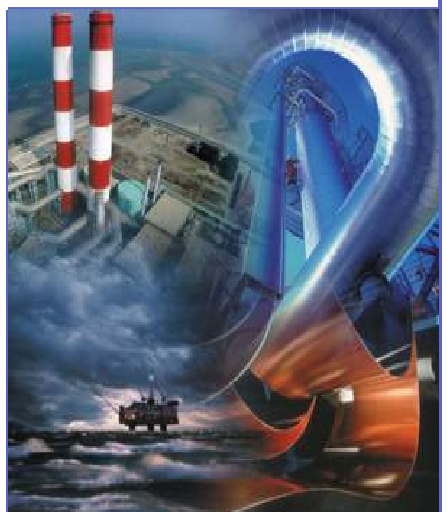
Christian Bruderer



Medium Voltage Drives

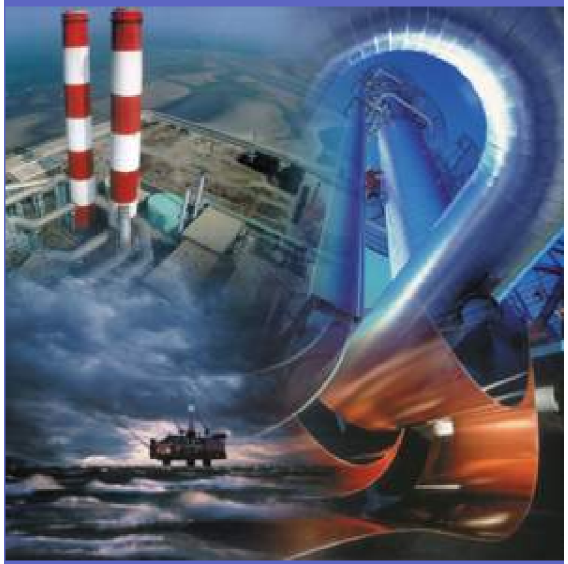
Technologies & Applications

MUSIC CITY POWER QUALITY

IEEE Central Tennessee Section

ABB

Overview



- Variable Speed Drives
  - Definitions
  - VSD Topologies
  - Motor Control Platforms
  - Comparison LV- vs. MV Drives
- Industries and Applications
- Benefits of Variable Speed Control
- VSD System Issues and Considerations
  - Network
  - Transformer
  - Variable speed drive
  - Motor

Overview

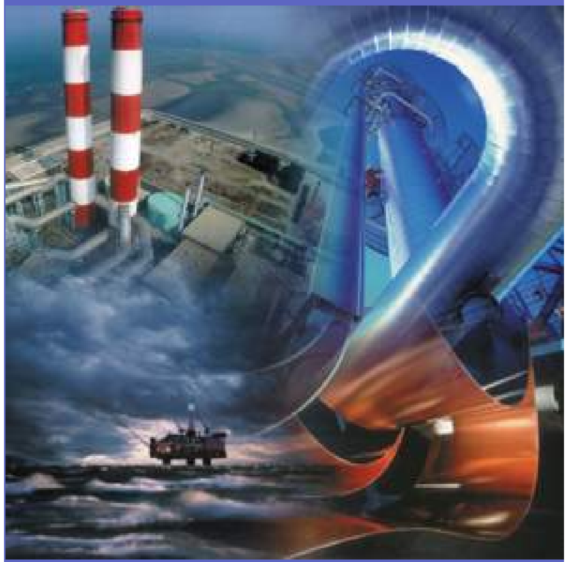


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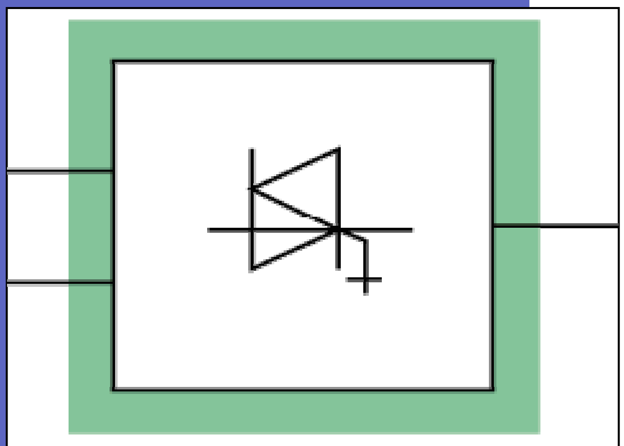
ABB

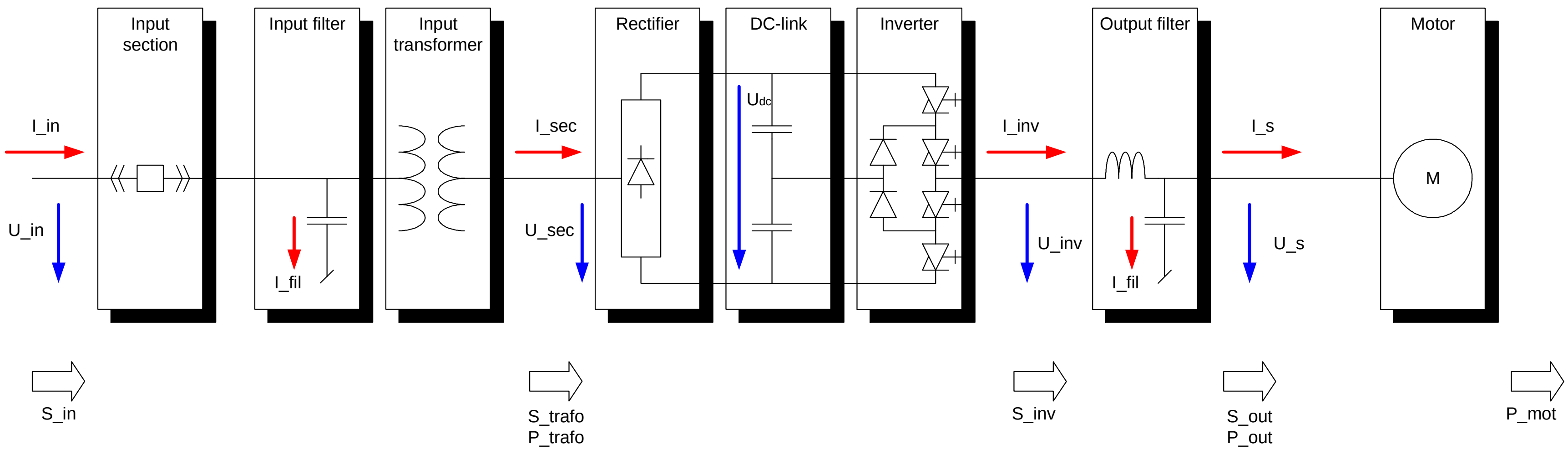
What is a Variable Speed Drive (VSD)[*1]?



- A device that converts a fixed voltage and frequency into a variable voltage and frequency
- It provides functionality to adjust motor speed and torque in a wide range

*1) A Variable Speed Drive is often referred to as a VSD, an AC Drive, a converter, an inverter or quite simply a drive. Other alternatives include VVVF = Variable Voltage Variable Frequency; and ASD = Adjustable Speed Drive

Basic MV Drive System Components



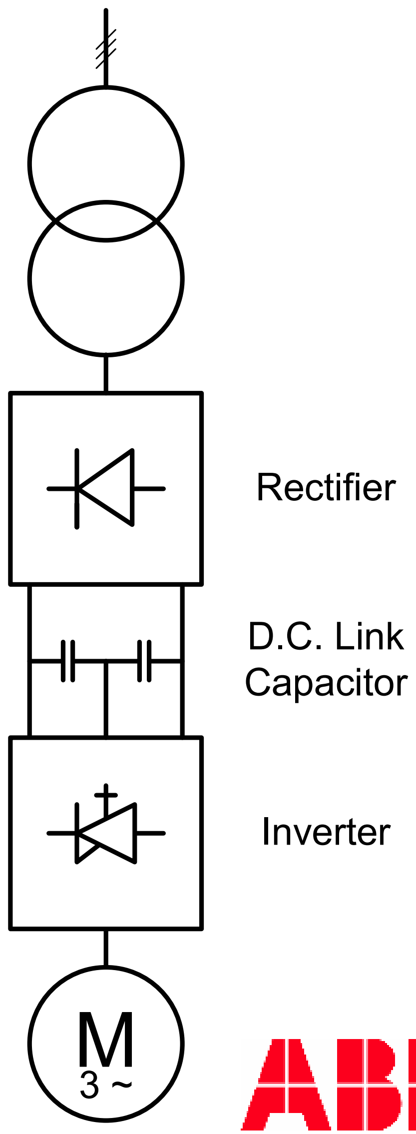
Classification of VSD Topologies

- Converter Configuration
  - Indirect
  - Direct
- Commutation Mode
  - External
  - Self-commutated
- Motor Type
  - Induction
  - Synchronous

Different combinations of these classifications are used in the various VSD types

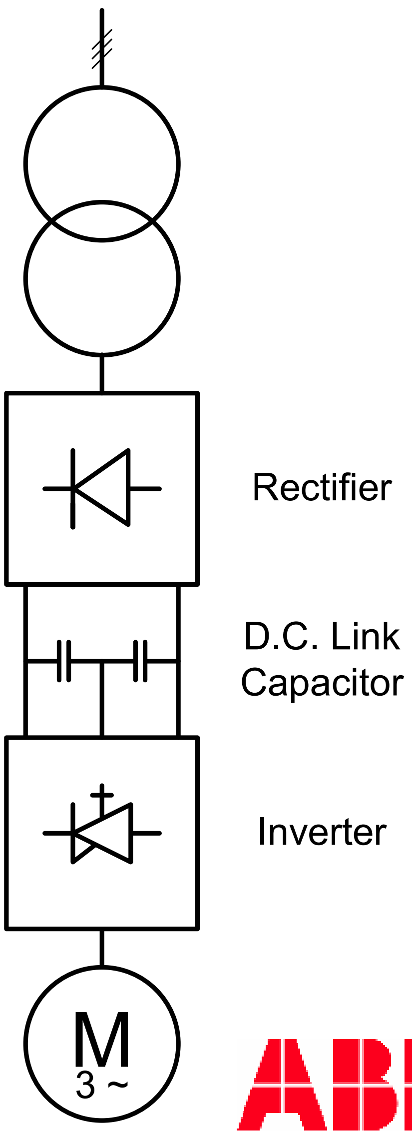
Types of medium voltage VSDs

- Voltage Source Inverter (VSI)
- Current Source Inverter (CSI)
- Load Commutated Inverter (LCI)
- Cyclo-converter (direct converter)
- Cascade drive

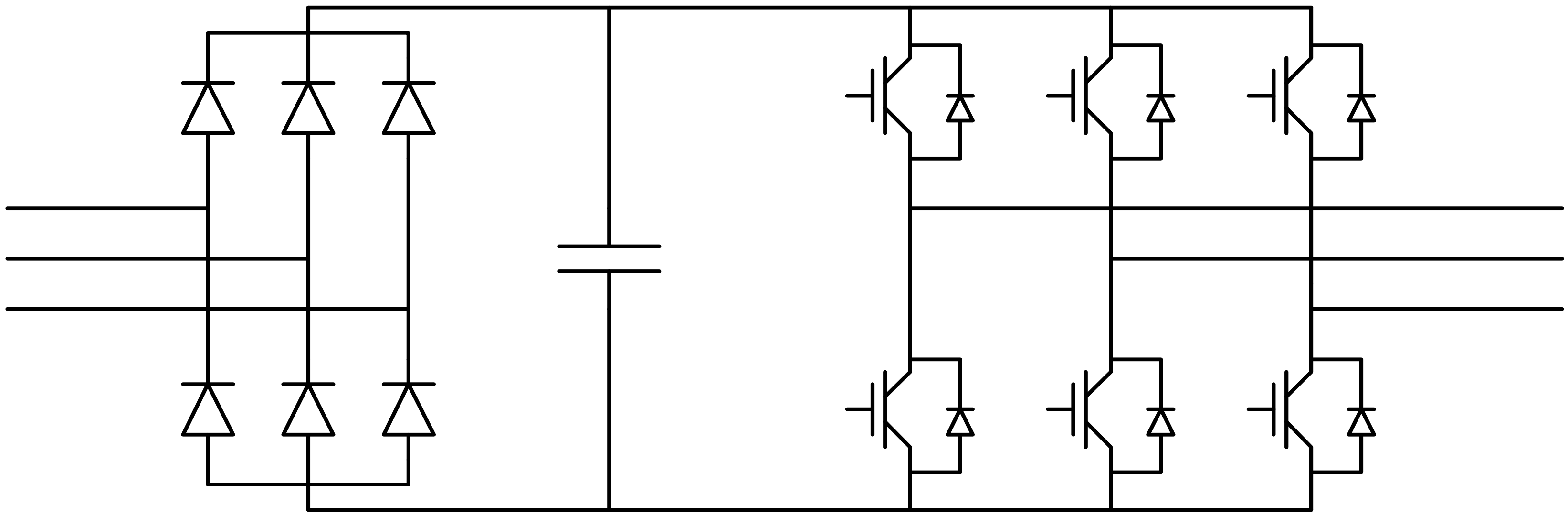


VSI Characteristic

- Voltage Source converter (diode rectifier or AFE)
- DC Link capacitors
- DC Link voltage constant
- Self-commutated inverter
- VSI modulation controls current at AC terminals
- Inductions or Synchronous motor

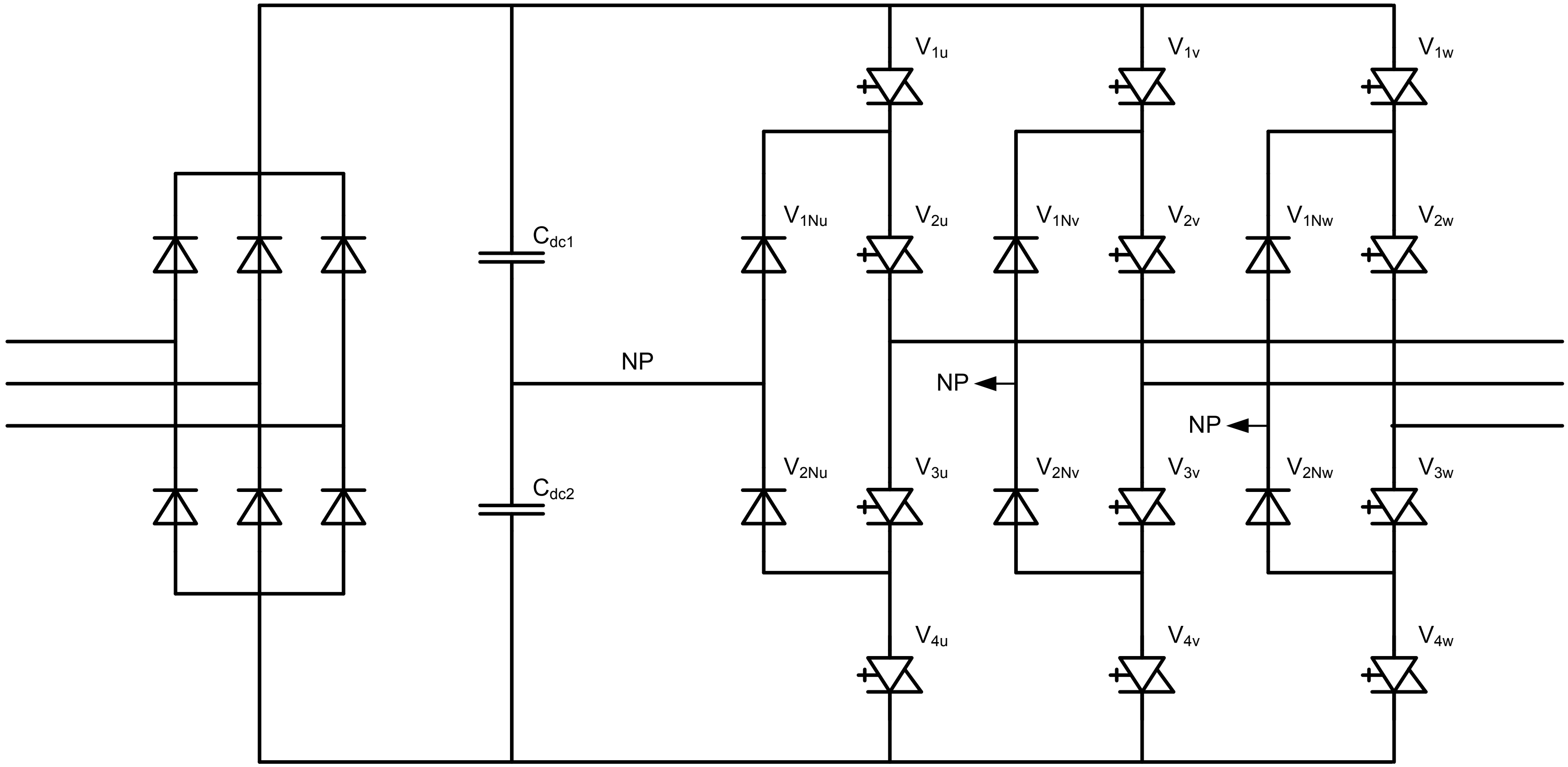


Voltage Source Inverter (2-Level)



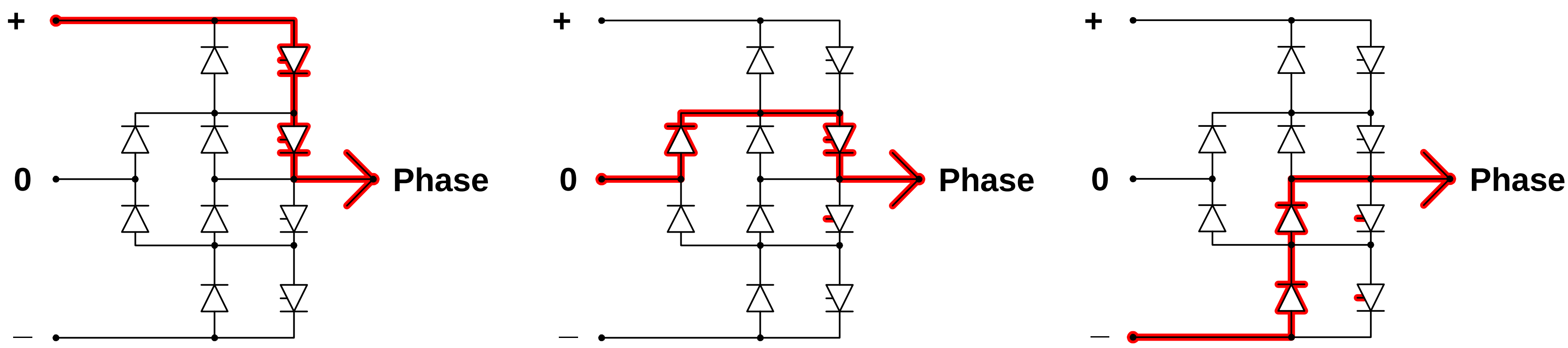
Today's standard for LV drives

Voltage Source Inverter (3-Level)

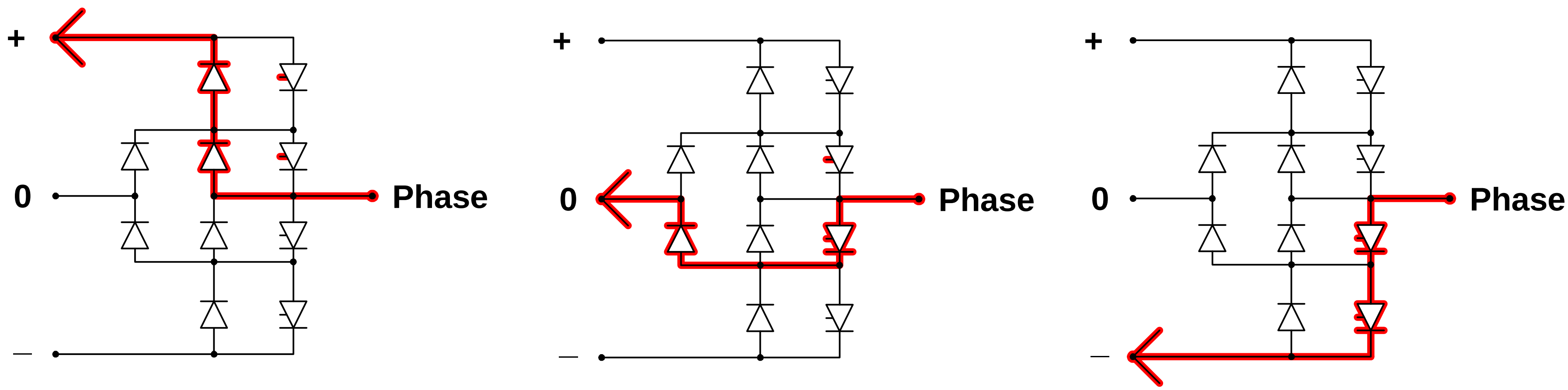


Voltage Source Inverter (3-Level)

Positive Current:

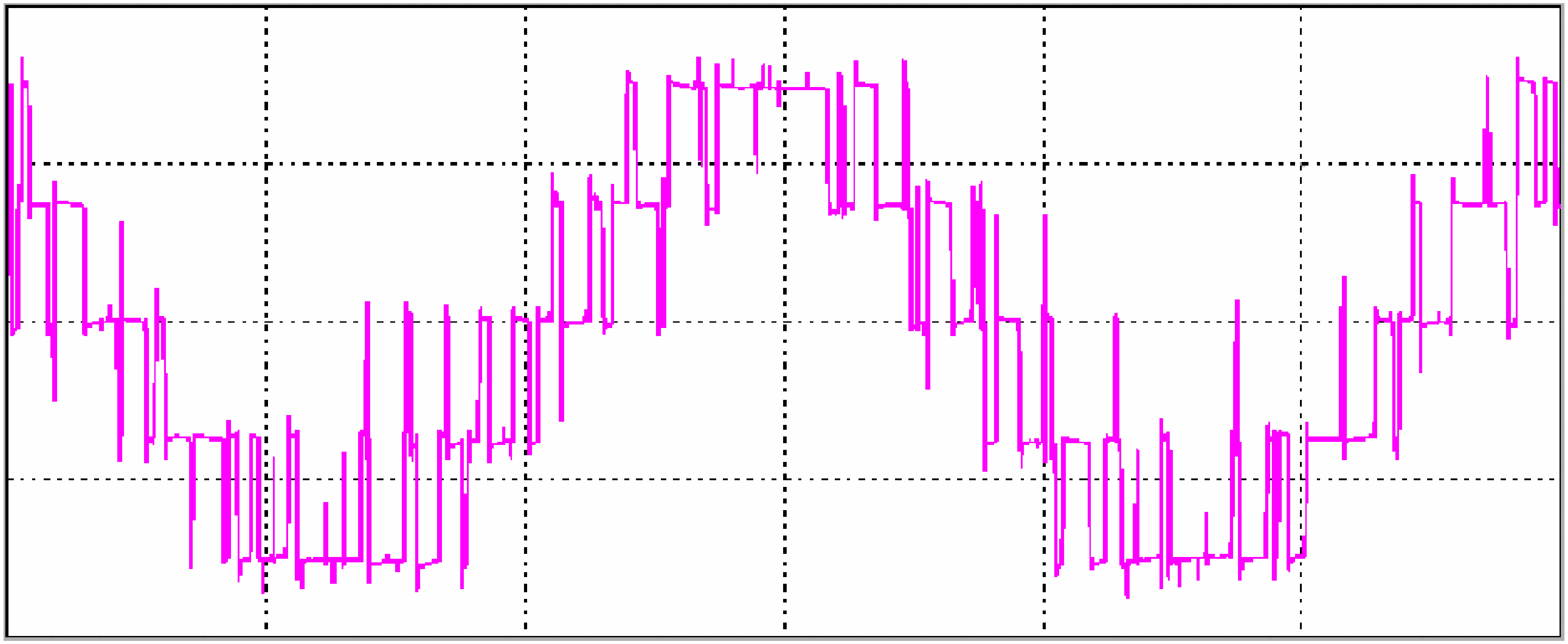


Negative Current:



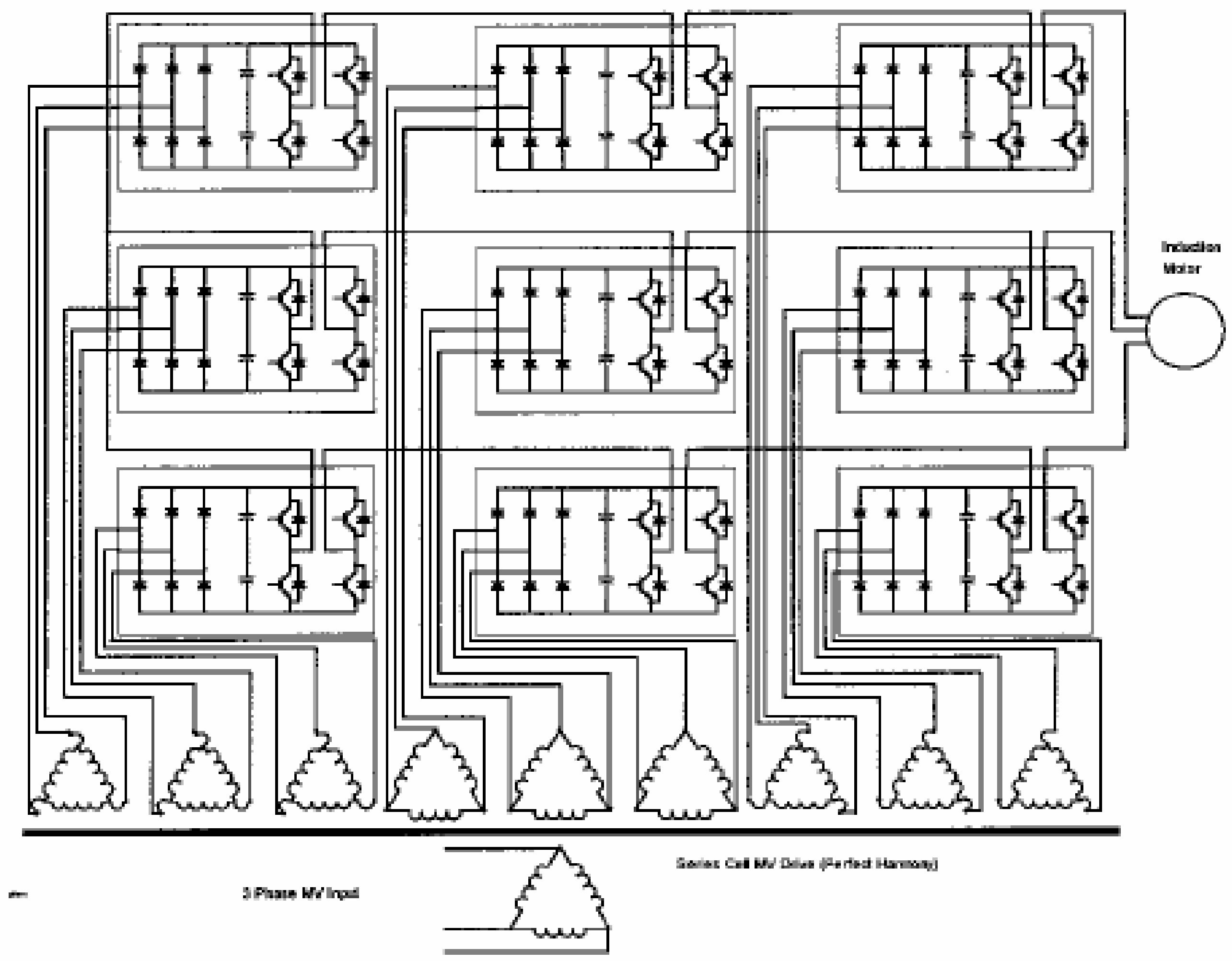
Voltage Source Inverter (3-Level)

- Phase to Phase Inverter Output Voltage



- Five voltage levels (phase to phase) due to 3-level inverter topology

Voltage Source Inverter (Multi-level)



Voltage Source Inverter - VSI

- **Advantages**
  - Full torque even at standstill and very low speeds
  - Input power factor near unity for entire speed range
  - Low network harmonics
  - Small footprint
  - Multilevel VSI has a quasi sine wave output without additional filter
- **Disadvantages (Multilevel)**
  - Very high parts count gives low inherent reliability

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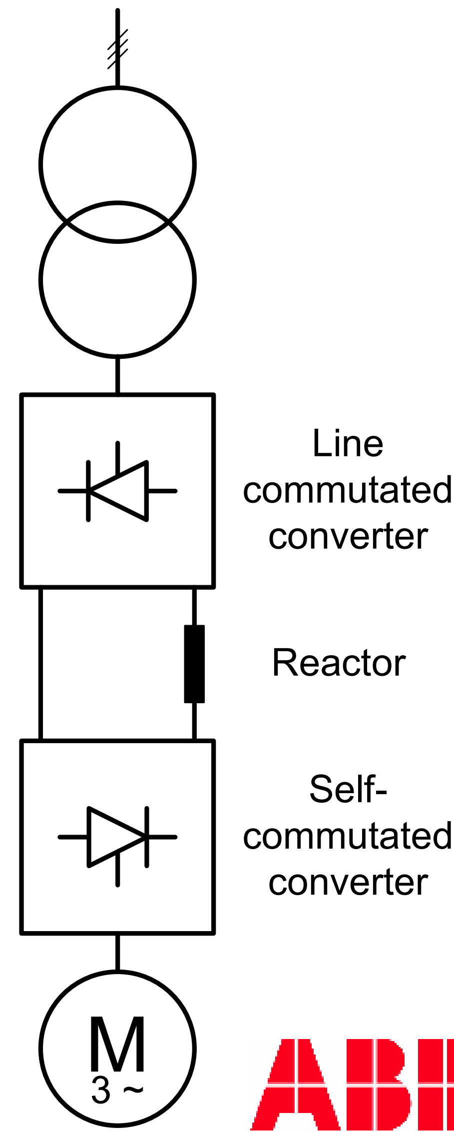
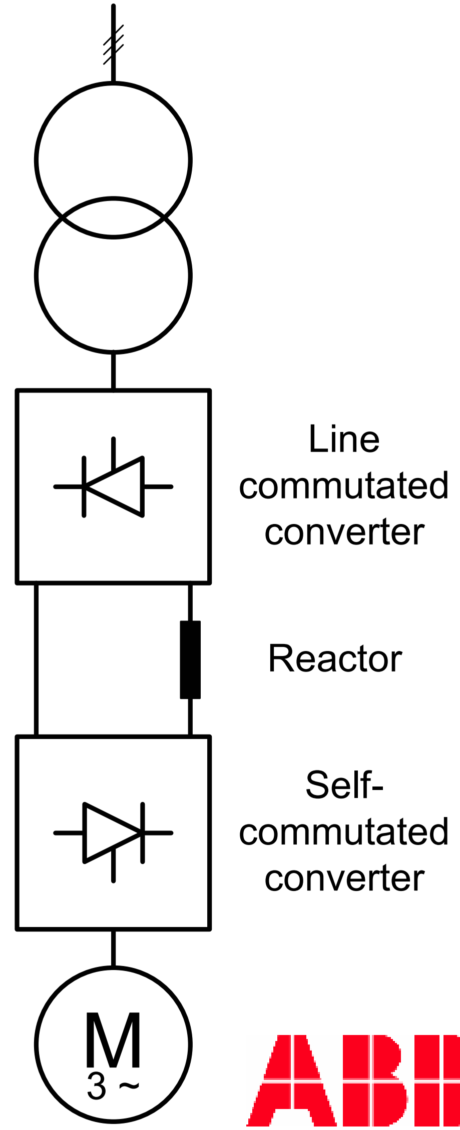


CSI Characteristics

- Current source converter (SCR's)
- DC Link reactor
- Constant DC current
- Self-commutated motor side converter
- CSI controls voltage at AC terminals
- Synchronous or inductions motor



Current-Source Inverter (CSI)

- **Advantages**
  - Four quadrant operation
- **Disadvantages**
  - Continuous operation at very low speed is not always possible
  - Power factor is not constant over the entire speed range (poor pf at low speeds) – requires filter
  - DC link reactor introduces additional losses as well as a larger drive and higher costs

Types of medium voltage VSDs

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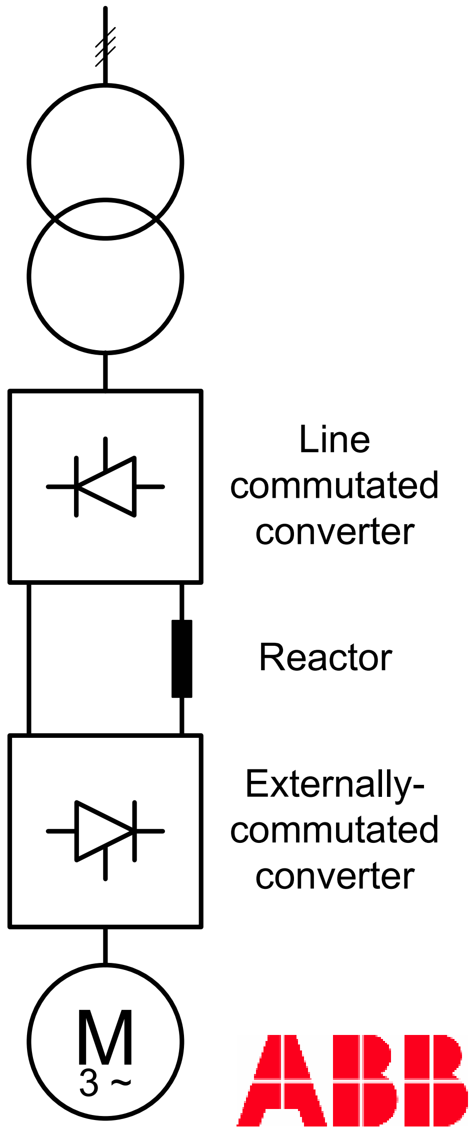
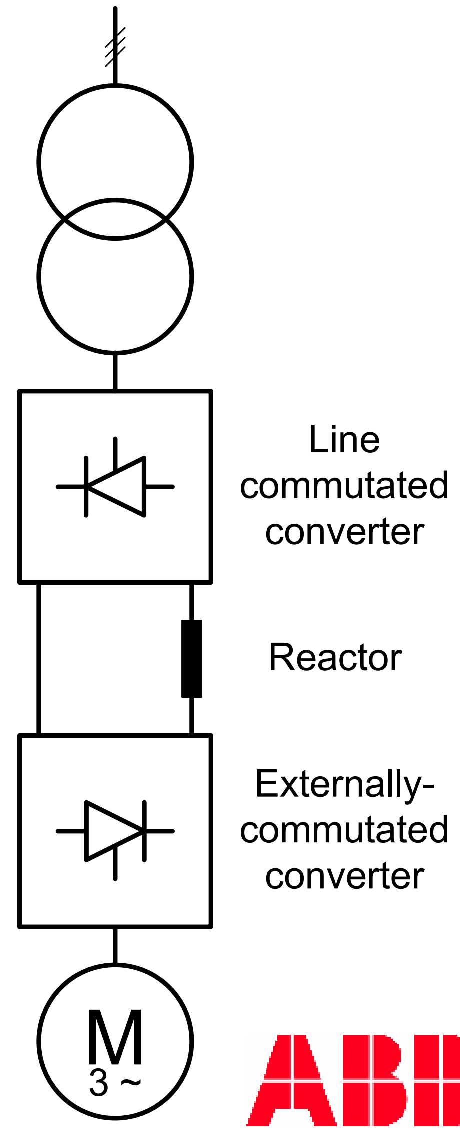


LCI Characteristics

- Line Commutated line side converter
- DC Link reactor
- Constant DC current
- Externally commutated motor side converter
- Synchronous motor



Load Commutated Inverter (LCI)

- **Advantages**
  - Four quadrant operation
  - Single motor drive for medium and high power ratings (e.g. 135,000 HP)
- **Disadvantages**
  - Low line side power factor
  - Not suitable for standard squirrel cage induction motors
  - May not be cost effective for simple applications

Types of medium voltage VSDs

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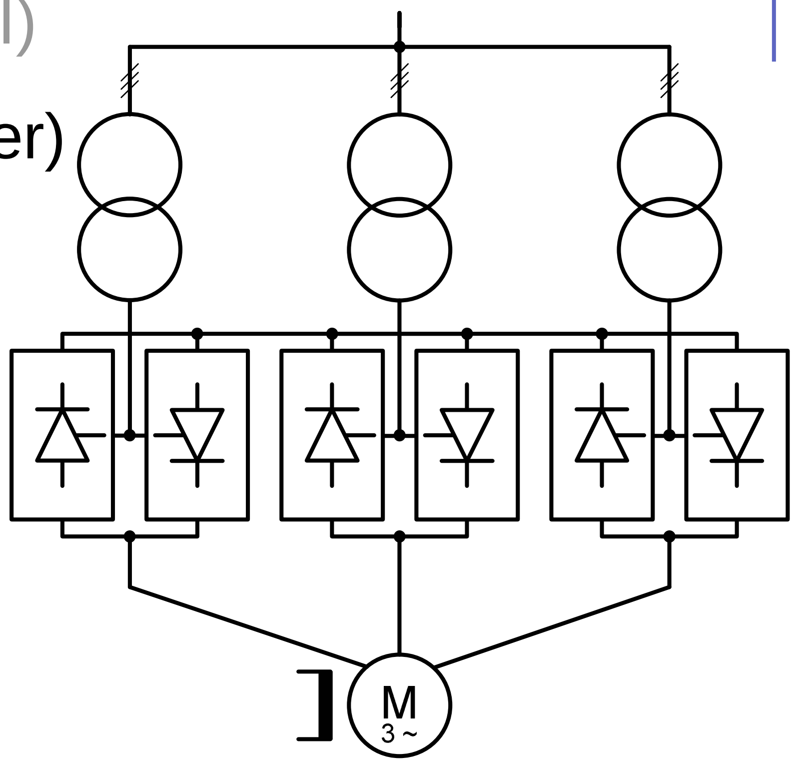
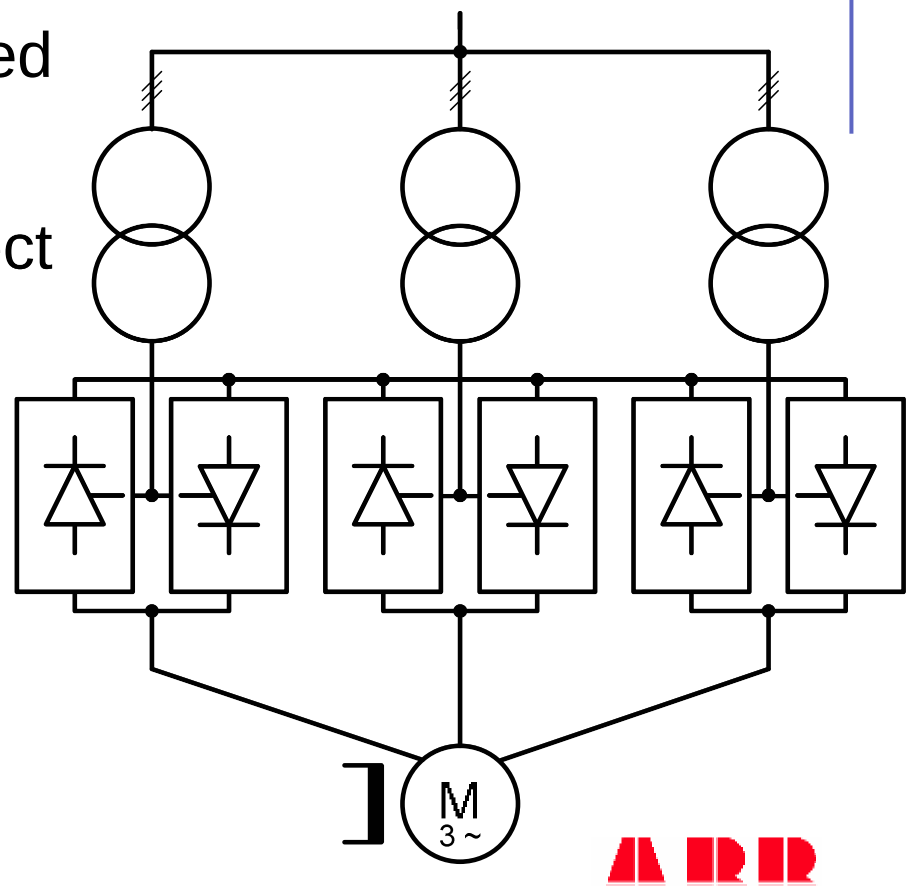


Direct converter characteristics

- No intermediate energy storage in a DC link
- Three externally commutated reversible converters
- Output waveform has a direct effect on the input waveform
- Requires filters



Cyclo-converter

- **Advantages**
  - 4-quadrant operation
  - Motor cos phi = 1.0 possible
  - High stall and holding torque available
  - Excellent performance at low speeds
  - High dynamic overload capacity
  - Field weakening range 1:3

- **Disadvantages**
  - Limitation on maximum output frequency (< f_{line} / 2)
  - Power factor not constant over entire speed range
  - May not be cost-effective on standard applications
  - Has larger footprint compared to standard drives

Types of medium voltage VSDs

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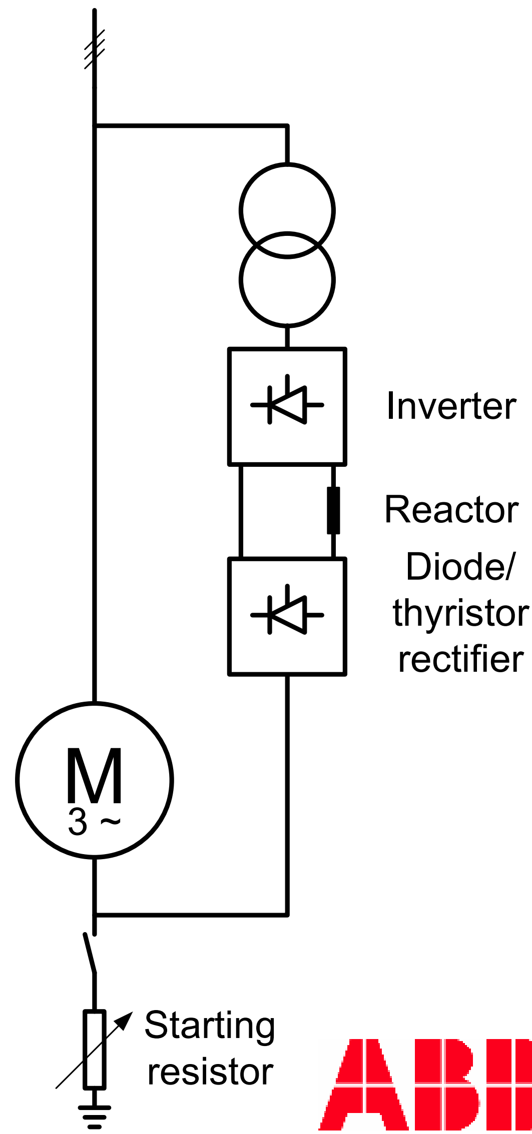


Cascade Drive

- **Advantages**
  - Cost effective because converter only needs to be dimensioned for feedback power
  - High total efficiency
  - Inherent bypass
  - Suitable for retrofitting of existing slip-ring motors
- **Disadvantages**
  - Cannot be used on standard squirrel cage induction motors
  - Power factor not constant over speed range

VSD Topology summary

- Voltage Source Inverter
  - Most commonly used technology in the general industry
  - Power: up to 80,000 HP
- Current Source Inverter
  - Alternative to VSI depending on manufacturer
  - Power: up to 34,000 HP
- Load Commutated Inverter
  - Special industries (Gen-starters, very large HP applications
  - Power: up to 135,000 HP
- Cyclo / Cascade
  - Rarely used
  - Special industries & applications
  - Power: up to 40,000 HP

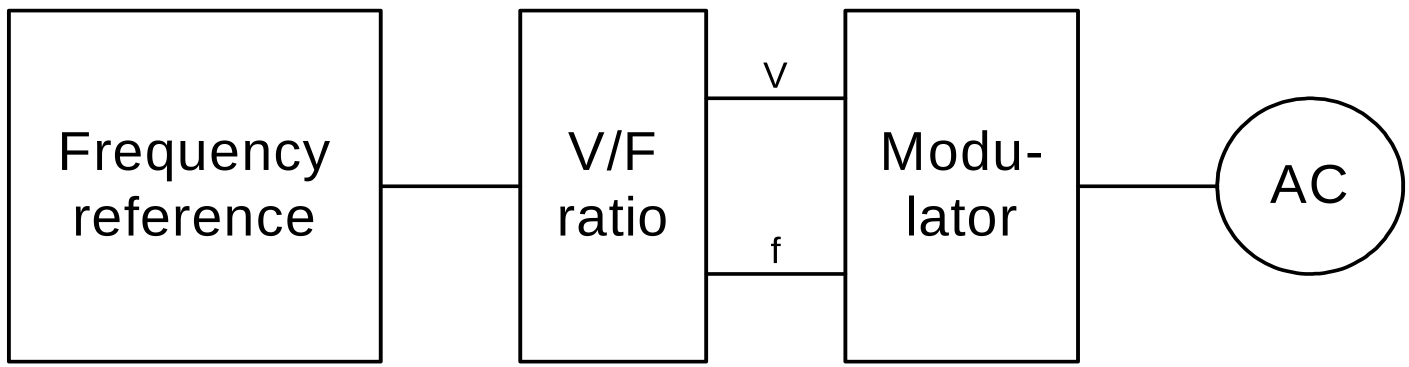
Motor Control Platform

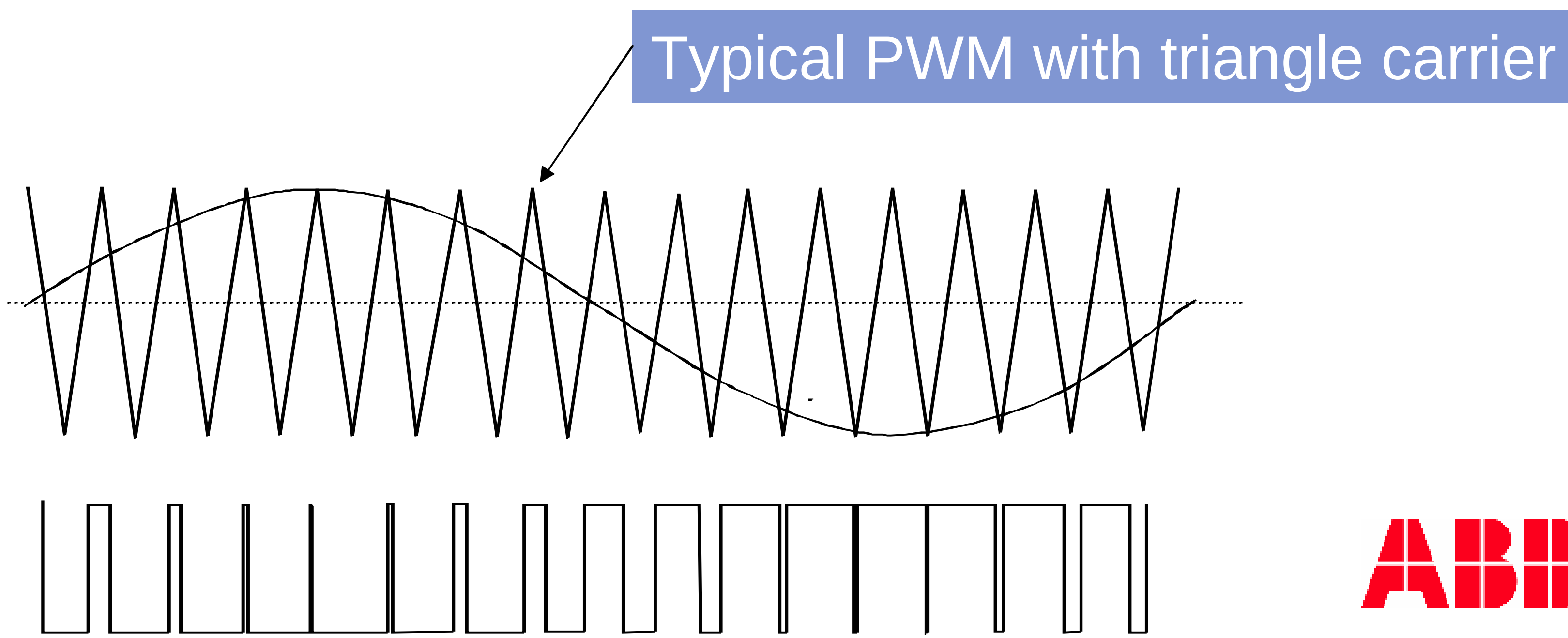
- Motor Control
  - Scalar or V/F control
  - Flux Vector control
  - Direct Torque Control (DTC)

- Modulation
  - PWM (Pulse Width Modulation)

Motor Control Platform

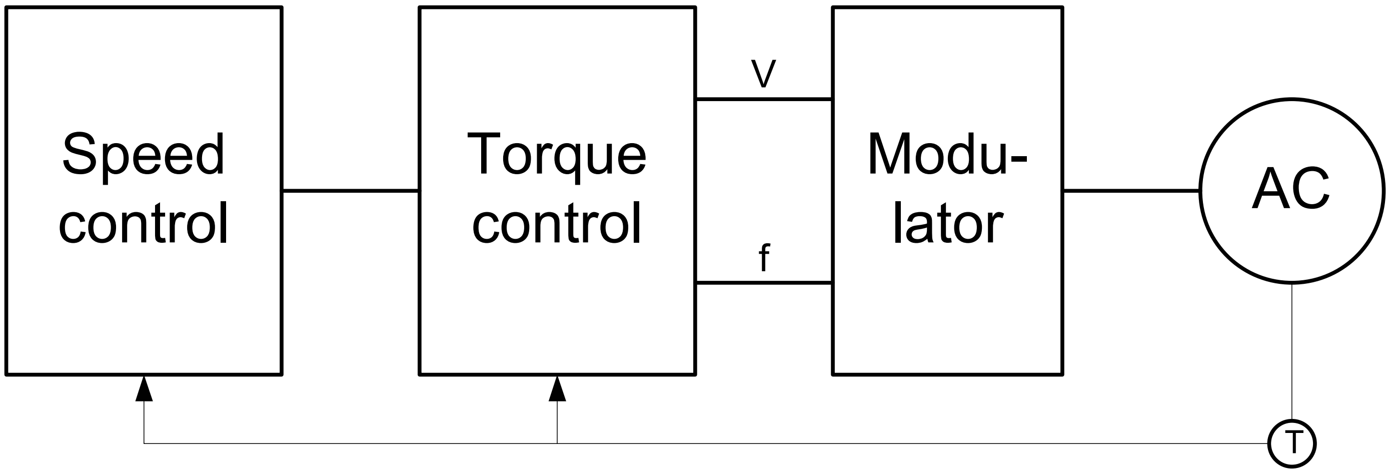
- Scalar control





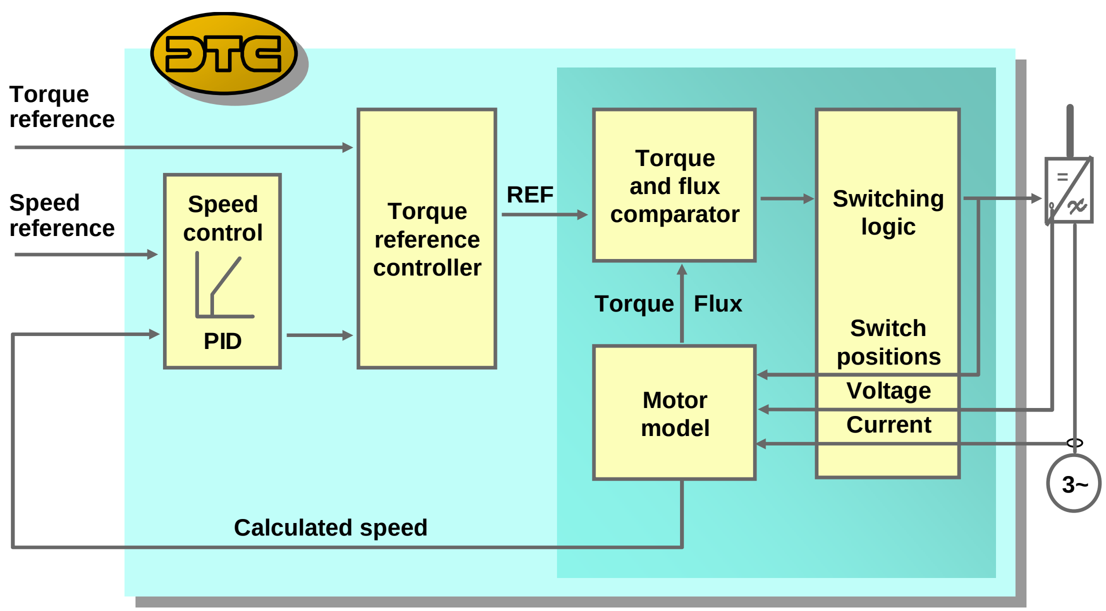
Motor Control Platform

- Flux Vector control
  - Indirect torque control
  - Better performance than Scalar control V/f
  - Closed- or open-loop control
  - < 5Hz sensorless (open-loop) Flux vector control is inaccurate



Motor Control Platform

- DTC is the newest control method.
  - DTC optimize the switching pattern according to torque and flux in the motor.
  - Therefore the converter is not switching with a constant frequency, like in other PWM control schemes.
  - Since the switching's are creating losses and DTC gives the benefit that the converter is only switched, when the motor requires it, the losses are reduced in the converter.



Low Voltage- vs Medium Voltage Drives

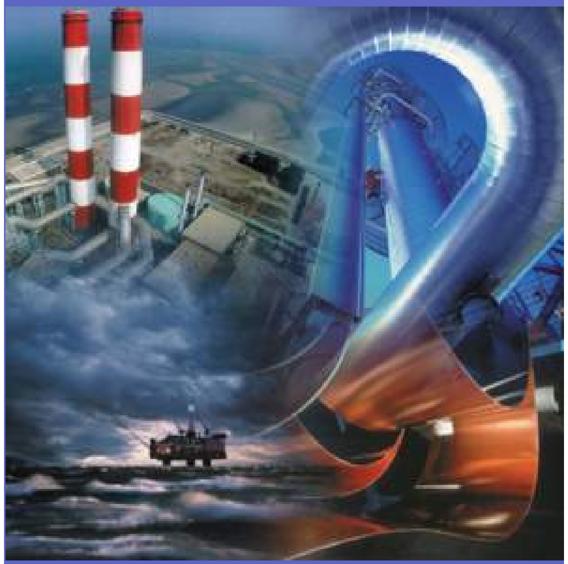
- **Low Voltage Drives**
  - Voltage Rating ≤ 600 V (NEC), ≤ 1000 V (IEC)
  - Power Rating ≤ 5000 HP
  - Drive Type
    - Voltage Source – PWM (Majority Applications)
    - Current Source – (very few systems)
  - Type of Motor - Induction
  - Packaging
    - Chasis Type
    - Wall mount
    - Stand alone

- **Medium Voltage Drives**
  - Voltage Rating > 600 V (NEC), > 1000 V (IEC)
  - Power Range 500 HP to 135,000 HP
  - Drive Type
    - Voltage Source – PWM
    - Current Source
  - Type of Motor
    - Induction
    - Synchronous
    - Permanent Magnet
  - Packaging
    - Stand alone

Why Medium Voltage?

- For a given power, current is lower compared to LV drives
- Smaller cables, lower current rating for breakers
- Lower losses
- As the power increases, it is the only practical solution

Overview



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Industries where MV Drives are used

Cement, Mining & Minerals

Chemical, Oil & Gas

Marine

Metals

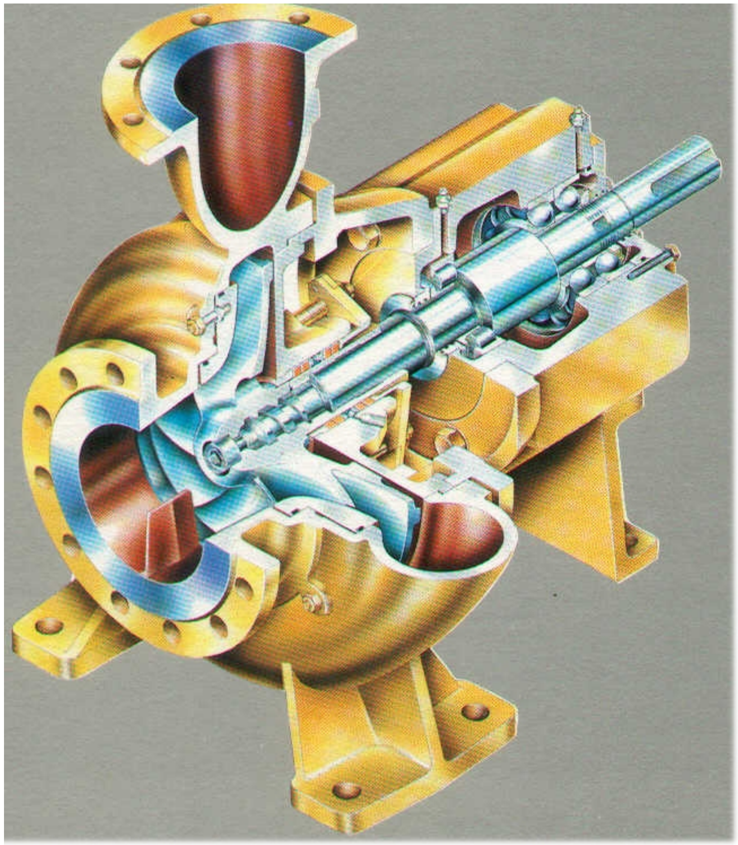
Power

Pulp & Paper

Water & Waste Water

Special applications, e.g. wind tunnels

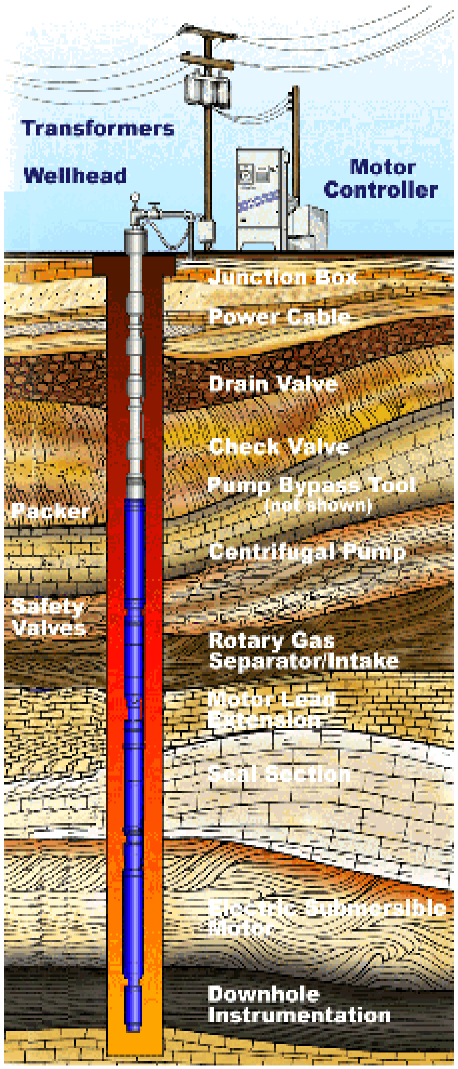
Medium Voltage Drive Applications



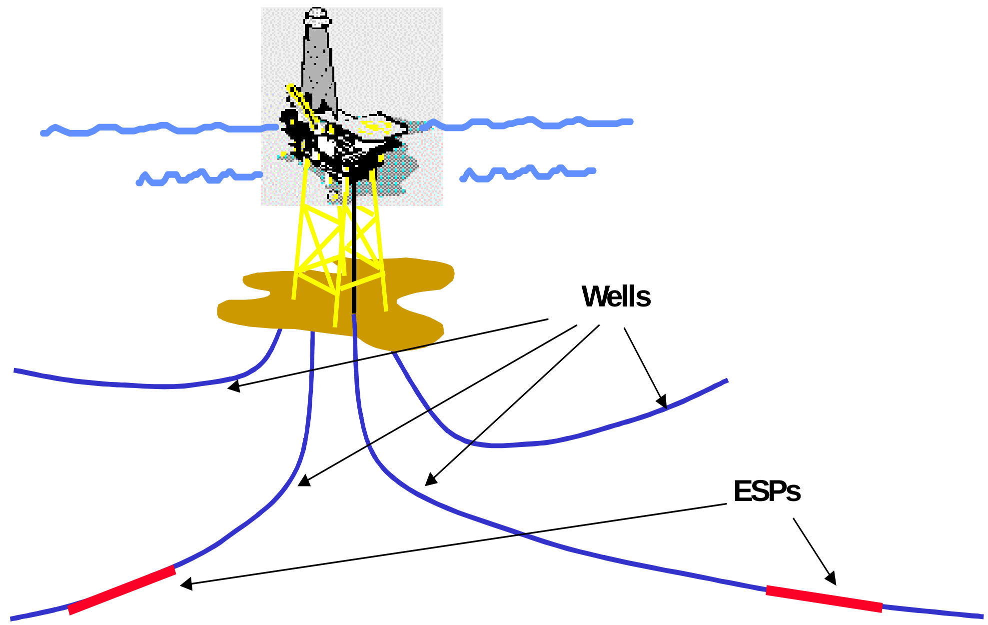
Pumps

- Municipal Water
- Progressive Cavity
- Multi-phase
- Electric Submersible
- Multi-stage
- Slurry
- Pipeline
- Boiler feed, ...

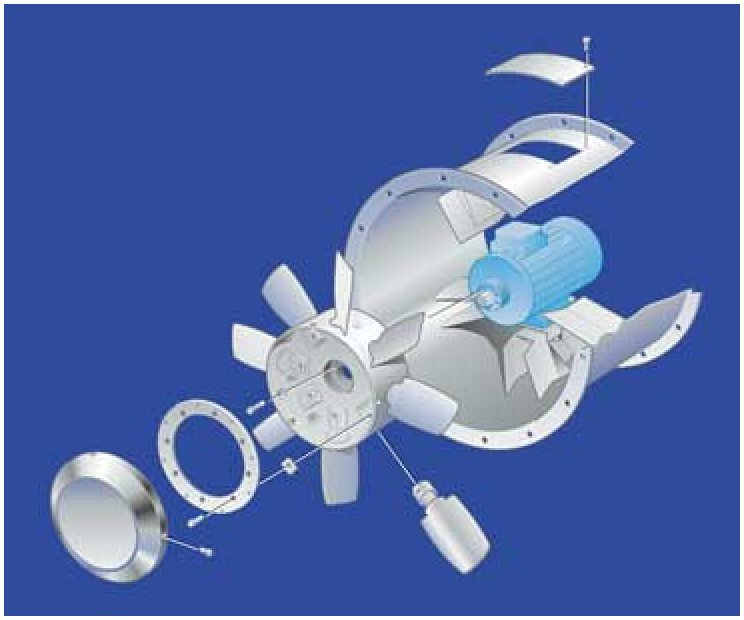
Medium Voltage Drive Applications



Electric Submersible Pump, ESP Drives



Medium Voltage Drive Applications



Fans

- Induced Draft (ID)
- Forced Draft (FD)
- Dust collectors
- Kiln Fans
- SCR applications
- Tunnels

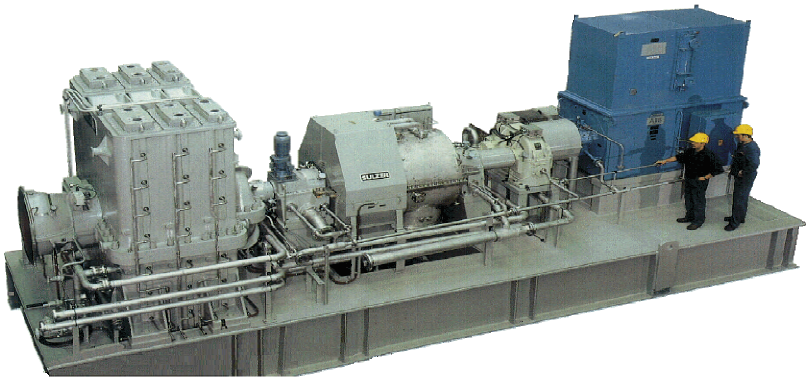
Medium Voltage Drive Applications

Worsley Alumina Refinery, Australia

World's longest conveyor belt (51km)
6 x MV Drives (total 16 MW)

conveyors

Medium Voltage Drive Applications



Compressors

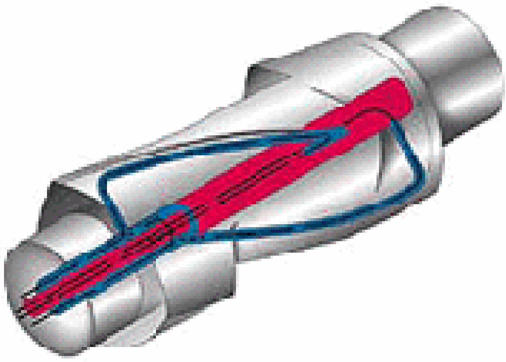
- Centrifugal
- Reciprocating

Ratings up to 130,000 HP

Medium Voltage Drive Applications

Extruders/Mixers

- Rubber and Plastics
- Food Processing

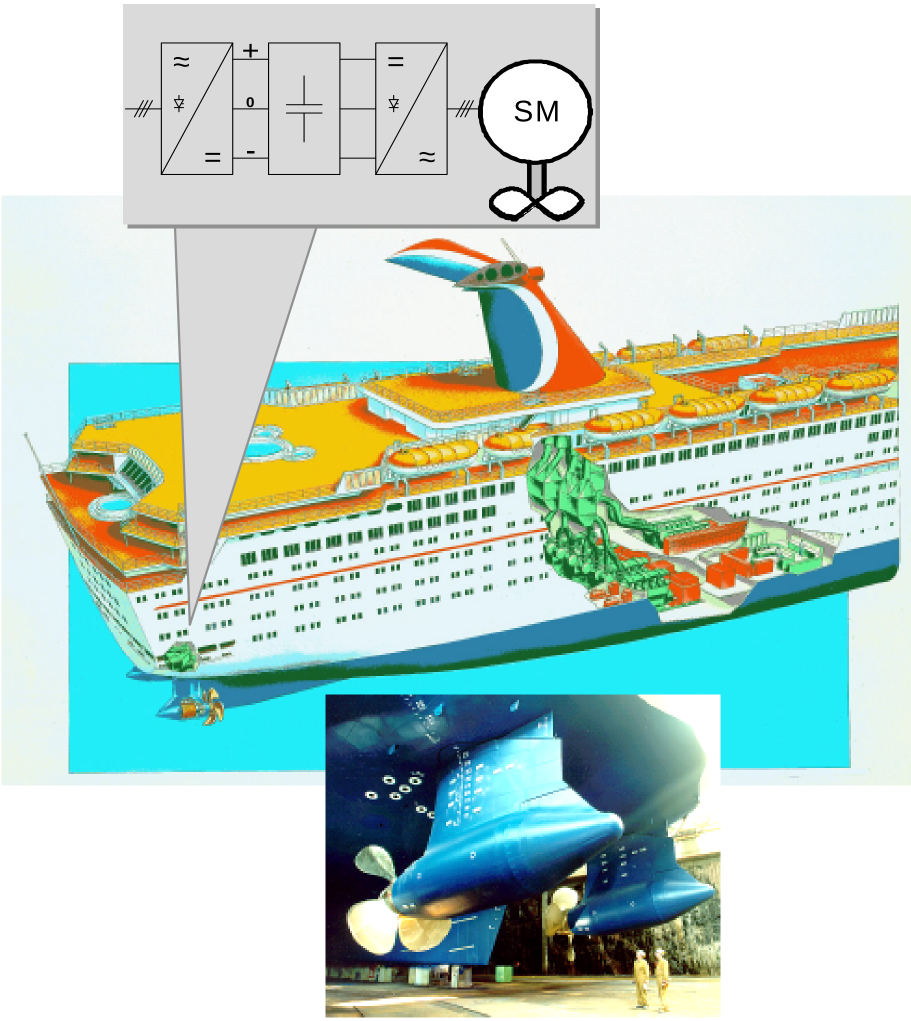


Medium Voltage Drive Applications

Chillers

- Energy Savings
- Retrofitting two 1000HP chillers with a VFD saved this building $500,000 annual electricity cost

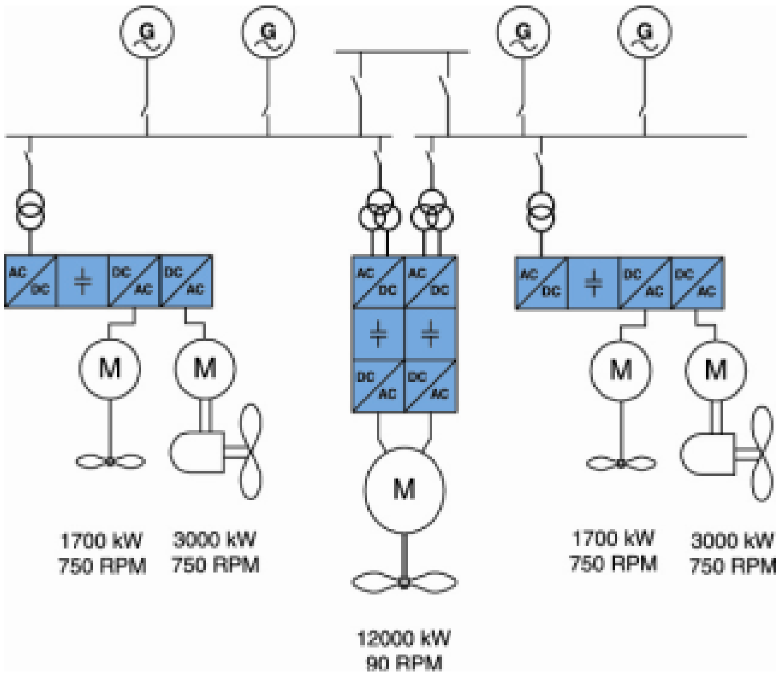
Medium Voltage Drive Applications



Marine Propulsion

- Icebreakers
- Tankers
- Passenger Vessels
- Cable Layers
- Drilling Ships
- Supply Ships

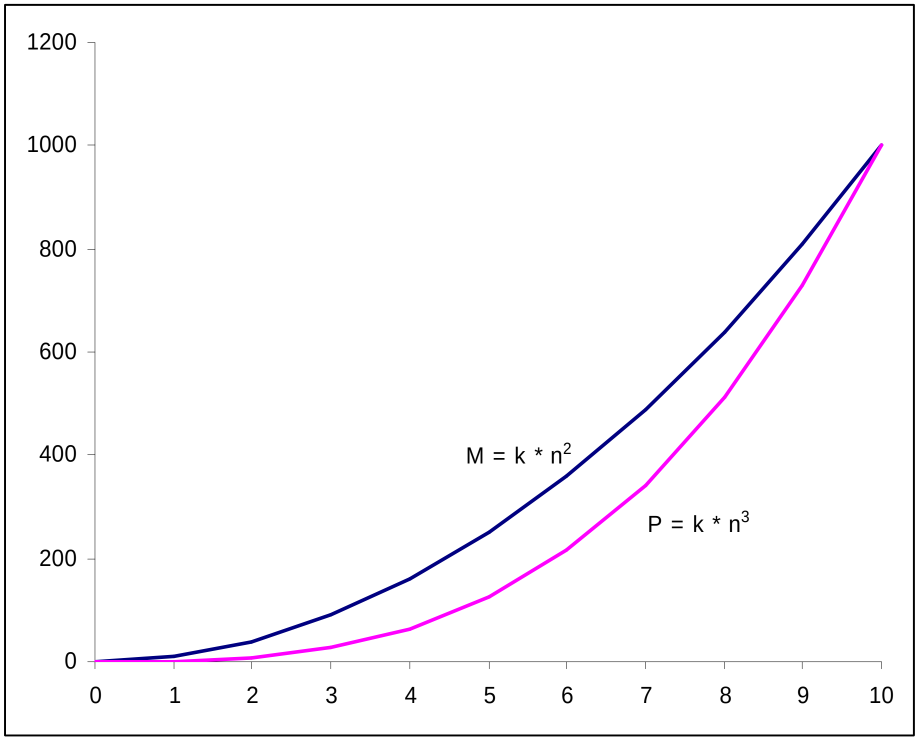
Configuration example – redundant concept



- Propulsion and thruster for shuttle and service vessels: redundant concept
  - Power system can be split
  - Operation at reduced power is maintained in case of partial failure of converter

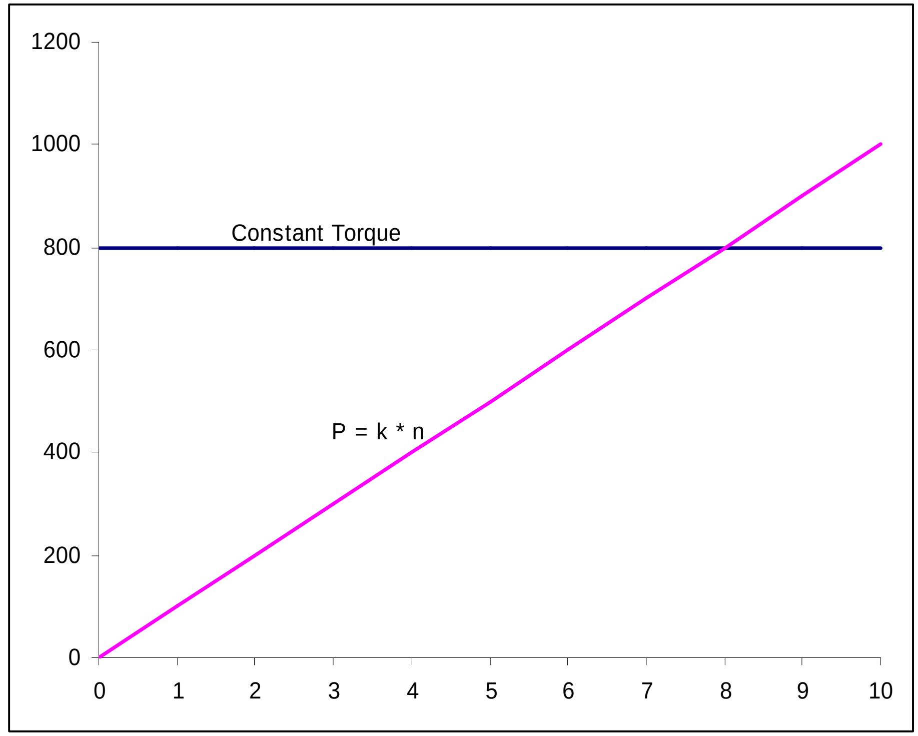
Quadratic Torque Applications

- The most common load type is the quadratic torque.
- The power is cubically proportional to the speed.
- Applications
  - Centrifugal pumps and fans



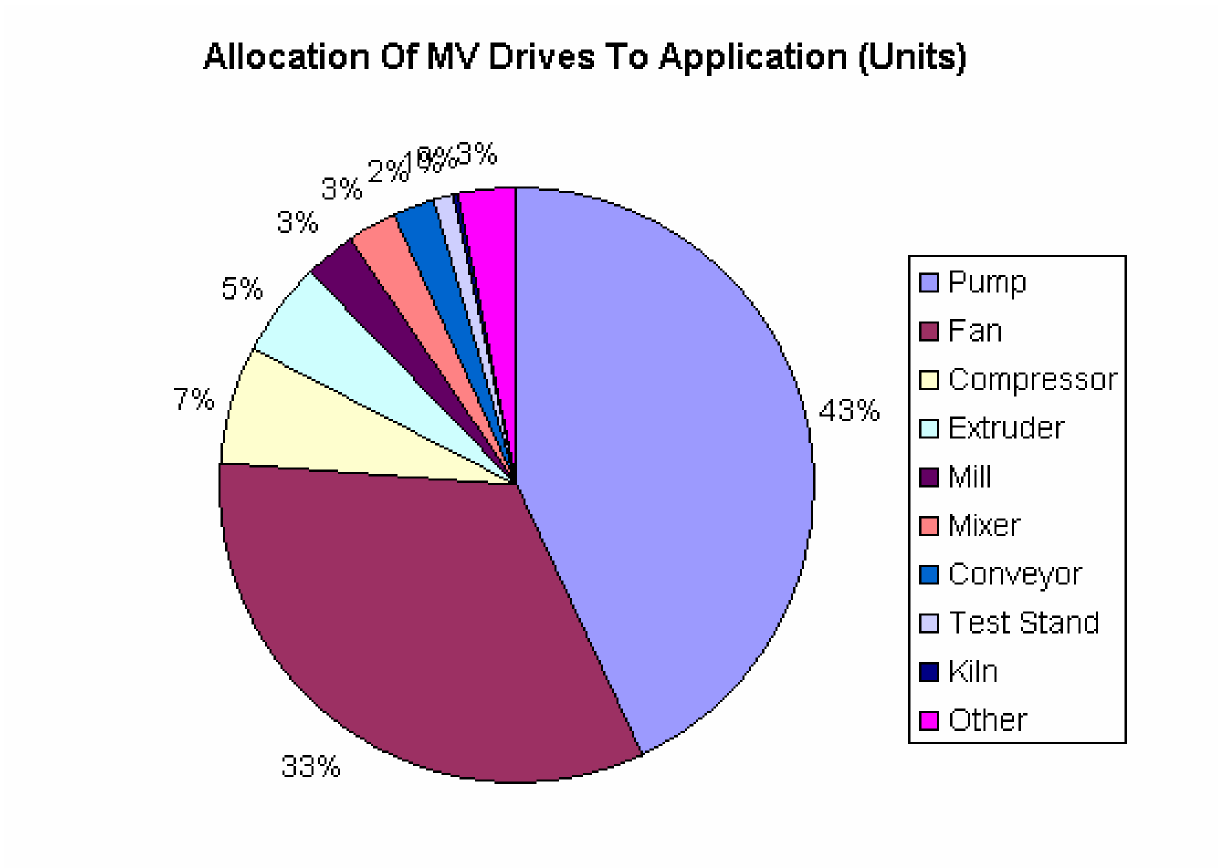
Constant Torque Applications

- A constant torque load type is typical when fixed volumes are being handled.
- The power increases linear with the speed
- Applications
  - Screw compressors
  - Conveyors
  - Piston pump



Medium Voltage Drive Application Summary

- Fans
- Pumps
- Compressors
- Conveyors



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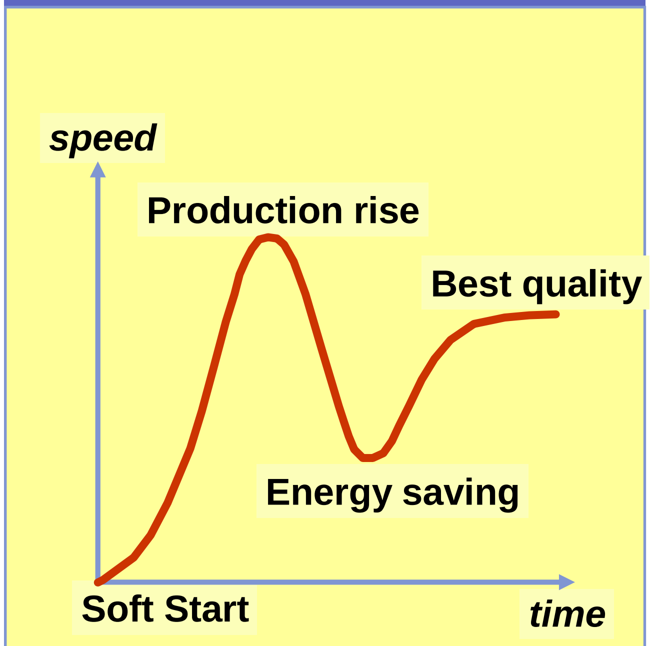
Benefits of Variable Speed Control



- Energy savings
- Improved product quality through better process control
- Reduced process equipment wear and longer lifetime of equipment
- Soft start and stop reduce waste and save raw material
- Noise reduction
- Improved process efficiency

Lower operation cost
Increased productivity
Increase of maintenance intervals =>
Reduction of maintenance cost

Energy Savings – Motivation

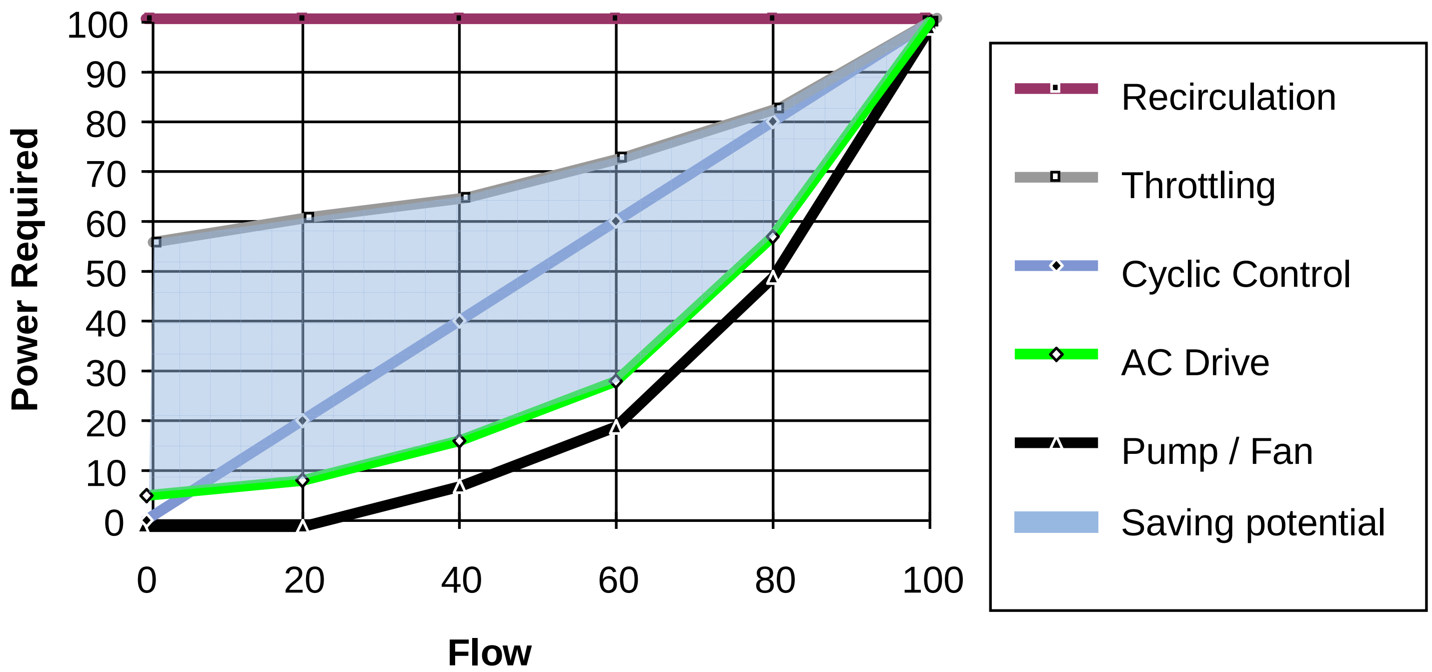
- Over 65% of all electricity consumed in Industry today is for electrical motors.
- Up to 70% of the energy used running motors can be save by varying the speed.
- Today only about 5% of the world's motors are fitted with energy saving devices

High potential to save energy costs

Example: Pump Control

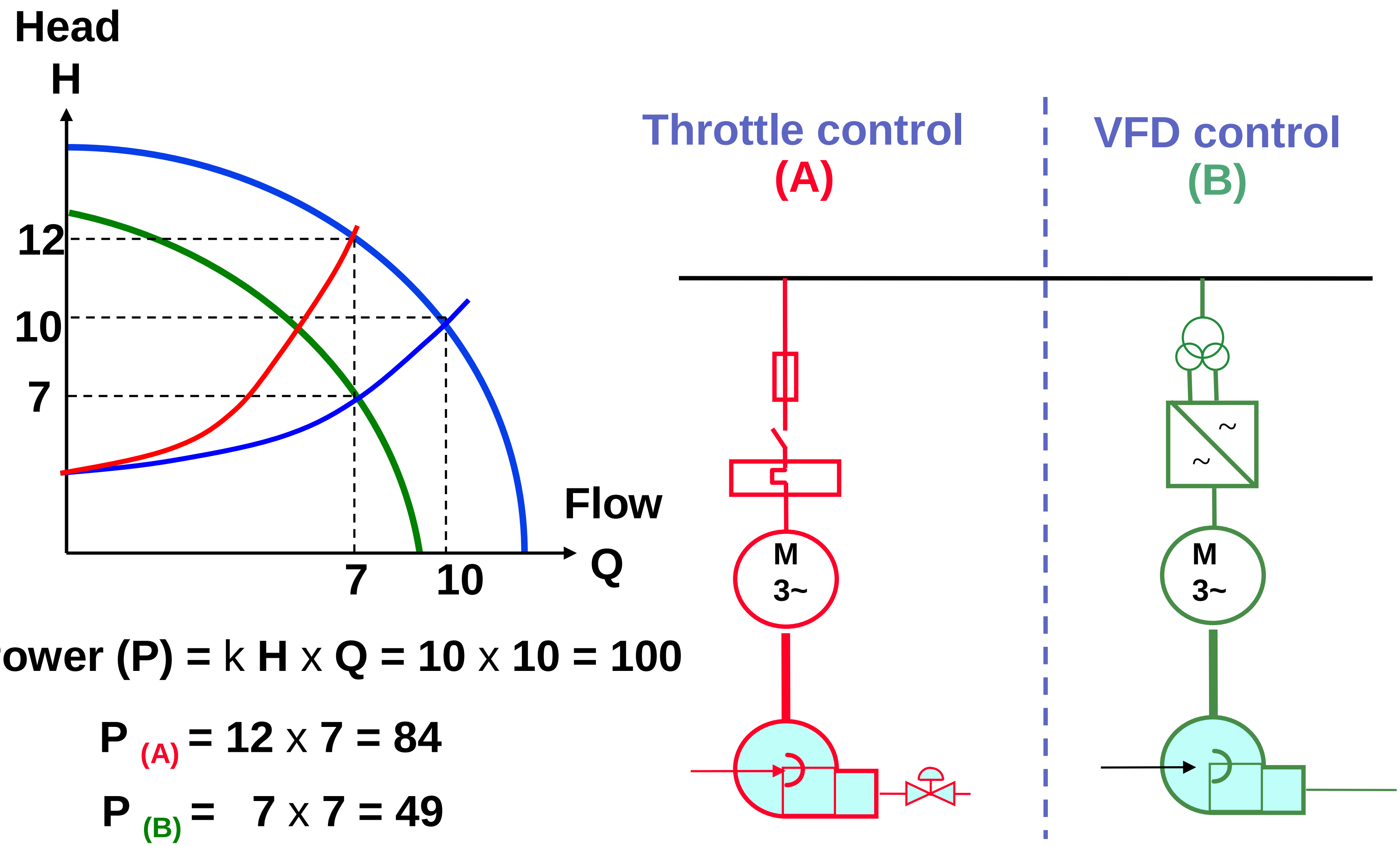
- Throttling

Power requirements for different control methods



- Process equipment often runs at partial load, resulting in unnecessary high energy bills
- Many businesses find that a 20% cut in energy costs gives the same benefit to the bottom line as a 5% increase in sales

Energy Savings with VFD's



Power (P) = k H x Q = 10 x 10 = 100

P $_{(A)}$ = 12 x 7 = 84

P $_{(B)}$ = 7 x 7 = 49

P $_{(saved)}$ = 35 => 42%!

Example: Energy Saving

- US: University power plant
- Installed 1,000 hp AC drive for its scrubber booster fan
- Energy efficiency: improved by 25% over inlet vanes
- Energy saving: 1,460,000 kWh/year
- Reduced CO_2 emissions: 730,000 kg/year
- Better process controllability
- Less maintenance by soft starting
- No more start-up problems

Example: Energy Saving

- Mexico: Cement Cruz Azul
- Replace existing damper fan control of two 1000 hp fixed speed ID fans
- Increased availability pushed productivity up by 42,000 tonnes
- Increased revenue of 900,000 USD p.a.
- In 2000, energy savings of 260,000 USD p.a.
- Maintenance reduced from 12 days to 8 hours
- Reduced speed reduces erosion of fan blades

Other Benefits - Starting

- Direct online start of a motor requires:
  - Approx 5-7 * Full load current
    - During starting, power factor is very low (reactive current)
  - Special motor design (high starting current capability)
  - Voltage dips on a weak supply

- Starting with a VFD keep the current always below nominal current.
  - Power factor is always high (for VSI typically > 0.95)

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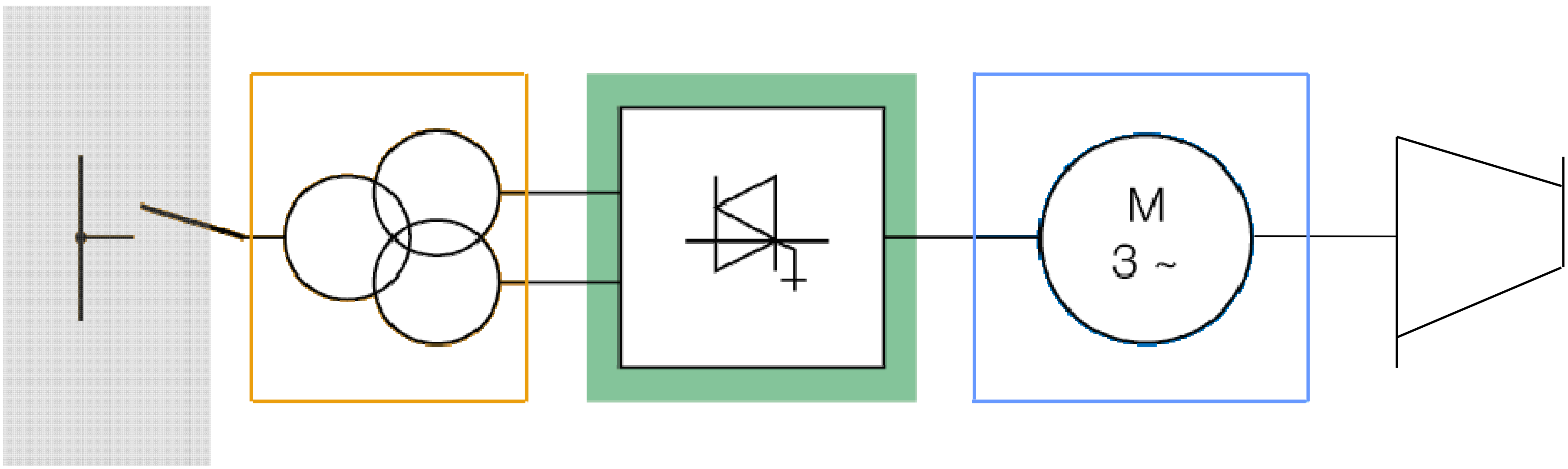
Issues & Considerations - Network



Harmonics

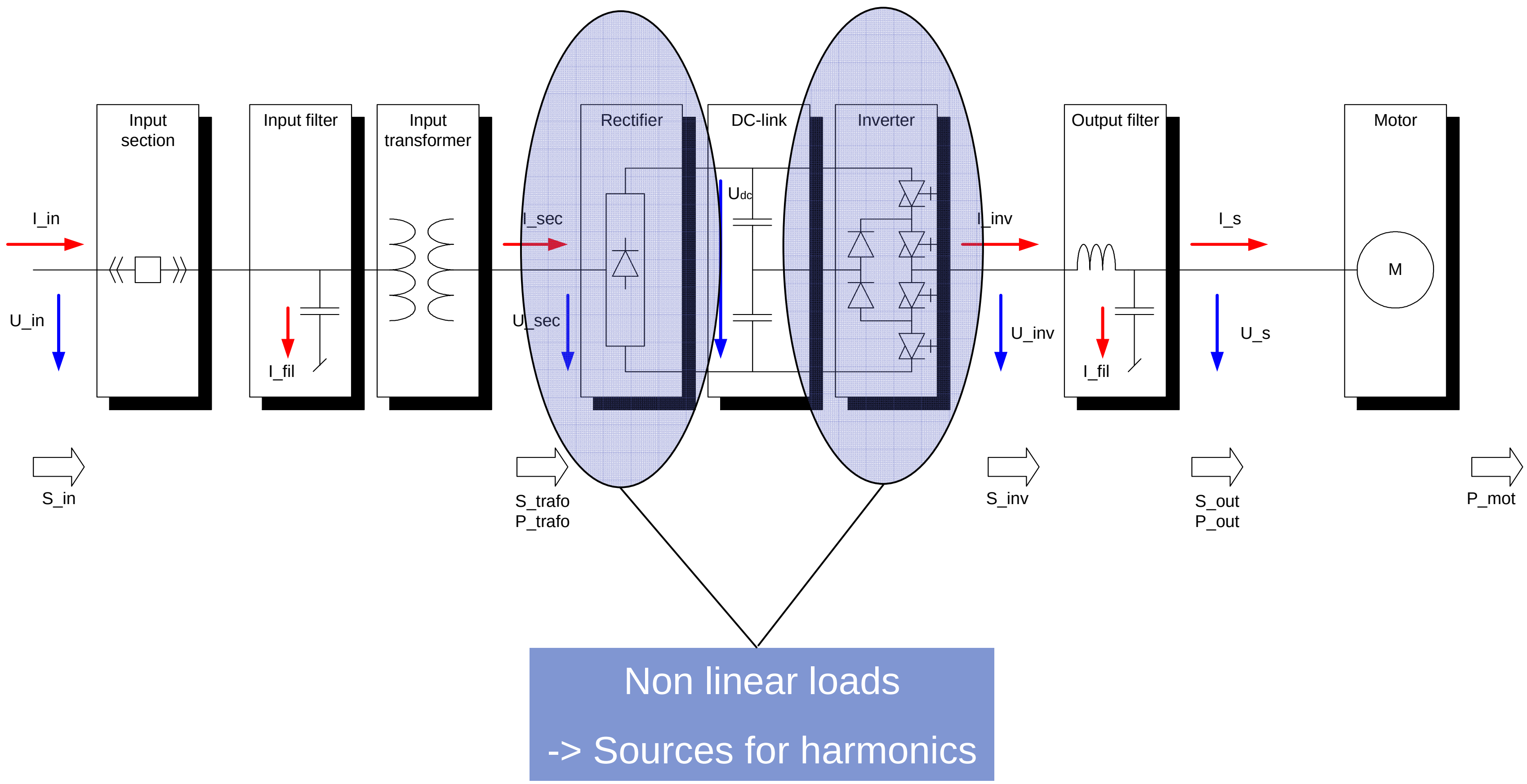
Harmonics

- Harmonics are desired in music instruments, but not in industrial networks or motors.
- Harmonic - A sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency.
- Harmonic, characteristic - Under ideal operating conditions, the current harmonics generated by a *p*-pulse line-commutated converter can be characterized by $I_h = I_1 / h$ and $h = pn \pm 1$ (characteristic harmonics) where n = 1, 2, ... and p is an integral multiples of six (voltage consideration analogue to current).
- Harmonic, no characteristic – Those are emerging in case of non-ideal conditions (e.g. unbalanced converter input voltage, unequal commutation reactance,..). Even, triple, odd non-characteristic and non-integral (inter-harmonics) harmonics belong to this group.

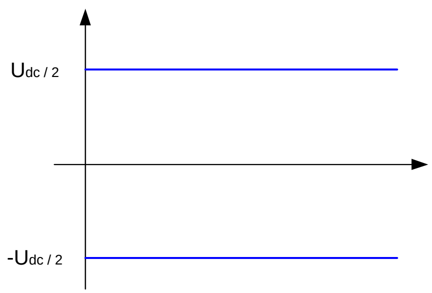
Harmonics

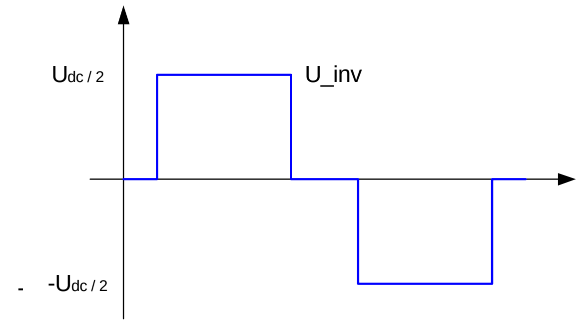
- Problems with harmonics on the supply network can include:
  - Exceeding limits given by power provider and standards
  - Disturbing other load on the same bus. Some types of equipment is more sensitive than other.
  - Overloading existing filter installations in the plant
- Problems with harmonics on the driven motor can include:
  - Thermal heating beyond allowed temperature rise
  - Torque oscillations that could turn out harmful to the shaft string (coupling overloads)

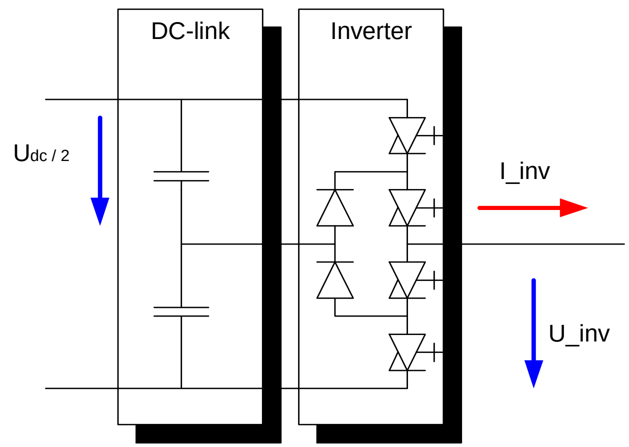
Harmonics – Basic building blocks



Sources of Harmonics



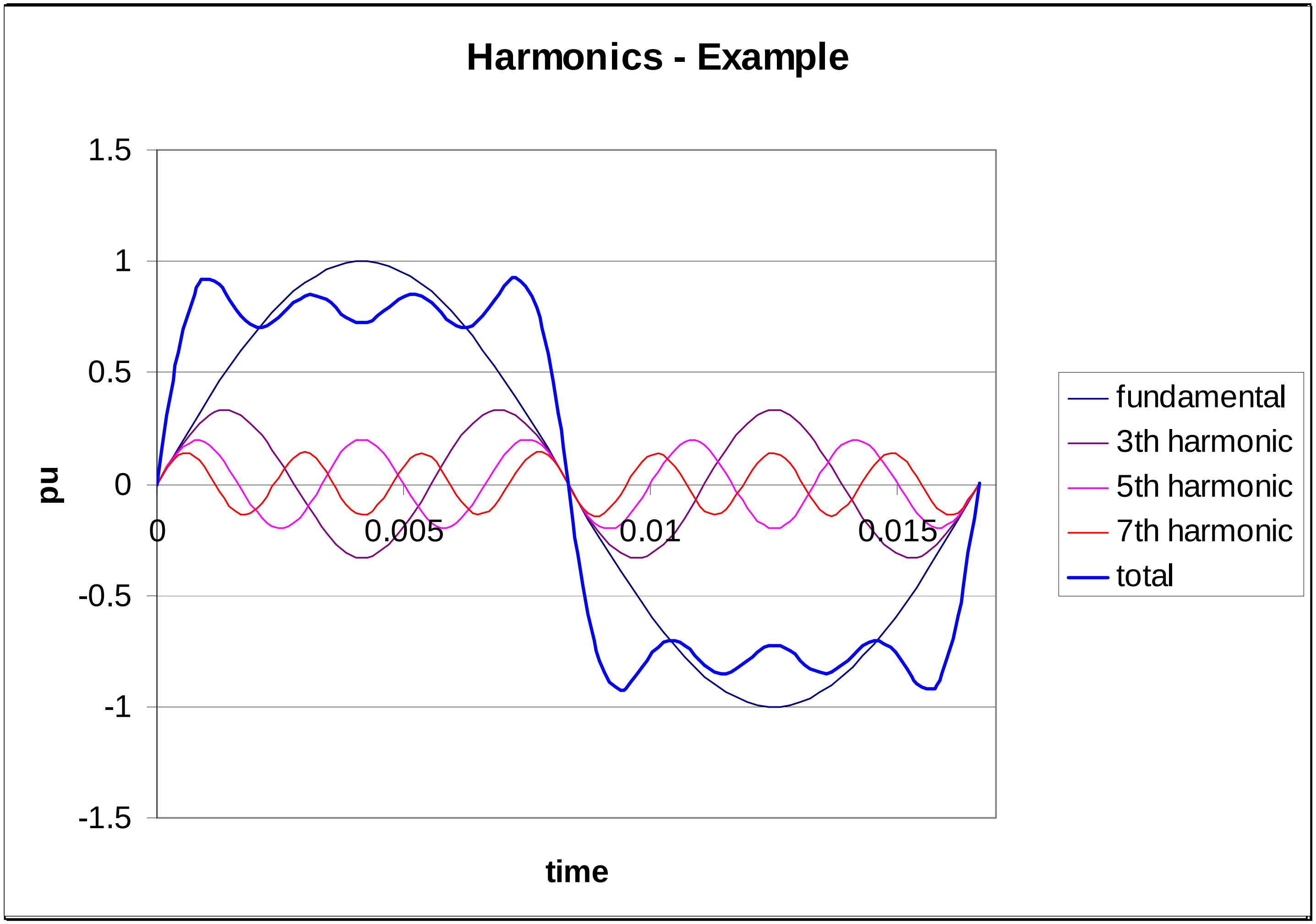




Udc/2 * s(t) = u_inv(t)

Udc/2	= DC link voltage
S(t)	= Switching function
U_inv(t)	= Inverter output voltage

Harmonics - visualization

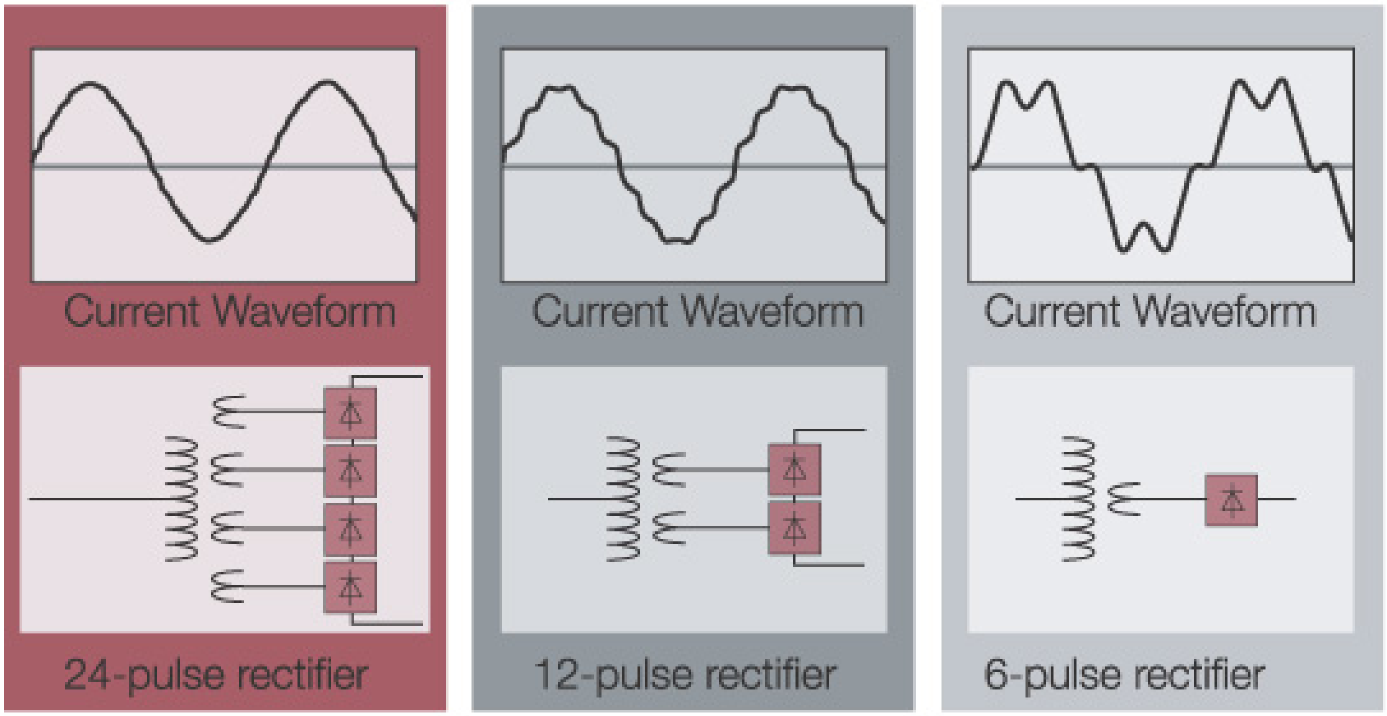


Solutions

- Solutions
  - Major harmonics removed using a 12-pulse uncontrolled diode bridge rectifier
  - 18, 24 or 36-pulse unit used for weaker networks where more stringent harmonic requirements apply
  - Active Front End (AFE)
- Harmonic analysis tools which enable rapid and efficient harmonic calculations allow selection of best configurations
- The solutions used for the vast majority of applications have effective harmonic suppression features and special investigations are normally not necessary.

Solutions

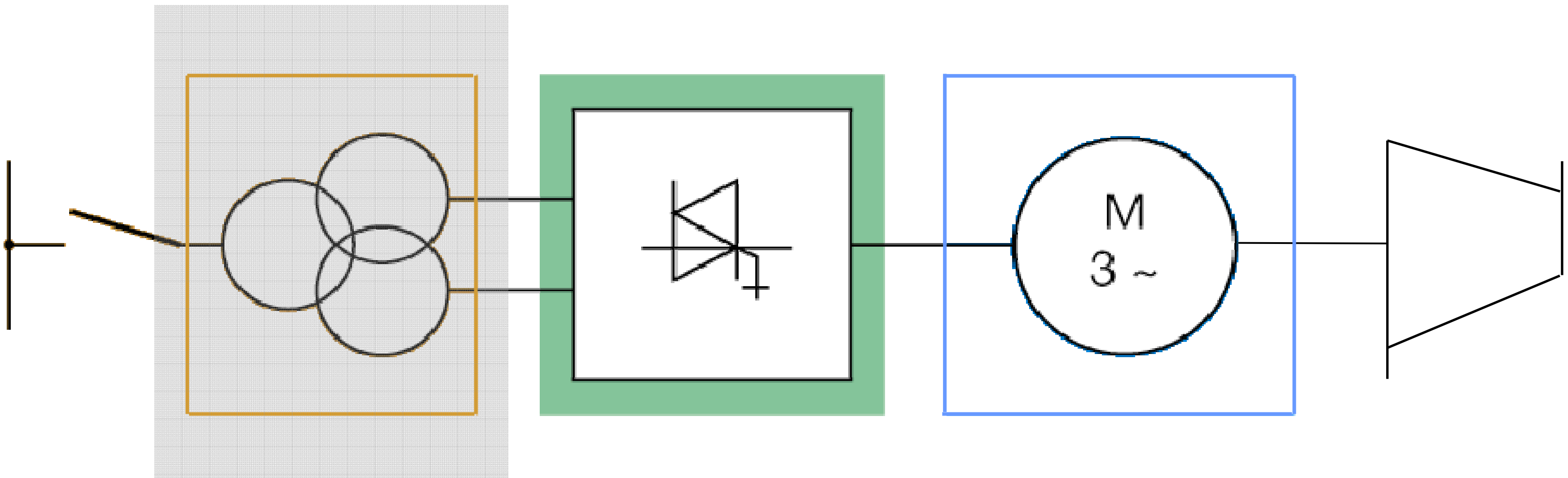
- 6, 12 or 24 pulse transformer



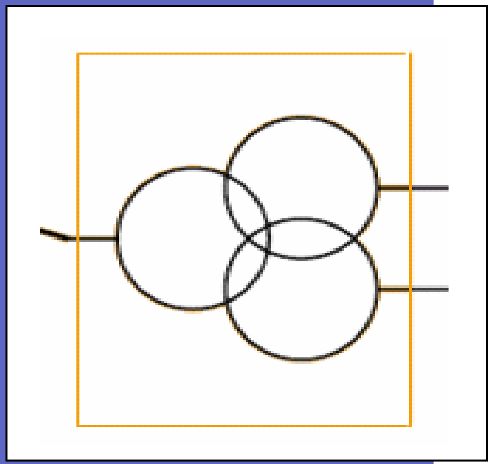
Input power factor

- The higher the power factor the greater the cost savings
  - No extra reactive power compensation is needed
  - Cables and transformers can be dimensioned for lower currents
  - Avoids penalties from utilities
- Target
  - Total power factor better than 0.95
- Power factor should be constant over entire speed range without need for power factor correction equipment
  - Remember – the goal is to run drive at other than full speed

Issues & Considerations - Transformer



Input Transformer



- Purpose of transformer
  - Adapt the network voltage to that of frequency converter
  - Reduce the fault level of the network to a level that the converter can handle in case of a short circuit
  - Galvanic isolation of the drive from the network to simplify the protection system
  - Relieve the motor and/or network from common mode voltages
- Types of transformers
  - air cooled
  - oil-immersed

Transformer location

- Depending on the drive system or topology, the transformer can be placed inside or outside the electrical room or can be integrated into the drive
  - Benefits of placing transformer outside electrical room:
    - Smaller overall drive size
    - Losses from transformer not dissipated in electrical room
    - Cooling requirements greatly reduced
  - Benefits of placing transformer inside electrical room:
    - Minimized cable length
  - Benefits of integrating transformer into drive:
    - Quick installation
    - 3 cables in, 3 cables out

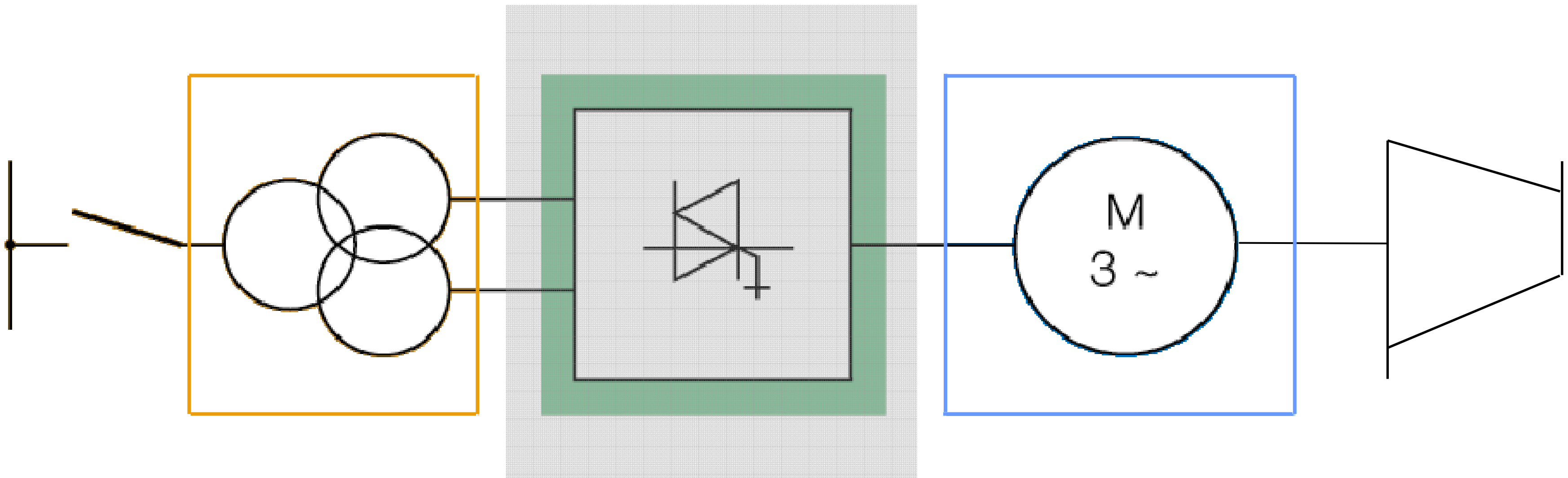
Transformer flexibility

Common practice

Transformer location	Type of transformer	
	Air	Oil-immersed
Indoors	Yes	No*
Outdoors	Yes	Yes
Integrated	Yes	No

* Possible with special oil and containment

Issues & Considerations - VSD

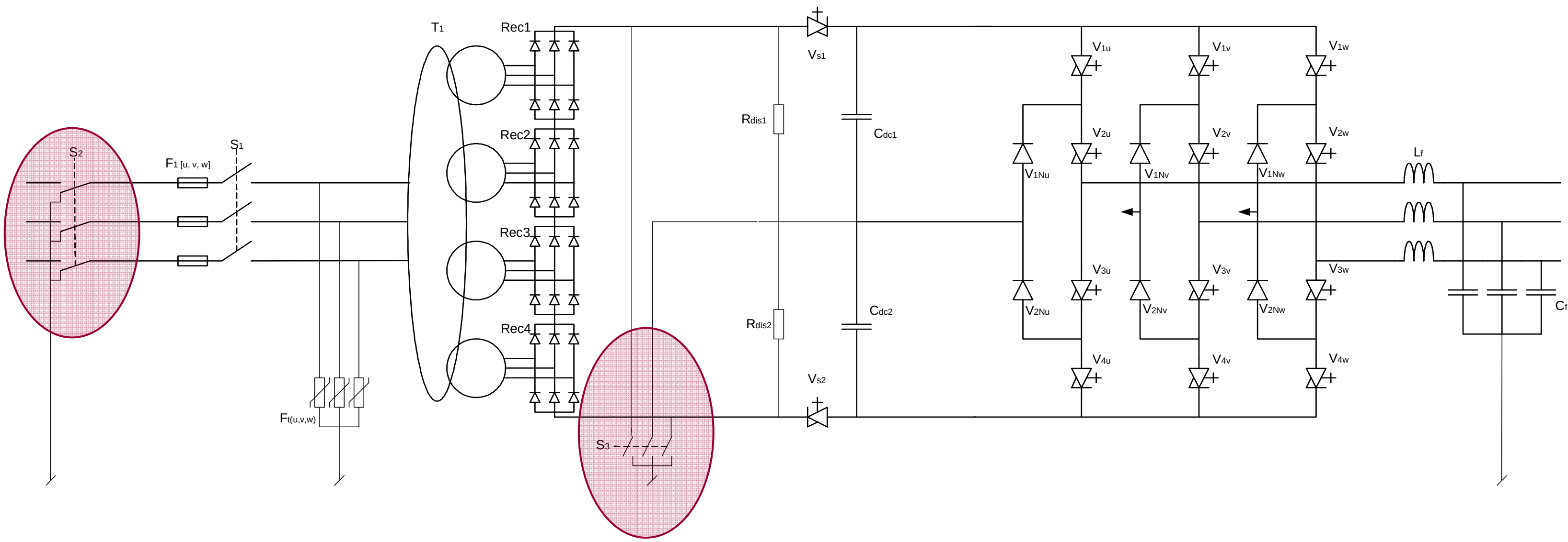


Selection criteria for a MV drive

- Safety
- Reliability
- Efficiency
- Network friendliness
- Motor friendliness
- Control performance
- Low maintenance
- Small overall dimensions
- Low audible noise
- Compliant to EMC regulations

Selection criteria

- Safety should be considered the most important design criteria



- Doors can only be opened, when the main supply is disconnected and the DC link is grounded

*Picture illustrates the interactions for an ACS 1000i.

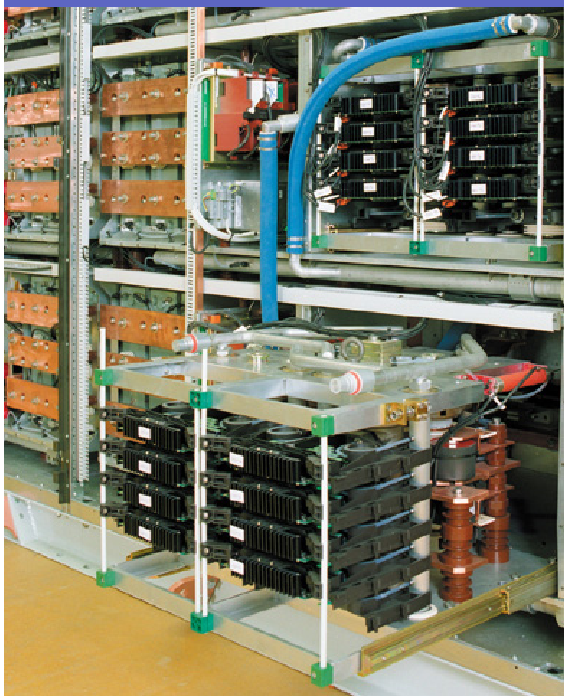
Selection criteria

- Reliability
  - Reliability is achieved by:
    - Low parts count, particularly power semiconductor switches
    - Design margins
    - Fuseless design
- Efficiency
  - Better than 98%
- Network friendliness
  - Compliant with harmonic standards, e.g. IEEE519, IEC 61000 or G5/4
  - VSD isolation transformer for mitigating common mode voltages and safer and simpler protection concepts

Selection criteria

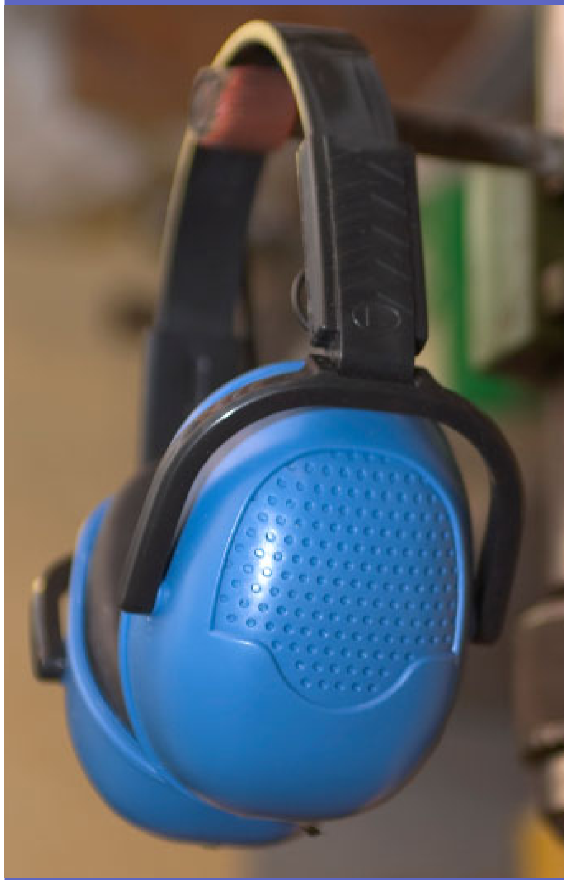
- Motor friendliness
  - Use of standard motors with:
    - No special insulation required due to common mode voltages or high dv/dt values
    - No harmonic de-rating required
  - Retrofit suitable
  - MV-VSD has close to sinusoidal output voltages
- Control performance
  - Highly dynamic (torque step response times < 5ms) and accurate (0.1%)
  - Encoderless

Selection criteria



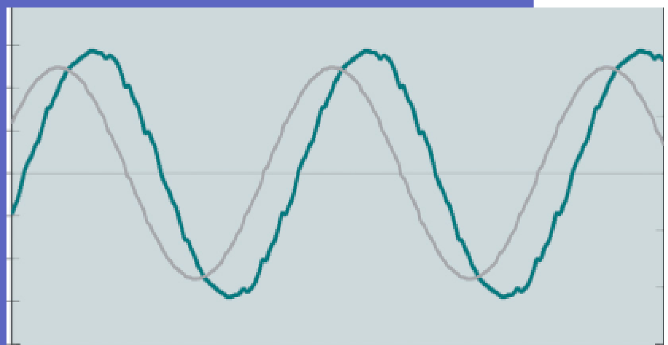
- Low maintenance
  - Only few components need maintenance
    - Air-filter, de-ionizer vessel, back-up battery
  - Reliable cooling fans and pumps
  - No electrolytic DC-link capacitors
    - Lifetime limited to about 5 years
- Small overall dimensions
  - Small size achieved through semiconductor developments

Selection criteria



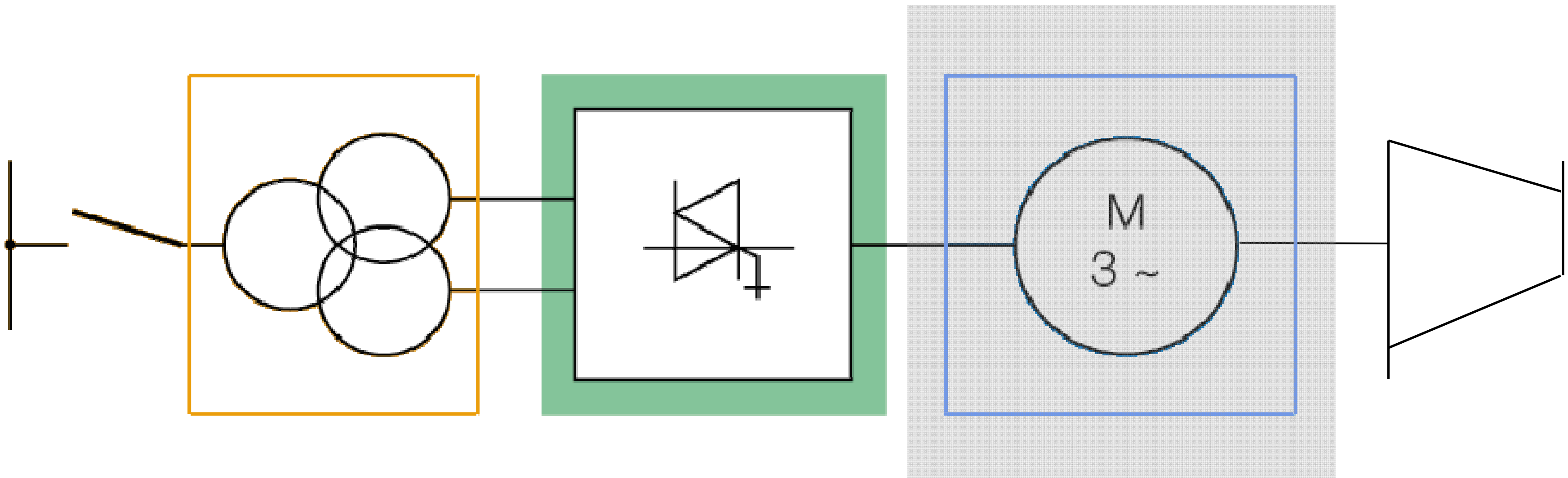
- Low audible noise
  - Health and safety legislation
    - Noise levels must not subject personnel to harmful or irritating noise

Selection criteria

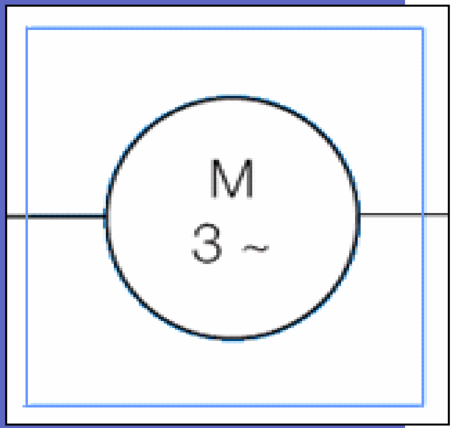


- Compliant to EMC regulations
  - Drives must not pollute environment with high levels of electro-magnetic radiation
  - Installed drive must be immune from effects of radiation coming from surrounding equipment

Issues & Considerations - Motor

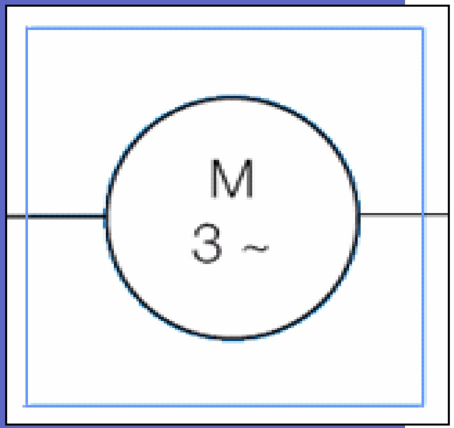


Motor



- Purpose of motor
  - The motor is driving an application
- High-voltage motors
  - Air- or water cooled
  - Designs for harsh environmental conditions or hazardous areas
  - Types
    - Induction motors
      - Power range: up to 18 MW
    - Synchronous motors
      - Power range: up to more than 100 MW
      - With brushes, brushless or permanent magnet

Motor-related issues



- Common mode voltages
- De-rating
- Flying start
- Motor inrush currents
- Motor noise
- Power loss
- Torque pulsations
- Voltage fluctuations
- Voltage stress

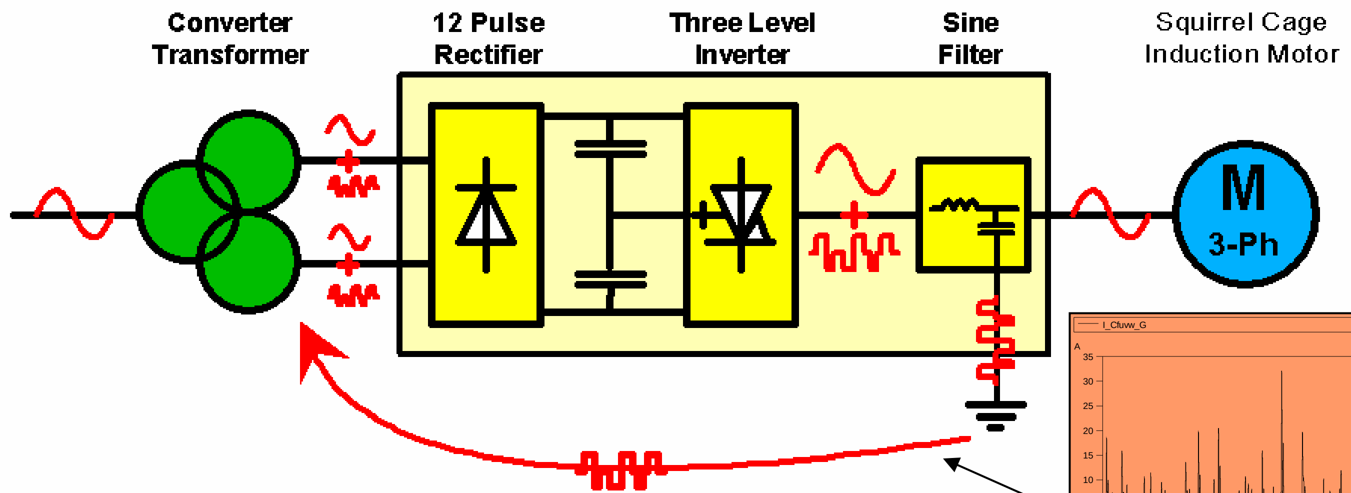
Common mode voltages

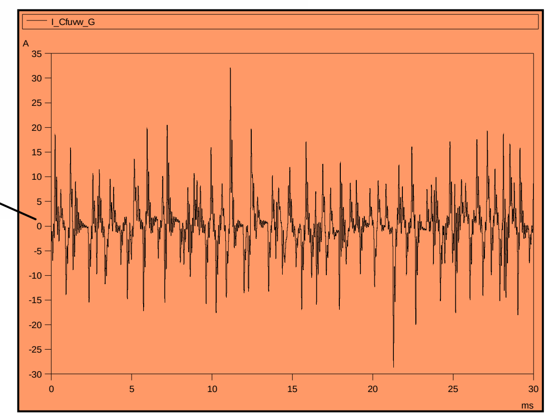
- Common mode voltages
- De-rating
- Flying start
- Motor inrush currents
- Motor noise
- Power loss
- Torque pulsations
- Voltage fluctuations
- Voltage stress

- All frequency converters are a source of common mode voltages
- Common mode voltages may damage motor insulation and bearings
- Measures to mitigate common mode voltages
  - Minimization at source (drive)
    - Suitable drive topology
    - Suitable grounding concept
  - Suitable motor design (e.g. grounding brushes, insulated bearings)
- When retrofitting a drive onto existing motor ensure that:
  - converter does not subject motor to high common mode voltages

Common mode voltages

- Common modes inside the Drive System





  - Common Modes are produced from every inverter, independent which topology is used and which manufacturer is considered.
- In this example they are directed back to the transformer, but kept away completely from the motor.

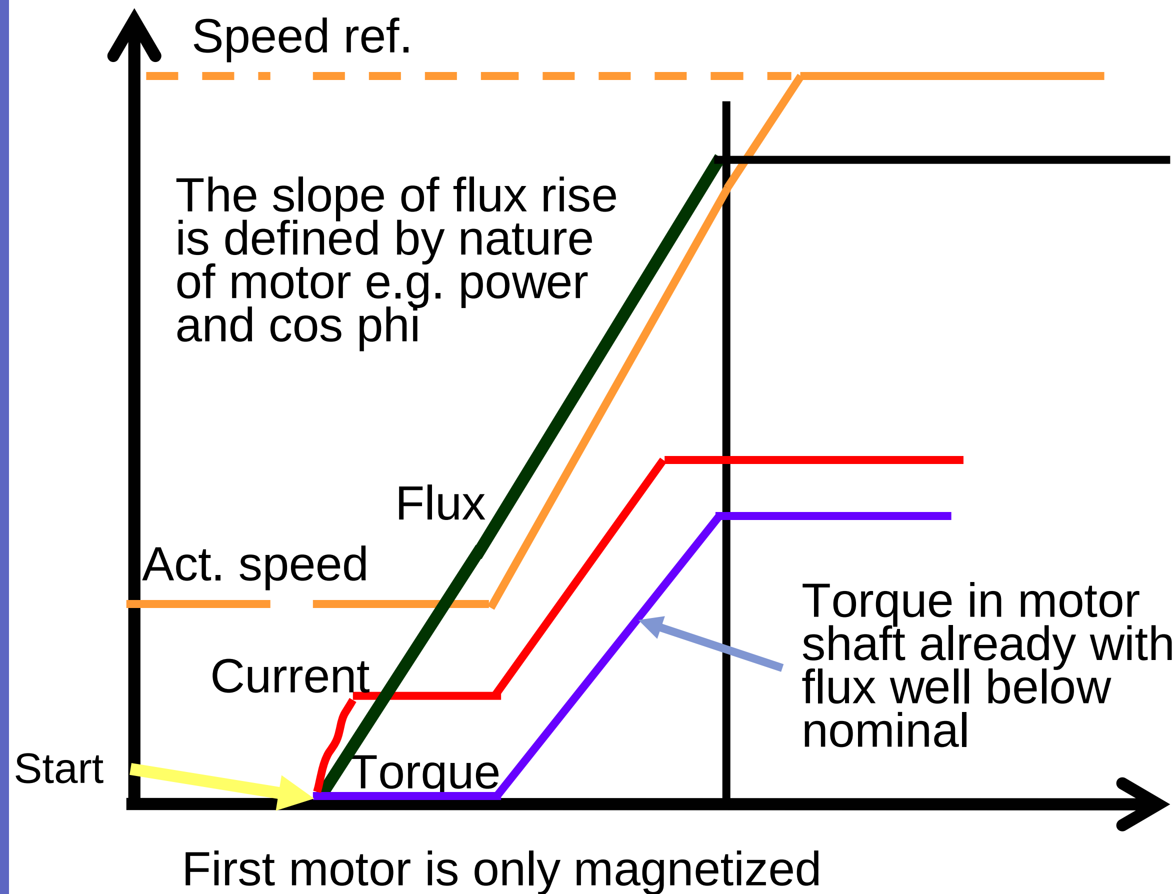
De-rating due to harmonics

- Common mode voltages
- De-rating
- Flying start
- Motor inrush currents
- Motor noise
- Power loss
- Torque pulsations
- Voltage fluctuations
- Voltage stress

- Harmonics cause additional heating
  - leads to the need to de-rate motor
- When buying a motor for a MV drive check if de-rating is necessary

Flying start

- Common mode voltages
- De-rating
- Flying start
- Motor inrush currents
- Motor noise
- Power loss
- Torque pulsations
- Voltage fluctuations
- Voltage stress



Motor inrush currents

- Common mode voltages
- De-rating
- Flying start
- Motor inrush currents
- Motor noise
- Power loss
- Torque pulsations
- Voltage fluctuations
- Voltage stress

- DOL (Direct-On-Line) connected motors draw very high inrush currents (3-7 times the nominal current) during start-up
  - Can cause significant network voltage drops that lead to tripping of other loads
  - Can disturb other connected loads and adjacent busbars
  - Frequent trips mean process disturbances and even long process downtime for motors connected direct-on-line

Motor inrush currents

- Common mode voltages
- De-rating
- Flying start
- Motor inrush currents
- Motor noise
- Power loss
- Torque pulsations
- Voltage fluctuations
- Voltage stress

- MV motors - number of starts limited without damage occurring from temperature rise
- MV drives overcome such limitations by providing soft start
  - Unlimited number of starts can be achieved with no inrush currents
  - Soft start capability means motor can be designed less expensive
  - Reduced stress on mechanical equipment

Motor noise

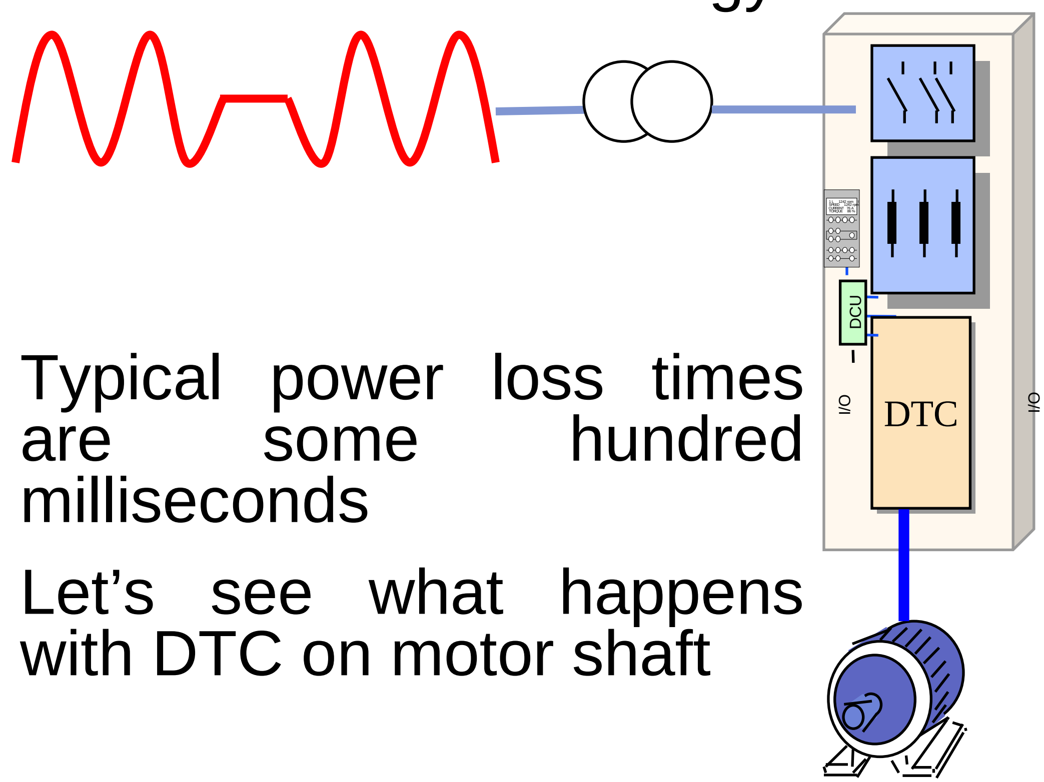
- Common mode voltages
- De-rating
- Flying start
- Motor inrush currents
- Motor noise
- Power loss
- Torque pulsations
- Voltage fluctuations
- Voltage stress

- DTC does not use fixed carrier frequencies and incorporates flux optimization – both of which provide lowest motor noise
- Low noise fans can reduce noise levels

Power Loss Ride Through

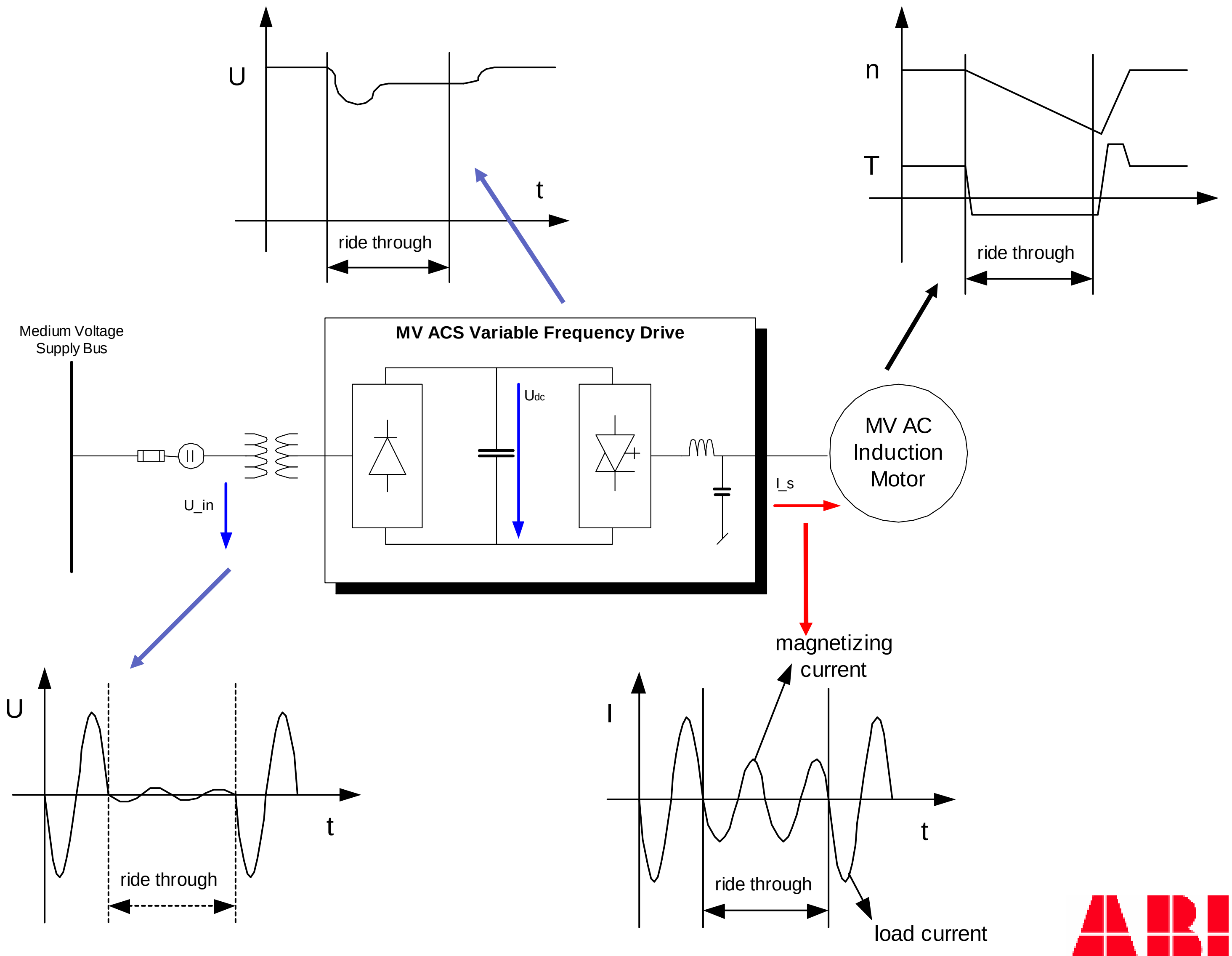
- Common mode voltages
- De-rating
- Flying start
- Motor inrush currents
- Motor noise
- Power loss
- Torque pulsations
- Voltage fluctuations
- Voltage stress

- Power loss is critical in many processes
- DTC utilizes kinetic energy



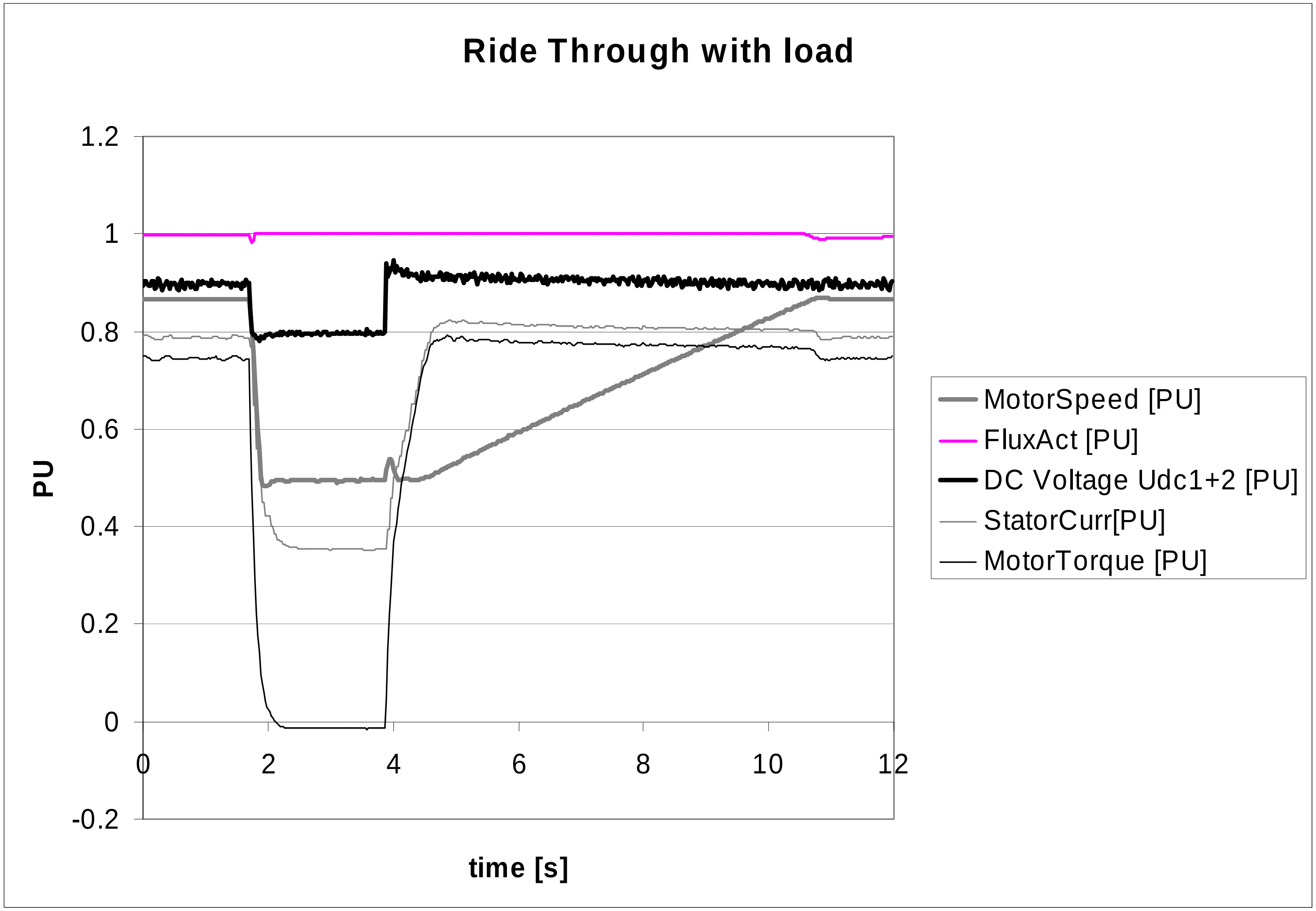
- Typical power loss times are some hundred milliseconds
- Let’s see what happens with DTC on motor shaft

Power Loss Ride Through



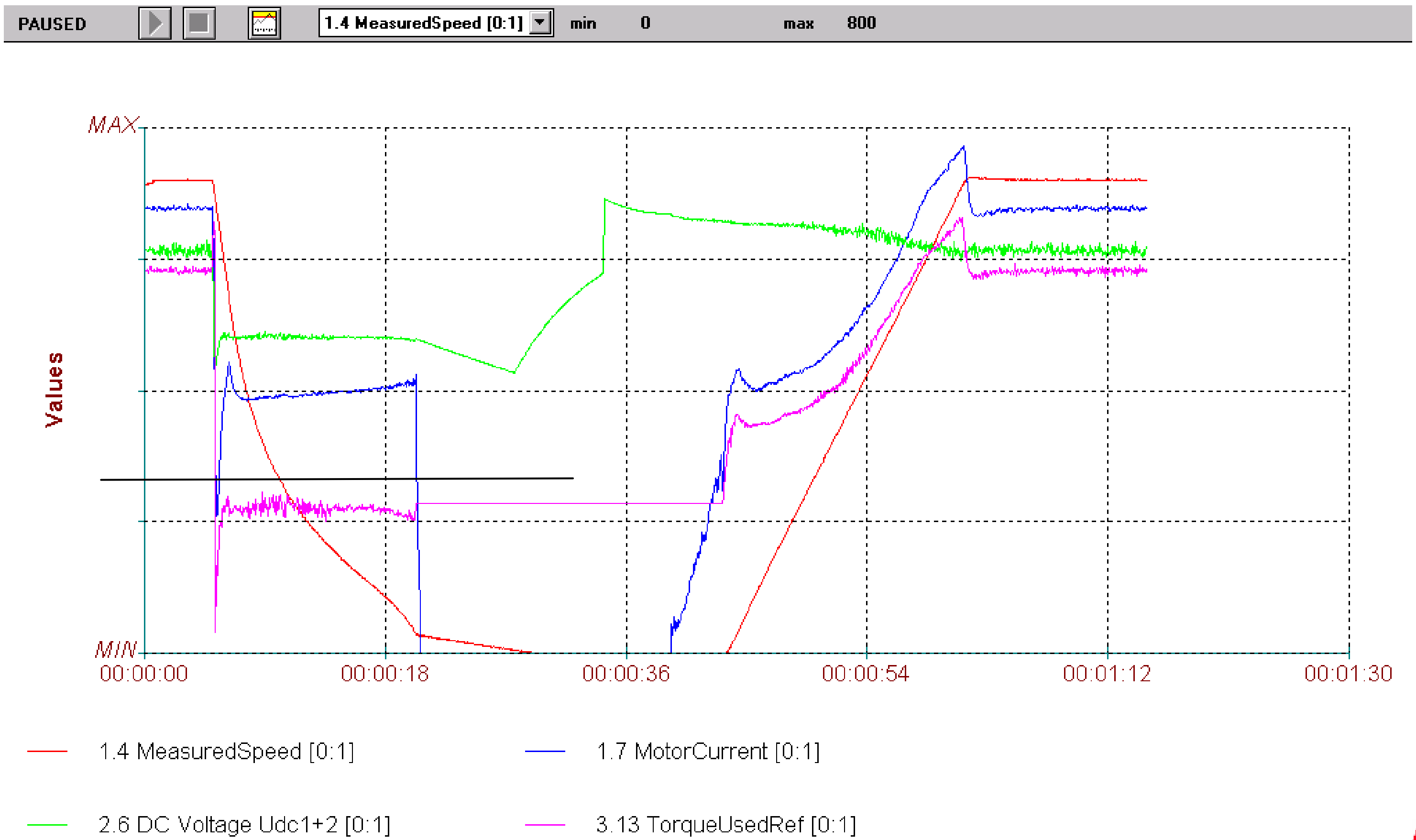
Measuring example

- Ride-Through with load (Measurement)
  - Load speed is constant on 50% of the nominal ASM speed



Measuring example

- Autorestart (square load, speed ref = 100%)
  - Scaling: Speed: 0..800 rpm, DC Voltage: 0..4500 V
  - Motor Current: 0..500 A, TorqueUsedRef: - 40..100 %



Torque pulsations

- Common mode voltages
- De-rating
- Flying start
- Motor inrush currents
- Motor noise
- Power loss
- Torque pulsations
- Voltage fluctuations
- Voltage stress

- Some MV drives produce problematic torque pulsations
- These can damage the weakest link in the chain such as motor, coupling, gearbox or load
- A full torsional vibration analysis may be needed

Voltage fluctuations

- Common mode voltages
- De-rating
- Flying start
- Motor inrush currents
- Motor noise
- Power loss
- Torque pulsations
- Voltage fluctuations
- Voltage stress

- A weak network or unreliable power supply can result in voltage fluctuations
- Motor running on such a network should **ride through** transient voltage dips
- MV drives can handle certain fluctuations of feeding network without tripping

Voltage stress

- Common mode voltages
- De-rating
- Flying start
- Motor inrush currents
- Motor noise
- Power loss
- Torque pulsations
- Voltage fluctuations
- Voltage stress

- Drives using fast switching semiconductors can have a high voltage rate of change dv/dt
  - this can damage motor insulation
- Make sure to check the motor can handle the dv/dt from the drive
  - dv/dt filters or output filter reduce voltage stresses to a minimum

Thank you very much

Questions ?

ABB

Power and productivity
for a better world™