UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

MOTOR SYSTEMS OPTIMIZATION

EXPERT TRAINING

PARTNER FOR PROSPERITY

1. Electric Motor basics

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ISR-University of Coimbra

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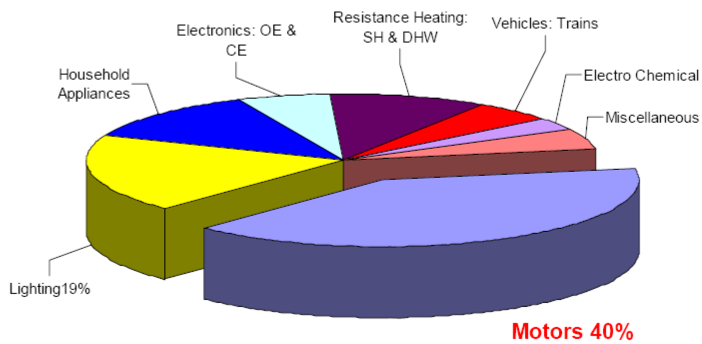
Discussed Topics

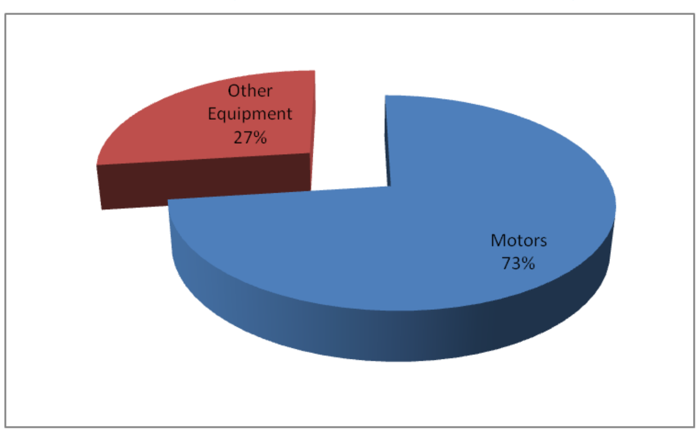
- Motor systems energy use
- Definition of motor system
- Types of electric motors
- Electric Motor Efficiency
- High Efficiency Electric Motors

Motor Systems' Energy Use



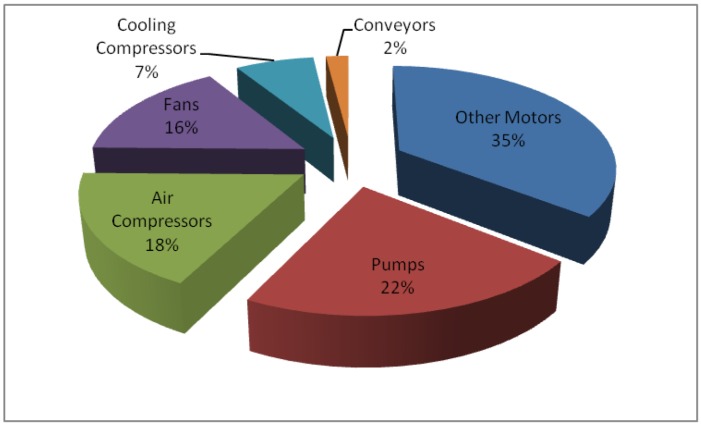
Global Electricity demand by end-use
Source: A+B International 2008

Motor Systems Energy Use



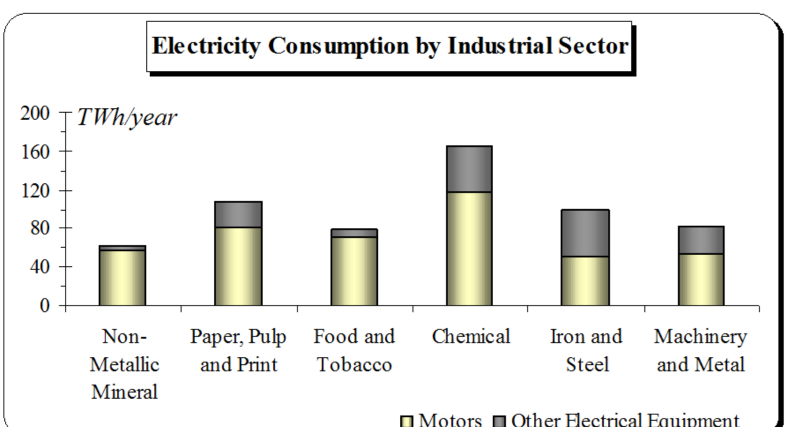
Electricity Consumption in the European Union Industrial Sector
Source: ISR – University of Coimbra

Motor Systems Energy Use

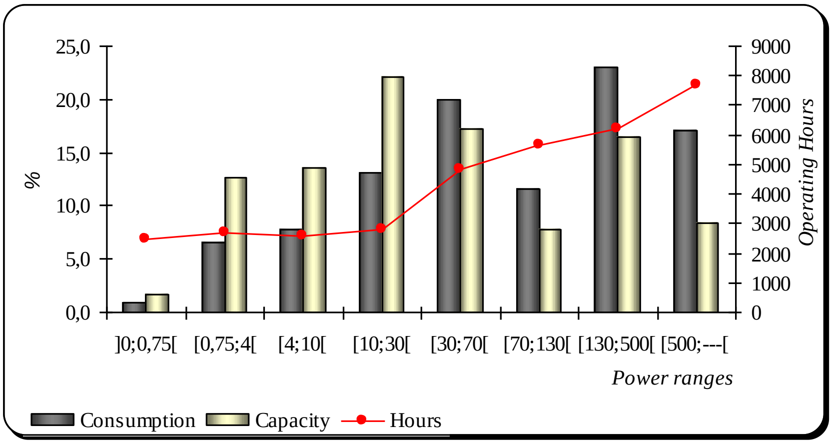


Disaggregation of motor electricity consumption by end-use, in the EU Industrial sector
Source: ISR – University of Coimbra

Motor Systems Electricity Consumption by Industrial Sector



Motor Electricity Consumption by power range in the industrial sector



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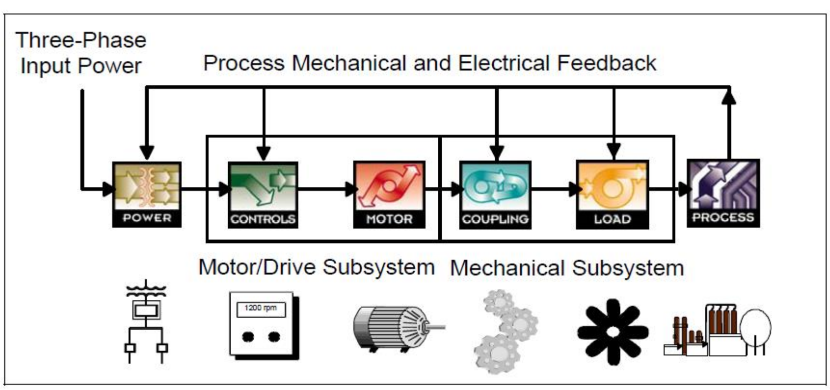
Motor System



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Motor Systems Energy Use

The efficiency of a motor system depends on several factors, including:

- motor efficiency
- motor speed/torque control
- proper sizing
- power supply quality
- distribution losses
- mechanical transmission
- maintenance practices
- end-use mechanical efficiency (pump, fan,
- compressor, etc).

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Efficiency of an Electric Motor System

$$\eta = \frac{P_{OUTPUT(USEFUL)}}{P_{INPUT}} = \frac{P_{SHAFT}}{P_{ELECTRICAL}} \qquad \eta = 1 - \frac{P_{LOSSES}}{P_{INPUT}} \qquad P_{SHAFT} = T \cdot \omega$$

$$\eta_{SYSTEM} = \eta_{VEV} \cdot \eta_{MOTOR} \cdot \eta_{TRANSMISSION} \cdot \eta_{END-USE} = \frac{P_{USEFUL}}{P_{INPUT}}$$

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	Electrical components	Mechanical components	Application	Factory Automation	Energy Recovery
	Proper and regular maintenance				
S1 Continuous Duty	Energy-efficiency motors Power-factor correction devices	Energy-efficient gearboxes, belts, ... Energy-efficient pumps, fans, compressors,...	Variable speed drive systems Reducing elec. transmission losses	Most efficient power-supply Low-energy mode during stand-still	
S2 Short-Time	Use most economical components				
S3...S10 Intermittent Duty	Soft-start with frequency control	Minimize rotating inertia	Variable speed drive systems Optimized mass and flow	Most efficient power-supply Low-energy mode during stand-still	Regenerative braking DC-link coupling Batteries, ultra-caps, fly-wheels etc.

Operating Principles

All motors have two basic parts:

- The STATOR (stationary part)
- The ROTOR (rotating part)

The design and fabrication of these two components determines the classification and characteristics of the motor.

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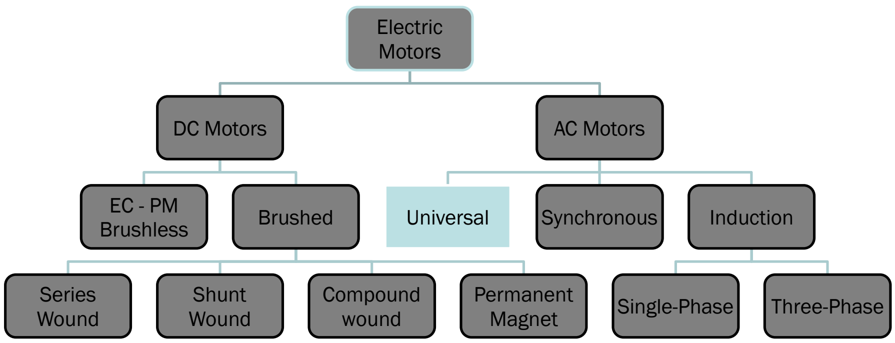
Motor types



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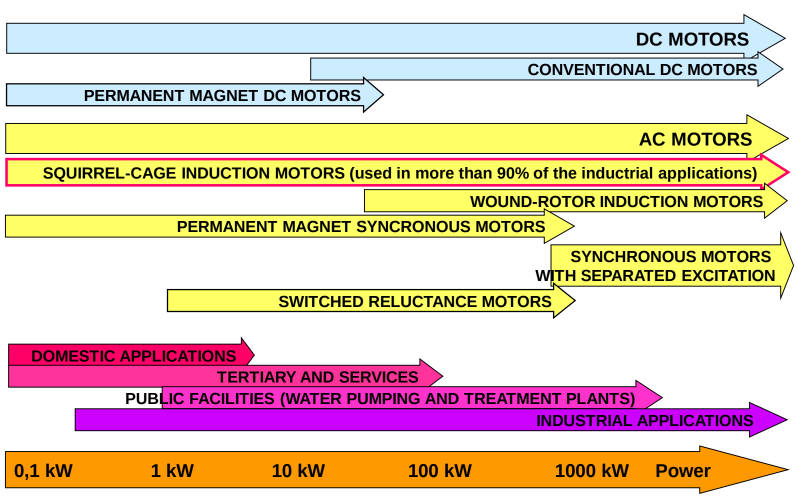
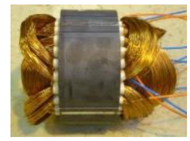
Motor types and applications



Squirrel-Cage Induction Motors

Used in more than 90% of electric motor systems;

- Good efficiency and high realibility (reduced maintenance);
- Low cost (when compared to other motor types);
- Easy to control, when fed by VSDs.



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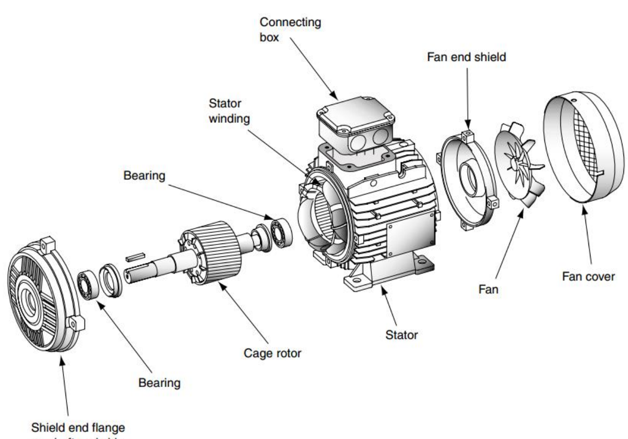
Squirrel-Cage Induction Motors



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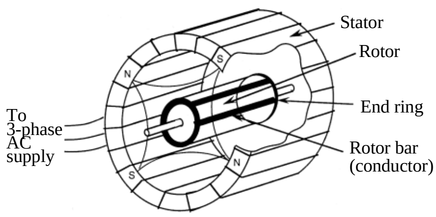
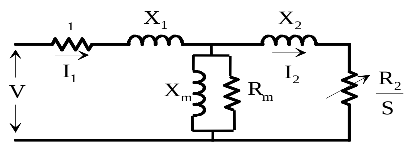
Squirrel-Cage Induction Motors





R1, R2 = Stator and Rotor Resistance,
X1, X2 = Stator and Rotor Leakage Reactance
s=Rotor Slip

Xm = Magnetising Reactance
Rm = Magnetising Resistance

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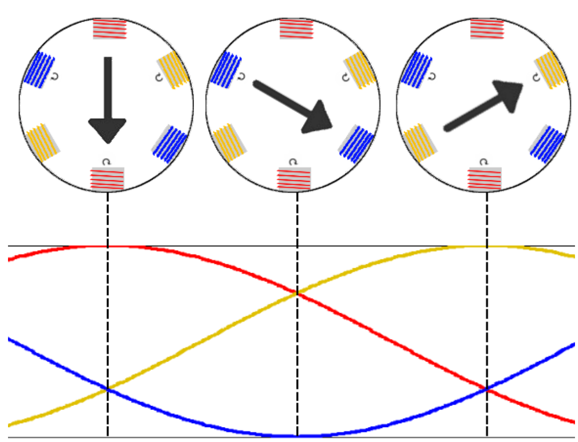
IM – Working principle

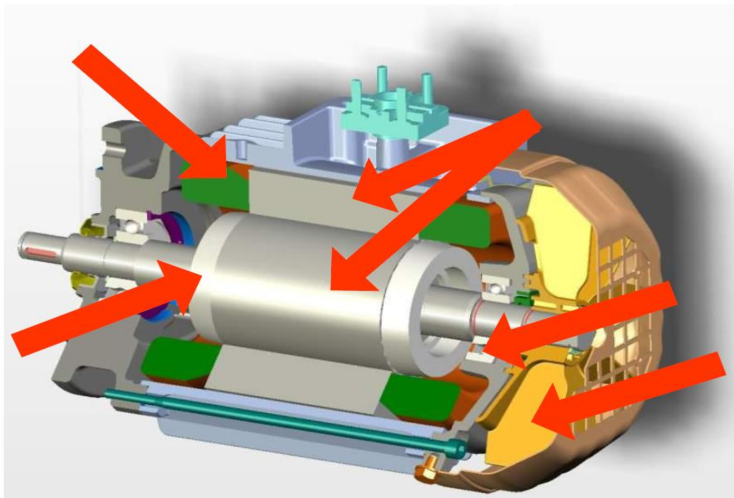


Motor Losses

- The **electrical losses** (also called Joule losses) are expressed by I^2R, and consequently increase rapidly with the motor load. Electrical losses appear as heat generated by electric resistance to current flowing in the stator windings and in the rotor conductor bars and end rings.
- **Magnetic losses** occur in the steel laminations of the stator and rotor. They are due to hysteresis and eddy currents, increasing approximately with the square of the flux-density.
- **Mechanical losses** are due to friction in the bearings, ventilation and windage losses.

Motor Losses

- **Stray load losses** are due to leakage flux, harmonics of the air gap flux density, non-uniform and inter-bar currents distribution, mechanical imperfections in the air gap, and irregularities in the air gap flux density.
- **The brush contact losses (only for motors with brushes)** result from the voltage drop between the brushes and the commutator, as well as include additional friction losses.



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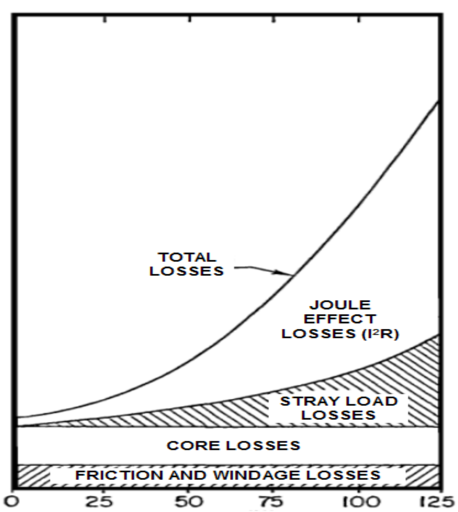
IM Losses Vs. Load



Motor Losses

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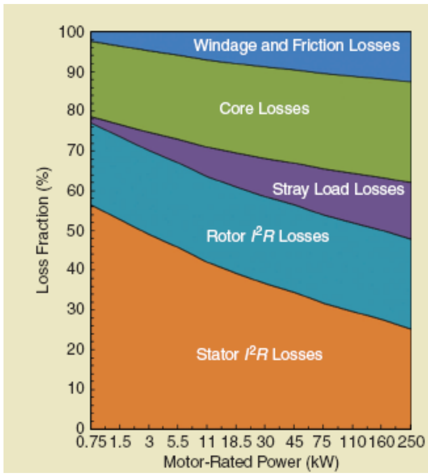
Motor Losses



Typical fraction of losses in 50-Hz, four-pole IMs

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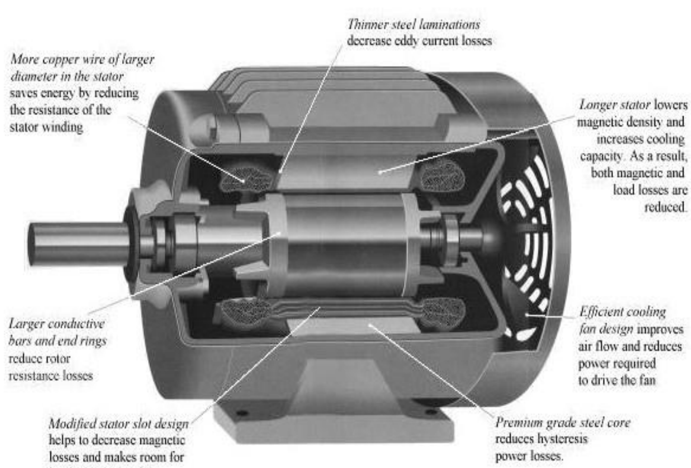

Premium motor features

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Induction motors – die casting copper rotor

- **EXAMPLE: 1.1-kW DIE CASTING COPPER ROTOR**

Higher efficiency and lower rotor inertia, when compared to the aluminum rotor EEMs.

Características nominais dos MIs utilizados nos ensaios.

	MI_A	MI_C
Gaiola Rotórica	Alumínio	Cobre
Classe de Rendimento	EFF II	EFF I
Tipo	TEFC	TEFC
Tensão Nominal, U_N	400 V	400 V
Corrente Nominal, I_N	2.80 A	2.45 A
Frequência Nominal, f_N	50 Hz	50 Hz
Velocidade Nominal, n_N	1400 r.p.m.	1460 r.p.m.
Potência Nominal, P_N	1.1 kW	1.1 kW
Factor de Potência Nominal, $\cos\varphi_N$	0.77	0.78

COMPARISON BETWEEN COPPER (MI_C) AND ALUMINUM (MI_A) CAGE MOTORS

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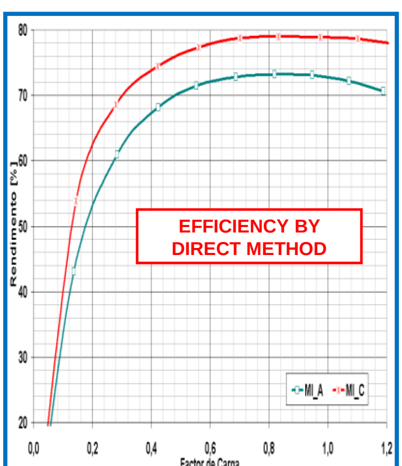
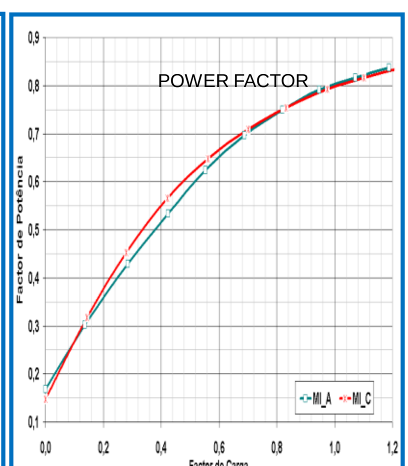
Energy Efficient IM – die casting copper rotor and aluminum rotor (4 pole, 1.1 kw)





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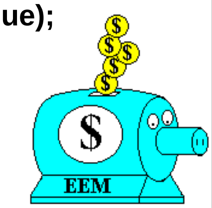
Energy Efficient Induction Motors

- **Higher efficiency (2-10% more depending on motor power);**
- **They can reduce energy bills as well as the maintenance costs;**
- **More material of higher quality – more expensive (25-30%);**
- **Longer lifetime (lower operating temperature);**
- **Typically, lower starting torque (depends on the rotor slot shape);**
- **Higher starting current (depend on starting torque);**
- **Lower slip;**
- **Higher rotor inertia.**



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Squirrel-cage Induction Motors Lifecycle Cost

- In Industry, an induction motor can consume per year an energy quantity equivalent to 5-10 times its initial cost, along all its lifetime of about 12-20 years, representing 60-200 times its initial cost.

- This fact justifies a life-cycle cost (LCC) analysis including the repair/maintenance.

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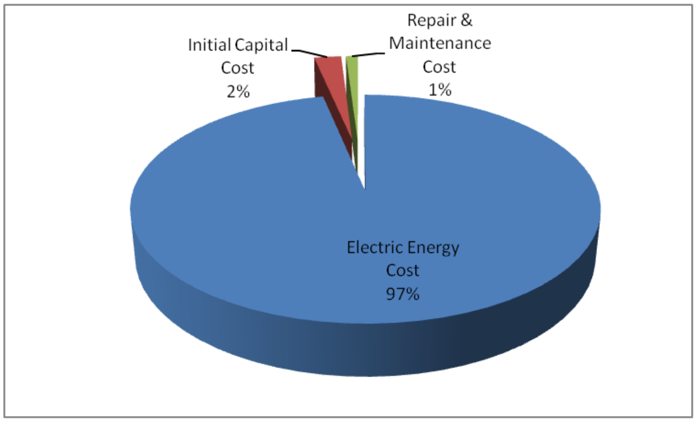
Motor Systems Energy Use



11 kW IE3 Motor, 4000 operating hours per year, 15 years life cycle 0,0754 €/kWh
Source: ISR – University of Coimbra

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Exercise

Economic Analysis – Simple Payback of High Efficiency Motor versus Standard Motor:

-New application

-Retrofit of existing motor

-When a motor fails

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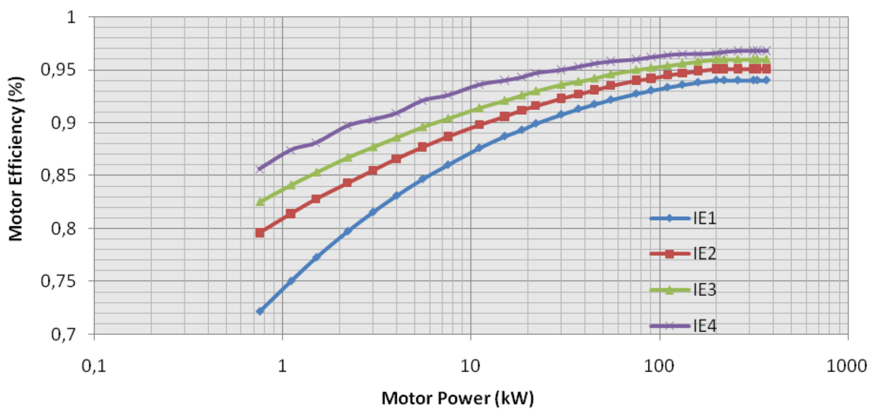
IM Efficiency Classification



IEC 60034-30 efficiency classes and IEC 60034-31 IE4 Super-Premium Efficiency Class

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Labelling – CEMEP / EU Agreement (1998-2010)

Motors included on this scheme:

- 3 phase AC squirrel cage induction motors
- Rated power: 1.1 kW to 90 kW
- Totally enclosed fan ventilated
- Line voltage: 400 V
- 50 Hz
- S1 duty class (continuous mode)
- In accordance with IEC 34-2 (indirect method)

Class definition for 4-pole motors

Kw	EFF3 motors η_n	EFF2 motors η_n	EFF1 motors η_n
1.1	< 76.2	>= 76.2	>=83.8
1.5	< 78.5	>= 78.5	>=85.0
2.2	< 81.0	>= 81.0	>=86.4
3	< 82.6	>= 82.6	>=87.4
4	< 84.2	>= 84.2	>=88.3
5.5	< 85.7	>= 85.7	>=89.2
7.5	< 87.0	>= 87.0	>=90.1
11	< 88.4	>= 88.4	>=91.0
15	< 89.4	>= 89.4	>=91.8
18.5	< 90.0	>= 90.0	>=92.2
22	< 90.5	>= 90.5	>=92.6
30	< 91.4	>= 91.4	>=93.2
37	< 92.0	>= 92.0	>=93.6
45	< 92.5	>= 92.5	>=93.9
55	< 93.0	>= 93.0	>=94.2
75	< 93.6	>= 93.6	>=94.7
90	< 93.9	>= 93.9	>=95.0

Class definition for 2-pole motors

Kw	EFF3 motors η_n	EFF2 motors η_n	EFF1 motors η_n
1.1	< 76.2	>= 76.2	>=82.8
1.5	< 78.5	>= 78.5	>=84.1
2.2	< 81.0	>= 81.0	>=85.6
3	< 82.6	>= 82.6	>=86.7
4	< 84.2	>= 84.2	>=87.6
5.5	< 85.7	>= 85.7	>=88.6
7.5	< 87.0	>= 87.0	>=89.5
11	< 88.4	>= 88.4	>=90.5
15	< 89.4	>= 89.4	>=91.3
18.5	< 90.0	>= 90.0	>=91.8
22	< 90.5	>= 90.5	>=92.2
30	< 91.4	>= 91.4	>=92.9
37	< 92.0	>= 92.0	>=93.3
45	< 92.5	>= 92.5	>=93.7
55	< 93.0	>= 93.0	>=94.0
75	< 93.6	>= 93.6	>=94.6
90	< 93.9	>= 93.9	>=95.0

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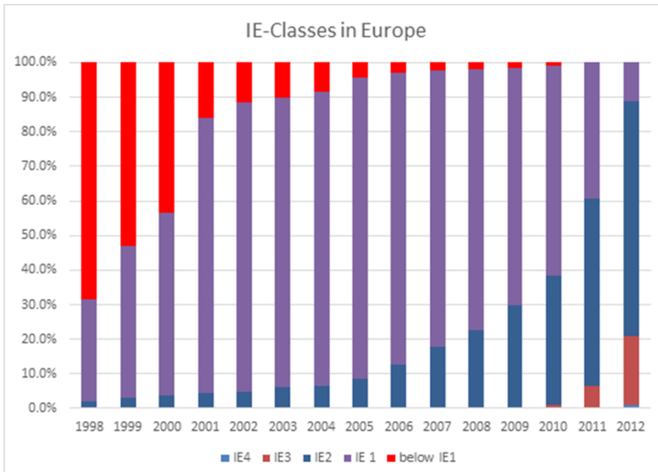
Economics and Markets in Europe



Total motor-sales in the EU-27 (0,75 to 375 kW)

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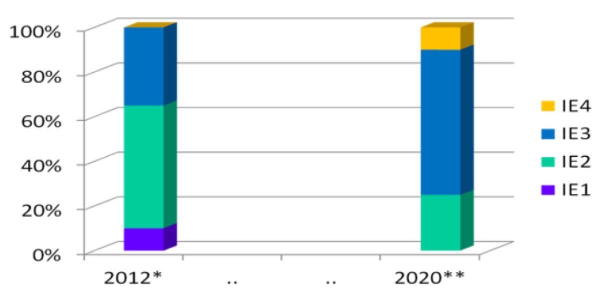
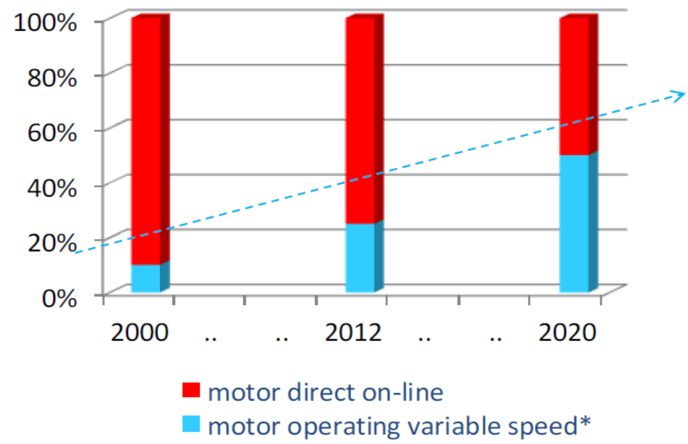
Expected Evolution of the European LV Motor Market (units; line-fed)



* Shares in 2012, when the scope of the Regulation 640/2009 affected about 70% of the sold motors.

** Expectation for 2020+: For line-fed motors the leading technology will remain the asynchronous induction motor (>90%).

Expected European shares of Line-Fed and Converter Fed Motors



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DC Motors

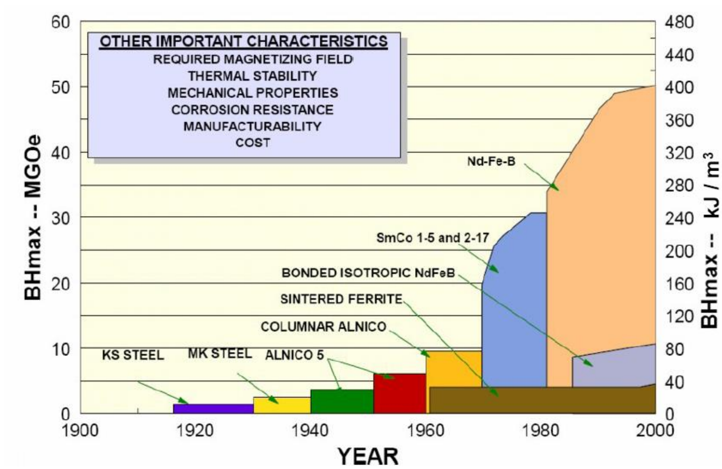
- Brushed with stator winding
- Brushed with PM stator
- Brushless

Simple to control

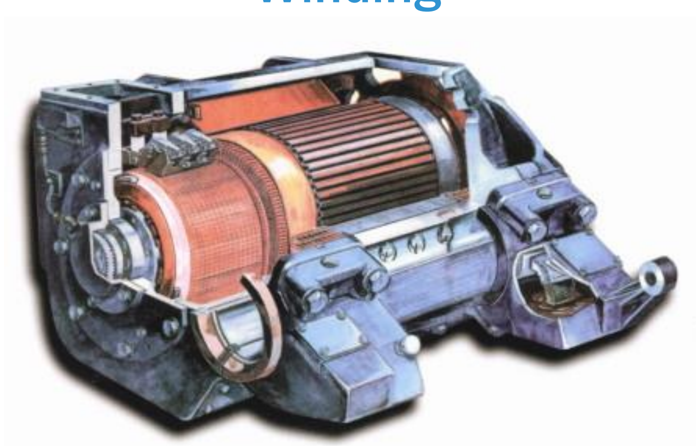
High maintenance requirements

Poor reliability

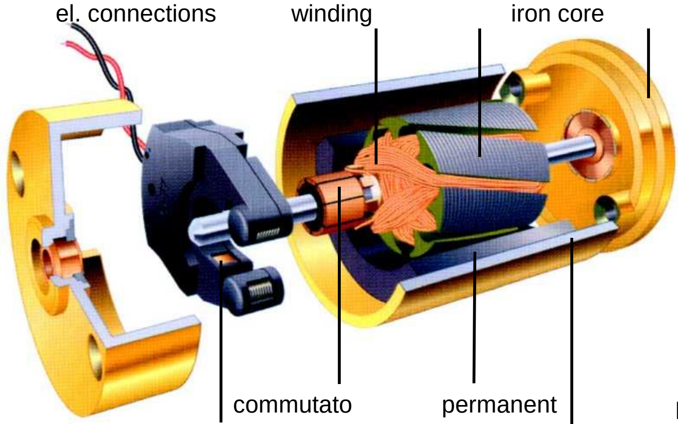
History of Permanent Magnets



Brushed DC Motors with Stator Winding



Conventional PM DC Servo motor



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Brushless DC Motors / EC Motors

Electronically commutated motor similar to the ac synchronous motor with permanent magnets.

- names: EC motor, BLDC motor, PM Synchronous motor
- motor behavior similar to DC motor
  - design similar to synchronous motor (3 phase stator winding, rotating magnet)
  - the powering of the 3 phases according to rotor position
- main advantages: higher reliability, higher speeds
- slotless windings
  - similar advantages as coreless DC motors
  - no magnetic detent, less vibrations
- becomes more attractive: costs, size, magnets

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Brushless DC Motor

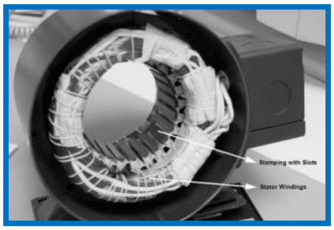
Brushless DC Motors / EC Motors

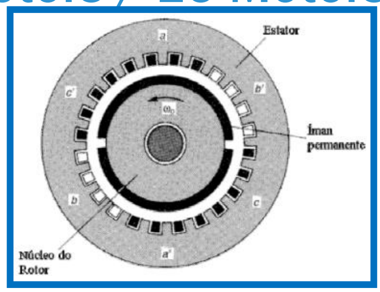
Main advantages:

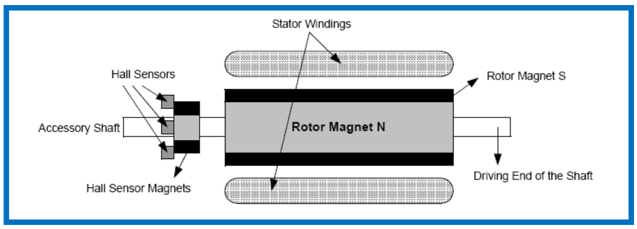
- Excelent torque-speed curve;
- Excelente dynamic response;
- High efficiency and reliability => low maintenance;
- Longer lifetime;
- Low accoustical noise;
- High speed capability;
- High torque/volume ratio or high power density.

Main disadvantage: High cost and there is allways the necessity of a controller (VSD).

Brushless DC Motors / EC Motors

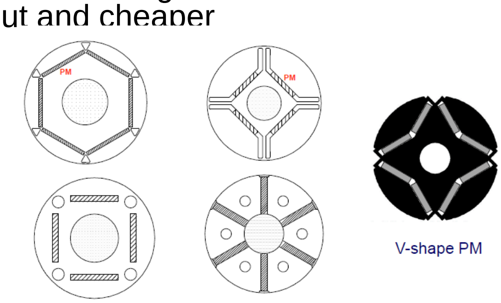






Brushless DC Motors / EC Motors

- The rotor position is detected by hall effect or optical sensors, which is used to excite the stator windings properly. The control electronic be circuit can embedded in the motor
- The magnets are typically ferrite or rare-earth alloy (*neodymium (nd)+ferrite+boron (ndfeb)*). High currents or temperatures can demagnetize the rotor. Interior magnets are more robut and cheaper



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PM Machine Comparisons

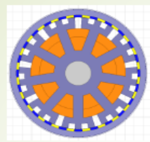

Table – 4 Qualitative comparison under harsh environment

	PMPM	*SPM*	*IPM*
Machine cost	Very High due to more magnet weight	Higher than IPM due to arc shaped magnets	Lower due to rectangular magnets
Drive cost	Higher due to poor pf and higher drive current	Lower as compared to PMPM	Lower as compared PMPM
Performance measures	Poor pf and higher Drive current, No demagnetization at higher temperatures	Demagnetization at high temperatures	Robust under high temperatures

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PM Machine Comparisons

- **Pole-modulated PM machine:** Higher power density and reliability under higher temperatures – Higher machine cost – Very Poor power factor – Large Drive size and cost. Lower magnet weight can reduce cost but suffers even worst power factor, which causes even higher drive cost.
- **Surface PM Machines:** Better choice for direct drive solutions - at a cost of arc shaped magnets- but are more prone to demagnetization under higher ambient temperature.

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PM Machine Comparisons

- **Interior PM Machines:** Less susceptible to demagnetization as compared to surface type PM machines - more reliable under higher temperatures and extreme operating conditions - cost of IPM machines - lower as compared to surface PM machines and PM2 machines.

- **Considering cost and demagnetization, IPM machines are the most competitive choice for low-speed direct-drive applications in demanding environments.**

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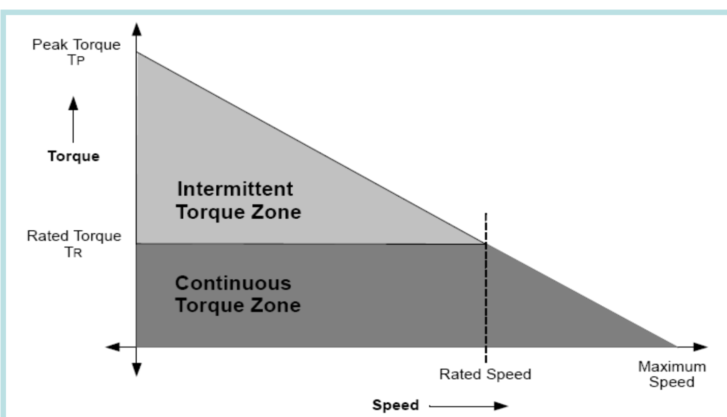
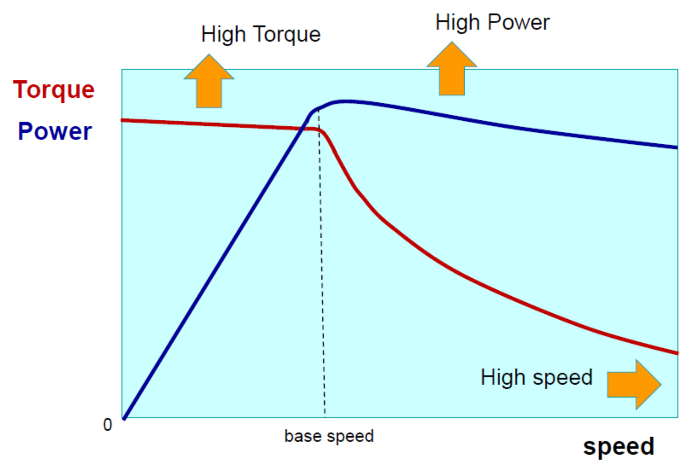
Permanent Magnet Synchronous Motors



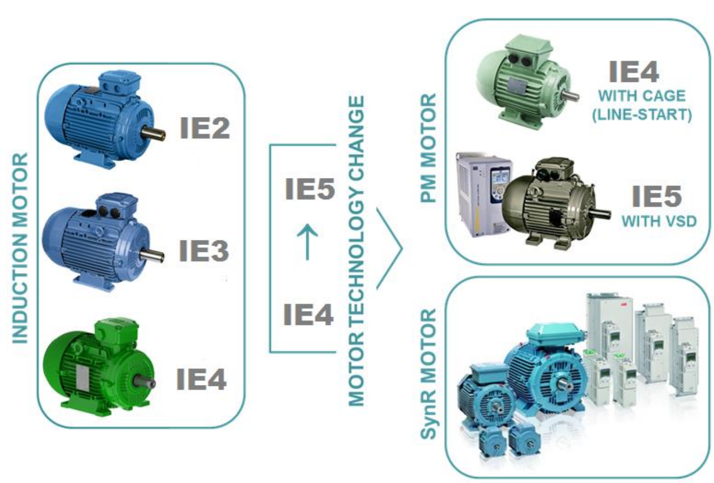
TORQUE-SPEED CURVE OF BLDCs

Torque Speed characteristics of PMSM

PMSM - Permanent Magnet Synchronous Motors



Technologies for Higher Efficiency Motors



What is a Super-Premium Motor?

- IE3 have at least 15% lower losses than IE2 motors
- A Super-Premium IE4 Class has at least a 15% loss difference in relation to IE3 / Premium.
- A Ultra-Premium (new IE5 Class) has at least a 15% loss difference in relation to IE4 / Super- Premium.

	Line- Start	IE1	IE2	IE3	IE4	IE5
Three-phase cage-induction motors (ASM)	Yes	Ok	Ok	Ok	Difficult	No
Wound-rotor induction motors	Yes	Ok	Ok	Ok	Difficult	No
Single-phase induction motors (one capacitor)	Yes	Ok	Difficult	No	No	No
Single-phase induction motors (two switchable capacitors)	Yes	Ok	Ok	Difficult	No	No
Permanent-magnet synchronous motors (PMSM)	No	Ok	Ok	Ok	Ok	Difficult
Wound-rotor synchronous motors	Some	Ok	Ok	Ok	Ok	Difficult
Line-start permanent-magnet motors (LSPM)	Yes	Ok	Ok	Ok	Ok	Difficult
Sinusoidal-field reluctance motors	Some	Ok	Ok	Ok	Difficult	No

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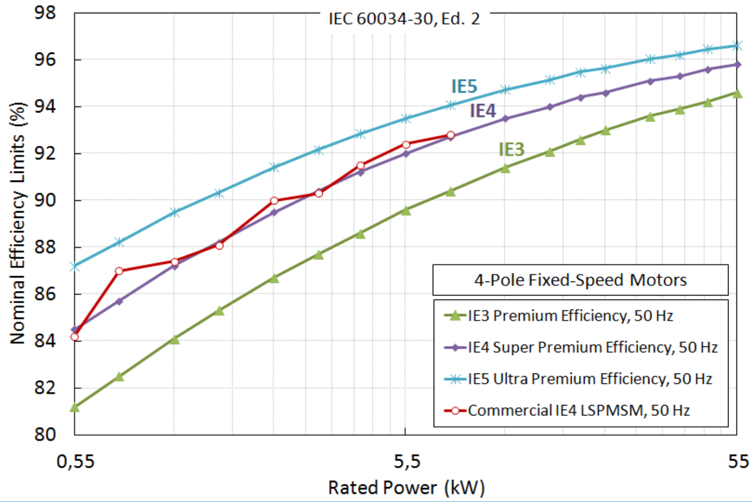
Super-Premium Motors

IEC 60034-30 Standard



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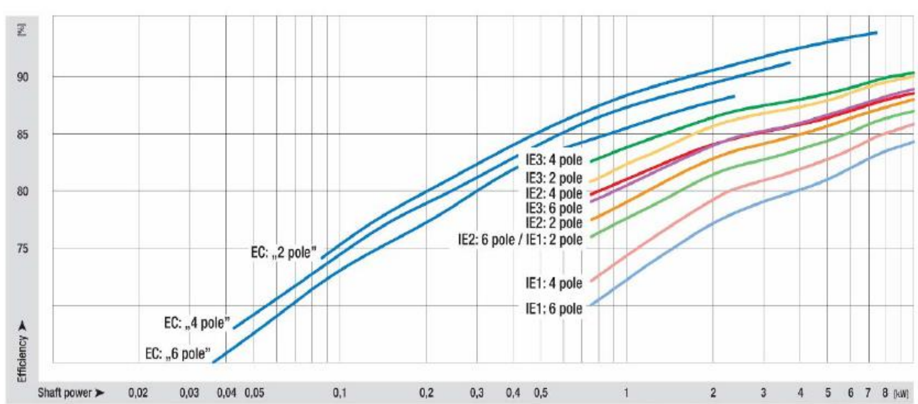
PM Fan Motor Efficiency



Reference: Data according to IEC 60034-30, 50 Hz

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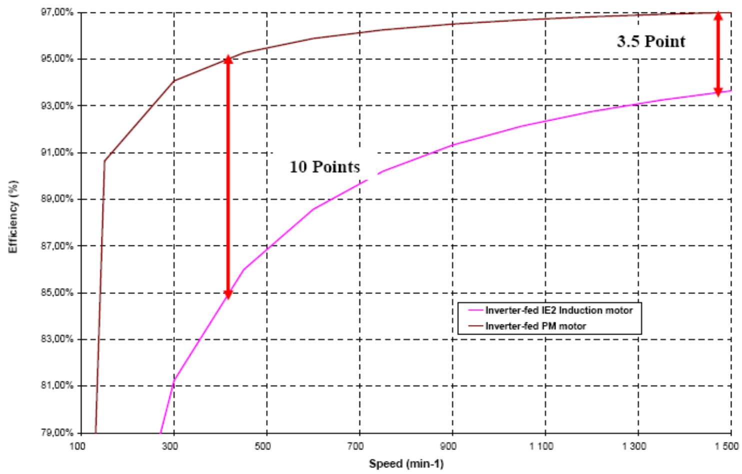
PM Motor Part-Load Efficiency



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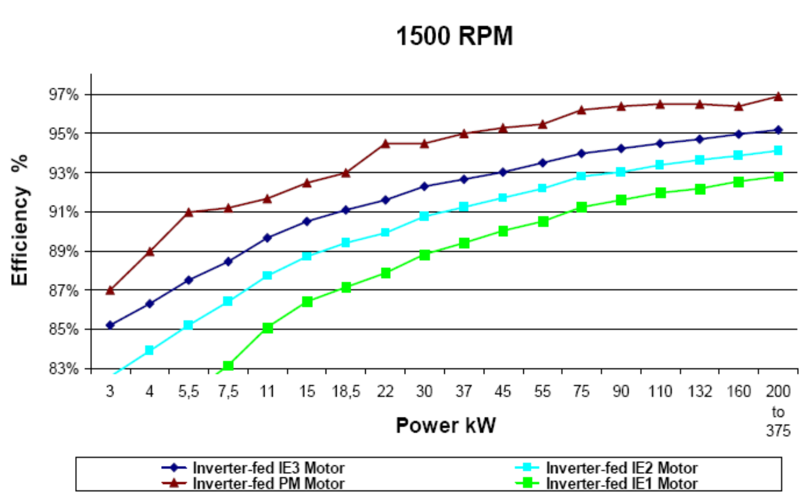

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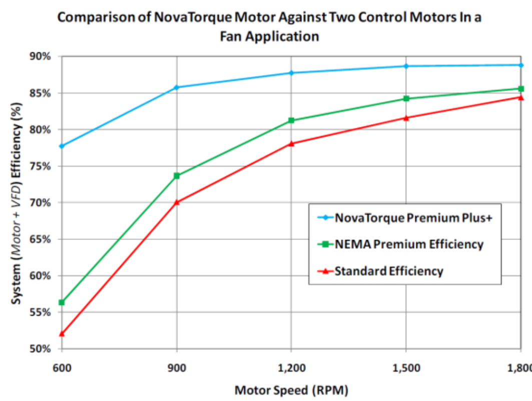
Low Cost Ferrite PM Motors

Based on an innovative geometry for the motor rotor and stator, the NovaTorque motor uses less costly ferrite magnets to deliver the performance level typically found in much more expensive rare earth-based permanent magnet motors



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Super Premium PM motor using Ferrite magnets

Motor Compared in Size to Conventional Motor

Super Premium PM motor using Ferrite magnets

- The new 11 kW double-rotor, axial-gap motor uses a laminated stator core based on a low-loss amorphous iron material. The losses from its laminated material are about 10% of those of conventional electromagnetic steel laminations.
- An amorphous metal has a disordered atomic structure versus the crystalline structure of conventional metals, and features a high tensile strength and extremely low magnetic losses.

Super Premium PM motor using Ferrite magnets

- The structure of the motor employs an “axial gap method” that uses two rotors to sandwich a stator in the direction of the axis of rotation in the aim of increasing the amount of ferrite magnet used for the motor.

Amorphous Iron Core

LSPM motors

- Hybrid motor with squirrel cage rotor fitted with high energy permanent magnets (NeFeB) making it suitable for direct on line start

- Interchangeable with induction motors (same output x frame ratio)

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Switched Reluctance Motors (SR)

An SR motor is a doubly salient design with phase coils mounted around diametrically opposite stator poles. Energisation of a phase will cause the rotor to move into alignment with the stator poles, so minimizing the reluctance of the magnetic path. As a high performance variable speed drive, the motor's magnetics are optimized for closed-loop operation. Rotor position feedback is used to control phase energisation in an optimal way to achieve smooth, continuous torque and high efficiency.

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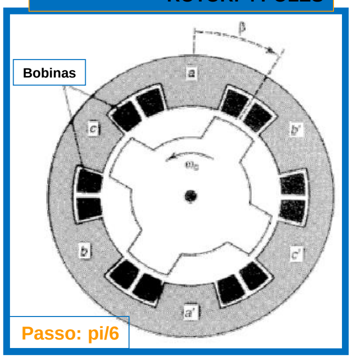
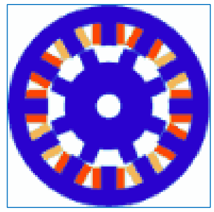
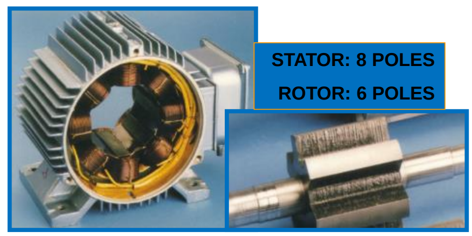
Switched Reluctance Motors

STATOR: 6 POLES (3 PHASES)
ROTOR: 4 POLES







STATOR: 8 POLES
ROTOR: 6 POLES

SR Motor: Rotor

- Simple and robust laminated steel construction: no brushes, windings, rotor bars or magnets
- Minimal losses in rotor
  - no cage or rotor bars
  - indefinite stall possible, no limit to frequency of starts
  - reduced shaft temperatures and prolonged bearing life

The simple SR Drive® rotor has many advantages over conventional types which utilise magnets or conductors

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SR Motor: Stator

- No magnets: straightforward laminated iron construction
- Simple coil windings: absence of phase overlaps significantly reduces the risk of inter-phase shorts
- Compact and short coil overhangs make efficient use of active coil area

Compact end-windings permit construction of high-performance motors with unusually flat aspect ratios.

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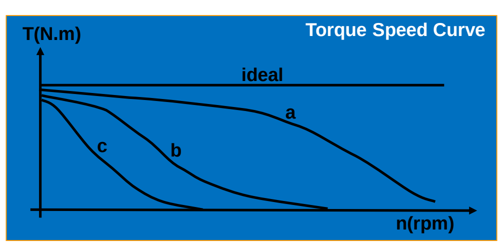
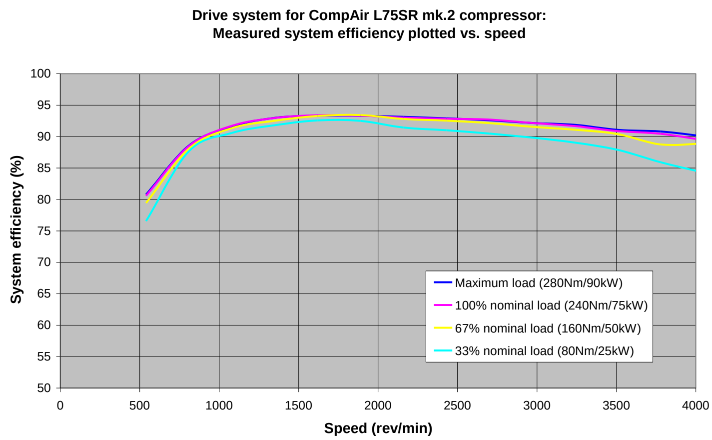
Switched Reluctance Motors

- APPLICATIONS UP TO 75 kW: High speed centrifugal machines, compressors, washing machines, vacuum cleaners, vacuum pumps, HVAC, variable-speed drive systems, machine-tools, automation, traction, etc.



System efficiency vs. speed & load



Switched Reluctance Motors

Main advantages:

- High efficiency;
- High torque and high speed capability;
- High reliability and long lifetime;
- Simple construction, robustness;
- Low cost;
- Simpler controller (1 power switch per phase);
- High power density;
- Available in diferent sizes and shapes.

Main disadvantage: ripple torque and high accustical noise due to the high vibration level – reasearch is made to improve these aspects. The controller is allways necessary.

Synchronous Reluctance Motors

- New synchronous reluctance motor (SynRM) and drive packages optimized for pump and fan applications
- The new rotor has neither magnets nor windings, and thus suffers virtually no power losses – which makes it uniquely cool.
- A standard IM fitted with a new rotor, combined with a standard drive with new software, results in a high output, high efficiency VSD system

Synchronous Reluctance Motors

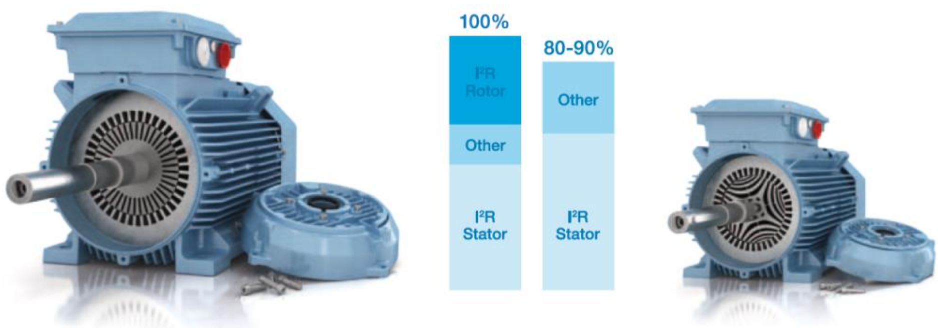
Advantages:

- No winding and PM in the rotor
- Low inertia
- Good acceleration performance
- Good flux weakening operation
- Low manufacturing cost

Disadvantages:

- Low power factor
- Torque ripple

Synchronous Reluctance Motors



Traditional induction motor

Losses

High output SynRM motor

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Synchronous Reluctance Motors

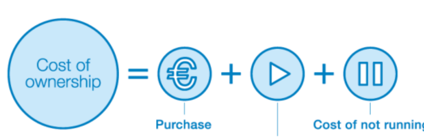
- Requires VSD supply => suitable for variable-speed applications.
- No rotor cage losses => lower overall losses => higher efficiency and smaller size (up to two frame sizes smaller than conventional SCIM). Output and efficiency performance comparable to a PM motor drive, but using technologies associated with the robust induction motor, bring the best of both worlds to users. Higher efficiency than conventional VSD plus IE2-SCIM units, especially with partial load variable-speed operation.
- No magnets and no cage => higher reliability and lower material cost

Synchronous Reluctance Motors

- Lower stator temperature => extended insulation lifetime and higher power density (20-40% in relation to SCIM) and/or higher efficiency. Possibility of achieving standard power and torque levels at merely a low class-A temperature rise (60 K).
- For the same rated power, efficiency improvement potential associated with lower losses:
  - smaller size for the same efficiency, and and temperature rise;
  - higher efficiency & reduced temperature rise for the same frame size;
  - combination of the two previous options (approach used for the commercial version presented).

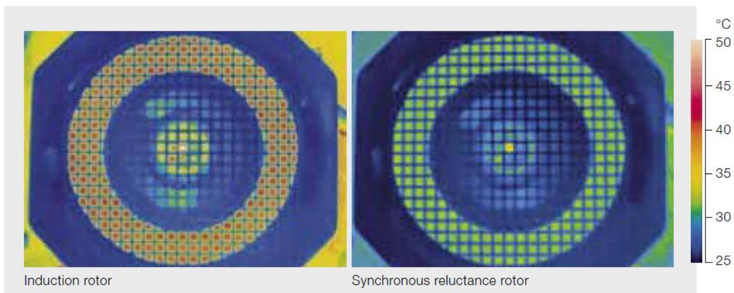
Synchronous Reluctance Motors

- Lower bearing temperature => extended bearings lifespan and service/greasing intervals and higher motor reliability.
- No magnets in the rotor => Easier maintenance in relation to PM motors: there are no magnetic forces involved, making the bearing change as fast and easy as with an SCIM.
- Lower cost of ownership due to the higher MTBF and VSD+Motor Efficiency.

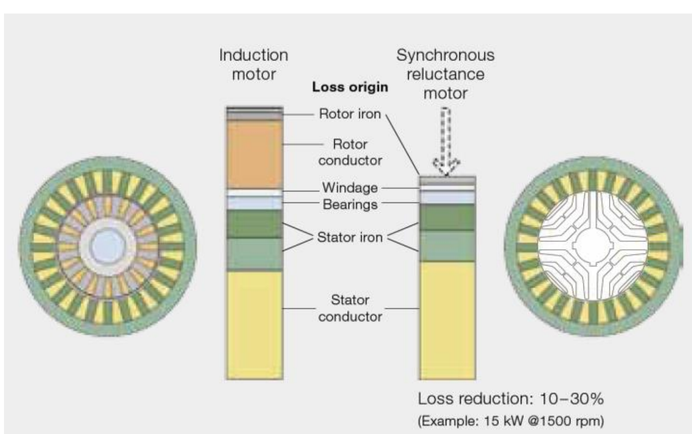


Synchronous Reluctance Motors

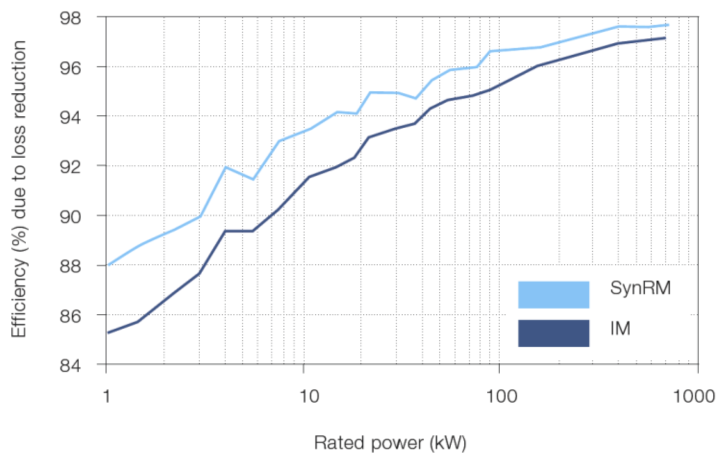
- Reduced heat load on nearby parts, particularly in closed cabinets.



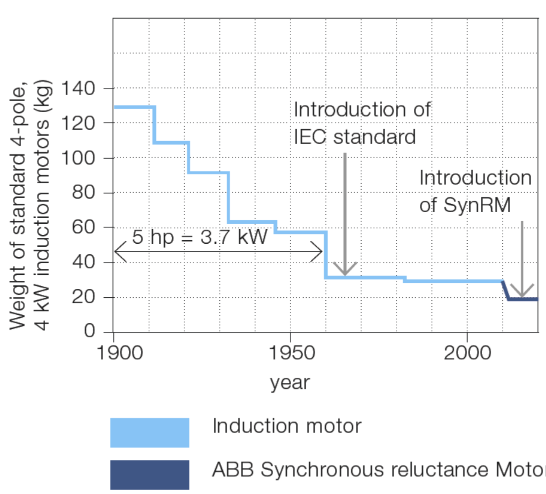
Potential efficiency increase due to rotor loss reduction in SynR Motors



Potential efficiency increase due to rotor loss reduction in SynR Motors



Power to Weight Ratio



size	Induction motor	SynRM	Out-put
100	3.3kW η=83%	4.3kW η=90%	+30-45%
160	22kW	29kW	+32%
280	90kW	110kW	+22%

Technology comparison measured ratings

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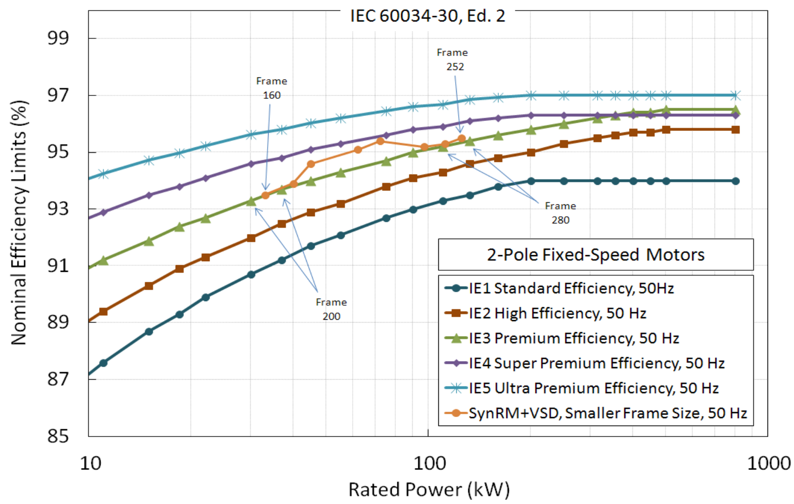
SynR Motors – Promising Technology for IE4



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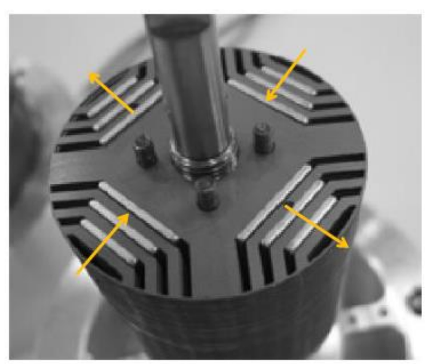
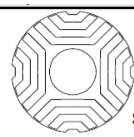
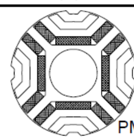
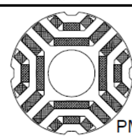
PM-Assisted SynR Motors

- Low cost ferrite
- Easy to handle
- High efficiency
- High power density
- Good Power Factor
  (→impact size of the inverter)



Effect of inserting PM

		Torque Nm	ΔTorque %	cosφ
1		26	-	0.71
2		31	+19 %	0.86
3		33	+27 %	0.90

Source: UnivAQ

Retrofitting Example

As an example of retrofitting, an IE0-Class Equivalent, 5.5-kW, 4-pole, SCIM driving a fan in an industrial facility, has been replaced by an IE4-Class LSPM.

(a) IE0 SCIM

(b) IE4 LSPMSM

Photos of the replaced and replacing motors: (a) Brand A, 132S, IP55, Cl. F, 5.5 kW, 380-420V, 11.5 A, 1450 r/min, PF=0.83, Eff.=83.2% (IE0/EFF3 Class); (b) Brand B, 132S, IP55, Cl. F, 5.5 kW, 380-420V, 9.34 A, 1500 r/min, PF=0.93, Eff.=92.5% (IE4 Class).

Summary of the Motor Performance for the SCIM and LSPM

	Before Replacement	After Replacement
Motor Type	SCIM	LSPM
Efficiency Class	IE0/EFF3	IE4
Rated Efficiency	83.2%	92.5%
Rated Power	5.5 kW	5.5 kW
Rated Voltage	400 V, 50 Hz	400 V, 50 Hz
Rated Current	11.5 A	9.34 A
Rated Power Factor	0.83	0.93
Rated Speed	1450 r/min	1500 r/min
Actual Voltage	≈ 400 V	≈ 400 V
Actual Current	≈ 7,5 A	≈ 5,5 A
Actual Power Factor	0,75	0,90
Actual Input Real Power	3750 W	3500 W
Actual Input App. Power	5100 VA	4000 VA
Actual Speed	1472 r/min	1500 r/min
Estimated Load	< 57%	< 59%

The original motor was oversized (load lower than 57%) and, therefore, a 4-kW LSPM would be enough for this application, but the user decided to maintain the rated power. Moreover, since the new 5.5-kW LSPM has a load lower than 60%, it can benefit in terms of efficiency and power factor from voltage regulation.

Thank you

2. Taking measurements

Hugh Falkner &
Anibal de Almeida

Taking measurements
Contents

- What do you need to know?
- Be Safe
- Metering Options
- Meter Accuracy

Ex.1 What are you going to measure?

What measurements?

- Measurements cost
- What do you really need to know?
- A Yes/ No question – should I make this investment or not?
- Only minimal evaluation of definite Yes or No opportunities.
- Reserve expensive data collection and evaluation for “in between” projects OR very expensive projects where you will have to defend it.

What Measurements can do

- Tell you how the system works at the moment
- An idea of the load pattern could point out obvious opportunities

What they can't do:

- Tell you how much the system could use when optimised.
- Show you how readings correlate with the actual system load.

Avoid embarrassment – Understand the real load requirements

- The Power consumption only tells you what the power is the way the plant is set up, including any problems. To understand the true power requirement, you need to know understand what is going on in the system.
- Avoid buying a new motor or VSD without thinking through what is going on – otherwise you could have an over-sized and over-priced system!
- Even if you don't change the motor, the VSD or other controls should be matched to the electrical power, not the nameplate motor rating.

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Beware of a spot reading – is it telling the whole story?

- Even a "steady" system may have unexpected increases in energy consumption;
- Can the motor start safely? Starting is often the most onerous time for motors, and if the motor torque doesn't exceed the load torque at all times during start up, then it won't start. Instead it will overheat and trip out.
- What about cold starts? The greater density of cold air at starting of a furnace will mean higher power consumption.
- Viscosity of oil will be worse on cold days, but non-Newtonian fluids such as paint or some foodstuffs will see dramatic changes in properties during stirring.

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Understand future requirements

- What are the future plans?
- Don't optimise a system that's about to change, or even be de-commissioned!
- Will the demand be different another day?

Measuring Motor Efficiency

- Measuring in situ motor efficiency would be wonderful. But it can't practically be done. Sorry. But let us know if you come across anyone who can!
- While it would be nice to know, for most decisions its really not critical. There are bigger opportunities than worrying about actual motor efficiency!

Saving ready:reckoners

- There are lots of free VSD energy saving estimator calculators available. They're easy to use, but rely on you knowing the following:
  - Load:time profile
  - Pump/fan/... Characteristics
  - System torque:speed characteristics
- Spot readings aren't really going to help here, but may give an idea of whether it is worth doing something.

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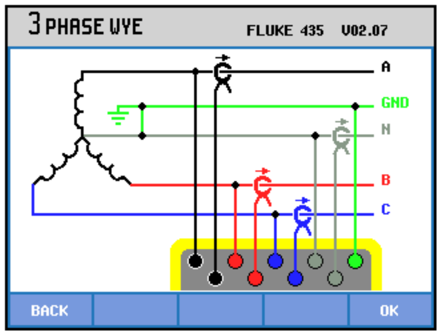
Connecting a 3-phase power meter

Power = √3 . V . I . cosΦ



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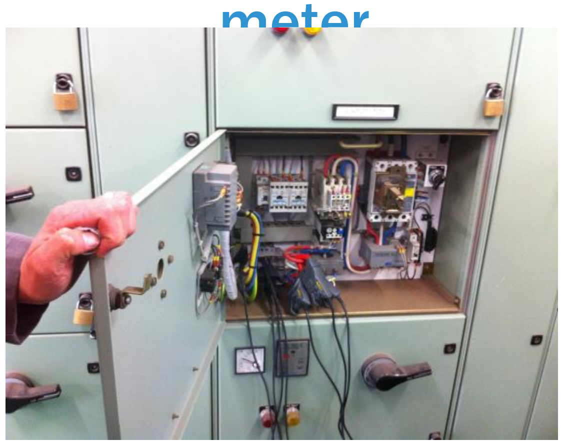
Connecting a three phase power meter



Exercise – Estimation of Mechanical Motor Load without a power meter

Name plate data:

Rated kW of Motor = 30 kW
Rated Amps = 55 A
Rated voltage = 400 V
Name plate efficiency = 92%
Name plate speed = 1440 rpm

Measured Data

Measured speed = 1460 rpm
Input load current = 33 A
Operating voltage = 415 V
Input power = 20 kW

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Estimation of Motor Load by measuring current only

Based on Input Power Method Measurement:

Nominal input power = 30/0,92 = 32,6

Load = 20 /32,6 = 0,61

Note: the accuracy of method drops when load is below 40% since efficiency drops sharply below that value.

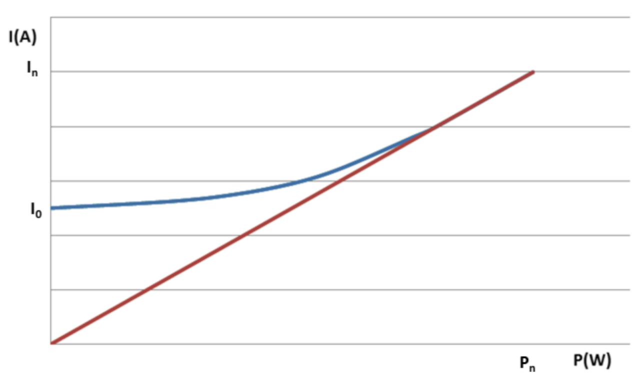
Estimate of Motor Load from current (and voltage) only, no Power Factor

$$Load\ (\%) = \frac{V_{measured} \times I_{measured}}{V_{rated} \times I_{rated}}$$

$$Load\ (\%) = \frac{415 \times 33}{400 \times 55} = 0{,}623$$

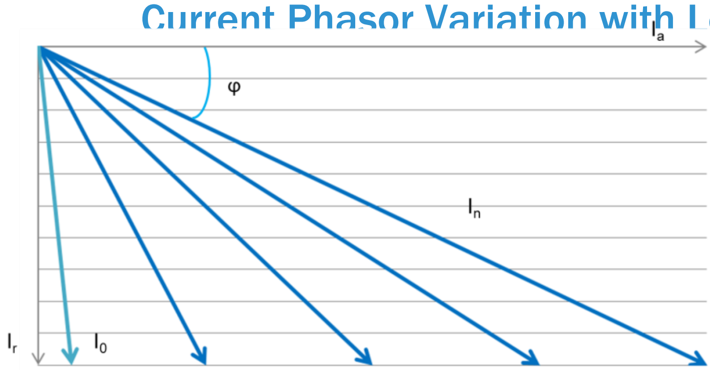
Note:This method has larger errors for loads below 50% because of decreasing PF

Motor current variation with load



I_0 – No load Current
I_n – Nominal Current

Current Phasor Variation with Load



$$I_0 \cong I_n \sin\varphi$$

I_a – Active Current
I_r – Reactive Current
I_0 – No load Current
I_n – Nominal Current
Cos φ – Full Load power factor (nameplate rating)

Estimation of Motor Load by measuring slip speed

Synchronous speed = 60 x 50/2= 1500 rpm

Slip = Synchronous Speed – Measured speed in rpm,

= 1500 – 1460 = 40 rpm

$$Load\ (\%) = \frac{Slip}{(S_{synch} - S_{nameplate}) \times \left(\frac{V_{measured}}{V_n}\right)^2} \times 100$$

$$Load\ (\%) = \frac{40}{(1500 - 1440) \times \left(\frac{415}{400}\right)^2} \times 100 = 61{,}9\%$$

Note:This method has larger errors for big motors because of their smaller slip

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Measuring Speed

- Useful if there is a transmission – especially for system considerations.
- Might influence choice of speed controls.

Most relevant for fans

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Direct Contact Tachometer

Requires access to the middle of the shaft. The rotational speed is measured while the machine is operating.

If the fan is operating at a high speed, safety becomes an issue.

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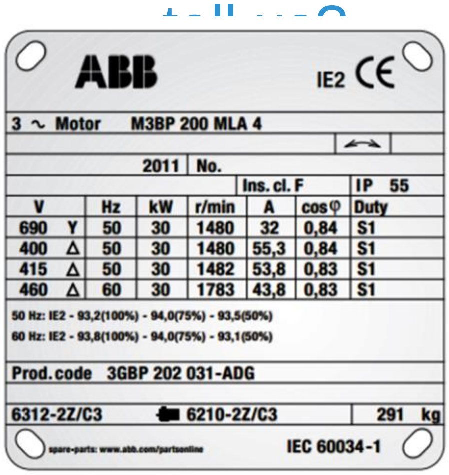
Strobe Tachometer

Safer, but need visual contact

A motor nameplate – What can it tell us?



Slide Courtesy of Oak Ridge National Laboratory

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Data-logging Options

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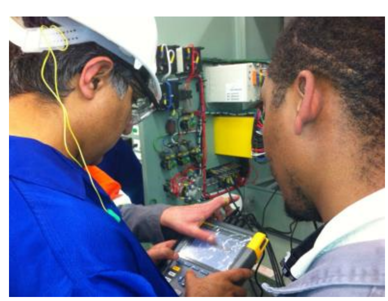
Data Loggers

- Data loggers can provide more insight on how a system operates over an hour, a day or several weeks.
- Many power meters also have data logging features that can be used



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Data costs!

- Data logging often means a second visit to collect the results.
- Don't forget to put it in data collection mode.
- Check the batteries.
- Set the resolution correctly.
- Be prepared to pay for the software.
- Don' t collect, and certainly don't analyse, information that you don't need.

Meter Accuracy

- Accuracy is usually specified as a % of full scale, and/or the lowest digit difference it can display.
- If a meter has an error of +/-1% at Full scale, what is the error when measuring something at 10% of Full scale?

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Continual Improvement

- Building up a picture of energy use in your plant will take time, your knowledge will continually improve over time:
- Understanding how additional equipment operates.
- Understanding how equipment changes over time.
- Understanding the relationships between different equipment.

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Calibration & Accuracy

- Important if the results are going to be challenged or used as a financial payback mechanism.
- Keep to the calibration schedule.
- Use rms meters.
- If using a digital meter, ensure you know what it is measuring.

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Calibration Matters!

ISO 50001 Energy Management System Standards requires organization to calibrate measuring equipment (sub-clause 4.6.1).

Calibration does cost money and time to organise, and so your calibration policy needs to be thought through carefully.

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Be Safe!

- Are you qualified to take measurements?
- Beware of measuring equipment and plant that you are not familiar with.
- Double check that you know what you are measuring.
- Don't compromise on equipment quality.
- Check the condition of leads.
- Avoid live working if at all possible.
- Watch out for high personal stress situations.
- If overseas, climate, jet lag and unintelligible writing an additional hazard.
- Ensure an electrician is available to fit instruments. It removes blame if anything goes wrong.

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Taking measurements Summary

- What do you need to know?
- Be Safe
- Metering Options
- Meter Accuracy

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Thank You

And Be Safe

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3. Electric motor standards

Anibal T. De Almeida
ISR-University of Coimbra

Discussed topics

- Key motor standards
- Energy efficiency related standards
- Worldwide energy efficiency regulation

Key Efficiency Test and Related standards

- *IEC 60034-1 (Edition 12: 2010)*: Rating and performance

- *IEC 60034-2-1 (Edition 2.0:2014):* Standard methods for determining losses and efficiency from tests

This standard establishes methods of determining efficiencies from tests, and also specifies methods of obtaining specific losses. It applies to DC machines and to AC synchronous and inductions machines of all sizes within the scope of IEC 60034-1.

Key Efficiency Test and Related standards

- *IEC 60034-30-1 (Edition 1.0: 2014):* Efficiency classes of line operated AC motors (IE code)

This standard defines efficiency classes for single-speed motors for operation on a sinusoidal voltage supply (DOL). It harmonizes the different efficiency levels in use around the world. This standard establishes a set of limit efficiency values based on frequency, number of poles and motor power.

No distinction is made between motor technologies.

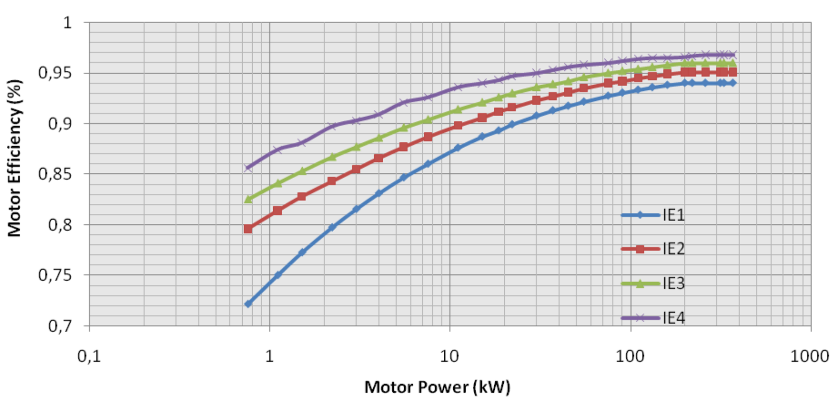
Harmonization of efficiency classification standards in the World – IEC 60034-30-1

Four efficiency classes:

- **IE3**: Premium efficiency (16-20% lower losses than IE2)
- **IE2**: High efficiency (existing Eff1, EPAct)
- **IE1**: Standard efficiency (existing Eff2)
- **IE4**: Super-Premium Efficiency

- **IE5:** only presented in the form of an informative annex (Annex A). It is the goal to reduce the losses of IE5 by about 20 % relative to IE4.

Harmonization of efficiency classification standards in the World – IEC 60034-30



IEC 60034-30 efficiency classes and IEC 60034-31 IE4 Super-Premium Efficiency Class

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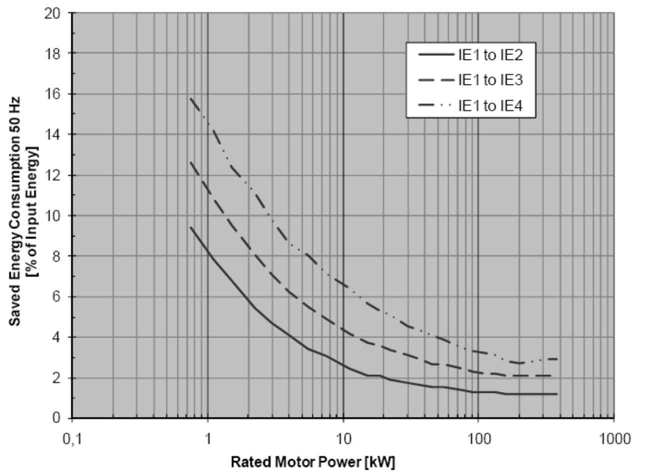
Energy Savings



Potential energy savings by improvement of efficiency-classes

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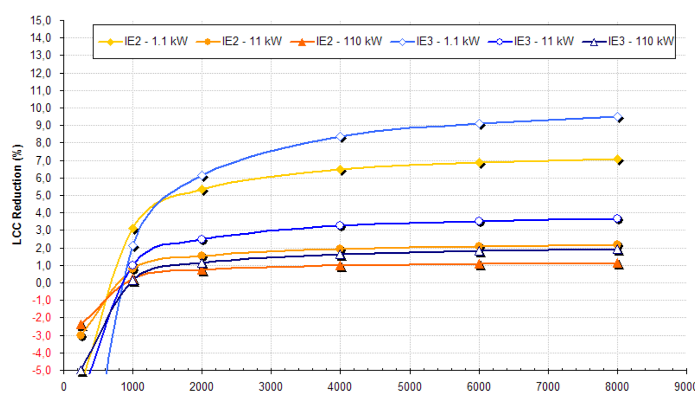
Energy Cost - Saving



LCC reduction as a function of the number of operating hours (0,075 €/kWh), BAT vs. BaseCase

1 Euro ≈ 10 ZAR Source: ISR – University of Coimbra

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MEPS Worlwide

Efficiency Levels	Efficiency Classes	Testing Standard	Performance Standard
	IEC 60034-30	IEC 60034-2-1	MEPS
Premium Efficiency	IE3	Low Uncertainty	USA 2011 Europe 2015* (>7,5kW), 2017
High Efficiency	IE2		USA Canada Mexico Australia New Zealand Brazil Korea China (2011) Europe (2011) Switzerland (2011)
Standard Efficiency	IE1	Medium Uncertainty	China Brazil Costa Rica Israel Taiwan Switzerland

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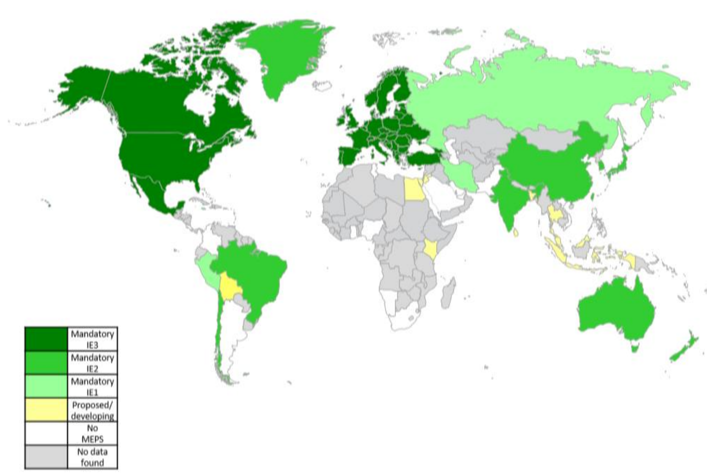
MEPS Worlwide



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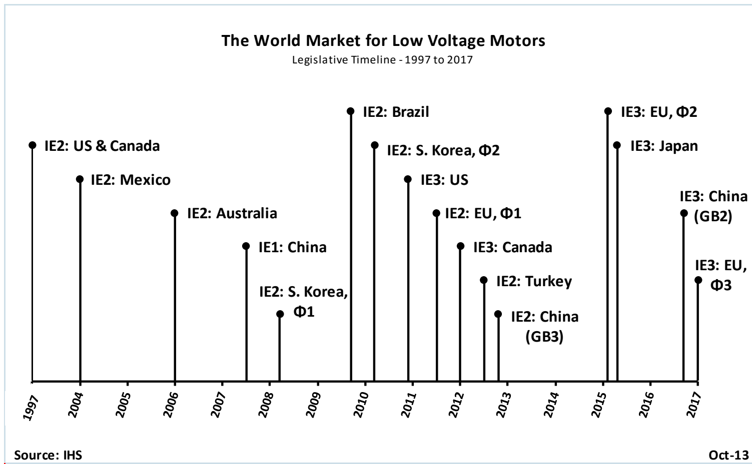
MEPS Timeline



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Key Efficiency Test and Related standards

- *IEC 60034-30-2 (in development):* Efficiency classes of variable speed AC motors (IE-code)

This standard will define efficiency classes for motors that are rated for converter operation (with a VSD).

No distinction is made between motor technologies.

Key Efficiency Test and Related standards

- **IEC 60034-31 (Edition 1.0: 2010): Guide for the selection and application of energy-efficient motors including variable-speed applications**

The gives technical guidelines for the application of energy-efficient motors in constant-speed and variable-speed applications. It does not cover aspects of a pure commercial nature.

New standards EN50598 / IEC 61800-9

- **EN 50598-1**: (released December, 2014) General requirements for setting energy efficiency standards for power driven equipment using the extended product approach (EPA) and semi-analytic model (SAM).
- **EN 50598-2:** (released December, 2014) Energy efficiency indicators for Power Drive Systems and Motor starters
- **EN 50598-3:** (released March, 2015) Quantitative ecodesign approach through life cycle assessment including product category rules and the content of environmental declarations

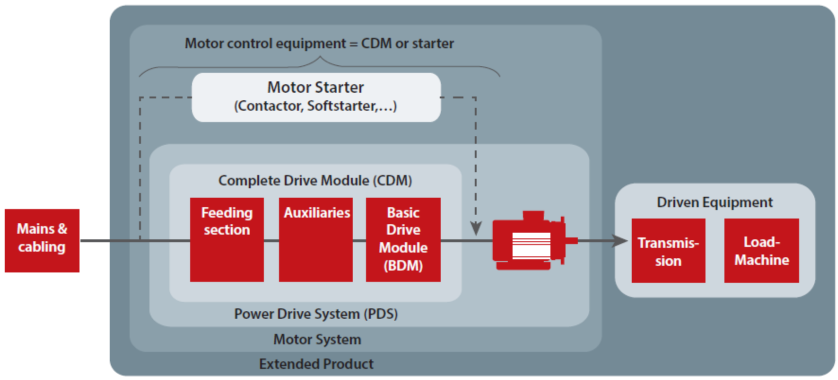
New standards EN50598 / IEC 61800-9

- Specifies IE classes from the Energy Efficiency point of view of the complete Motor system and its sub-parts.
- Enables the system energy efficiency to be determined based on defined criteria such as speed/load profiles, the duty profiles, drive topologies and architectures.
- Provides limits for the maximum losses of sub-parts or the overall losses of the motor system. It also describes the methodology of determination of losses.

New standards EN50598 / IEC 61800-9

- Describes the methodology to quantify the influence of system parameters like cabling, filtering and control strategy for the energy efficiency requirements of the Motor system.
- Suggests a methodology for characterization of the best Energy efficiency solution to be implemented, depending on the motor driven system architecture, the speed/load profile and the duty profiles of the application.

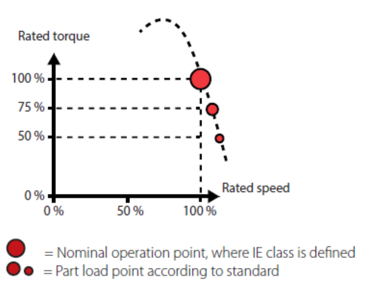
New EN50598 / IEC 61800-9



Source: Danfoss

System Efficiency Classification -Motor

Motor IE classes according to IEC60034-30-1



- IE classes are defined at the nominal motor load
- Efficiency levels for 50% and 75% rated torque at mains frequency need to be stated in the documentation
- The efficiency classes are defined for direct on line motors, independent of the motor technology
- Asynchronous motors with a higher efficiency typically run at a higher speed (RPM). Consider this in retrofit applications.
- Mechanical dimensions can vary depending on motor technology and IE class

Source: Danfoss

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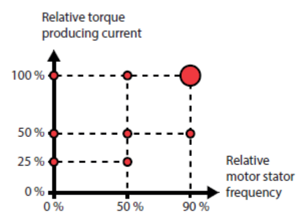
System Efficiency Classification – CDM/VSD

IE classes for frequency converters according to EN 50598-2



= Nominal operation point, where IE class is defined
= Part load point according to standard

- The IE class is defined at an operating point of 90% frequency and 100% torque-producing current.
- Special test settings are not permitted.
- The classification for the frequency converter includes integrated options.
- Losses in options that are not built in (for example, EMC filters or chokes) are not included in the efficiency class but need to be documented if they
  - Comprise more than 0.1% of the rated frequency converter power, and
  - Are greater than 5 W.
- Losses at partial load can be documented by the manufacturer.

Source: Danfoss

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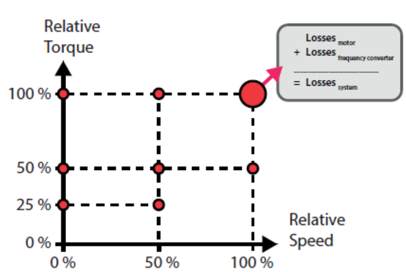
System Efficiency Classification - PDS

IES classes for power drive systems according to EN 50598-2:



= Nominal operating point, where IES class is defined
= Part load point according to standard

- The IES class applies for frequency converter – motor systems
- The IES class is defined at 100% speed and 100% torque
- The cable length between frequency converter and motor is defined.
- Deviations from the standard cable length or switching frequency are permitted, but must be documented
- Losses at partial load are documented by the manufacturer

Source: Danfoss

System Efficiency Classification

Combination of	CDM	Test CDM	Reference CDM (RCDM)	
Motor	**determine the IES class of the resulting PDS**	determine the IE performance of the given motor (IEC TS 60034-2-3)	determine the IES Class of the resulting PDS	**Guidance for motor manufacturer**
Test Motor	determine the IE performance of the given CDM	combination not used	combination not used	
Reference Motor (RM)	determine the IES Class of the resulting PDS	combination not used	calculation model of a reference PDS	
	Guidance for CDM manufacturer			

CDM = Complete Drive Module = Converter

PDS = Power Drive System (Converter plus Motor)

Thank you

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4. Pumps – the Motor perspective

Why are Pump measures missed?

- Good consultants look for pump control measures. Rarely are pump upgrades suggested.
- A proper PSO (Pump System Optimisation Assessment) is a longer job, but with some knowledge of different types of systems, you CAN with confidence spot many good options.
- *Its about making the right decision with limited information. And knowing your limits.*

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Pumps - The motor perspective

Contents

- Pump Basics
- Pump Control
- Time flow Profiles
- Other types of Pump
- Multiple Pump Configurations
- Pump Problems
- Top 10 Energy Saving Opportunities

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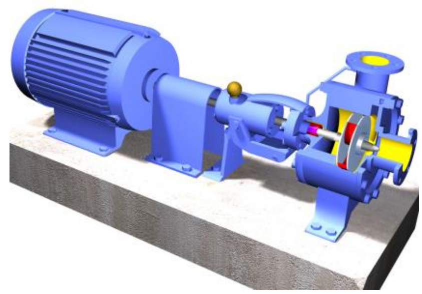
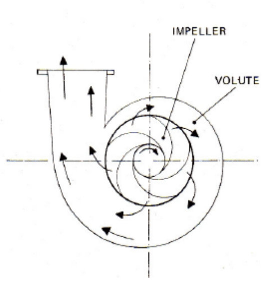
Pump Basics

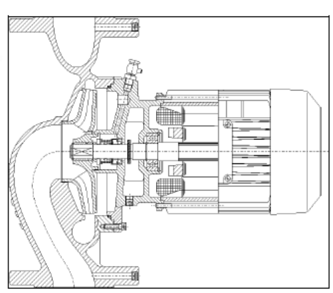
The Centrifugal Pump

- Pumpset efficiency can be altered by choice of motor, and performance can be changed by motor speed.



Anatomy of an End Suction Close Couple Pump





Affinity Laws

$$Q \propto N$$

$$H \propto N^2$$

$$P \propto N^3$$

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$$

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3$$

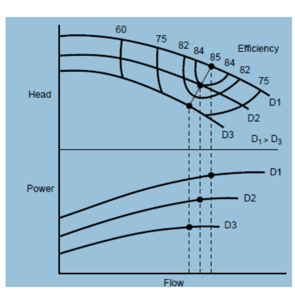
Where,
N = rotational shaft speed
Q = Flow
H = Head
P = Power

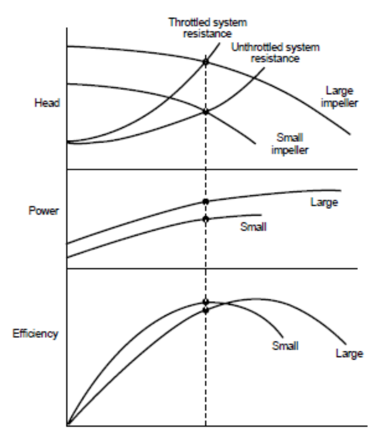
Impeller Sizing

Pump impeller will be most efficient close to maximum diameter.

A smaller impeller will be less efficient, but the system energy savings will be large.

Replacing or trimming an impeller is an option.





Impeller Trimming Case Study

- Brine pump at salt works condensate distribution system was over –sized and causing maintenance problems.
- Impeller trimmed, motor size falling from 110kW to 75kW
- Payback in 11 days

UK EEBPP GPCS300 Energy savings by reducing the size of a pump impeller

Two types of pump systems

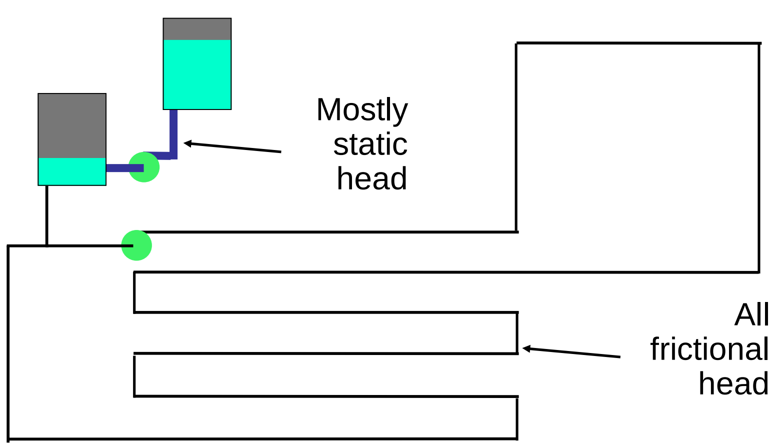
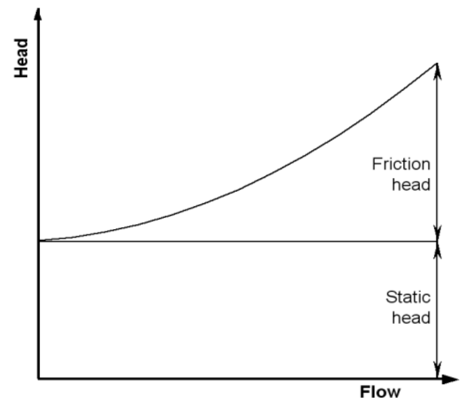


Figure Courtesy of Oak Ridge National Laboratory

Centrifugal Pumps

Total system resistance from frictional losses (vary as function of the cube of speed) plus static head losses to provide lift.

Head falls with the **Square** of the speed, so falls off very quickly.



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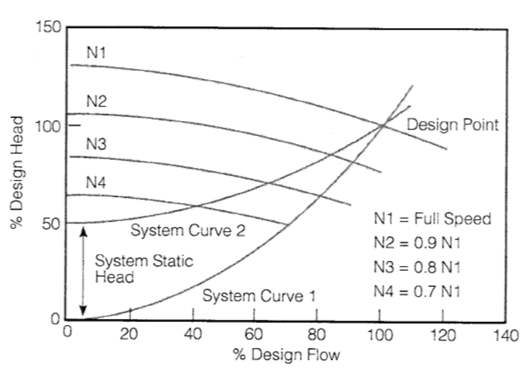
Affinity Laws

All system losses must be friction losses for the affinity laws to apply.

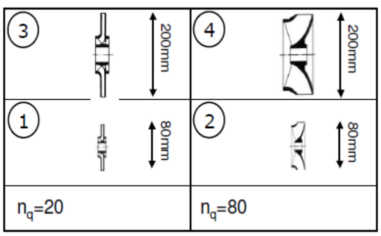
Therefore, systems with low static head tend to be better candidates for VSDs.

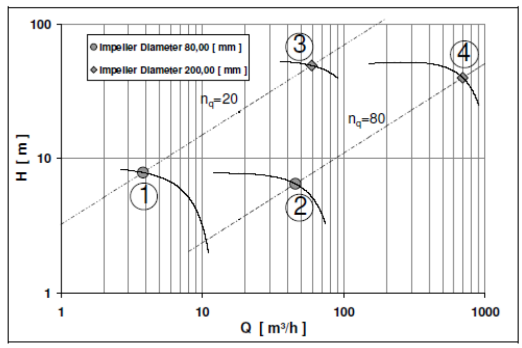


Specific speed

Ns = Specific speed
N = Speed
Q = Flow
H = Head

$$n_s = n \cdot \frac{(Q_{opt})^{1/2}}{(H_{opt})^{3/4}}$$





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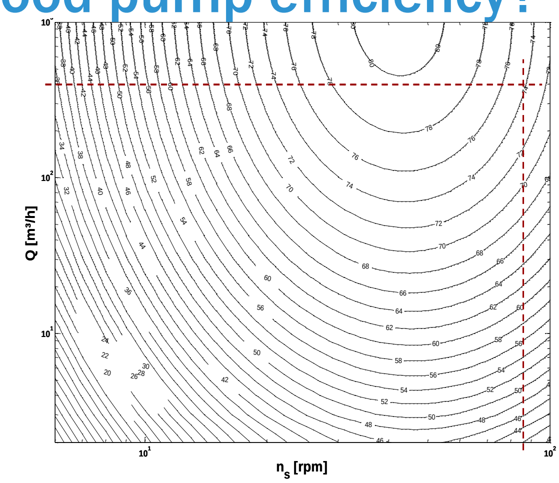
What is a good pump efficiency?

It depends on the flow an d specific speed of the pump.

For a particular flow, there is an optimum head.

Figure from European Union Regulations on minimum efficiency levels of pumps



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Pump Control

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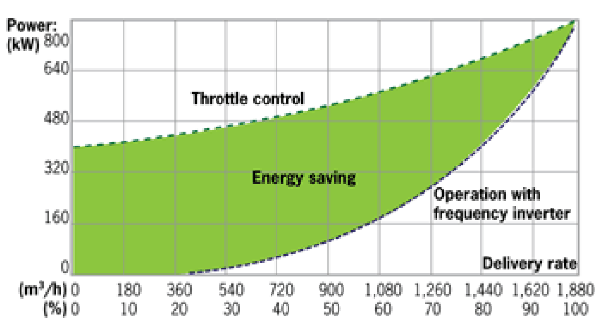
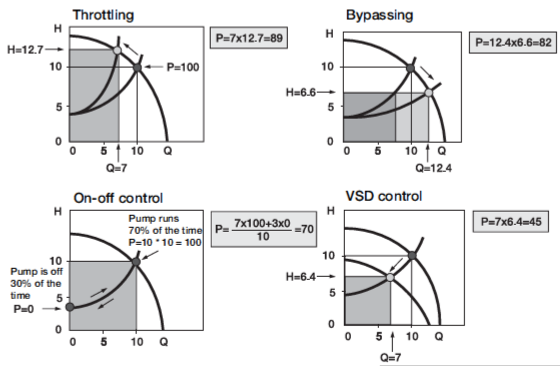
Example



The energy saved by replacing a throttle control with a VFD is given by the area bounded by the two power curves.

Pump Control Methods

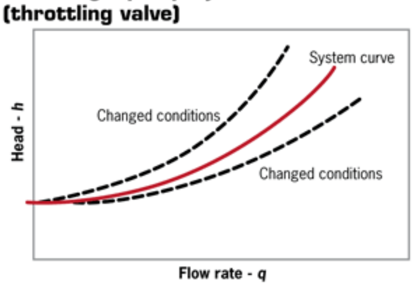


Relative power consumption on an average flow rate of 70% with different control methods.

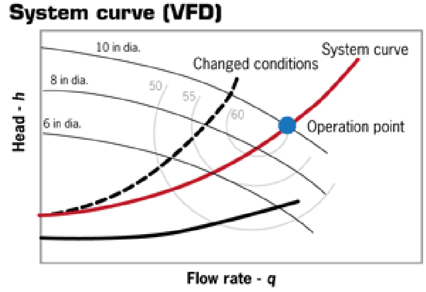
Control	Energy
Throttling	89
Bypassing	82
On-off control	70
VSD control	45

Centrifugal Pumps

Centrifugal pump system curve (throttling valve)



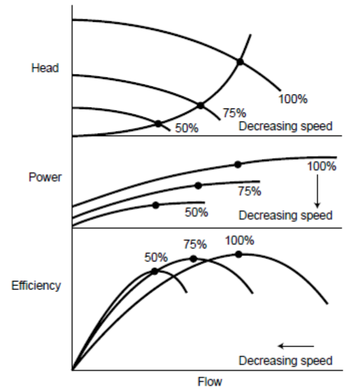
System curve (VFD)



With centrifugal pump systems, throttling changes the system curve by use of a control or throttling valve. But a VFD changes the pump curve by varying the pump speed. *The Best Efficiency will remain similar as the speed reduces.*

Pump Efficiency at different speeds

Small reduction in efficiency – due to increase in internal recirculation



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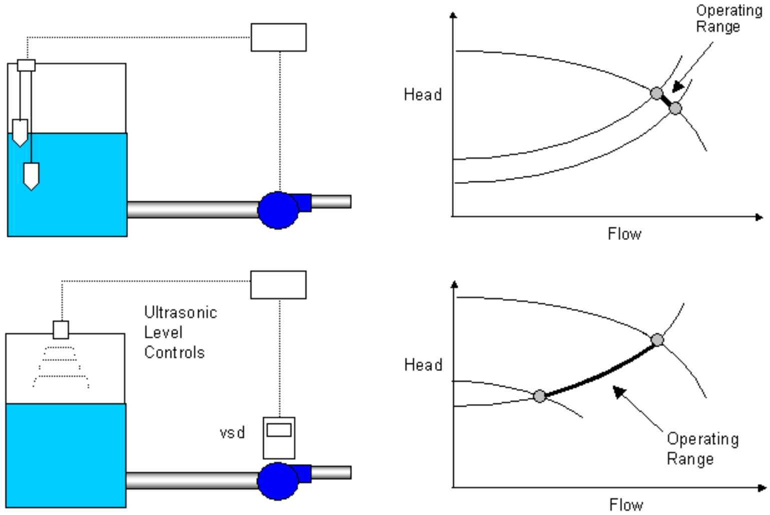
New Motors

- More efficient motors will have lower slip and hence higher speed.
- For many pumps, More efficiency, but more energy.
- But for low frictional head (and high static head), the effect will be minimal.
- It is not material if the pump is controlled properly.

Level Control Methods



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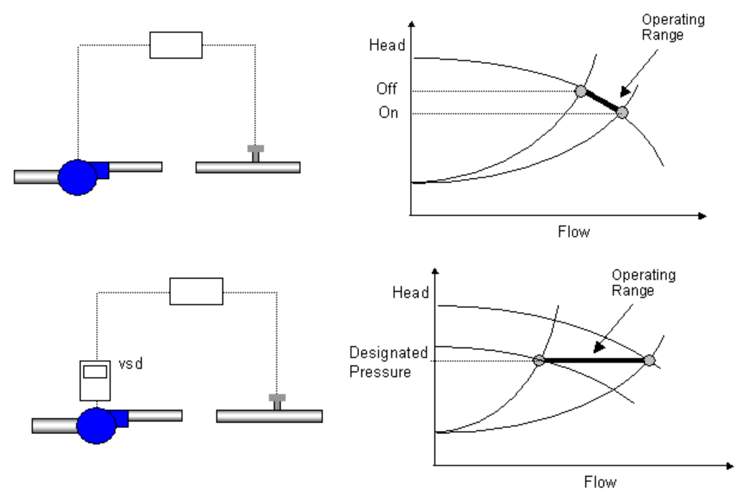
Pressure control methods



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Multiple Pump configurations

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Parallel and series pumping "laws", like the pump affinity laws apply to the pump curves *only*

- Parallel pumps - sum the flow rates at a given head
- Series pumps - sum the heads at a given flow rate

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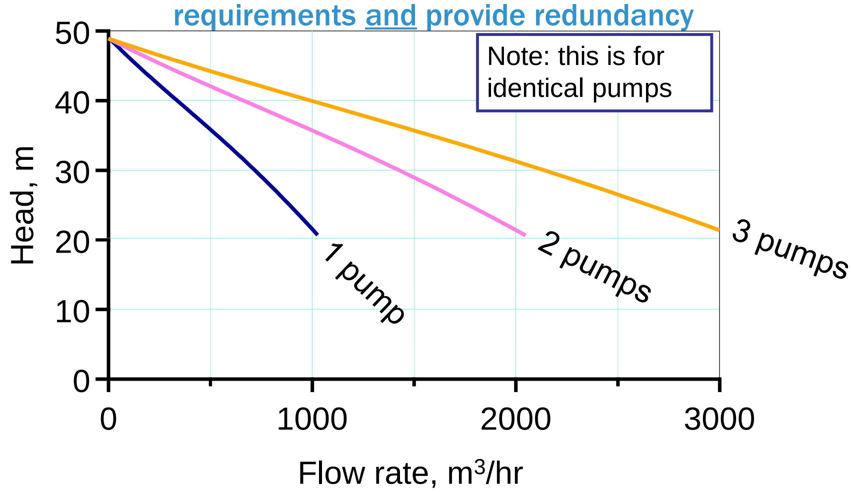
Parallel pumps can help adapt to changing system requirements and provide redundancy



Slide Courtesy of Oak Ridge National Laboratory

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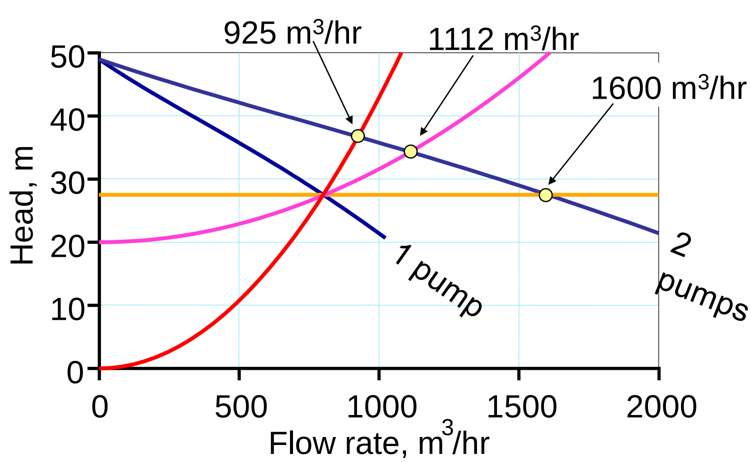
The effect of turning on a parallel pump also depends on the nature of the system



Slide Courtesy of Oak Ridge National Laboratory

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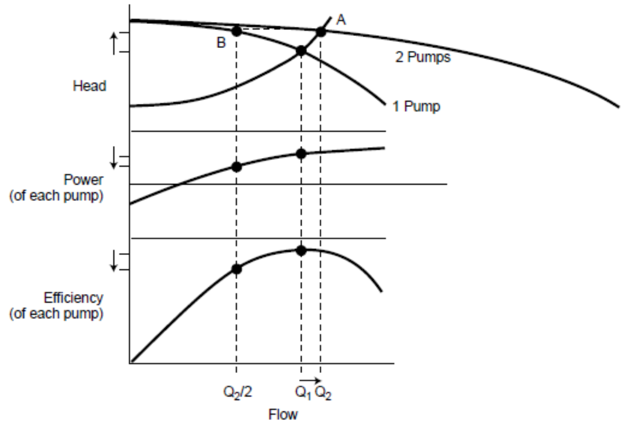
Parallel pumps – watch the power!

Parallel systems are optimised for a specific number of pumps. Operating away from this can have severe power consequences.

Additional pumps often left on for safety



Time : Flow Profiles

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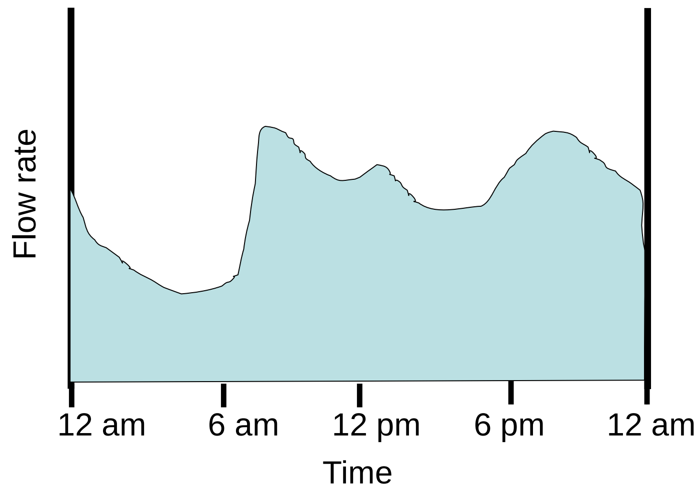
Daily flow fluctuation example



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Annual flow fluctuation example

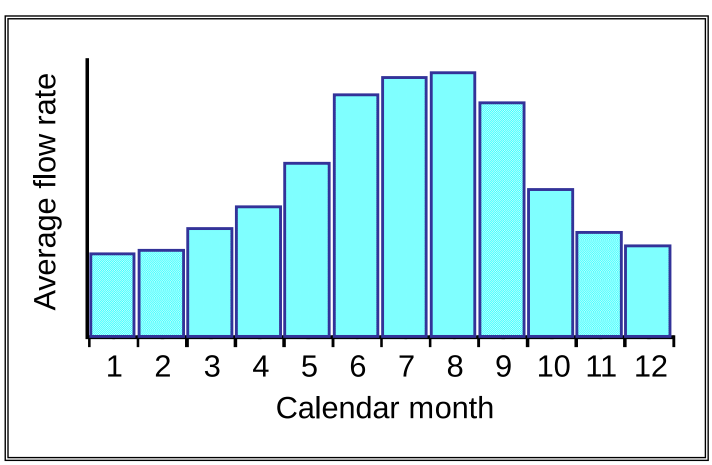

Figure Courtesy of Oak Ridge National Laboratory

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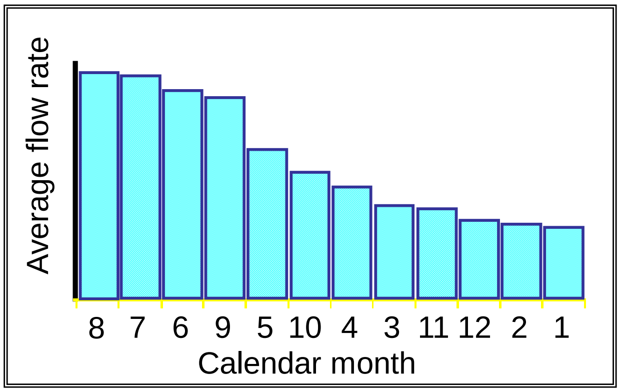
We can sort the months by flow rate:



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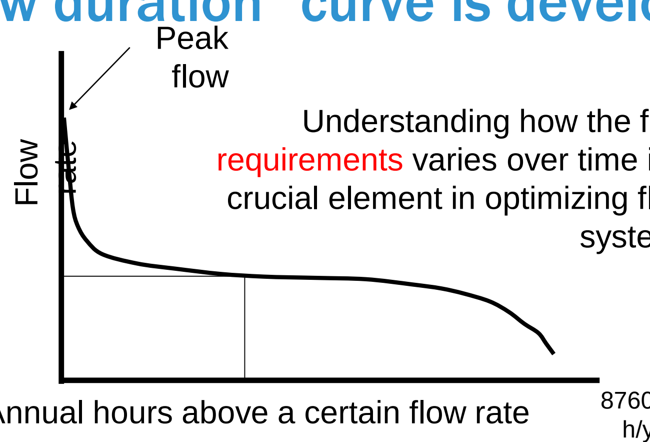
By tracking flow rate over time, a "flow duration" curve is developed



Understanding how the flow requirements varies over time is a crucial element in optimizing fluid systems

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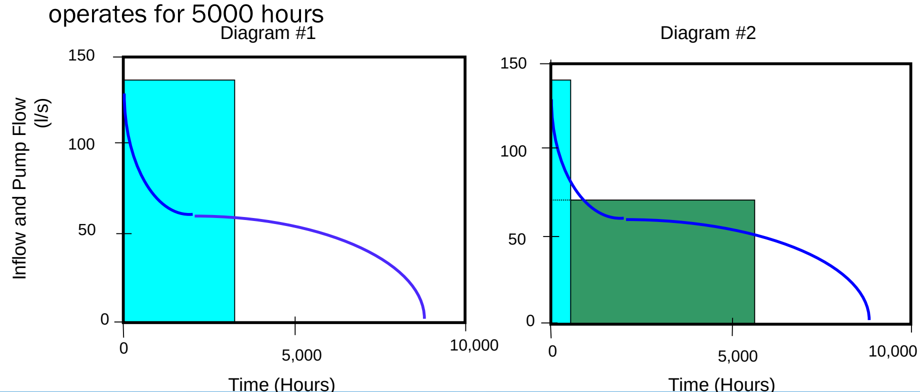
Using smaller pumps to handle low flows

- Diagram #1 shows a pump operating for 2500 hours per year at a flow rate of 130 l/s – total flow is represented by the area under the curve.
- Diagram #2 shows the same total flow pumped by two pumps. The 130 l/s pump only operates 200 hours per year and a smaller pump rated for 70 l/s operates for 5000 hours



Other types of pumps

Waste Water Pumps

- Pumping stations designed to have a minimum fluid velocity to move the waste. The water is the transport means, not the objective of the system.
- VSDs can be useful for freeing blocked pumps by rapid bi-directional cycling.
- BUT be careful not to reduce flow too much, otherwise you get pipe blockages.
- VSDs useful at treatment plants for smoothing flow.

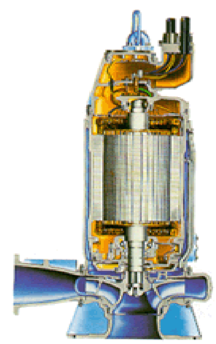
- So some scope for savings, but you really need to be confident what you are doing

Archimedes Screw pumps

- These are self-regulating, so VSDs not useful.
- Can turn on/off
- Poor low flow efficiency

Submersible Pumps

- Submersible pumps comprise an electric motor and pump in a single sealed unit, where the whole pump is installed within the media being pumped. These are typically found in wastewater distribution networks as the pumping station area is small, and they have a small visual impact. Submersible wastewater pumps are commonly available in range of sizes from less than a kW up to 400 kW and cover flow rates from about 4 l/s up to over 1,000 l/s
- The standard motor used is an induction motor which is shrunk-fit to the casing, ensuring excellent thermal coupling to the water it is standing in. The best motors are wound to Class H (180 °C operation), giving an excellent thermal margin over the typical operating point, hence giving much greater reliability, and allowing for frequent stop/starts.
- Most pumps have a pull out design, enabling the removal of the motor, impeller and top-volute casting without needing to touch the pipework or base mounting connections. This is important to allow much quicker change-outs or maintenance.
- Some manufacturers offer bespoke alarm systems that track parameters including temperature, leakage, vibration, current and power.



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Dry Well Pump

- Dry well pumps have the same pump body construction and variation in impellor configurations as submersible pumps, however the motors are not connected to the casing. The pumps are located outside of the wastewater wet well which increases the access ability for maintainabilty. The motors can be long-coupled to the pump body allowing the motor to be kept at the surface for deep pumping applications. These are commonly available in range of sizes from less than a kW up to 400 kW and cover flow rates from about 4 l/s up to over 1,000 l/s
- They are preferred where there is space, as they are easier to maintain.
- Some manufacturers offer bespoke alarm systems that track parameters including temperature, leakage, vibration, current and power.
- Some pumpsets have rugged belt drives enabling the fine adjustment of impeller speed and hence duty without the use of a VSD. The prospects for impeller trimming on these types of pumps is much more restricted than on clean cold water pumps.
- Small sized pumps. Vortex impellers are common, but because of their low efficiencies are only recommended for use in applications with low duty.
- Medium sized pumps. Open two channel impellers are common, with the wear disc adjustable to compensate for wear and hence maintain efficiency over pump life.
- Some larger pumps have closed channels (two sides to the impeller).
- Some pumps have an NPSH that allows mounting over the sump

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Slurry Pumps

- Slurry pumps, sometimes referred to dewatering pumps, are typically used to empty liquids with abrasive solids out of tanks, sumps and ditches. They are usually portable which allows them to be manually lowered into the liquid to be pumped as and when required. The flow rates typically range from about 4 to 30 l/s with heads typically up to 50 m, although larger pumps can deliver flows all the way up to 200 l/s. Power ratings are found all the way up to 60 kW.
- Due to the abrasive nature and solids content of the liquids that are pumped with slurry pumps, the components used in its construction are selected based on their resistance to wear. Many slurry pumps have a double outer casing and good heat convection that enables the pump to operate continuously at low levels or even run dry without damaging the motor. This is useful when attempting to completely empty a tank or sump. They are not practical for use with unscreened wastewater or with sludge with a dry solids content higher that 8%.
- The impellors are designed to offer the free passage of solids, typically up to 40mm but larger sizes are available, although there is an efficiency penalty for this.

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Domestic Drainage Pumps

- In domestic situations, small drainage pumps are required to lift wastewater and drainage into the local sewerage collection network. These pumps are designed for domestic flow rates and power supplies, therefore they are typically sized for flows up to 4 l/s at 10 m head, and power ratings of less than 0.5 kW.
- Typically the pump and motor section form a pressure-tight encapsulated unit, fully flood-proof, with motor housing constructed from corrosion resistant material, and the outer jacket and impeller of durable plastics. The pumps have integral level controls which controls their operation.
- Many of the pumps have a check valve built into the outlet that prevents the wastewater flowing back into the sump.

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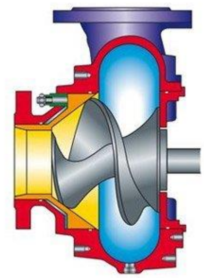
Paper and Pulp pumps

- Paper and pulp pumps are also considered to be in the scope, because although not connected with WWT, they do need to pump cooked pulp with up to 70% solids content. In addition it may be at a high temperature, and so requires abrasion and sometimes corrosion-resistant pumps. Paper manufacturing pumps must be versatile, durable and reliable as unexpected down time can be extremely costly on a large paper mill.
- In outward appearance they are much like standard clean cold water centrifugal pumps, but the big difference is in their impeller design. In order to deal with these demands the pumps are designed with Semi-Open, Full Vane Impeller with back pump-out vanes that prevents clogging. They also have large suction Inlets that facilitate inflow of stock, minimizes clogging, and prevents stock separation or dewatering.
- Available pump flow rates are typically available up to 10,000 m3/h with heads up to 100 m. The pumps are typically designed to operate at pressures up to 14 bar and temperatures up to 150°C.



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Progressing cavity pumps

Progressing cavity pumps can pump very high solid materials, well in excess of what is possible with rotodynamic pumps. They are typically used in the sludge treatment stages of a WWT works such as tank de-sludging and de-watering.

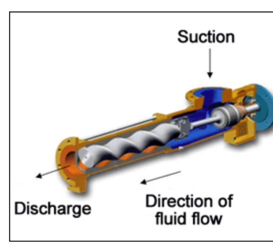
In a progressing cavity pump a single helix rotor revolves eccentrically within the double helix of the stator, a continuous cavity is formed and progresses towards the discharge end of the pump as the rotor rotates. The progressing cavity pump principle is ideal for handling slurries, sludge, viscous, shear sensitive or two or tri phase mixtures or when applications require, significant suction lift capabilities.

The large continuous cavities of progressing cavity pumps allow suspended solids to be handled with ease. The gentle pumping action also ensures that delicate solids that have to be kept intact are not damaged. The rolling action of the metal rotor within the resilient stator means any solids that become trapped are released quickly, reducing abrasive wear.

Progressing cavity pump is a self-priming pump with a suction lift up to 8.5m, and they can be installed vertically or horizontally.

The efficiency of the pumps is dependent on the quality of the seal between the rotor and the stator. 'Slip' is the term given to the process when liquid passes past the gap in the rotor and stator. The most common method of measuring efficiency in progressing cavity pumps is by volumetric efficiency. This is defined as the benchmark flow rate at zero m head minus the slip at the rated head. It is expressed as a percentage. The amount of slip a pump experiences is dependent on both the pressure and viscosity of the liquid.

Progressing cavity pumps are typically available in sizes up to 500 m^3/h and pressures up to 48 bar.



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Fountains & Garden pumps

- How much head do you want!?
- How much flow – can you fit a better nozzle?

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Pump Problems

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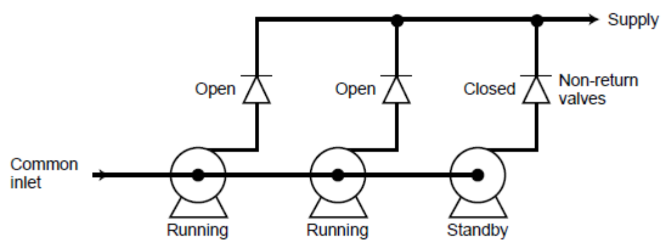
Jammed Non-returned Valve

- Valve that doesn't open properly will act as a throttle.
- Jammed open non-return valves mean water from one pump may return through an "off pump".



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Water hammer

- Symptom: Banging when the pump is turned off.
- Caused by: Sudden stopping of flow
- Will cause damage to pipe hangers and joints
- Solution: Controlled reduction of flow by variable speed or possibly soft starter

Gravelly noise

This is cavitation!

Solution: Increase the inlet pressure

- Lower inlet
- Reduce pump speed
- Cooler fluid

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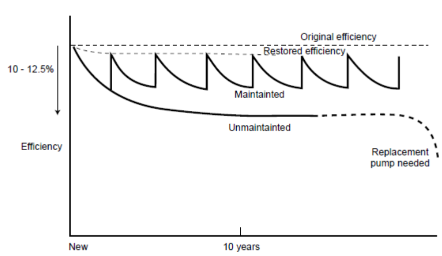
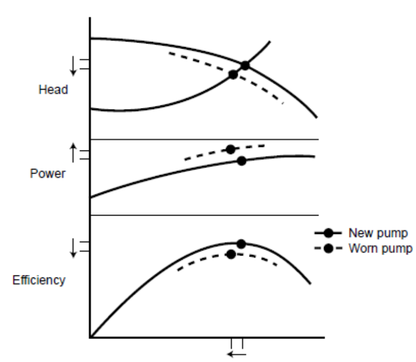
Pump Wear

Pumps lose efficiency over time, but this will usually go un-noticed

Pump efficiency monitoring useful on larger pumps for determining when to refurbish





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Blocked pumps

- Not a direct energy issue, but the call-out and clean-up costs are big.
- Proper specification of pump:
- Abrasiveness
- Stickiness
- Stringiness

Unfortunately there is NO standard, and so selection on custom and practice.

There is no one size fits all.

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Pump Operation

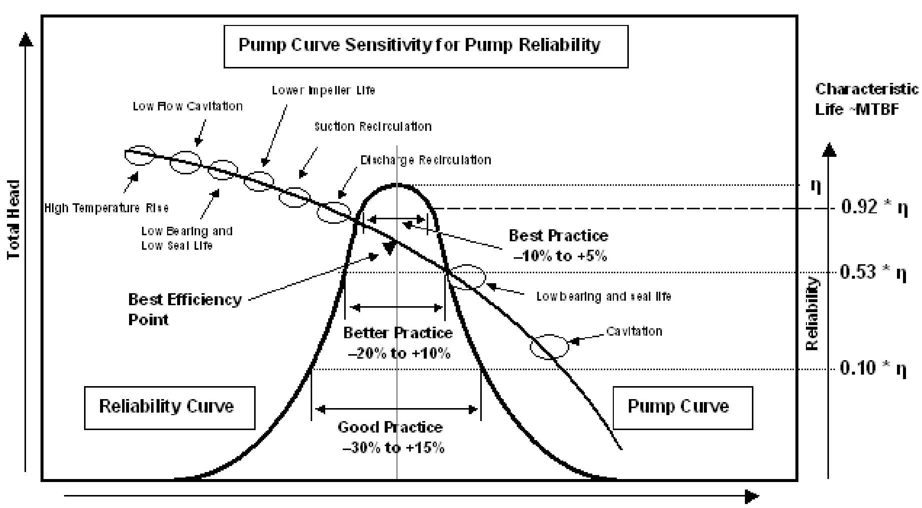

Figure Courtesy of P. Barringer.

Top 10 Energy saving opportunities

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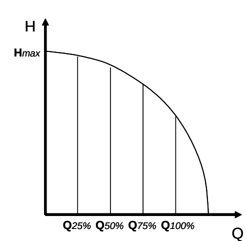
Building heating system

Building heating systems follow a standard demand: time profile. The total running hours vary with location.

A sealed circulation system, and so variable speed is an ideal solution.

Similarly with secondary cooling system loops

Flow (%)	Time (%)
100	6
75	15
50	35
25	44

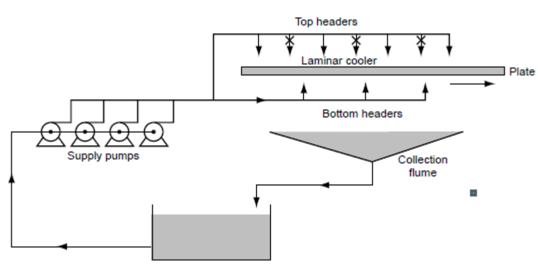


Swimming pool pumps

- Different countries have different regulations to ensure adequate water quality. Don't contravene these!
- Varying speeds to ensure minimum filtration rates under all circumstances recommended. May be 2 speed or Variable speed.
- Look for a good pump at replacement.
- Avoid over-sizing.

Steel mill laminar cooler

Control water flow to match instantaneous cooling requirements



Steel strip mill De-scaling pump

- Batch process with cyclical demand.
- Large pumps impractical to turn on and off very frequently
- Variable Speed drives allow smooth speed increase and decrease.

Corus, Llanwern, Wales

Aeration Blowers

- These should be sized "on the safe side" to ensure adequate water quality.
- But by monitoring the water quality for oxygen content, the amount of air added can be set to the absolute (but safe) minimum.
- A good option for VSDs.
- A lower cost option is pulley ratio changing.

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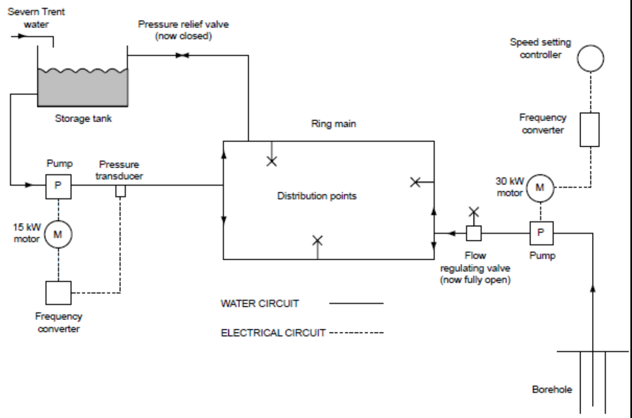
Water distribution system

VSD instead of recirculation system on header tank

VSD instead of throttle on borehold pump



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Hydraulic pump

Vary the pressure to match the instantaneous demand.

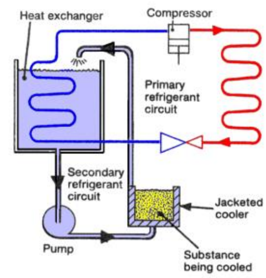
Eg Hydraulic presses or other hydraulic driven equipment.

Rexroth Variable Speed Hydraulic pump

VSD on refrigeration system

- Brewery cooler had 75kW pump operating under pressure regulator to bypass excess coolant.
- Replaced by VSD controlled by pressure transducer

UK EEBPP GPCS 124: Secondary refrigeration pumps at a brewery



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Lubricant Pump

- Can the pump be switched off when not being used?
- Use of VSDs to further vary flow when cutting

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Chiller control

- Air handling Units used 3 way valves to divert excess cold water back to the main chillers.
- Local thermostatic valves control zone temperatures, allowing pressure transducer to control speed of new VSD fitted to the pump
- UK EEBPP GPCS 89. Variable Speed Drives on chilling water pumps

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Pumps - The motor perspective

Contents

- Pump Basics
- Pump Control
- Time flow Profiles
- Other types of Pump
- Multiple Pump Configurations
- Pump Problems
- Top 10 Energy Saving Opportunities

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Thank you for listening

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5. Fan systems – A motor perspective

Hugh Falkner, Atkins

Spotting fan savings

Look for:

- Variable demand
- Changes in demand since system installed
- Old control technologies
- Poorly controlled systems

But it is harder to identify or resolve these other types of problems:

- Mis-specified fans (wrong size or type)
- System design problems (ducting, filters, etc)

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1. About Fans

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Physics of Centrifugal Fans

As the fan spins, the housing:

1. Collects air
2. Slows it down to recapture pressure
3. Provides direction to air leaving fan

Changing rotational speed changes ability of fan to do work

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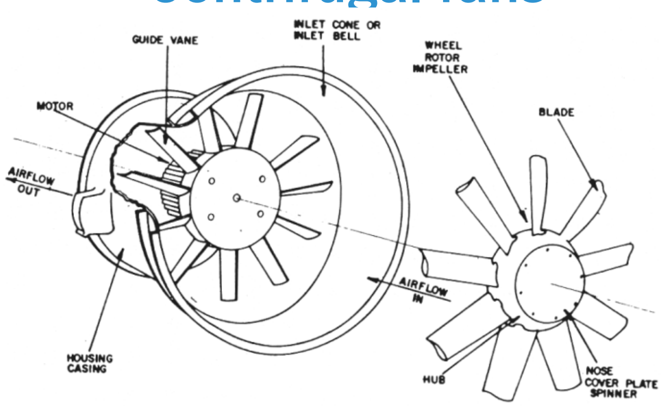
Why are fans shaped differently?

Performance is determined by many factors:

- Type of fan (blade shape)
- Diameter of the impeller
- Width of the impeller
- Rotational speed
- Density of the fluid

Centrifugal fans



Ashrae

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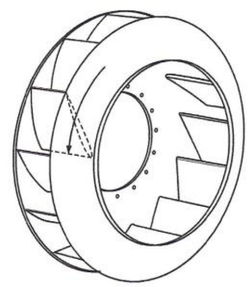
Aerofoil – Efficient but costly

Highest efficiency

Non-overloading

Hollow blades can fill with dust

Ideal for high velocity ventilation and supply systems



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Backward-Inclined

- Fairly good efficiency
- Can stall at low flows
- Blades weaker than backward-curved blade
- **Not as compact as forward bladed, but more efficient**

Fan Engineering Ltd

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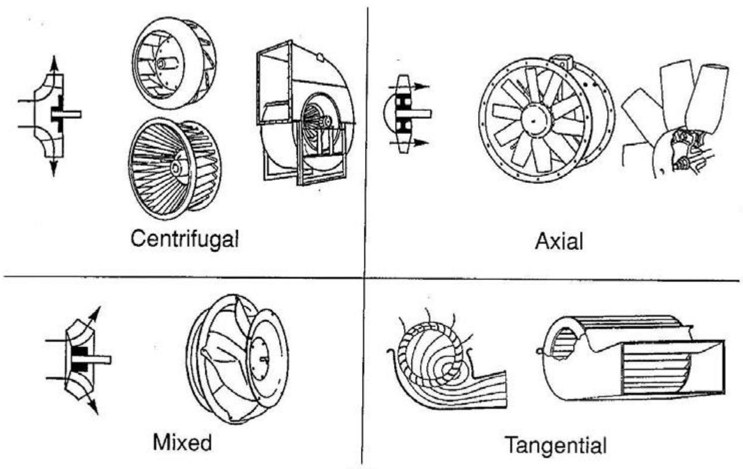
Types of fan



Typical Fan Efficiencies

Excludes housing.

A guide only!

Fan type		Fan total efficiency % (peak)
Centrifugal	Aerofoil	88
	Backward-curved	84
	Backward-inclined	80
	Forward-inclined	70
Axial	Vane-axial	85
	Tube-axial	75
	Propeller	55
Mixed-flow		75
Tangential		25

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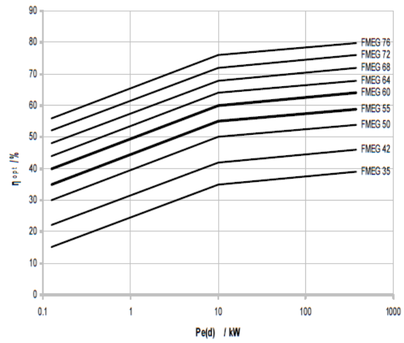
How does fan efficiency vary with size?

ISO12759: Categorisation scheme for centrifugal backwards bladed fan – now used as the basis of EUP regulations



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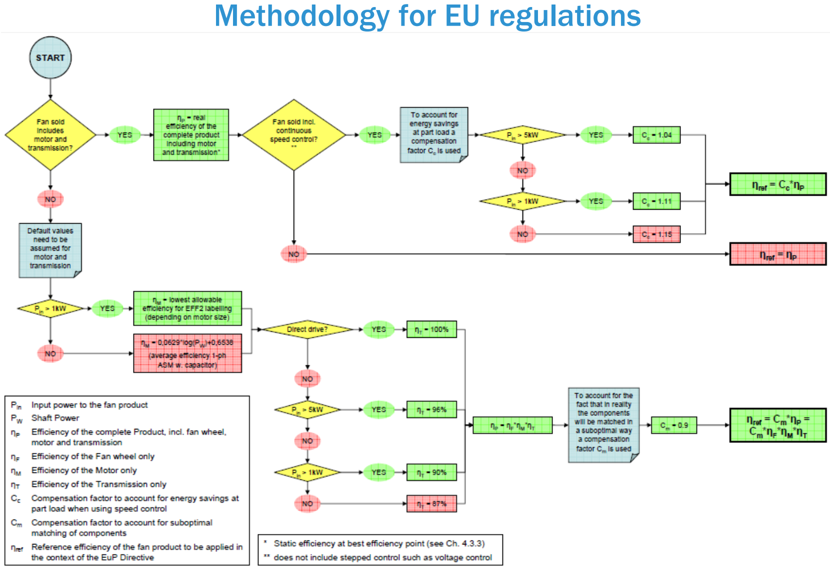
Methodology for EU regulations



Integrated fan:motors

High efficiency PM Variable Speed

EBM Papst fans

2. Fan Systems and Controls

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Fan Systems

- The most efficient flow of air into a fan is a non-restricted, uniform path.
- Elbows located directly on fan inlets increase losses and are to be avoided.
- Obstructions at fan inlets and outlets disrupt the flow, causing turbulence.
- Flex connections often cause poor transitions that disrupt flow.
- Circular ducting is better, but less compact

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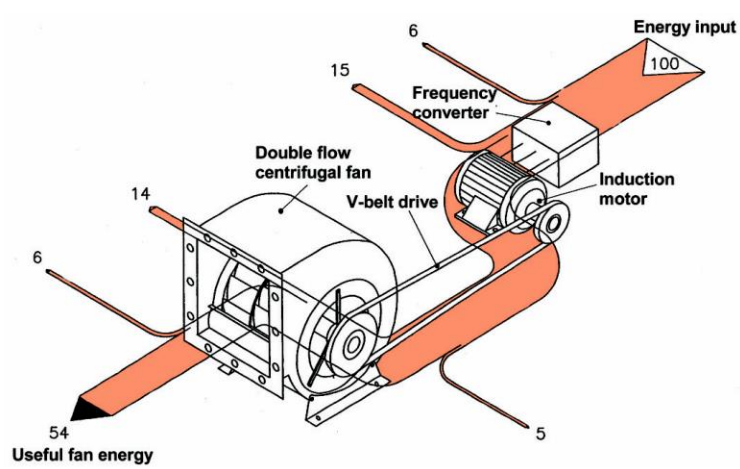
Energy flows in a fan system



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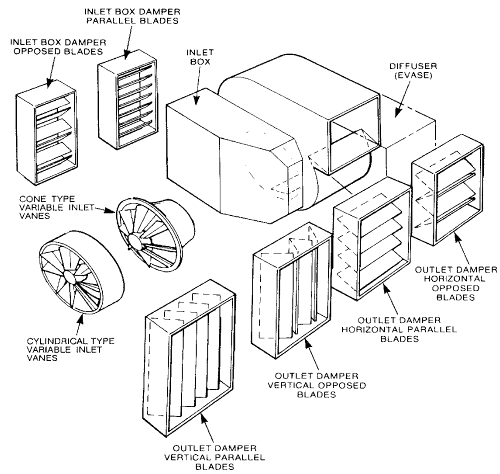
Fan Accessories

- All the extras cost more and increase power consumption!



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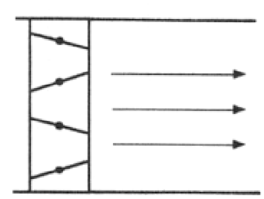
Damper Types

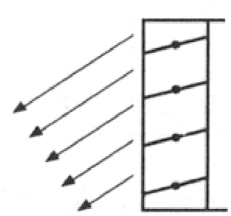
Opposed Blade

- Each blade rotates in opposite direction
- Produces uniform airflow and more stable control



Parallel Blade

- Can produce non-uniform airflow
- Lower energy efficiency



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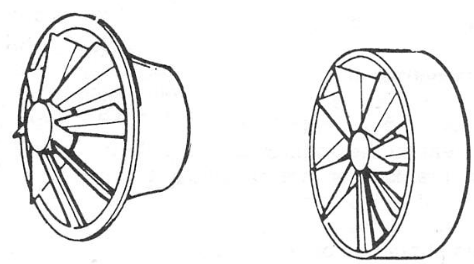
Damper Types – Variable Inlet Vane

- Pie-shaped blades
- Slightly more efficient
- Use to trim airflow down to 85%



CONE TYPE VARIABLE INLE VANES

CYLINDRICAL TYPE VARIABLE INLET VANES

Fan Dampers

- Designers tend to oversize fans for safety.
- The system then needs to be balanced (if it is) with dampers.
- A damper that is always mostly or partly closed in an indicator of a good optimization opportunity.

Location for dampers

- Inlet Louver Damper usual
- Outlet dampers much less efficient
- Or somewhere else in the system

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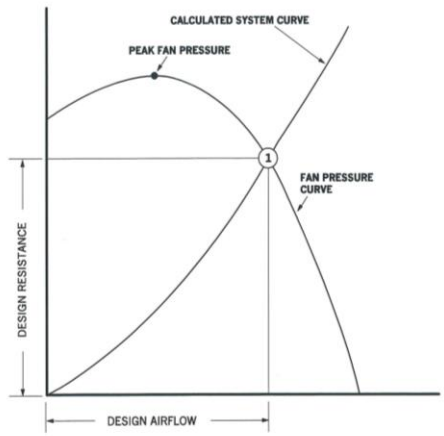
Fan and System Curve Interaction

- Fan operates on fan curve
- System operates on system curve
- The operating point is the intersection of the fan curve and the system curve



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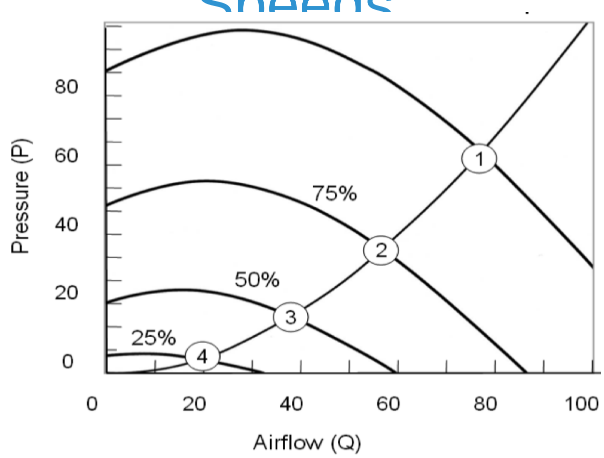
Fan Performance at Variable Speeds



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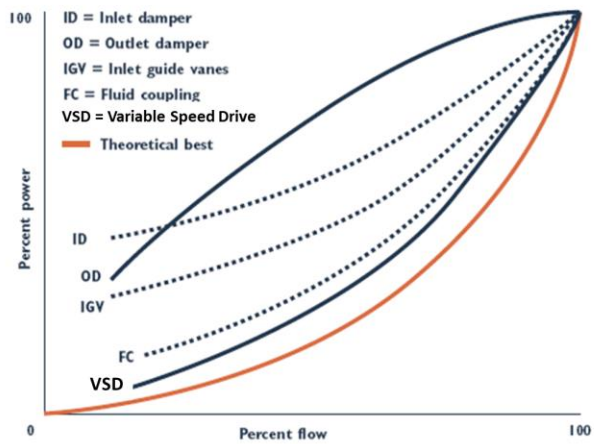
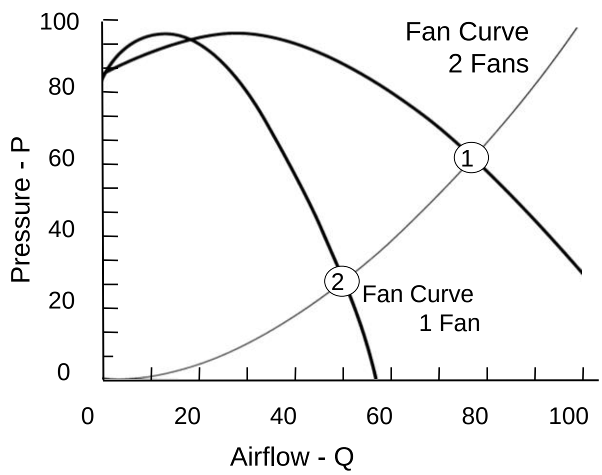
Fan systems



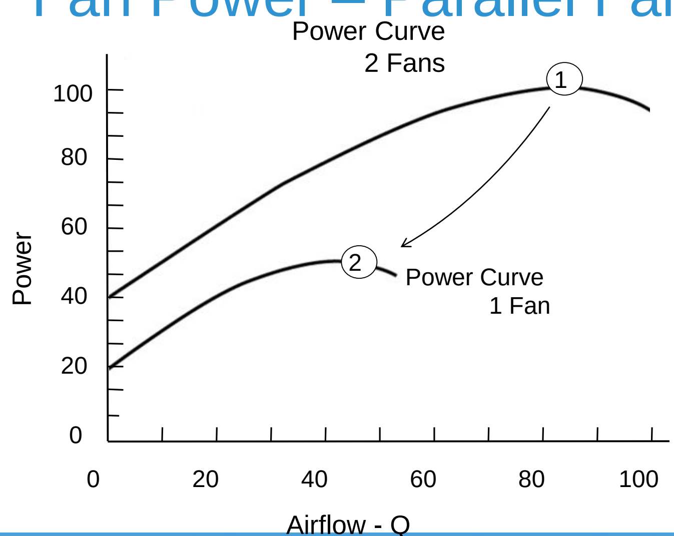
Other Speed Reduction techniques

- Alter the pulley ratio
- Ensure multiple belt assemblies are matched
- Use a Multiple speed or different speed motor

Fan Performance – Parallel Fans



Fan Power – Parallel Fans



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Maintenance Issues

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Preventive Fan System Maintenance

Part	Preventive Maintenance
Air filter	Create a filter changing schedule based on recent life cycle cost analysis.
Bearing	Grease
Belt drive	Replace, then properly adjust tension and alignment.
Damper	a. Grease and adjust linkages b. Verify correct operation: make sure it opens and closes when it should.
Electric supply	Maintain specified balance, voltage and power factor.
Impeller	Clean and balance.
Inlet cone	Inspect for wear. Verify alignment and spacing between cone and impeller is within factory specs.

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Some running problems

- Unbalance – perhaps due to sag if unused for long periods
- Shaft fan misalignment (where there is a coupling)
- Belt misalignment
- Eccentricity

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Fan starting – motor considerations

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Fan Starting

- Fans are a high inertia load
- At all times the motor torque must exceed the fan torque
- If starting in star, check there is sufficient torque at switchover time.
- Autotransformer starting gives 3-4 discrete voltages, hence smoother starting.
- Voltage important, as torque proportional to voltage squared.

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Fan starting and motor selection

- 18 seconds is a maximum suggested start time.
- If motor power is increased from 5 to 7.5kW, new starting time will be 11 seconds.
- Protection. Only the forward bladed centrifugal fan is likely to see overload condition.

Air temperature and density

- Because cold air is denser, warm air systems will take more power at start up.
- On furnaces the inlet draft fan may be larger than the outlet draft fan.

Example of UK temperature variation

-3°C 105kPa

20°C 101.3kPa

Difference in density is 12%

Example of cold start on a hot gas fan

75kW absorbed fan power at 325C.

Zero flow is 35% of rated fan flow by use of closed damper (small flow)

Starting: $75 \times \frac{325+273}{20+273} \times \frac{35}{100} = 53.4\text{kW}$

If fan started at 20C with open damper, then power would be (100/35 x 53.4kW) = 153.1kW

Important to take account of higher power when starting motors on air colder than design operating point.

3. Top 10 Fan Energy Saving Opportunities

A personal selection!

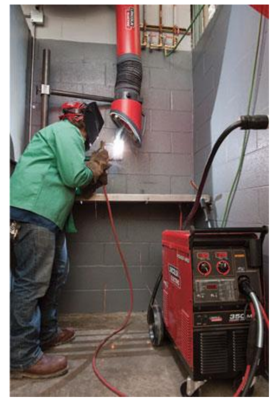
But first - some simple questions

- When are things switched off?
- How is the air pressure or speed controlled?
- What is the right air flow?

Fume extract Interlock

Interlocks on fume extract systems so that only on when in use.

- Welding booths – eg torch hook
- Fume Cupboard - switch



Lincoln Electric Welding

Aeration blowers

- Aeration blower
- Fit with VSD to adjust pressure to minimum

Spencer

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Machine Shop Isolation

- Fit automatic isolation dampers on ports of centralised extract system when machines not being used.
- Could use motor state sensors
- Can use VSDs to vary speed of fan to match total demand

W

Nor

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Domestic Ventilation

Its not the fan power, but the loss of heat that matters

- Does outdoor flap work properly?
- What speed, and for how long is it on?

Wickes, UK

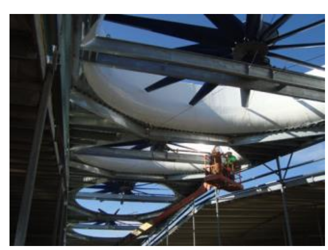
Whirlpool

Air quality Controls

- Carbon Monoxide detection – avoids having fan on all the time "just in case"
- Carbon Dioxide sensor – for demand led ventilation systems

Cooling Tower Fans

- Cooling power varies with load and temperature.
- Fit a VSD
- Also prolongs life of these high inertia loads and can avoid resonant frequencies.



Swifter Industrial Fan

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Dual purpose Ventilation / Emergency extract fans

- Increasingly common to save cost.
- Larger clearances reduce normal running efficiency
- If fitting a VSD, rating may be less than that needed for emergency extract.

WEG / Flakt-Woods

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Boiler Combustion Control

- Oxygen trim improves burner efficiency by saving fuel.
- But replacing damper drive with VSD control gives further fan power savings.
- Also use oxygen trim on kilns and furnaces.

Cleanboiler.org

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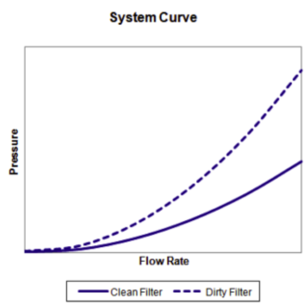
Baghouse fan

- Required air pressure less when filter is clean.
- Use a VSD to increase pressure only as bag becomes clogged.



Swimming pool ventilation fan

- Control ventilation to match demand
- Humidity sensors or day/night controls.

Etwall Leisure Centre, UK

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Any Questions?

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6. Air Compressors – the Motor perspective

Aims and Objectives

Understand the motor implications of compressed air systems.

Understand how to optimally select and control air compressors to meet actual requirements.

Understand how system problems will have a huge impact on motor running hours.

Learn to ask pertinent questions about compressed air systems as you walk around on a motor audit – you will never be lost for words and you will learn more about how the plant works!

Contents

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The Cost of Compressed Air

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Why Compressed Air offers rich pickings

- Most compressed air systems are initially designed with:

The assumption that "more" is better, where supply is concerned

Little or no thought given to system efficiency

No plan for increases or decreases in system demand

A "lowest first cost" goal

A demand very different from how things have evolved

And they need regular maintenance

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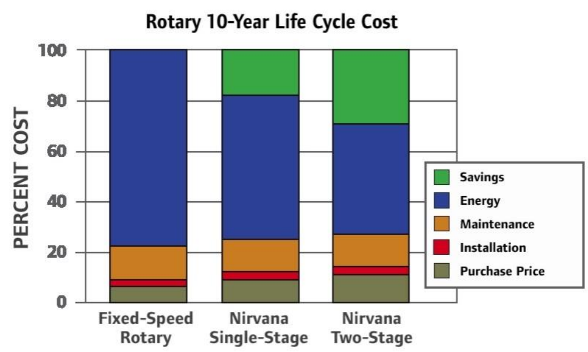
What's the delivered price of compressed air?

Per kWh

Based on an electricity cost of 40 Piasters/kWh

Air Compressor Life Cycle Costs

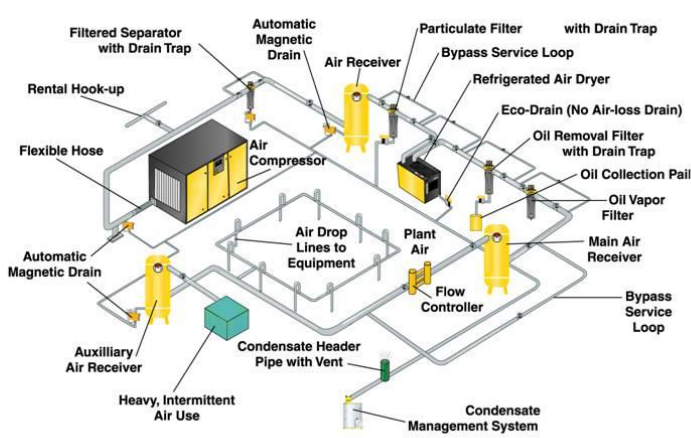


Rotary comparison at 70% average volume capacity; 4,000 hours per year; €0.05/kWh.

Ingersol Rand Nirvana Variable Speed Air Compressor

Compressed Air Systems

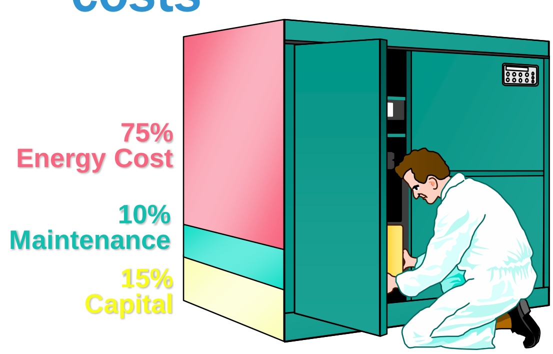
Typical Compressed Air System



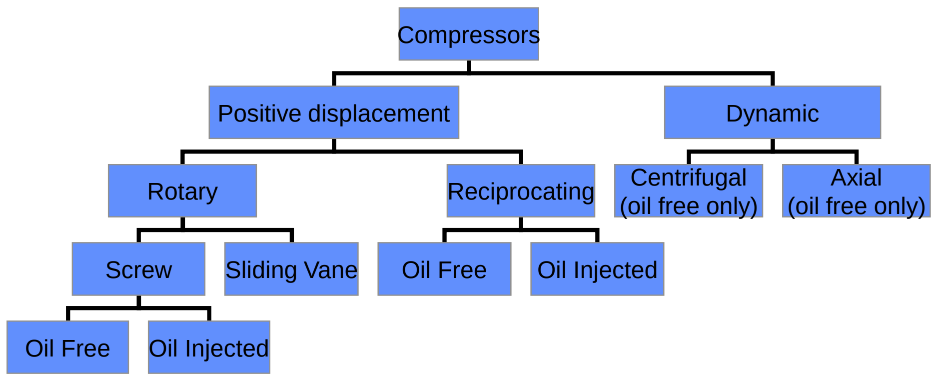
The Air Compressor

Compressor life cycle costs

"Where you pay for all the mistakes made elsewhere in the system"



The compressor family



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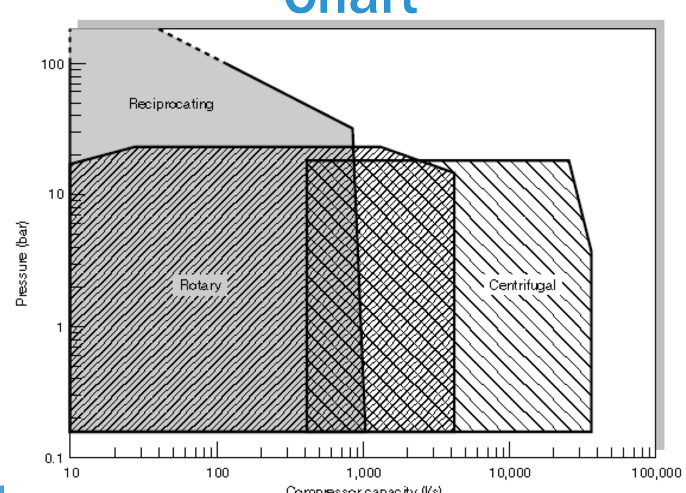
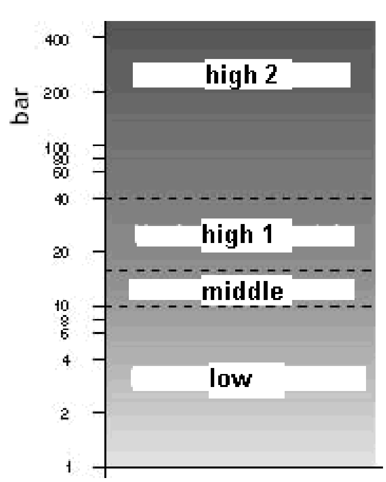
Industrial Air Compressor Range Chart



Range of efficiencies

Type	Range m3/h	SPC kW/100m^3/h	Part load efficiency
Lubricated piston	2-25	15-16	Good
	25-250	11-13.5	Good
	250-2500	10-11.5	Excellent
Oil injected screw	2-25	15-16	Poor
	25-250	11-13.5	Fair
	250-2500	10-11.5	Fair*
Oil free screw	25-250	12-15.3	Good
	250-2500	10-12.2	Good
Centrifugal	500-2500	11-13.5	Excellent**
	>2500	9.7-11	Excellent**

Pressure applications



High pressure 2: Leak testing, power stations and rolling plants, oxygen compression. Compressors:
3-4 stage piston compressors

High pressure 1: Pipe pressure testing, blow moulding of plastic containers. Compressor: 3-stage piston and screw compressors

Med. pressure: Heavy vehicle tyres, special machinery

Low pressure: Most applications in industry and trade lie within this pressure range. Compressor:
1-2 stage piston, screw and centrifugal compressors

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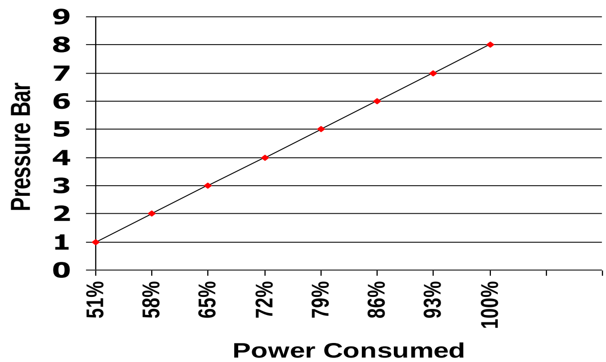
Reducing pressure - Reducing cost



"A reduction of 1 bar saves 6-7% in energy"

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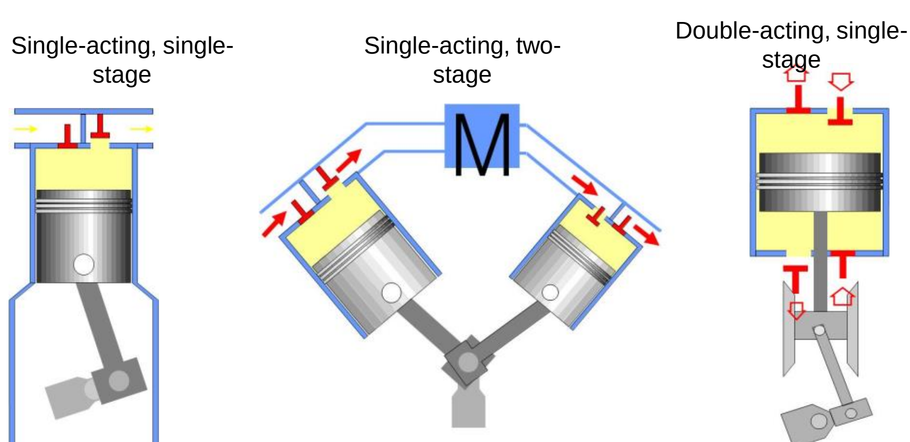
Reciprocating compressors



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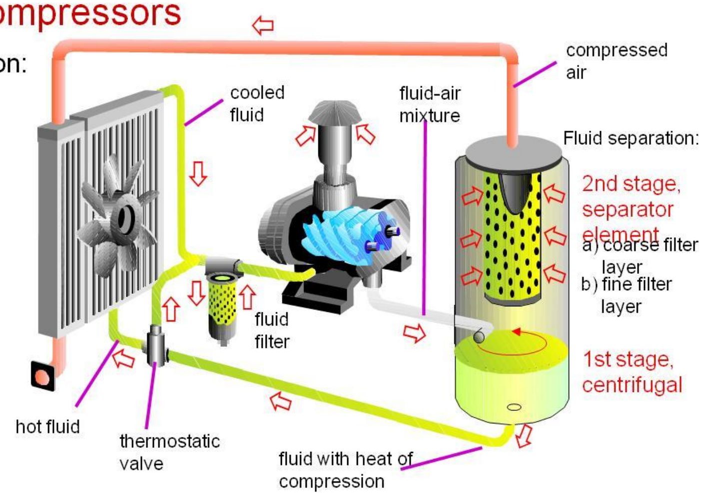
Compressed Air Systems

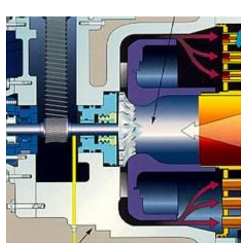
Screw compressors

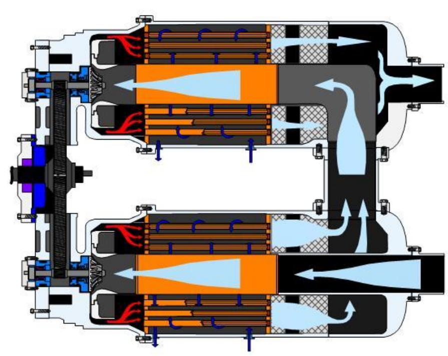
Construction:

Up to 85m³



Centrifugal turbo compressor





Characteristics:
Capacity: 35 - 1200 m^3/min
Stages: 1 - 6
Pressure range: 3 - 40 bar (g)
Speed range: 3000 - 80000 min^{-1}

Control of Air Compressors

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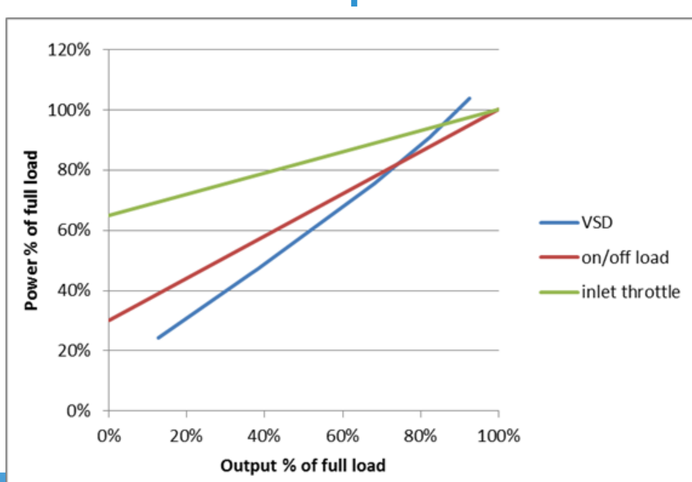
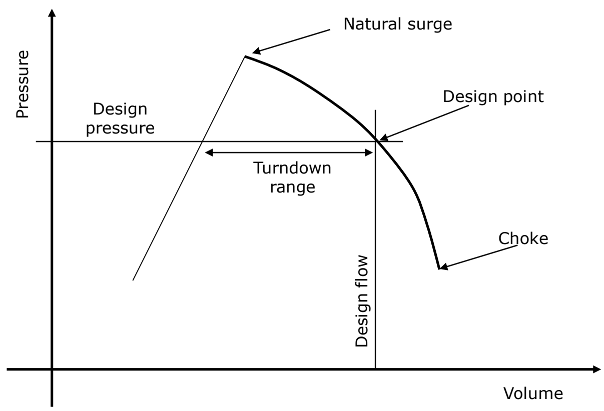
Control of Positive Displacement Air Compressors



Centrifugal Compressor Performance Characteristics



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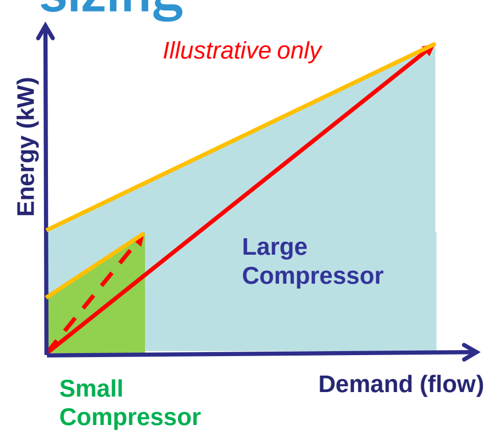
The importance of compressor sizing

A compressor at part load operation has a poor operating efficiency.

It is best practice to use a smaller compressor to satisfy low loads, despite its inherently lower full load efficiency.

The red lines show the Specific Energy Consumption, (SEC). The further the compressor is from this line, the worse the SEC.



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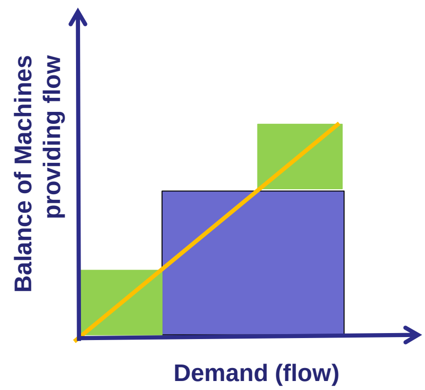
Multiple Compressor Sequencing

Air Compressors are switched in/out to match machines to demand

Ensures large machines not running for extended times at low load

A duty + standby large compressor and a single small compressor is a popular configuration



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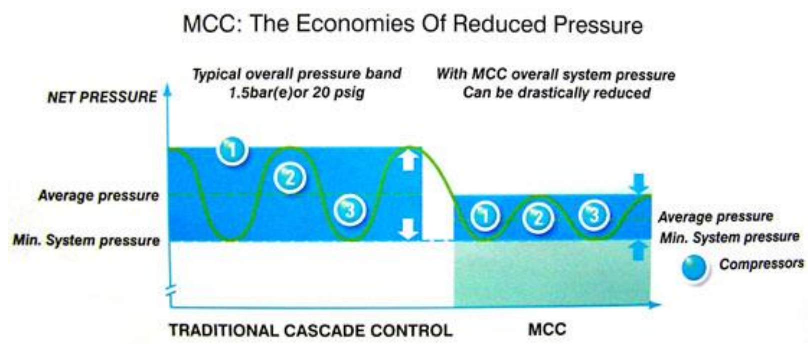
Controller Sequencer

- More stable pressure
- Less leakage
- Dual pressure set point
- Preferential use of better machines

Anglian Compressors

Multiple Compressor Controllers



Atlas Copco Electronikon Multiple Compressor Controller

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Variable Speed Control

Better part load performance

Close pressure tracking

No gearbox

BUT Higher full load energy consumption:

-Not suitable for base load supply

-Only one machine per system

Off load running of rotary machines

- Very small compressors can be switched on/off via a pressure switch.
- All others need to limit number of on/off switching intervals by using run-on timers. *Do not override these!*
- During off load running, no useful work being done and power consumption falls. Some machines switch the motor from delta to star.

Air Receivers

- Size to prevent compressor cycling too quickly
- Typical size in litres is 6-10 times compressor output in litres/second
- Ensure receivers are well drained, 50% full of water = 50% less air storage capacity
- Receivers can only absorb short duration peak flows

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Watch out for open drain valves!

An open valve to drain water can cost more each month than the cost of an automatic drain that prevents air loss.

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Heat Recovery

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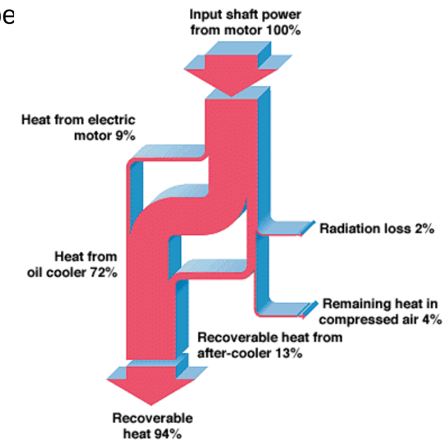
Heat recovery

On average 85% of input energy can be recovered for heating applications.

The possibility for heat recovery depends on:

- Heating demand of the factory
- Matching of compressor operation and heat demand
- Proximity of compressor station to heating distribution lines/consumers
- Temperatures



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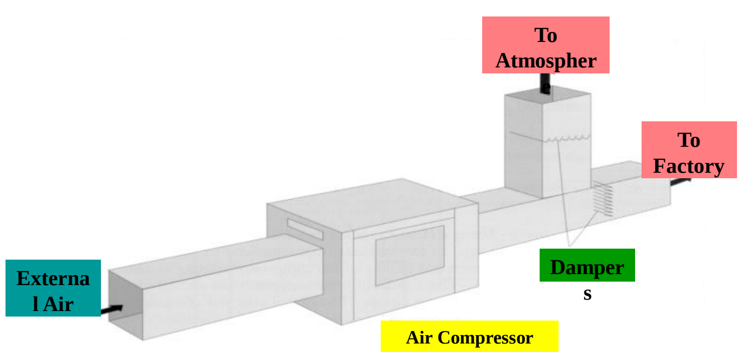
Hot air for space heating



NB Need a fire damper if going through fire walls

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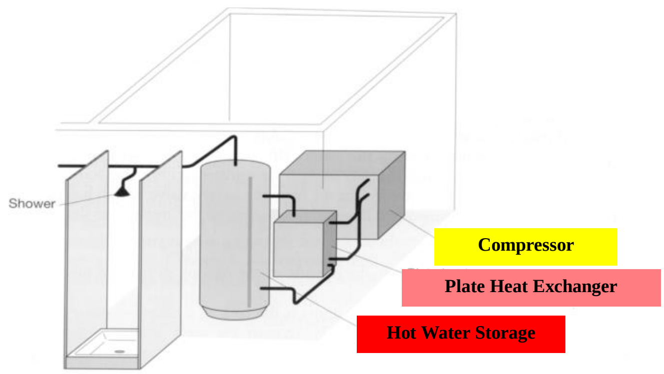
Using hot water from air coolers



Many compressors will have a factory hot water take off.

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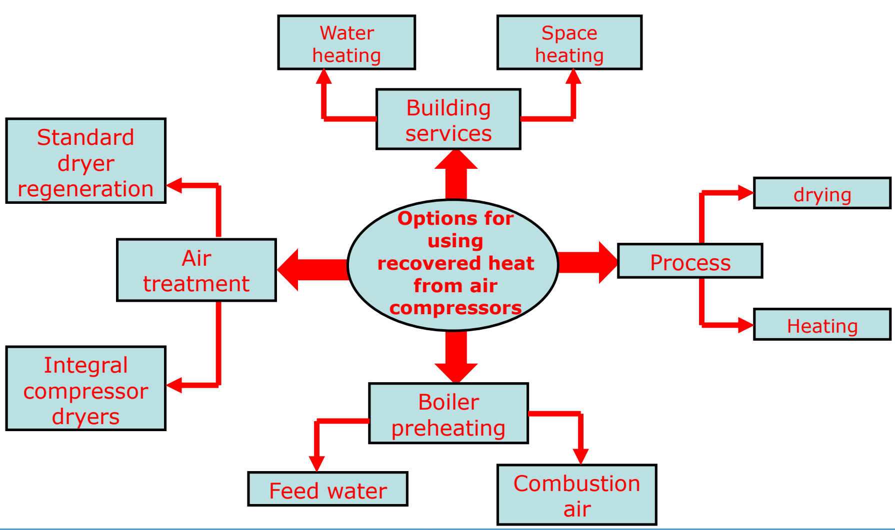
Options for heat recovery



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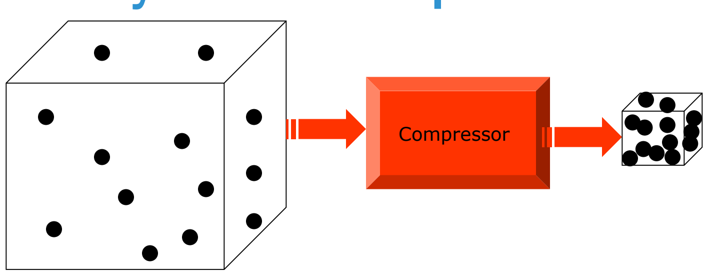
Treatment

Why Treat Compressed Air?



Compression concentrates impurities

In atmospheric air there are around 150 million dust particles/m^3
At 7 barg there are 1.2 billion dust particles/m^3

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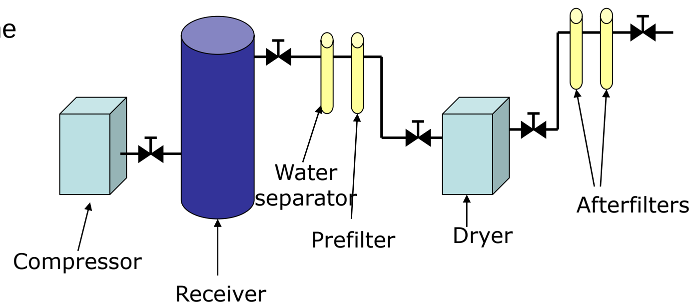
Treatment systems

Reduces water, dust and oil in the delivered air

Treat the main supply of air to minimum quality then upgrade at point of use where required



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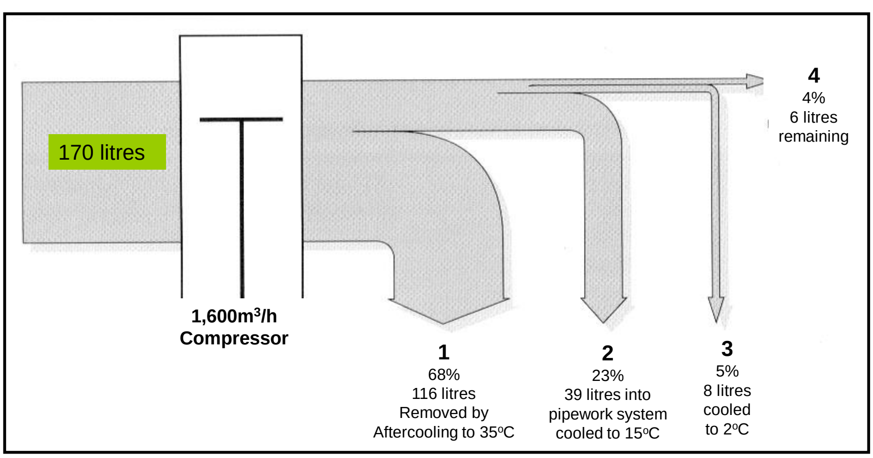
Condensate removal



All amounts are based on a single 8 hour shift

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Energy Implications of Compressed Air Treatment

Pressure dewpoint, C	Dryer type	Filtration	Typical additional cost
+3	Refrigerant	General purpose	2-3%
-20	Waste heat sorption	None	1%
-40	Air regenerated	Pre & After	15-18%
-40	Heat regenerated	Pre & After	12-18%
-70	Air regenerated	Pre & After	up to 25%

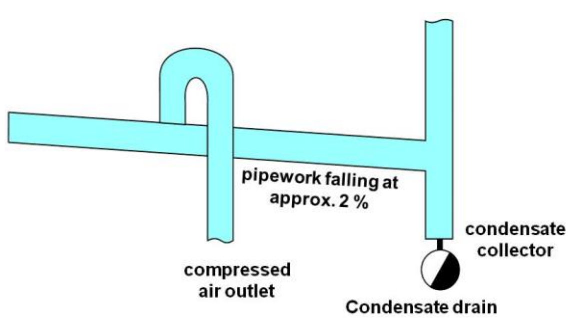
- Over sizing can significantly increase running costs
- Under sizing can give pressure drops and reduce performance of systems
- Consider energy conserving methods eg dewpoint control

Condensate separation

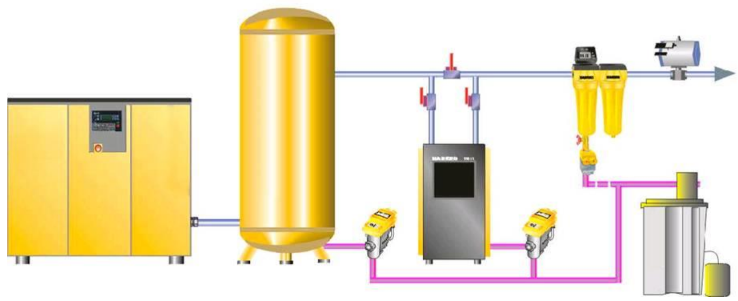
The compressed air discharged from the aftercooler of a compressor is normally 100% saturated with water vapor.

If the temperature of the compressed air falls, the water vapor condenses.

A coarse separation of the condensate can be achieved if the pipework and the compressed air outlets are installed as shown in the illustration.



Condensate drainage



Reliable drainage must be ensured at all condensate collecting points of the air main

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Zero loss condensate traps

Much more reliable than mechanical types.

Minimum time off compared to fixed timers

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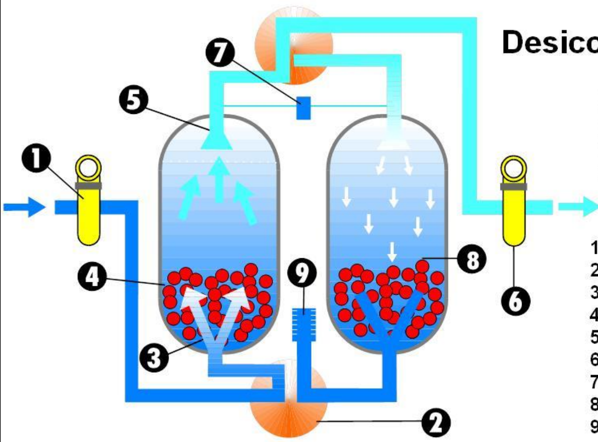
Compressed Air Systems



Desiccant drying - heatless

Application:

Systems subjected to freezing.
High ambient temperatures.
Extreme requirements of air quality.

1 microfilter (0.01 µm, 0.01 ppm)
2 changeover valve
3 flow diffuser
4 desiccant bed: moisture adsorption
5 outlet collector
6 particulate filter 1 µm
7 purge (regeneration) air valve
8 desiccant bed: regeneration
9 purge air exhaust silencer

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Treatment of compressed air

- Specify the minimum level you need at the compressor house
- Use point of use treatment for high quality, low demand areas
- Base the specification on ISO8573.1:2010
- Specify:
  - Particulate
  - Water (Pressure dewpoint)
  - Oil carry over
- Class 0 – 7 for each contaminant
- The higher the quality the higher the costs (capital & running costs)

Treatment – desiccant dryers

- Desiccant dryers can consume 15% of their rated throughput continuously
- Desiccant drying can add over 10% of the total generating cost over refrigerant drying
- Desiccant dryers should have dewpoint switching

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Demand side

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Distribution

- Remove the bottlenecks – don't just increase generation pressure
- Use local receivers & ring mains
- Increase feeding main sizes
- Don't develop a tubing jungle
- Consider zone isolations

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Machine isolation

Isolate air using production machinery when not being used

Use local solenoid valves operated by:

- No product flow sensing
- Isolation switches
- No operator (burglar alarm mats)
- Turning off the air with the lights when everyone goes home

Use similar methods for unused zones

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Misuses of compressed air

- Cleaning
- Component ejection
- Ventilation - cooling of people & products
- Agitation of paint or cleaning baths
- Moving product around bends or on conveyors
- Keeping product in line
- Using air at higher pressures than necessary
- Vacuum generation on large scale

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Misuses of Air

- Energy saving improvements can lead to process improvements
- Can a dedicated small compressor be used in non-production hours and turnoff the main compressors?
- Can a lower pressure compressor be used for some duties such as powder conveying?

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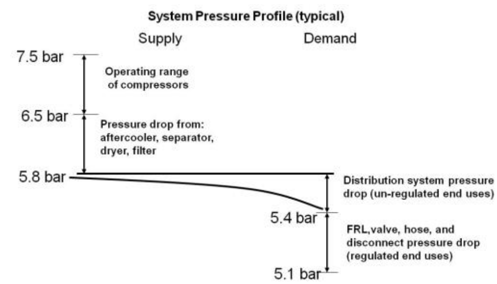
Pressure losses

- Pressure loss due to:
  - Excessive filtration
  - Small bore tubing or kinks
  - Small fittings causing local restrictions



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Blowing

- Use intensifying nozzles (can save 40%)
  - For product ejection
  - For cooling
- Quieter can overcome area noise issues
- Use air knives at reduced pressure
- Use fans
- Use low pressure blow guns that are safer and quieter

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Leakage

Cost of leakage

Hole diameter	Air consumption at 6 bar (g) m^3/min	Loss kW
1 mm	0.065	0.3
2 mm	0.240	1.7
4 mm	0.980	6.5
6 mm	2.120	12.0

* Electricity costs: $0.10 USD /kWh
Service hours: 8000 h/year
Does not include kVA or fixed service charge

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Leak demand

Compressed air leaks are expensive and can represent 20% to 50% of all air demand.

Non-production air demand can be measured, calculated from compressor load cycles, or calculated based on pressure drawdown rates. After subtracting residual valid air demands, the system leakage can be estimated.

Artificial Demand is a component of leakage, as well as any unregulated air demand. If leaks are repaired and system pressure is allowed to increase, the leakage repaired can be consumed by artificial demand. Controlling and/or reducing system pressure will minimize the amount of loss to artificial demand.

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Common sources of leaks

- Filter, Regulator, Lubricator
- Manual Drain Valves
- Quick Disconnect (QD) fittings
- Hose clamps
- Push-on Hose fittings
- Cut or Punctured Hose
- Pipe fittings
- Pipe Unions
- Flange Gaskets
- Old Rusted Piping
- Pneumatic Cylinder Rod Packing
- Pneumatic Cylinder Body
- Directional Control Valves
- Valve Pilot Lines and Ports
- Valve Stems and Packing

Prevention of leaks

Isolate compressed air lines and pneumatic equipment from sources of physical damage, heat, and vibration.

Establish piping practice and equipment connection standards, which provide for strong and durable connection to the compressed air system.

Avoid use of plastic tubing, and push-on connectors.

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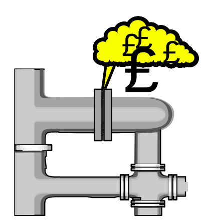
Leakage

- Conduct leakage rate test no load running decay time or data logging
- Should not be more than 10% of the mean production demand in a normal factory
- Can be up to 20% for large sites, over 80% measured on occasion
- Leaks come back but seldom in the same place
- Regular on going leakage campaigns must be conducted



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Leakage Detection

- By ear:
  - Very effective during quiet hours
- Using soapy water:
  - Tried and trusted, time consuming but sometimes the only way
- Ultrasound
  - Very effective even in high background noise areas

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Review

- The Cost of Compressed Air
- The Air Compressor
- Control of Air Compressors
- Heat Recovery
- Treatment
- Demand side
- Leakage

7. Selling it – How to win approval for your idea

USER: Motor System Optimisation Training

An Opportunity you can't refuse?

- Why wouldn't you invest in the motor energy saving scheme being offered by the presenter?

Selling It! Contents

- Identifying with your audience
- Worked Examples
- Are the financials convincing?

Why good projects don't happen

- Energy Efficiency is perceived as:
  - Discretionary
  - Less important because small scale
  - Technically risky
  - Optional, as no legal drivers

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What do Decision Makers want to see?

- Some common problems:

- Using unexplained jargon or ambiguous terms.
- Failing to address any issues of relevance to the board.
- Failing to consider other options.
- Failing to identify and deal with risk factors.
- Not using the appropriate financial appraisal method.
- Giving a rambling presentation.
- Not giving a single clear recommendation.

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Understand the audience

- Who are you trying to influence?
- What are they interested in?
- What are their motivations?
- How do you need to present information to them?
- Can you engage their interest early on?

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Can you find senior level support?

- Help you understand the decision makers' perspectives.
- Steer you away from options compromised. by factors you are not privy to.
- Be your ambassador during the development of the project proposal.
- Act as an advocate in the presentation.

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Be Credible

- Evaluate projects diligently and never promote something you are unsure of.
- Never make exaggerated claims.
- Try to leave yourself headroom to deliver more than you promised.
- When you get approval for something, implement it without delay and do everything you can to ensure its success.
- Make sure people know what you have achieved, and keep it all on record.
- Keep up with the news. You want to be seen as the person in the organisation that knows about the world energy situation, the state of play with emissions trading schemes, the outlook for prices and so on. Let your superiors treat you as an authority on the subject.

Project Projections

- Your data must be robust
- Crosscheck where possible
- Check assumptions are reasonable
- Leave headroom for the unexpected
- Take up references from other users of the technology
- Check the view on forward fuel prices

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Look for other benefits

- Reduced maintenance
- Free up supply capacity
- Improved quality
- Better environmental conditions
- Customers may value a reduction of carbon footprint
- Good publicity

The IEA "Flower of Secondary Benefits"

Is the price right?

- Get several quotes
- Check what assumptions are being made
- Allow for the cost of downtime
- Is an independent assessment worthwhile

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Financing

- Capital budget – when is this considered?
- Revenue – is it small and quick enough payback?

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Calculatin Net Present Value

Years	Present value of £1,000
0	£1,000
1	£909.09
2	£826.45
3	£751.31
4	£683.01
5	£620.92

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Risk

- Technical
- Cost
- Time to install and commission
- Economics

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Other risks

- Closure or relocation of the business
- Redundancies or outsourcing
- Takeover of the business
- Change of product mix
- Entering into an energy services contract

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Plan for Objections

- **We are not convinced because…**
- …the problem is not clear
- …we don't understand your solution
- …there is no evidence it would work
- …we disagree with your assumptions.
- **We like the project, but…**
- …installing it sounds like it would be disruptive
- …we are not sure how long we are going to retain this building/process/equipment
- …the workforce would not accept it
- …we do not have any money available to fund the project
- …the necessary staff resources are needed for other work
- …one of us has got a better idea
- …why haven't you done anything about this issue before?

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Financial assumptions

- Is sensitivity analysis needed on any of these?
- Fuel price Inflation
- Plant throughput
- Project cost
- Taxation
- Maintenance costs
- Project Lifetime

Bundling of Projects

- Critical to project funding!
- - Sell individually
- - Sell as a bundle

Writing a proposal

- Create a template that fits with your organisation's style, but it should include the following clear sections:
- Financials
- Other benefits
- Risks
- Next Steps

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Selling It! - Summary

- Put yourself in their shoes – would you invest in your proposal?
- What other benefits can you sell?
- Is your proposal succinct, and does it address risks?
- Have you portrayed the financing in the best way?
- Are you credible?

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Thank you

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8. Power Quality

Anibal T. De Almeida

Day 2

Discussed topics

- Voltage levels
- Voltage unbalance
- Power factor
- Harmonics

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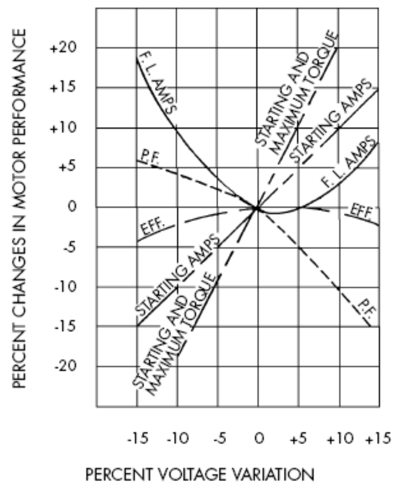
Power Quality

1. Maintain Voltage Levels

When operating at less than 95% of design voltage, motors typically lose 2 to 4 points of efficiency. Running a motor above its design voltage also reduces power factor and efficiency



Voltage Variation Effect on Motor Performance

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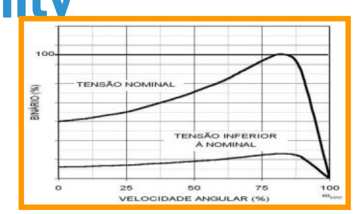
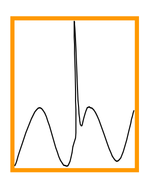
Power Quality



VOLTAGE AMPLITUDE REDUCTION

EFFECTS: EFFICENCY REDUCTION, TORQUE-SPEED CHANGE, MOTOR LIFETIME REDUCTION IF THEY ARE OPERATING AT FULL-LOAD.



VOLTAGE TRANSIENTS

EFFECTS: LIFETIME REDUCTION DUE TO VOLTAGE STRESS AND PARTIAL DISCHARGE.

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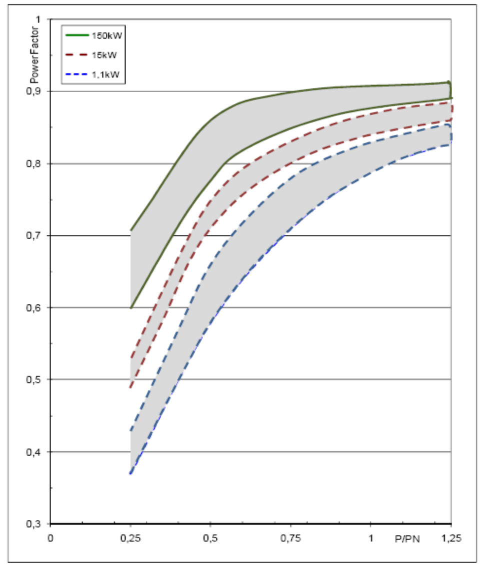
Power Quality

2. Maintain High Power Factor
Low power factor reduces the efficiency of the electrical distribution system both within and outside of your facility. Low power factor results when induction motors are operated at less than full load.



Typical Power Factor versus Load
Source: IEC 60034-31

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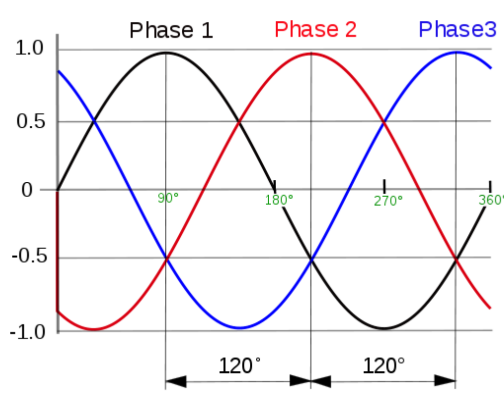
Power Quality

Balanced system

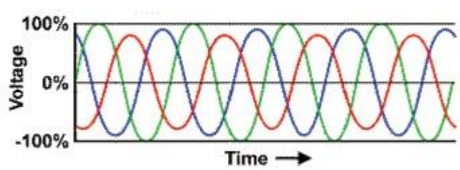


Voltage unbalance

Definition

Voltage unbalance (VU) is given by:

$$\%VU = \frac{max.\,voltage\ deviation\ from\ the\ avg.\,voltage}{avg.\,voltage} \times 100$$



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Example

L1 = 600 V

L2 = 585 V

L3 = 609 V

$$Average\ Voltage = \frac{600 + 585 + 609}{3} = 598\ \mathrm{V}$$

$$Max.\,deviation\ from\ avg. = 598 - 585 = 13\ V$$

$$\boldsymbol{Voltage\ Unbalance = \frac{13}{598} \times 100 = 2,17\%}$$

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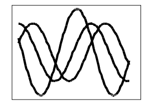
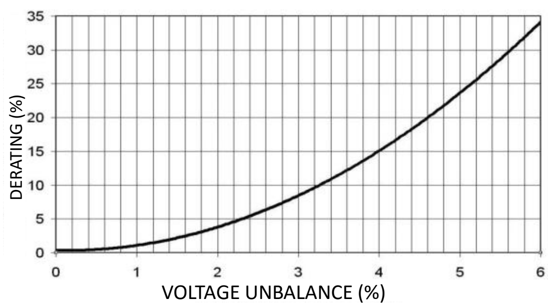
Power Quality

3. **Minimize Phase Unbalance**

   An unbalanced system increases distribution system losses and reduces motor efficiency.





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Exercise

- Assume a 100 kW motor operated at 75 % load, 8000 hours per year at a 2,5% voltage unbalance

Motor Efficiency* Under Conditions of Voltage Unbalance

Motor Load % of Full	Motor Efficiency, % Voltage Unbalance		
	Nominal	1%	2.5%
100	94.4	94.4	93.0
75	95.2	95.1	93.9
50	96.1	95.5	94.1

- Calculate the savings if corrective action was taken

Exercise

Savings = 100 x 0,75 x 8000 x (1/0,939 – 1/0,952) =
= 9000 kWh

Effects of High Harmonic Levels

- poor power factor, i.e. high current for a given power,
- interference to equipment which is sensitive to voltage waveform,
- excessive heating of neutral conductors (single-phase loads only),
- excessive heating of induction motors,
- high acoustic noise from transformers, busbars, switchgear and so on,
- excessive heating of transformers and associated equipment, and
- damage to power factor correction capacitors.

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Types of Harmonics

- Negative Sequence – 5th, 11th, 17th…
- Positive Sequence - 7th, 13th, 19th..

In unbalanced systems with neutral conductor

- Triplet (homopolar)-3rd, 6th, 9th…

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Power Quality

Voltage distortion can be quantified by:

Harmonic Voltage Factor **HVF** or Total Harmonic Distortion, **THD**:

$$HVF = \sqrt{\sum_{n=5}^{n=\infty} \frac{V_n^2}{n}}$$

$$THD = \frac{\sqrt{\sum_{k=2}^{n} V_k^2}}{V_{RMS}}$$

CAUSES: VSDs, rectifiers, voltage controllers, variable impedance loads, saturated core load (transformers).

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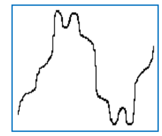
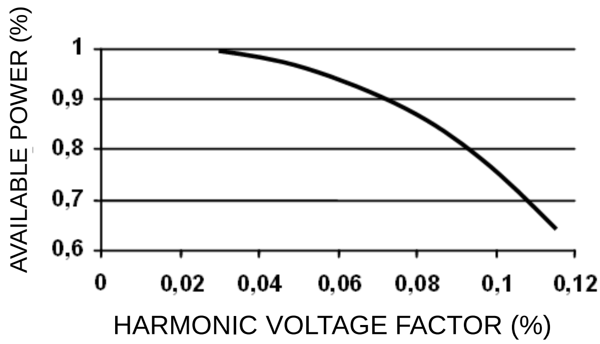
Power Quality



4. **Maintain Good Power Quality**

   Using power with distorted wave forms will degrade motor efficiency.



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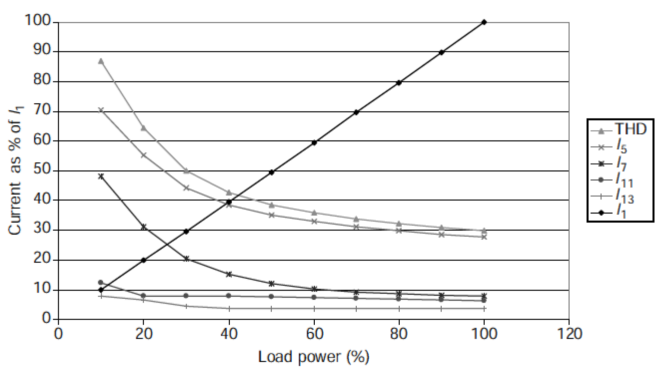
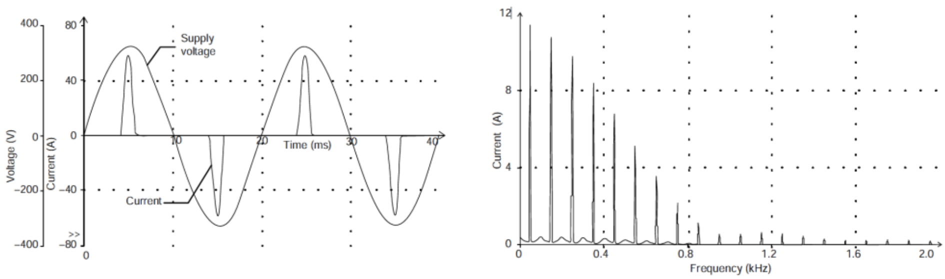
Harmonics vs. Load



Variation of input current harmonics and THD as a percentage of fundamental current with variation of load power for an a.c. drive

Harmonic Generation within VSDs



Typical input current waveform for a 1.5 kW single-phase drive (with supply voltage) and corresponding harmonic spectrum

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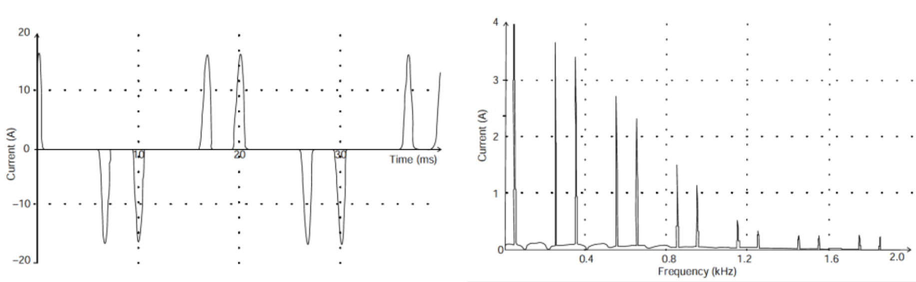
Harmonic Generation within VSDs



Typical input current waveform for a 1.5 kW three-phase drive (with supply voltage) and corresponding harmonic spectrum

Remedial Techniques

Connect the equipment to a point with a high fault level (low impedance)

When planning a new installation, there is often a choice of connection point. The harmonic voltage caused by a given harmonic current is proportional to the system source impedance (inversely proportional to fault level). For example, distorting loads can be connected to main busbars rather than downstream of long cables shared with other equipment.

Remedial Techniques

Use three-phase drives where possible

Harmonic current for a three-phase drive of given power rating is about 30 per cent of that for a single-phase drive, and there is no neutral current. If the existing harmonics are primarily caused by single-phase loads, the dominant 5^{th} and 7^{th} harmonics are also reduced by three-phase drives.

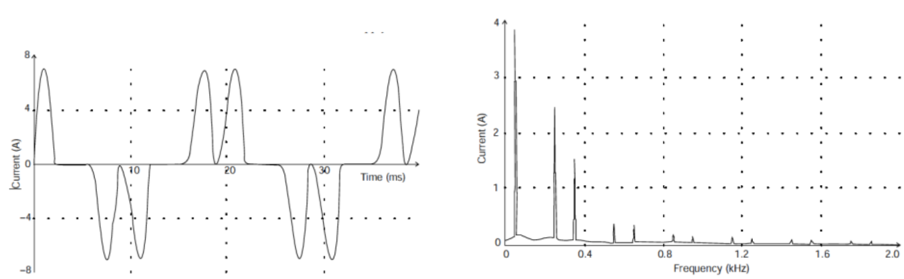
Remedial Techniques

Use additional inductance

Series inductance at the drive input gives a useful reduction in harmonic current. The benefit is greatest for small drives where there is no d.c. inductance internally, but useful reductions can also be obtained with large drives.

Remedial Techniques

Use additional inductance



Typical input current waveform for a 1.5 kW three-phase drive (with supply voltage) and corresponding harmonic spectrum, with 2 per cent input inductors

Remedial Techniques

Use a lower value of d.c. smoothing capacitance

For a three-phase rectifier, the capacitance value can be much reduced provided that the inverter is adapted to compensate for the resulting voltage ripple. The input current waveform is then improved and tends towards the ‘ideal’ case with a large d.c. inductance, where the current is approximately constant during the 120° conduction period.

Remedial Techniques

Use a higher pulse number (12 pulse or higher)

- Standard three-phase drives rated up to about 200 kW use six-pulse rectifiers. 12-pulse rectifier eliminates the crucial 5th and 7th harmonics (except for a small residue caused by imperfect balance of the rectifier groups). Higher pulse numbers are possible if necessary, the lowest harmonic for a pulse number *p* being (p–1).

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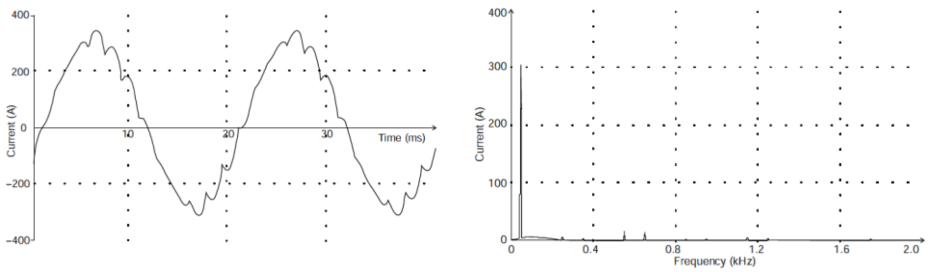
Remedial Techniques

Use a higher pulse number (12 pulse or higher)



Input current waveform for 150 kW drive with 12-pulse rectifier and corresponding harmonic spectrum

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Remedial Techniques

Use a drive with an active input converter

An active input converter using PWM generates negligible harmonic current, as well as permitting the return of power from the load to the supply.

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Remedial Techniques

Use a harmonic filter

Harmonic filters are built using an array of capacitors, inductors, and resistors that deflect harmonic currents to the ground. Each harmonic filter could contain many such elements, each of which is used to deflect harmonics of a specific frequency.

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Harmonic current levels for AC Drive arrangements

	Harmonic current as percentage of fundamental					
	I_3	I_5	I_7	I_{11}	I_{13}	I_{THD}
Single-phase, no inductance	97	91	83	62	51	206
Single-phase, 2% inductance	90	72	50	13	6	130
Three-phase, no inductance	0[a]	49.6	28.2	6.6	6.0	58
Three-phase, 3% inductance	0[a]	35.0	12.2	7.4	3.9	38
12-pulse	0[a]	1.8	0.6	4.5	3.1	5.8
Active input converter	0[a]	1.4	0.3	0.5	0.2	3.3

[a]For a balanced supply.

Power Quality

5. **Select Efficient Transformers**

   Install efficient and properly sized step-down transformers. Older, underloaded, or overloaded transformers are often inefficient.

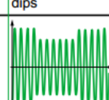
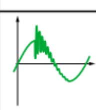
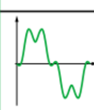
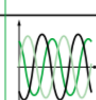
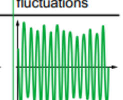
6. **Identify and Eliminate Distribution System Losses**

   Regularly check for bad connections, poor grounding, and shorts to ground. Such problems are common sources of energy losses, hazardous, and reduce system reliability.

7. **Minimize Distribution System Resistance**

   Power cables that supply motors running near full load for many hours should be properly sized in new construction or during rewiring. This practice minimizes line losses and voltage drops.

Power Quality

Disturbances	Voltage dips	Overvoltages	Harmonics	Unbalance	Voltage fluctuations
Characteristic waveforms					
Origin of disturbance					
■ **Power system**					
□ Insulation fault, break of the neutral conductor...	Occasional			Occasional	
□ Switching, ferroresonance		Occasional			
□ Lightning		Occasional			
■ **Equipment**					
□ Asynchronous motor	Occasional				
□ Synchronous motor	Occasional		Frequent		
□ Welding machine	Occasional		Frequent	Frequent	Frequent
□ Arc furnace	Occasional		Frequent	Frequent	Frequent
□ Converter		Frequent	Frequent		
□ Data processing loads			Frequent		
□ Lighting			Frequent		
□ Inverter			Frequent		
□ Capacitor bank	Occasional	Frequent	Frequent		Occasional

: Occasional phenomenon (light green) : Frequent phenomenon (dark grey)

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Power Quality

Type of disturbance	Origins	Consequences	Examples of mitigation solutions (special equipment and modifications)
Voltage variations and fluctuations	Large load variations (welding machines, arc furnaces, etc.).	Fluctuation in the luminance of lamps (flicker).	Electromechanical reactive power compensator, real time reactive compensator, series electronic conditioner, tap changer.
Voltage dips	Short-circuit, switching of large loads (motor starting, etc.).	Disturbance or shutdown of process: loss of data, incorrect data, opening of contactors, locking of drives, slowdown or stalling of motors, extinguishing of discharge lamps.	UPS, real time reactive compensator, dynamic electronic voltage regulator, soft starter, series electronic conditioner. Increase the short-circuit power (Scc). Modify the discrimination of protective devices.
Interruptions	Short-circuit, overloads, maintenance, unwanted tripping.		UPS, mechanical source transfer, static transfer swtich, zero-time set, shunt circuit breaker, remote management.
Harmonics	Non-linear loads (adjustable speed drives, arc furnaces, welding machines, discharge lamps, fluorescent tubes, etc.).	Overloads (of neutral conductor, sources, etc.), unwanted tripping, accelerated ageing, degradation of energy efficiency, loss of productivity.	Anti-harmonic choke, passive or active filter, hybrid filter, line choke. Increase the Scc. Contain polluting loads. Derate the equipment.
Inter-harmonics	Fluctuating loads (arc furnaces, welding machines, etc.), frequency inverters.	Interruption of metering signals, flicker.	Series reactance.
Transient overvoltages	Operation of switchgear and capacitors, lightning.	Locking of drives, unwanted tripping, destruction of switchgear, fire, operating losses.	Surge arrester, surge diverter, controlled switching, pre-insertion resistor, line chokes, static automatic compensator.
Voltage unbalance	Unbalanced loads (large single-phase loads, etc.).	Inverse motor torque (vibration) and overheating of asynchronous machines.	Balance the loads. Shunt electronic compensator, dynamic electronic voltage regulator. Increase the Scc.

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Power Quality Costs

Direct costs

- Damage in the equipment
- Loss of production and raw material
- Salary costs during non-productive period
- Restarting costs

Indirect costs

- Inability to accomplish deadlines
- Loss of future orders

Non-material inconvenience

- Inconveniences that cannot be expressed in money, such as not listening to the radio or watch TV

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Power Quality Costs

- **Business Week (1991)** - 26,000 million USD per year in the United States
- **EPRI (1994)** - 400,000 million USD per year in the United States.
- **US Department of Energy (1995)** - 150,000 million USD per year for United States.
- **Fortune Magazine (1998)** - Around 10,000 million USD per year in United States.
- **E Source (2001**) - 60,000 to 80,000 USD per installation, per year for continuous process industries, financial services and food processing in the United States.
- **European Copper Institute (2001)** - 10,000 million EUR per year, in EU in industry and commerce.

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Power Quality Costs

	Minimum	Maximum
Industrial		
Automobile manufacturing	5	7,5
Rubber and plastics	3	4,5
Textile	2	4
Paper	1,5	2,5
Printing (newspapers)	1	2
Petrochemical	3	5
Metal fabrication	2	4
Glass	4	6
Mining	2	4
Food processing	3	5
Pharmaceutical	5	50
Electronics	8	12
Semiconductor manufacturing	20	60
Services		
Communication, information processing	2	3
Hospitals, banks, civil services	0,5	1
Restaurants, bars, hotels	0,1	0,5
Commercial shops	1	10

Cost of momentary interruption (1 minute)

in $/kW demand

Source: Electrotek Concepts

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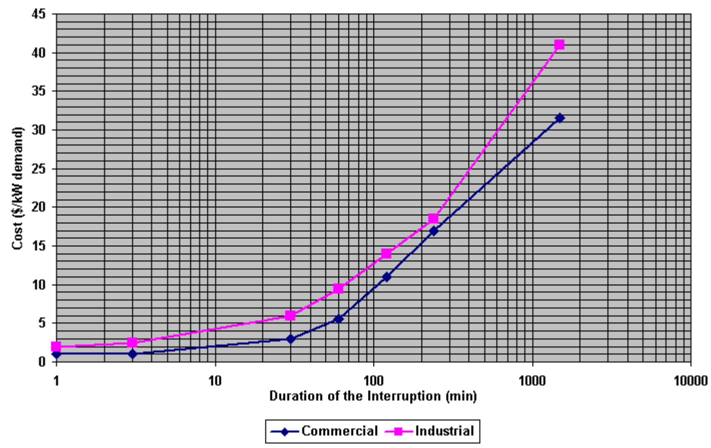
Power Quality Costs



Costs of interruptions vs. duration

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voltage sags of 10-30% below nominal for 3 to 30 cycle durations account for the majority of power system disturbances, and are thus the major cause of industry process disruptions.

VSD Ride-through Capabilities

Variable Speed Drive ride-through issues have caused increased concerns due to the susceptibility of VSDs to power disturbances, and the costly results of process disruptions.

Modifications To Existing VSD Topologies

- Additional Capacitors
- Use of Load Inertia
- Operate VSDs at Reduced Speed/Load
- Use of Lower Voltage Motors
- Boost Converter Ride-Through
- Active Rectifier VSD Front End

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Additional Capacitors

By adding capacitors to the dc-bus, additional energy needed for full power ride-through during a voltage sag can be provided to the motor.

Advantages:

- Simple and rugged approach, can provide limited ride-through for small disturbances.

Disadvantages:

- Cost is high.
- Large cabinet space, additional precharge circuits and safety considerations.

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Use of Load Inertia

The inverter control software can be modified such that when a power disturbance causes the dc-bus voltage to fall below a specified value the inverter will adjust to operate at a frequency slightly below the motor frequency, causing the motor to act like a generator.

It is best used in high inertia loads that can slow down during a momentary power disturbance. This approach can provide ride-through at reduced power (speed and torque) for up to 2 seconds for loads of 5kW-1MW.

Use of Load Inertia

Advantages:

- No additional hardware is required, only a software modification in the inverter.
- Commercial drives are available on the market with this feature with 2 seconds of ride-through for sags to 80% nominal voltage.
- Since the drive and motor have been actively transferring energy during the power disturbance, no loss of phasing has occurred between the drive and the motor and the motor's magnetic field has not de-energized. Thus, there are no delays to start accelerating the motor as soon as the ac power line returns to normal, assuming the load can handle it.

Disadvantages:

- The motor speed and torque will be reduced which may not be acceptable.
- The sustainable ride-through duration will be dependent on the load inertia.

Operate VSDs at Reduced Speed/Load

Since the dc-bus current varies with the frequency of the drive for variable torque loads, such as fans and pumps, a reduction in the motor speed will result in a reduction in the dc-bus current. Therefore, a fan and pump system running at 40Hz will draw less current than a system running at 60Hz and will therefore be able to operate for a longer period during a voltage sag situation.

Suitable Applications - Small drives, 5-10kVA, with variable torque (fans and pumps), high inertia and low friction loads. Can provide ride-through at reduced power for up to 0.01 seconds.

Operate VSDs at Reduced Speed/Load

Advantages:
- No additional hardware is required.
- At 50% speed and load, would provide four times the ride-through of a normal drive system.

Disadvantages:
- Application may not tolerate reduced speed/load operation.
- Only useful for variable torque (fans and pumps) loads.

Use of Lower Voltage Motors

If a 230V ac motor were used with a 460V ac drive, the dc-bus voltage (nominally 620V) could drop as low as 45% (to 280V) and still provide 230V ac to the motor. Then, as the voltage drops, the inverter changes its duty cycle to maintain a constant 230V ac to the motor.

Suitable Applications - Small motor drive systems, 5kVA to 10kVA, where the cost of a two-times larger drive is not twice the cost of the smaller drive. Can provide full power ride-through for up to 0.01 seconds.

Use of Lower Voltage Motors

Advantages:

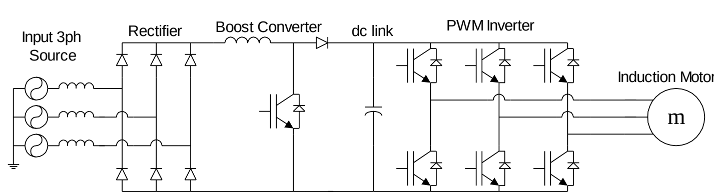
- No additional hardware is required.
- An increase of approximately 2.8 times the ride-through time of a normal drive system.

Disadvantages:

- The VSD rating is twice the power rating of the 230V motor.
- A 230V motor with the same power rating as a 460V motor will require twice the current at full load, and thus will have to be larger.
- The motor insulation must be capable of handling the higher voltages provided by a 460V VSD.

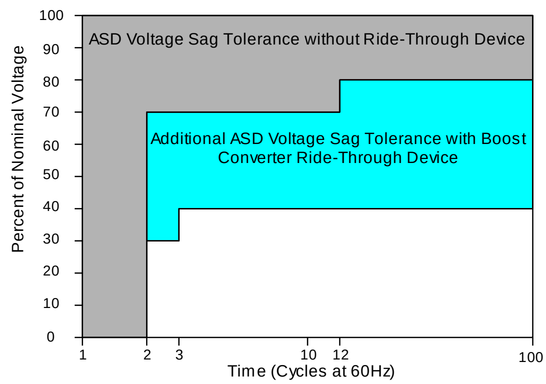
Boost Converter Ride-Through

During a voltage sag, the boost converter will sense a drop in the dc-bus voltage and begin to regulate the dc-bus to the minimum voltage required by the inverter .



Suitable Applications - New or retrofit applications, and where drives are connected to a common dc-bus. For 10 - 200 kW loads, can provide ride-through for 5 seconds at reduced power.

Boost Converter Ride-Through



Additional ride-through achieved with Boost Converter Ride-Through

Boost Converter Ride-Through

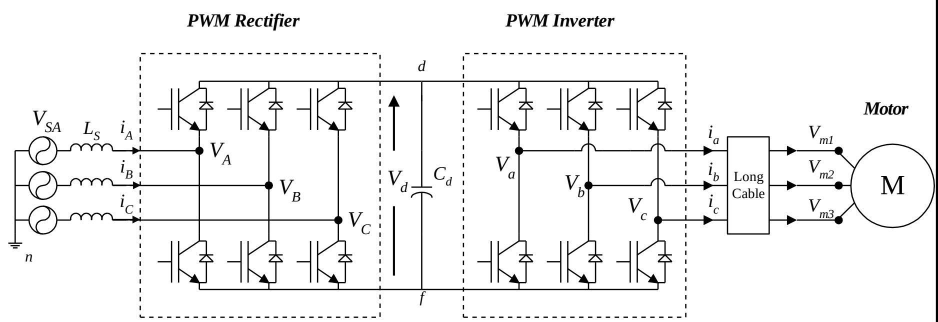
Advantages:

- Can provide ride-through for sags up to 50%.
- The dc-bus voltage can be regulated as required by the inverter, and is user adjustable.

Disadvantages:

- The dc-link inductor and the additional diode are in the series path of the power flow.
- Additional hardware required, which will have to be suitably rated due to the additional current drawn during a voltage sag.
- In the case of an outage, the boost converter will not be able to provide ride-through, and the drive will trip.

Active Rectifier VSD Front End



Suitable Applications - New VSD applications where regenerative braking is considered to improve overall efficiency. VSDs with active rectifiers are available from most drive manufactures up to 500kW, however at twice the cost of a standard diode rectifier option.

Active Rectifier VSD Front End

Advantages:

- Clean input power at unity power factor
- Active rectifier provides a regulated dc bus voltage, hence is self correcting under voltage sags. Suitable rectifier derating is necessary to provide a full power ride-through under a sag.
- Power flow in both directions enables regenerative braking. This feature could add to improved efficiency is some applications.

Disadvantages:

- An VSD with an active PWM rectifier is nearly equivalent to two diode rectifier VSDs. This approach comes with additional cost.
- The VSD package is larger in size since in addition to the active rectifier hardware, three input filter inductors become necessary.
- Active PWM rectifier operates the VSD with higher dc-link voltage, this results is higher differential mode dv/dt at the motor terminals. Also due to two PWM IGBT inverter stages the common mode dv/dt and EMI is higher.

Energy Storage Solutions

- Battery back-up
- Flywheels
- Supercapacitors
- Superconducting Magnetic Energy Storage (SMES)

Battery backup

Battery back up systems operate similarly to adding capacitive energy storage.

Electrochemical batteries prevail due to their low price and mature technology.

Suitable Applications - New or retrofit applications, and where drives are connected to a common dc-bus. For 5kW-10MW loads and can provide full power ride-through for up to 1 hour.

Battery backup

Advantages:

- Can provide ride-through for deep sags and full outages.
- Batteries are easily obtained.
- Transfer time is almost instantaneous.

Disadvantages:

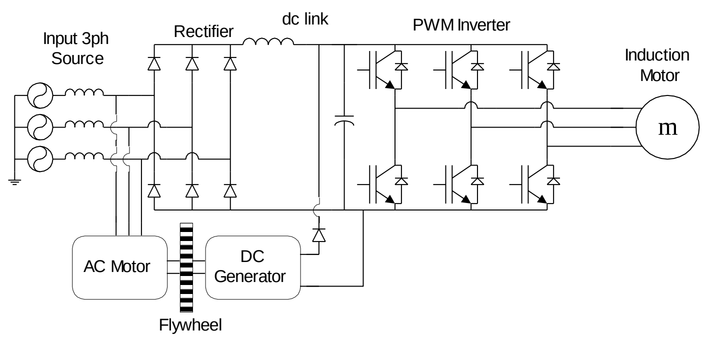
- Additional hardware and space required, though not as much as with standard capacitors.
- Relatively low cycle life
- More maintenance required to ensure peak performance.
- The electrolyte is corrosive and may be hazardous to the application, and will need to be properly disposed of when depleted.

Flywheel

A flywheel is an electromechanical device that couples a rotating electric machine (motor/generator) with a rotating mass to store energy for short durations. The motor / generator draws power provided by the grid to keep the rotor of the flywheel spinning.

During a power disturbance, the kinetic energy stored in the rotor is transformed to DC electric energy by the generator, providing power directly to the dc-bus of the ac drive.

Flywheel



M-G Set with a Flywheel

Flywheel

Advantages:

- Can provide ride-through for deep sags and full outages.

Disadvantages:

- Additional hardware and space required.
- Maintenance is required for the rotating components.

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Supercapacitors

Super capacitors offer substantial increases in energy density over conventional capacitors due to the choice and preparation of the electrode materials and increases in the effective capacitive plate surface area.

A VSD can be designed with integrated super capacitors, or as an add-on module. The add-on bank of super capacitors would be about the size of the drive itself.

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Supercapacitors

Advantages:

- Can provide ride-through for deep sags and full outages.
- Long cycle life and fast recharge rates.
- Easily monitored state of charge.
- Minimal maintenance needs.

Disadvantages:

- Additional hardware and space required, though not as much as with standard capacitors.

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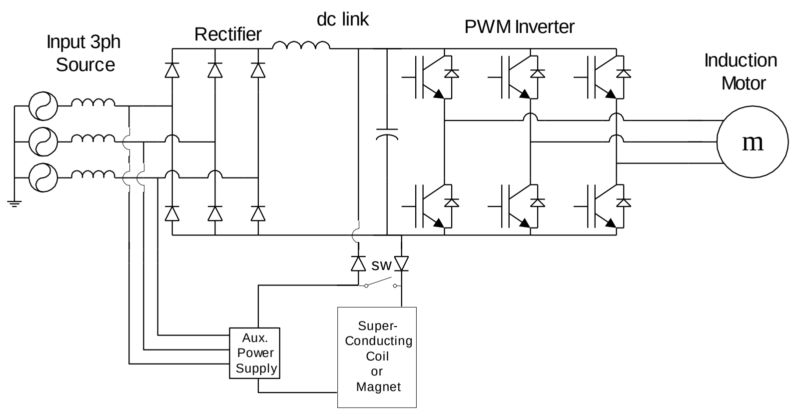
SMES



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SMES

In a SMES system, a large amount of current is kept circulating in a superconducting coil or magnet, to be supplied to the system when needed. Since there are only negligible losses in the superconducting coil, the transfer of energy in and out of storage is highly efficient, and rapid.

However, to remain superconducting, the coil must be cooled to cryogenic temperatures. Low temperature SMES cooled by liquid helium is commercially available.

SMES

Advantages:

- Reliable, with little maintenance.
- SMES can handle rapid repeated discharging and charging without affecting its performance or life.

Disadvantages:

- Additional hardware and space required.
- Sophisticated cooling system required to maintain cryogenic temperatures and the power loss associated with it.
- High cost.

ASD Ride- Through Alternatives	Cost Rs/KW	Ride-Through Duration Limit	Power Range	Efficiency	Cycle Life	Charging Time
Additional Capacitors*	30000	0.1sec.	100kw	95%	10000	Seconds
Load Inertia	≈0	2.0 sec.	1kw-1mw	---	---	Continues
Reduced Speed/Load	≈0	0.01 sec.	5-10kw	---	---	---
Lower Voltage Motors*	≈0	0.01 sec.	5-10kw	---	---	---
Boost Converter**	5000-10000	5.0 sec.	5-200kw	90%	---	---
Active Rectifier**	5000-10000	5.0 sec.	5-200kw	---	---	---
Battery Backup*	5000-10000	5.0 sec.,1hr.	5kw-1MW	70-90%	2000	Hours
Ultra Capacitors*	15000-20000	5.0 sec.	5-100kw	90%	10000	Seconds
Motor-Generator Sets*	10000-15000	15.0 sec.	100kw	70%	---	---
FlyWheels*	10000-15000	15.0 sec.,1hr.	1kw-10MW	90%	10000	Minutes
SMES*	30000-40000	10.0 sec.	300-1000KW	95%	10000	Minutes-hours
Fuel Cells*	75000	1 hr.	10kw-2MW	40-50%	continues	continues

* provides Full-power ride-through
** provide full-power ride-through for single-phase sags<50%

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Thank you

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9. Motor selection

Anibal T. De Almeida

Day 2

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Discussed topics

- How to select an efficient motor for your application

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Motor Selection

The following should be considered when selecting a motor for a particular application:

- The mechanical requirements of the driven load.
- Motor classification.
- The electrical distribution system.
- Physical and environmental considerations.

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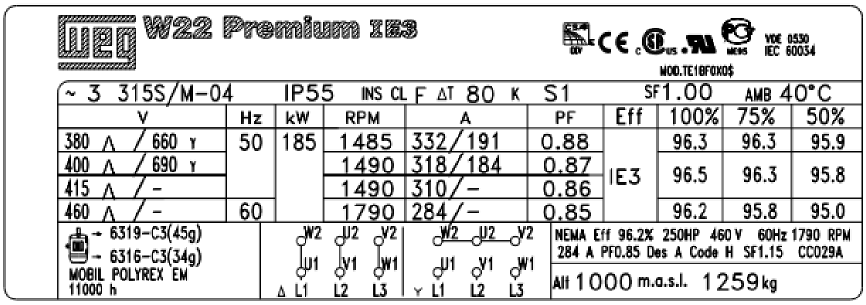
Induction motor selection

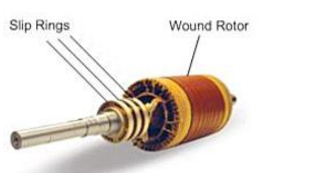
	NEMA Classification	Starting Torque (% Rated Load Torque)	Breakdown Torque (% Rated Load Torque)	Starting Current	Slip	Typical Application
IEC Design N	Design B normal starting torque & normal starting current	100-200%	200-250%	Normal	< 5%	Fans, blowers and centrifugal pumps, where starting torque requirements are relatively low.
IEC Design H	Design C high starting torque & normal starting current	200-250%	200-250%	Normal	< 5%	Conveyors, stirring machines, crushers, agitators, reciprocating pumps & compressors, etc., where starting under load is required.
	Design D high starting torque & high slip	275%	275%	Low	> 5%	High peak loads, loads with flywheels such as punch press, shears, elevators, extractors, winches, hoists, oil well pumping & wire drawing machines.

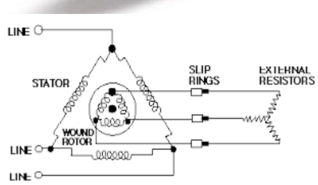
Induction Motor label

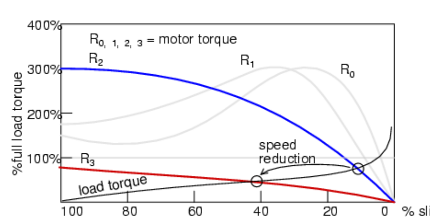


Induction motor selection

- Wound rotor induction motors are useful in some applications because the resistance of the rotor circuits can be altered to give the desired starting or running characteristics.
- More expensive and more maintenance







Synchronous motor selection

Speed:

- Synchronous motors operate at synchronous speed with no speed drop over the load range. They should be selected if exact speed is required.

Power Factor Correction:

- Synchronous motors can generate reactive power to correct poor supply system power factor while delivering mechanical power. When supplying reactive power they are said to be operating at a leading power factor.

Lower Operating Costs:

- Synchronous motors are often more energy efficient than induction motors, especially in the very large horsepower ranges (above 1000 hp).

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Direct Current Motor Selection

- DC motors are often selected where precise speed control is required, as DC speed control is simpler, less costly and spans a greater range than AC speed control systems.
- Where very high starting torque and/or high over-torque capability is required, DC motors are often selected.
- They are also appropriate where equipment is battery powered.

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Single-phase motor selection

Type	Typical RPM	Starting Torque as Percent of Full-Load Torque	Comparative Efficiency	Typical Applications
Shaded Pole	1050, 1550, 3000	Very Low 50-100%	Low	Small direct-drive fans and blowers.
Permanent Split Capacitor (PSC)	825, 1075, 1625	Low 75-150%	Moderate	Direct-drive fans and blowers
Split-Phase	1140, 1725, 3450	Low to Moderate 130-170%	Moderate	Belt-drive and direct-drive fans and blowers, small tools, centrifugal pumps, and appliances
Capacitor-Start	1140, 1725, 3450	Moderate to High 200-400%	Moderate to High	Pumps, compressors, tools, conveyors, farm equipment, and industrial ventilators

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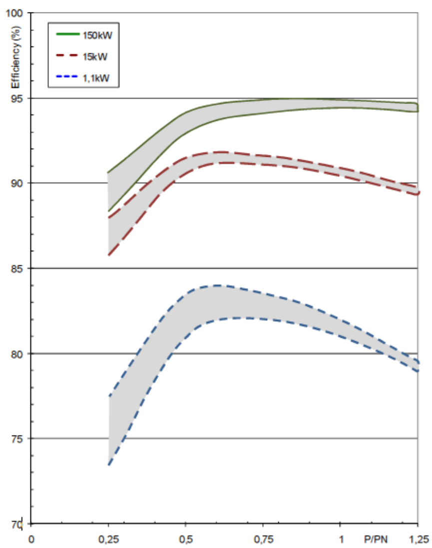
Load

Motors must be sized to accommodate the running load's speed and torque requirements. Load types can be classified into different duty cycles describing operating time and load variations.

- *If replacing an existing motor is considered, monitoring the power input to the motor over a period of time will determine an optimum size. Inexpensive battery powered data loggers work well for load trending.*



Efficiency vs. Load

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Starting and Stopping

Frequency of starting and stopping.

- For frequent starts, ensure winding and core temperature do not exceed motor rating.

Starting torque requirement.

- Pay special attention to high inertia loads to ensure motor starting torque is adequate.

Acceleration restrictions.

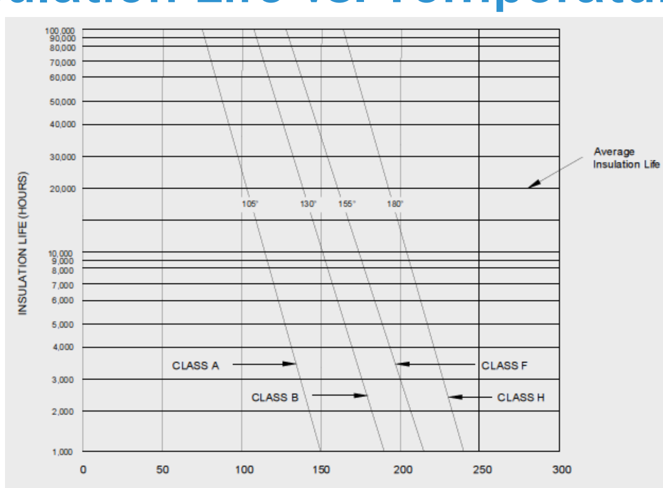
- Ensure the motor driving the load reaches full speed quickly enough to avoid tripping the overload protection. Conversely, some loads require time to accelerate to full speed, e.g. a conveyor belt – a variable speed drive may be justified to achieve this and keep current lower when starting up.

Operating Temperature

The standard IEC 60085 gives the maximum operation temperature for each thermal class

Thermal classes for insulation systems	A	E	B	F	H
Maximum operation temperature (ºC)	105	120	130	155	180

Insulation Life vs. Temperature



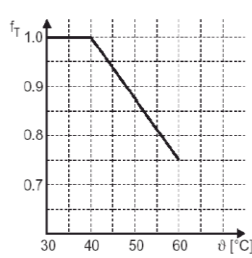
Service Factor

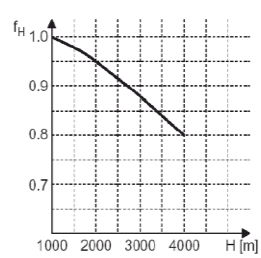
- Motor service factor is an indication of the ability to exceed the mechanical power output rating on a sustained basis. A service factor of greater than 1.0 allows a margin for peak power demand without selecting the next larger motor size.
- Motor efficiency is usually reduced during operation at the service factor rating.

Motor Derating

For temperatures above 40° C and below 60° C

For altitudes above 1000m





$$P_{Nred} = P_N \bullet f_T \bullet f_H$$

Energy Saving Strategies

Choose a Replacement Before a Motor Fails

Sometimes in trying to get a motor back into service as quickly as possible, decisions are made that satisfy the short-term goal but negatively impact long-term efficiency and motor life. When conducting this evaluation it may determined that it is beneficial to replace working motors with properly sized more efficient ones.

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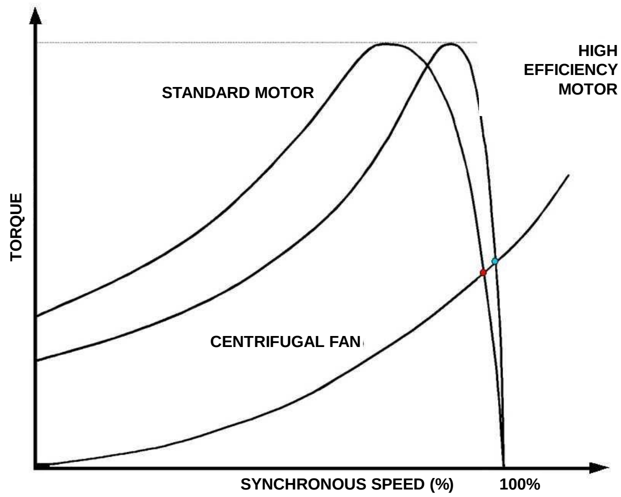
Energy Saving Strategies

Match Motor Operating Speeds

In general, motors with higher efficiency have a higher operating speed i.e. a reduced slip compared to motors of lower efficiency. On average, the slip is reduced by some 20 to 30% per next higher efficiency class for motors of the same rated output power.

For most turbomachinery, power consumption is proportional to the cube of the rotational speed. For example, increasing operating speed by 2% can increase the power required to drive the system by 8%. This can easily offset the savings expected by the replacement of a motor with a more efficient one.

Match EEM Motor Operating Speed



Motor sizing

Properly Size the Motor for your Application

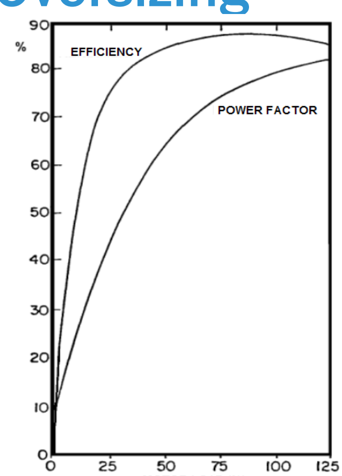
Motor efficiency is fairly constant down to approximately 50% of rated load, below which it drops off quickly. Care should be exercised in leaving an adequate but not excessive safety margin. The motor should be sized for the peak load expected. Oversized motors can significantly increase costs since all electrical components must be sized to the motor rating.

Motor sizing

Properly Size the Motor for your Application

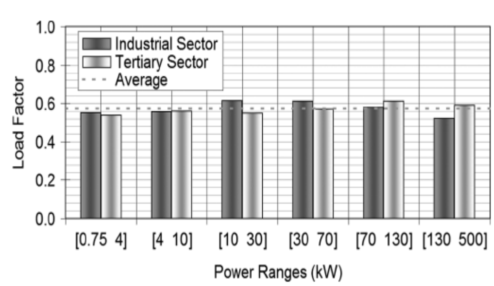
Due to the low temperature utilization of more efficient motors their overload capacity is typically higher when compared to standard motors. Therefore, oversizing the motor for occasional peak-power demands is seldom required and certainly not cost effective.

Oversizing



DISADVANTAGES:

- HIGHER CAPITAL COST (MOTOR AND COMMAND AND PROTECTION EQUIPMENT);
- LOWER MOTOR EFFICIENCY AND POWER FACTOR;



AVERAGE LOAD FACTOR BY POWER RANGE, IN NDUSTRY AND TERTIARY SECTOR, EUROPEAN UNION, 2000.

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Exercise – Estimation of Mechanical Motor Load

Estimation of approximate load based on of motor speed and voltage

Name plate data:

Rated kW of Motor = 30 kW
Rated Amps = 55 A
Rated voltage = 400 V
Name plate efficiency = 92%
Name plate speed = 1440 rpm

Measured Data

Measured speed = 1460 rpm
Input load current = 33 A
Operating voltage = 415 V
Input power = 20 kW

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Exercise – Estimation of Motor Load

Based on Input Power Method Measurement:

Nominal input power = 30/0,92 = 32,6

Load = 20 /32,6 = 0,61

Note: the accuracy of method drops when load is below 40% since efficiency drops sharply below that value

Exercise – Rough Estimation of Motor Load

Based on the Speed Measurement:

Synchronous speed = 60 x 50/2= 1500 rpm

Slip = Synchronous Speed – Measured speed in rpm,

= 1500 – 1460 = 40 rpm

$$Load\ (\%) = \frac{Slip}{(S_{synch} - S_{nameplate}) \times \left(\frac{V_{measured}}{V_n}\right)^2} \times 100$$

$$Load\ (\%) = \frac{40}{(1500 - 1440) \times \left(\frac{415}{400}\right)^2} \times 100 = 61{,}9\%$$

Note:This method has larger errors for big motors because of their smaller slip

Exercise – Rough Estimation of Motor Load

Based on the Current Measurement:

$$Load\ (\%) = \frac{V_{measured} \times I_{measured}}{V_{rated} \times I_{rated}}$$

$$Load\ (\%) = \frac{415 \times 33}{400 \times 55} = 0{,}623$$

Note:This method has larger errors for loads below 50% because of decreasing PF

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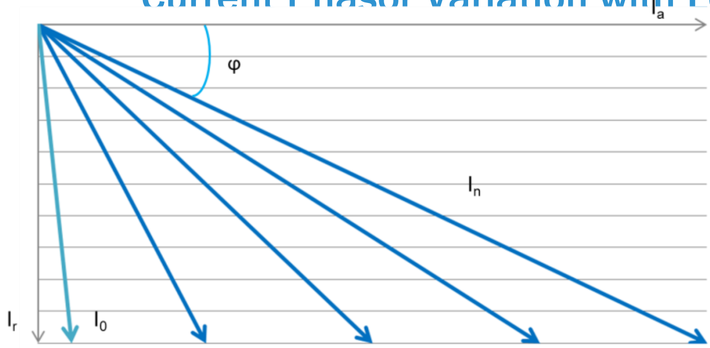
Current Phasor Variation with Load



$$I_0 \cong I_n \sin \varphi$$

I_a – Active Current
I_r – Reactive Current
I_0 – No load Current
I_n – Nominal Current
Cos φ – Full Load power factor (nameplate rating)

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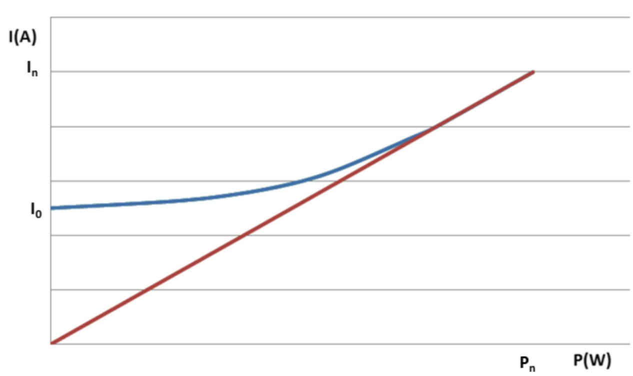
Motor current variation with load



I_0 – No load Current
I_n – Nominal Current

Estimating Motor Efficiency in the Field

When evaluating the replacement of an existing motor with a Premium or a Super-Premium solution it is important to know the efficiency of the existing motor.

Efficiency is output power divided by input power, yet most of the methods and devices attempt to assess losses to circumvent the difficult task of measuring shaft output power.

Estimating Motor Efficiency in the Field

The most common methods used are:

- Loss accounting methods
- Current Method
- Software tools

Loss accounting methods

These measure most of the above losses using either special dedicated “lab-in-a-box” devices or very accurate conventional instruments, for example, power meters, thermometers, and micro-ohmmeters.

These methods have the potential of being accurate within 1% to 3% if carefully applied. The necessary instruments are costly and the process is very time and labor consumptive. Power meters must be accurate at very low power factors that occur when motors operate unloaded.

Current Method

This method is based on the current method for the estimation of load and has the same limitations (large error for loads below 50%).

$$P_{out} = \frac{V_{measured} \times I_{measured}}{V_{rated} \times I_{rated}} \times P_N$$

$$\eta = \frac{P_{out}}{P_{in}}$$

Software Tools

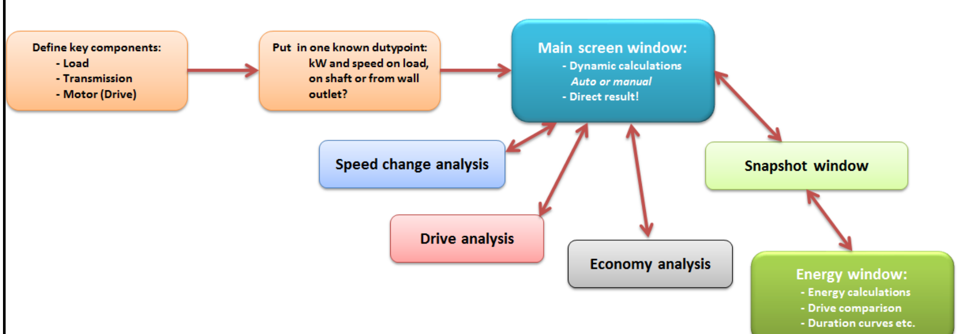
Software tools such as ***MotorMaster+*** (available at no cost in the DoE website) incorporate several methods for determining motor load. These involve the use of motor nameplate data in conjunction with selected combinations of input power, voltage, current, and/or operating speed.

With the percent load known, the software determines as-loaded efficiency from default tables based on the motor type, condition, and horsepower. MotorMaster+ automatically chooses the best available method based upon the data it is given.

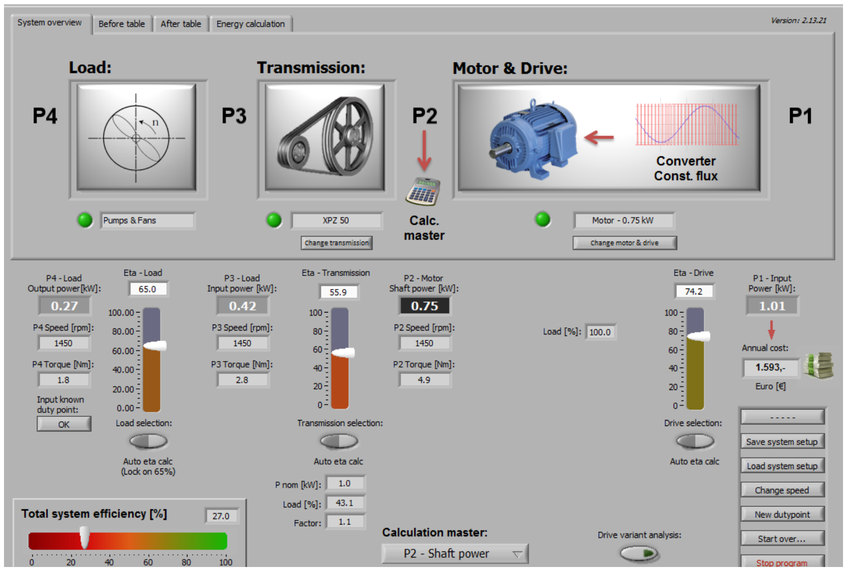
http://www1.eere.energy.gov/manufacturing/tech_deployment/software_motormaster_intl.html

EMSA - Motor Systems Tool

for Motor Selection



https://www.motorsystems.org/motor-systems-tool



2. Use the following formulas to calculate the annual energy savings and simple payback from selecting a more efficient motor. Simple payback is defined as the time required for the savings from an investment to equal the initial or incremental cost.

Annual Energy Savings

$$\text{Savings} = \text{hp} \times L \times 0.746 \times \text{hr} \times C \times \left[\frac{100}{\text{Estd}} - \frac{100}{\text{Eee}}\right]$$

E Savings	=	Expected annual dollar savings
hp	=	Motor rated horsepower
L	=	Load factor (percentage of full load/100)
hr	=	Annual operating hours
C	=	Average energy costs ($/kWh)
Estd	=	Standard motor efficiency rating, %
Eee	=	Energy-efficient motor efficiency rating, %
0.746	=	Conversion from horsepower to kW units

Simple Payback

For a new motor purchase, the simple payback is the price premium minus any utility rebate for energy-efficient motors, divided by the annual dollar savings:

$$\text{Simple payback (years)} = \frac{\text{Price premium} - \text{Utility rebate}}{\text{Annual dollar savings}}$$

When calculating the simple payback for replacing an operating motor, you must include the full purchase price of the motor plus any installation costs:

$$\text{Simple payback (years)} = \frac{\text{Motor price} + \text{Installation charge} - \text{Utility rebate}}{\text{Annual dollar savings}}$$

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10. Motor Controls

Anibal T. De Almeida

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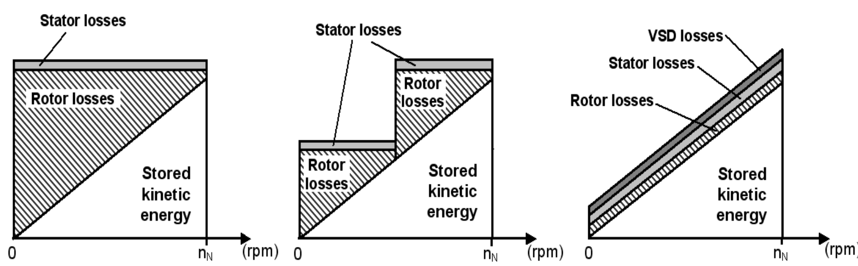
Discussed topics

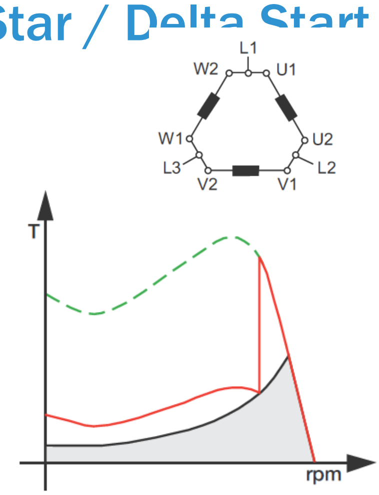
- Starting
- Soft-Starters
- Variable Speed Drives

Motor Controls - Starting

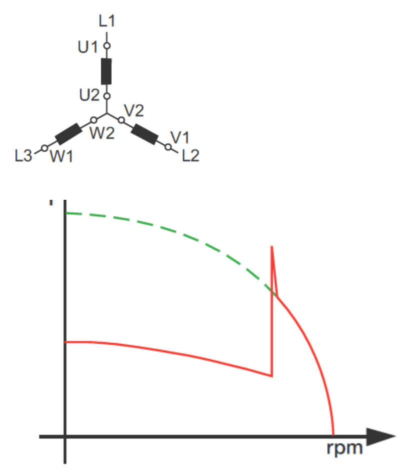
Energy-Consumption for an Acceleration Period: (a) Standard Motor; (b) Pole Changeable Motor; (c) Variable Speed Drive (VSD).



Star / Delta Start



Torque/speed curve at Star-Delta start



Current curve at Star-Delta start

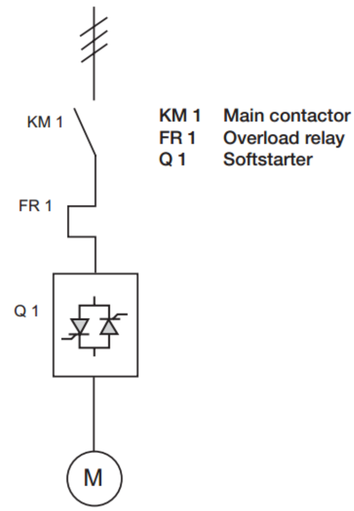
Soft Starter

- A softstarter has different characteristics to the other starting methods. It has thyristors in the main circuit, and the motor voltage is regulated with a printed circuit board. The softstarter makes use of the fact that when the motor voltage is low during start, the starting current and starting torque is also low.
- During the first part of the start the voltage to the motor is so low that it is only able to adjust the play between the gear wheels or stretching driving belts or chains etc. In other words, eliminating unnecessary jerks during the start.

Soft Starter

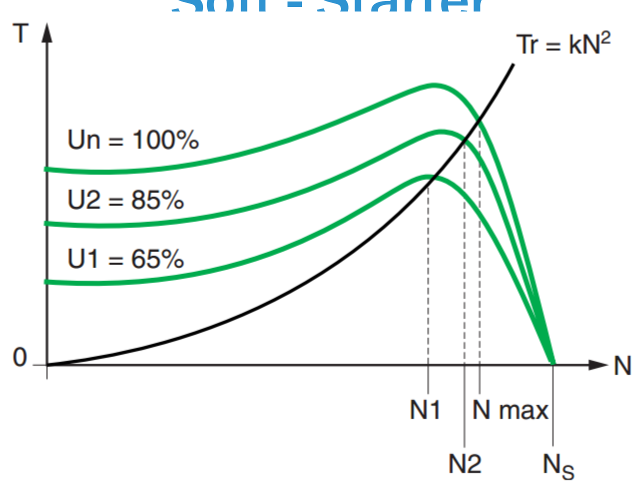
- Gradually, the voltage and the torque increase so that the machinery starts to accelerate. One of the benefits with this starting method is the possibility to adjust the torque to the exact need, whether the application is loaded or not. In principle the full starting torque is available, but with the big difference that the starting procedure is much more forgiving to the driven machinery, with lower maintenance costs as a result.
- Another feature of the softstarter is the softstop function, which is very useful when stopping pumps where the problem is water hammering in the pipe system at direct stop as for star-delta starter and direct-on-line starter. The softstop function can also be used when stopping conveyor belts to prevent material from damage when the belts stop too quickly.

Soft Starter



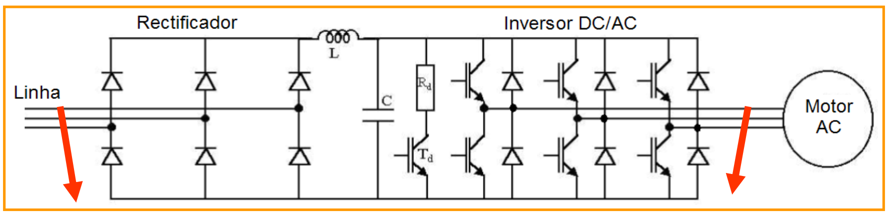
Single line diagram for a softstarter

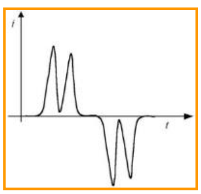
Soft - Starter

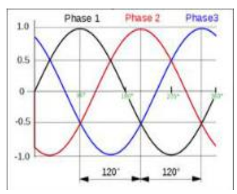


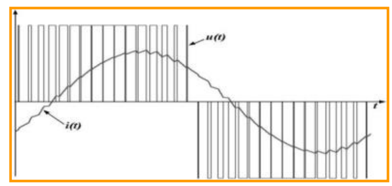
Variable Speed Drives – VSDs

For Induction Motors









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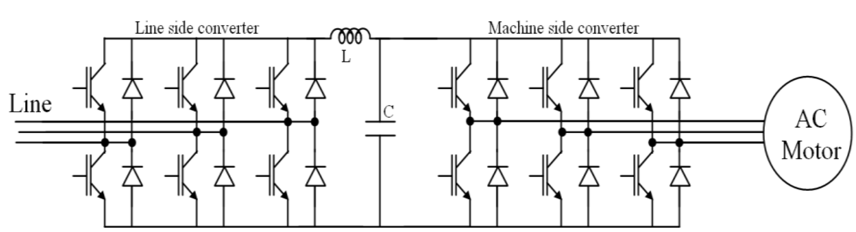
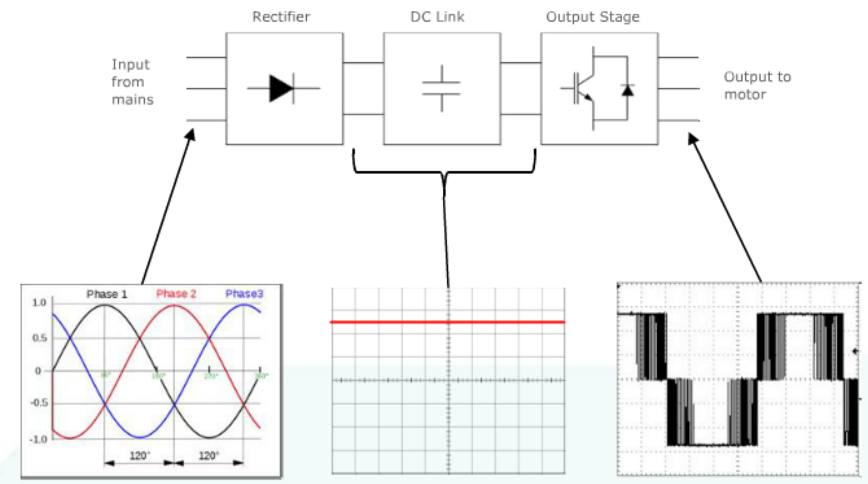
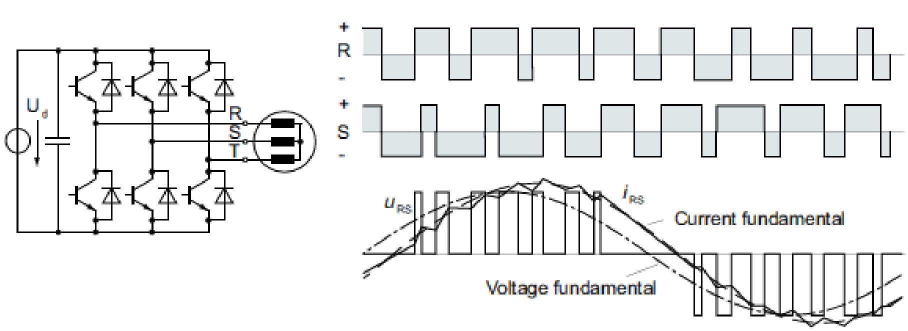
VSDs - Regeneration



Variable Speed Drives – VSDs

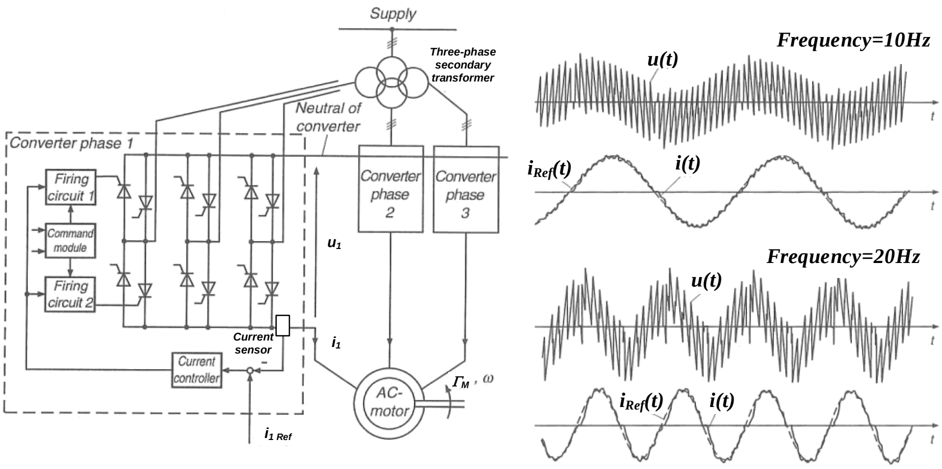


PWM inverter



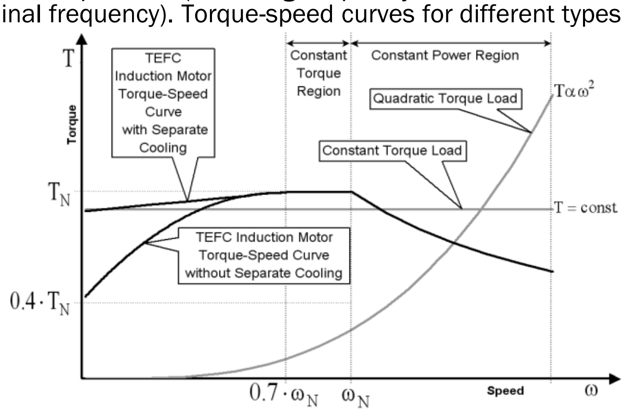
Circuit diagram and control principle of a PWM inverter

Cycloconverters

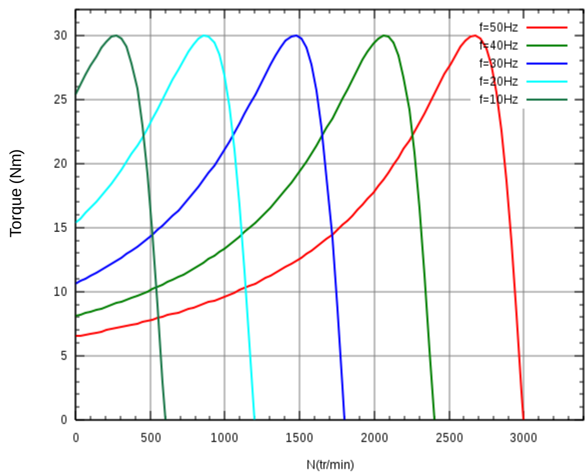


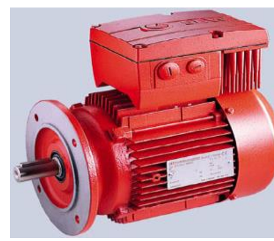
Variable Speed Drives – VSDs

Motor torque and power limitations in totally-enclosed fan-cooled induction motors fed by a VSI-PWM VSD, assuming motor constant nominal operation temperature (switching frequency > 5 kHz, field weakening point at nominal frequency). Torque-speed curves for different types of loads.



Variable Speed Drives – VSDs





V/f Control

- The voltage amplitude is specified as a function of the actual motor frequency.
- The V/f characteristic can be adjusted. The most usual characteristic types are those with a constant torque or a square-law characteristic for pumps and fans.

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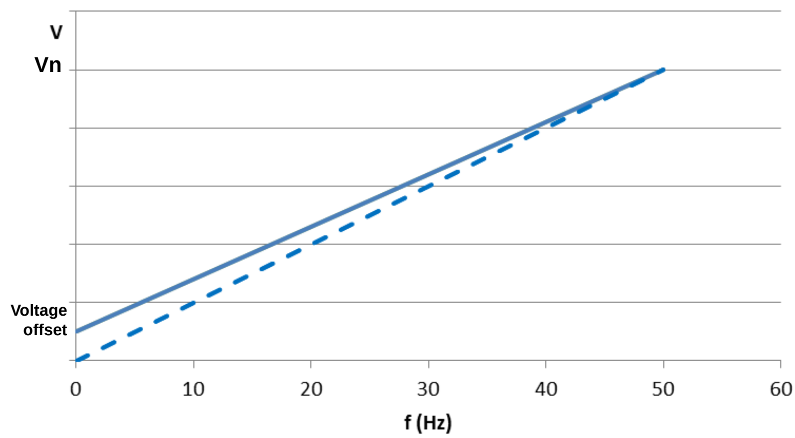
Voltage Variation with Frequency



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V/f Control

The following measures improve the properties of V/f control:

- Slip compensation maintains the speed constant during load changes using a load current-dependent frequency boost. The slip compensation becomes effective from approx. 10 % of the rated motor speed. This therefore allows a speed holding accuracy of approx. (0.2 x rated slip) to be achieved. The rated slip is, e.g. for motors from 30 KW and above, approx. =1.5 %.
- FCC control (Flux Current Control, extended i*R compensation) also improves the speed holding accuracy during load changes. FCC adapts the voltage - and therefore the rotor flux - to the load.
- The voltage increase at low frequencies ("boost") optimizes the starting behavior.
- Resonance damping attenuates electromechanical oscillations in the range between 10 and 40 Hz for induction motors up to approx. 160 kW.
- The current limiting control is used as stall protection.

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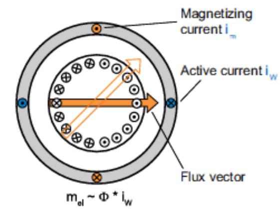
Vector Control

Vector control (Also called Field-oriented control - FOC) is a control technique for polyphase motors (induction and synchronous motors), which allows a three-phase motor to be operated with the same dynamic performance as a DC motor.

The behaviour of a DC motor is emulated in an induction motor by orienting the stator current with respect to the rotor flux so as to attain independently controlled flux and torque.



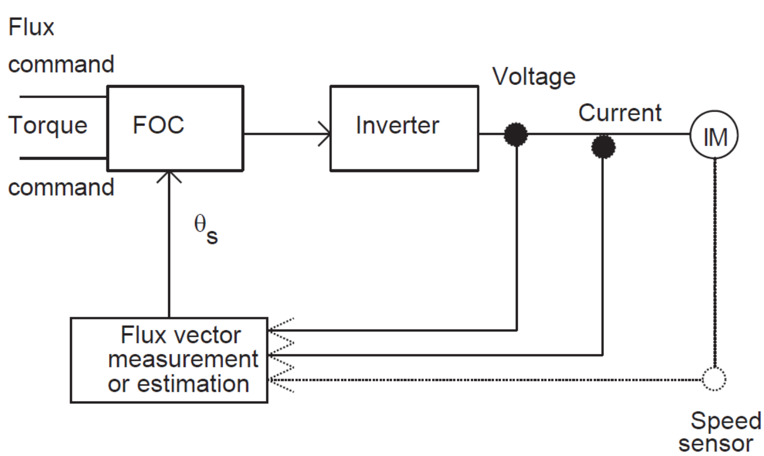
Vector Control

- The reference system of the machine equations is not orientated to the stationary stator, but to a rotating magnetic field.
- The field appears to be stationary in this rotating reference system. The voltages - and especially the currents - in the motor can now be referred to this system
- The current in the motor is split up into a field-generating component (magnetizing current i_d, in the direction of the field) and a torque generating component (active current i_q, perpendicular to the field [quadrature axis]); both of these can be controlled independently of one another.
- Using a matrix operations, the quantities between the rotating ***d-q*** axis reference frame are transformed in the stationary i_1, i_2, i_3 reference frame, and vice-versa.

Vector Control

- Knowing the alignment of the magnetic field in the motor is a precondition for field-orientated control. This is determined from measured data (currents, voltages, speed or position of the rotor) in a motor model or flux model.
- Initial vector control required the use of shaft encoders
- So-called sensorless closed-loop controls, which do not require a position and speed encoder, also calculate these quantities.

Direct Vector Control



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Advantages of the VSDs

- Energy savings associated to the speed control;
- Improvement of the dynamic performance of induction motors;
- High efficiency of the VSDs (96-98%) and high reliability;
- High power factor (if active front end is used);
- Small size and location flexibility;
- Soft starting (savings!) And controlled/regenerative braking;
- Motor protection features;
- Lower acoustic noise and improvement of the process control;
- Less wear maintenance needs of the mechanical components.

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Possible Disadvantages of VSDs

- Inject harmonic distortion in the network
- Voltage spikes leading to failure of insulation in windings of old motors
- Bearing current leading to premature failure

Types of VSDs – Pros and Cons

VSD Type	Advantages	Disadvantages
Pulse-Width Modulation (PWM)	Good power factor throughout speed range. Low distortion of motor current. Wide speed range (100:1). Multi motor capability.	No regeneration capability. Limited to VSDs bellow 1000 kW *. Slightly (about 1%) less efficient than VSI or CSI
Six-step Voltage-Source Inverter (VSI)	Good efficiency. Simple circuit configuration. Wide speed range (10-200%). Multi-motor capability.	Poor power factor at low speeds (unless a rectifier/chopper AC/DC converter is used). No regeneration capability. Operation below 10% of rated speed can produce cogging.
Force Commutated Current-Source Inverter (CSI)	Simple and robust circuit design. Regenerative capability. Built-in short circuit protection. Wide speed range (10-150%).	Bulky. Poor power factor at low speed/load. Possible cogging below 10% of rated speed.

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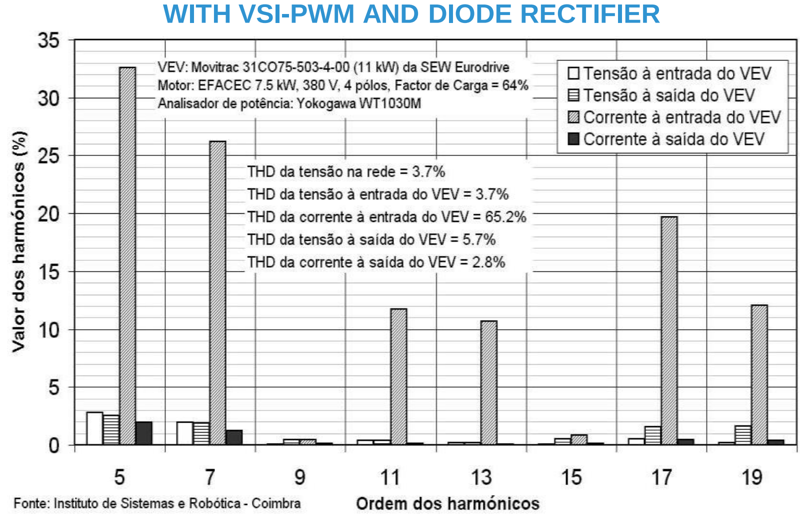
Types of VSDs – Pros and Cons

VSD Type	Advantages	Disadvantages
Load-Commutated Inverter (LCI)	Simple and inexpensive circuit design. Regeneration capability. Built-in short-circuit protection.	Poor power factor at low speed. Can only be used with synchronous motors.
Static Kramer Drive	VSD power is less than motor power. Can be retrofitted to wound rotor induction motor (W.R.I.M.) with external resistor.	Can only be used with W.R.I.M. Poor power factor at low speeds. Subsynchronous speed (50-100%)only.
Static Scherbius Drive	VSD power is less than motor power. Wider speed range (70-130%). Can be retrofitted to W.R.I.M. with external resistor if overspeed is possible.	More complex and costly than Kramer drive. Can only be used with W.R.I.M.
Cyclo-Converters	Can operate down to zero speed. High torque capability with field-oriented control. Can be used with induction and synchronous motors.	Cannot be used above 33% of input frequency. Complex circuit design. Poor power factor at low speed.

Common Types of VSD and Applications

Controlling the	Three-phase AC drive	Application
Stator voltage	Three-phase AC power controller with squirrel-cage induction motor	Drive for pumps, fans, up to 6 kW - in special cases up to 50 kW
Stator frequency, stator voltage	Current-source DC link converter with synchronous motor (converter motor)	Drive for processing machines, pumps, blowers, up to 60 MW
	Voltage-source DC link converter with synchronous motor or squirrel-cage induction motor	Drive for textile machines, roller tables, machine tools, up to 20 MW
	Cycloconverter with synchronous motor or squirrel-cage induction motor	Drives with very low speeds, e.g. rock crushers, up to 15 MW
Stator frequency, stator current	DC link converter with squirrel-cage induction motor	Drive for fans, centrifuges, mixers/agitators, up to 1800 kVA

THD AND HARMONICS AT THE INPUT AND OUTPUT OF A VSD WITH VSI-PWM AND DIODE RECTIFIER



Fonte: Instituto de Sistemas e Robótica - Coimbra

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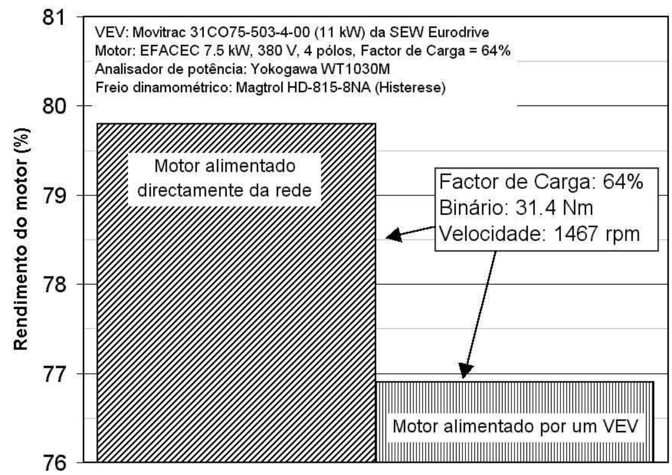
MOTOR EFFICIENCY REDUCTION IN AN INVERTER FED INDUCTION MOTOR



Fonte: Instituto de Sistemas e Robótica - Coimbra

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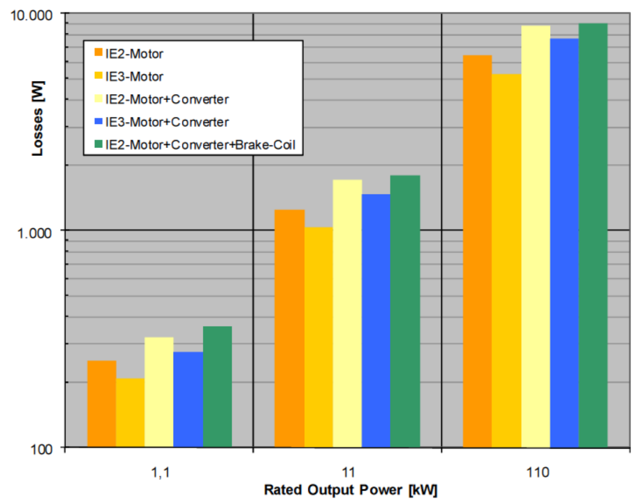
Motor Efficiency Reduction of VSD fed Induction Motor

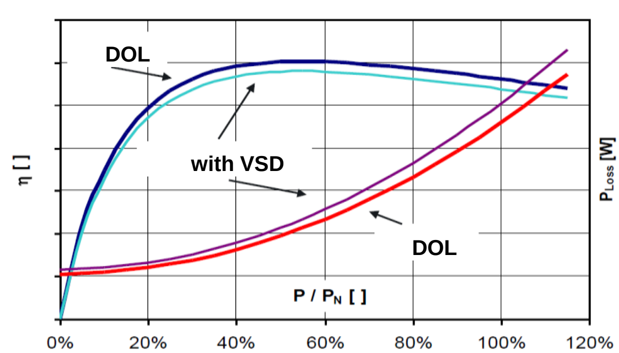
Operation of a.c. machines on a non-sinusoidal supply inevitably results in additional losses in the machine. These losses fall into three main categories.

- **Stator copper loss**. This is proportional to the square of the rms current. Additional losses due to skin effect must also be considered.
- **Rotor copper loss.** The rotor resistance is different for each harmonic current present in the rotor. This is due to the skin effect and is particularly pronounced in deep bar rotors. Because the rotor resistance is a function of frequency, the rotor copper loss must be calculated independently for each harmonic. Although these additional losses used to be significant in the early days of PWM inverters, in modern drives with switching frequencies above 3 kHz the additional losses are minimal.
- **Iron loss.** This is increased by the harmonic components in the supply voltage.

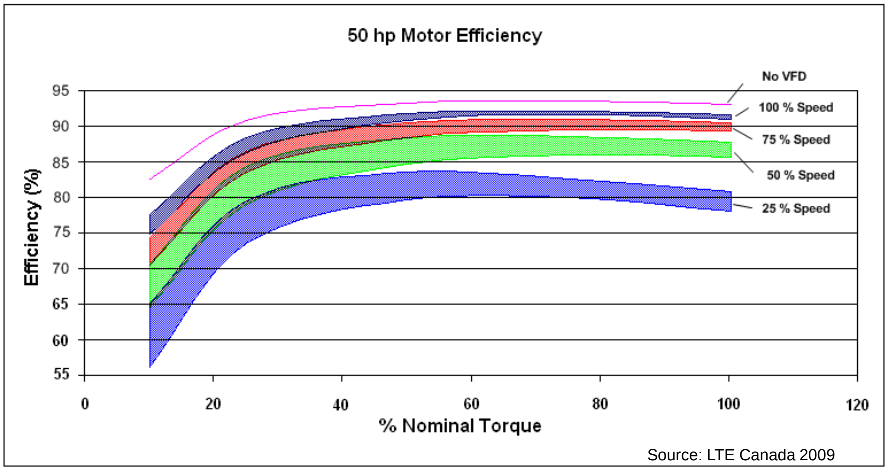
Typical losses of energy-efficient motors, converters and electromechanical



Efficiency and losses of motor versus load, direct-on-line and fed by a VSD



Motor Efficiency (37 kW)



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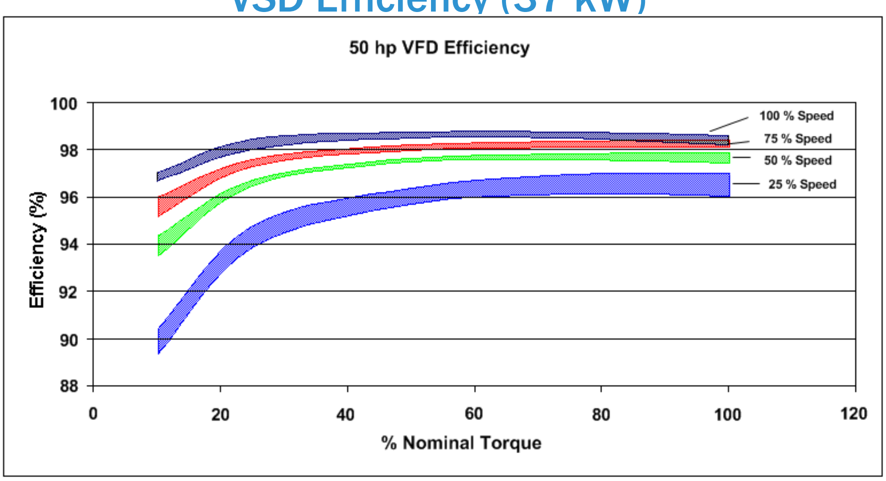
VSD Efficiency (37 kW)



Source: LTE Canada 2009

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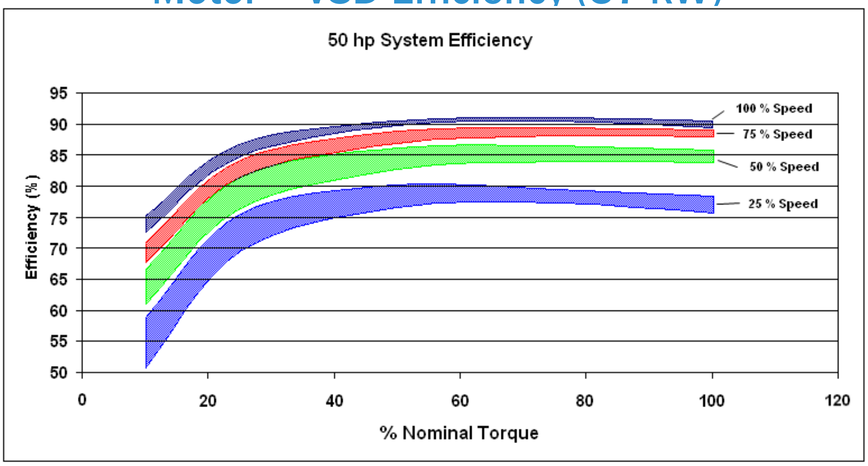
Motor + VSD Efficiency (37 kW)



Source: LTE Canada 2009

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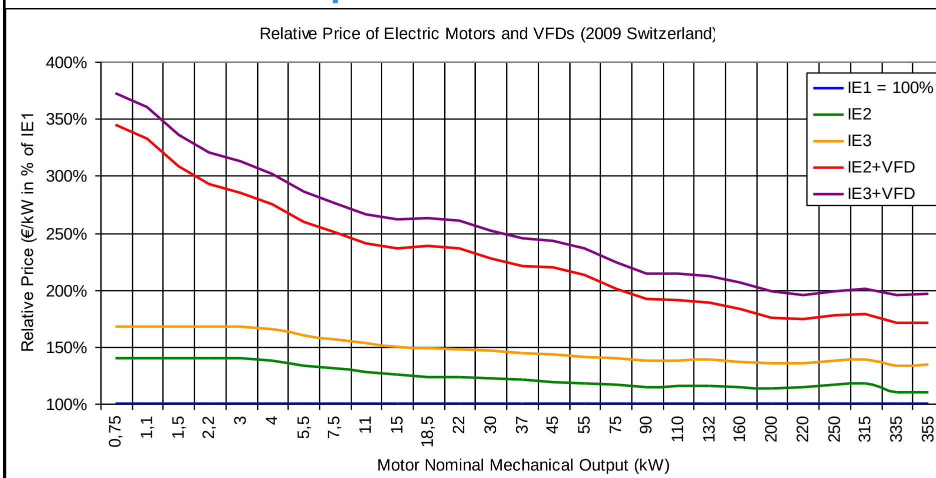
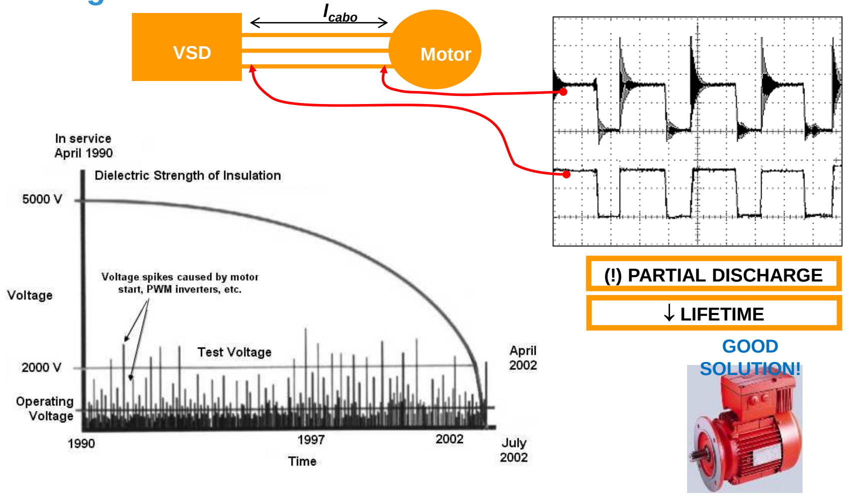
Relative prices of Motor and VSDs

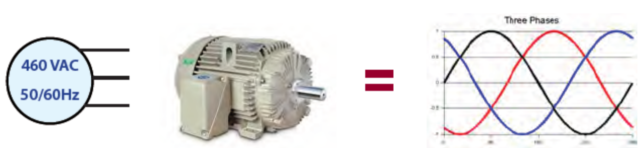


Voltage transients at the inverter-fed motor terminals



Electric Motors Operating on Line Voltage

Balanced voltage condition



- Electric induction motors are designed for operation on 3 phase sine wave power - either 50 or 60 Hz.
- The input power is balanced in frequency, phase (120 degree phase shift) and in amplitude.
- Common mode voltage - the sum of the 3 phases always equal zero volts when properly balanced.

Note: Bearing protection generally not needed except for large frame motors.

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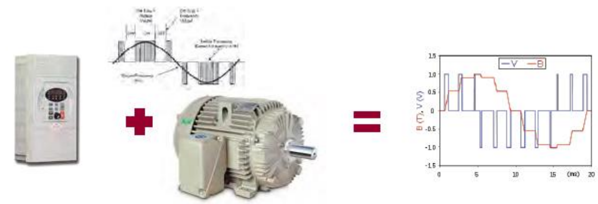
Electric Motors Operated by Variable Frequency Drives (VFD)

Unbalanced voltage condition



- When operated by VFD, the power to the motor is a series of positive and negative pulses instead of a smooth sine wave.
- The input voltage is never balanced because the voltage is either 0 volts, positive, or negative with rapid switching between pulses in all three phases.
- The common mode voltage is usually a "square wave" or "6 step" voltage wave form.

! Bearing protection needed to mitigate electrical discharge machining (EDM) damage in bearings.

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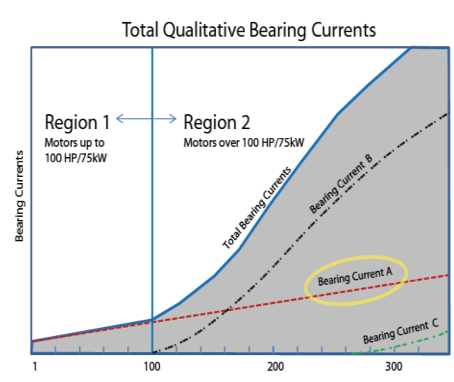
There are two primary sources of bearing currents in VFD driven AC motors *(Bearing Currents A and B)*:

Bearing Current A: is a capacitive induced shaft voltage that discharges in the motor bearings. The VFD induced shaft voltages are capacitively coupled from stator to rotor through parasitic capacitance and create the possibility of bearing currents.

a. Virtually any motor from fractional HP to large motors may have bearing currents from this source.

a. Voltages can discharge through the motor bearings resulting in EDM pitting and fluting failure.

! Best Practice: Ground the motor shaft with the AEGIS® Shaft Grounding Ring to provide a path of least resistance to ground and divert current away from the motor's bearings.



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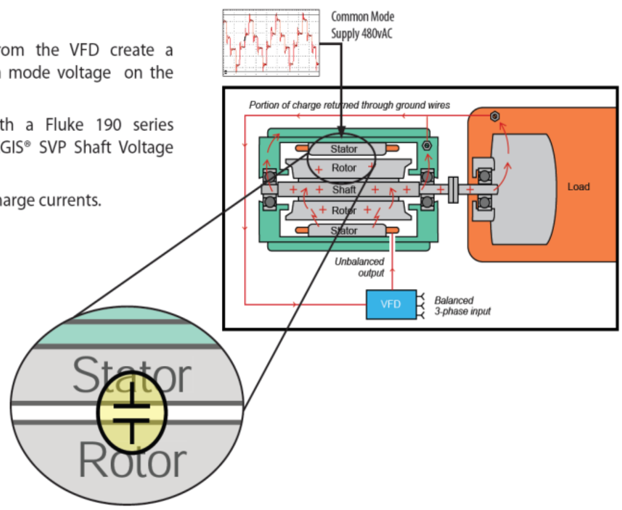
An Electric Motor works like a Capacitor *(Bearing Current A)*

- The pulses to the motor from the VFD create a capacitively coupled common mode voltage on the motor shaft.
- Voltages are measurable with a Fluke 190 series portable oscilloscope and AEGIS® SVP Shaft Voltage Probe Tip.
- Creates electrical bearing discharge currents.



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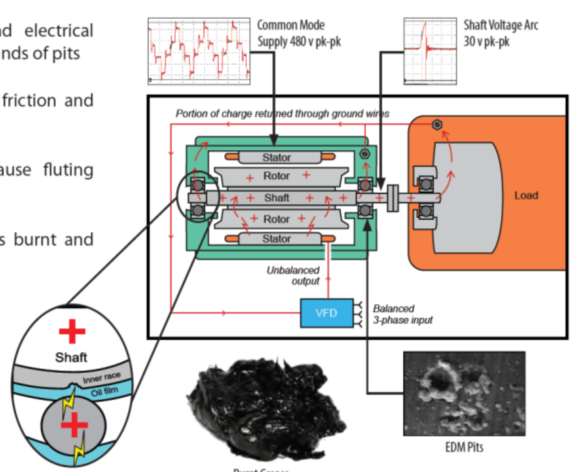
Voltage arcs through the bearing

- Voltages arc through the bearings, and electrical discharge machining (EDM) creates thousands of pits
- Bearings degrade, resulting in increased friction and noise
- Eventually, the rolling elements can cause fluting damage to the bearing races
- Bearing lubrication/grease deteriorates, is burnt and fails
- Potential for costly unplanned downtime



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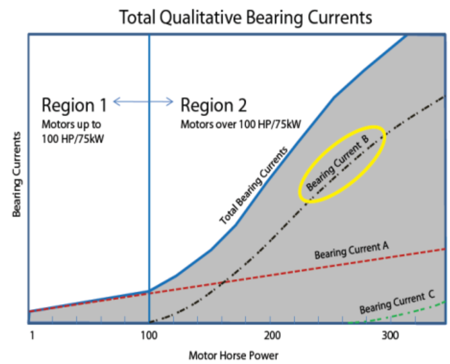
High Frequency Circulating Currents

Bearing Current B: High frequency circulating currents may flow due to a high-frequency flux produced by common-mode currents. High frequency inductive circulating currents from VFDs are in the KHz or MHz frequencies.

a. May be present in motors above 100 HP.

a. Circulate through the motor bearings, shaft to frame.

Best Practice: Interrupting the high frequency circulating current in the bearing is the best approach to mitigating potential bearing damage. Also, motors subject to Current B (high frequency circulating currents) will also be subject to Current A (capacitively induced shaft voltage) and therefore need an AEGIS® Shaft Grounding Ring.



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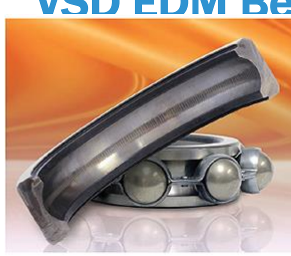
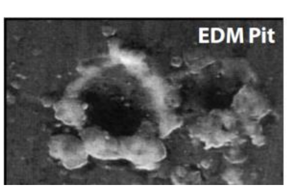
VSD EDM Bearing Damage





Bearing current in inverter-fed motor

To mitigate the bearing currents in inverter-fed motors several techniques can be adopted:

- proper switching frequency selection;
- cables with of proper type and size;
- well designed ground system;
- High frequency filters between the motor and inverter;
- **insulated bearings (coating on rings or ceramic balls));**
- **shaft-ground connection (e.g. using a shaft grounding ring or contact brush);**

the users should ask manufacturers about these issues.

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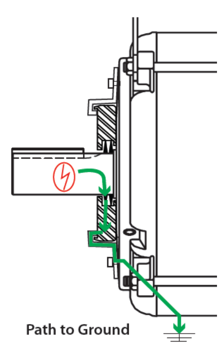
Shaft Bypass Ring



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Insulated Bearings

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New Ceramic Ball Bearings

-Longer lifetime

-Lower friction, low operation Temperature

Comparison of the material properties of bearing steel and bearing grade silicon nitride

Material properties	Bearing steel	Bearing grade silicon nitride
Mechanical properties		
Density (g/cm^3)	7,9	3,2
Hardness, HV 10	700	1 600
Modulus of elasticity (GPa)	210	310
Thermal expansion ($10^{-6}/K$)	12	3
Electrical properties (at 1 MHz)		
Electrical resistivity (Ωm)	$0,4 \times 10^{-6}$ (conductor)	10^{12} (insulator)
Dielectric strength (kV/mm)	–	15
Relative dielectric constant	–	8

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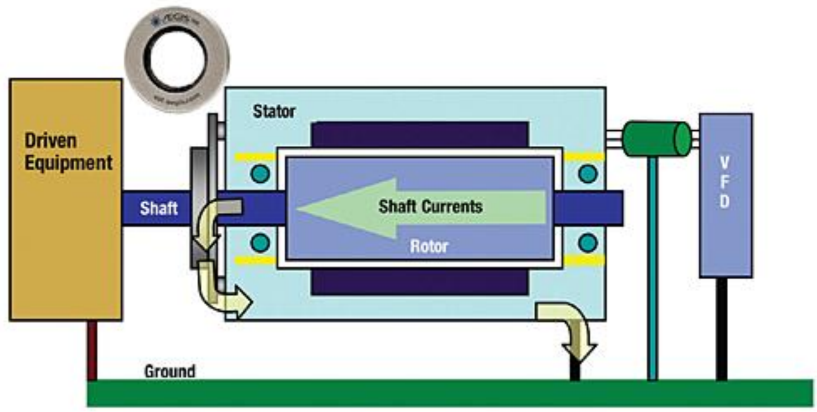
For motors up to 75 kW, where common mode voltages could cause bearing damage, adding a shaft grounding ring to the motor, either inside the motor or externally, provides effective protection against bearing currents for motor bearings as well as attached equipment.



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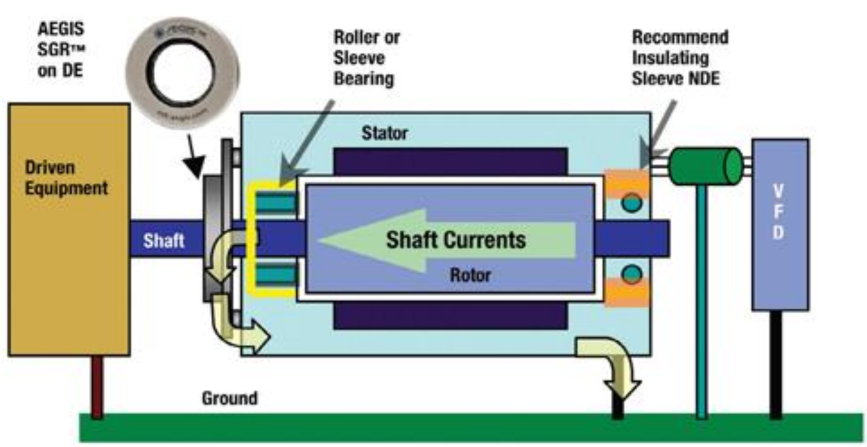
For motors above 75 kW, where both circulating currents and common mode voltages could cause bearing damage, combining an insulated bearing on one end with a shaft grounding ring on the opposite end provides the best protection



Thank you

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11. Motor Controls - Applications

Anibal T. De Almeida

Day 2

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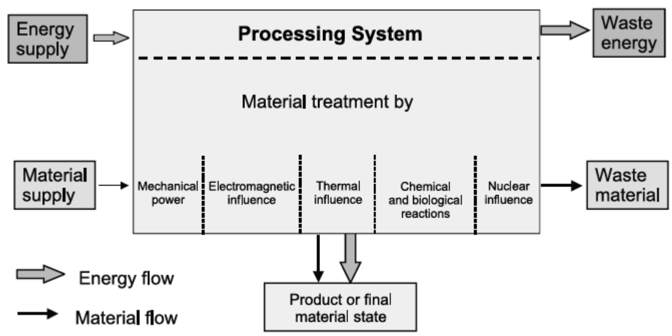
Discussed topics

- Fluid control
- Motion control
- Material handling
- Machine tools

Variables in Processing Systems



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Energy Saving Strategies

Motor Controls

1. Use Variable Speed Drives

   In variable load applications VSDs can save

1. Use controls to turn off idling motors

Energy Saving VSD Applications

1. Centrifugal pumps, fans and compressors in which torque increases with the square of the rotating speed of the motor.
   The electric power sharply increases with the speed (up to the cube) and a smooth adaptation to the real need can lead to large savings.
2. Conveyors, escalators, hoists, cranes and similar types of equipment where the torque is more or less independent from speed.
   The cost and energy efficiency benefits are smaller compared to the first group of applications because the change of input power is only linear with the speed. Regenerative braking can lead to additional savings.

Affinity Laws

$$Q \propto N$$

$$H \propto N^2$$

$$P \propto N^3$$

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$$

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2$$

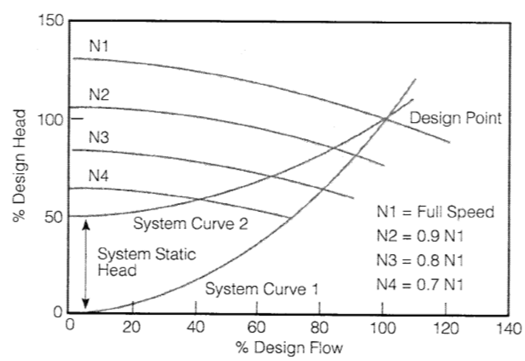
$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3$$

Where,
N = rotational shaft speed
Q = Flow
H = Head
P = Power

Affinity Laws

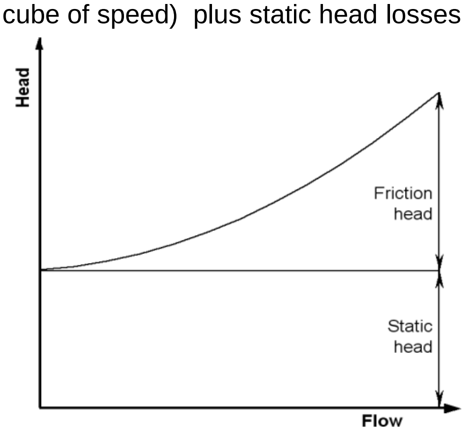
All system losses must be friction losses for the affinity laws to apply.

Therefore, systems with low static head tend to be better candidates for VSDs.



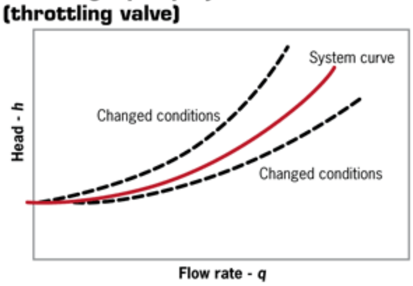
Centrifugal Pumps

Total system resistance from frictional losses (vary as function of the cube of speed) plus static head losses to provide lift.

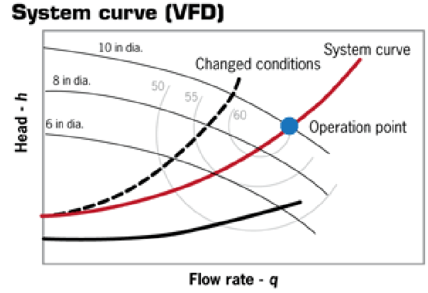


Centrifugal Pumps

Centrifugal pump system curve (throttling valve)

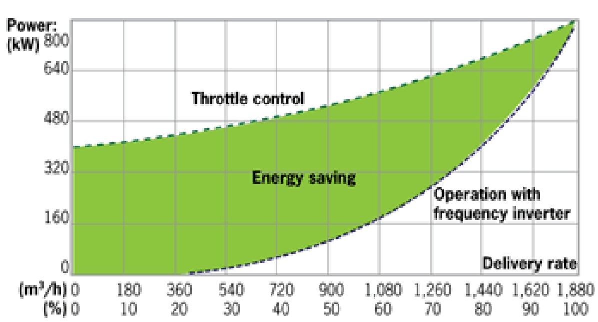


System curve (VFD)



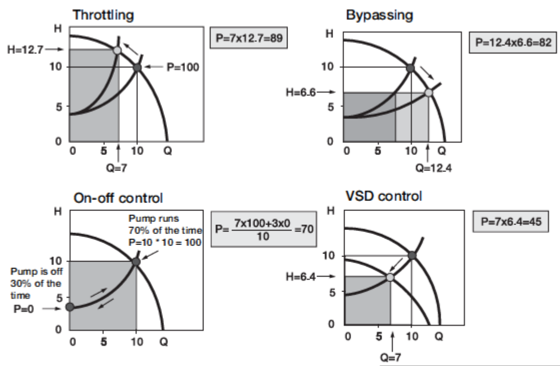
With centrifugal pump systems, throttling changes the system curve by use of a control or throttling valve. But a VFD changes the pump curve by varying the pump speed.

Example



The energy saved by replacing a throttle control with a VFD is given by the area bounded by the two power curves.

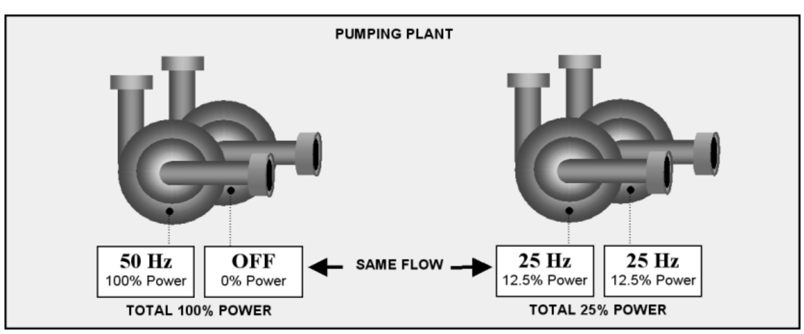
Pump Control Methods



Control	Energy
Throttling	89
Bypassing	82
On-off control	70
VSD control	45

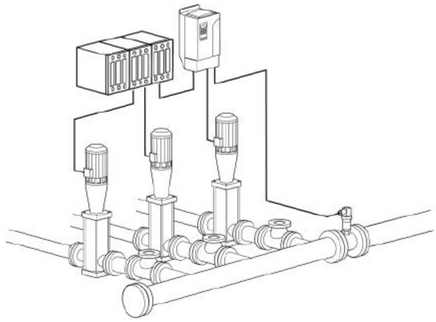
Relative power consumption on an average flow rate of 70% with different control methods.

Pumping plant: Useful relationship to consider with closed loop circulating independent systems (two hydraulic circuits) where “static head" is not a major factor.

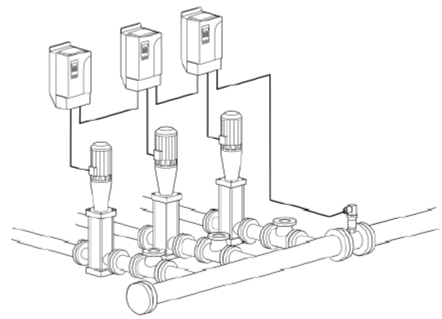


VSDs + Pumps - Example

Using VSDs to control pressure reduces the electrical energy requirements by reducing the amount of hydraulic energy actually produced.



pumping system with one VSD



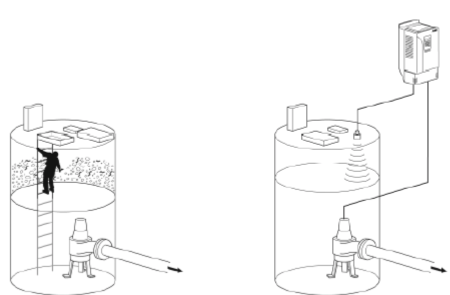
pumping system with three VSDs

Drives share information such as status of the drive, priority, running time, process feedback, etc.

VSDs + Pumps - Example

In many pump applications there is a tank for liquid storage. With liquids containing particles, wall sedimentation (Figure 15, left tank) is a common problem if fixed levels are used when filling and emptying the tank.

Varying randomly the surface level within a range of preset limits, it is possible to avoid wall sedimentation. Manual tank cleaning can then be performed at longer intervals. Eliminating unnecessary stops for tank cleaning maximizes operating time.



Pump Systems

- Pumps purchased based on cheapest initial price can be upgraded or replaced with higher efficiency models.
- Erosion by abrasive particles can affect clearances and efficiency.
- Special coatings can be applied to repair cavities and smooth internal surfaces to reduce friction losses.
- The suction inlet design should ensure that flow approaching the inlet is uniform and steady.
- A straight run of suction pipe of at least eight diameters in length immediately prior to the pump suction flange is recommended.

Pump Systems

European Guide to pump efficiency for single stage centrifugal pumps

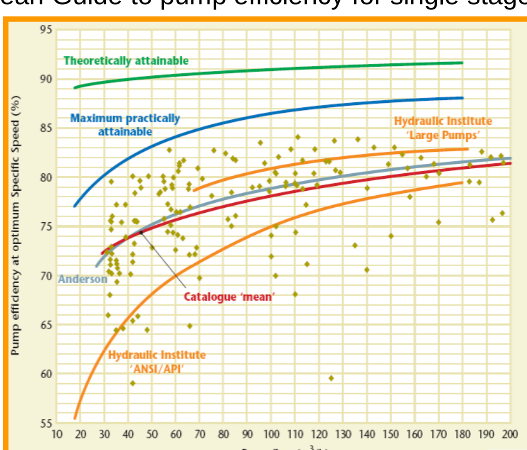


Figure 9: Comparison of efficiencies of end suction pumps from various sources.

http://energyefficiency.jrc.cec.eu.int

Exercise

- Using ABB PumpSave Software tool calculate the savings between using VSD or throttle to control flow:

http://new.abb.com/drives/software-tools/pumpsave

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Exercise

Pump

Nominal volume flow	560	m3/h
Nominal head	33	m
Max head	44	m
Efficiency	88	%
Liquid density	1000	kg/m3
Static head	5	m
Existing flow control	Throttling control	

Exercise

Drive and motor

Supply voltage	400 V	
Required motor power	**62.9**	kW
Motor power	75	kW
Motor efficiency	95	% IE3
Improved control by	ACS550	

ACS550-01-157A-4

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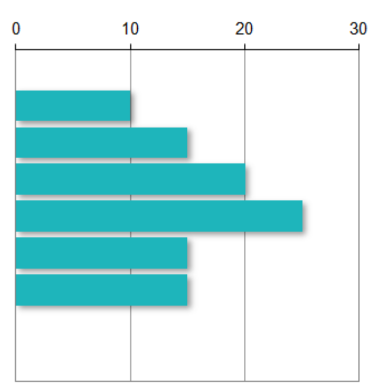
Exercise

Flow profile

Annual running time 8760 h

DEFAULT

Flow				
100 %:	0	% =	0	h
90 %:	10	% =	876	h
80 %:	15	% =	1314	h
70 %:	20	% =	1752	h
60 %:	25	% =	2190	h
50 %:	15	% =	1314	h
40 %:	15	% =	1314	h
30 %:	0	% =	0	h
20 %:	0	% =	0	h
Sum	**100**	%	**8760**	h



Exercise

Flow profile

Annual running time 8760 h

Flow DEFAULT

Flow	%		h	
100 %:	0	% =	0	h
90 %:	10	% =	876	h
80 %:	15	% =	1314	h
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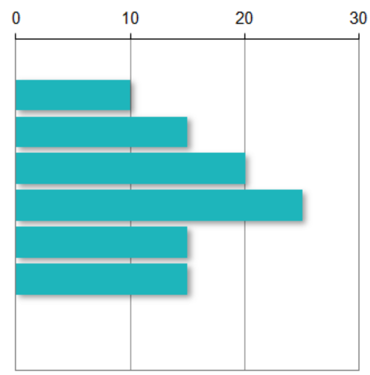
60 %:	25	% =	2190	h
50 %:	15	% =	1314	h
40 %:	15	% =	1314	h
30 %:	0	% =	0	h
20 %:	0	% =	0	h
Sum	**100**	%	**8760**	h



Exercise

Economic data

Currency unit	€	
Energy price	0.075	€/kWh
Investment cost	6000	€
CO2 emission	0.45	kg/kWh

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Exercise

Calculated savings

Annual energy saving	**226**	**MWh**
Energy consumption		
with existing control method	**428**	MWh
with new control by ABB drive	**203**	MWh
Saving percentage	**52.7**	%

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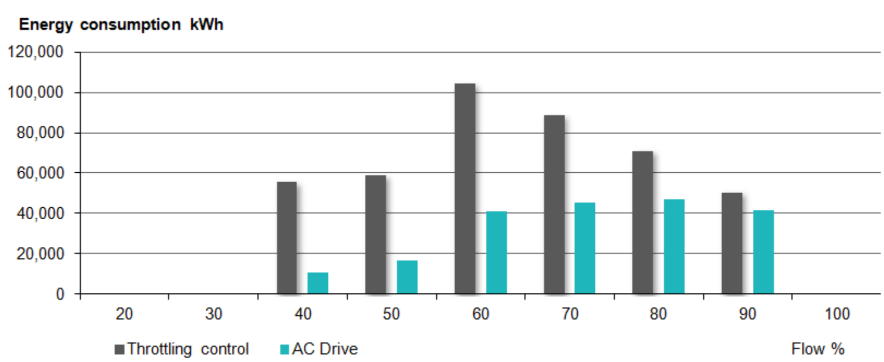
Exercise



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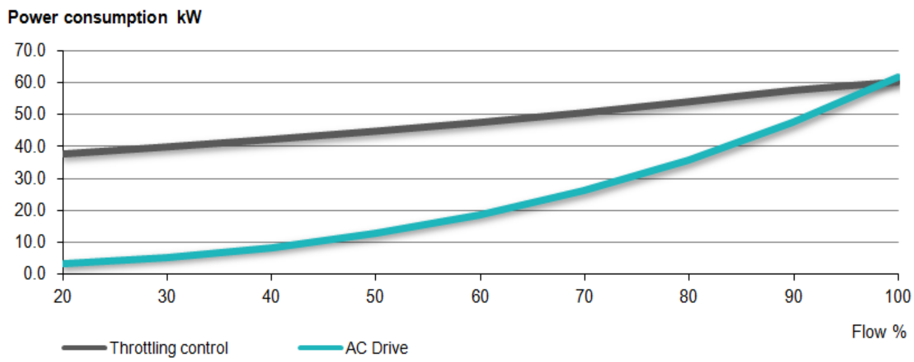
Exercise



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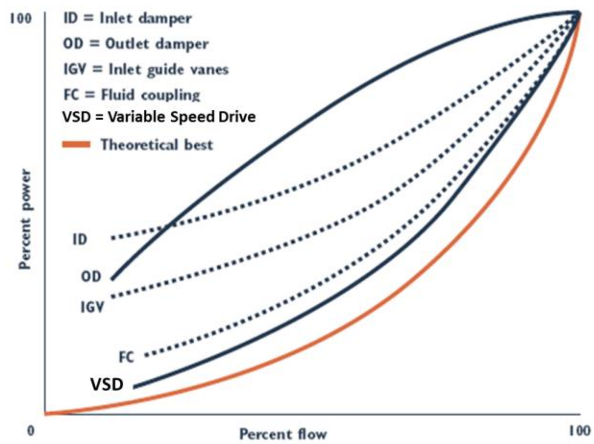
Exercise

Economic Results

Annual Saving	**16,943**	€
Payback period	**0.4**	years
CO2 reduction	**101.7**	t/year

Fan systems



Fan Systems

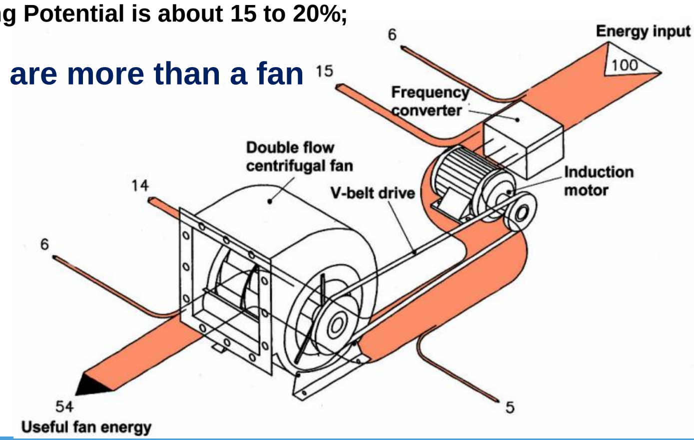
- Fans originally purchased based on cheapest initial price can be upgraded or replaced with higher efficiency models.
- Variable speed drive (VSD) control provides superior savings over the full range of flow.
- Causes of high system resistance include dirty screens, filters and coils.
- Flow that is lost due to leakage is a waste of energy.
- Fan systems are susceptible to developing leaks in flexible connections, at loose or distorted flanges and due to deteriorated gaskets.

Fan Systems

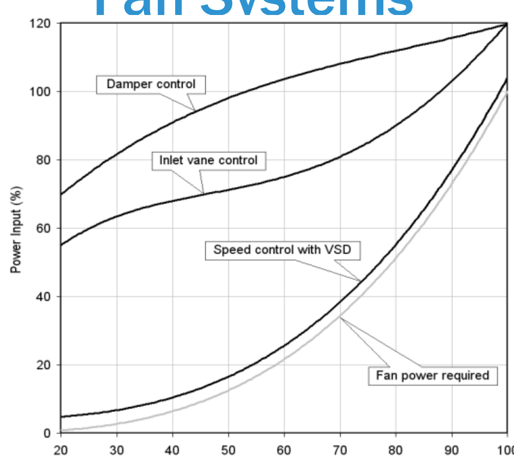
-Fan Saving Potential is about 5 to 10 %;

-Fan System Saving Potential is about 15 to 20%;

Fans systems are more than a fan



Fan Systems



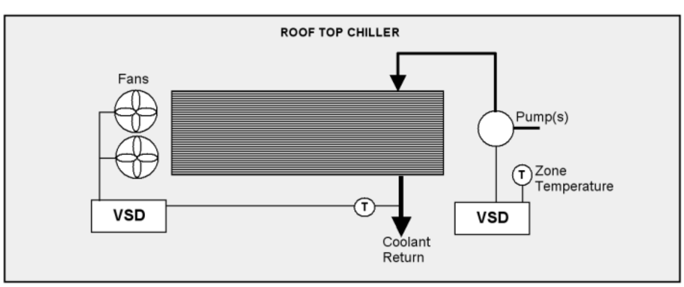
Input power for different flow control methods of a centrifugal fan.

Fan Systems

- The most efficient flow of air into a fan is a non-restricted, uniform path.
- Elbows located directly on fan inlets increase losses and are to be avoided.
- Obstructions at fan inlets and outlets disrupt the flow, causing turbulence.
- Flex connections often cause poor transitions that disrupt flow.

VSD Application

Application of VSDs on a roof top chiller.



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Low-speed direct drive applications

- Paper mills,
- Cooling towers,
- Sewage and water treatment plants,
- Cranes,
- Mining machines and more…

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Low-speed direct drive applications

- Higher overall system efficiency for direct drive (specially at speeds less than 100 rpm)
- Eliminates the mechanical gear and the corresponding losses and maintenance requirement.
- Lower system weight and volume as compared to geared drive.

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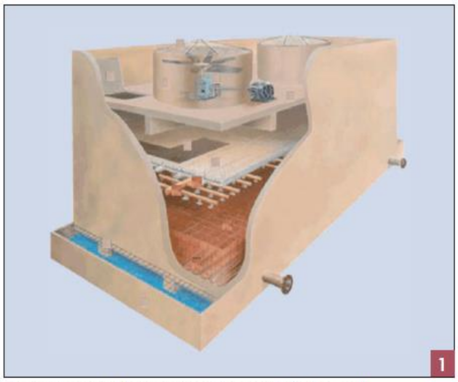
Low-speed direct drive applications Cooling tower



Typical cooling tower arrangement with two cells.

Typical fan drive arrangement.

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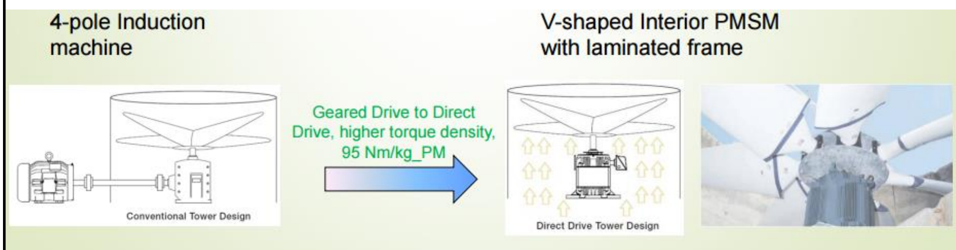
Low-speed direct drive applications Cooling tower

Existing Design Gearbox with Drive Shaft

Drop In Replacement No Pedestal Modification

Fan Mounts Directly To Motor Shaft

Low-speed direct drive applications Cooling tower

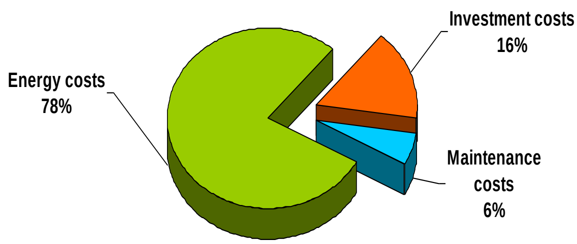


Low-speed direct drive applications Cooling tower

- The motors used for the HVAC cooling towers are ranging from few kW to few hundreds of kW.
- The Speed of cooling fan : 10-300 RPM
- Conventionally, cooling systems employ the use of a motor driven fan, typically coupled to a gear reducer via a drive shaft
- Today, many plants have lost the experienced maintenance personnel needed to properly take care of this mechanical equipment.

Compressor Systems

- Compressed air accounts for 10% of industrial consumption of electricity
- Compressed air systems often have poor energy efficiency: possible energy savings are in the range from 5% to 50%...

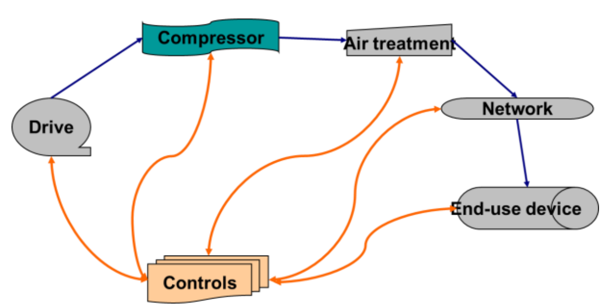


Assumptions

Power 110 kW
Equipment life 15 years
Operating hours 4000 h/year
Electricity price 5 c€/kWh

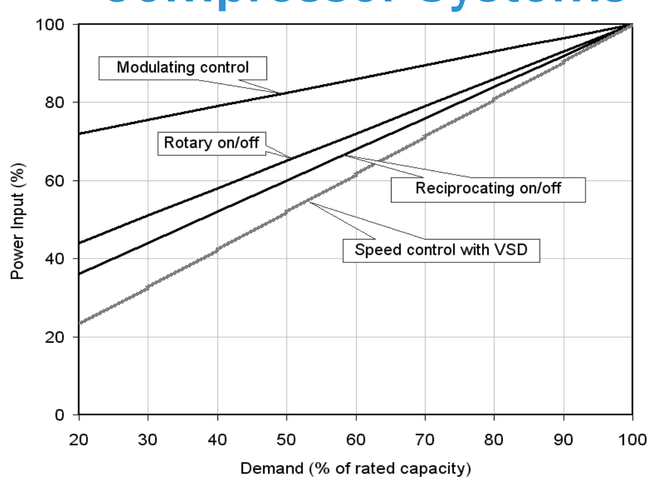
Compressor Systems

- The maximum overall system energy efficiency is limited by the component with the lowest efficiency in the system.
- The compressor itself is only one element of the system.



Energy savings measure	**Applicability** % applicable and cost effective	**Gains** reduction in annual energy consumption	**Potential contribution** Applicability x Gains
Reducing air leaks (develop a proper maintenance with a regular air leak detection program)	80%	20%	16.0%
Overall system design, to match air pressure, volume and quality to the needs, including multi-pressure systems	50%	9%	4.5%
Recovering waste heat for use in other functions	20%	20%	4.0%
Drives improvement - integration of adjustable speed drive, which is very cost effective when load shows variable conditions and in multi-machine installation	25%	15%	3.8%
Upgrading of compressor	30%	7%	2.1%
Use of sophisticated control systems, to match compressor output to system air demand, by optimizing transitions between the different states of the compressor (sequencers, control…)	20%	12%	2.4%
Optimizing certain end use devices, when buying the end uses, by choosing electrical or hydraulic equipment rather than compressed air end use devices	5%	40%	2.0%
Reducing frictional pressure losses (for instance increasing pipe diameter)	50%	3%	1.5%
More frequent filter replacement	40%	2%	0.8%
Drives improvement - use of high efficiency motors, especially for new systems and small machines	25%	2%	0.5%
Improved cooling, drying and filtering	10%	5%	0.5%

Compressor Systems



Energy saved by using a VSD on a rotary screw air compressor.

Compressor Systems

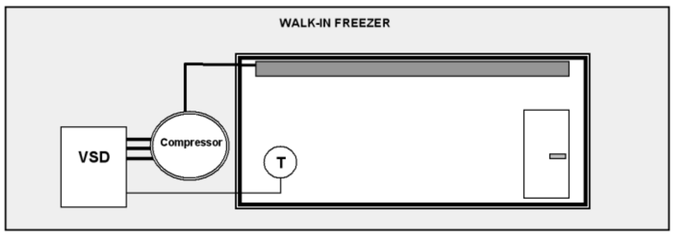
- Install intakes in locations providing the cleanest, driest and coolest air possible – outdoors if possible.
- Compressors charge the system to the preset pressure and maintain it by various methods includingrecirculation, venting, stop/start and speed control with variable speed drives.
- Choose filter systems with the lowest pressure drop.
- It is estimated that compressor cooling is approximately 5% to 7% of overall costs. Compressor systems give off high volumes of low-grade waste heat, which can be used efficiently by some industrial processes, boiler feed water, heating or ventilation systems.

Compressor Systems

- Leakage is the Largest Single Waste of Energy Associated with Compressed Air Usage
- Consider Alternate, More Efficient Methods. Low-pressure applications such as agitation, part ejection, cleaning, cooling and fume removal can be effectively done at greatly reduced cost by blowers or air amplifiers.
- Use Lowest Pressure Possible
- Pipe pressure loss is proportional to pipe length; the square of the compressed air velocity in the pipe is inversely proportional to the pipe diameter. Every 2 psi increase in pressure drop uses 1% additional power. Keep air velocities below 9 m/s.

VSD Application

Application of VSDs on a variable speed refrigeration compressor (ESTIMATED SAVINGS: 25%).



Other Energy Saving VSD Applications

3. Changes in load and speed but can benefit from a VSD in other ways like process control, soft starting and stopping, as well as the requirement of an especially high starting torque or of regenerative braking.
   The cost and energy efficiency benefits are small compared to the first two groups. VSDs allow for voltage optimization to improve motor efficiency if the torque changes.
4. Motion Control – AC drives can now provide high performance torque/speed control, similar to motor servo drives.

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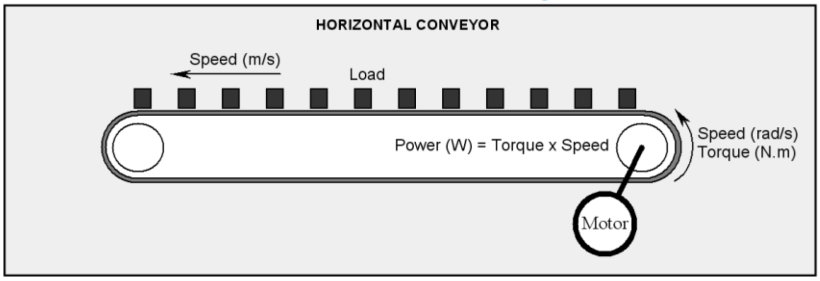
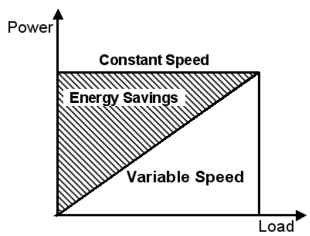
VSDs in conveyors





Energy savings in a conveyor using speed control, in relation to the typical constant speed.

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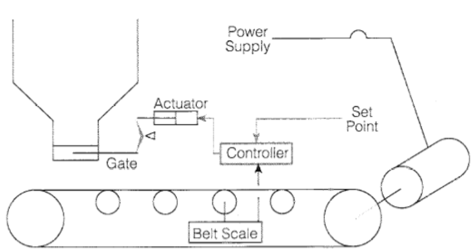
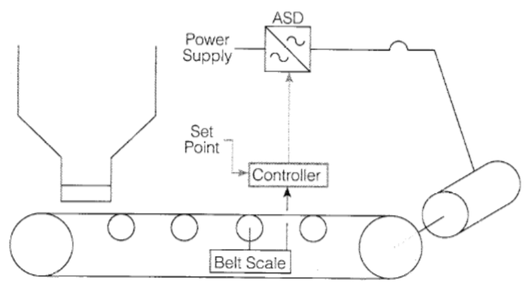
VSDs in conveyors



Coal feeder with gate aperture loading control

VSDs in conveyors



Coal feeder loading control with VSD

VSDs in Conveyors
Reducing electricity demand

Example: Filling a coal bunker from an outside pile.

- A system designed to fill the bunker in eight hours will require about three times the power demand of one design to keep up with the binker outflow.

- Another option is to fill the bunker at off-peak hours.

VSDs in Conveyors

Belt conveyors found in production lines can benefit from the use of VSDs + IM to accomodate changes in production lines.

Traditional methods to adjust speed are gear boxes, varible sheaves, and DC motors.

These methods have flexibility and maintenance limitations when compared to VSDs. For example:

- Gear boxes have only discrete speeds and production lines must be stopped to change speed.
- DC motors have more maintenance due to brushes

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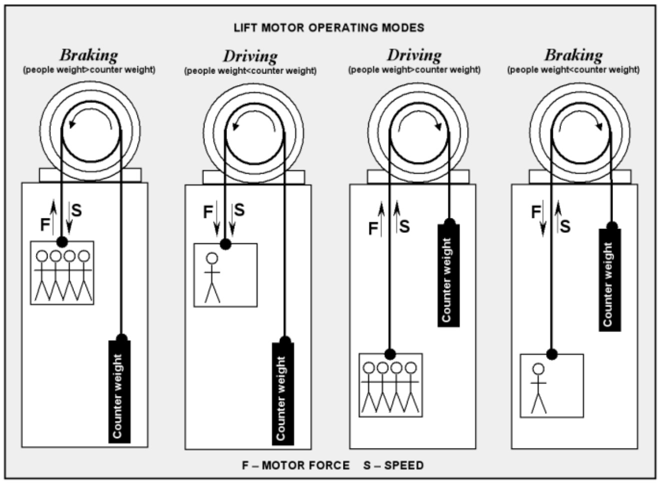
VSDs in conveyors

Main Benefits:

- Precise process control
- Turndown ratio (The ratio between the maximum and minimum throughputs possible. Typically expressed as a ratio like 5:1 or 10:1)
- Response time
- Reduced wear rates
- Soft-start capability

VSDs in Lifts



Machine tools

- Lathe, drills, milling machines are examples of machine tools.
- Rotary speed depends on the size and material type, finishing required, etc.

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VSDs in Machine tools

- VSDs provide continuosly adjustable speed that can be changed while the cutting operation is in progress.
- VSDs can provide high torque at low speed and low torque at high speed. These are requirements of most cutting operations.
- VSDs are also well suited to the digital control systems of automated machining.

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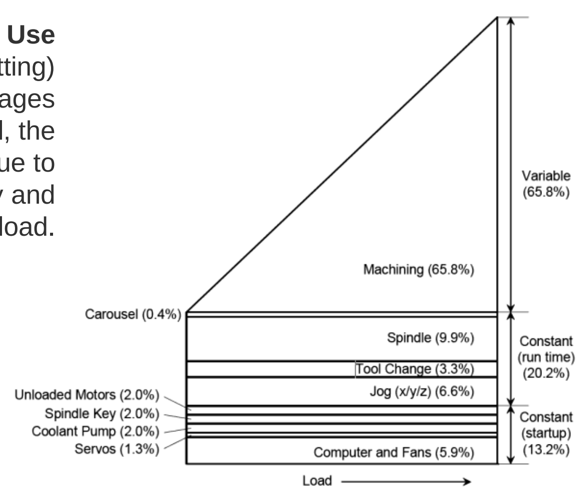
Machine Tools

Energy Use
Actual machining (cutting) energy typically averages just 15% of the total, the remainder is due to overhead energy and running at low load.



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Machine Tools

Energy savings – but not at any cost!

- ✓ Net machine efficiency is poor
- ✓ Value of throughput greatly exceeds energy costs
- ✓ Meddle at your peril.
- ✓ Do not play with machine settings
- ✓ Look for the extras

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Machine Tools - what to look for

- ✓ Long running hours
- ✓ High Power consumption
- ✓ Long periods of idle time
- ✓ Multi-purpose machines
- ✓ Lots of ancillaries
- ✓ Over-sized machines
- ✓ Blunt tools

Machine Tools - what to look for

- ✓ Coolant pump. Switch off, control speed
- ✓ Idle detection – sense load. Beware of frequent on/off cycling.
- ✓ Is the cooling fan on a thermostat?
- ✓ Is there an interlock to the chip remover?
- ✓ Focus on what is happening between cutting.
- ✓ Is there a better machine available?

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Machine Tools

Identical production lines?

- ✓ Look for data on throughput and energy consumption.
- ✓ Is equipment known to be different?

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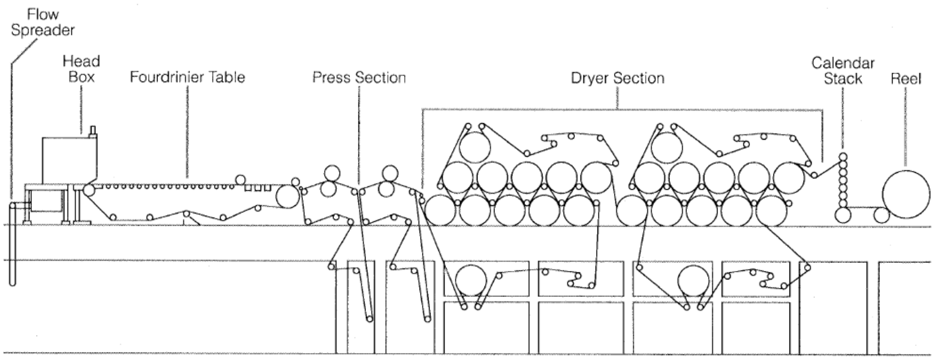
Paper Machine

- VSDs can accurately control the speed of the paper machine relative to the type and calyper of the paper.



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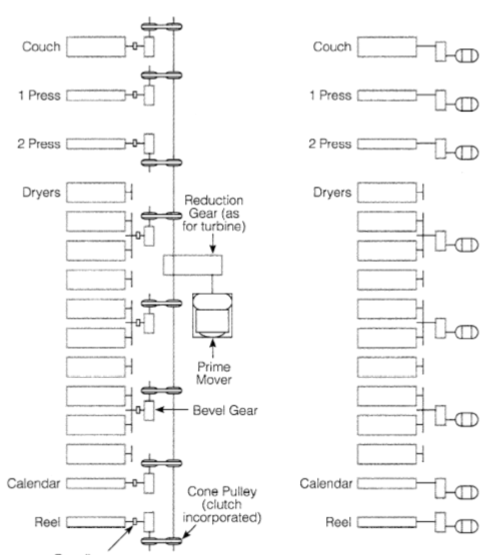

Using VSDs on the pumps and fans that support the paper machine can improve flow and save energy (e.g. Dryer fans; filtrate, dilution, cleaner and broke tank pumps).

These pumps generally operate well below rated capaciry, with higher capacities needed only during startup and upsets.

Furthermore, it avoids the use of gears and benefits from the inherent soft-start capabilities of VSDs.

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Plastic Extrusion

Basic Requirements:

- The extruder should be capable of processing polymer at high and consistent output rates. *To aid this, a drive with a high degree of torque/speed stability is required.*
- The polymer produced should be within an acceptable melt temperature range, and the temperature should not vary. A good-quality temperature controller with PID control will enhance temperature control.

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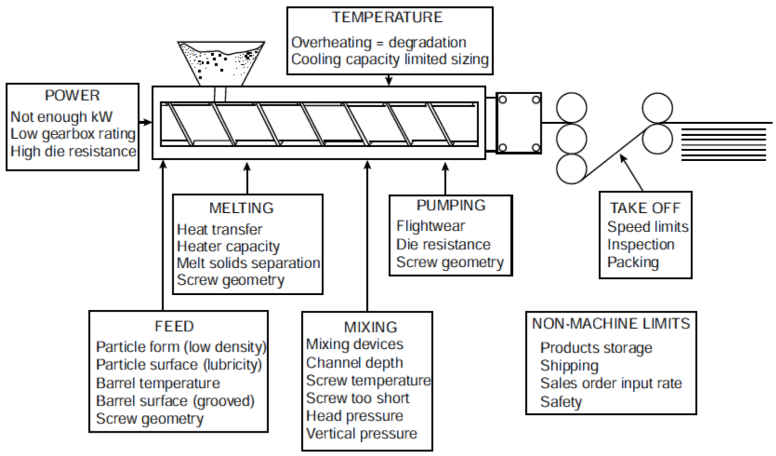
Plastic Extrusion

Basic Requirements (cont.):

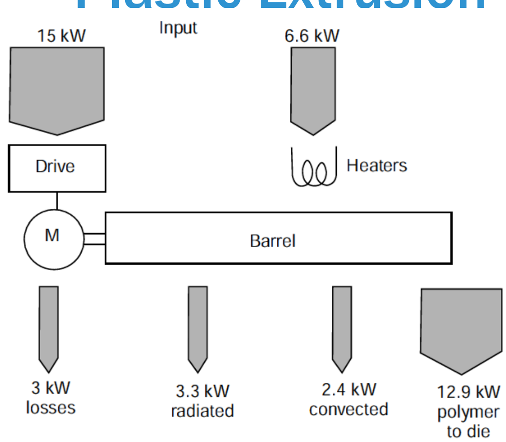
- The pressure developed in the extruder should be consistent. This requires a combination of good control of process variables and speed. *The use of a process controller and a carefully considered choice of variable-speed drive will aid consistent production quality.*
- The polymer should be sufficiently well mixed and not contain any low temperature volatiles that would spoil product appearance. Mixing is assisted by the screw design, both with single screws and twin screws.

Plastic Extrusion



Factors imposing output limitations

Plastic Extrusion



Typical Extruder Energy Balance

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Plastic Extrusion - Drives

Benefits:

- Power consumption becomes a function of applied load, thus creating a power saving as compared with the old a.c. drives.
- Extremely high resolution of speed holding is possible by using an encoder/tachometer feedback from the motor. This helps when a constant throughput is required from the extruder.
- As the screen becomes progressively obstructed, the pressure increases in the barrel causing an increase in the torque required to drive the extruder. A converter compensates automatically, to aid in achieving a constant throughput.

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Plastic Extrusion - Drives

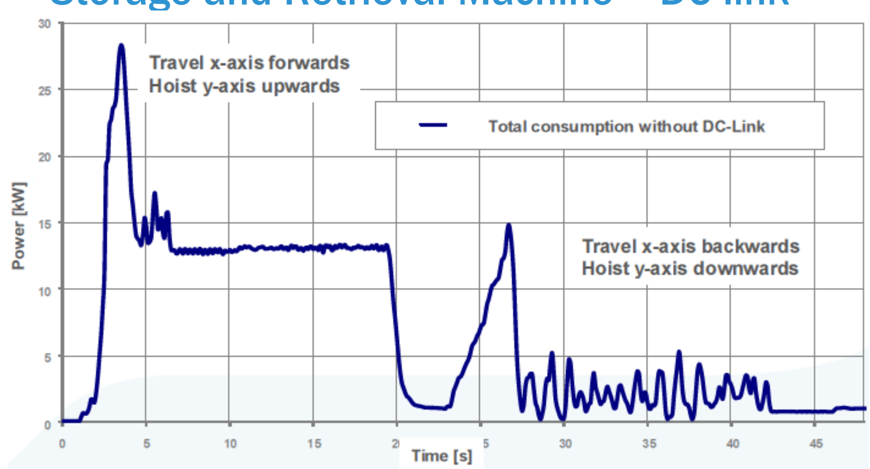
Benefits (cont.):

- For extruders that need to run at different speeds for different products, the speed is easily varied by the use of a potentiometer or increase/decrease push-buttons.
- Modern drives have serial communication ports to connect with computers and other drives. Computers enable automatic control of integrated systems, and as more extruder manufacturers move towards continuous production lines, fully integrated controls become essential. There is the further advantage that drive parameters can be changed ‘on line’. The communication ports can also be used for data collection.

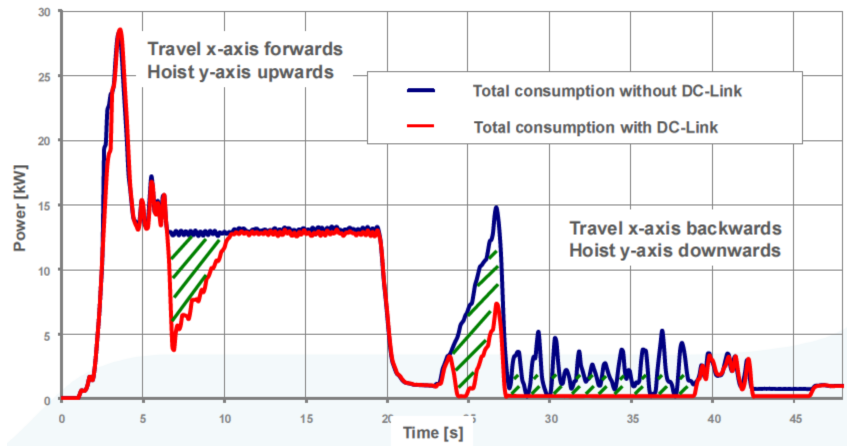
Storage and Retrieval Machine – DC link

- With conventional control, kinetic or potential energy is dissipated via a braking resistor
- With the intelligent control of the travel and hoist drives, kinetic or potential energy is used directly in the second axis

Storage and Retrieval Machine – DC link

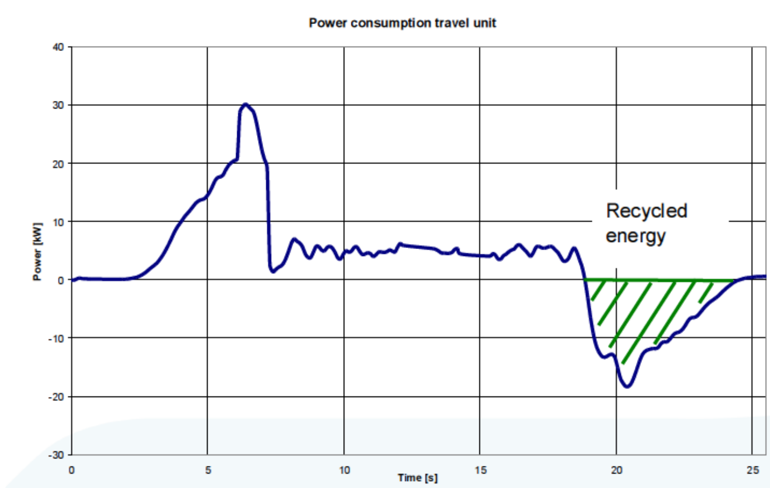


Storage and Retrieval Machine – DC link

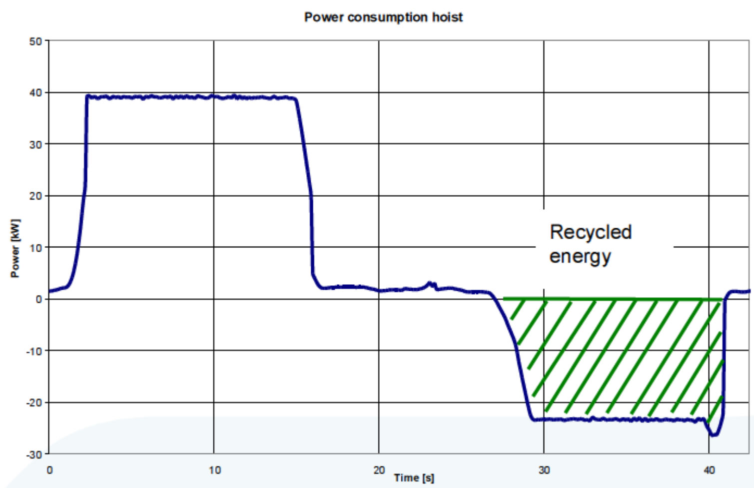


The total energy consumption falls dramatically by as much as **25%** with maximum unit power and optimum utilization of the unit dynamics

Storage and Retrieval Machine - Regeneration



Storage and Retrieval Machine - Regeneration



Storage and Retrieval Machine - Regeneration

Installing VSDs with regenerative capabilities can save up to **40 %** of the energy consumption of a Storage and Retrieval Machine.

Thank you