$

$$k \prec 0 \Rightarrow \omega_1\_is\_unstable\_po\mathrm{int}$$

$$k = \left.\left(\frac{\partial T_y}{\partial \omega} - \frac{\partial T_m}{\partial \omega}\right)\right|_{\omega=\omega_1}$$






$T_y > T_m$ $\quad k > 0$

$$(sJ + k)\,\Delta\omega = \Delta\omega_0$$

$$\Delta\omega_0 e^{-k/J\,t} = \Delta\omega$$

$$\underline{\Delta\omega \to 0} \qquad \underline{t \to \infty}$$

Increasing $\Delta\omega$ and T_y ; $T_y > T_m$, the system is rapidly slowing down and turns back to equilibrium point exponentially (ω_1)

Linearized around: $\omega=\omega_1$

$$J\ \frac{d\ (\omega_1+\Delta\omega)}{dt} = \left.\frac{\partial T_m(\omega)}{\partial\omega}\right|_{\omega=\omega_1}\Delta\omega - \left.\frac{\partial T_y(\omega)}{\partial\omega}\right|_{\omega=\omega_1}\Delta\omega$$

$$J\ \frac{d\Delta\omega}{dt} = \left(\left.\frac{\partial T_m(\omega)}{\partial\omega}\right|_{\omega=\omega_1} - \left.\frac{\partial T_y(\omega)}{\partial\omega}\right|_{\omega=\omega_1}\right)\Delta\omega$$

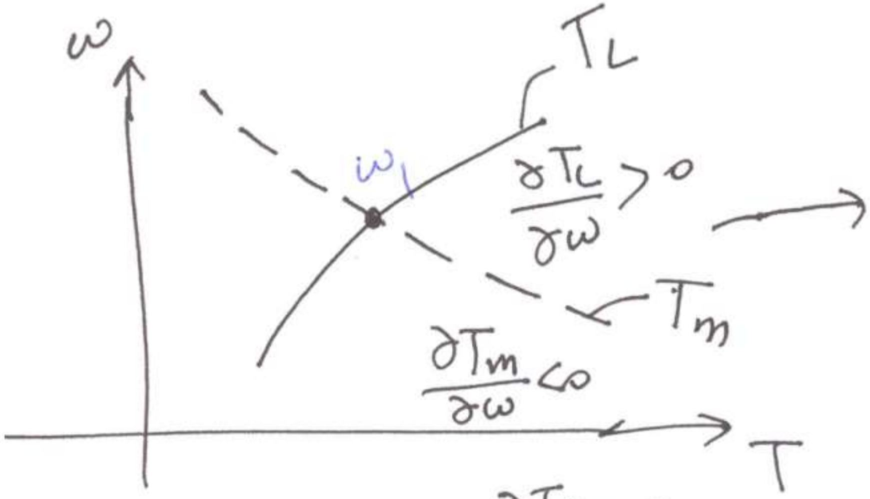
$$k = \left(\left.\frac{\partial T_y(\omega)}{\partial\omega}\right|_{\omega=\omega_1} - \left.\frac{\partial T_m(\omega)}{\partial\omega}\right|_{\omega=\omega_1}\right)$$

$$J\ \frac{d\Delta\omega}{dt} + k\ \Delta\omega = 0$$

$$\Delta\omega(t) = \Delta\omega(0)\ e^{-\frac{k}{J}t}$$

$k >$0 stable

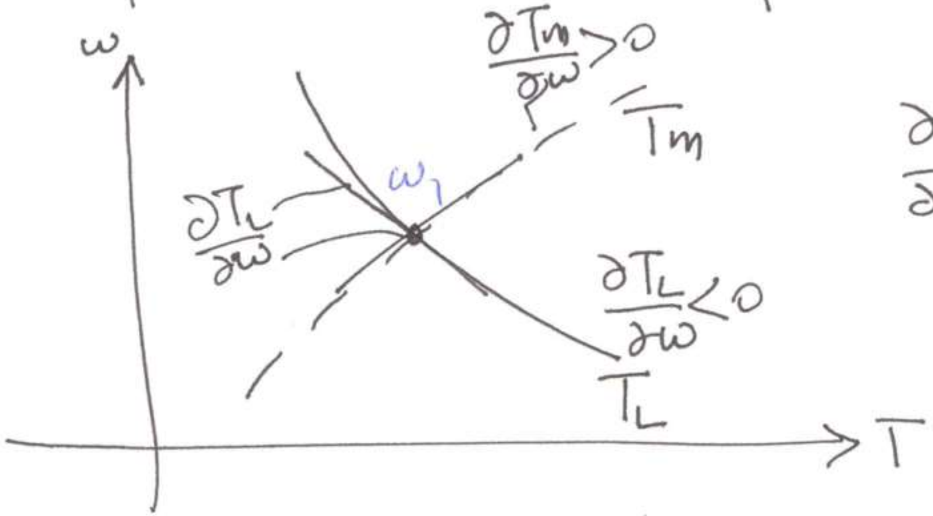
$k <$ 0 unstable



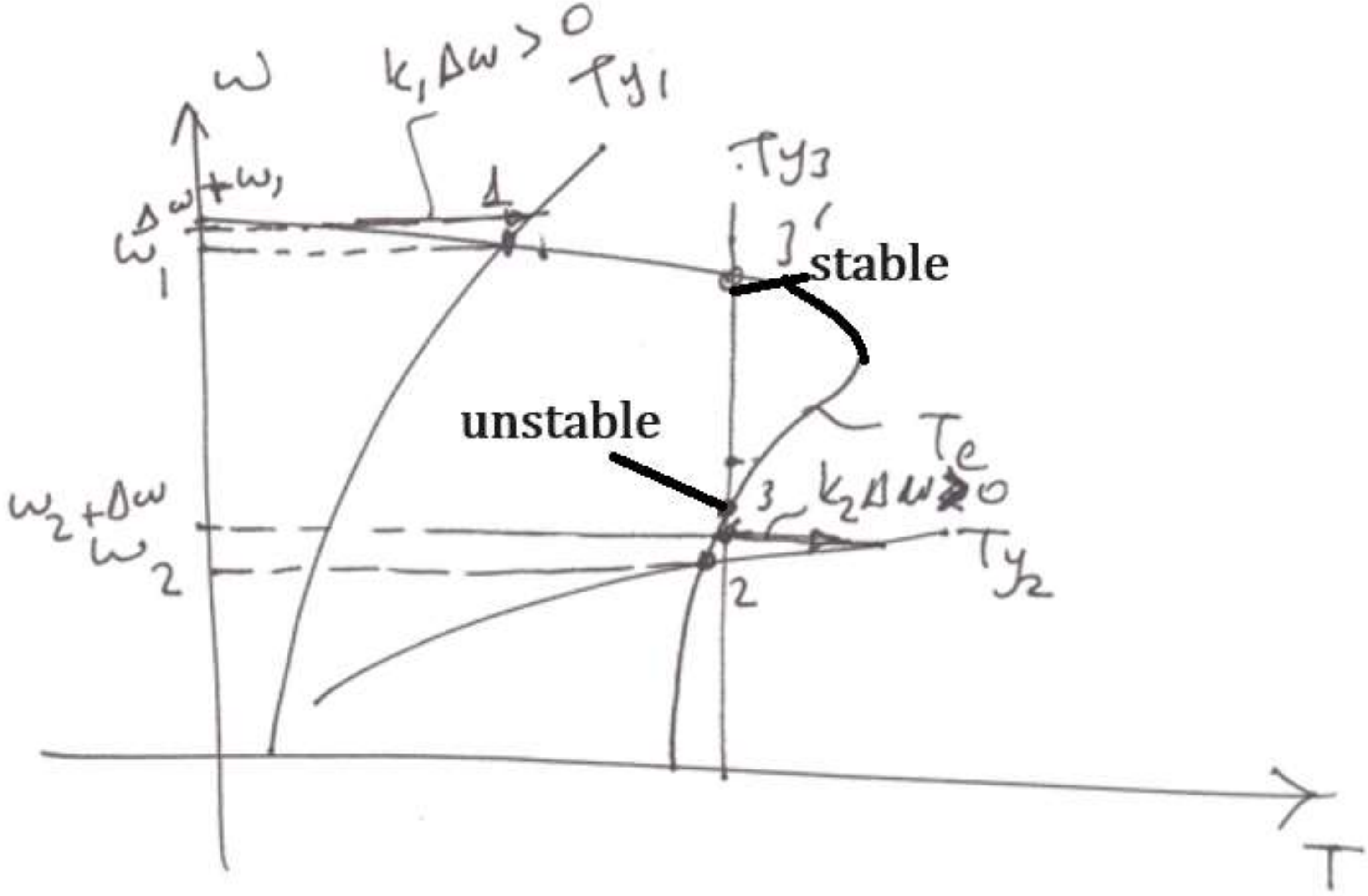
$$\frac{\partial T_L}{\partial \omega} - \frac{\partial T_m}{\partial m} > 0$$

Stable

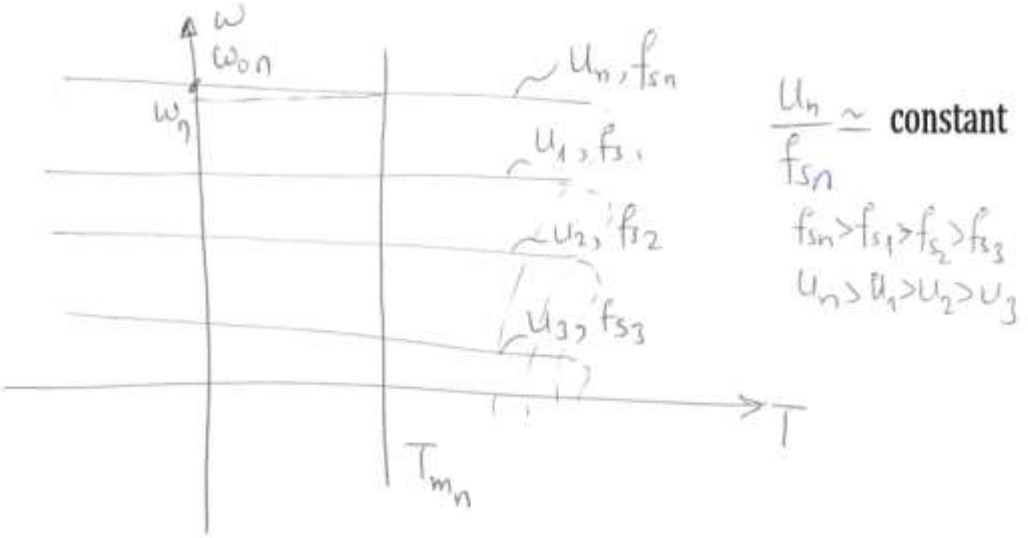
Unstable



$$\frac{\partial T_L}{\partial \omega} - \frac{\partial T_m}{\partial \omega} < 0$$


ω
$k_1\Delta\omega > 0$
T_{y1}
T_{y3}
$\Delta\omega + \omega_1$
ω_1
1
1
3'
stable
unstable
T_e
$\omega_2 + \Delta\omega$
ω_2
3
$k_2\Delta\omega > 0$
T_{y2}
2
T

Asynchronous Motor



For the motor to rotate at nominal speed (it must be supplied with nominal supply voltage) and loaded with nominal load. In this case, the motor draws its nominal current from the source with a nominal supply voltage.

Nominal efficiency →

$$\eta_{m,n} = \frac{\tau_{m,n}.\omega_{m,n}}{U_{m,n}.I_{\mathrm{m},n}}$$

If there is no load when the motor is supplied with the nominal voltage amplitude and frequency, the motor rotates at the nominal speed at idle. If ~~the motor is fed with a nominal load under these feeding conditions, it~~ rotates at nominal speed and is at nominal efficiency.

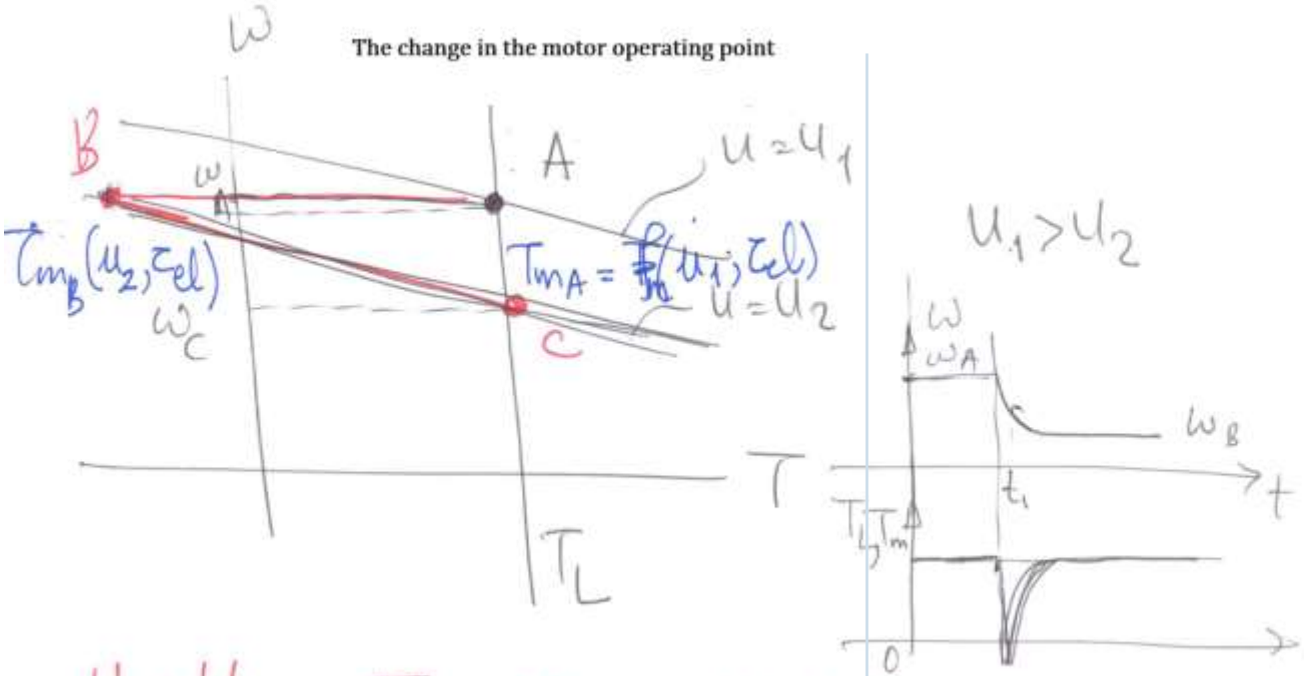
$$\eta_{m,n} = \frac{P_{mech,n}}{P_{elec,n}} = \frac{T_{m,n}.\omega_{m,n}}{\sqrt{3}U_{m,n}I_{m,n}\cos\left(\varphi_{m,n}\right)}$$

Effective nominal voltage

Effective nominal current

Phase difference between the nominal voltage and nominal current

The change in the motor operating point



$U = U_1$ $T_m = T_L$ $\omega = \omega_1$

$$T_m - T_l = J\dot{\omega} + B\omega$$

$$T_l \succ T_m \Rightarrow motor\_will\_decrease\_speed$$

$$the\_operating\_po\text{int}\_changes$$

Critical Criteria for Servo Motor Selection

1. Low Inertia

The inertia of a servo motor is a measure of the resistance to changes in its rotational speed. Low-inertia motors are essential for applications requiring quick acceleration and deceleration. They enable the motor to respond rapidly to control signals, making them ideal for high-precision tasks.

2. High Efficiency

Efficiency refers to the motor's ability to convert electrical energy into mechanical energy with minimal losses. High-efficiency motors are crucial for reducing operational costs and heat generation, thus extending the life of the motor and associated drive systems.

3. Peak Torque

Peak torque is the maximum torque a servo motor can generate. It's vital for applications where the motor needs to overcome high inertial loads or start heavy loads. Understanding the peak torque requirements ensures the motor won't be overstressed during these high-demand scenarios.

4. Zero-Speed Holding Torque

This is the torque that a servo motor can maintain when at a standstill. It's crucial for applications requiring the motor to hold a load in position without movement, ensuring stability and precision in stationary phases.

5. Quick Start/Stop Cycles

The ability to start and stop rapidly is essential for applications involving frequent changes in motion or direction. This capability is critical for ensuring process efficiency and precision in operations like assembly lines or robotic movements.

6. High Accelerating Torque

This refers to the motor's ability to quickly reach its required speed. High accelerating torque is essential for reducing cycle times in repetitive processes, thus enhancing overall productivity.

7. Repeatable Velocity and Torque Profiles

The capability to reproduce specific velocity and torque profiles consistently is crucial for precision in repeatable processes. This consistency ensures product quality and process reliability.

8. Synchronization

In multi-motor systems, synchronization ensures that all motors work in harmony, maintaining the precise timing and coordination essential for complex motion control tasks.

9. Positioning Capabilities

Precise positioning is critical for tasks requiring high levels of accuracy, such as CNC machining or robotic assembly. The servo motor must be able to reach and maintain specific positions reliably.

10. Precise Speed Control

The ability to control speed with high precision is vital for applications where the speed of the motor directly influences the quality of the output, such as in conveyor systems or spindle drives.

Peak Torque Capacity

In positioning applications, the ability to provide high peak torque is essential. This attribute is particularly important during periods of accelerated movement and deceleration. The peak torque capacity dictates the motor's ability to handle sudden changes in load and speed, which are common in precise positioning tasks.

Thermal Capacity

The thermal capacity of a servo motor is indicative of its ability to operate under sustained loads without overheating. Motors with high thermal capacity ensure longer life and higher endurance, as they can better dissipate heat generated during operation. This characteristic is crucial for applications with continuous or frequent motor use, where overheating risks could lead to motor damage or failure.

Cogging and Oscillation Torques

Cogging torque refers to the torque ripple or fluctuations experienced by a motor due to interactions between the magnetic fields of the stator and rotor. Similarly, oscillation torques are the unwanted torques that may arise due to system dynamics. Minimizing these factors is crucial in high-precision applications, as they can affect the motor's ability to maintain stable and repeatable movements. High repeatability is a critical requirement in positioning tasks, where even minor deviations can lead to significant errors.

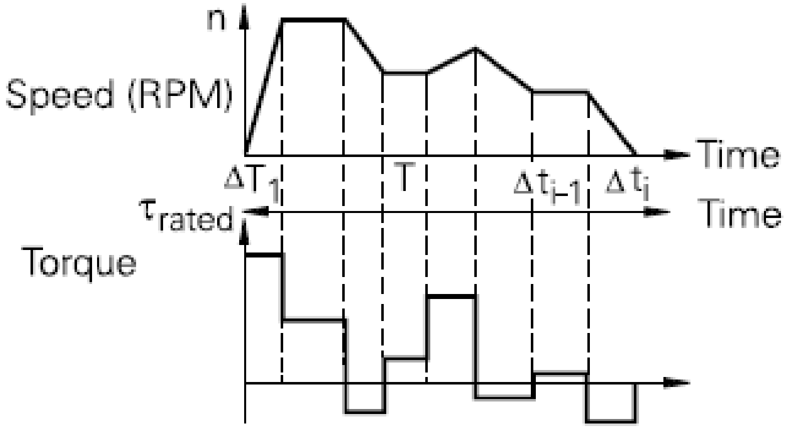
Efficiency Calculations

The efficiency of a servo motor is not just about its energy conversion capabilities; it's also about how effectively it performs in its intended application. Efficient motors reduce operational costs and are less prone to overheating. In positioning applications, where motors may operate for extended periods, efficiency becomes a critical factor. Calculating and understanding the efficiency of a motor in its specific operational context helps in selecting a motor that not only meets the technical requirements but also operates economically.

Flow Diagram for Selection Process

Required Information

The specific speed and load cycle of your application must be known to select the proper drive and motor.



Step 1

Determine Degree of Protection

IP 23, IP 55, IP 64, IP 67

Step 2

Determine Supply Voltage

380 to 400 V, 460 - 480V

Step 3

Determine Type of Construction

IM B 3 (foot mounting), IM B 5 (flange mounting), IM B 35 (foot/flange)

Step 4

Determine Maximum Torque from Load Cycle Profile

Step 5

Determine RMS Mean Torque

Step 6

Determine Type of Motor Needed (Synchronous/Asynchronous)

1FK6, 1FT6, 1PH7, 1PL6, 1PH14

Step 7

Select Motor from Appropriate Data Page of General Motion Control Catalog Part 2 that fulfills the following criteria:

Synchronous Motors	Asynchronous Motors
$N_{max} \leq N_{rated}$	$N_{max} \leq N_{rated}$, $T_{max} < 2 \times T_{rated}$
$T_{RMS} \leq T_{rated}$	$T_{RMS} \leq T_{rated}$
Points of Cycle (N1, T1) must be in Intermittent Operating Region	Points of Cycle (N1, T1) must be below breakdown curve by a min. clearance of 30%

Step 8

Determine the Kind of Feedback Device Required

Pulse Encoder, Resolver, Sin/Cos Encoder, Absolute Value Encoder

Step 9

Complete Motor Part Number Based on Options Required

1FK6 ☐☐☐ – ☐☐☐☐☐☐ – ☐☐☐☐
1FT6 ☐☐☐ – ☐☐☐☐☐☐ – ☐☐☐☐
1PH7 ☐☐☐ – ☐☐☐☐☐☐ – ☐☐☐☐
1PL6 ☐☐☐ – ☐☐☐☐☐☐ – ☐☐☐☐
1PH4 ☐☐☐ – ☐☐☐☐☐☐ – Option Codes

Step 10

Determine Length and Size of Prefabricated Power Cable Required or Determine Size of Coupling for Customer Assembly

Power Cable Order Number: ______________________________

Step 11

Determine Length and Size of Prefabricated Signal Cable Required or Determine Size of Coupling for Customer Assembly

Encoder/Resolver Cable Order Number: ______________________________

Step 12

If Standard Overload (160% for 30 s during 300 s load cycle)

Select Converter/Inverter that Corresponds to the Chosen Motor from the Motor Data Based on Standard Overload Conditions

Skip to Step 15

Step 13

If Above Standard Overload

If Higher Overload Time and Overload Percentage is Needed go to General Motion Control Catalog Part 1 MASTERDRIVES MC

Determine $I_{motor\ max}$ and I_{RMS}

Step 14

Determine Whether an AC - AC or DC - AC Unit and "Form Factor" is Needed

AC - AC: Typical Single Axis System
DC - AC: Typical Multi-Axis System (Rectifier Required)

Step 15

Select Converter/Inverter that Fulfills Overload Requirements

$I_{RMS} < I_{Un}$ in 300 s Cycle Time
$I_{max} < 1.6 \times I_{Un}$ for 30 s in a 300 s Cycle Time (Compact/Chassis Units)
or $I_{max} < I_{Un}$ for 250 ms in a 1 s Cycle Time (Compact PLUS Units)

Drive Order Number: ______________________

Step 16

Select Rectifier

Step 17

Determine Feedback Options for Drive

SBP, SBR 1/2, SBM

Feedback Board Order Number: ______________________

Step 18

Determine if Communication Board is Required

PROFIBUS - CBD, SIMOLINK - SLB

Communication Board Order Number: ______________________

Step 19

Determine if Additional Input/Output is Required

Expansion Board EB1 or EB2
Expansion Board Order Number: ______________________

Step 20

Determine if Optional Technology Functions are Required

Software or Technology Board Order Number: ______________________

Step 21

Determine if Additional Options such as Line Reactors, OP1S, RFI Filters, Capacitor Modules, etc. are Required

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Step 22

Determine Enclosure Needed

Rotary System Selection

This section provides useful information for calculating your application's mechanical requirements, and selecting the proper motor and drive to meet your needs. To ensure the proper motor/drive system is selected, follow these steps:

1. **Sketch the move profile and calculate acceleration, deceleration, and maximum velocity required to make the desired move.**
2. **Select the mechanical drive mechanism to be used and calculate inertia, friction, and load torque using formulas for the mechanical drive mechanism.**
3. **Determine peak and continuous (RMS) torque requirements for the application.**
4. **Select a system – choose the appropriate motor and drive combination that meets all of the application requirements.**

The process of sizing servo motors, a fundamental aspect of servo motor applications, revolves around ensuring that the selected motor and its driver are capable of delivering the desired motion for a given load. This task is not only about choosing the right motor but also involves a comprehensive understanding of the entire motion system, including transmission elements and the dynamic characteristics of the load. Let's break down these key aspects:

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1. Defining Transmission Elements and Load

The first step in sizing a servo motor involves defining the transmission elements (such as gears, belts, or lead screws) and the load. Understanding the mechanical configuration and the load's physical characteristics (mass, inertia, etc.) is crucial. These elements impact how the motor's torque and speed are transferred and modified, influencing the overall performance of the system.

2. Variation in Load Torque

The load torque is the torque required to move the load under various conditions. This torque can vary significantly based on the operation – starting, stopping, accelerating, or moving at a constant speed. Accurately estimating these variations is vital for selecting a motor that can provide sufficient torque throughout the entire range of operations without being oversized or undersized.

3. Variation in Load Speed

Just like torque, the speed requirements of the load can also vary. Understanding these variations is crucial for selecting a motor and drive system that can provide the necessary speed range. This includes considering the maximum speed required and the speed profile during different phases of the operation.

In essence, sizing a servo motor is a detailed exercise that requires a comprehensive analysis of the mechanical system and the load dynamics. It's not just about picking a motor based on its standalone specifications; it's about ensuring that the motor when integrated with the transmission system and the load, can perform the required tasks efficiently and reliably. This process involves understanding the mechanical leverage provided by transmission elements, the inertia of the load, and how these factors interact with the motor's torque and speed capabilities. The objective is to achieve a balanced system where the motor is neither over-spec'd (leading to unnecessary cost and energy use) nor under-spec'd (leading to performance issues or system failure). This careful selection ensures optimal performance, efficiency, and reliability of the motion control system.

1. Objective of Sizing a Servo System:

The primary goal in sizing a servo system is to correctly dimension both the servo motor and its driver. This ensures that the system can deliver the required performance for the specific application. The elements that are already defined at this stage include transmission elements and the loads they will handle.

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2. Determining the Desired Motion Profile of the Mechanism:

A crucial step in this process is defining the motion profile that the mechanism is expected to perform. This involves outlining the specific movements, positions, and sequences required during the operation. The motion profile dictates the requirements for speed and torque at various stages of the operation.

3. Extracting Torque and Speed Profiles:

From the defined motion profile, we derive the torque and speed profiles. These profiles are critical in understanding the dynamic demands placed on the servo motor throughout the operational cycle. They help in identifying the peak and average requirements for both torque and speed.

4. Selection of Motor and Driver Based on Profiles:

With these profiles in hand, the selection of the appropriate motor and driver can be made. This selection is not just based on the peak values of torque and speed but also considers the average or typical values over the operation cycle.

5. Considerations in Periodic Load Profiles:

In applications with periodic load profiles, the selection of the servo motor is nuanced due to the cyclic nature of motion control applications. Servo motors are rated both for continuous and intermittent operations.

The continuous rating is crucial and to determine the correct continuous rating, it's necessary to understand the effective torque, often referred to as RMS (root-mean-square) torque. This RMS torque provides a more accurate representation of the motor's typical workload over time, as opposed to peak torque values.

Similarly, for speed, it's not the instantaneous values that are most critical but the average speed over the operation cycle.

The acceleration torque is generally considered for short-duration requirements and may not be as critical in the continuous operation of the motor.

6. Importance of Effective Torque and Average Speed:

In systems with periodic load and speed variations, it's essential to consider the effective torque and the average speed as the basis for motor selection. These values provide a more realistic picture of the motor's operating conditions and ensure that the motor is neither overburdened nor underutilized.

Acceleration Torque

The torque required to accelerate a machine should be determined first.

The following information is needed:

- Inertia of the machine in kgm^2 (J)
- Amount of change of speed in RPM (Δn)
- Time taken to change speed in seconds (Δt)

The torque required to accelerate a system with a total inertia of 0.005 kgm^2 from rest to 3000 RPM in 0.2 seconds would be:

$$\tau_a = \frac{2\pi \cdot \Delta n \cdot J}{60 \cdot \Delta t}$$

$$\tau_a = \frac{6{,}28 \cdot 3000 \cdot 0{,}005}{60 \cdot 0{,}2}$$

$$\tau_a = 7.85 \text{ Nm}$$

Example

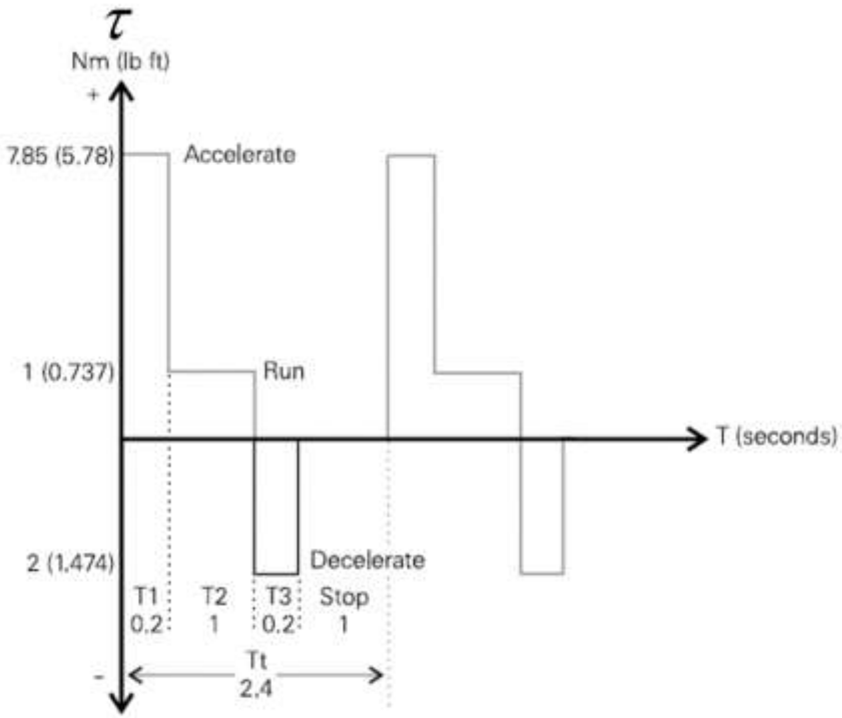
Three operating points are used during a cycle in the following example.

The load requires 7.85 Nm of torque to accelerate the load (T1) in 0.2 seconds.

During constant state run the load requires 1 Nm of torque to overcome losses due to friction and maintain speed (T2) for 1 second.

To decelerate the load and stop requires 2 Nm of torque (T3) for 0.2 seconds.

The system will remain stopped for 1 second before repeating the cycle. The total cycle time is 2.4 seconds (Tt).



Cycle Increment	Torque (Nm)	Torque (lb ft)	Time (seconds)
1	7.85	5.78	0.2
2	1	0.737	1
3	2	1.474	0.2
Time Between Cycles			1
Total Time			**2.4**

$$\tau_{eff} = \sqrt{\frac{\Sigma(\tau^2 \text{Mot i} \cdot \Delta ti)}{Tt}}$$

$$\sqrt{\frac{(\tau 1^2 \cdot \Delta t1) + (\tau 2^2 \cdot \Delta t2) + (\tau 3^2 \cdot \Delta t3)}{Tt}}$$

$$\tau_{eff} = \sqrt{\frac{(7.85^2 \cdot 0.2) + (1^2 \cdot 1) + (2^2 \cdot 0.2)}{2.4}}$$

$$\tau_{eff} = \sqrt{\frac{12.3 + 1 + 0.8}{2.4}}$$

$$\tau_{eff} = \sqrt{\frac{14.1}{2.4}}$$

$$\tau_{eff} = \sqrt{5.875}$$

$$\tau_{eff} = 2.423 \text{ Nm}$$

1) Required peak motor torque and peak motor speed

2) Required r.m.s. motor torque and r.m.s. motor speed (average speed is usually an acceptable approximation).

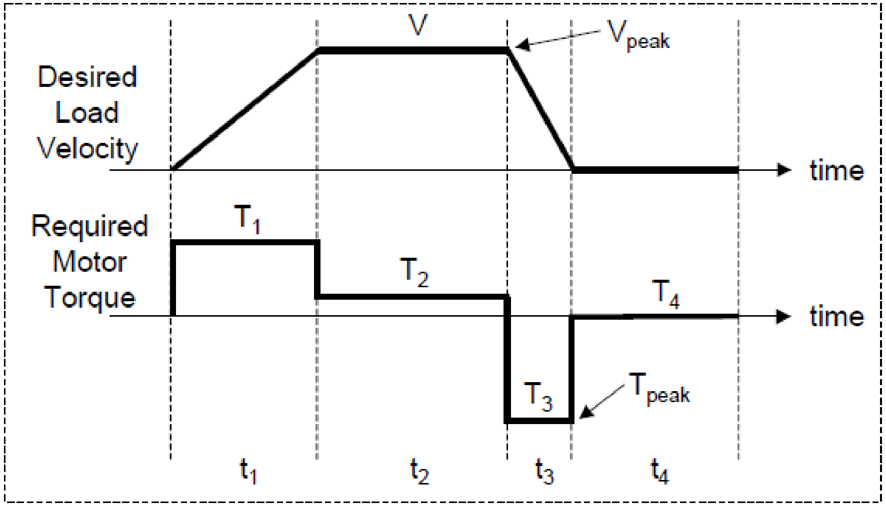
$$J_{total} = J_{motor} + J_{coupling} + J_{load}$$

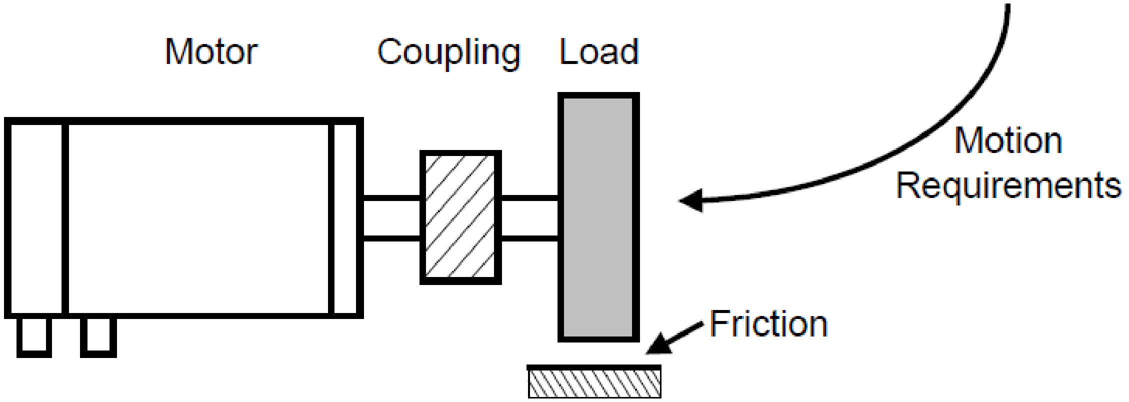
$$T_{acc} = J_{total} \frac{dn}{dt}$$

$$T_{motor} = T_{acc} + T_{friction}$$

$$T_{r.m.s.} = \sqrt{\frac{T_1^2 t_1 + T_2^2 t_2 + T_3^2 t_3 + T_4^2 t_4}{t_1 + t_2 + t_3 + t_4}}$$

$$n_{average} = \frac{½V\, t_1 + V\, t_2 + ½V\, t_3}{t_1 + t_2 + t_3 + t_4}$$

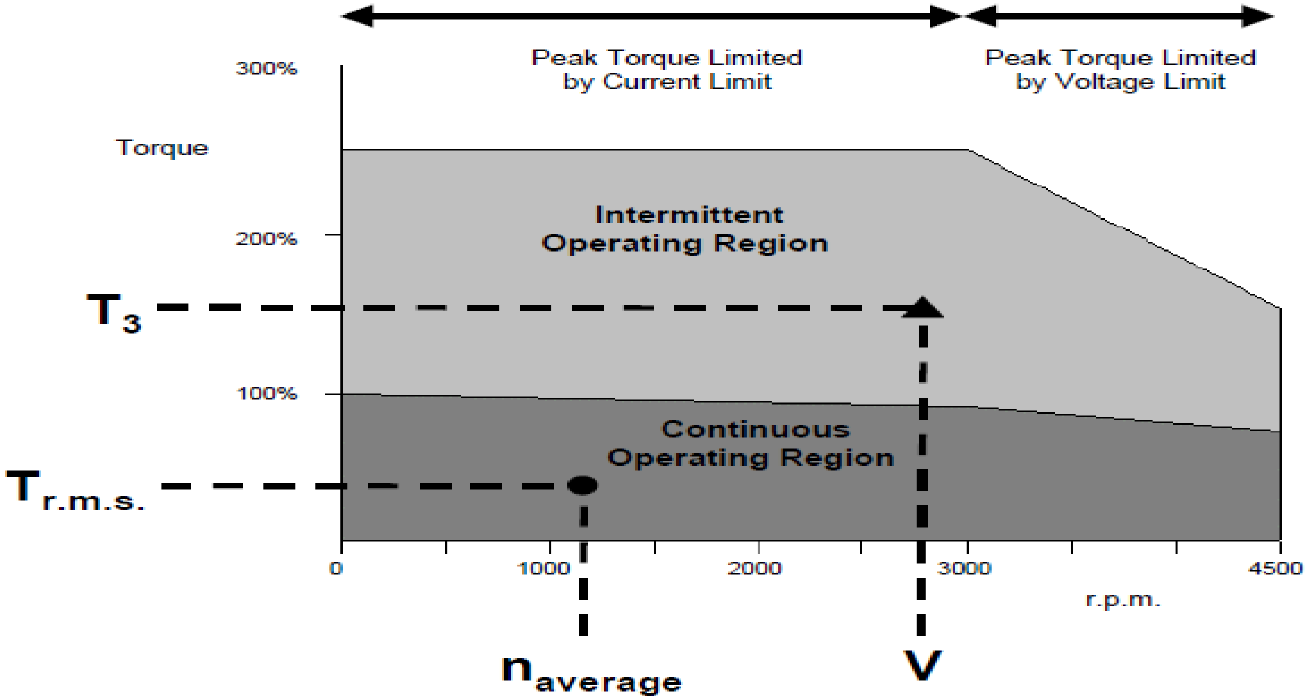


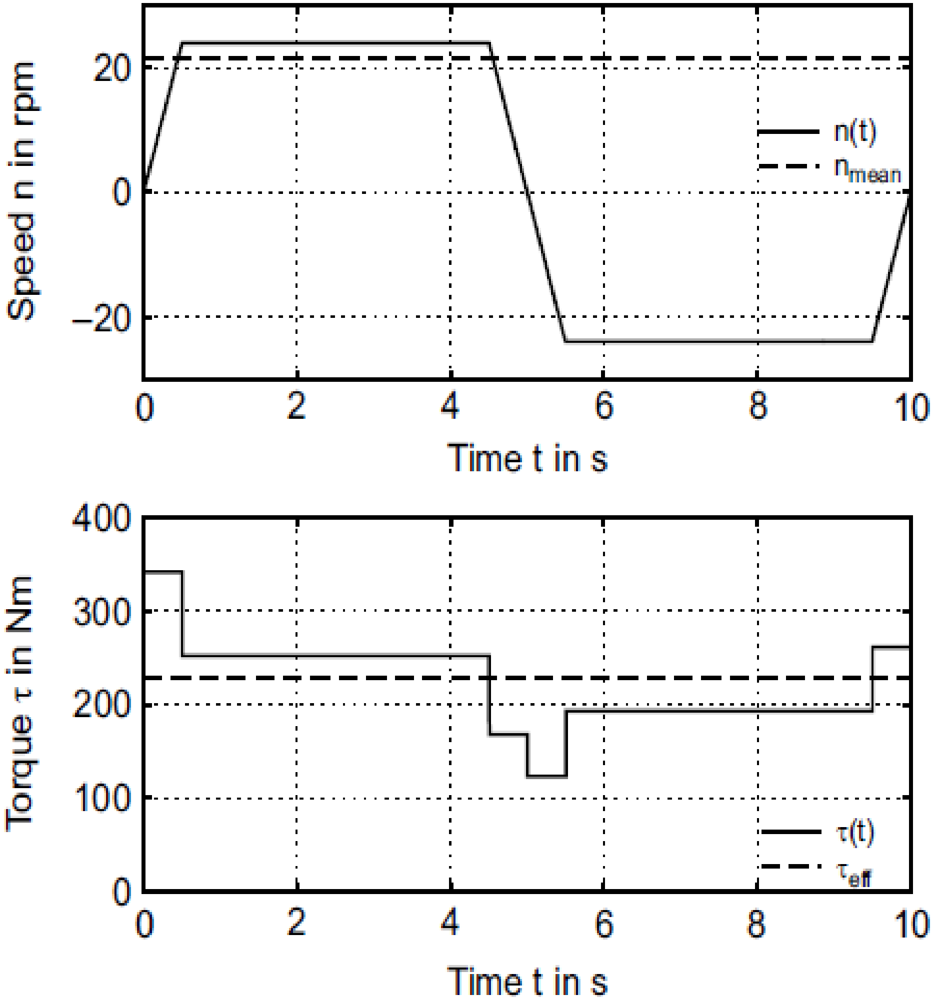


Power loss and, in proportion to this, motor temperature are important in determining operating conditions.

As can be seen from the figure, there are two important working areas:

- Continuous operating region
- Intermittent operating region





- Maximum torque $\tau_{P,max}$:

$$\tau_{P,\max} = \max(\tau_z)$$

- R.m.s. torque τ_{eff}:

$$\tau_{eff} = \sqrt{\frac{1}{T}\sum_{z=1}^{m} \tau_z^2 \cdot \Delta t_z}$$

- Average speed n_{mean}:

$$n_{mean} = \overline{\left|n_{L,z}\right|} = \frac{1}{T}\sum_{z=1}^{m} \left|n_{L,z}\right| \cdot \Delta t_z$$

- Maximum speed n_{max}:

$$n_{\max} = \max(n_{L,z})$$

<u>These four variables are decisive for the selection of the components, in particular the motor, the gearbox and the inverter.</u>

Duty Cycle

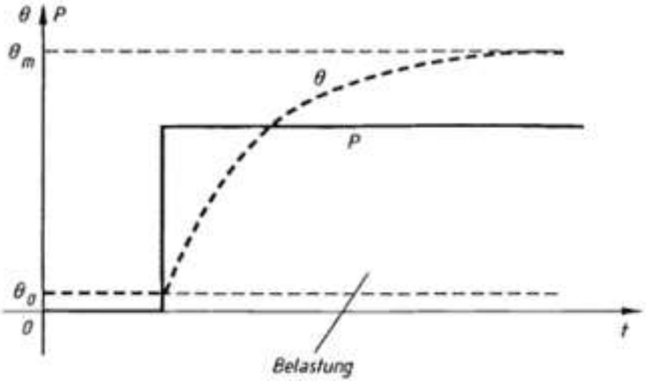
All motors are limited by the amount of heat that can develop in the motor windings.

Speed-torque curves are based on standardized duty cycles which lead to the same temperature rise.

The number of possible duty cycle types is almost infinite.

To help promote a better understanding, duty cycles have been divided into nine standardized categories, which cover most of the applications encountered.

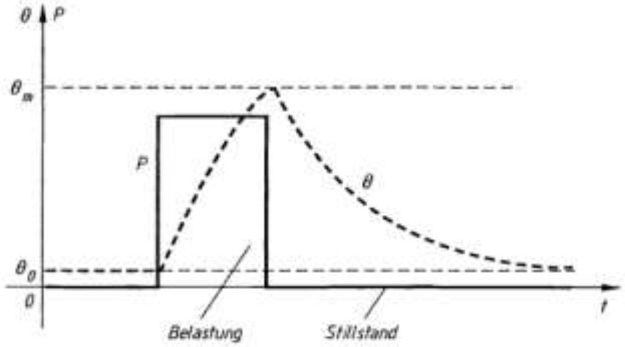
S1	Continuous Running Duty
S2	Short-Time Duty
S3	Intermittent Periodic Duty Without Starting
S4	Intermittent Periodic Duty With Starting
S5	Intermittent Periodic Duty with Starting and Electric Braking
S6	Continuous Operation Periodic Duty
S7	Continuous Operation Periodic Duty with Starting and Electric Braking
S8	Continuous Operation Periodic Duty with Related Load/Speed Changes
S9	Continuous Operation Duty with Non-Periodic Load and Speed Variations

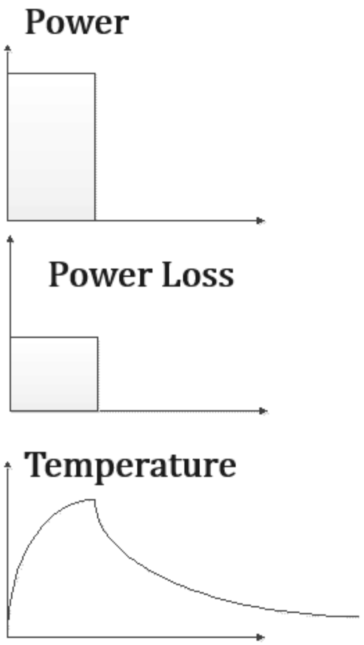


S1 Continuous Running Duty

Each duty cycle is characterized by cycle times, cycle durations, and load. S1 duty cycle, for example, characterizes a condition where the motor operates under a constant load of sufficient duration for thermal equilibrium to be established. In this study, the motor can operate for an unlimited period with nominal load. The lost power under constant load reaches the limited temperature of the engine and remains constant at that value. The motor is sized to withstand this temperature in continuous operation, and this temperature does not damage the motor due to the placement of the windings in the slots in addition to the required cooling structure.

S2 Short-Time Duty





The motor can only operate in this operating mode for a short and specific period.

It should not exceed the maximum temperature given for the speed.

In general, the maximum torque of the motor is reached. In this case, losses are also high.

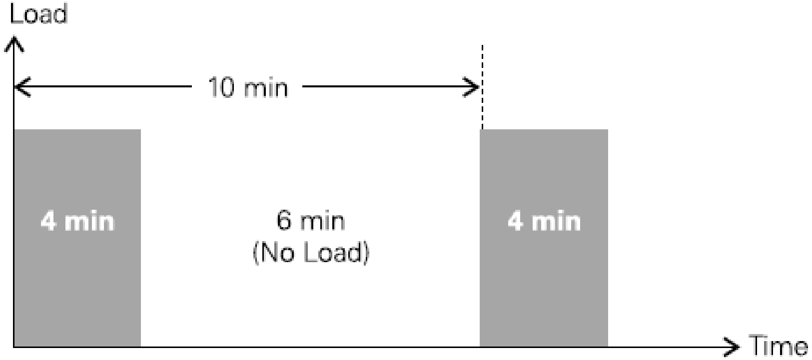
It is necessary to wait for the temperature to drop before the machine can operate for short periods again.

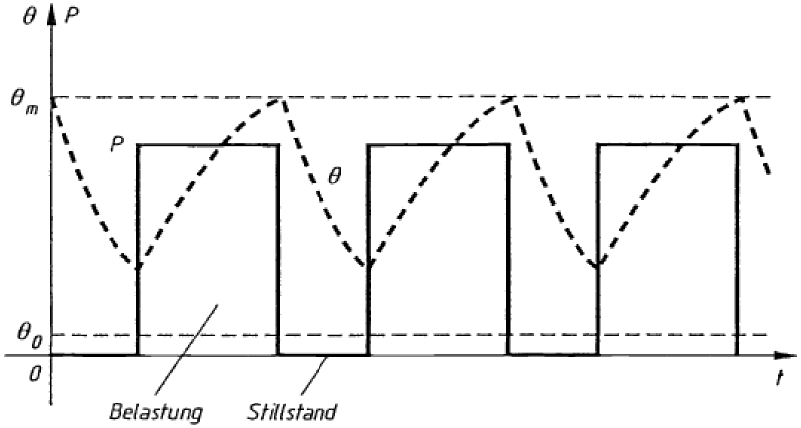
For this reason, it is necessary to wait a long time after working for a short time. Otherwise, the engine may be damaged due to temperature.

In this mode, the engine operates at its maximum torque.

For this reason, the losses will be large and the engine will warm up quickly.

Therefore, it is necessary to wait a long time until it cools down.



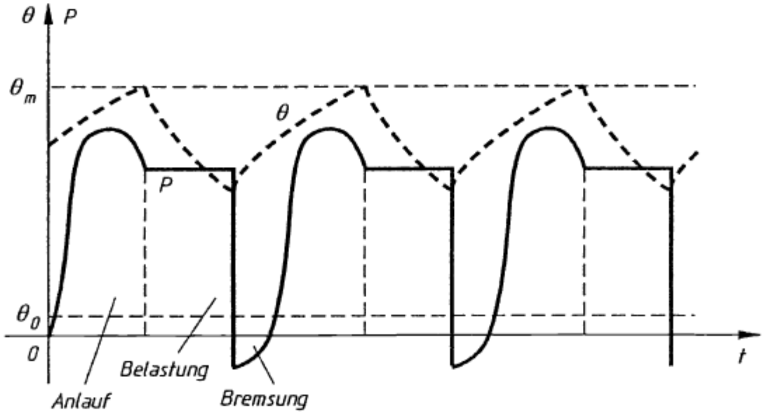


S3 Intermittent Periodic Duty Without Starting

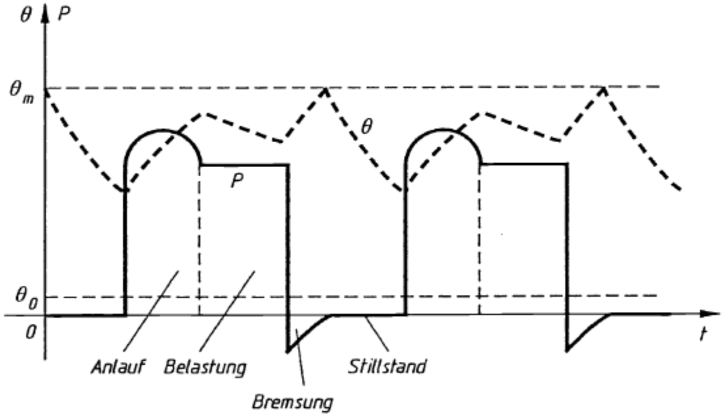
S3 duty operation is comprised of a sequence of identical duty cycles, each of which consists of a period of constant load followed by an interval of no load. The starting current has no marked effect on the temperature rise of the motor. Operating time is given in minutes, such as 10 minutes, 30 minutes, or 60 minutes. If no time is given a 10-minute cycle time is assumed.

Cycle duty is given in a percentage such as 15%, 20%, 25%, 30%, or 40%. An S3 duty cycle of 40% for 10 minutes, for example, would indicate a motor load would be constant for 40% of the time (4 minutes). A no-load condition would occur for 60% of the time (6 minutes).

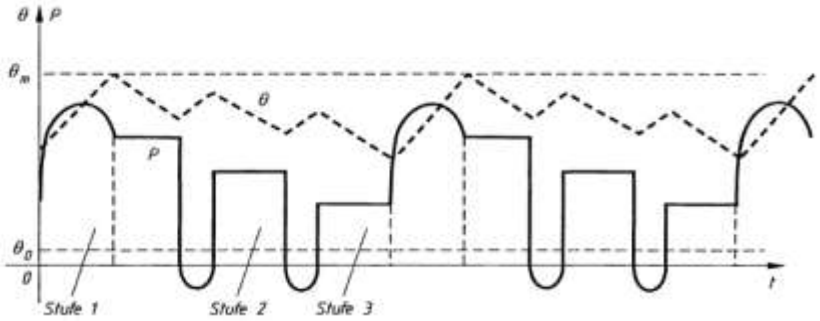
Periodic operation: including starting, loading and rest conditions.



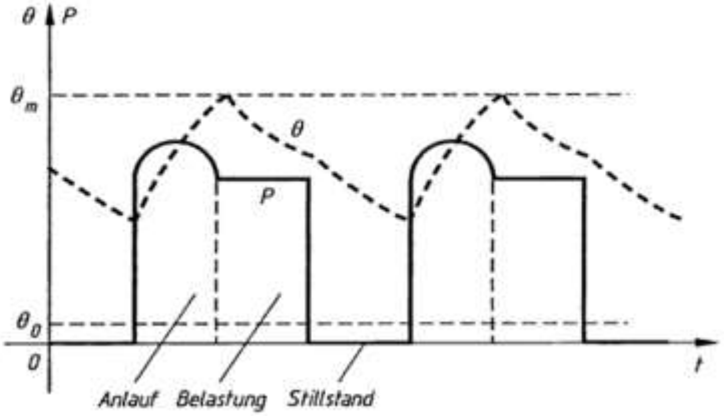
Periodic operation: Including starting, loading, electrical braking and resting states.

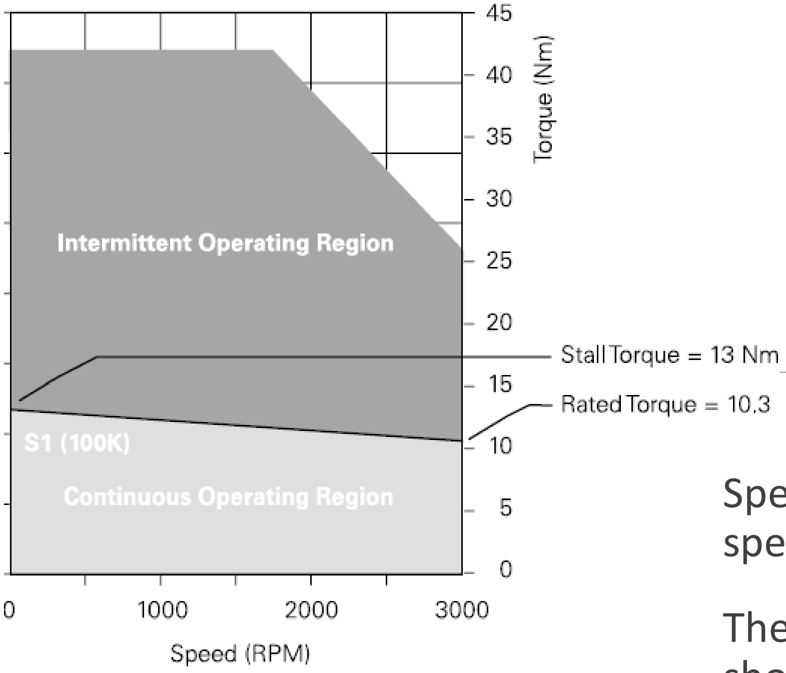


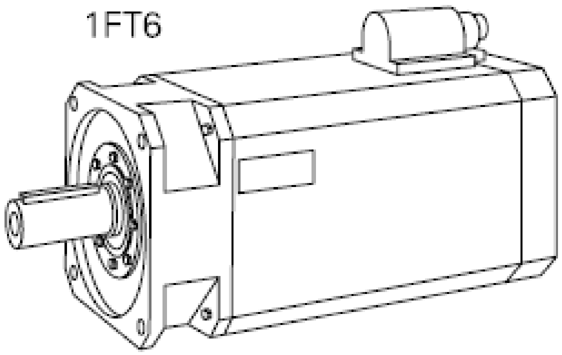
Periodic operation, which includes gradual work at different speed values.



Periodic operation: including starting, loading, electrical braking and reverse starting, loading and electrical braking.







Speed-torque curves can also be supplied for a specific motor.

The following speed-torque curve, for example, shows the operating capabilities of a 1FT6082 motor.

The motor associated with this curve can deliver 13 Nm at stall and 10.3 Nm at rated speed (3000 RPM) continuously.

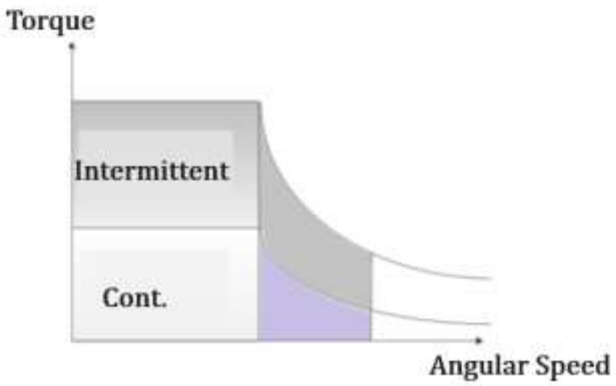
The region in the light grey area of the graph represents a continuous operating range (S1 duty cycle).

The area represented by the dark grey region of the graph represents the intermittent operating region.

Motor characteristics are fundamental to understanding how motors operate under different conditions.

These characteristics are divided into two main regions:

1. **Continuous Operating Region**
2. **Intermittent Operating Region**



Each of these regions has two sub-regions:

- Constant Torque Area
- Constant Power Area (Field Weakening Area)

Continuous Operating Region

In the continuous operating region, the motor operates within its designed capabilities for extended periods without overheating or experiencing undue stress.

- **Constant Torque Sub-Region**: Here, the motor delivers a steady amount of torque, which is essential for applications requiring uniform speed under varying load conditions. The limit of this region is characterized by the motor's nominal torque.
- **Constant Power Sub-Region (Field Weakening Area)**: In this area, the motor maintains a constant power output, allowing the speed to increase beyond the nominal rating while reducing torque. This region is crucial for applications where high speed is necessary, such as in certain machining operations or electric vehicles.

Intermittent Operating Region

The intermittent operating region involves operations that the motor can sustain for short periods without incurring damage.

- **Peak Torque**: In this region, the motor can produce torque higher than its nominal rating but only for a limited duration. This is typically used for applications requiring short bursts of high power, like starting a heavy load.

Speed Limits

- In the continuous operating region, the speed limit is generally the motor's nominal speed.

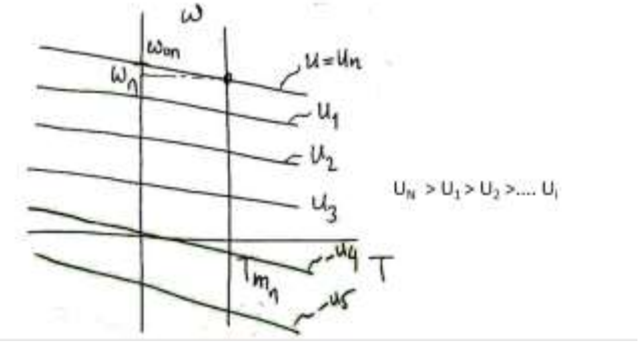
In the intermittent operating region, the speed can be at or slightly above the nominal speed.

Motor Nominal Values

Motor nominal values are critical parameters that define the motor's standard operating conditions. These values are determined by two main inputs:

1. **Power Supply (Input)**: This can be either DC or AC. The nominal values for a DC machine are typically given as the average DC voltage (UortN), while for an AC machine, it's the effective value and frequency of the AC supply (UetN and fUN).
2. **Load Torque (Output)**: The nominal value of the load torque is denoted as TloadN.

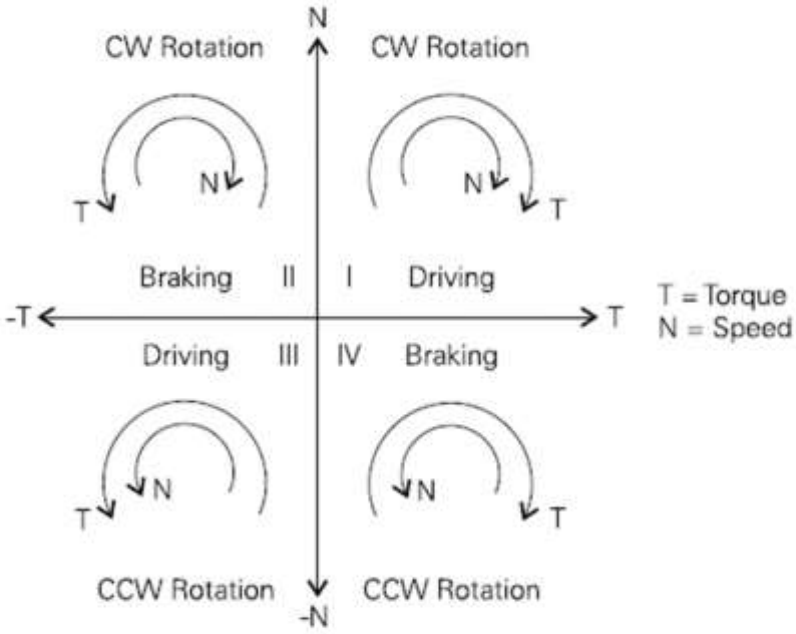
When the motor operates at its nominal values, it w



- Rotate at its nominal speed.
- Draw its nominal current from the power source.
- Operate at its nominal efficiency.

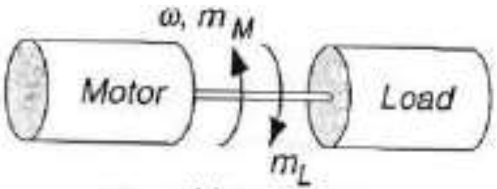
Effect of Power Supply Variations

- **Shunt Characteristic Maintenance**: Even when the supply values change, the motor maintains its shunt characteristics approximately. This results in characteristic curves that change in parallel.
- For a DC motor, different supply values like UN, U1, U2, etc., illustrate this variation



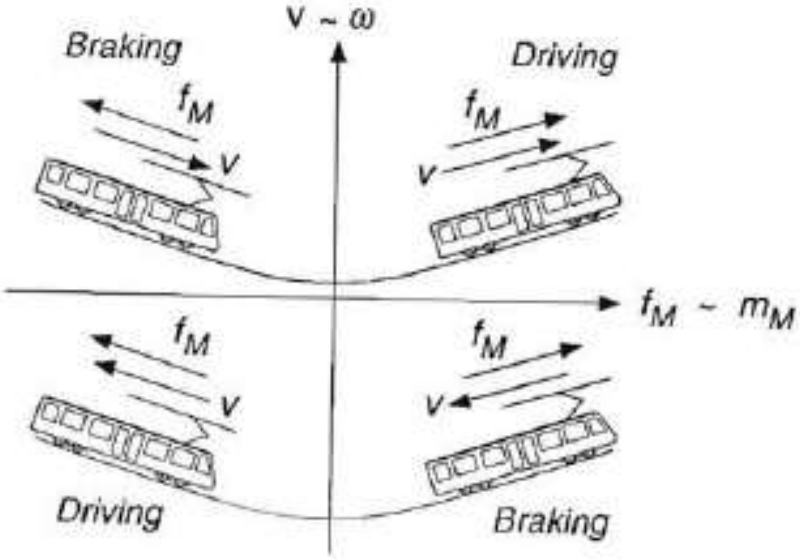
An electric drive system must operate with acceleration or deceleration in forward and reverse directions.

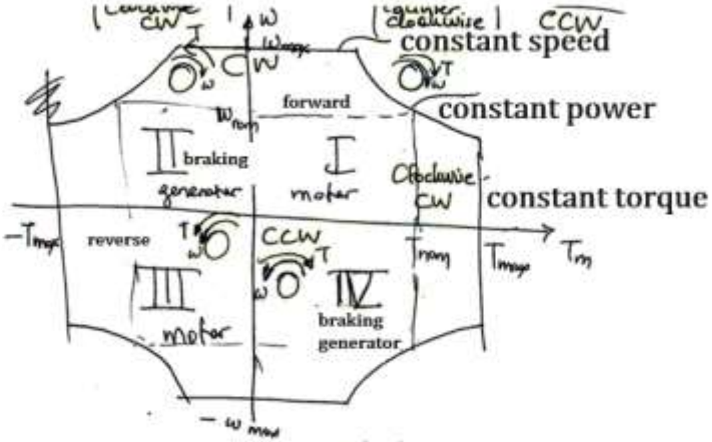
Operation Mode	Clockwise, Acceleration	Clockwise, Deceleration	Counter clockwise, Acceleration	Counter clockwise, Deceleration
Speed	+	+	-	-
Torque	+	-	-	+
Electric Power Flow	+	-	+	-



m_M = Motor torque

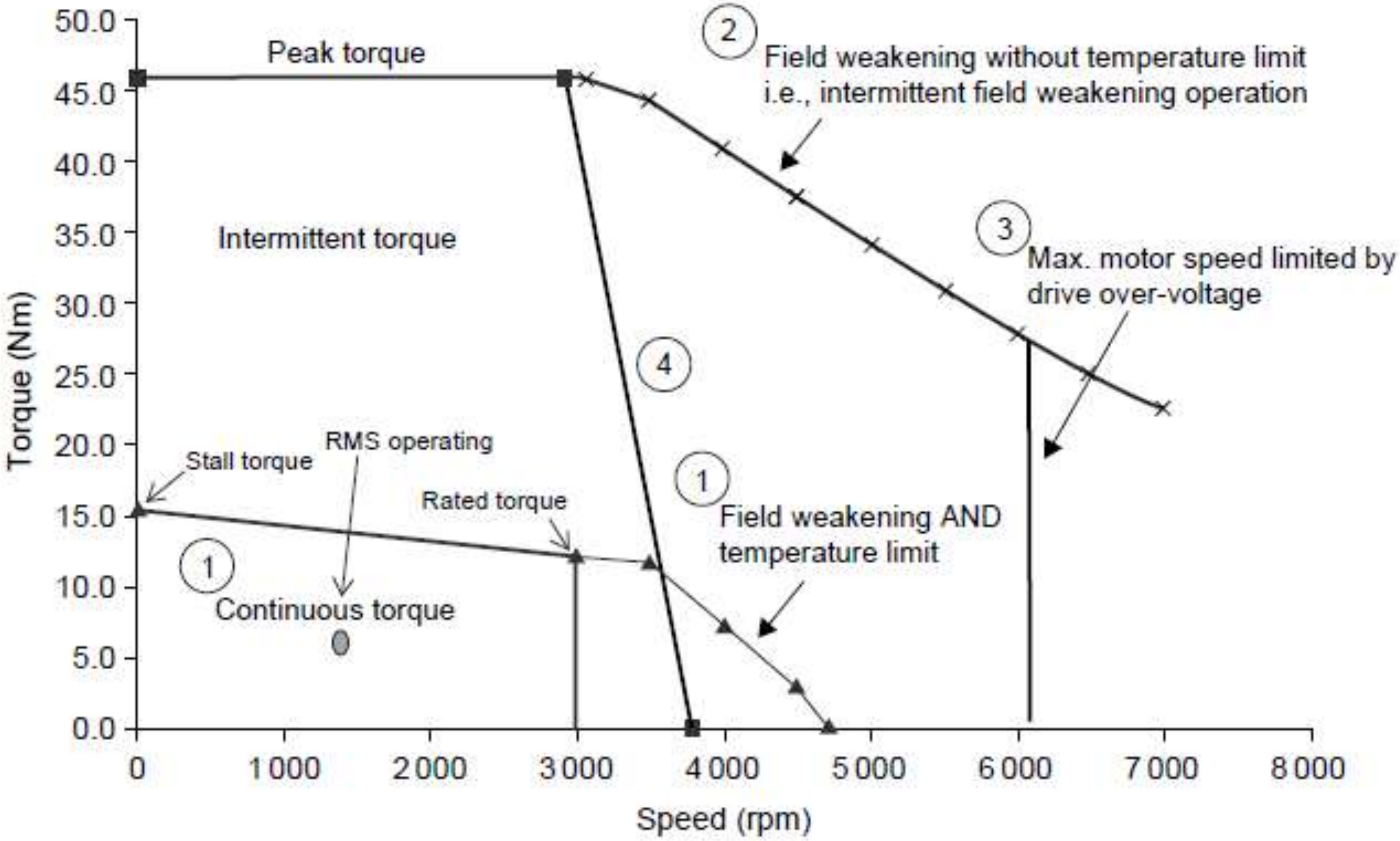
m_L = Load torque





Clock wise

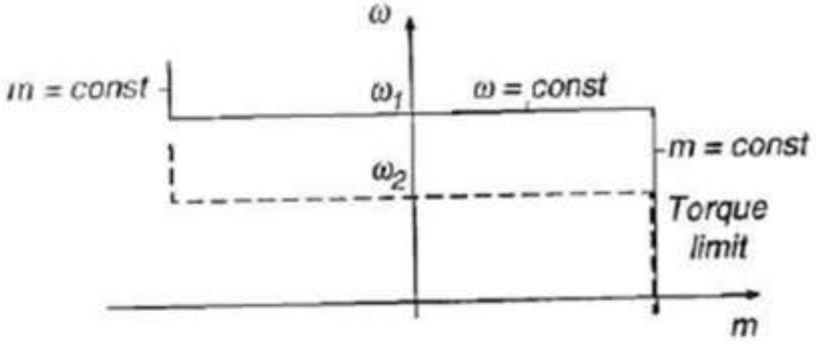
Counter clock wise

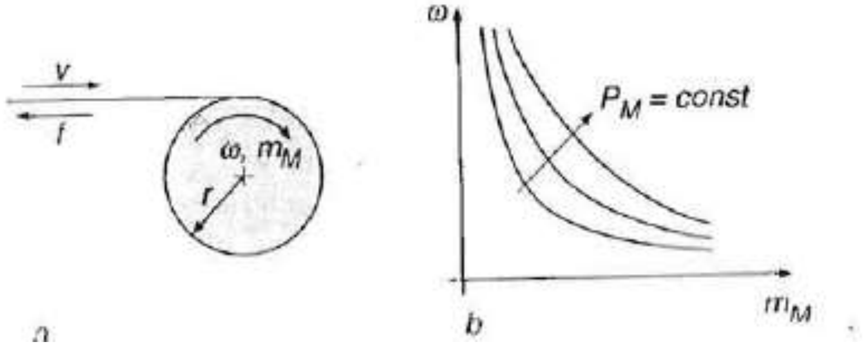

50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Torque (Nm)
0
1 000
2 000
3 000
4 000
5 000
6 000
7 000
8 000
Speed (rpm)
Peak torque
②
Field weakening without temperature limit
i.e., intermittent field weakening operation
Intermittent torque
③
Max. motor speed limited by
drive over-voltage
④
Stall torque
RMS operating
Rated torque
①
Field weakening AND
temperature limit
①
Continuous torque

When winding or unwinding materials such as wire, thread, or cable, we often desire to maintain constant tension and velocity to ensure uniformity and prevent material damage.

Increasing Radius in Winding Operations

As the material winds onto a spool or drum, the effective radius (r) increases.
To maintain a constant velocity (v), we must understand the relationship: ωr = v, where ω is the angular velocity, and r is the radius.
As r increases during the winding process, ω (angular velocity) must decrease to keep v (velocity) constant.





Maintaining Constant Power

The power (P) in this context is given by P = Fv = Tω, where F is the force applied, v is the linear velocity, T is the torque, and ω is the angular velocity.

If we aim to keep F (force) and v (velocity) constant, then P (power) should also remain constant. However, as the radius increases and ω decreases, the torque (T) must be increased to compensate and maintain constant power.

Practical Implications

In practical terms, this means the motor controlling the winding mechanism needs to be capable of varying its torque output to compensate for the changing radius.

As the radius increases, the motor should automatically increase its torque to maintain constant tension and velocity.

Key Considerations

Control Systems: Advanced control systems are needed to monitor and adjust the parameters (like torque and angular velocity) in real-time.

Motor Selection: The motor must be capable of variable torque output. It should handle the highest torque required during the winding process without overheating or losing efficiency.

Mechanical Design: The design of the winding mechanism must accommodate changes in radius without affecting the material being wound.

Servo Motor Selection Criteria
Calculation and Review

Selection Criteria Calculation

Revolving Speed

Revolving Speed on Load Shaft $N_l = \frac{V_l}{P_B} = \frac{15}{0.01} = 1500 \text{ r/min}$

As it is direct connection to coupling, decelerating rate is $1/R = 1$

therefore, $N_M = N_l \times R = 1500 \times 1 = 1500 \text{ r/min}$

Load Torque

$$T_l = \frac{9.8\mu M P_B}{2\pi R\eta} = \frac{9.8 \times 0.2 \times 500 \times 0.01}{2\pi \times 1 \times 0.9} = 1.73 \text{ N·m}$$

Load Inertia Moment

Linear Movement Part $J_{L1} = M\left(\frac{P_B}{2\pi R}\right)^2 = 500 \times \left(\frac{0.01}{2\pi \times 1}\right)^2 = 12.7 \times 10^{-4}$

$\text{kg}\cdot\text{m}^2$

Ball Screw

$$J_B = \frac{\pi \rho L_B D_B^{\ 4}}{32} = \frac{\pi}{32} \times 7.87 \times 10^3 \times 1.4 \times 0.04^4 = 27.7 \times 10^{-4}\ \text{kg}\cdot\text{m}^2$$

Coupling $J_C = \frac{1}{8} \times M_C \times D_C^{\ 2} = \frac{1}{8} \times 0.06^2 = 4.5 \times 10^{-4}\ \text{kg}\cdot\text{m}^2$

Load Inertia Moment on Motor Shaft $J_L = J_{L1} + J_G + J_C = 44.9 \times 10^{-4}$

$\text{kg}\cdot\text{m}^2$

Load Operation Power

$$P_0 = \frac{2\pi N_M T_L}{60} = \frac{2\pi \times 1500 \times 1.73}{60} = 272\text{W}$$

Load Acceleration Power

$$P_a = \left(\frac{2\pi N_M}{60}\right)^2 \times \frac{J_L}{t_a} = \left(\frac{2\pi \times 1500}{60}\right)^2 \times \frac{44.9 \times 10^{-4}}{0.1} = 1108\text{W}$$

Tentatively select a servo motor based on the conditions above.
The motor specifications are as follows..

- Rated Output CSMD-1000(W)
- Rated Revolving Speed 2000 r/min
- Rated Torque 4.8 N·m
- Instant Maximum Torque 14.4 N·m
- Motor Shaft Inertia Moment: 6.17×10^{-4} kg·m²
- Allowed Load Inertia Moment on Servo Drive: 61.7×10^{-4} kg·m²

Tentative Selection of Servo Motor

When selecting a servo motor, the following conditions must be met.

- $J_L \leq$ Allowed Inertia Moment on Servo Drive
- Consumed Acceleration Torque = Instant Maximum Torque of Motor
- Consumed Deceleration Torque = Instant Maximum Torque of Motor
- T_{rms} = Rated Torque of Motor
- $P_o + P_a$ = (1 to 2) X Rated Output of Motor
- Motor Shaft Revolving Speed N_M = Rated Revolving Speed of Motor

Review Selection Criteria of Tentatively Selected Servo Motor

1. Motor Side Load Inertia Moment J_L

$J_L = 44.9 \times 10^{-4}$ kg·m² < Allowed Load Inertia Moment on Servo Drive: 61.7×10^{-4} kg·m²

2. Required Starting Torque (Consumed Acceleration Torque T_P)

$$T_P = \frac{2\pi N_M (J_M + J_L)}{60 t_a} + T_L = \frac{2\pi \times 1500 \times (6.17 \times 44.9)}{60 \times 0.1} + 1.73$$

$= 9.75$ N·m < Instant Maximum Torque of Motor

3. Require Stopping Torque(Consumed Deceleration Torque)

$$T_S = \frac{2\pi N_M (J_M + J_L)}{60 t_a} - T_L = \frac{2\pi \times 1500 \times (6.17 \times 44.9)}{60 \times 0.1} - 1.73$$

$= 6.29$ N·m < Instant Maximum Torque of Motor

4. Effective Torque (average)

$$T_{rms} = \sqrt{\frac{T_P^2 t_a + T_L^2 t_c + T_s^{\ 2} t_d}{t_c}}$$

$$= \sqrt{\frac{9.75^2 \times 0.1 + 1.73^2 \times 10 + 6.29^2 \times 0.1}{1.5}}$$

$= 3.31\ \mathrm{N{\cdot}m} <$ Rated Torque of Motor

5. Power

$P_a + P_o = 1108 + 272 = 1380\mathrm{W}$ < Motor Rated Output 1000W X (1 to 2)

6. Revolving Speed

$N_M = 1500\ \mathrm{rpm} < 2000\ \mathrm{rpm}$ < Rated Revolving Seed of Motor 2000 rpm

Final Selection of Servo Motor

The tentatively selected servo motor should meet all criteria above to be used. Selected AC servo motor generates torque which is influenced by speed as presented below.