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VFD and motor system saving potentials

Complete drive Systems – motors & VFD

Prof. Dr. Andrea Vezzini, Bern University of Applied Sciences

An online training seminar for:

SAARC ENERGY CENTRE

Energy for Peace & Prosperity

- On-line Training of Stakeholders on Digitizing Industrial Motor Systems for Energy Efficiency

About the Speaker

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Vita / Current Activities

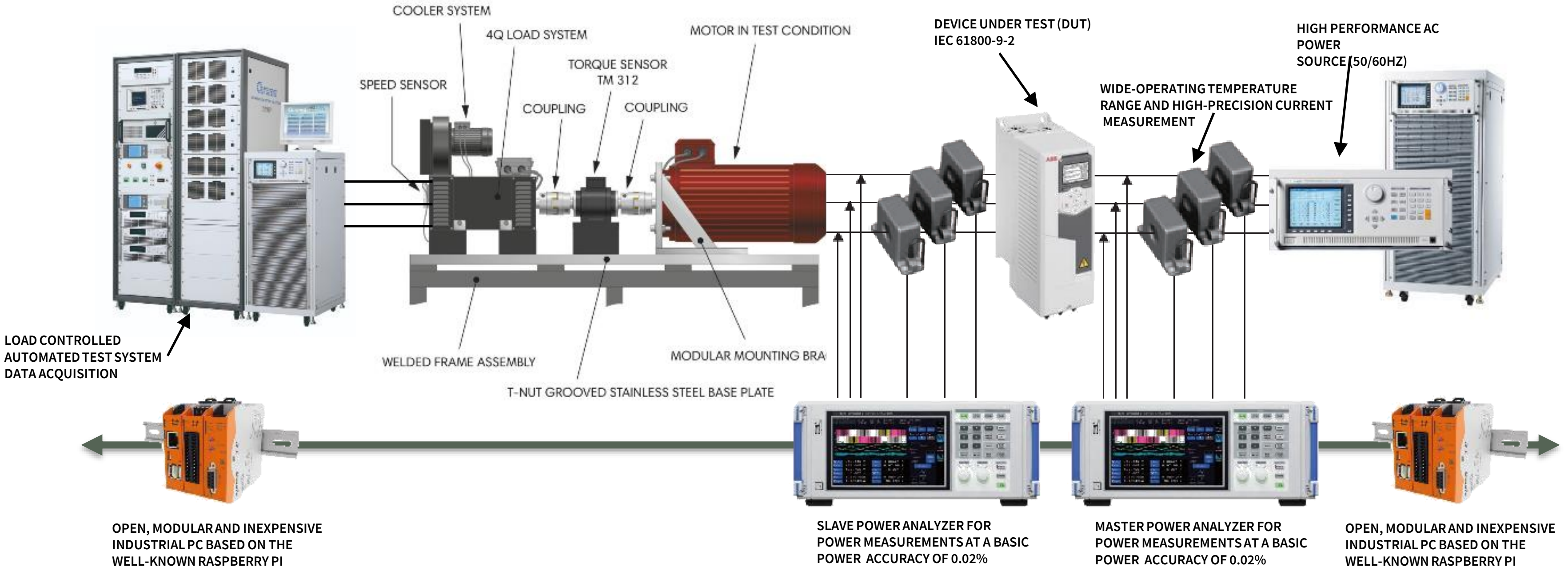
- Professor for Industrial Electronics and Electrical Machines since 1996 at Bern University of Applied Sciences
- Member of IEC TC2 WG 28 & WG 31 and IEC 22G WG18 since 2017
- Member of the Federal Energy Research Commission (CORE) since 2015
- Head of the BFH Energy Storage Research Center since 2014
- Deputy Head of the Swiss Competence Center for Energy Research “Mobility” 2013 - 2020
- Co-founder and Member of the Board of “Integrated Power Systems AG” since 2009
- Co-founder and Chairman of the Board of drivetek ag since 2002
- Inventor/Co-Inventor of 8/23 patents in the field of electric motor design and lithium-ion battery technology

BFH Electric Machine Test benches

- Seven electrical machine test beds in the range from 0.1 kW to 60 kW.
- Torque measuring shafts from 0.2 to 500 Nm at speeds up to 10'000 rpm
- Automated test bed for motor measurements up to 11kW according to test standard IEC 600034-2-1
- Two modern 6-phase power meters HIOKI POWER ANALYZER PW6001 for recording all relevant parameters of electric drives (operation in master-slave mode possible)

Automated efficiency testing

- In addition to conventional motor tests involving the test object, load machine and torque measurement standard efficiency testing requires a high-quality power source, a winding ohmmeter, a power analyzer and a test automation system



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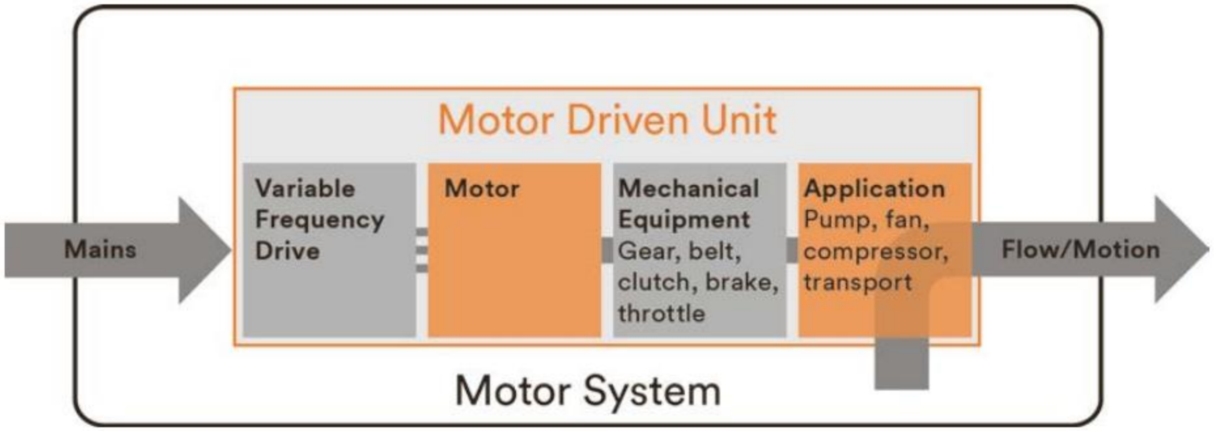
- Motor Driven Unit definition
- Improving Motor Efficiency
  - IEC Standards
  - Loss optimized motors
- Improving Inverter Efficiency
  - Inverter Efficiencies for different topologies
- Energy savings potential for VFD + Pump
  - Energy savings potential for VFD + Pump
- Conclusions

Motor Driven Units

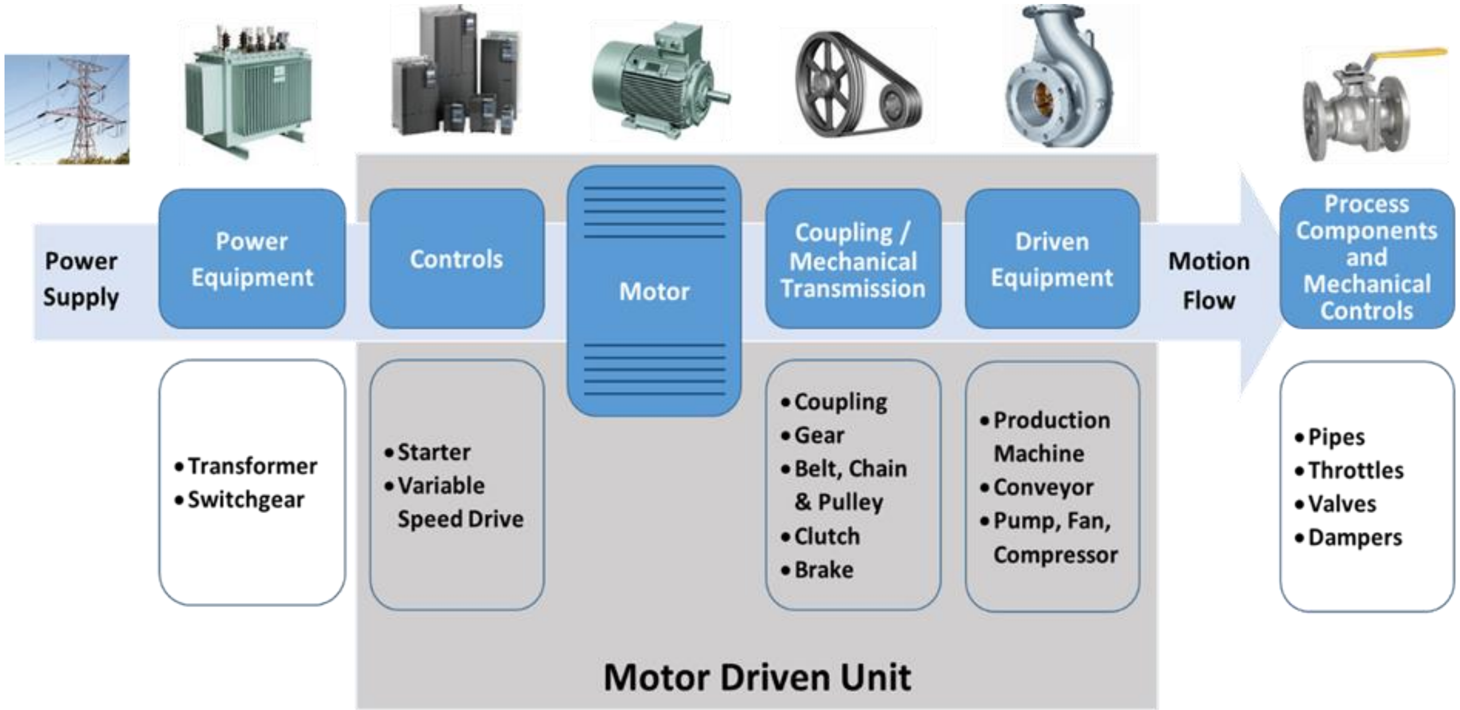
Introduction

Motor Driven Unit definition

- A Motor Driven Unit converts electrical power into rotational mechanical power and may consist of the following individual components: variable frequency drive, electric motor, mechanical equipment (e.g. gear, belt, clutch, brake, throttle) and a driven application (e.g. pump, fan, compressor, transport).



Motor Driven Unit and related equipment of a system



- Electric motors account for a good half of the world's electrical energy consumption.
- They are used at the heart of all drive systems for pumps, fans, compressors, transport and process machinery.

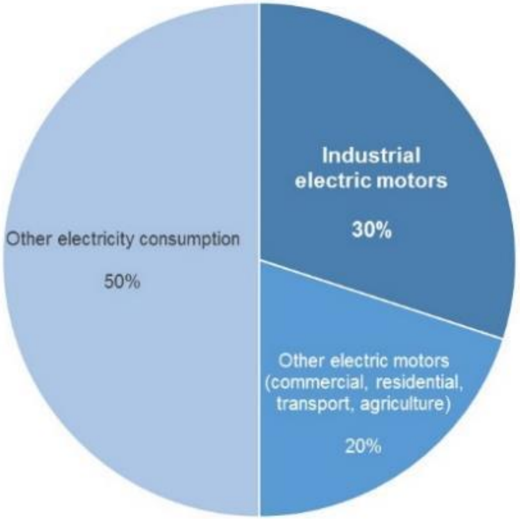
Source: Prof. Anibal de Almeida

Typical Centrifugal Pump incl. variable speed drive

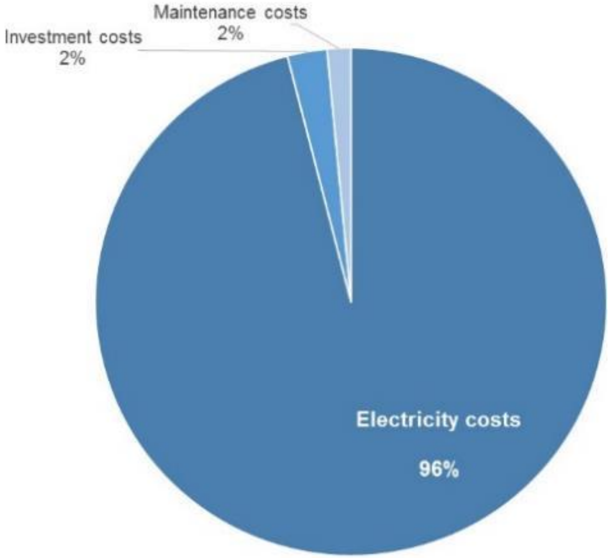
MegaCPK with SuPremE®-motor, PumpDrive and PumpMeter (https://www.ksb.com/)

- MegaCPK is a particularly powerful standardized pump destined for the chemical and petrochemical industry, and many other fields of application. The optimized design of its hydraulic components sets new standards in energy efficiency.
- The KSB SuPremE® motor is so energy-efficient that it meets IE5* efficiency requirements, making it the most efficient magnet-less pump motor in the world. (https://www.ksb.com/supreme-en/)

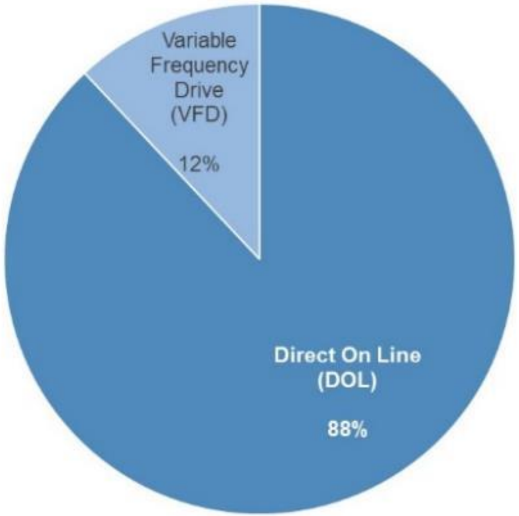
Motor Driven Units: Market Overview



- Share of global electricity consumption per component type



- Share of life cycle costs components for industrial electric motors



- Share of constant speed or variable speed control of installed global industrial electric motor base

- The economical benefits by implementing energy saving measures on electric motor systems and driven applications are more cost efficient than not doing the same investments.

Improving Motor Efficiency

IEC Standards

Loss optimized motors

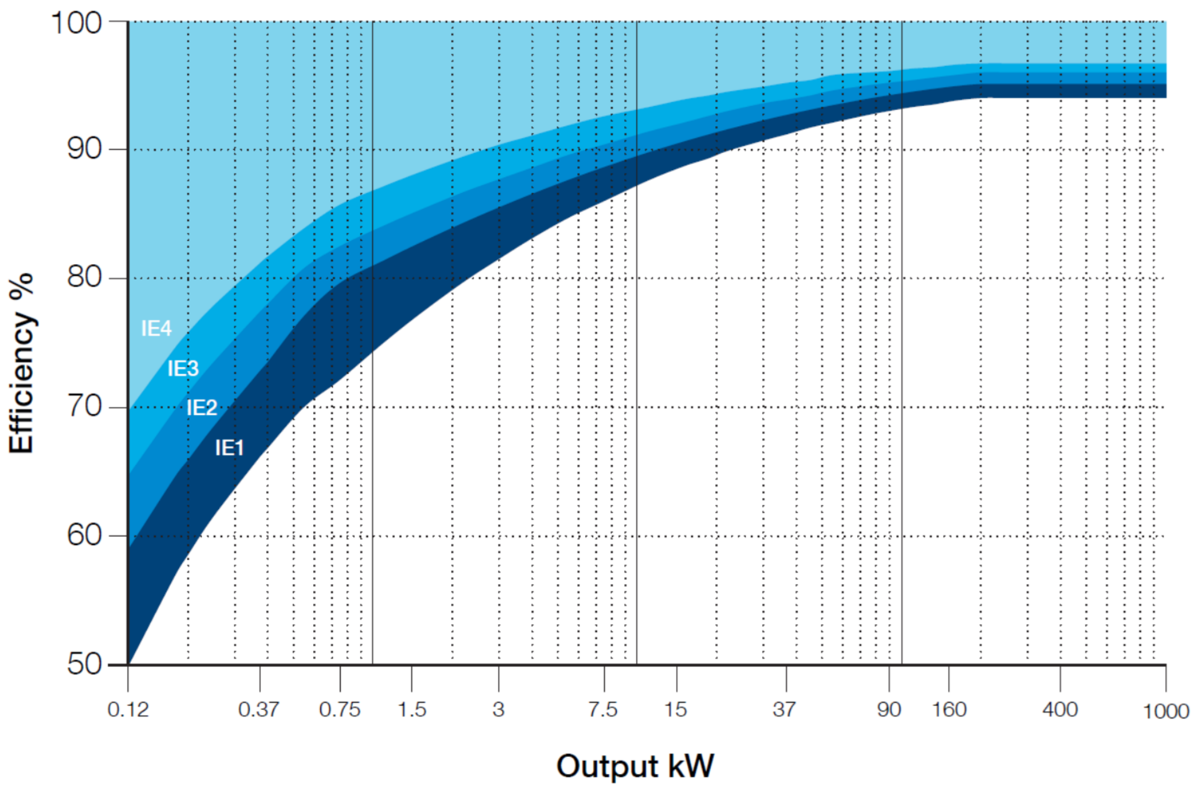
Introduction to IEC standards

Overview of IEC standards on energy efficiency of power drive systems and motor driven units

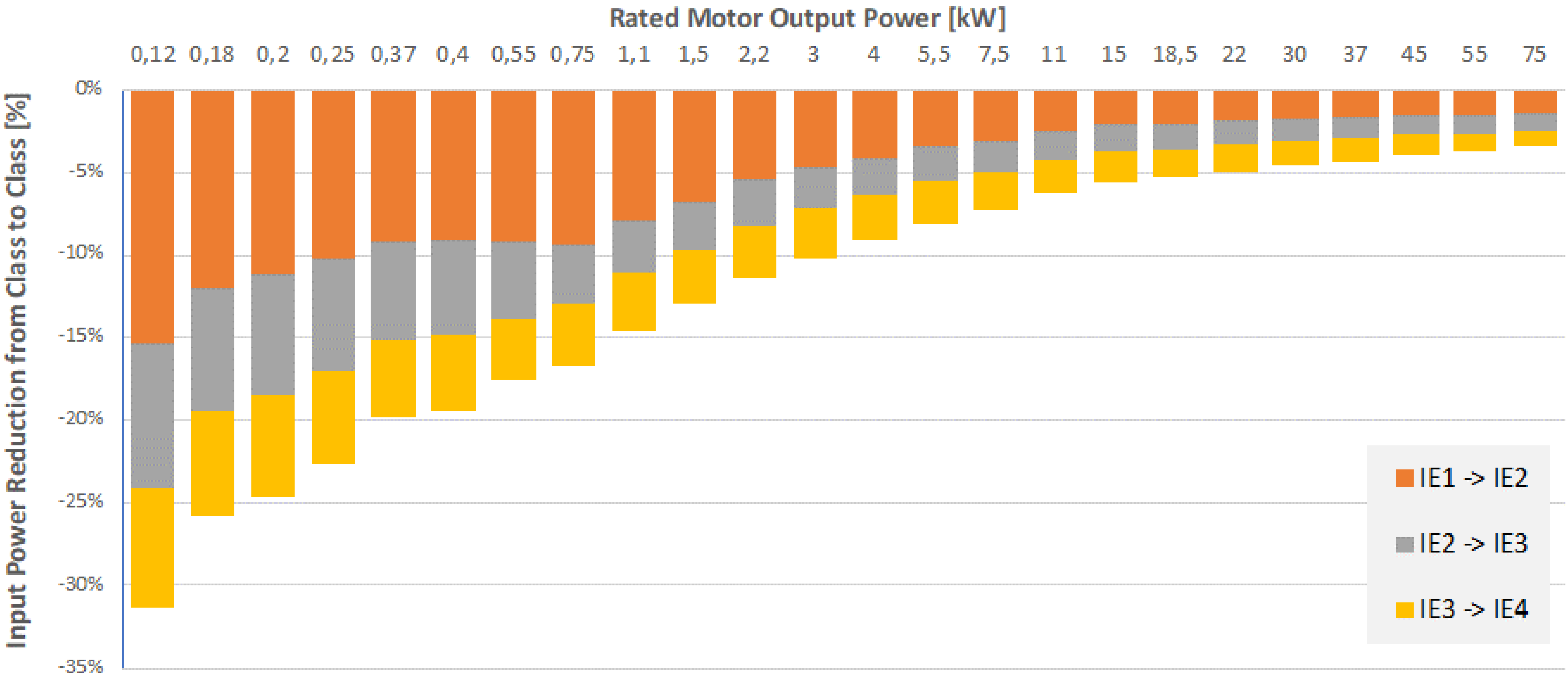
		Scope	Efficiency testing	Efficiency classification
1	Motor	Motor	IEC 60034-2-1 Edition 2: 2014-06 IEC TC2 WG28	IEC 60034-30-1 Edition 1: 2014-03 IEC TC2 WG31
2	VFD Motor	Motor, driven by VFD	IEC 60034-2-3 Edition 2: 2018 IEC TC2 WG28	IEC TS 60034-30-2 Edition 1: 2016-12 IEC TC2WG31
3	VFD Motor	VFD	IEC 61800-9-2: VFD **Classification/Testing** Edition 1: 2017-03 IEC SC22G WG18	
4	VFD Motor	Motor + VFD		

IE efficiency classes for 4-pole motors at 50 Hz

- Electric motors with 2 to 8 poles and rated powers between 0.12 kW and 1000 kW are tested according to IEC 60034-2-1 and classified according to their efficiency into the efficiency classes IE1 to IE4 (IE code according to IEC 60034-30-1)
- Efficiency classes:
  - IE4 – Super Premium Efficiency
  - IE3 - Premium Efficiency
  - IE2 - High Efficiency
  - IE1 – Standard Efficiency
- Nominal efficiency limits for 1201 ... 1800 /min rated speed motors determined at 90% rated speed, 100% rated torque



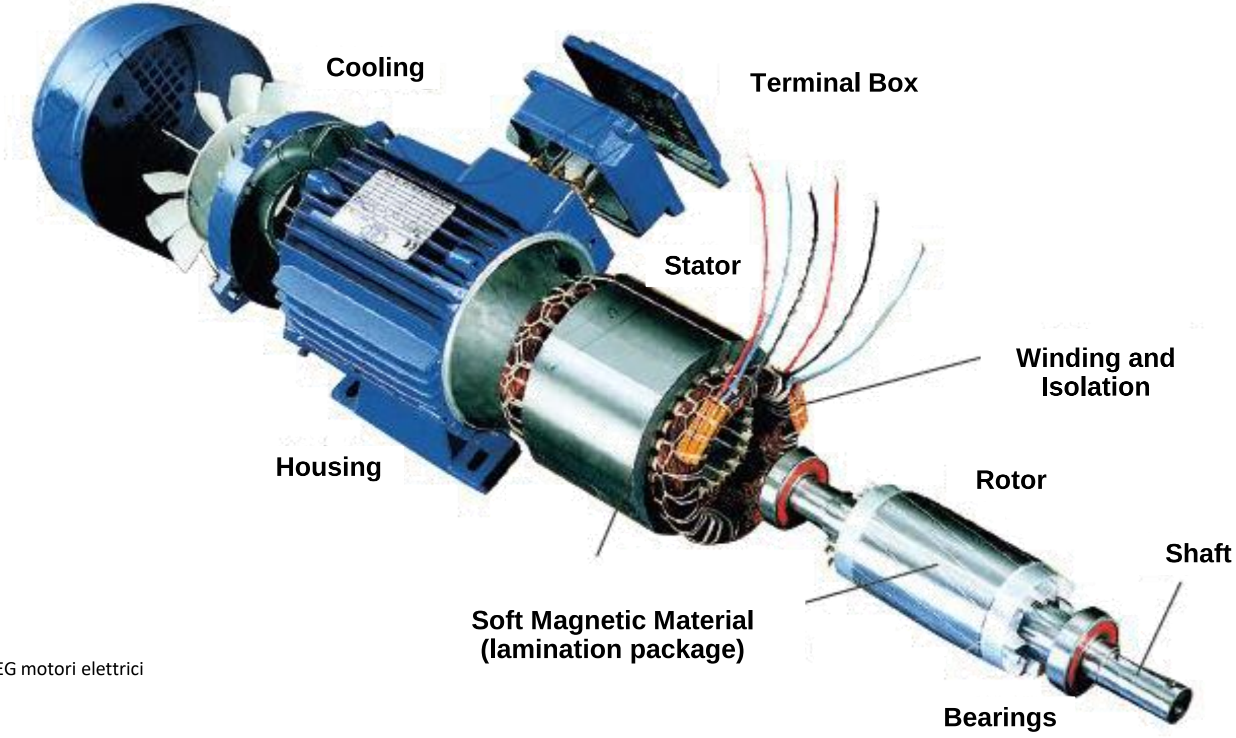
Reduction of motor losses from IE1 to IE4



- Reduction of motor input power between one efficiency class to the next higher class in percentage versus rated motor output power, shown cumulative for 4-pole motors of all IE classes

Structure of an Asynchronous Motor

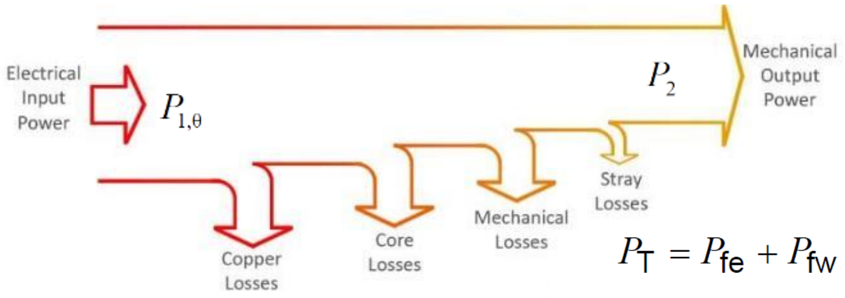
- Rotor of the asynchronous machine usually constructed as a squirrel-cage rotor with conductive, short-circuited bars.



Losses and Efficiency of Induction Motor

- I^2R losses,
  - Stator Cu loss ($P_{s\theta}$)
  - Rotor I^2R loss ($P_{r\theta}$)
- Core Losses (P_{fe})
  - Hysteresis loss
  - Eddy current loss
- Mechanical losses (P_{fw})
  - Friction loss
  - Windage loss
- Stray Losses (P_{LL})

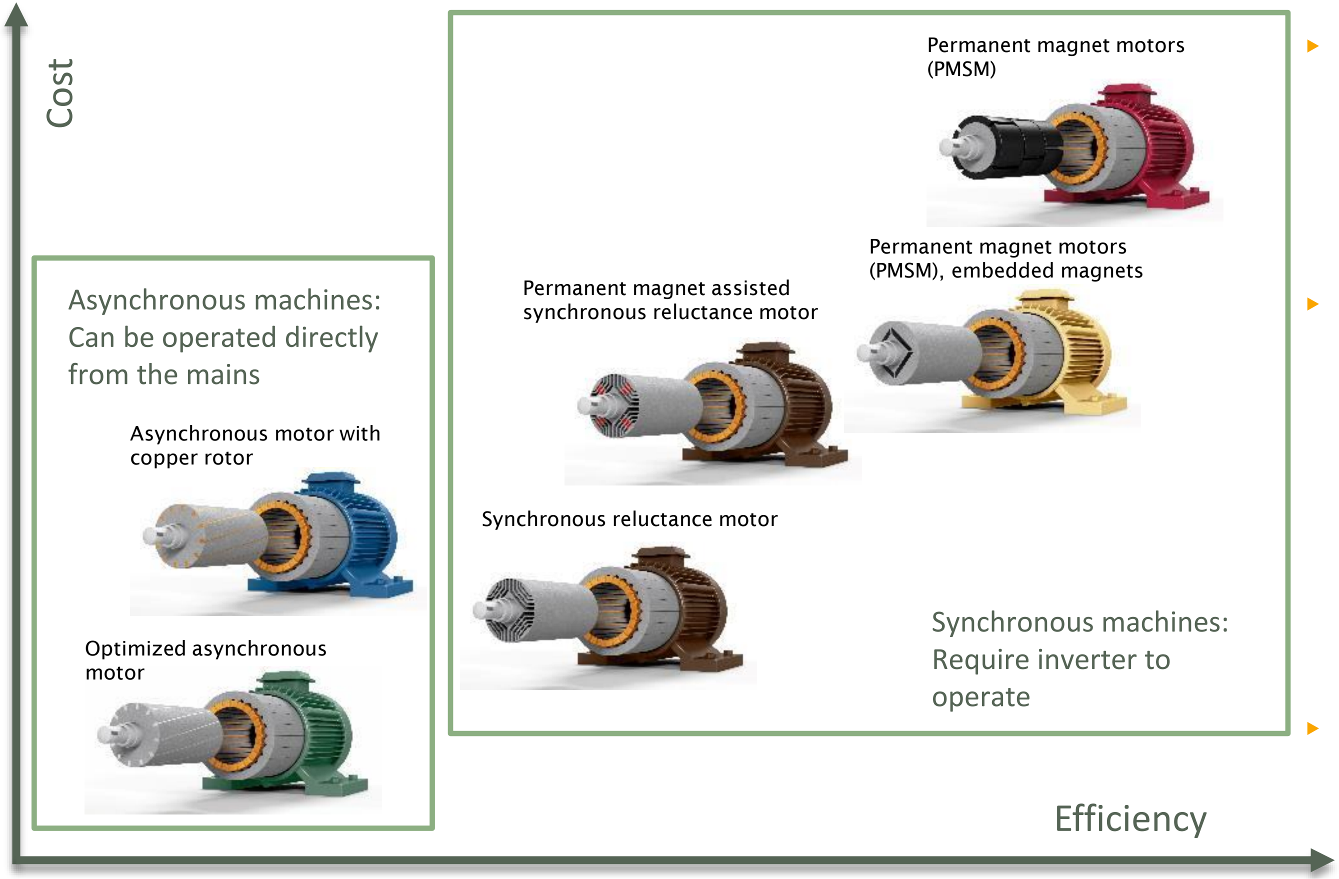
- Efficiency (η) $\eta = \dfrac{P_{1,\theta} - P_T}{P_{1,\theta}} = \dfrac{P_2}{P_2 + P_T}$



$$P_T = P_{fe} + P_{fw} + P_{s\,\theta} + P_{r\,\theta} + P_{LL}$$

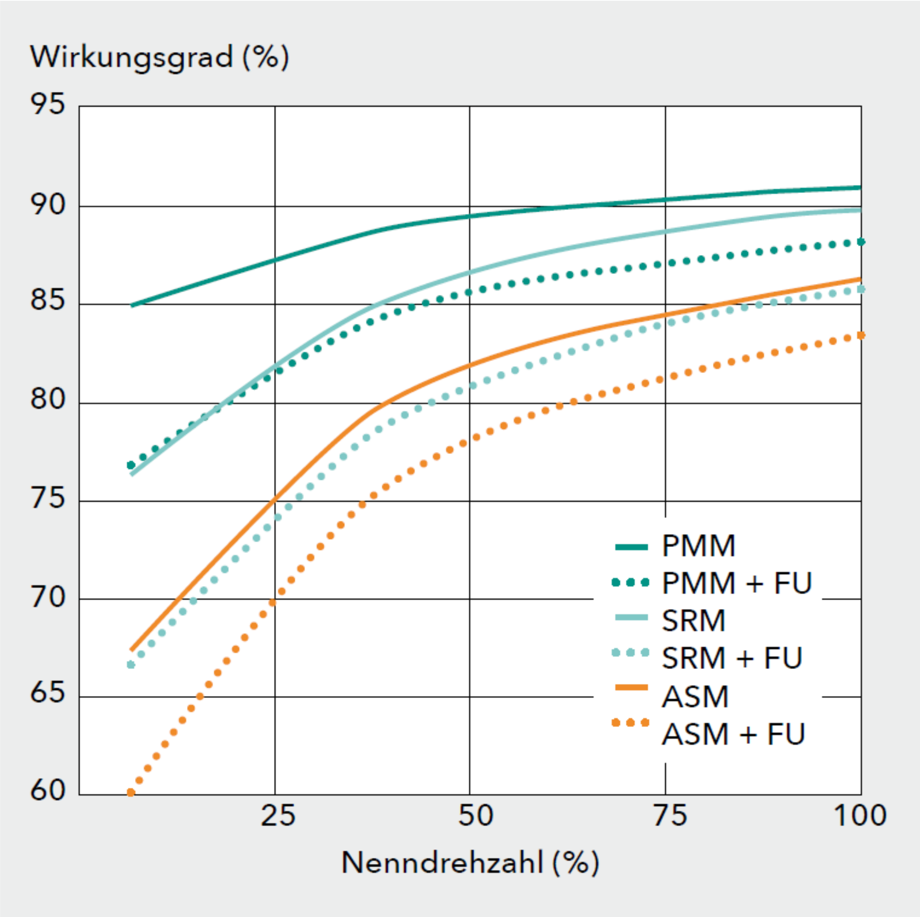
Name	Percent of Total Losses	Description	Fixed or Variable	How to reduce
Core Losses	15-15%	Energy required to magnetize core.	Fixed	Improved permeability steel, lengthening core, using thinner laminations in the core.
Windage and Friction	5-15%	Losses due to bearing friction and air resistance, which is primarily caused by the cooling fan.	Fixed	Lower friction bearings, improve fan design and air flow.
Stator Losses	25-40%	Heating due to current flow through the resistance of the stator winding.	Variable	Increasing the volume of copper wire in the stator, through improved stator slot designs, and by using thinner insulation.
Rotor Losses	15-25%	Heating due to I2R losses in the rotor conductive bars.	Variable	Increasing the size of rotor conductive bars and end rings to reduce resistance.
Additional Load Losses	10-20%	Leakage fluxes induced by load currents and various other minor losses.	Variable	Various design and manufacturing details

Loss optimized motors



- Today, a variety of new motor technologies are available to the user. Both the Optimized Asynchronous Motor and the ASM with copper rotor today achieve IE3 in some cases even IE4.
- For efficiency classes IE4 and higher, however, there is a trend in the industry towards synchronous reluctance motors. Either completely without magnetic materials or then with cheaper, problem-free magnetic materials, which offer more stable market availability in procurement.
- Finally, the market offers also numerous high-efficiency drives with permanent magnet motors.

Efficiency comparison



- Efficiencies for the synchronous motor apply for supply via the frequency inverter.
- For comparison with the asynchronous motor in variable-speed applications, the efficiency of the grid-connected asynchronous machine must be corrected.
- A VFD makes an additional loss of about 3-4% at the nominal point.

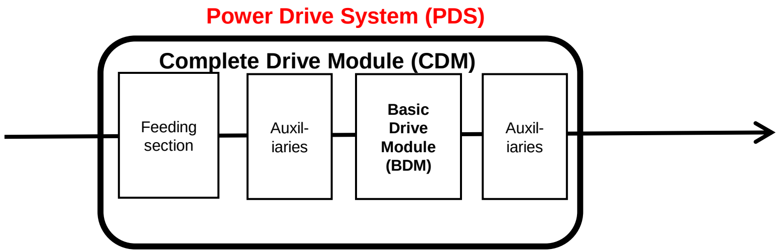
4-Pole-Motors 2.2 kW with 7 Nm torque (source: Jorge Estima/EEMODS'17)

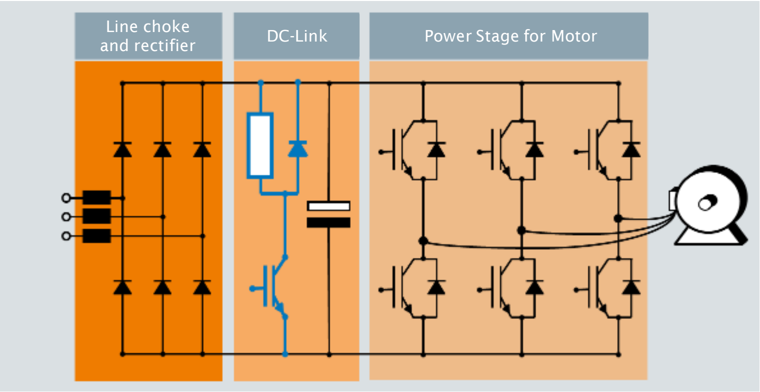
Improving Inverter Efficiency

Inverter Efficiencies for different topologies

Complete Drive Module

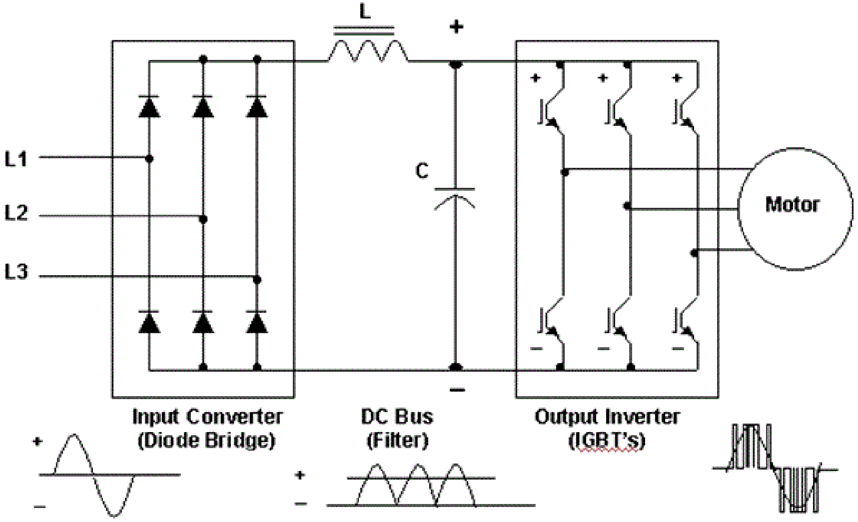
- A VFD makes an additional loss of about 3-4% at the nominal point. Due to its pulse width modulation, it supplies the motor with a chopped sinusoidal current, which also leads to a loss of efficiency of about 1% for the motor. Therefore, the advantages and disadvantages of using an FI, as well as the additional costs, must be carefully weighed up.

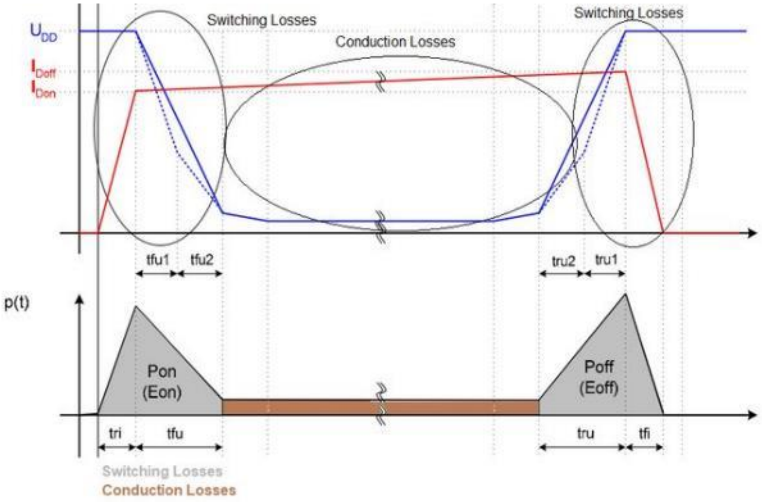




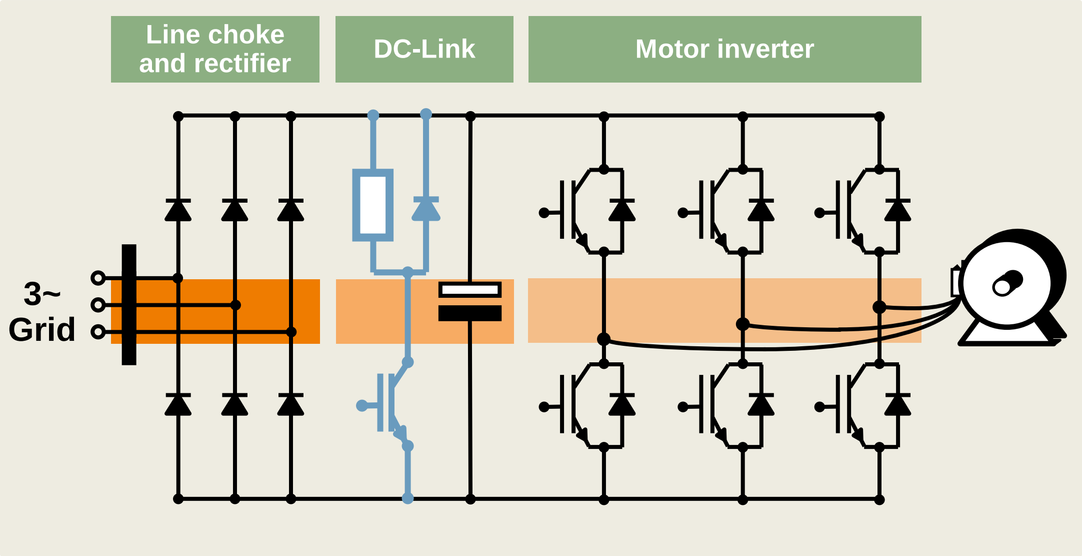
Inverter Losses

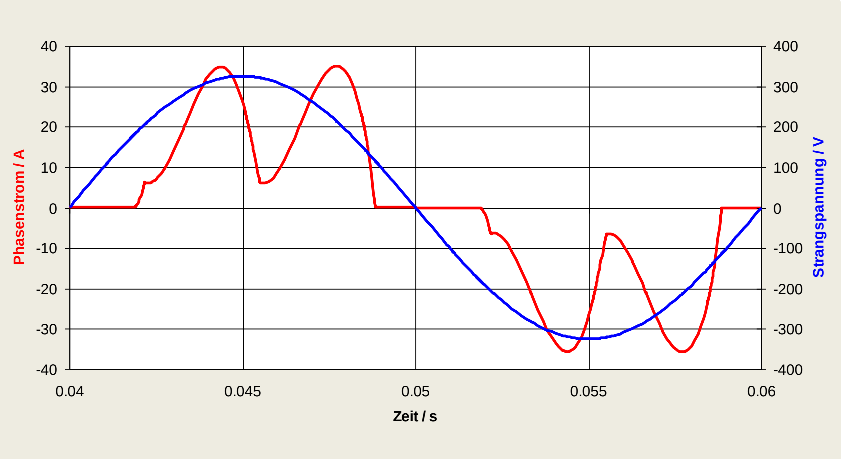
- The inverter has power losses that can be divided into two different types: conduction losses and switching losses.
- Conduction losses are produced when the switch is in the on- state, and switching losses appear when the switch is turned on and off.





Diode rectifier: Input current

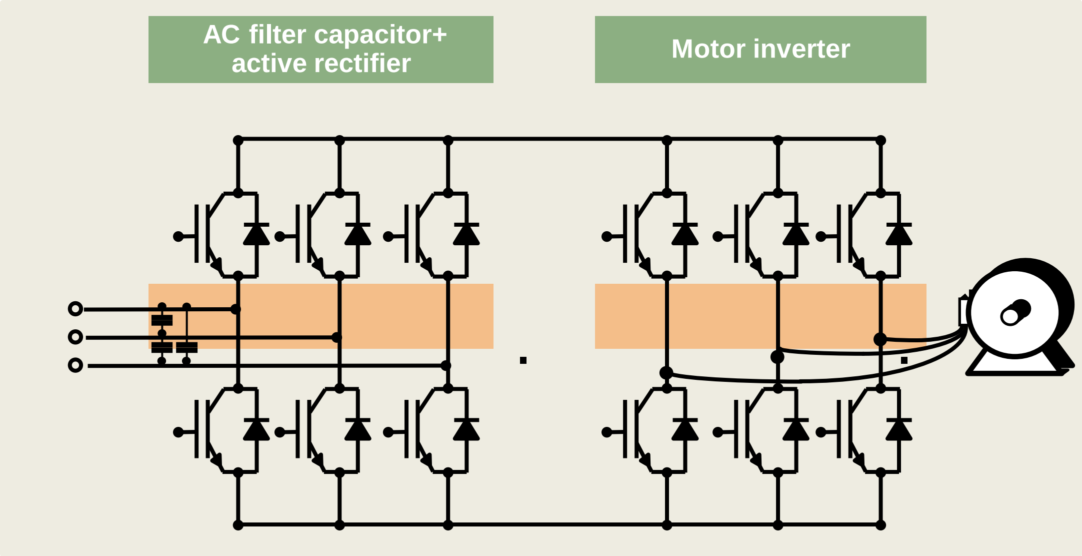


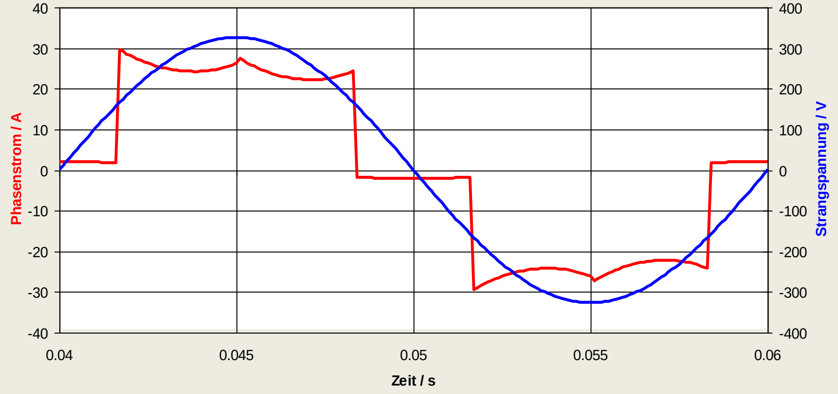


- Maximum current depends on the size of the line choke
- Power factor approx. 0.7

- **Features:**
  - Motor operation only
  - Large mains choke
  - Large braking resistor

Fundamental Frequency Front End (F3E): Input current

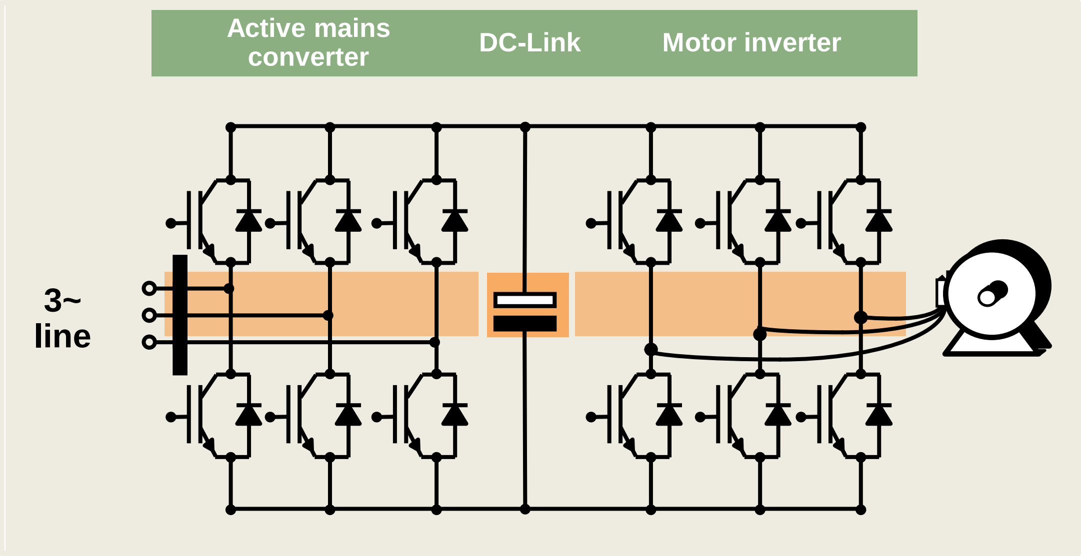


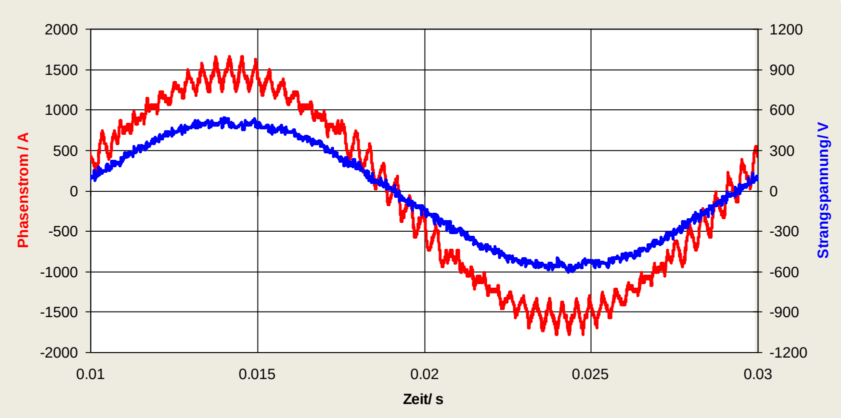


- Approximate block-shaped input current waveform
- Power factor close to 1

- **Features:**
  - Regenerative mains rectifier with mains-frequency (typ. 50Hz) switched IGBTs
  - No input choke
  - Small line filter capacitors (typ. approx. 1% of today's DC links)

Active Front End (AFE): Input current

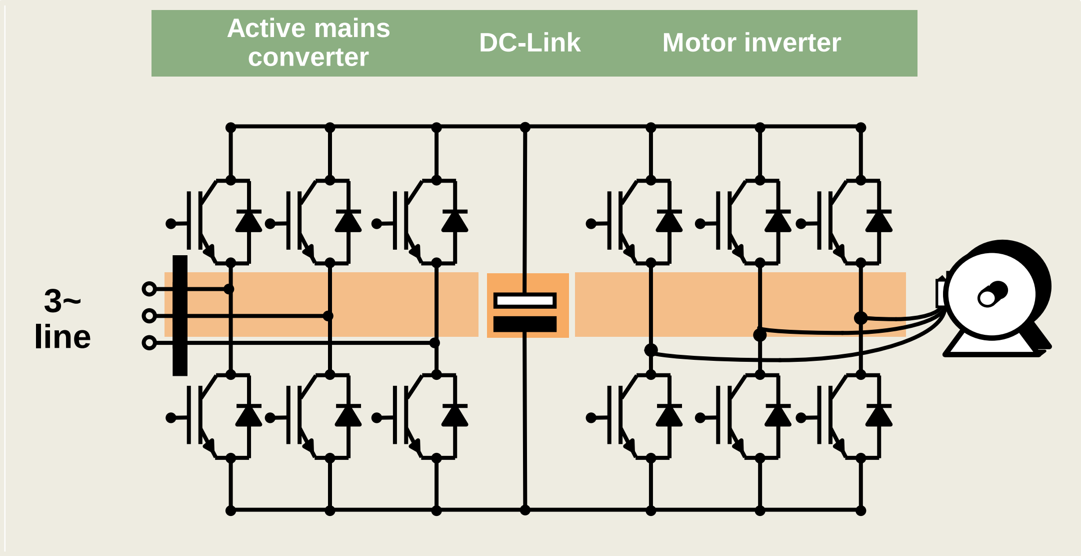


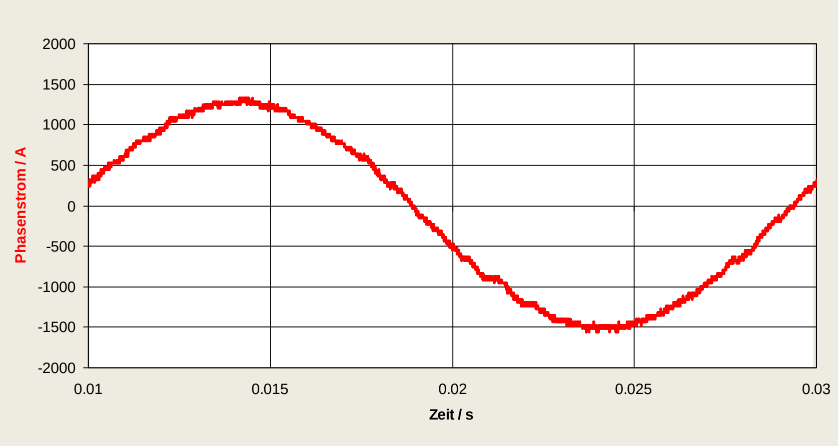


- Sinusoidal input current
- Power factor 1
- Ripple current depending on switching frequency and inductance

- **Features:**
  - Sinusoidal input current
  - High frequency (typ. 4-8kHz) switched IGBTs
  - Regenerative capability
  - HF line choke

Active Front End (AFE): additional mains filter

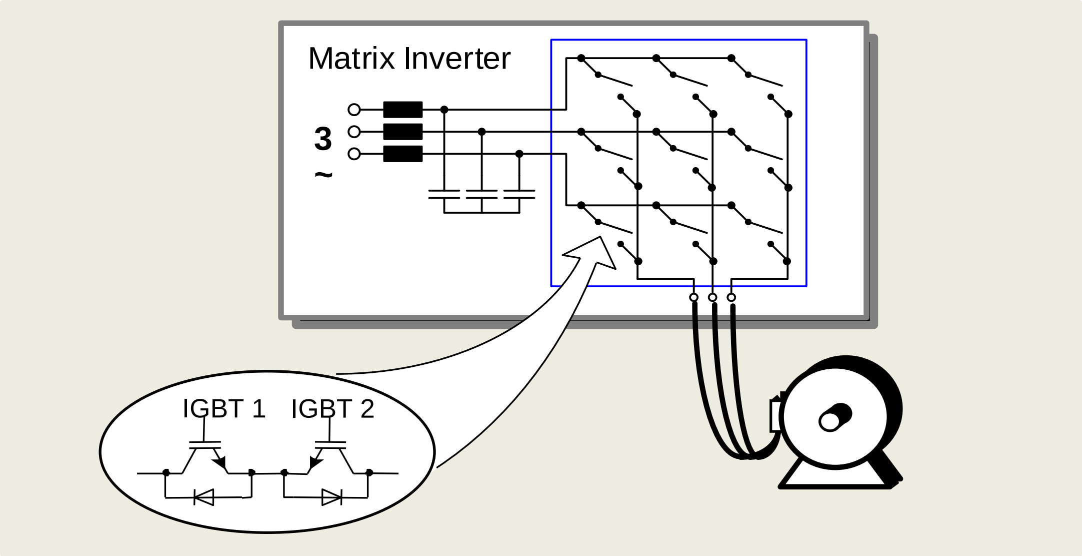


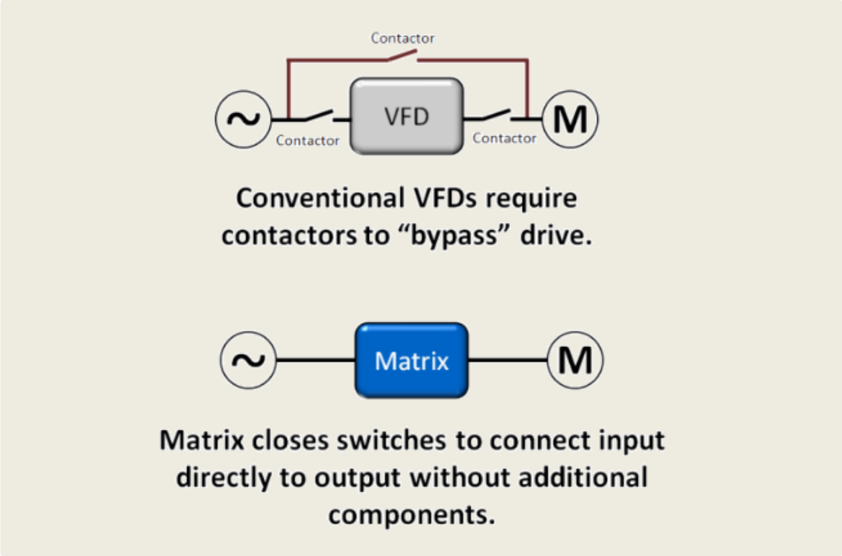


- Reduction of harmonics by additional mains filter

- **Features:**
  - Sinusoidal input current
  - High frequency (typ. 4-8kHz) clocked IGBTs
  - Regenerative capability
  - HF line choke

Active Front End (AFE): Input current Matrix Inverter





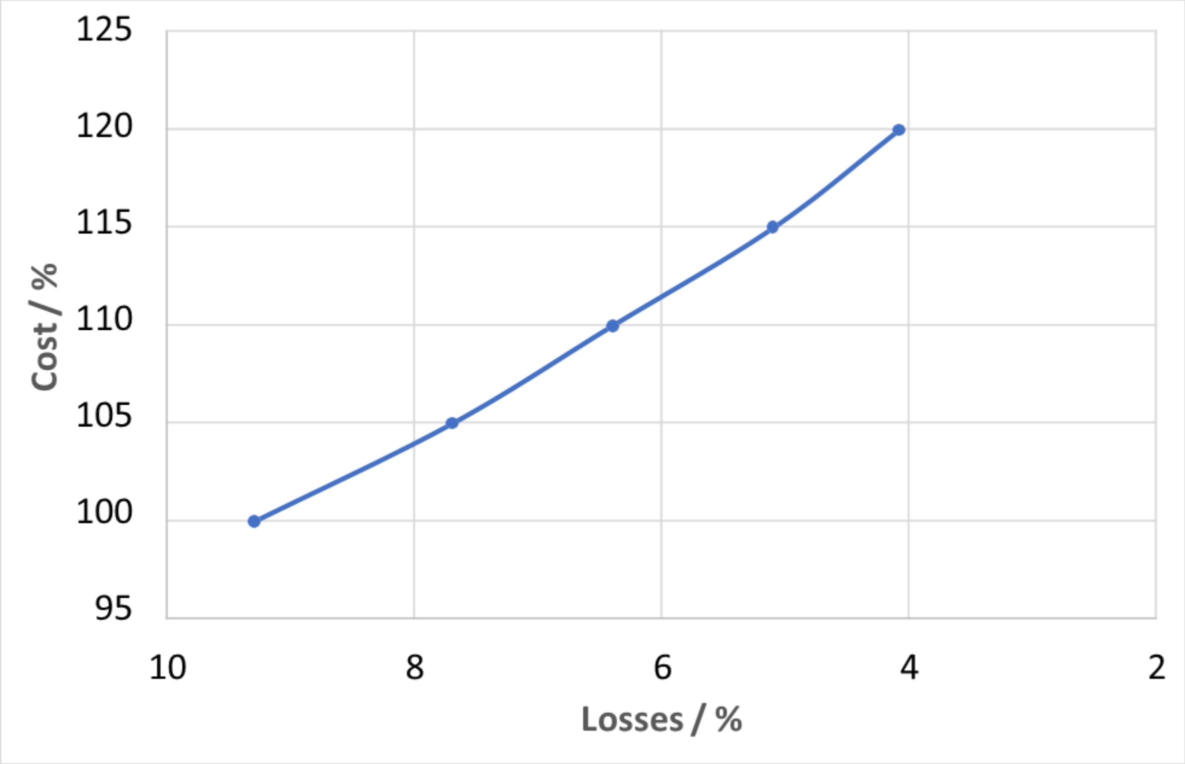
- **Features:**
  - Sinusoidal input current comparable to AFE (PF close to 1)
  - Regenerative capability
  - HF line filter
  - Bypass capable

Summary at a glance

	Diode Rectifier	F3E	AFE	Matrix
Regenerative capability	--	++	++	++
Losses	++	++	--	-
Harmonics and power factor	--	0	++	++
Cost	++	+	--	-

Motor cost over losses (example 30kW, 4 pole, 50Hz)

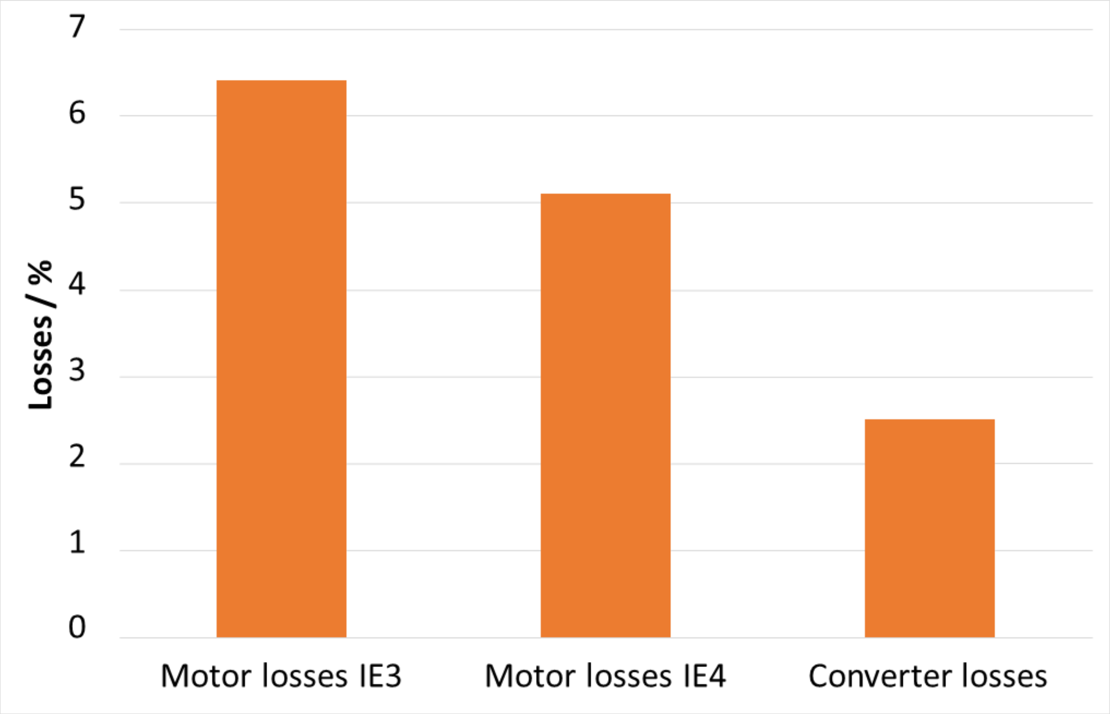
Lower motor losses -> Higher motor cost -> MEPS on motors make a lot sense



Dr. Benno Weis / Siemens / EEMODS 2019, Tokyo, Japan

Energy saving potential of frequency converters

Energy saving potential is much smaller than for motors



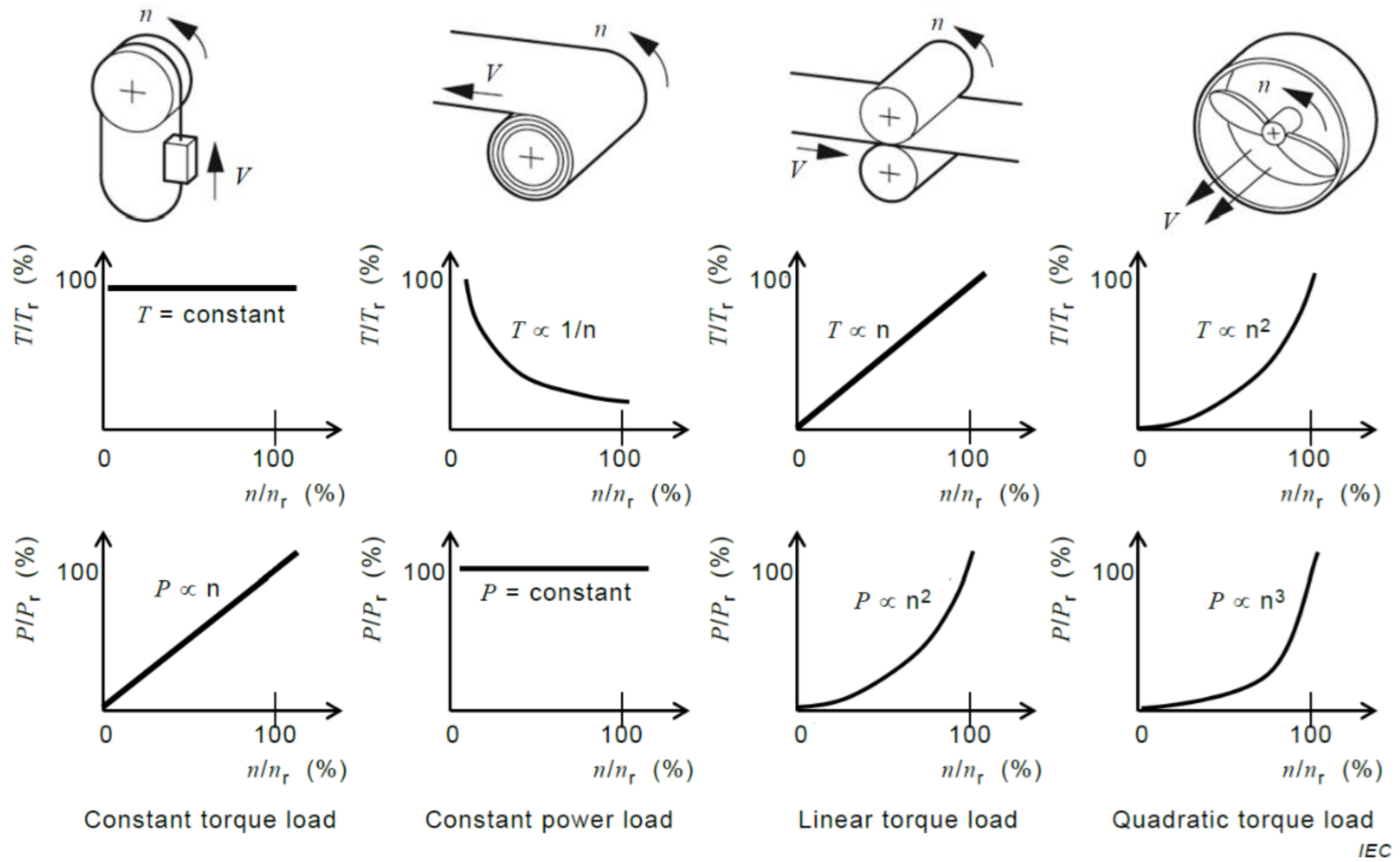
- Increasing the efficiency class of the motor from IE3 to IE4 will give you more than if you would half the losses of the inverter

Dr. Benno Weis / Siemens / EEMODS 2019, Tokyo, Japan

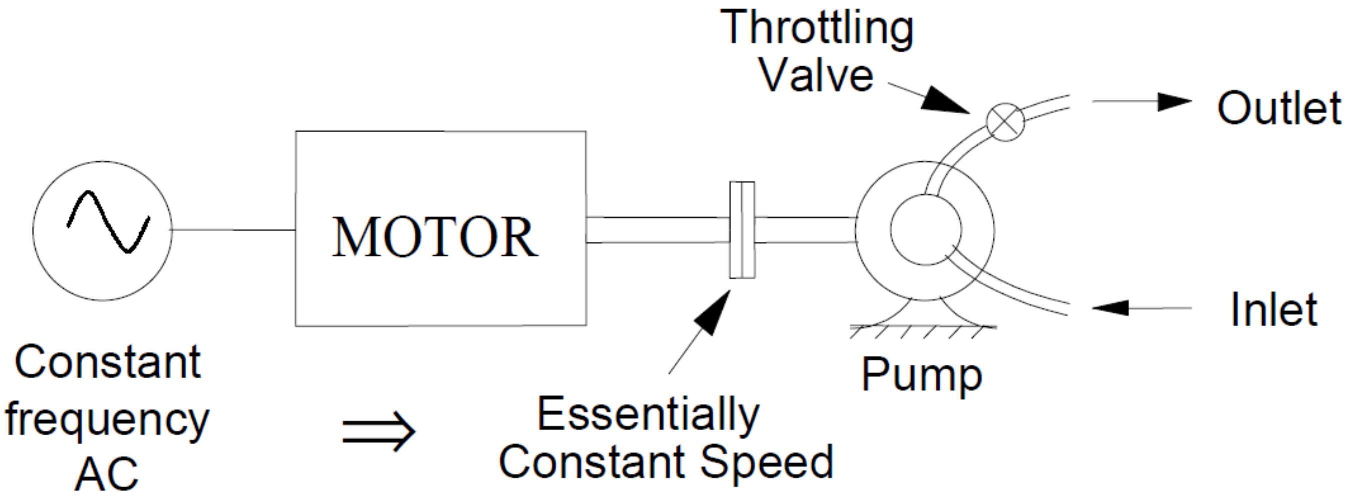
Application Efficiency

Energy savings potential for VFD + Pump

Typical basic torque and power vs. speed profiles

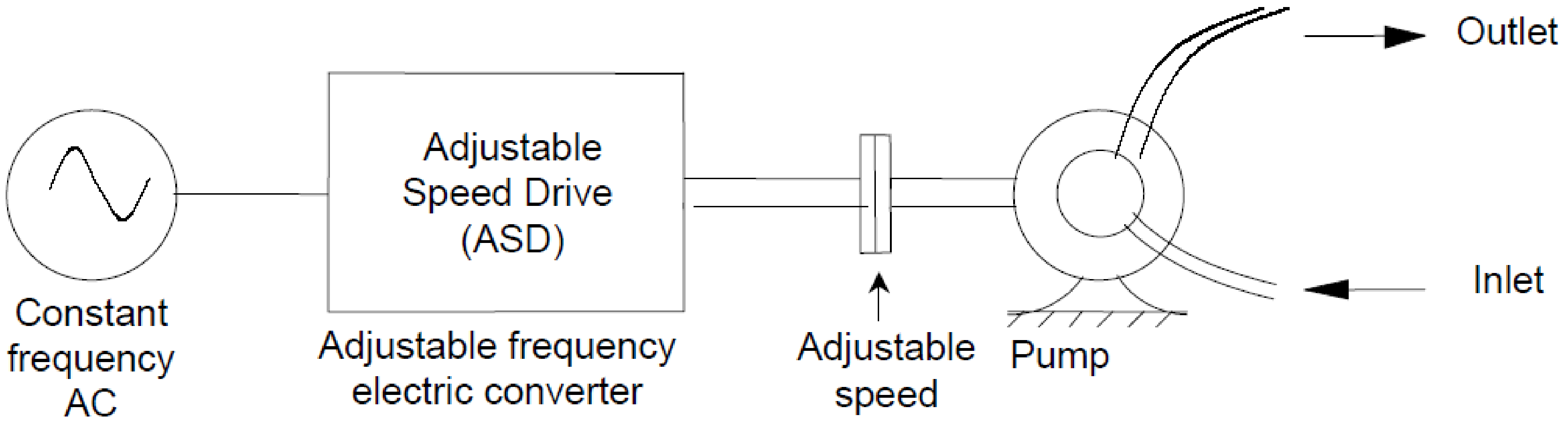


Traditional Pump-Driven Systems



- Constant frequency AC - essentially constant pump speed
- Inefficient - Heat generated in pump and throttling valve
- Not amenable to automation

Adjustable Speed Drives (ASDs)

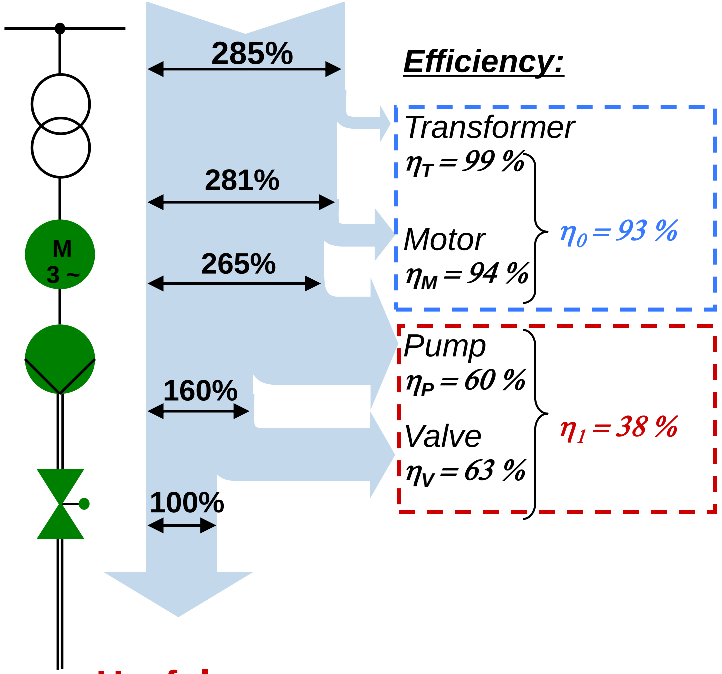


- Driven at appropriate speed
  - No need for the throttling valve
  - High Efficiency

Efficiency using the example of a pump application

Flow regulation through throttle valve

power consumed

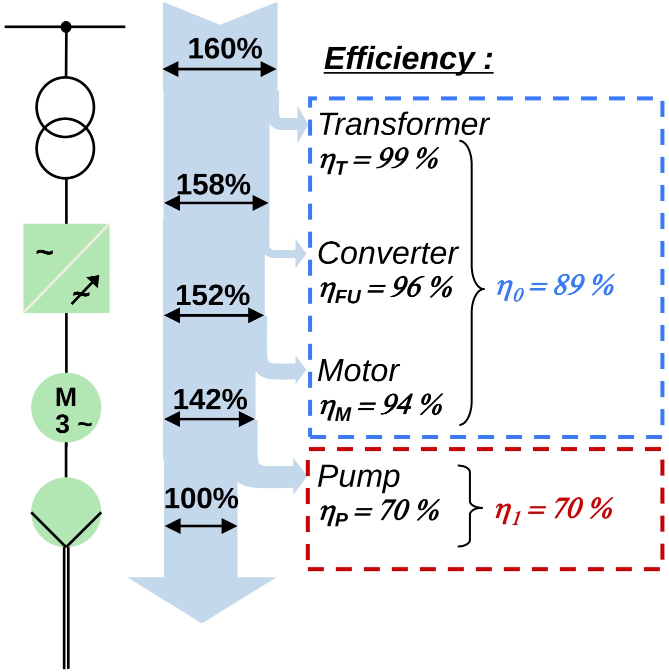


Useful power

$\eta_{steuer} = \Pi\, \eta_\nu = 35\ \%$

Flow regulation via speed control

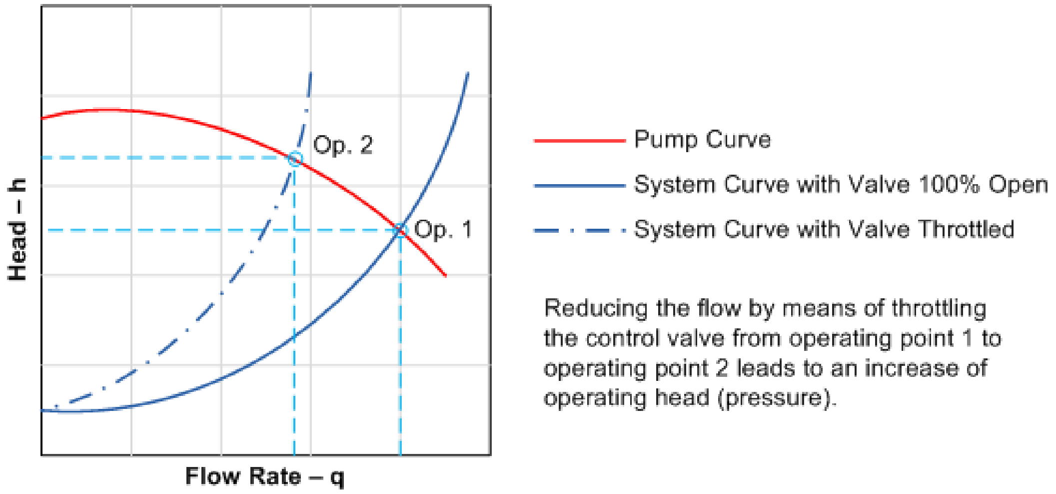
power consumed

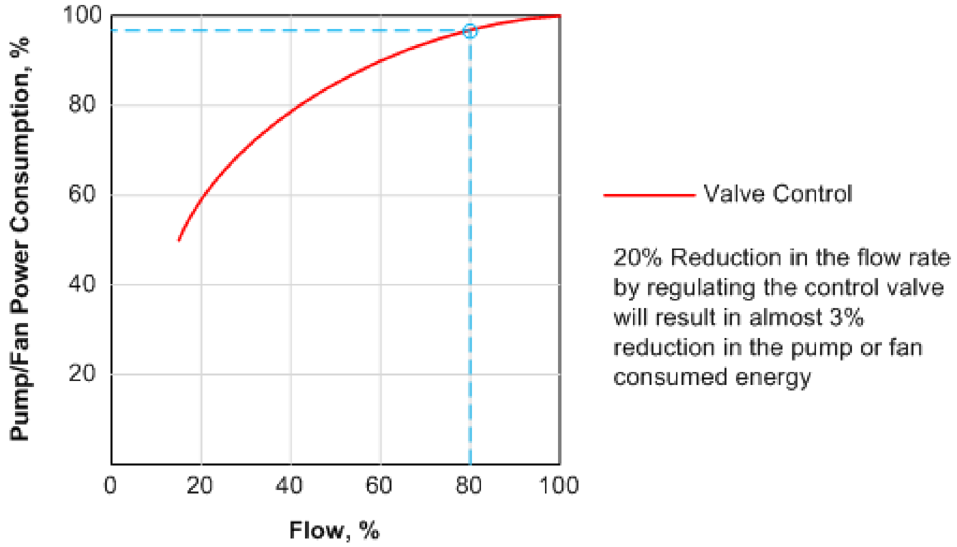


Useful power

$\eta_{regel} = \Pi\, \eta_\nu = 63\ \%$

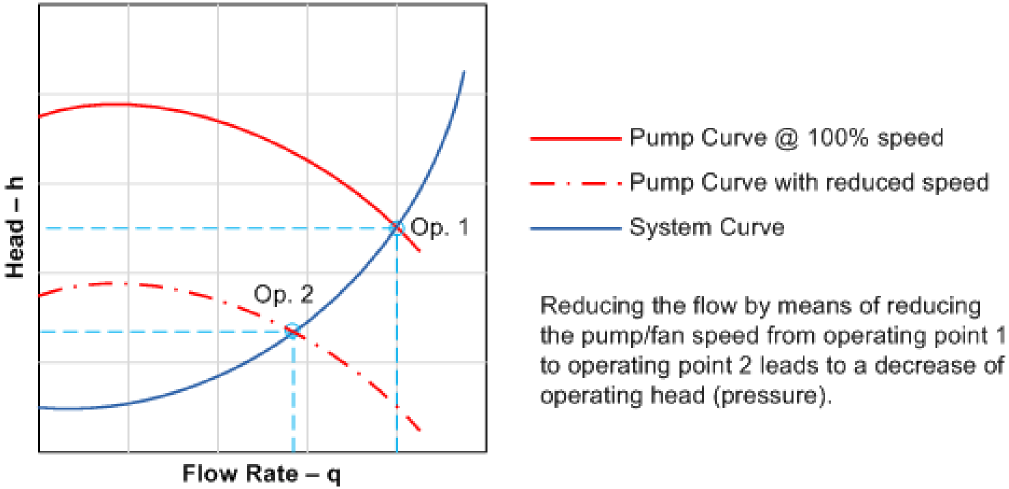
Throttled pump: Energy requirements



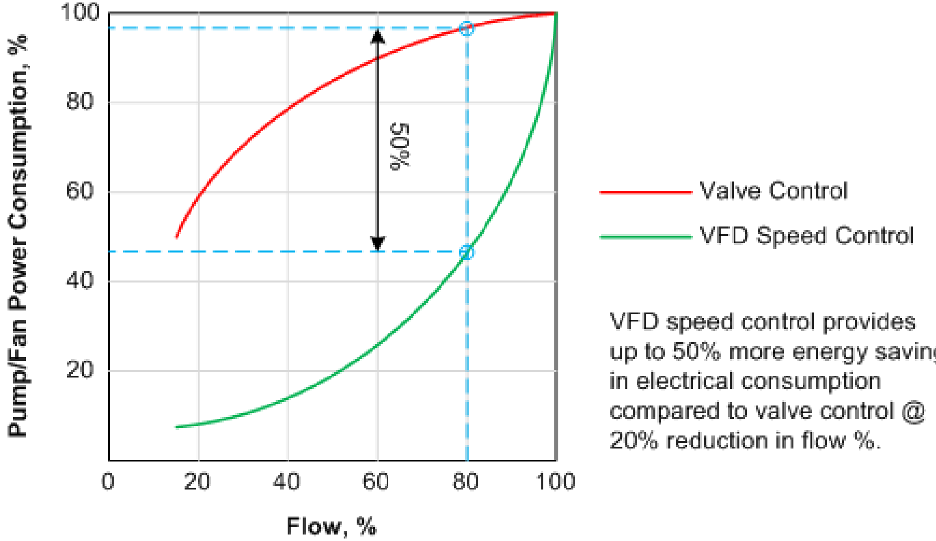


- By throtteling the flow with a valve, system pressure is increasing. As a result, the consumed energy is only slightly decreased.

Adjustable speed: Energy savings by lowering the speed



Reducing the flow by means of reducing the pump/fan speed from operating point 1 to operating point 2 leads to a decrease of operating head (pressure).



VFD speed control provides up to 50% more energy saving in electrical consumption compared to valve control @ 20% reduction in flow %.

- By reducing pump speed to reach required flow, up to 50% energy savings are realized.

Exercise: Energy Conservation in Pumps, Blowers and Fans

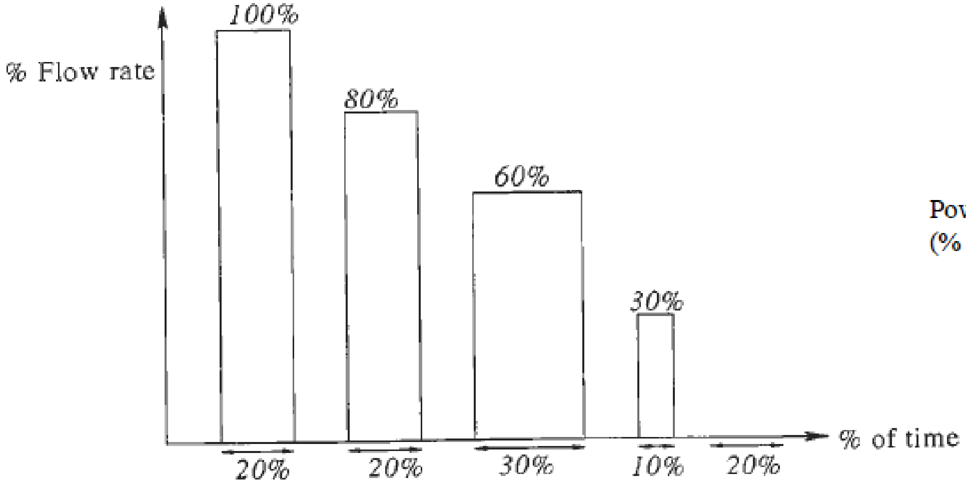
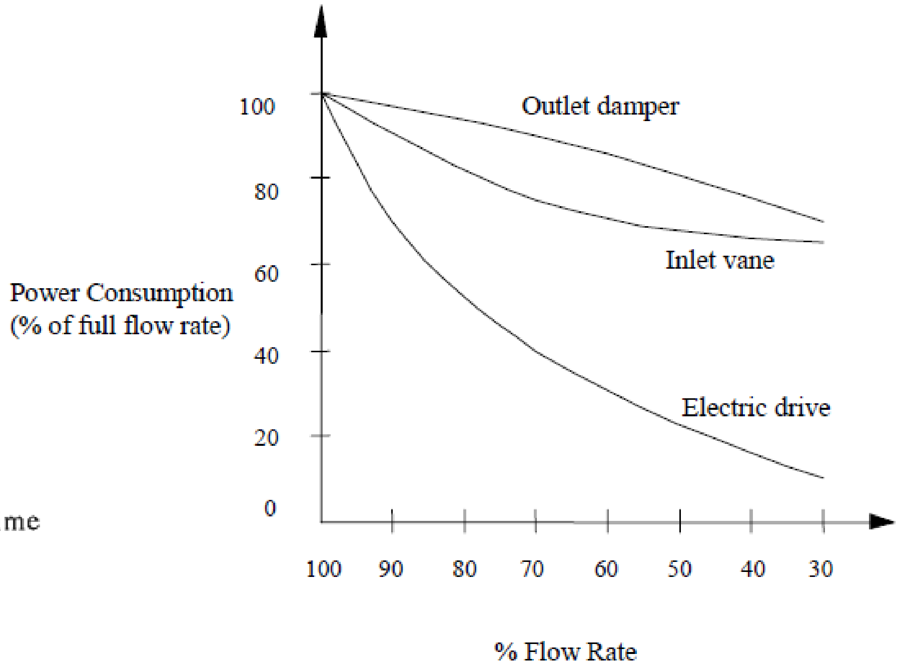


Figure P1-5 Flow rate profile of the blower.



- In a process, a blower is used with the flow rate profile shown in figure P1-5. using the information in Figure 1-8 estimate the percentage reduction in power consumption resulting from using an adjustable-speed drive rather than a system with a) an outlet damper and b) an inlet vane

Energy Savings over complete application profile

Outlet Damper normalized useful energy per kWh:

$$W_{OD} := W_0 \cdot (20\ \% \cdot 100\ \% + 20\ \% \cdot 95\ \% + 30\ \% \cdot 90\ \% + 10\ \% \cdot 75\ \% + 20 \cdot \% \cdot 0 \cdot \%) = 735\ W\ hr$$

Inlet Vane normalized useful energy per kWh:

$$W_{IV} := W_0 \cdot (20\ \% \cdot 100\ \% + 20\ \% \cdot 85\ \% + 30\ \% \cdot 75\ \% + 10\ \% \cdot 70\ \% + 20 \cdot \% \cdot 0 \cdot \%) = 665\ W\ hr$$

VFD normalized useful energy per kWh:

$$W_{VFD} := W_0 \cdot (20\ \% \cdot 100\ \% + 20\ \% \cdot 50\ \% + 30\ \% \cdot 30\ \% + 10\ \% \cdot 10\ \% + 20 \cdot \% \cdot 0 \cdot \%) = 400\ W\ hr$$

Energy Savings:

$$\frac{W_{IV}}{W_{OD}} = 90.48\ \% \qquad \frac{W_{VFD}}{W_{OD}} = 54.42\ \%$$

Summary

VFD and motor system saving potentials

- Energy savings are possible within every components of the complete motor driven unit, but the extended product approach will achieve maximum savings
- Electric Motors are are moving towards efficiency classes IE4 and higher, with a trend in the industry towards synchronous reluctance motors.
- A VFD makes an additional loss of about 3-4% at the nominal point but allows to control the driven equipment over a large torque and speed range.
- Additional functions like input chokes or output filters will reduce the converter efficiency but might improve efficiency of other components (line harmonics, motor harmonics)
- VFD driven pumps and fans offer the highest potential for energy savings, especially if they are operated at variable loads

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Questions?

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