DEMec - Dep. of Mechanical Engineering
SAIC- Automation, Instrumentation and Control Section
Master in Mechanical Engineering

Electromechanical Systems

1st Year– 2nd Semester
2025-2026

Support documents to TP classes

Starting Methods and Control for Induction Motors

Paulo Abreu

2026 Edition

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Starting Methods and Control for Induction Motors

Paulo Abreu

April 2026

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Contents

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The Importance of Starting Methods for Induction Motors

The choice of a suitable starting method for an induction motor depends on several factors, including:

- The specific application requirements (e.g., on/off control, speed control, torque control, and position control)
- The motor's power rating
- The type and characteristics of the load it drives
- The environmental conditions in which the motor operates

The selected starting method directly impacts:

- The motor's mechanical and electrical performance
- The overall stability and efficiency of the electrical installation

During startup, an induction motor can draw a high inrush current and generate significant torque, which may lead to mechanical and electrical stress on its windings, bearings, and shaft

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Induction Motor Starting Methods

Common starting methods

- Direct-on-line (DOL) starter
- Reduced-voltage starting methods
  - Auto-transformer Starter
  - Stator Resistors Starter
  - Star-Delta Starter

→ **Use of electromechanical components**

- Soft starter
- Variable frequency drive (VFD)

→ **Use of power electronics devices**

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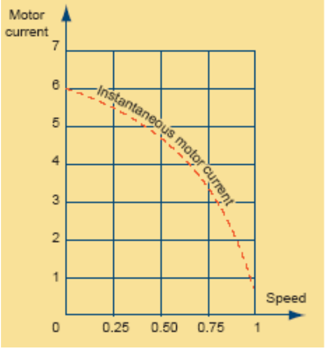
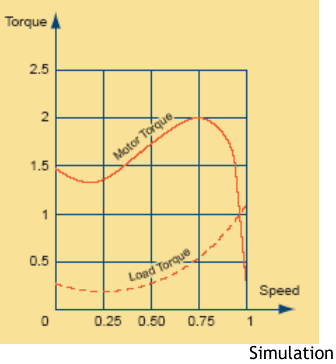
Direct-on-line (DOL) Starter

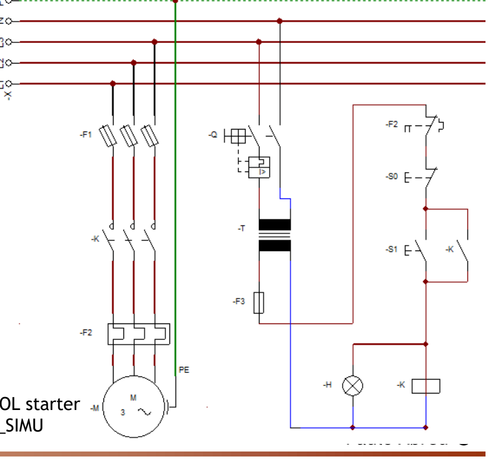
- Working Principle
  - Applies full voltage directly to the motor terminals, enabling an immediate startup. The motor is connected directly to the power supply through a contactor
- Advantages
  - Simple, cost-effective, and easy to implement
  - High starting torque (typically 0.5 to 2 x nominal torque)
  - Use of contactors and other protective switchgear
- Disadvantages
  - High inrush current (typically 5 to 8 x rated current) may cause electrical and mechanical stress
- Applications
  - Used for small motors, typically below 7.5 kW, with low starting torque requirements, such as pumps and fans

Direct-on-line (DOL) Starter





Circuit diagram



Simulation of DOL starter with CADe_SIMU

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Direct-on-line (DOL) Starter

Benefits

- Simple and cost-effective method
- Suitable for small to medium-sized motors
- No additional equipment or control circuitry is required, making it easy to install and maintain
- High starting torque, making it ideal for applications that require heavy starting loads

Drawbacks

- High start torque can be problematic for the application
- The current spike at start-up can affect the electrical network
- Need to have electrical power to accommodate start-up current
- Abrupt stops and starts
- The starting torque is fixed and cannot be adjusted, which may limit its usefulness in certain applications that require precise speed or torque control

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Reduced Voltage Starting Methods

Working principle (common to all methods)

- Reduces the applied voltage during startup to limit inrush current and minimize mechanical and electrical stress on the motor

Available methods

- **Auto-transformer Starter**
  - Use of auto-transformers between the electrical source and the motor
- **Stator Resistance Starter**
  - Use of resistors in serial on the stator windings
- **Star-Delta Starter**
  - Change of motor wiring configuration

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Auto-transformer Starter

- It uses an auto-transformer to step down the voltage supplied to the motor during startup. Typically, the start-up sequence involves three distinct voltage levels
- The auto-transformer is placed between the power supply and the motor, delivering 50-70% of the rated voltage to limit inrush current and starting torque
- Typical starting current ranges from 1.7 to 4 times the rated current, while starting torque varies from 0.5 to 0.85 times the rated torque
- Commonly used in the United States and for high-power motors exceeding 100 kW
- Potential current peaks during switching
- Higher cost due to transformer expenses

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Auto-transformer Starter

Benefits

- Reduced starting current and torque reduce the mechanical stress on the motor, leading to longer motor life
- Lower starting current also reduces the impact on the power supply, making auto-transformer starting suitable for larger motors
- Auto-transformer starting provides smooth starting, reducing the potential for voltage drops and other electrical issues

Drawbacks

- Auto-transformer starting is more complex and expensive than DOL starting
- The auto-transformer itself can be a potential point of failure, requiring maintenance and monitoring
- The starting torque is fixed and cannot be adjusted, which may limit its usefulness in certain applications that require precise speed or torque control

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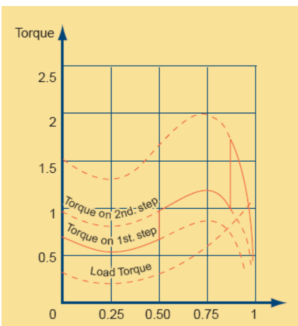
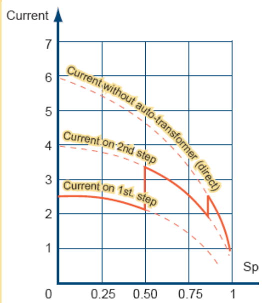
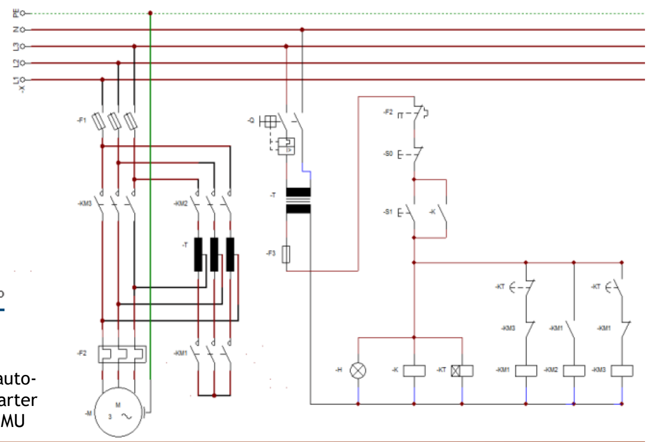
Auto-transformer Starter

Circuit diagram







Simulation of auto-transformer starter with CADe_SIMU

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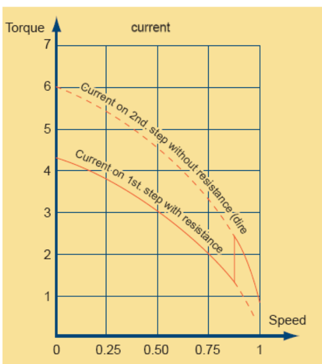
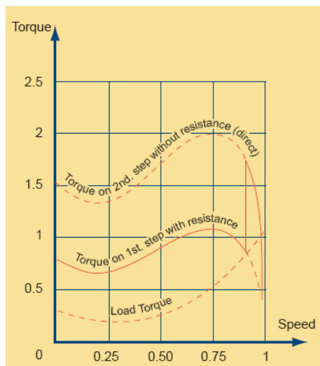
Stator Resistance Starter

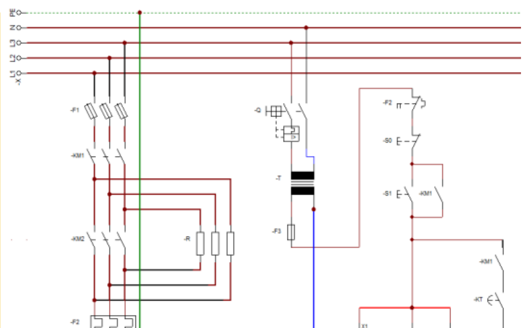
- **Working Principle**: introduces external resistances in the stator circuit to reduce initial voltage. Use of external power resistors, contactors, and timer relays
- **Advantages**: reduces starting current and provides smooth acceleration. Access to the six motor winding terminals is not required
- **Disadvantages**: inefficient due to power loss in resistors. A reduction in the voltage applied to the motor implies lower current levels and lower start torques
- **Applications**: used in older motor designs and specific industrial applications, such as the ones where the load torque increases with speed, such as fans

Stator Resistance Starter

Circuit diagram







Simulation of stator resistance starter with CADe_SIMU

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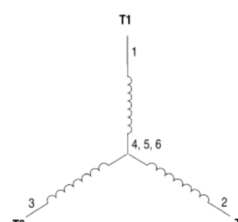
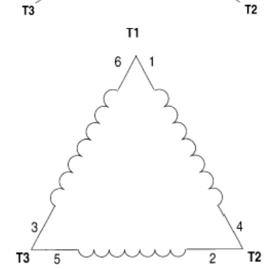
Star-Delta Starter

- **Working Principle**: this method reconfigures the stator windings from Star to Delta during the acceleration phase. By starting in Star, the voltage across each phase is reduced to $1/\sqrt{3} \approx 58\%$, which subsequently reduces the starting torque and current to $1/3$ of their DOL values

$$I_Y = \frac{1}{3} I_\Delta \quad and \quad T_Y = \frac{1}{3} T_\Delta$$

- **Advantages**: reduces initial inrush current and mechanical stress
- **Disadvantages**: it requires additional wiring and is not suitable for high-torque applications. A reduction in the voltage applied to the motor implies lower current levels and lower motor torque
- **Applications**: common in large industrial machines and HVAC systems





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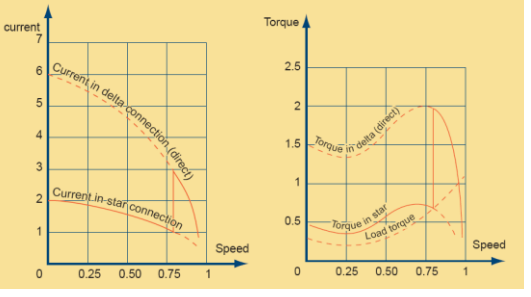
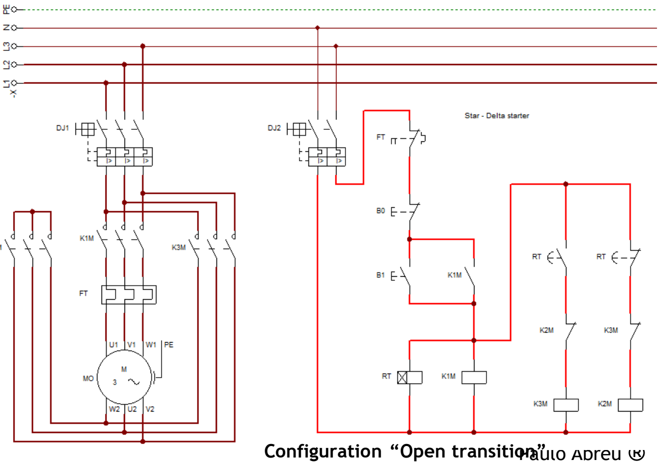
Star-Delta Starter



Simulation of star-delta starter with CADe_SIMU



Configuration "Open transition"

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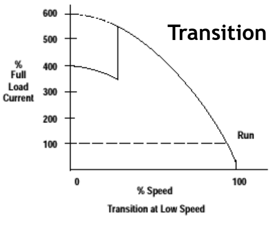
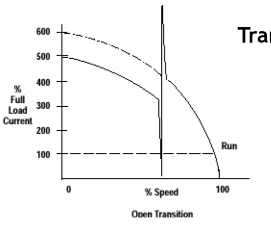
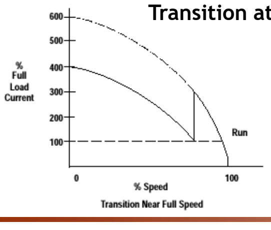
Star-Delta Starter



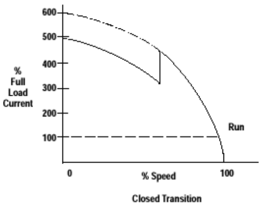
Transition at low speed



Transition with "open circuit"



Transition at high speed



Transition with "closed loop"
- Reduced spike during transition
- Need to use resistors and a 4th contactor

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Star-Delta Starter

Benefits

- Reduced starting current (1.5 to 2.6 x rated current) and starting torque (0.2 to 0.5 x rated torque)
- Economical control solution
- No major problems for the power grid

Drawbacks

- Smaller start torque can be an issue
- Problems can occur at the time of switching from star to delta by
- Current surge can trigger magnetic protection
- Possibility of using a delay of 1 to 2 s in the transition (inconvenience of being able to make the speed drop)
- Requires motors with 6 leads

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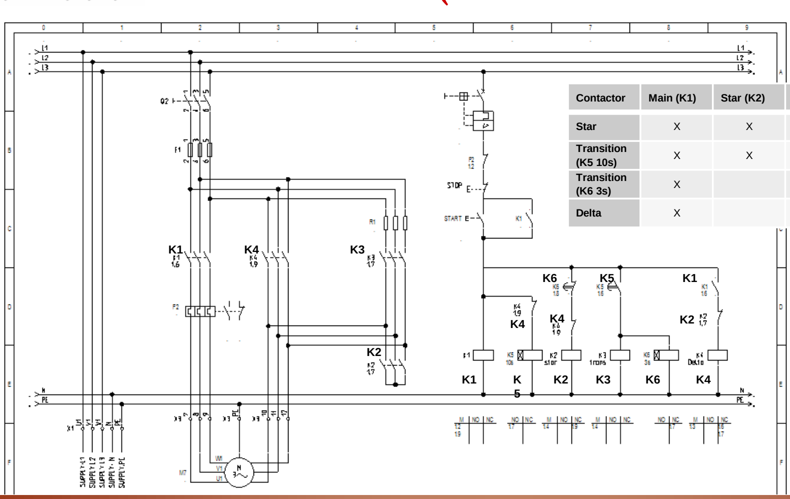
Star-Delta Starter (Closed Transition)



Contactor	Main (K1)	Star (K2)	Trans (K3)	Delta (K4)
Star	X	X		
Transition (K5 10s)	X	X	X	
Transition (K6 3s)	X		X	
Delta	X			X

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Soft Starters

- Working Principle: gradually increases the applied voltage using semiconductor devices. Solid-state power electronics devices are used to control/limit the voltage and current applied to the motor
- Advantages: provides smooth acceleration and extends motor life. Possible to define acceleration and deceleration ramps. Possibility of incorporating protection devices (e.g. thermal and magnetic) and motor diagnostic functions. Elimination of sudden changes in current (and torque)
- Disadvantages: higher cost and greater complexity than traditional methods
- Applications: used in water pumps, compressors, and HVAC systems. Wide range of motors, up to 900 kW

See video

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Soft Starters

The typical starting modes of a softstarter are

1. **Voltage Ramp (Timed Start)**
   The softstarter increases the RMS voltage from an initial value (e.g., 0 or 40% of nominal) to full line voltage over a user-defined time.
2. **Current Limit Starting**
   It is programmed a maximum allowable current (typically 200% to 400% of I_n), and the driver increases voltage until the current reaches the limit; then holds that voltage until the motor accelerates and the current naturally drops, allowing the voltage to climb again. In this way, the inrush current is restricted to prevent electrical stress
3. **Kick-Start Mode (Boost Start)**
   The softstarter applies a very high voltage pulse (nearly 100%) for a very short duration (typically 0.1 to 2.0 seconds) to break the load loose. Immediately after the "kick," it reverts to a standard Voltage Ramp or Current Limit mode.

See video

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Soft Starters

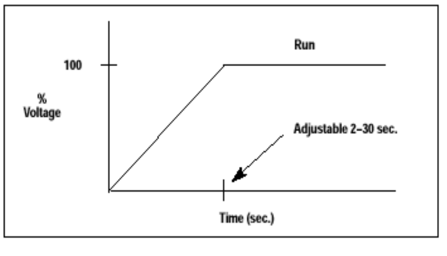
The typical starting modes of a soft starter are

4. Torque Control (The "Smart" Start)
   This is the most sophisticated method. Instead of focusing on electrical variables (Volts/Amps), the algorithm calculates the motor's actual air-gap torque
   The drive ensures a linear increase in torque. Since $T \propto V^2$, the voltage ramp is actually non-linear to compensate.

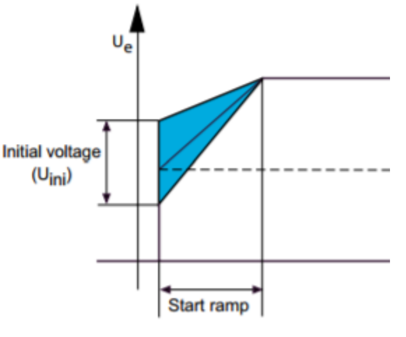
See video

Soft Starters: Start Modes

1. **Voltage Ramp (Timed Start)**



Mode "soft start"

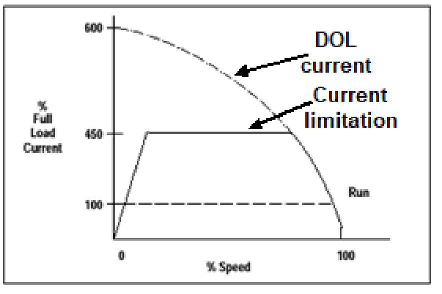


Voltage ramp, with non-zero initial value

Soft Starters: Start Modes

2. Current Limit Starting

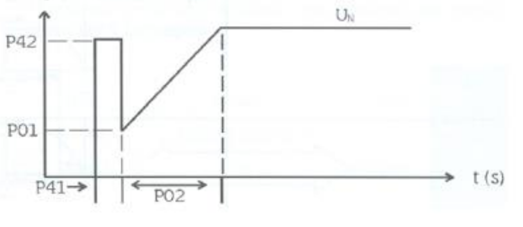
- current limitation (with voltage ramp)



Soft Starters: Start Modes

3. Kick-Start Mode (Boost Start)

voltage ramp with initial voltage pulse



Soft Sstarters: Typical Settings

- Typical Settings for Soft Starters with Current Limiting Function

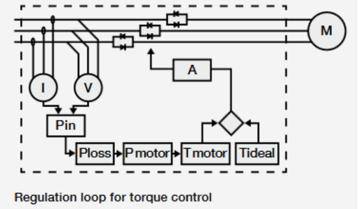
Additionally, a ramp-down time can also be defined for stopping

Type of load	Ramp time for start (sec.)	Ramp time for stop (sec.)	Initial voltage Uini	Current limit (x I_e)
Bow thruster	10	0	30 %	3
Centrifugal fan	10	0	30 %	4
Centrifugal pump	10	20	30 %	3.5
Centrifuge	10	0	40 %	4.5
Conveyor belt	10	0[1)]	40 %	4
Crusher	10	0	60 %	5
Escalator	10	0	30 %	3.5
Heat pump	10	20	30 %	3.5
Hydraulic pump	10	0	30 %	3.5
Lifting equipment	10	10	60 %	4
Mill	10	0	60 %	5
Piston compressor	10	0	30 %	4
Rotary converter	10	0	30 %	3
Scraper	10	10	40 %	4.5
Screw compressor	10	0	40 %	4
Screw conveyor	10	10	40 %	4
Stirrer, Mixer	10	0	60 %	5
Unloaded motor	10	0	30 %	2.5

(ABB Softstarter Handbook)

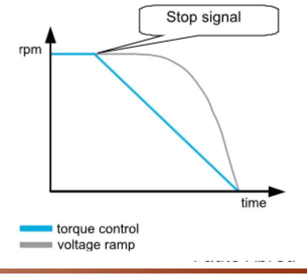
Soft Starters with Torque Control

- Some Soft Starters can implement a torque ramp, in addition to a voltage ramp and current limiting functions
- Torque control requires a regulation loop in which torque is calculated based on both current and voltage measurements. The calculated torque is then compared to the reference torque, and the voltage is adjusted accordingly to achieve the desired torque variation.



Regulation loop for torque control

Torque control for stopping a motor



(ABB Softstarter Handbook)

Comparison of Starting Mode in Soft Starters

Starting Mode	Controlled Variable	Primary Engineering Goal
Voltage Ramp	Voltage vs. Time	Mechanical smoothness on light loads
Current Limit	Amperes (I)	Grid stability / Protection of upstream breakers
Torque Control	Newton-meters (Nm)	Eliminating "Torque Snaps" and Water Hammer
Kick-Start	Instantaneous Torque/Voltage vs. Time	Overcoming high static friction (Stiction)

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Soft Starter with Torque Control

- Torque control is especially useful for stopping pumps where a sudden decrease of the speed may cause pressure peaks leading to water hammering

Example: ABB PSE soft starter

Catalogue

Technical specifications
- Rated operational current: 18...370 A
- Operational voltage: 208...600 V AC
- Wide rated control supply voltage: 100...250 V AC, 50/60 Hz

Features
- Voltage ramp and torque control for both start and stop
-- Current limit
- Kick-start
- Built-in bypass for energy saving and easy installation
- Illuminated display that uses symbols to become language neutral
- External keypad rated IP66 (Type 1, 4X,12) as an option
- Analog output for display of motor current

Protections
- Electronic overload protection
- Underload protection
- Locked rotor protection

Communication
- Built-in Modbus RTU and Fieldbus communication

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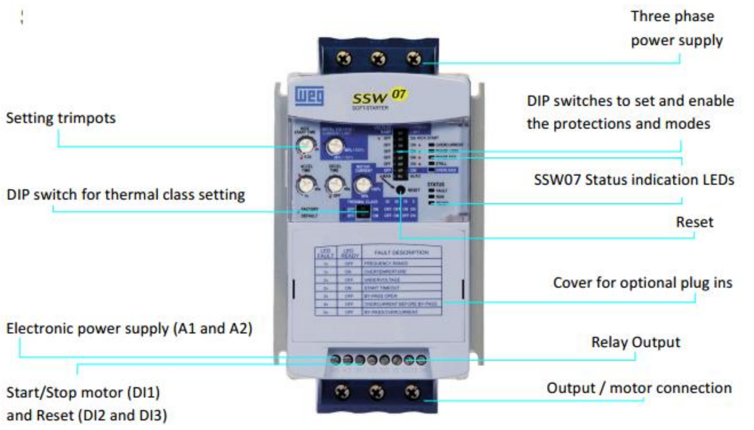
Soft Starter WEG SSW-07 series

Main features:

- Currents: 17 to 412 A
- Voltage: 220 to 575 V
- Built-in bypass
- Protection of the motor and built-in starter
- "Kick-Start" function for starting loads with high static friction
- RS-232, RS-485, DeviceNet or Ethernet communication (optional)



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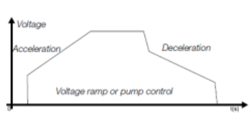
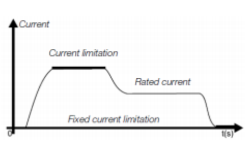
Soft Starter WEG SSW-07 series

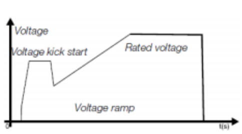
Voltage Ramp

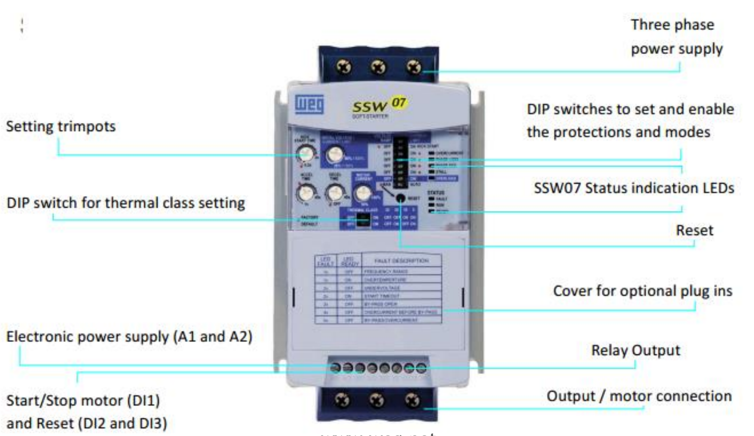


Current limitation



Kick start mode (voltage peak)





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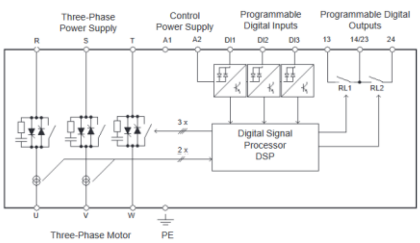
Soft Starter WEG SSW-07 series

- User manual
- Programming manual



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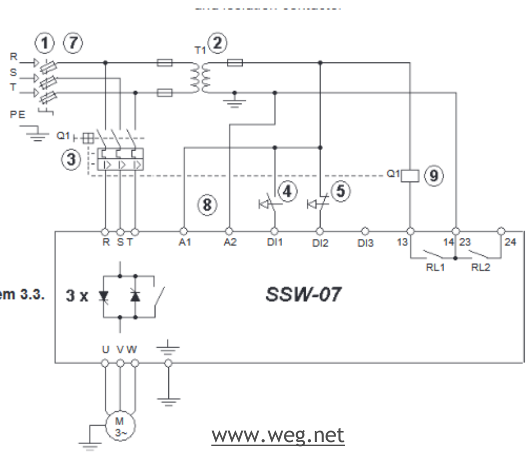
Soft Starter WEG SSW-07 series

Recommended Set-up with Command via Three-wire Digital Inputs and Circuit-Breaker

Refer to notes in item 3.3.



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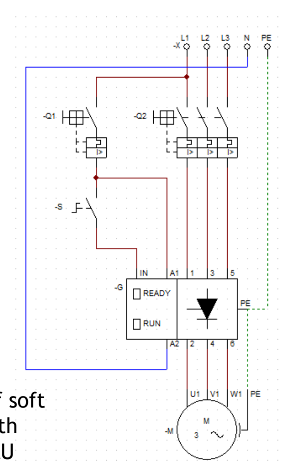

Simulation of soft starter with CADe_SIMU

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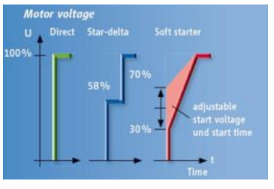
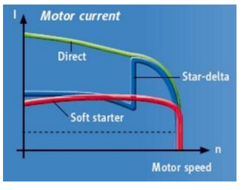
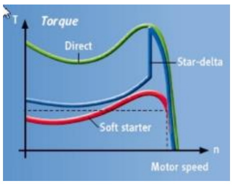
Comparison of starting times for Induction Motors

	Approximate starting times		
	DOL- direct on line start	Star-delta start	*Soft starter* (time ramp 10s)
Motor without load	0.2 - 0.5 s	0.4 s	1 s
Motor with reduced load	2 - 4 s	3 - 6 s	6 s
Motor with high load	6 - 8 s	8- 12 s	8-12 s







Images from [ref.]

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Comparison of Starting Methods for Induction Motors

Feature	Direct-On-Line (DOL)	Star-Delta (Y-Δ)	Soft Starter (SCR-based)
Starting Voltage	Full Line Voltage (V_L)	Reduced to 58% ($\frac{V_L}{\sqrt{3}}$)	Gradually ramped (Phase-angle control)
Starting Current	Highest: 500% to 800 x I_n	Moderate: ≈ 33% of DOL current	Controlled: Typically 200% to 400% x I_n
Starting Torque	Highest: 1.5 to 2.5 x T_n	Low: ≈ 33% of DOL torque	Adjustable: Low to Medium
Mechanical Stress	Severe: Instantaneous "jerk" on couplings and belts	Moderate: High stress during the star to delta transition.	Minimal: Smooth, linear acceleration
Cost & Complexity	Lowest; simple contactor and overload	Moderate; requires 3 contactors, timer, and 6-lead motor	Higher; involves power electronics (SCRs)
Dimensions	Smallest footprint	Bulky (multiple components)	Compact, but requires heat dissipation
Deceleration	Coast to stop only	Coast to stop only	Soft Stop: Controlled ramp-down (ideal for pumps)
Typical Applications	Small fans, pumps, compressors (< 7.5 kW)	Medium-sized motors with light starting loads	Conveyors, large pumps, high-inertia loads

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Variable Frequency Driver Definition and Purpose

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- **Definition:** a variable frequency drive (VFD) is an adjustable-speed electrical power drive system (IEC 61800) that controls an AC motor by converting a fixed-frequency power supply into a variable-frequency, variable-voltage output using power electronic converters
- **Functionality**: VFDs primary function is the control the speed and torque, adapting the motor's performance to varying load requirements. VFDs allow a smooth start and stop of the motor (acceleration/deceleration ramps). VFDs can reverse the direction of the motor by changing the phase sequence of the power supplied
- **Energy Efficiency**: VFDs improve energy efficiency by matching motor speed to the actual load, significantly reducing power consumption, especially in variable torque applications like pumps and fans
- **Applications:** VFDs are used in escalators, lifts, HVAC systems, industrial machinery, pumps, compressors, conveyors, crushers, and mills. VFDs are compatible with three-phase asynchronous Induction Motors (IM), Synchronous Reluctance Motors (SyncRM), and Permanent Magnet Synchronous Motors (PMSM)

VFDs generally have a higher initial cost compared to soft starters for equivalent motor power

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Variable Frequency Driver Internal Architecture

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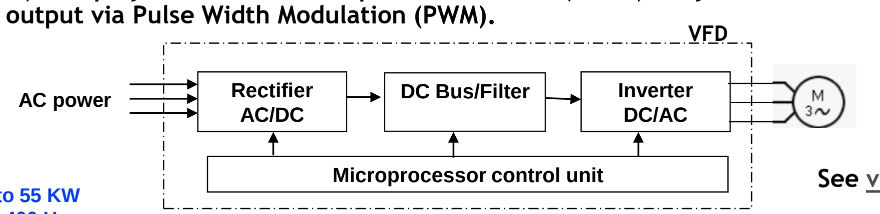
A Variable Frequency Drive (VFD) is composed of three main power stages:

1. **Rectifier (AC/DC) - Converts the fixed-frequency AC supply into DC using a diode bridge or an Active Front End (AFE)**
2. **DC Bus (DC Link) - Stores and smooths energy using capacitors (and sometimes reactors), providing a stable DC voltage and energy buffering**
3. **Inverter (DC/AC) - Employs Insulated Gate Bipolar Transistors (IGBTs) to synthesize a variable-frequency AC output via Pulse Width Modulation (PWM).**



- **Typical features:**
  - **Power range: 0.3 KW to 55 KW**
  - **Frequency range: 0 to 400 Hz**
  - **Power supply: single-phase or three-phase**

See video

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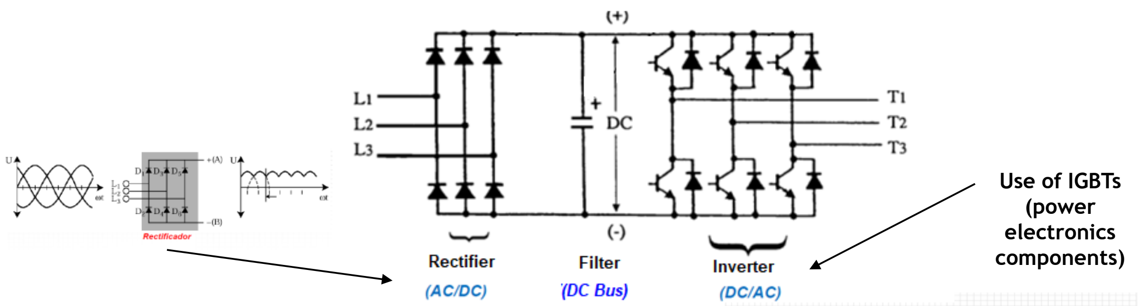
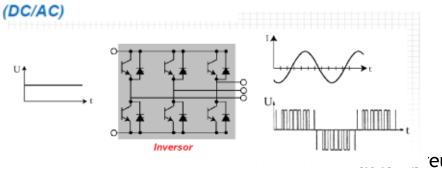
Variable Frequency Driver Internal Architecture



Note: voltage in DC circuit

- $V_{DC} = V_{in} * 1.35$ (three-phase VFD)
- $V_{DC} = V_{in} * 1.41$ (single-phasee VFD)



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Variable Frequency Driver Electrical Characteristics

- **DC Bus Characteristics**
  - The DC bus voltage is proportional to the supply voltage:
    - Three-phase supply: $V_{DC} \approx 1.35 \times V_{AC}\ (3 - Phase)$
    - Single-phase supply: $V_{DC} \approx 1.41 \times V_{AC}\ (1 - Phase)$
  - The DC link decouples the grid from the motor, enabling dynamic control and energy buffering
  - Over-voltage protection is critical during braking and regenerative operation

- **PWM Operation**
  - The inverter uses Pulse Width Modulation (PWM) to approximate sinusoidal phase voltages
  - Output frequency determines motor speed, while voltage amplitude controls magnetic flux
  - Switching frequency is typically in the range of 2–20 kHz, balancing output waveform quality, switching losses, and acoustic noise

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Variable Frequency Driver Electrical Characteristics

- **Power Semiconductor Devices (IGBTs)**
  - Insulated Gate Bipolar Transistors (IGBTs) are the most common switching devices
  - Key characteristics: high voltage and current capability; fast switching suitable for PWM; integrated free-wheel diodes
  - Emerging technologies (SiC MOSFETs) offer higher efficiency at higher switching frequencies
- **Control Perspective**
  - Although inverters generate voltage waveforms, modern VFDs internally regulate current, torque, or flux, depending on the control strategy (V/f, FOC, or DTC). The required voltage references are computed by the control unit and applied via PWM.

Variable Frequency Driver Key Benefits and Features

- Continuous speed regulation
- Controlled motor start
- Customizable speed ramps
- Incorporation of protection devices (thermal, magnetic, phase failure)
- Power factor correction
- Enhanced energy efficiency
- Motor control at constant torque up to rated speed and constant power above rated speed
- Operation above rated speed
- Support for direction reversal
- Mandatory use of VFDs for class IE2 motors

Variable Frequency Driver Control Methods

Modern Variable Frequency Drives (VFDs) implement different motor control strategies to regulate speed and torque. These methods differ in complexity, performance, required motor information, and suitability for industrial applications

- **Scalar Control (V/f Control)**
- Vector control (also known as Field Oriented Control, FOC)
  - **Sensor-less FOC**: open loop, without rotor position feedback signal
  - **Sensor-based FOC**: closed loop, with rotor position feedback signal
- **Direct Torque Control (DTC)**

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VFD with Scalar Control (*V/f* Control)

Concept

- Adjusts voltage and frequency of power supplied to the motor to maintain a constant *V/f* ratio up to the base frequency

Control Mechanism

- **PWM** (Pulse Width Modulation) voltage source inverter, to control the output voltage and frequency supplied to the motor

Applications

- **Speed Control (open loop)**: widely used for AC induction motors in pumps, fans, conveyors, etc.
- **Cost-Effective Solution**: provides a simple and economical method for motor control

Additional Features

- **Overload Protection**: safeguards the motor from excessive current
- **Fault Detection**: identifies and responds to operational issues
- **Integration**: includes *I/O* and communication interfaces for system integration

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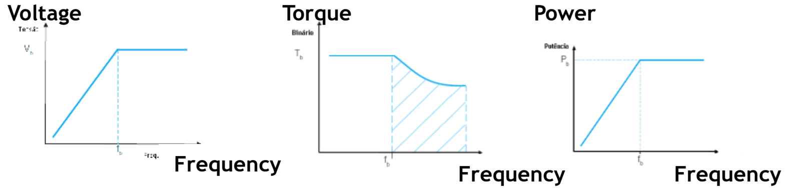
VFD with Scalar Control (V/f Control)

- **Constant V/f Ratio:** maintains a constant voltage-to-frequency ratio up to the base frequency(f_b). Beyond this frequency ($f > f_b$), the voltage remains constant at the motor's rated voltage, while only the frequency varies



Operating regions
- **Constant torque:** $0 < f < f_b$
- **Constant Power** (Field weakening): $f > f_b$

Some VFD provide Performance Enhancements at Low Speeds
- **Slip Compensation**: reduces speed variation based on load, improving motor performance at low speeds
- **Voltage Boost**: increases the V/f ratio to enhance motor performance

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VFDs with Vector Control
FOC - Field Oriented Control

- **Concept**
  - Vector Control allows for precise control of motor speed and torque by decoupling the control of flux and torque, mimicking the behavior of a separately excited DC motor. This method provides high performance, especially in applications requiring smooth and accurate motor control, even at low speeds and during transient conditions
- **How It Works**
  - **Current Measurement**: measure the motor's three-phase currents (I_a, I_b, I_c)
  - **Transformation:** use Clarke and Park transformations to convert these currents into a two-axis system:
    - ***d-axis* (direct):** aligned with the rotor's magnetic flux
    - ***q-axis* (quadrature):** perpendicular to the d-axis, responsible for torque production
  - **Control Loops**: independent PI (proportional-integral) controllers regulate the d-axis current (flux) and q-*axis* current (torque) based on desired speed/torque set points
  - **Inverse Transformation**: convert the controlled *d-q* currents back to three-phase voltages via inverse Park and Clarke transformations
  - **PWM Generation**: apply these voltages to the motor using pulse-width modulation (PWM) through an inverter
  - **Motor Model Identification**, by inputting parameters or auto-tuning

  (see Book from Infineon)

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VFDs with Vector Control
FOC - Field Oriented Control

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Applications

- Position, Speed, and Torque Control: ideal for applications requiring precise control of motor position and speed, such as robotics, CNC machines, and elevators
- Wide Speed Range: suitable for applications that demand high dynamic performance across various speeds

Additional Features

- **High Efficiency and Energy Savings**: optimizes motor performance and reduces energy consumption
- **Maximum Torque at Zero Speed**: capable of delivering full torque even when the motor is stationary
- **Enhanced Performance**: provides high dynamic performance and stability, making it suitable for demanding applications
- **Motor Compatibility**: suitable for various types of motors, including IM, PMSM, SynRM, BLDC and stepper motors

Implementation Methods

- **Sensor-less FOC**: operates without rotor position feedback, estimating rotor position and speed using motor parameters and feedback from current/voltage; requires motor modelling – possible to use autotuning
- **Sensor-based FOC**: uses an encoder or resolver for real-time feedback on rotor position, offering higher precision

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VFDs with Vector Control
Sensor-less FOC

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Concept

- Sensor-less FOC operates the motor without physical sensors like encoders or resolvers. Instead, it estimates the motor's position and speed using advanced algorithms based on stator current and voltage measurements

Applications

- Torque and Velocity Control

Additional Features

- Lower Performance at Low Speeds, when compared to sensor-based FOC
- Cost-Effective Solution, as it eliminates the need for position sensors

See Sensorless field-oriented control (FOC) using PSoC™ 6 MCU , **from Infineon**

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VFDs with Vector Control
Sensor-based FOC

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Concept

- Sensor-based FOC operates the motor with physical sensors like encoders or resolvers

Applications

- Position, Velocity and Torque Control: ideal for applications requiring precise control of motor position and speed, such as robotics, CNC machines, spindles, and elevators

Additional Features

- High Efficiency and Energy Savings: optimizes motor performance and reduces energy consumption
- High Dynamic Performance: provides dynamic performance close to that of PMSM
- Maximum Torque at Zero Speed: capable of delivering full torque even when the motor is stationary
- Enhanced Low-Speed Performance: offers better performance at low speeds compared to sensor-less FOC

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VFDs With Vector Control
Sensor-based FOC

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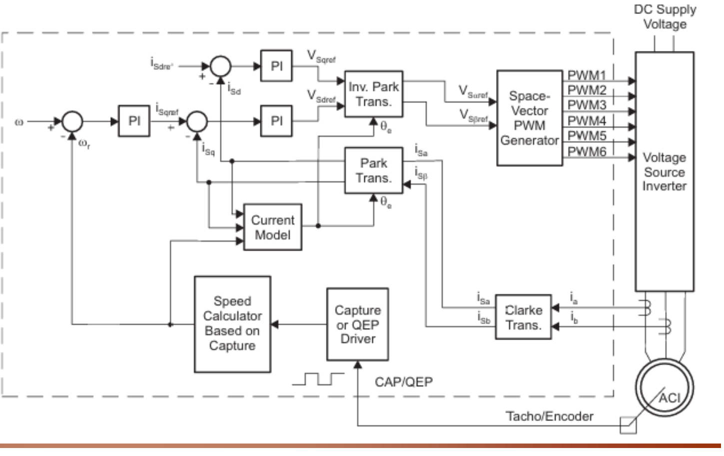
Sensored Field Oriented Control of 3-Phase Induction Motors from Texas Instruments



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VFD with Direct Torque Control - DTC

Direct Torque Control – DTC is an alternative to FOC. ABB did pioneering work in developing and refining DTC technology for high-performance motor control and has several patents.

- **Concept**
  - DTC is a simpler, more direct method that controls torque and flux magnitude directly by selecting appropriate voltage vectors from a predefined switching table, rather than regulating currents in a transformed frame, as in FOC
- **How It Works**
  - **Estimation:** measure stator currents and voltages to estimate the motor's torque and stator flux magnitude in real-time (using a motor model)
  - **Comparison:** compare the estimated torque and flux with reference values
  - **Switching Table:** use a hysteresis controller to select voltage vectors from the inverter (typically a 2-level or 3-level voltage source inverter) to correct torque and flux errors:
    - Torque too low? Increase it with a specific vector
    - Flux too high? Reduce it with another vector
  - **PWM-Free Operation:** directly applies the selected voltage vector without continuous PWM modulation (though some modern DTC variants incorporate PWM)

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VFD with Direct Torque Control - DTC

Applications

- Speed and Torque control
- Heavy machinery or dynamic loads, such as rolling mills, winders, and traction systems, where there is a need of rapid torque response and robustness

Advantages

- Extremely fast torque response (ideal for high-performance drives like traction systems)
- Robustness against motor parameter variations (less dependent on motor parameters)
- Simpler implementation than FOC: no need for coordinate transformations or continuous current control
- Can operate sensor-less more easily (flux and torque estimation often suffices)

Disadvantages

- Higher torque ripple due to hysteresis control and discrete voltage vector selection
- Variable switching frequency, which can increase losses and noise

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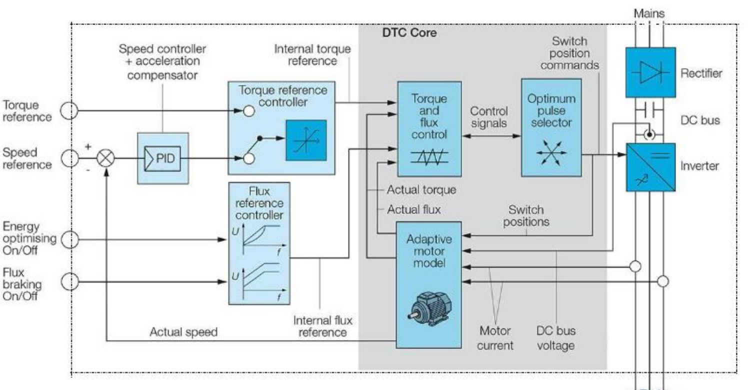
VFD with Direct Torque Control - DTC

ABB *Direct Torque Control*

Driver ACS880



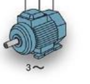


ABB Direct Torque Control

Technical guide No. 1, 2011

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Comparison (I)

Aspect	Scalar Control (V/f)	Sensorless Vector (FOC)	Sensor-Based Vector (FOC)	Direct Torque Control (DTC)
Controlled Quantities	Frequency and Voltage magnitude	Decoupled I_d (flux) and I_q (torque) currents	Decoupled I_d (flux) and I_q (torque) currents with position feedback	Stator Flux (ψ_s) and Electromagnetic Torque (T_e)
Torque Control	Indirect; relies on slip. Poor accuracy	Good; calculated via motor model	Excellent; highly accurate and linear	Superior; direct control without a modulator
Dynamic Response	Slow (> 100 ms)	Fast (10-20 ms). Suitable for most industrial loads	Very Fast (< 5 ms). Used for high-performance servos	Fastest (< 2 ms). Limited only by CPU and DC bus
Low-Speed Performance	Poor	Moderate	Excellent	Excellent
Zero-Speed Torque	None (no holding torque)	Limited (typically 150% for short periods)	100% Continuous (can hold full load at 0 RPM)	100% Continuous (High precision at standstill)

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Comparison (II)

Aspect	Scalar Control (V/f)	Sensorless Vector (FOC)	Sensor-Based Vector (FOC)	Direct Torque Control (DTC)
Motor Model Dependency	Very Low; only requires *V* and *f*	High; requires precise R_d, L_s, L_r, L_m	High; model must be perfectly tuned for stability	Moderate/High; requires R_s and flux estimator
Sensors Required	None	Current sensors only	Encoder/Resolver + Current sensors	Current and DC Link voltage sensors
Switching Frequency	Constant (Fixed PWM)	Constant (Fixed PWM)	Constant (Fixed PWM)	Variable (Hysteresis-based switching)
Torque Ripple	Low	Low	Very Low	High (inherent to hysteresis control)
Implementation Complexity	Simple; "Plug & Play"	High; requires Clarke/Park transforms and observers	Very High; requires feedback scaling and alignment	High; requires complex lookup tables/estimators
Typical Applications	Centrifugal pumps, fans, HVAC, simple conveyors	Extruders, mixers, industrial conveyors	Cranes, hoists, elevators, paper/steel mills	Crushers, traction, high-inertia test stands

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VFD with Four-Quadrant Operation

Concept

- Four-quadrant operation refers to the capability of an electric drive to operate with both positive and negative speed and both positive and negative torque. This allows the drive to function either as a motor (absorbing electrical energy) or as a generator (returning mechanical energy), in both directions of rotation
- The operating mode is defined by the sign of speed (ω) and sign of torque (T)

Quadrant	Speed (ω)	Torque (T)	Operating Mode
I	Positive	Positive	Forward motoring
II	Positive	Negative	Forward braking (generating)
III	Negative	Negative	Reverse motoring
IV	Negative	Positive	Reverse braking (generating)

VFD with Four-Quadrant Operation

Forward vs Reverse Braking

- Forward braking (Quadrant II): the motor rotates forward while torque opposes motion
- Reverse braking (Quadrant IV): the motor rotates in reverse while torque opposes motion
- Both cases involve energy dissipation or recovery, depending on the drive topology

Relation to Regenerative Drives

- In a non-regenerative VFD, braking energy is dissipated in a braking resistor
- In a regenerative drive (e.g. Active Front End, AFE), the inverter allows energy to be fed back to the grid or shared via a common DC bus
- Four-quadrant capability is a prerequisite for true regenerative operation

Four-quadrant operation is not a control algorithm, but a functional capability of the drive system. It enables bidirectional motion, controlled braking, and, when combined with regenerative hardware, energy recovery.

Braking Methods in Variable Frequency Drives

Purpose of Braking in Electric Drives

Braking methods are used to decelerate the motor, control overhauling loads, and manage the mechanical energy stored in rotating masses. During braking, an induction motor operates in generating mode, and the drive must safely handle the resulting energy

Three braking methods:

1. DC Injection Braking

- **Principle**: application of a direct current to the stator windings after the AC supply is removed. This creates a stationary magnetic field that produces a braking torque opposing rotor motion
- **Characteristics:**
  - Dissipates energy as heat in the motor
  - Simple and inexpensive
- **Typical Applications**: small drives, emergency stops, holding at low speed and near standstill, applications with infrequent braking

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Braking Methods in Variable Frequency Drives

2. Dynamic Braking (Braking Resistor)

- **Principle**: during deceleration, the motor operates as a generator and feeds energy back into the DC bus. When the DC-bus voltage exceeds a threshold, a braking chopper diverts energy to a braking resistor, where it is dissipated as heat
- **Characteristics**
  - Provides high braking torque
  - Widely used in industrial VFDs
  - Energy is not recovered, only dissipated
  - Requires external resistor and thermal management
  - Limited by resistor duty cycle
- **Typical Applications:** conveyors, cranes, elevators (non-regenerative), centrifuges, and machines with high inertia

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Braking Methods in Variable Frequency Drives

3. Regenerative Braking (Active Front End - AFE)

- **Principle**
  - The VFD uses an Active Front End (AFE) or regenerative inverter to convert mechanical energy back into electrical energy and feed it back to the grid or a common DC bus.
- **Characteristics**
  - True four-quadrant operation
  - High braking performance
  - Energy recovery improves efficiency
  - Low harmonic distortion and near-unity power factor
  - Higher cost and system complexity
- **Typical Applications**
  - elevators, hoists, cranes, winders/unwinders, test benches, traction systems, and energy-efficient industrial plants.

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Comparison of Braking Methods

Aspect	DC Injection	Dynamic Braking (Resistor)	Regenerative Braking (AFE)
Energy handling	Dissipated in motor	Dissipated in resistor	Returned to grid / DC bus
Braking torque	Low	High	High
Speed range	Low / near zero	Medium-high	Full range
Thermal stress	Motor heating	Resistor heating	Minimal
Hardware complexity	Very low	Medium	High
Energy efficiency	Poor	Low	High
Typical cost	Low	Medium	High
Four-quadrant capable	No	Partial	Yes

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Industrial Compliance: EMC and Harmonics

VFDs are non-linear loads that introduce **harmonics** into the power grid and **high-frequency Electromagnetic Interference** (EMI)

- **Harmonics**
  - Low-frequency distortion that affects the power quality of the electric grid
  - Mitigation requires DC reactors, line reactors, passive filters, and Active Front Ends (AFE)
- **EMC (**Electromagnetic Interference (EMI) and Electromagnetic Susceptibility (EMS))
  - IEC 61800-3 classifies drives according to their intended environment and emission limits, defining four categories from C1 (Residential), C2 (Commercial/ Light Industrial, C3 (Industrial) and C4 (Large Industrial)
  - **Compliance requires shielded cables, proper grounding, and RFI filters**

Shielded cables are not optional in professional installations!

Standards and Regulations for Variable Frequency Drives

Energy Efficiency Regulations (IE Classes)

- Motor efficiency is classified according to IEC 60034-30-1: IE1, IE2, IE3 or IE4
- Since July 2021, the VFD itself now has its own mandatory efficiency rating (see EU Eco design directive doc)

- The VFD specification extends beyond functional speed control to encompass strict legal compliance
- In Europe, the choice must ensure the system adheres to the Ecodesign Directive (EU 2019/1781), mandating minimum IE2 efficiency levels for the power converter. Simultaneously, the EMC Category (C1, C2, or C3) must be selected based on the installation environment to mitigate electromagnetic interference and ensure electromagnetic compatibility with sensitive peripheral electronics

Motor Thermal Protection and Low-Speed Derating

For self-ventilated (TEFC) motors, the cooling fan is shaft-mounted.
At low speeds, airflow drops significantly, reducing the motor's ability to dissipate heat.

- Engineering Solution: if continuous T_{rated} is required at low speeds, "Forced Ventilation" (an independent electric fan) must be utilized

- Alternative: the motor must be **thermally derated** according to manufacturer's curves

The VFD can also use motor temperature sensors (PTC/PT100) to prevent overheating

Note: it is a common failure point in mechanical design to assume a motor can provide rated torque indefinitely at 5Hz without extra cooling!

Variable Frequency Driver Selection

When selecting and sizing a Variable Frequency Drive (VFD), consider the following factors:

- **Motor Type**
  - **Asynchronous Induction Motors**: commonly used with VFDs, but **Permanent Magnet Synchronous Motors** and **Reluctance Motors** can also be suitable for VFD applications
- **Motor Characteristics**
  - **Rated Current and Supply Voltage**: ensure the VFD voltage matches the motor's voltage (e.g., 230V, 400V, or 480V). For example, if the VFD is powered at 230 V, it cannot provide a higher output voltage. The VFD must handle the motor's current at full load
- **Application/Drive Type**
  - **Torque and Speed Requirements**: determine the specific needs of your application
  - **Overload Level**: Consider the typical overload values:
    - Low Duty (LD): 120% of rated current for 60 seconds
    - Normal Duty (ND): 150% of rated current for 60 seconds

Variable Frequency Driver Selection

When selecting and sizing a Variable Frequency Drive (VFD), consider the following factors:

- **Load Type**
  - **Variable Torque Applications**: such as fans and pumps
  - **Constant Torque Applications**: such as conveyors, mixers, crushers, extruders, and winches
- **Environmental Conditions**
  - Consider factors such as temperature, humidity, and exposure to dust or chemicals where the VFD will be installed
- **Input Power Supply**
  - Match the VFD to the supply voltage and phase type (single-phase or three-phase).
  - Consider harmonics management to comply with distortion regulations
- **Control Features**
  - Look for VFDs that offer the necessary control methods (V/F, sensor-less FOC, sensor-based FOC, DTC), interfaces, programmability, and communication protocols
- **Safety and Protection Features**
  - Ensure the VFD includes overload protection, thermal management, and compliance with the relevant safety standards

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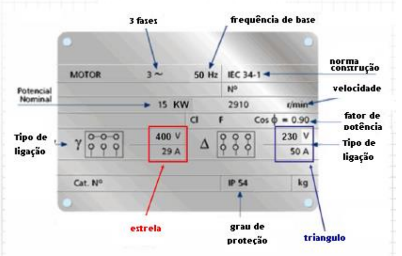
Variable Frequency Driver Selection



Trifásico: 3G3RX-□			A4004	A4007	A4015	A4022	A4040	A4055	A4075	A4110	A4150
Motor kW*1			0,4	0,75	1,5	2,2	4,0	5,5	7,5	11	15
acterísticas de salida	Capacidad del convertidor kVA	400 V	1,0	1,7	2,5	3,6	6,2	9,7	13,1	17,3	22,1
		480 V	1,2	2,0	3,1	4,3	7,4	11,6	15,8	20,7	26,6
	Corriente nominal de salida (A) en CT		1,5	2,5	3,8	5,3	9,0	14	19	25	32
	Corriente nominal de salida (A) en VT		1,9	3,1	4,8	6,7	11,1	16	22	29	37

For this motor:

- Single-phase powered VFD (230V) requires motor configured with delta connection
- Three-phase powered VFD, requires motor configured with star connection

CT - heavy load
VT - light load

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Variable Frequency Driver Selection

A VFD is a thermally-limited device rather than a fixed-power one, operating on a trade-off between between **Current (*I*)** and **Time (*t*)**.

- Through "Dual" or "Triple" ratings (e.g.,VLD, LD, and ND), the same hardware can be optimized for different applications. By selecting specific software parameters, the drive adjusts its thermal management of the IGBTs to prioritize either high continuous current or superior overload resilience.
- VFD drives series like the Omron RX2 (pp.281) or Yaskawa provide 3 rating modes

Rating Mode	Overload Capacity	Typical Load Profile	Engineering & Commercial Benefit
ND - Normal Duty	150% for 60 sec	Constant Torque: Conveyors, Hoists, Crushers, Extruders	High "Breakaway Torque" to overcome static friction; ruggedness against shock loads
LD - Low Duty	120% for 60 sec	Variable Torque: Centrifugal Pumps, Standard Fans, Blowers	Allows a one-size larger motor to be driven by the same VFD frame, reducing system cost
VLD - Very Low Duty	110% for 60 sec	Ultra-Low Torque: HVAC Fans, Clean water circulation	Maximum Power Density: Allows up to a two-size larger motor, maximizing energy efficiency and space

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Variable Frequency Driver Selection - Typical Rating Modes

Characteristic	Very Low Duty (VLD)	Low Duty (LD/VT)	Normal Duty (ND/CT)
Typical Load Type	Constant/Ultra-low Torque	Variable Torque	Constant Torque / High Impact
Overload Capacity	110% for 60 sec	120% for 60 sec	150% for 60 sec
Power Capacity	Highest (Maximized)	High	Standard (Nominal)
Continuous Current (I_c)	120%-130% of Nominal	~115% of Nominal	100% (Nominal)
Primary Applications	Fans, Centrifugal Pumps (low head), HVAC	Mixers, Pumps, light Conveyors	Crushers, Hoists, Cranes, Extruders
Carrier Frequency	High (Quiet operation)	Medium	Low (to manage heat)
Motor Size vs. VFD Frame	Motor is often two sizes larger than VFD frame	Motor is one size larger than VFD frame.	Motor matches the VFD frame size
Thermal Protection	Very Sensitive; minimal headroom for surges	Standard variable-torque protection	Robust; allows for significant thermal transients

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Variable Frequency Driver Selection

- While multi-rating features offer significant flexibility, the most appropriate criterion for VFD selection is the **Effective Motor Current** (I_{RMS}), aligned with the application's **Transient Overload Profile** and **Duty Cycle**.
- Furthermore, for constant torque loads at low speeds, the reduction in the motor's self-cooling capacity must be accounted for by checking the motor and VFD's derating curves
- Sizing by nominal power (kW/HP) is insufficient; precise selection requires aligning the drive's **thermal current limit** with the **peak** and **continuous demands of the application**

Note:

A common industrial failure occurs when a VFD is specified in **VLD** mode for a pump handling high-viscosity fluid. If the fluid settles, the "Static Friction" (Stiction) required to restart the pump may exceed 110% of the drive's current limit. The drive will trip on an I^2t (**Overload**) fault before the shaft even moves. In such cases, the choice should be **Heavy Duty** even if the load is technically a "pump"

Variable Frequency Driver Selection

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Parameterization Example (Omron MX2)

The choice of operating mode is made by selecting one of the inverter configuration parameters (B049

Example: VFD Omron 3G3 MX2

Rated voltage	Enclosure ratings	Max. applicable motor capacity		Model
		CT: Heavy load	VT: Light load	
3-phase 400 VAC	IP20	0.4 kW	0.75 kW	3G3MX2-A4004
		0.75 kW	1.5 kW	3G3MX2-A4007

Parameter No.	Function name	Data	Default setting	Unit
b049	Heavy Load/Light Load Selection	00: Heavy load mode (CT)	00	–
		01: Light load mode (VT)		

	Heavy load (CT)	Light load (VT)
Feature	A load that requires high torque under certain conditions such as at the start and during acceleration/ deceleration.	A load that does not require much torque.
Application	Lifts, cranes, conveyors, etc.	Fans, pumps, air-conditioners, etc.
Rated current (example)	1.0 A (3-phase 200 V 0.1 kW)	1.2 A (3-phase 200 V 0.1 kW)
Overload current rating	150% 60 s	120% 60 s

Variable Frequency Driver Selection

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Example: VFD 3G3 MX2 - A4004

Three-phase 400 V Class

CT: Heavy load, VT: Light load

Function name			3-phase 400 V			
Model name (3G3MX2-)			A4004	A4007	A4015	A4022
Applicable motor capacity	kW	CT	0.4	0.75	1.5	2.2
		VT	0.75	1.5	2.2	3.0
Rated output capacity [kVA]	380 V	CT	1.1	2.2	3.1	3.6
		VT	1.3	2.6	3.5	4.5
	480 V	CT	1.4	2.8	3.9	4.5
		VT	1.7	3.4	4.4	5.7
Rated input voltage			3-phase 380 V – 15% to 480 V + 10%, 50/60 ± 5%			
Rated output voltage			3-phase 380 to 480 V (The output cannot exceed the incoming voltage).			

CT: Heavy load, VT: Light load

Function name		3-phase 400 V			
Model name (3G3MX2-)		A4004	A4007	A4015	A4022
Rated output current [A]	CT	1.8	3.4	4.8	5.5
	VT	2.1	4.1	5.4	6.9
Short-time deceleration braking torque (%) (Discharge Resistor not connected)		50	50	50	20
Braking Resistor circuit*1	Regenerative braking	Built-in Braking Resistor circuit (separate Discharge Resistor)			
	Min. connectable resistance [Ω]	180	180	180	100
Weight [kg]		1.5	1.6	1.8	1.9
Dimensions (width × height) [mm]		108 × 128			
Dimensions (depth) [mm]		143.5	170.5		

*1. The BRD usage is 10%.

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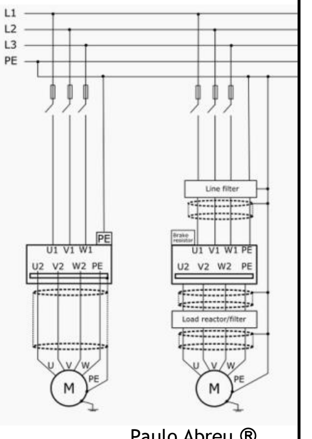
Variable Frequency Driver Wiring

- **Power wiring**
  - Input power wiring: use fuses, switches, and line filters
  - Motor connections: use load filter
- **Control wiring**
  - Control terminals for digital and analog inputs. These are used for start/stop commands, speed reference signals, and other control functions
  - Communication Wiring
- **Grounding**
  - Proper grounding is crucial to prevent electrical noise and ensure safety. Connect the VFD's ground terminal to a reliable ground point
- **Additional Considerations**
  - Use Shielded Cables for control wiring to minimize electrical interference.
  - Keep power and control wiring **separate** to reduce noise and interference

Simulator in CADe_Simu



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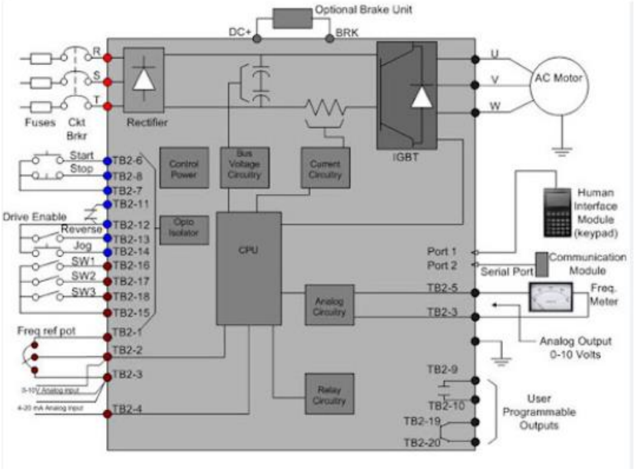
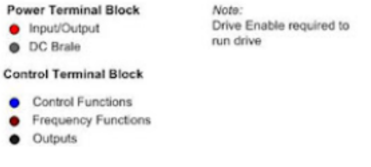
Variable Frequency Driver Wiring





http://www.vfds.org/

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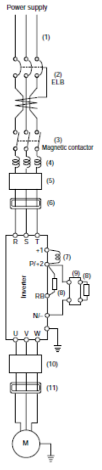
Variable Frequency Driver Wiring



(1) (2) (3) Switchgear components for protection and control
(2) (4) Input AC reactor
Apply this reactor as a harmonic suppression measure, or when the imbalance ratio of power supply voltage is 3% or more, power supply capacity is 500 kVA or more, or power supply voltage changes suddenly. It also helps improve the power factor.
(5) Input noise filter
This noise filter reduces the conducted noise generated by the Inverter and traveling through the wires. Connect it to the primary (input) side of the Inverter.
(6) Radio noise filter
When the Inverter is used, noise may generate in a nearby radio, etc. through the power wiring, etc. Use this noise filter to reduce such noise (= reduce radiated noise).
(7) DC reactor
This reactor suppresses the harmonics generated by the Inverter.
(8) Braking resistor and (9) Regenerative braking unit
Use this Unit to increase the braking torque of the Inverter to permit frequent ON/OFF switchings, or decelerate a load whose inertial moment is large.
(10) Output noise filter
This noise filter is installed between the Inverter and motor to reduce the radiated noise emitted from the wires. Use it to reduce radio interference in radios and TVs, or prevent malfunctioning of measuring equipment, sensors, etc.
(11) Radio noise
Apply this noise filter to reduce the noise generating on the output side of the Inverter (both the input side and output side).

(from 3g3MX2 manual)

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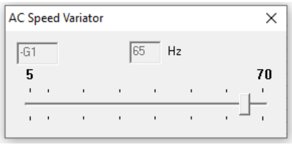
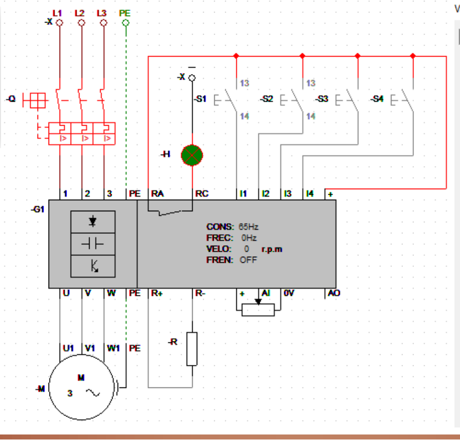
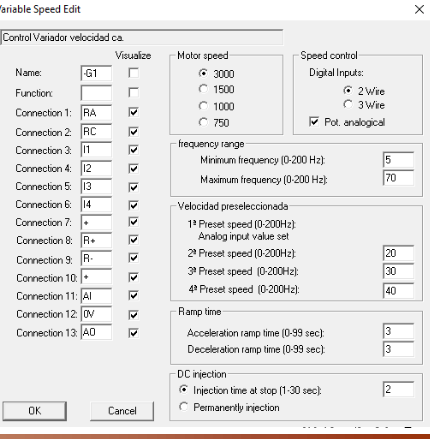
Variable Frequency Driver Simulation with CADe_SIMU







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Variable Frequency Driver Commissioning

Some special care to be taken with the use of VFDs

- **Harmonics in the Electrical Network**
  - **Harmonics**: VFDs can introduce harmonics into the electrical network, affecting other equipment. Using harmonic filters can mitigate these effects
- **Installation of Output Filters**
  - **Load Reactance**: helps to reduce voltage spikes and protect the motor
  - **dV/dt Filters**: reduce the rate of voltage change, protecting motor insulation
  - **Sinusoidal Filters**: provide a near-sinusoidal voltage waveform to the motor, reducing motor heating and noise
- **Increase in Switching Frequency**
  - Higher switching frequencies can reduce motor noise but may increase losses in the VFD. Balance is key

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Variable Frequency Driver Commissioning

Some special care to be taken with the use of VFDs

- **Noise (High-Frequency Disturbances)**
  - **Install Chokes (Ferrites)** to reduce high-frequency noise and protect sensitive equipment
- **Minimize Length of Inverter/Motor Electrical Cables**
  - Shorter cables reduce the risk of voltage drops and electromagnetic interference (EMI)
- **Installation in Electrical Cabinet**
  - Ensure adequate space for cooling and proper ventilation to prevent overheating of VFD
- **Protections in the Electrical Supply of the VFD**
  - **Circuit Breaker or Fuses + Switch to** protect the VFD from overcurrent and short circuits
  - **Use a Differential Switch (Class B), suitable** for high-frequency leakage currents

Variable frequency driver Commissioning

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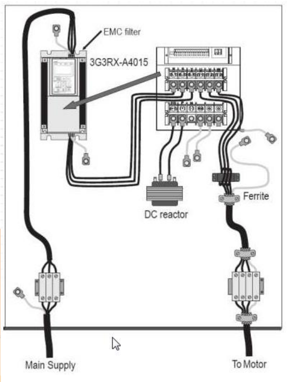
- **EMC filter (for high frequencies)**
  - Categories C1, C2 and C3 (standard IEC 61800-3:2022)

  - Ferrites



  - Reduce the level of radiated emissions, complying with EMC
  - Ferrite selection taking into account the size of the electrical cables use

Referencia 3G3IV-	D (mm)	Potencia aprox. variador (KW)
PFO OC/1	21mm	≤ 2.2KW
PFO OC/2	28mm	≤ 15KW
PFO OC/3	50mm	≤ 45KW
PFO OC/4	58mm	> 45 KW

	3G3IVPFOOC/1E-V1		
Nº VUELTAS	1	2	3
SECCION HILO	10mm^2	6mm^2	4mm^2
INDUCTANCIA	38µH	86µH	153µH
CORRIENTE MAX.	60A	45A	30A

Variable frequency driver Commission and Parameterization

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Practical commissioning involves a structured sequence:

- Input Motor Nameplate Data: Current, Voltage, and Base Frequency
- Auto-tuning: especially critical for Vector Control to identify internal motor constants (R_s, L_m)
- Select Control Mode: choose the appropriate control method.
- Select rating mode (VLD, LD, ND)
- Configure inputs: Assign Start/Stop logic and Speed Reference (e.g., 0-10V or Modbus)
- Configure Outputs: Actual speed, Fault or Alarm detection, Current
- Protection Limits: Set I_{limt}, Acceleration/Deceleration ramps, and thermal models
- Save settings

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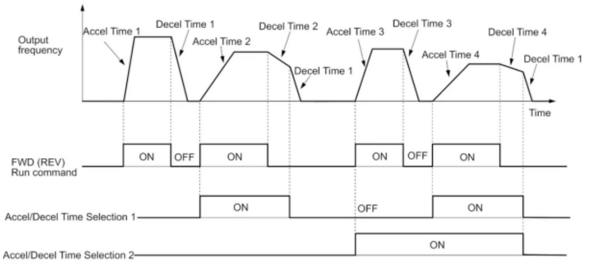
Variable Frequency Driver Commissioning

- **Typical configuration of VFD**
  - Ramps: the ramp-up and ramp-down time parameter define the maximum motor acceleration when the speed set-point changes



Timing Diagram of Accel/Decel Time Change

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Variable frequency driver commissioning

- Typical protection functions
  - Overload protection: protects the motor from overheating by monitoring the current and ensuring it does not exceed the motor's rated capacity for a prolonged period
  - **Phase Loss Protection:** detects the loss of one phase in the power supply, which can cause unbalanced currents and potential damage to the motor
  - **Load Loss Protection:** monitors the load on the motor and detects if the load is lost, which can indicate a mechanical failure or disconnection
- Typical alarm functions
  - Output current drops below-set value: triggers an alarm if the output current falls below a predefined threshold, which can indicate a loss of load or other issues
  - Output current reaches set value: alerts when the output current reaches a set value, indicating that the motor is operating at its maximum capacity
  - Operating at a set value of frequency: generates an alarm when the VFD operates at a specific frequency, which can be used to monitor and control critical operating conditions

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VFD
Omron 3G3MX2-A4004-EV2

- Drive control method: Open loop V/f, open loop vector
- Drive supply voltage: 400 V three-phase
- Dual rating, 0.4/0.75 kW (CT/VT), 1.8/2.1 A (CT/VT),
- Max. output frequency: 400 Hz
- Four control modes: constant torque, reduced torque, free V/f setting e sensor-less vector control
- PID control
- High starting torque (200% at 0.5Hz, with sensor-less vector control mode)
- Side-by-Side (Zero Clearance) Installation
- Electric power: cable AWG 16(1.3 mm), contactor H10C, fuse 10A, class J,600V AC,200kA (ex. Cooper Bussemann) DFJ 5A drive fuse, earth leakage breaker EX50C (5A, 100 mA, time delay type)
- Compatible motor type: Induction motor (IM), Permanent magnet motor
- Possibility of controlling two motors (not simultaneously!)
- Automatic energy saving function

MX2 Series Type EV2 User Manual (614 pages)

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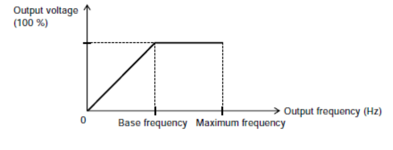
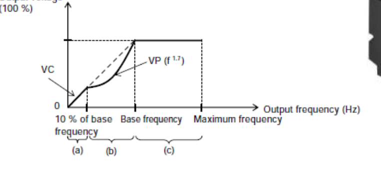
VFD
Omron 3G3MX2-A4004-EV2

Control mode (parameter A044/A244)

- 00: constant torque

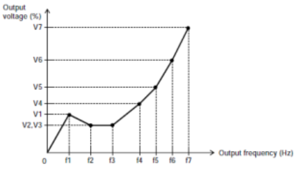


- **01: reduced torque**



- 03: free V/f setting

7 working points



- **04: sensor-less vector control requires auto tuning active “torque limit” function, uses preset values or selectable via digital or analog inputs**

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VFD
Omron 3G3MX2-A4004-EV2

Other parameters (non-exhaustive list - manual with 614 pages!)

- Monitoring mode:
  - Parameter d001 Output monitor frequency
  - Parameter d002 Output current monitor
  - Parameter d013 Output voltage monitor
- Operating mode
  - Parameter A003 Base frequency 1
  - Parameter A004 Maximum frequency 1
  - Parameter A082/A282 Motor Incoming Voltage Selection 1/2
  - Parameter A002 Run command selection 1
  - Parameter f001 Starting frequency to maximum frequency 1
  - Parameter f004 Run direction selection
  - Parameter A071 PID Selection
  - Parameter b083 Carrier Frequency

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