MINISTRY OF
INDUSTRY AND TRADE

EU - VIET NAM SUSTAINABLE ENERGY
TRANSITION PROGRAMME (SETP)

Global Gateway
Funded by
the European Union

UNIDO
UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Project "Accelerating energy efficiency (EE) in large industries through energy management system, system optimisation and the promotion and adoption of EE in SMEs" (IEEP)

EXPERT TRAINING PROGRAMME ON MOTOR SYSTEMS OPTIMISATION

Ha Noi, 01- 04/12/2025

AGENDA

Expert Training on Motor System Optimisation (MSO)
01-04 December 2025

At: - Adonis Hotel – 55 Quang Trung Street, Hai Ba Trung Ward, Ha Noi
- Xuong Giang Paper Company – Bac Ninh province

Day 1 (Adonis Hotel)

Time	Contents	Speakers
8.00-8.30	Registration and welcome	
8.30-8.45	Opening speech	Representative of IEEP Project Office
8.45-9.00	Introduction to course	Lecturer
9.00-10.00	Motor Technologies	Lecturer
10.00-10.15	**Tea-break**	
10.15-10.45	Motor Standards	Lecturer
10.45-12.00	Motor Operations & Controls	Lecturer
12.00-13.15	**Lunch at the hotel**	
13.15-13.45	Centrifugal Machines	Lecturer
13.45-15.00	Cases: Centrifugal Machines	Lecturer
15.00-15.15	**Tea-break**	
15.15-16.00	Compressors	Lecturer
16.00-16.30	Cases	Lecturer

Day 2 (Adonis Hotel)

Time	Contents	Speakers
8.00-8.30	Registration	
8.30-8.45	Review of Day 1 (Q&A)	Lecturer
8.45-10.00	Power Quality	Lecturer
10.00-10.15	**Tea-break**	
10.15-10.55	Maintenance & Repair	Lecturer
10.55-11.30	MSO Assignment Report	Lecturer
11.30-12.00	Introduction to Project Finance	Lecturer
12.00-13.15	**Lunch at the hotel**	All the class
13.15-13.45	Cases: Project Finance	Lecturer
13.45-15.00	Demonstration of Measurement Tools	Equipment supplier, Lecturer
15.00-15.15	**Tea-break**	
15.15-15.45	Demonstration of Measurement Tools	Equipment supplier, Lecturer
15.45-16.15	Site Visit Preparation	Lecturer
16.15-16.45	Next Steps	Lecturer

Day 3 (Xuong Giang Paper Company)

Time	Contents	Speakers
8.00-8.30	Registration	
8.30-9.00	Welcome and Introduction	IEEP Project, Xuong Giang Paper Company
9.00-9.30	Plant Overview & Welcome by Top Management	Top Management of Xuong Giang Paper Company
9.30-9.40	Safety Briefing	Lecturer
9.40-10.00	Training Objectives & Split into Groups	Lecturer
10.00-10.15	**Tea-break**	
10.15-11.00	Review of Motor Systems	Lecturer
11.00-12.00	Site Visit - First inspection of the system	All the class
12.00-13.15	**Lunch**	All the class
13.15-14.00	Motor System Assessment Session 1	All the class
14.00-15.00	Motor System Assessment Session 2	All the class
15.00-15.15	**Tea-break**	
15.15-16.00	Motor System Assessment Session 3	All the class
16.00-16.30	Analysis of observations and data	All the class

Day 4 (Xuong Giang Paper Company)

Time	Contents	Speakers
8.00-8.30	Registration	
8.30-8.45	Opening Discussion (Q&A)	All the class
8.45-10.00	Analysis of observations and data	All the class
10.00-10.15	**Tea-break**	
10.15-12.00	Summarise findings & observations	Lecturer
12.00-13.15	**Lunch**	All the class
13.15-14.00	Opportunities for each motor system	All the class
14.00-15.00	Presentation of findings & opportunities	All the class
15.00-15.15	**Tea-break**	
15.15-16.00	Feedback to Management	All the class
16.00-16.30	Next steps - Assignments & Webinars	Lecturer

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UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

Motor Systems Optimisation
Expert Training (Viet Nam)

Siraj Williams
December 2025

Welcome

- Name
- Organisation
- Energy management experience
- What do you expect to learn over these few days?

Acknowledgements

UNIDO

- Marco Matteini, Vienna

Original authors

- Prof Anibal T de Almeida, Portugal
- Dr Hugh Falkner, United Kingdom

Workshop Objectives

Why are we here?

Learn from each other and share experiences and knowledge

Gain understanding of the fundamentals of motor driven systems

Review new technologies and updates in industrial applications of motor driven systems

Agenda - 4 Day Programme

- Day 1 – Classroom
- Day 2 – Classroom
- Day 3 – On site assessment
- Day 4 – Onsite assessment and review

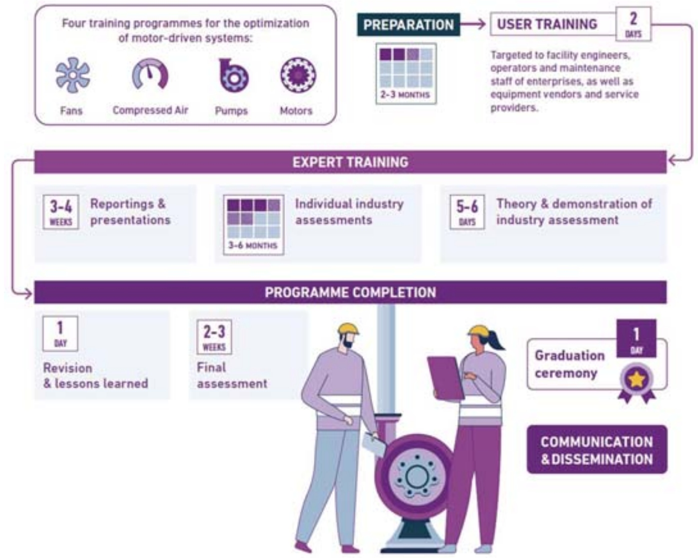
Agenda Day 1 – In Class Session

Time	Topic	Start Slide	End Slide	Slide count
Day 1 - Classroom				
08h30	Welcome and Introduction			
08h45	Introduction to course	1	7	7
09h00	Motor Technologies	8	34	27
10h00	TEA			
10h15	Motor Standards	35	52	18
10h45	Motor Ops & Controls	53	88	36
12h00	Lunch			
13h15	Centrifugal Machines	89	100	12
13h45	Cases: Centrifugal Machines	101	129	29
15h00	TEA			
15h00	Compressors	130	157	28
16h00	Cases	156	163	8
16h30	End of Day	164	164	1

The MSO Training Cycle

Key elements:

- User training class
- Expert training class and site demonstration
- Individual industry assessment
- Final examination



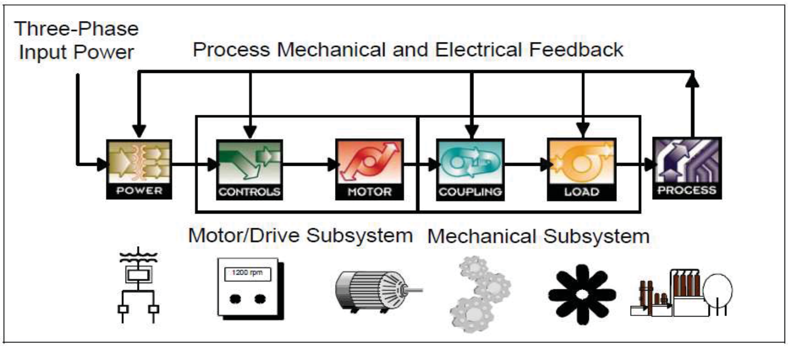
01. Electric Motor Technologies

Electric Motor Technology

User Training Review

- 70% of industrial energy
- More than 50% of all electrical consumption
- 90% of all industrial motors are squirrel cage induction
- Losses (electrical, magnetic, mechanical, stray)
- Traditional motors (DC, AC Synchronous, AC induction)
- Switched reluctance motor
- Synchronous reluctance motor

The Motor System



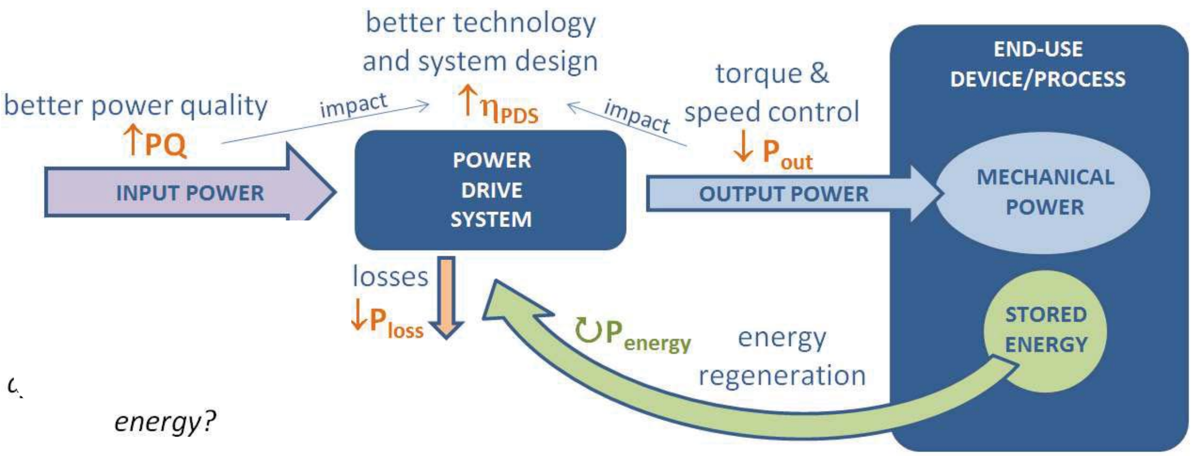
$$\eta_{system} = \eta_{VSD} \cdot \eta_{motor} \cdot \eta_{transmission} \cdot \eta_{end-use} = \frac{P_{useful}}{P_{input}}$$

Energy Efficient Motor Systems

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)

Strategies to improve electric motor system efficiency



energy?

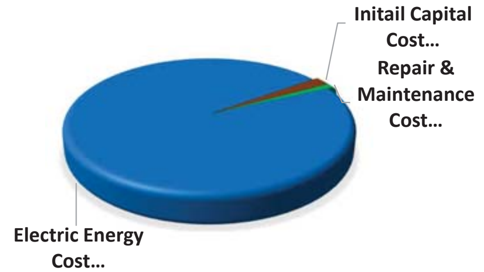
Opportunities for Savings

	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.

Source: IEC60034-31

Squirrel-cage Induction Motors Lifecycle Cost

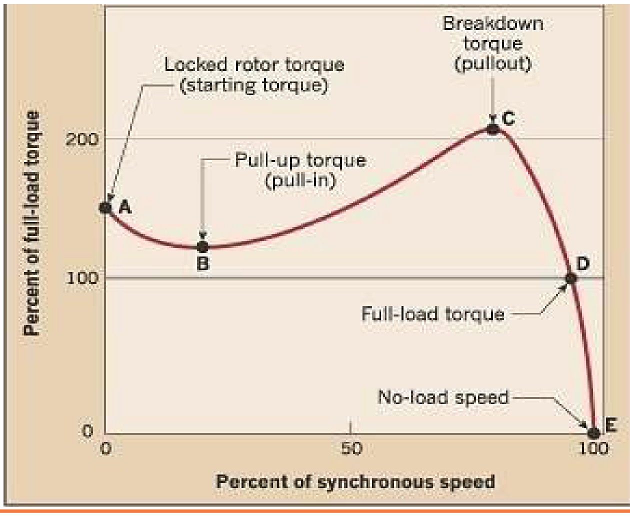
- In Industry, an induction motor can consume per year an energy quantity equivalent to 5-10 times its initial cost, along all its lifetime of about 12-20 years, representing 60-200 times its initial cost.
- This fact justifies a life-cycle cost (LCC) analysis including the repair and maintenance.



11 kW IE3 Motor, 4000 operating hours per year, 15 years life cycle US$ 0.1/kWh

Source: ISR – University of Coimbra

AC Induction Motor – Typical Torque-speed Curve



$$Power\ (kW) = \frac{2\pi \times Speed\ (rpm) \times Torque(kNm)}{60}$$

Typical Features of a Premium Induction Motor

Induction Motor with Die Cast Copper Rotor

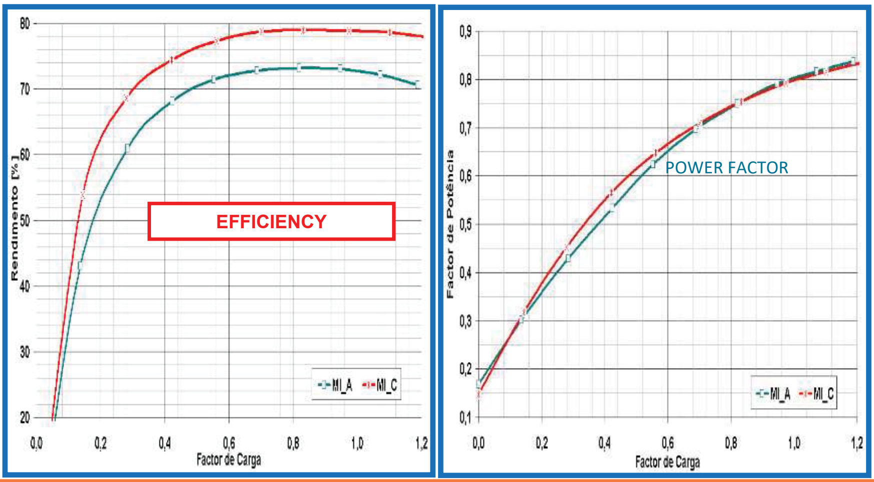
Most induction motors have a squirrel cage made with die cast aluminium

- A copper rotor is a rotor made of electrical steel (laminations) where the slots and end rings are filled with copper instead of the traditional material (aluminum).

- The use of copper in place of aluminum can lead to improvements in motor energy efficiency due to a significant reduction in I^2R losses in the rotor.
- Higher cost and larger rotor inertia

Induction Motors with Die Cast Copper Rotor

Die Cast Copper Rotor vs Aluminium Rotor (4 pole, 1.1 kW)



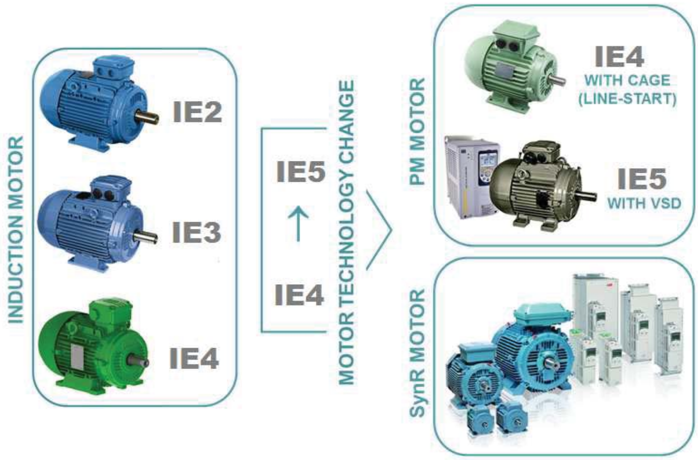
What is an IE4 and IE5 Motor?

IE3 have at least 15% lower losses than IE2 motors

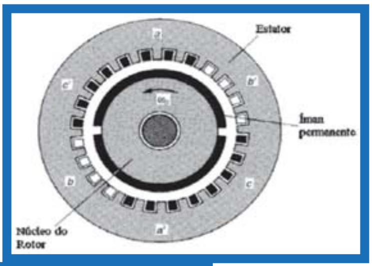
A Super-Premium IE4 Class has at least a 15% loss difference in relation to IE3 / Premium.

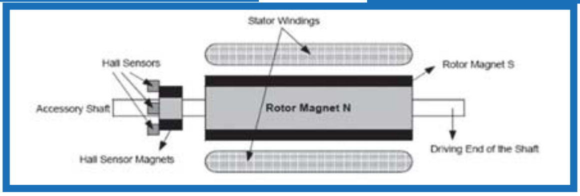
A Ultra-Premium (new IE5 Class) has at least a 15% loss difference in relation to IE4 / Super- Premium.

Technologies for Higher Efficiency Motors



Permanent Magnet Synchronous Motors (PMSM)





Permanent Magnet Synchronous Motor - Types

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

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

Surface PM Machines

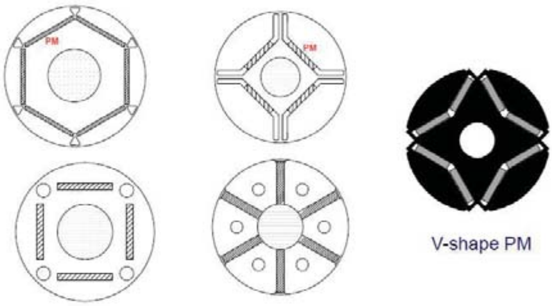
- Better choice for direct drive solutions - at a cost of arc shaped magnets- but are more prone to demagnetization under higher ambient temperature

Interior PM Machines

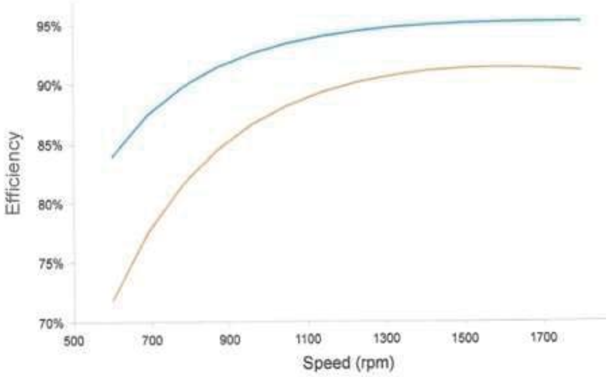
- Less susceptible to demagnetization as compared to surface type PM machines
- more reliable under higher temperatures and extreme operating conditions
- cost of IPM machines lower as compared to SPM and PMPM machines.

Permanent Magnet Synchronous Motors (PMSM)

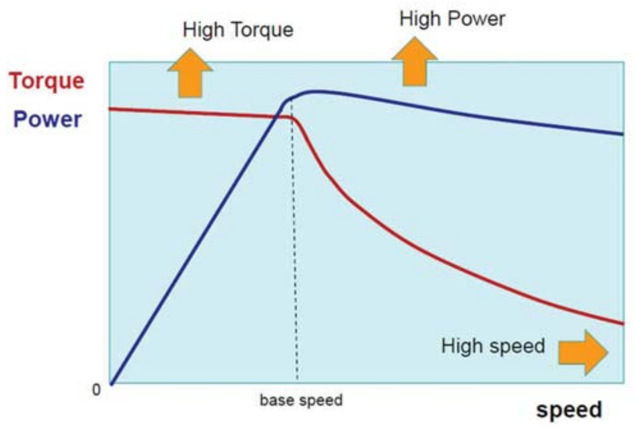
- The rotor position is detected by hall effect or optical sensors, which is used to excite the stator windings properly.
- The electronic control circuit can be embedded in the motor.
- The magnets are typically ferrite or rare-earth alloy (*neodymium (nd)+ferrite+boron (ndfeb)*).
- High currents or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



PMSM motor efficiency & weight versus IE3 Induction Motor



Torque Speed Characteristics of PMSM

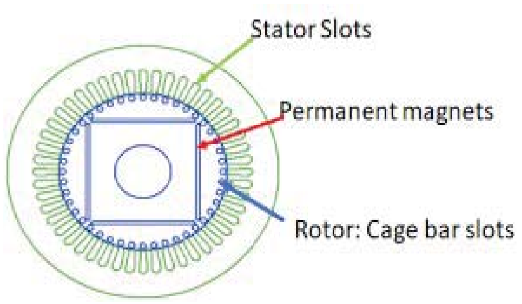


Typical characteristic for PMSM fitted to an electric vehicle

Line Start Permanent Magnet Motors (LSPM)

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

- IE4 and IE5 classes
- High cost
- Oscillating starting torque



**alloy of neodymium, iron and boron

Permanent Magnet Synchronous Motors (PMSM)

Main advantages

- Excellent torque-speed curve (e.g. may allow direct drive)
- Excellent dynamic response
- Higher efficiency and reliability
- Longer lifetime
- Low acoustical noise
- High speed capability
- Higher torque/volume ratio and higher power/ weight ratio

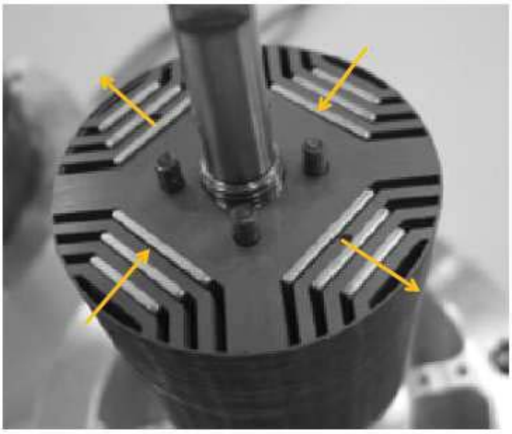
Main disadvantages

- High cost
- Need to use a speed controller (VSD).

Hybrid Motors PM-Assisted SynR Motors

- Low cost ferrite magnets
- Easy to handle
- High efficiency
- High power density
- Line-starting capabilities, but still limitatins
- Good power factor

(→impact size of the inverter)



Synchronous Reluctance Motors

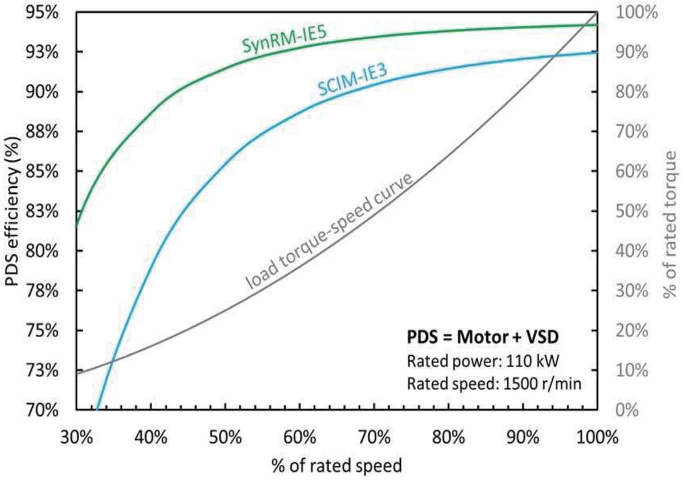
Advantages

- No winding and PM in the rotor
- Low inertia
- Good acceleration performance
- Good flux weakening operation
- Low manufacturing cost
- Because of much lower rotor losses they run cooler and have higher reliability

Disadvantages

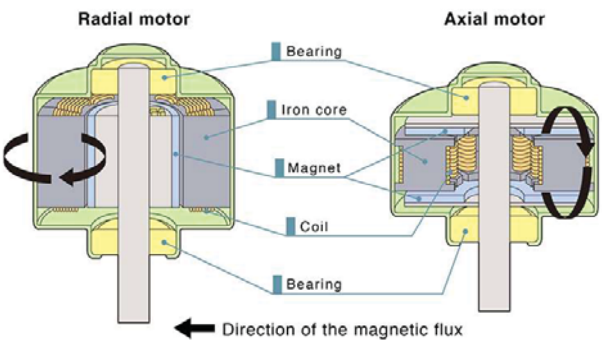
- Low power factor
- Torque ripple
- They require and electronic controller to start. For variable speed operation this is not a problem.

High Efficiency IE5 SynR Motor vs IE3 Induction Motor

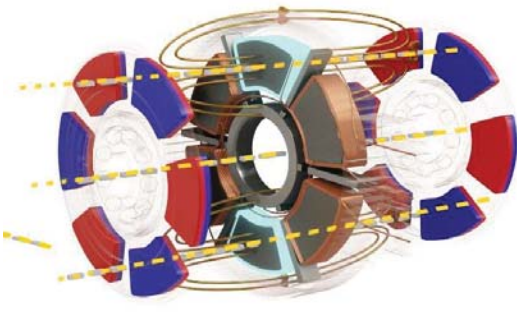


- IE5 SynR motors have higher efficiency than IE3 Induction Motors, but they cost the same.
- For lower speed the efficiency gain is larger

Radial and Axial Flux Motors

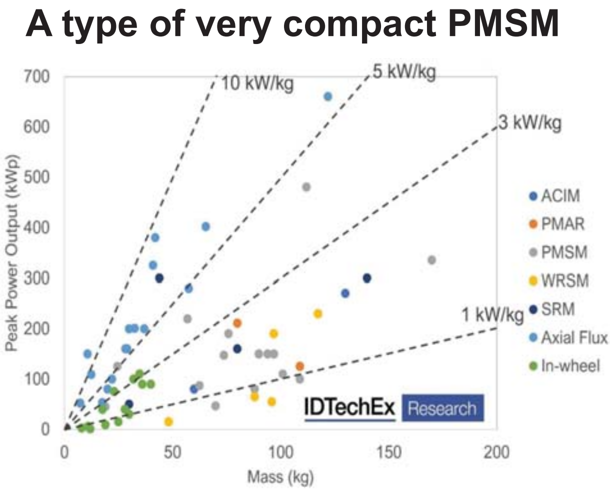


Radial flux Axial Flux



Axial flux motor – two rotor disks with PMs
-Very compact
-Less use of copper and magnetic materials

Axial Flux Motors

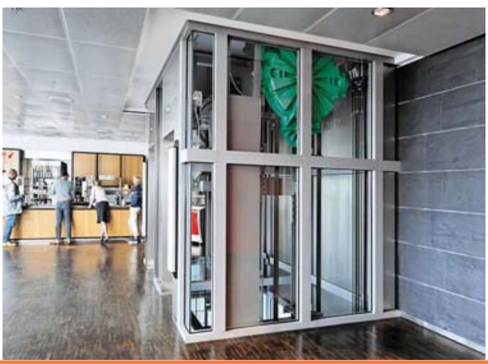


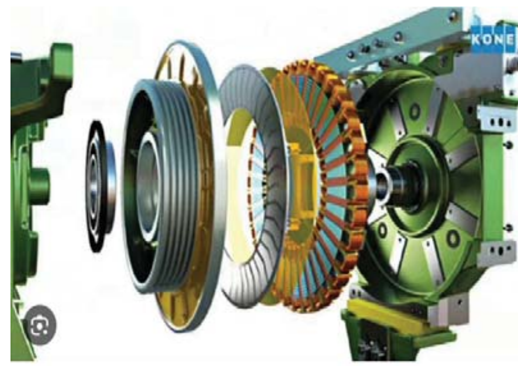
Large motor power and torque / weight ratio

- Motor power 300 kW (400 hp)
- Weight 26.5 kg

Axial Flux Motors

Have high power and torque to weight ratio
Can be used in direct drive applications like in elevators without gearboxes





Review & Discussion

02. Motor Standards

Electric Motor Technology

Review of User Training

- IEC 60034 – 30 Part 1
- MEPS (Viet Nam has minimum IE2)

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 (50 or 60 Hz), number of poles (2,4,6 and 8) and motor power (120W to 1000kW).
- (No distinction is made between motor technologies).

Four efficiency classes

IE1	Standard efficiency (existing Eff2)
IE2	High efficiency (existing Eff1, EPAct)
IE3	Premium efficiency (16-20% lower losses than IE2)
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 some 20 % relative to IE4.

Key Efficiency Test and Related Standards

IEC 60034-30-2 (2016): Efficiency classes of variable speed AC motors (IE-code)

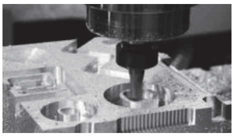
- This standard defines efficiency classes for motors that are rated for converter operation (with a VSD). No distinction is made between motor technologies.

INCLUDED:

- Pumps
- Fans
- Compressors
- Conveyors

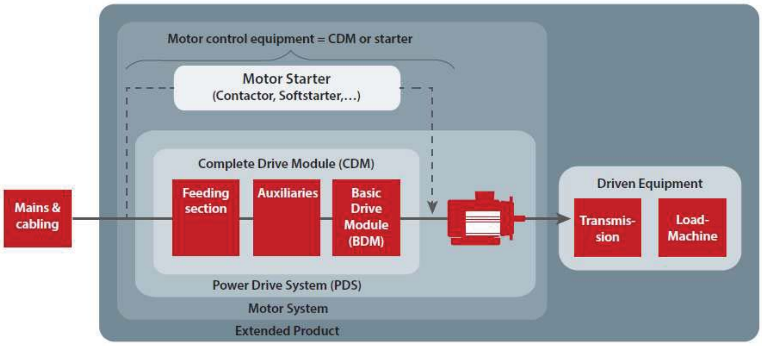
EXCLUDED:
(motion control applications)

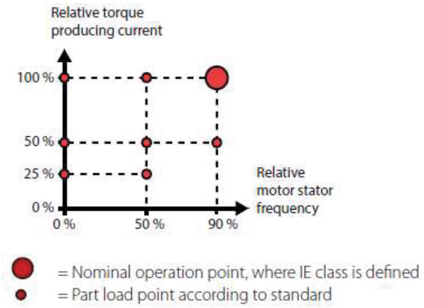
- Robots
- Hoist Drives
- Pick-and-Place Machines
- Machine Tools
- Rack Feeders



IEC 61800-9 Series

These set of standards specify IE classes from the energy efficiency point of view of the **complete power drive system** and its sub-parts.



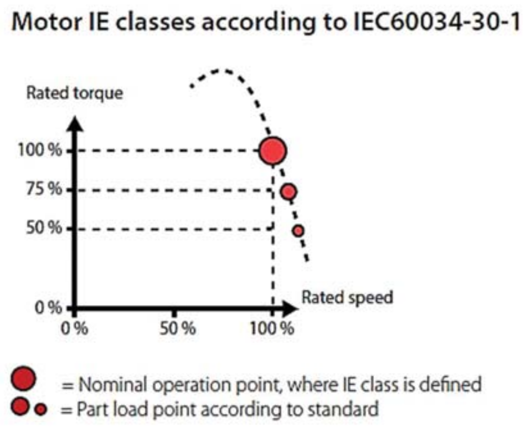


Source: Danfoss

IEC 61800-9 Series

- Enable the **system energy efficiency to be determined based on defined criteria such as speed/load profiles, the duty profiles, drive topologies and architectures.**
- Provide 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.
- 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.

System Efficiency Classification - Motor

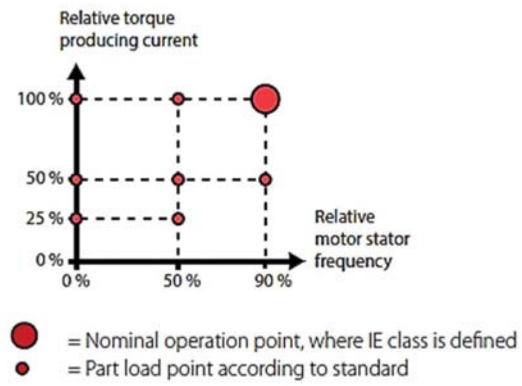


Source: Danfoss

- 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 fact in retrofit applications.
- Mechanical dimensions can vary depending on motor technology and IE class

System Efficiency Classification – CDM/VSD

IE classes for frequency converters according to EN 50598-2 / IEC 61800-9-2

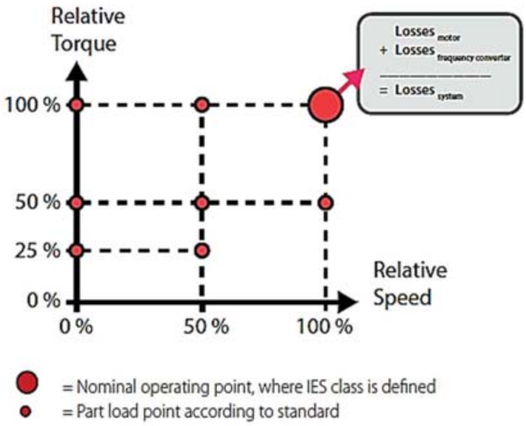


- The IE class is defined at an operating point of 90% frequency and 100% torque-producing current.
- Special test settings are not permitted.
- The classification for the frequency converter includes integrated options.
- Losses in options that are not built in (for example, EMC filters or chokes) are 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

System Efficiency Classification - PDS

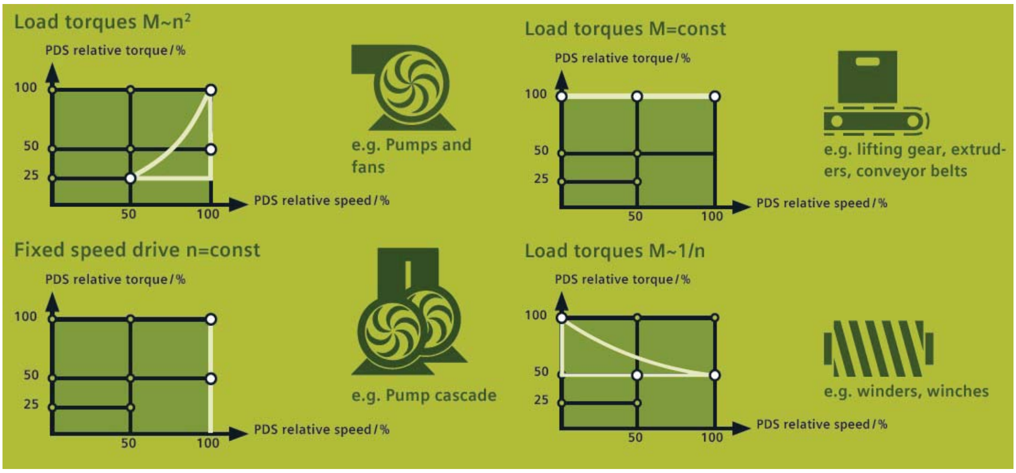
IES classes for power drive systems according to EN 50598-2 / IEC 61800-9-2



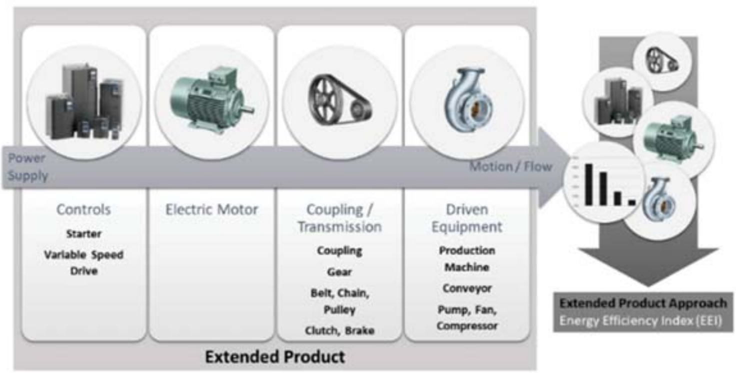
- The IES class applies for frequency converter – motor systems
- The IES class is defined at 100% speed and 100% torque
- The cable length between frequency converter and motor is defined.
- Deviations from the standard cable length or switching frequency are permitted, but must be documented
- Losses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

Source: Danfoss

Examples for Different Applications



The Extended Product Approach



-**The method can be used to determine the energy efficiency of the motor system** for a particular application, taking into account the time spent at the different operating points (speed-torque).

-Using a relative weighting system, the overall energy efficiency index (EEI) is determined for the actual operating conditions encountered.

The Extended Product Approach

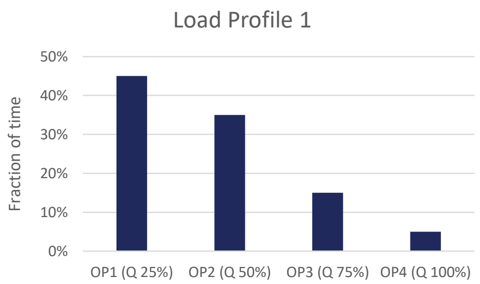
The method can be used to determine the energy efficiency of the motor system for a particular application, taking into account the time spent at the different operating points (speed-torque).

To calculate the EEI, the following inputs need to be known:

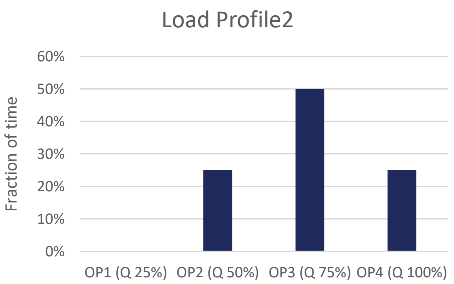
- Characteristics of the application load, namely, the torque or power as a function of shaft rotational speed, and the working time or fraction of time of each operating point (duty cycle), including standby mode.
- Power losses of components (Motor, CDM, end-use equipment, auxiliaries) at the operating points required by the application. Power losses are used instead of efficiency because they take into account particular conditions such as standby consumption (no-load condition, in which the efficiency is zero).

Comparison between two typical pumping applications

Knowing the values of the PDS losses in the eight operating points defined in standard IEC61800-9 allows users to evaluate the performance (both energy- and economic-wise) of any application for which typical operating points are known.

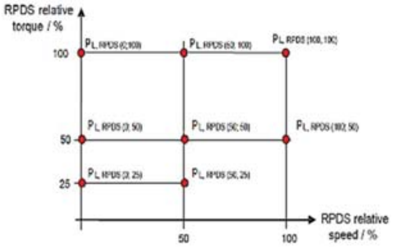


A typical HVAC application

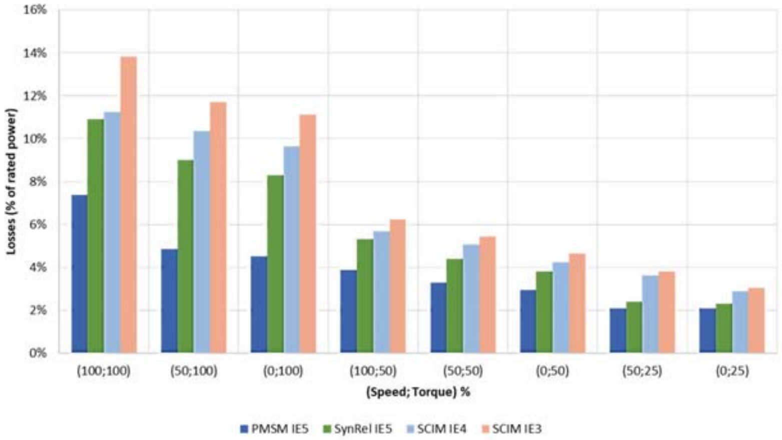


Fresh water pumping application

PDS Losses as a Percentage of the Output Rated Power



7.5 kW Motor + Drive Case Study



Results from tests carried out at the ISR-UC Lab

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Total Cost of Ownership (4000 operating h/year)

Load Profile 1

Load Profile 2

Motor Technology	Motor Price	VSD Price	Maintenance[1] (4000 h/year)	Lifetime
SCIM IE3	600 €	1200 €	450 €	15 years
SCIM IE4	720 €	1200 €	450 €	15 years
SynRM IE5	720 €	1200 €	450 €	15 years
PMSM IE5	1200 €	1200 €	450 €	15 years

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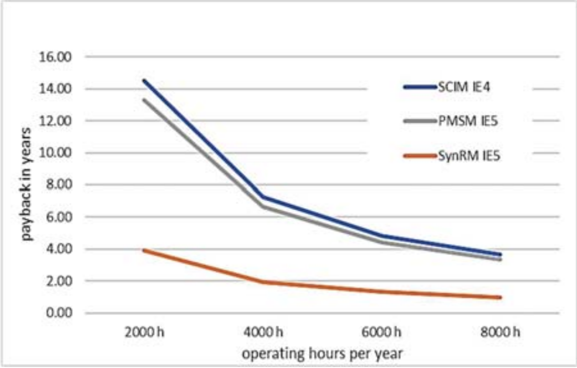
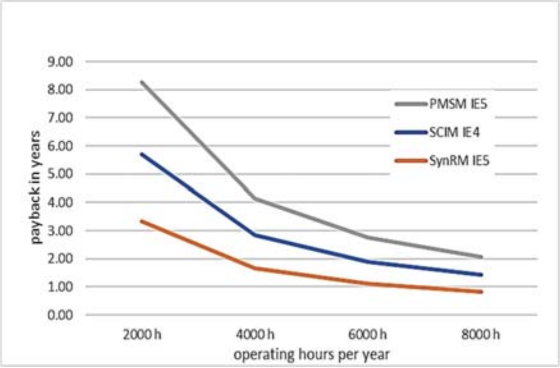
Payback time for SCIM IE4, SynRM IE5, and PMSM IE5, in relation to SCIM IE3

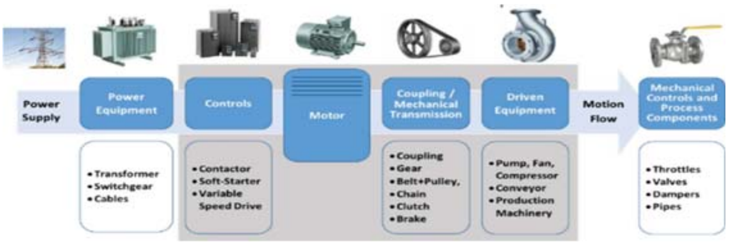
Load Profile 1



Load Profile 2



Standardisation Bodies – IEC and ISO



Motor control		Motor	Mechanical equipment		Driven equipment			
IEC TC 121	IEC TC 22 SC 22G	IEC TC 2	ISO TC 41	ISO TC 60	ISO TC115	ISO TC 117	ISO TC 86	ISO TC 118
Switchgear & controlgear	Adjustable speed drive	Rotating machinery	Pulleys & belts	Gears	Pumps	Fans	Cooling-Compressors	Air-Compressors
1927	1934	1911	1947	1947	1964	1964	1957	1965
Group Standard								

Review & Discussion

03. Motor Operations & Control

Electric Motor Applications

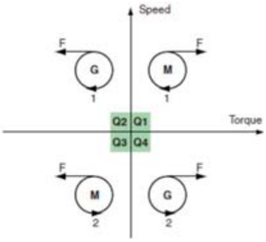
Review of User Training

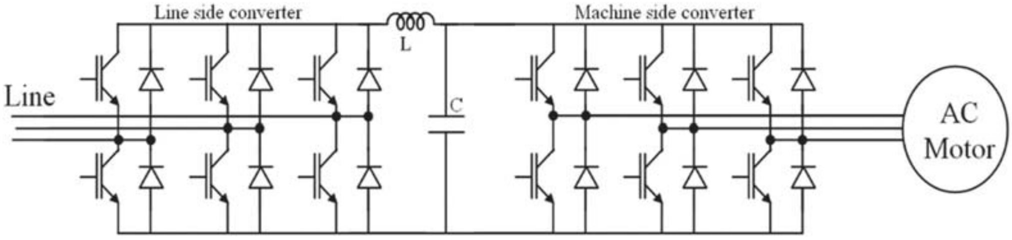
Comparison of Starting Methods

	Direct On Line	Star Delta	Autotransformer	Soft Starter	Variable Speed Drive
Network impact	• High voltage drop • High reactive power demand • High starting current	• Reduced voltage drop • Reduced reactive power demand • starting current at 1/3 of DOL	• Reduced voltage drop • Reduced starting current from network • Higher starting current to motor	• Reduced voltage drop • Reduced and controlled current from network • Smooth increase in current and reactive power demand	• No impact to network • Low starting current • Very low reactive power demand
Mechanical impact	• High starting torque • High stress • Coast stop • Rapid starting	• Reduced initial stress • High stress at transition from star • Coast stop • Prolongated start	• Higher torque for lower starting current from network • Reduced mechanical stress • Coast stop • Prolongated start	• Smooth application of torque to load • Soft-stop possible • Prolongated and repetitive start independent of voltage drop	• Smooth acceleration • No mechanical stress • Soft-stop possible • Controlled starting time
Thermal impact	• Slighly increased heating	• Slighly increased heating	• Higher heating	• Higher heating	• Very low heating
Main Applications	• All constant speed applications	• Pumps, compressors	• Pumps, compressors	• Pumps, fans, compressors	• All applications requiring speed / torque control
Not recommended	• weak supply (voltage dip) • For frequently started motors it	• High inertia loads like fans • For high starting torque applications	• High inertia loads like fans • For constant torque applications	• For constant torque applications	• For constant speed applications

Bidirectional VSD

- Four Quadrant Control Capacity
  Regeneration Capacity
  Bidirectional Power Flow

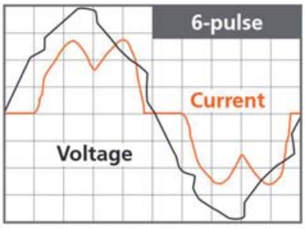




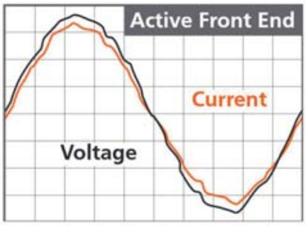
Advantage of bi-directional drives

KEY BENEFITS:

- Low Harmonic Distortion
- IEEE519-2014 compliant
- Regeneration clean supply 4-quadrant operation
- Will not interfere with sensitive equipment
- Not sensitive to line imbalances
- Maintains Unity Power Factor



Typical current distortion 35%



Typical current distortion 3%

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.

Types of VSDs – Pros and Cons

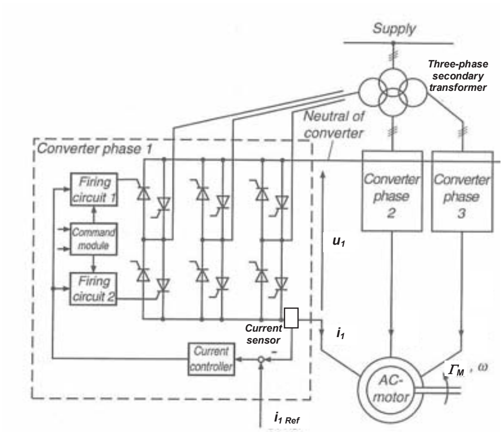
VSD Type	Advantages	Disadvantages
Load-Commutated Inverter (LCI)	• Simple and inexpensive circuit design. • Regeneration capability. • Built-in short-circuit protection.	• Poor power factor at low speed. • Can only be used with synchronous motors. •
Static Kramer Drive	• VSD power is less than motor 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 over speed 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. •

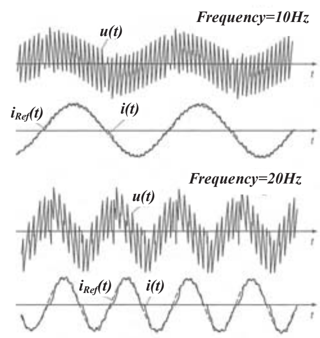
Common Types of VSD and Applications

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 Frequancy Stator Voltage	• Current – source DC link converter with synchronous motor (converter motor)	• Drive for processing machines, pump, blowers, up to 60 MW
	• Voltage – source DC link converter with synchronous motor or squirrel vage 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 Frequancy Stator Curret	• DC link converter with squirrel-cage induction motor	• Drive for fans, centerfuges, mixers/ agitators, up to 1800 kVA

Cycloconverters

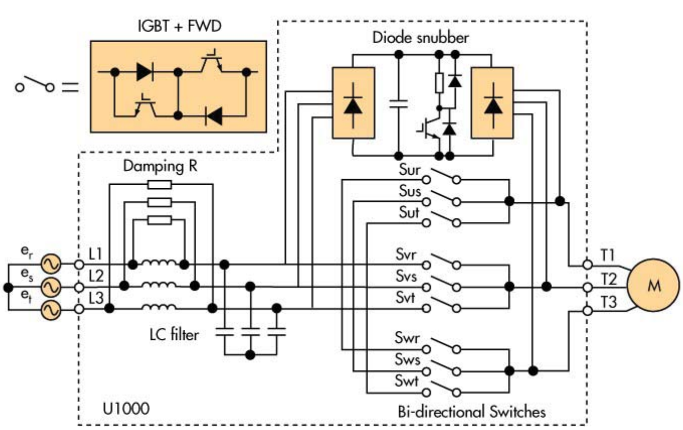
Special type VSD Direct AC-AC Conversion
(>1MW, Low Speed (0-15 Hz), High Power)





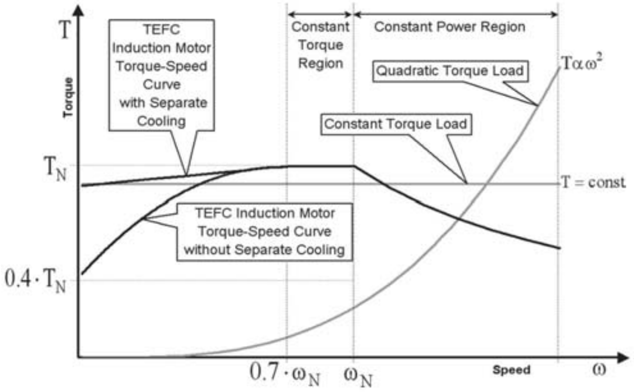
Matrix Converters

- A matrix drives employs a system of nine bi-directional switches arranged in a matrix to convert a three-phase AC input voltage directly into a three-phase AC output voltage.
- The matrix drive eliminates the need for a rectifying circuit and DC smoothing circuit found in conventional AC drive inverters.



VSDs-Variable Speed Drives – Operating Areas

- Motor torque and power limitations in totally-enclosed fan-cooled induction motors fed by a 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.



PWM – Pulse Width-Modulation
VSD – Variable Speed Drive

Open Loop Control Systems

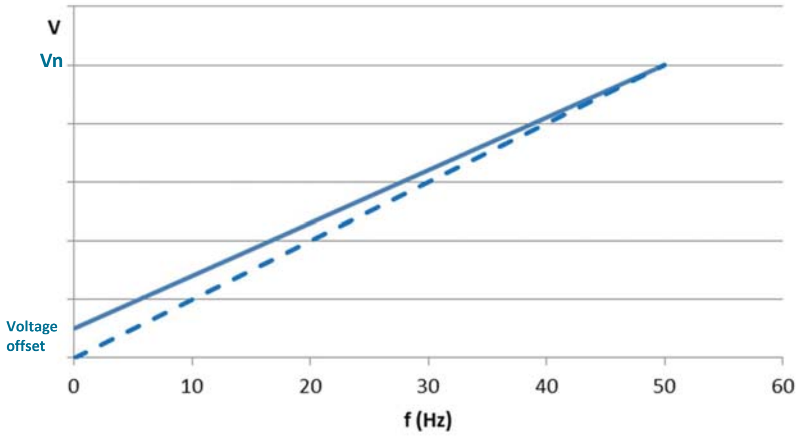
Open Loop Systems (Manual Control)

- In an open loop control system the controlling parameters are fixed or set by an operator and the system finds its own equilibrium state, depending on the load characteristics.
- Simple for process requirements that are very stable and static.
- Where process requirements vary, operation might not achieve optimal efficiency.

V/f (Voltage / Frequency) Control

- The voltage amplitude is specified as a function of the actual motor frequency, and the desired torque.
- In most VSDs 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.

Voltage Variation with Frequency



V/f Control Characteristics

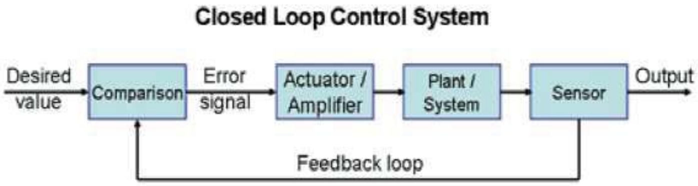
The following measures improve the properties of V/f control:

- 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 to be achieved.
- 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.
- The current limiting control is used as stall protection.

Closed Loop Control Systems

(Automatic Control)

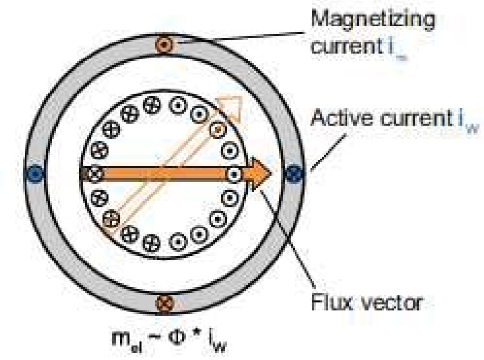
- Also called feedback control systems, or negative feedback systems, they allow the user to set a desired operating state as a target or reference and the control system will automatically move the system to the desired operating point and maintain it at that point thereafter.



Vector Control (or Field Oriented 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 high dynamic performance as a DC motor.

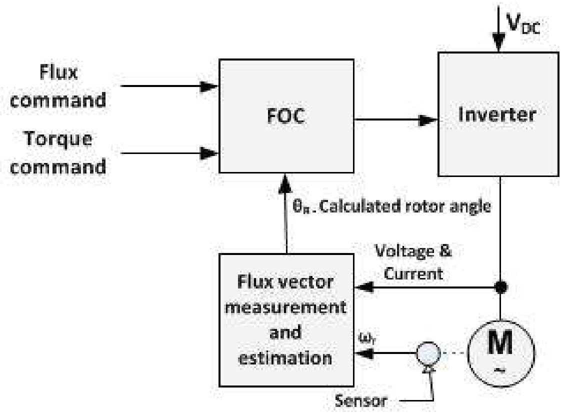
- The behaviour of a DC motor is emulated in an induction motor by orienting the stator current with respect to the rotor flux so as to attain independently controlled magnetic flux and torque.



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 matrix calculations, 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 derived from a sensor) in a motor model or flux model.
- So-called **sensorless closed-loop controls**, do not require a position and speed encoder, also calculate these quantities through sophisticated control algorithms.

Motor Efficiency Reduction of VSD Fed Induction Motor

Operation of AC 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.

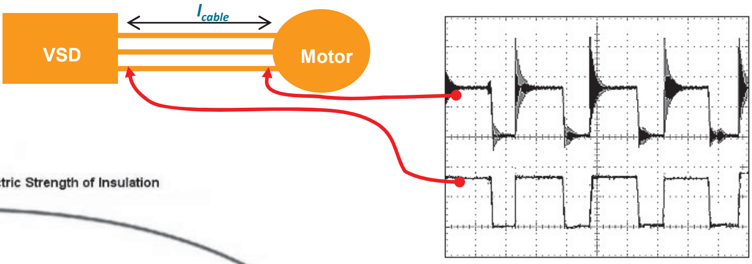
Iron loss

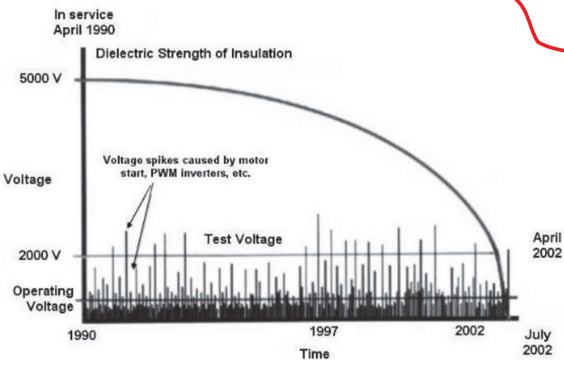
This is increased by the harmonic components in the supply voltage.

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.

Voltage Transients at the Inverter Fed Motor Terminals

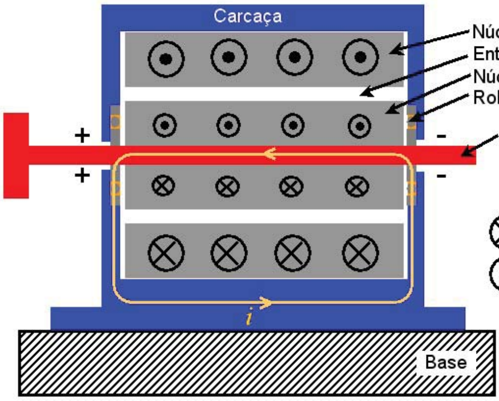


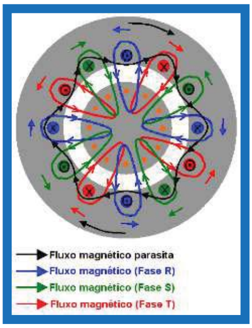


(!) PARTIAL DISCHARGE

↓ LIFETIME

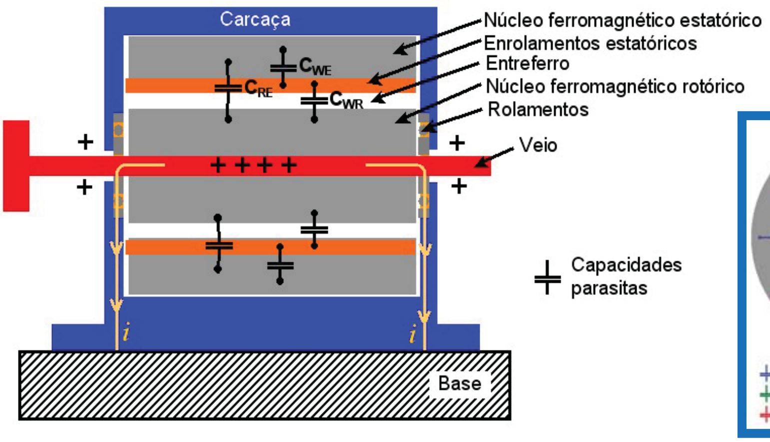
Bearing Current in Inverter Fed Motor

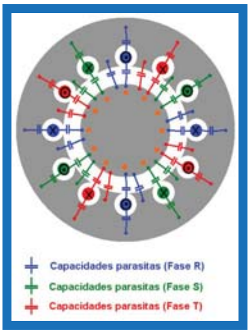




Circulating Currents

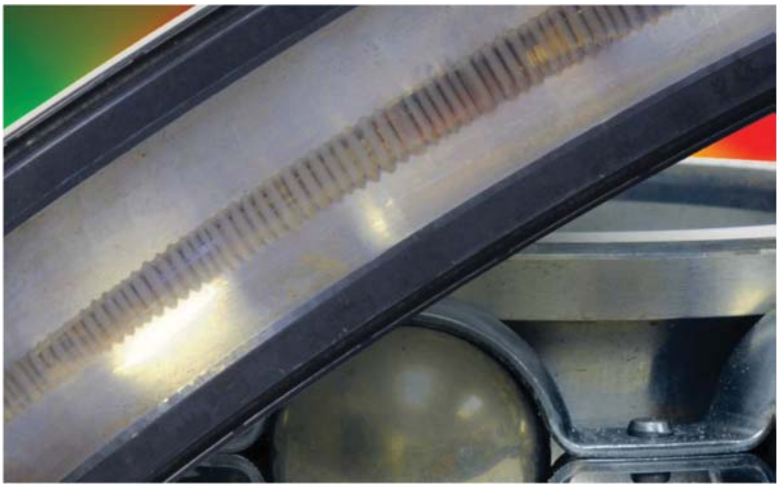
Bearing Current in Inverter-Fed Motor





Common Mode Currents

Bearing Race Pitting



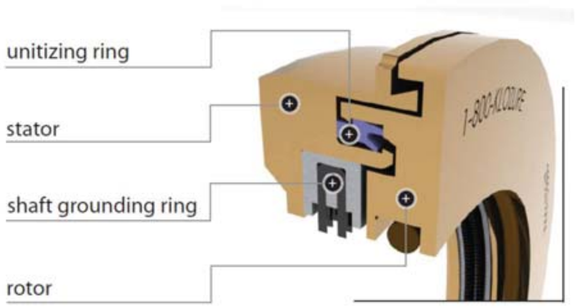
Bearing Current in Inverter Fed Motor

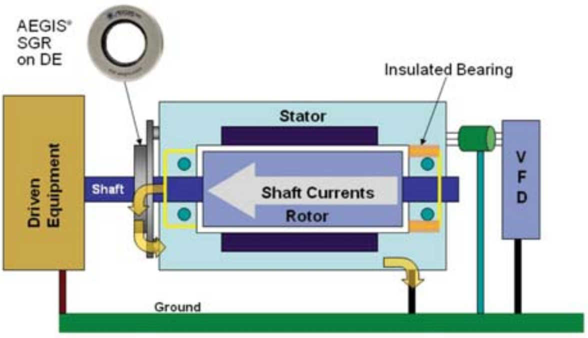
To mitigate the bearing currents in inverter-fed motors several techniques can be adopted:

- proper switching frequency selection
- cables with of proper type and size (e.g. shielded)
- well designed ground system
- filters between the motor and inverter
- insulated bearings
- shaft-ground connection (e.g. using a contact brush)

The users should ask manufacturers about these issues.

Shaft Grounding Rings





Aluminum Oxide Insulated Bearings

- Designed to prevent electric current from passing through the bearing
- Have the external surfaces of either **their inner** or outer **ring** coated with an **insulating aluminium oxide layer,** by applying a sophisticated plasma-spray process for an outstanding quality finish
- High electrical resistance
  The aluminium oxide coating provides a minimum electrical resistance of 200 MΩ and can withstand voltages up to 3,000 V DC.
-

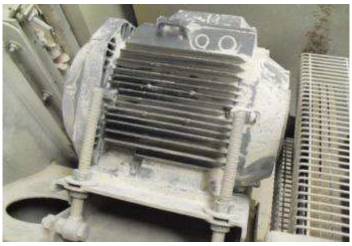
Ceramic Ball Bearings

Steel rings precision matched with silicon nitride (ceramic) balls

- Prevent electrical arcing
- Lower maintenance costs
- Increase service life
- Extend grease life
- Reduce wear from vibration
- Lower operating temperatures
- Reduce wear from contamination
- Suitable for high temperature and corrosive environments

Case Study - Super-Premium Retrofitting

As an example of retrofitting, an IE0-Class Equivalent, 5.5-kW, 4-pole, Induction Motor driving a fan in an industrial facility, has been replaced by an IE4-Class Line-Start Permanent Magnet Motor (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.

Savings & Payback

$$Electricity\ Savings\ [kWh/year] = Hr \times LF \times \left(\frac{P}{\eta_1} - \frac{P}{\eta_2}\right)$$

$$Electricity\ Savings\ [kWh/year] = 4000 \times 0.59 \times \left(\frac{5.5}{0.832} - \frac{5.5}{0.925}\right)$$
$$= 1557.6\ \text{kWh/year}$$

Hr	Number of Operating Hours per year
LF	Load Factor
P	Motor mechanical output power
η	Motor Efficiency

Savings & Payback

$$Simple\ Payback = \frac{Cost\ \ of\ new\ motor\ (US\$)}{Energy\ Savings(kWh/year) \times Electricity\ Cost(US\$/kWh)}$$

$$Simple\ Payback = \frac{\$300}{1557.6 \times \$0{,}10}$$
$$= 1.92\ years$$

Hr	*4000 hours*
LF	*0,59*
P	*5.5 kW*
η_1	*83.2%*
η_2	*92.5%*

Regeneration Opportunities

Raising and Lowering	• Here a load is raised, and then lowered. Power is required to raise against gravity, and braking is required when lowering. • Typical examples would be hoist operations in a vertical direction. • The recoverable energy is almost equal to the energy used for raising).
Periodic Deceleration	• Here a load is stopped very quickly and the inertia of the mechanical load tries to keep the motor turning. • Typical examples would be crane operations in a horizontal direction. (The load inertia, duration of the stop and the number of stops will determine the amount of energy that can be recovered).

Regeneration Opportunities (2)

Continuous Deceleration	• Here a load is continuously trying to accelerate the motor, usually because of gravity. • A typical example would be a decline conveyor, where the motor is used as a brake to control the speed of the belt. (The heat dissipated by the brake could be recovered).
Holding Tension	• Here two machines are usually used to hold some material at a set tension. Both machines will be running forward, but their torques will be opposite, one driving forward, the other holding in reverse, thereby creating the required tension on the material. • A typical example would be a metal strip in a steel strip mill.

Energy Recovery from Regeneration

- With new drive technology this energy can now be recovered.
- Requires a bi-directional drive (also called active front end)
- The higher initial drive cost (20-40%) may be offset by the energy savings
- Typical savings for systems with high vertical operations (raising and lowering) are above 20%

Review & Discussion

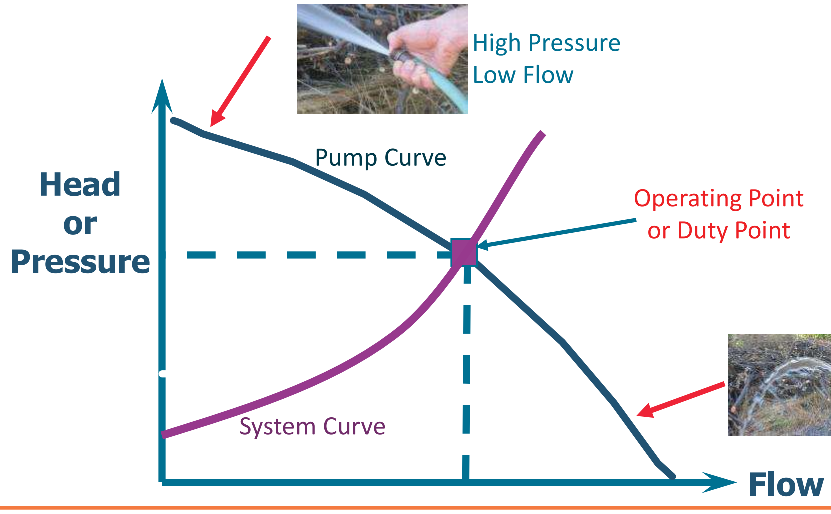
04. Centrifugal Pumps & Fans

Electric Motor Application

Review from User Training

- Pump and system curves
- Affinity laws

Pump Basics – Pressure Flow Relationship



How do we vary the operating point?

Affinity Laws for Centrifugal Machines (Pumps & Fans)

- Changes to centrifugal machine performance is governed by the Affinity Laws.
- These laws show how performance is affected when the pump/fan speed is changed, or when the impeller diameter is changed.

Relation between

- Machine Speed (N),
- Impeller Diameter (D)
- Flow (Q)
- Head (H)
- Power (P)

For changes in speed

$$Q_{new} = Qold * \left(\frac{N_{new}}{N_{old}}\right)$$

$$H_{new} = H_{old} * \left(\frac{N_{new}}{N_{old}}\right)^2$$

$$P_{new} = P_{old} * \left(\frac{N_{new}}{N_{old}}\right)^3$$

For changes in diameter

$$Q_{new} = Qold * \left(\frac{D_{new}}{D_{old}}\right)$$

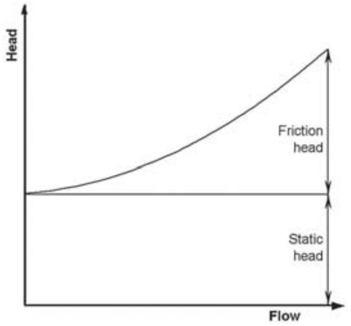
$$H_{new} = H_{old} * \left(\frac{D_{new}}{D_{old}}\right)^2$$

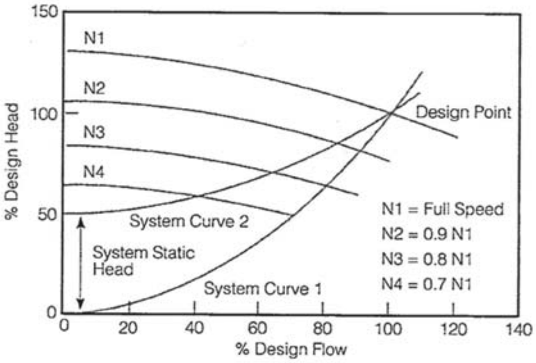
$$P_{new} = P_{old} * \left(\frac{D_{new}}{D_{old}}\right)^3$$

Affinity Laws – Centrifugal Pumps

Affinity laws only apply to the friction losses.

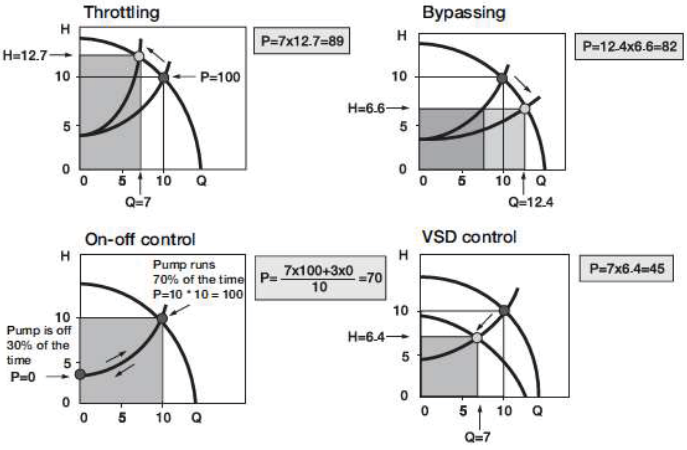
Static losses are constant at different speeds.





Therefore, systems with low static head tend to be better candidates for VSDs and thus for energy savings.

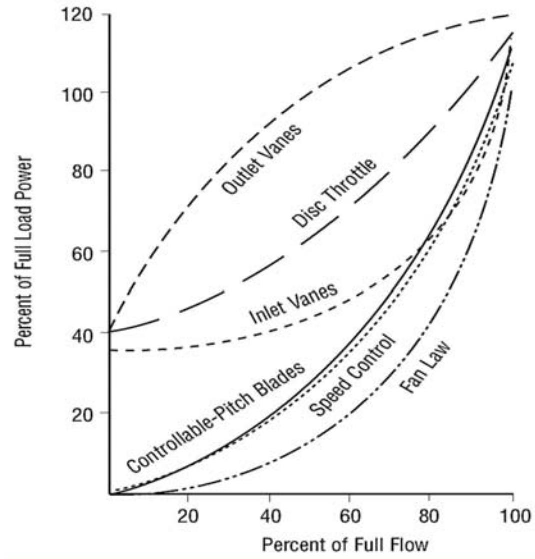
Comparison of Common Pump Control Methods



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

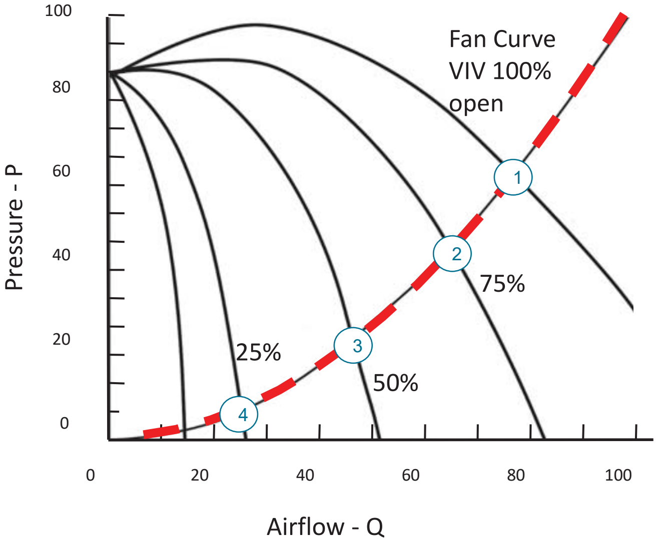
Control	Energy
Throttling	89
By Passing	82
On-Off control	70
VSD control	45

Comparison of Common Fan Control Methods

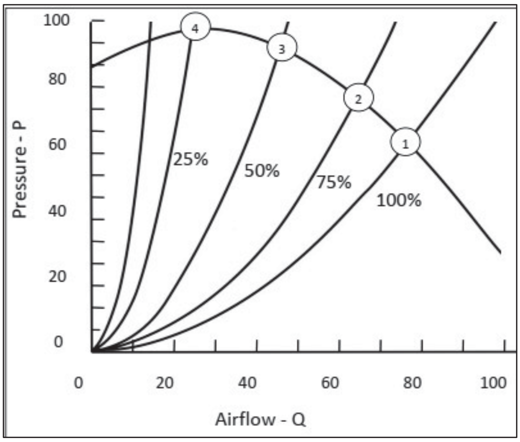


Source: DOE Improving Fan Performance

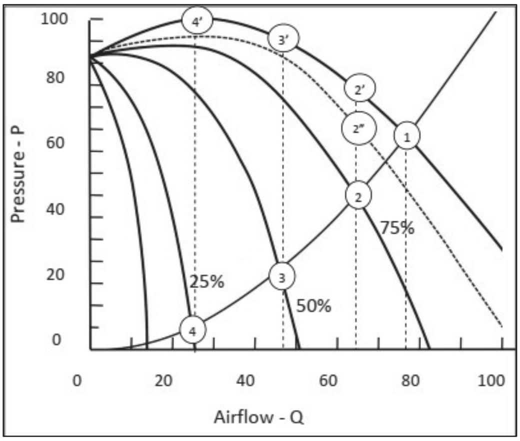
Fan Performance Curve with Variable Inlet Vanes



Fan Curve for Inlet & Outlet Louvre Dampers

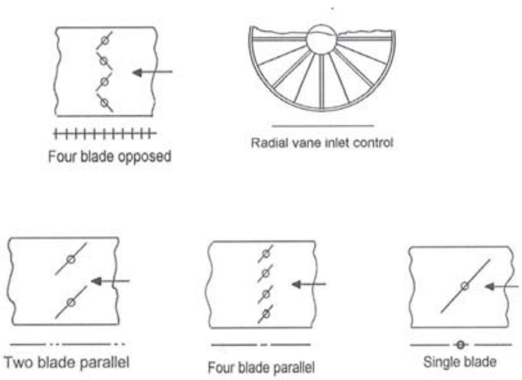


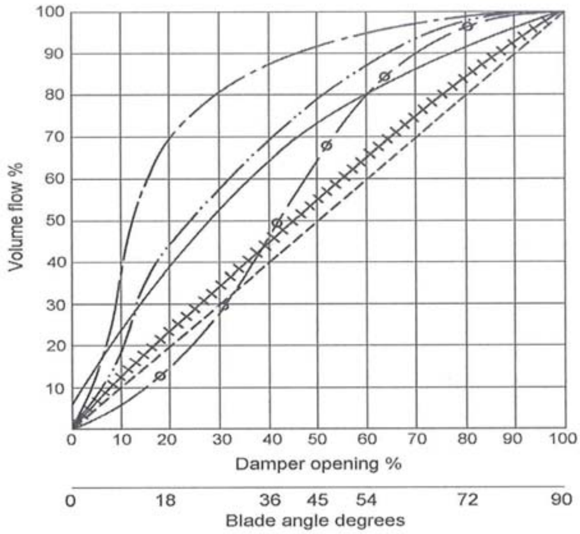
Outlet Louvre Damper



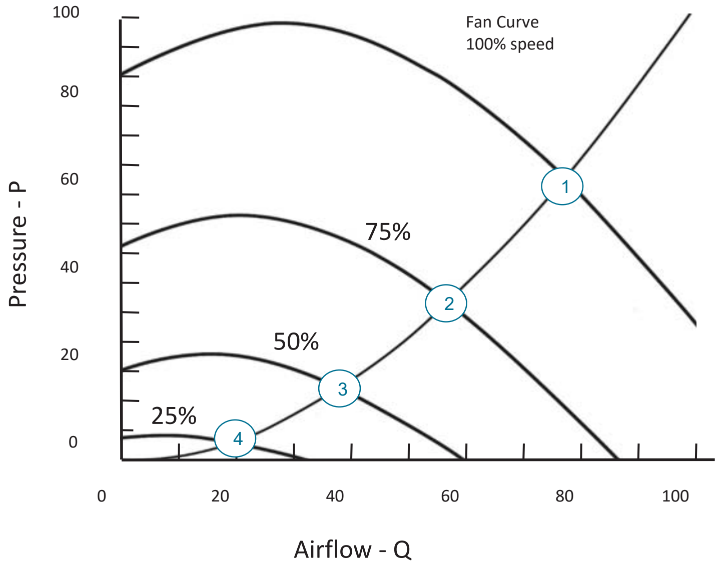
Inlet Louvre Damper

Damper Response





Fan Performance Curve with Variable Speed Drive



Typical Optimization Techniques for Existing Fan Systems

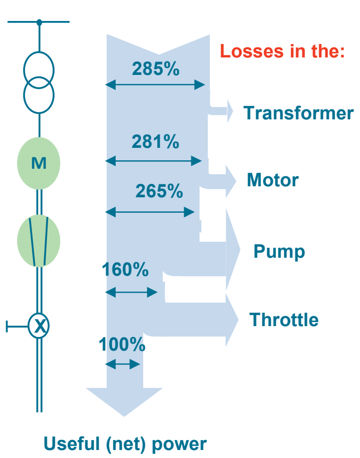
	OPPORTUNITY	RECOMMENDATION
1	Replace impeller	Best suited for 200 kW+ and where new impeller design would be more efficient
2	Replace fan	Best suited for fans smaller than 150 kW and for aging or deteriorating fans.
3	New belt drive ratio	Best suited when there is an existing belt drive, the load is fixed and the fan is oversized with a damper used as a control mechanism
4	Convert to belt drive	When the current fan is oversized and has a direct drive motor operating at 190 kW or less. If a VSD is too expensive or otherwise unsuitable for the system
5	Covert to VSD control	Best suited for fan motors at 300 kW or smaller, with a system that needs variable flow DO NOT USE A VFD with a system already at full capacity, under a steady load, or when there are only minor flow variations
6	Install fluid coupling	Best suited to vary the speed on larger motors (>200kW)

Centrifugal Machines: Cases

1. Energy value chain with losses
2. Impeller trimming
3. Developing flow duration curves for low flow periods
4. Parallel cooling water pumps at petrochemical company
5. Dryer ID fan at metals coating plant
6. Seawater cooling pumps at petrochemical company

Case 1 – Losses in Energy Value Chain

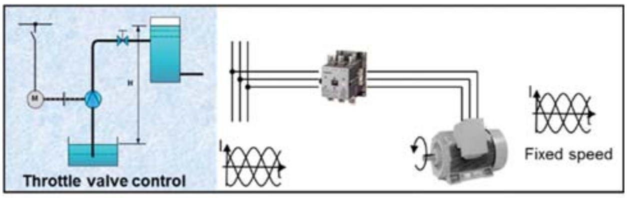
Direct on-line pump with throttle flow control



The drive process represents the main energy saving potential!

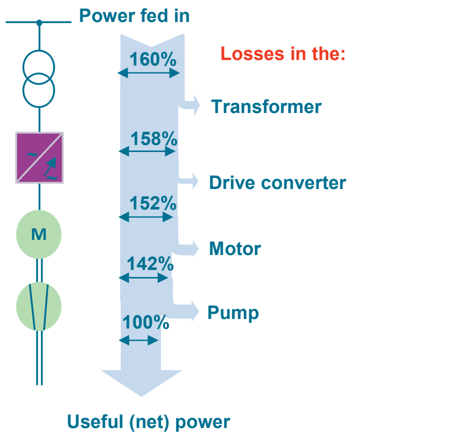
Example:

- For a conventional fixed-speed drive with flow control using a throttle, 285 % of the power used is supplied in the form of electrical energy.
- The energy balance of a pump, operated at constant speed, becomes increasingly more unfavorable, the lower the quantity of medium to be pumped.



Case 1 – Losses in Energy Value Chain

Direct on-line pump with VSD flow control

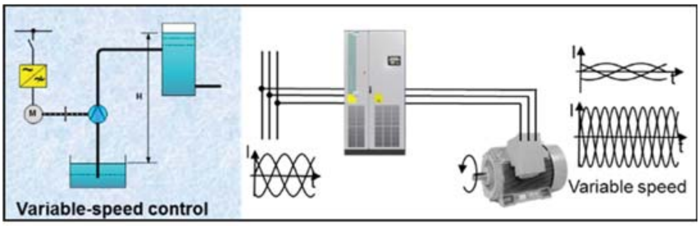


The drive process represents the main energy saving potential!

Example:

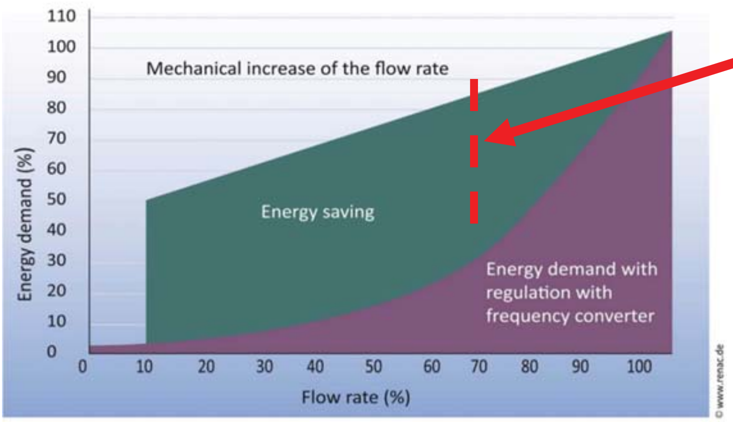
- With electronic speed control, the power fed in is only 160% of the power required to pump the medium and the total losses are reduced to 1/3.

The process quality is also improved.



Case 1 – Losses in Energy Value Chain

Centrifugal Pumps: Throttle vs VSD



Note:

- Most of the savings are made with just a 50% reduction.
- VSDs rarely run below this point.
- Bypass systems are even worse!

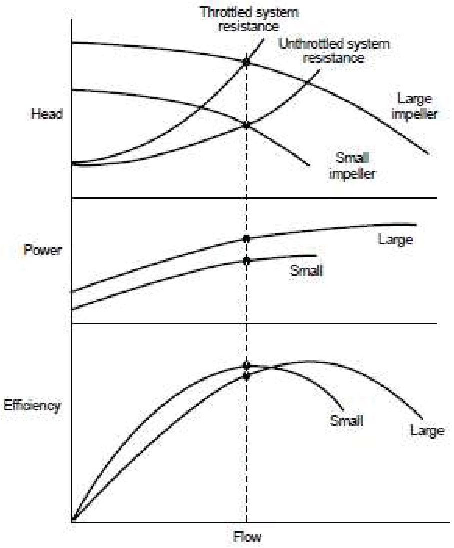
Source: RENAC

Case 2 - Impeller Trimming

- 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, usually for fixed load applications



Case 2 - Impeller Trimming

- A brine pump at salt works condensate distribution system was oversized and causing maintenance problems.
- The impeller was trimmed.
- Motor power required to drive the new pump configuration was reduced from 110kW to 75kW.
- Payback in 11 days.

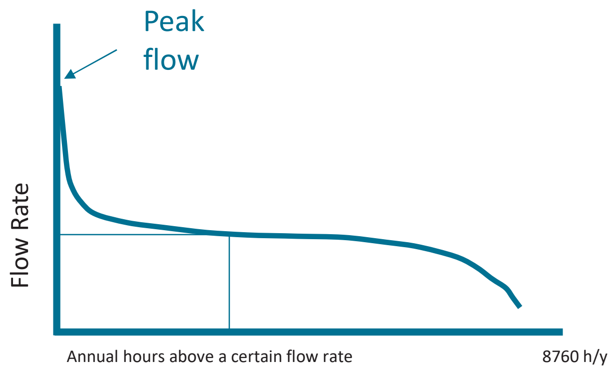
Source: UK EEBPP GPCS300 Energy savings by reducing the size of a pump impeller

Pump Flow Profiles

- Can be useful in understanding energy requirements of the motor system.
- Recording period of flow profile is dependent on production and other operating requirements.
- Also, consider the available data and whether additional metering or measurements need to be installed.

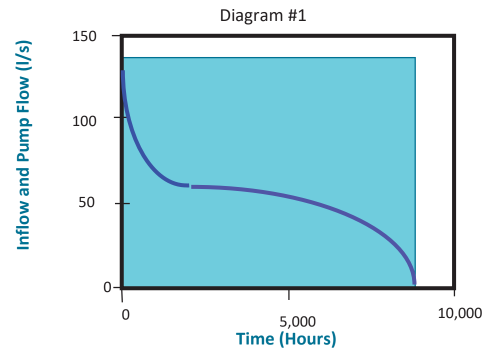
Flow Duration Curve

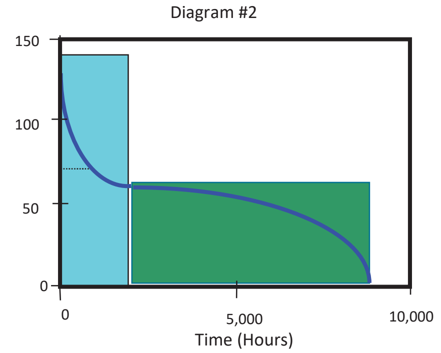
- By tracking flow rate over time, a "flow duration" curve is developed
- Understanding how the flow requirements varies over time is a crucial element in optimizing fluid systems



Case 3 – Optimising Pumps to Handle Low Flows

- **Diagram #1** shows a large pump operating for 8,760 hours per year at a flow rate of 140 l/s – total flow is represented by the area under the curve.
- **Diagram #2** shows the same total flow pumped by two pumps.
- The 140 l/s pump only operates 2,000 hours per year and a smaller pump rated for 60 l/s operates for 6,760 hours





Case 3 – Optimising Pumps to Handle Low Flows

- 85kW pump, rated at 270 l/s at 2 bar.
- Pump operates at full power with excess water flowing through a bypass.
- Actual process requires:
  - ✓ 260 l/s for 3 months per year
  - ✓ 160 l/s for 9 months per year

What is the energy cost of the pump if the electricity cost is USD 0.1/kWh? (Ignore motor losses)

NB. The maintenance engineer has found a spare motor in store (55kW, rated at 170 l/s at 2 bar)

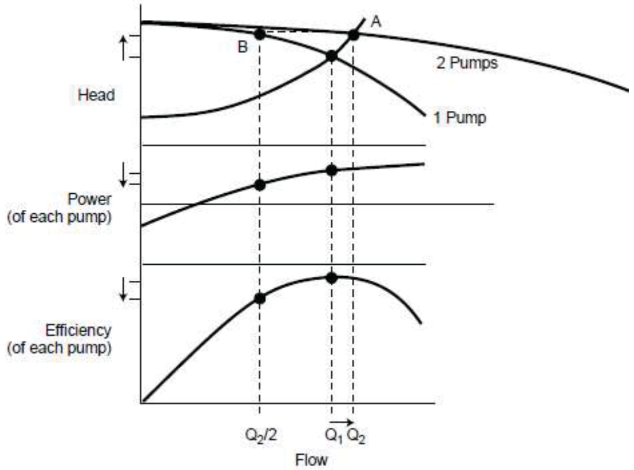
Case 3 – Optimising Pumps to Handle Low Flows

Solution

Existing Case	85kW x 8760h x USD 0.1	= USD 74,460
New case	55kW x (3/4) x 8760h x USD 0.1	= USD 36,135
	85kW x (1/4) x 8760h x USD 0.1	= USD 18,615
	Total (for new case)	= USD 54,750
	Saving	= USD 19,710

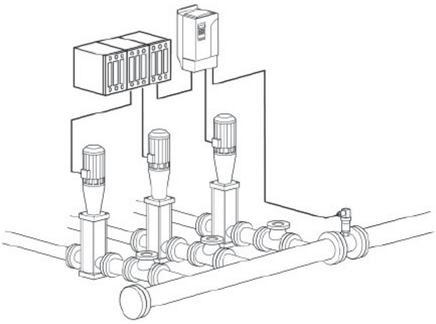
Multiple Pumps in Parallel

- Usually installed to provide redundancy, allowing rotation of pumps and maintenance.
- Can offer better matching of flow with process.
- Allows flexibility to changing requirements.
- Often a good opportunity for energy savings.
- Parallel systems are usually optimised for a specific number of pumps. Operating away from this could have severe power consequences.

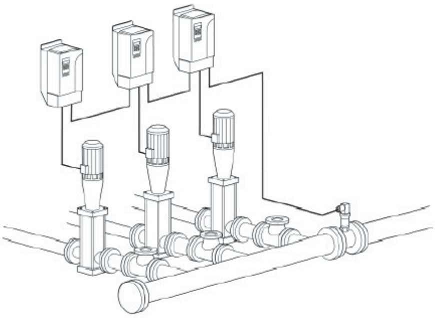


VSDs on Multiple Pump Systems

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.

Case 4: Pump System at Plastics Manufacturing Plant

A company draws cooling water from a nearby canal.

It is pumped using **one** of **two 315kW** motors. (One motor standby) and delivers a steady flow of **2100m³/h**.

The Energy Team has asked you to optimize the pump system.

What opportunities can you identify?

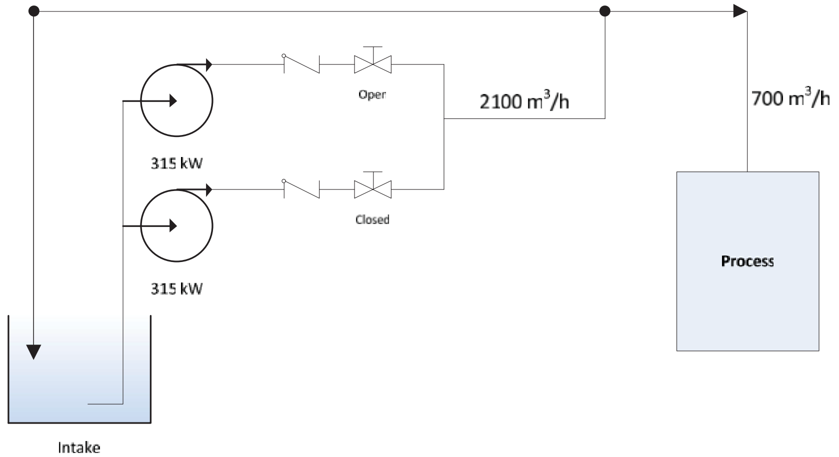
Case 4 – Pump System at Plastics Manufacturing Plant

Findings:

- The process only requires 700m^3/h on average
- Peak flow of 1000 m^3/h was recorded during extreme weather
- Excess water is pumped back to the intake sump via a bypass line
- Motors are direct on-line start
- Pumps are alternated on a regular basis

Case 4 – Pump System at Plastics Manufacturing Plant

System Diagram



Case 4 – Pumps System at Plastics Manufacturing Plant

Opportunities

- Resize 1 pump
- Resize 2 pumps
- Trim impellers on both pumps
- Install VSD on 1 pump
- Install VSD on 2 pumps
- Switch off one pump

Outcome

- Switch off one pump

Case 4 - Lessons Learned

Understanding load requirements and load profile is important in determining the most suitable option.

Energy efficiency interventions can sometimes include enhancement and improvements of maintenance activities.

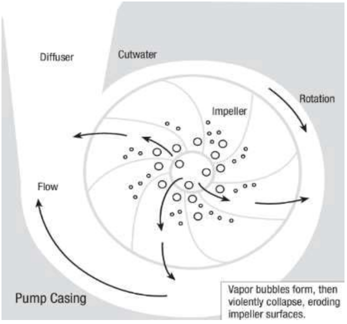
Applying MSO can be a good starting point to provide impetus for companies to implement an energy management system (EnMS).

Typical Problems - Pump Oversizing

Symptoms	Highly throttled, excessive bypass, low duty cycle, excessive noise, frequent bearing/seal replacement
Cause	Design, change in production requirements, replaced with bigger unit after failure
Result	Excessive energy consumption, higher maintenance cost
Solutions	Replace with appropriate size pump, trim impeller, install VSD, install smaller "jockey" pump

Typical Problems - Cavitation

Symptoms	Gravelly noise
Cause	Pressure at suction is too low ($NPSH_{actual}$ < $NPSH_{required}$)
Result	Early pump failure
Solutions	Increase the inlet pressure • Lower inlet height • Reduce pump speed • Cooler fluid • Modify inlet piping



Case 5 – Dryer Fan

- A 125 kW dryer ID fan in a metal coating factory is operating with input dampers 30% open.
- The system damper downstream of the fan is 40% open.
- The process requirements are steady once the process reaches normal operating temperatures and conditions.
- The fan is belt-driven.

Case 5 - Opportunities

FSO Strategy	Why Appropriate?	Why Not Appropriate?
(1) variable inlet vanes	It would reduce power	The variable inlet vanes would still be mostly closed, incurring some loss
(2) VFD	Mechanically simple and relatively easy to implement	There is no variability in the process and there would be parasitic loads
(3) opening the dampers and changing the belts and pulleys	Matches the capacity of the fan to the needs of the process and cost-effectively captures potential energy savings	
(4) a new fan that is optimally selected to the load	The fan capacity would be matched to the needs of the process	It is too expensive to justify based on energy savings.

Case 6: Sea Water Pumps at a Petrochemical Plant

- Cooling water is supplied to a petrochemical plant via a sea water pumping station.
- The pumping station consists **of 6 x 6.6kV** vertical pumps ranging from **825** to **925kW**, consuming approximately **13%** of total plant energy consumption.
- Under normal conditions **2** pumps are operational, with pumps being rotated on a regular basis.

The energy team have chosen this system as it is a lower risk for production but consumes a large quantity of energy.

What opportunities exist for MSO?

Case 6 - Possible MSO Opportunities

For the Motor System:

- Operate most efficient pumps
- Improve pump efficiency
- Install VSDs
- Upgrade motors to more efficient ones

Case 6 - Findings

- Pumps providing more than actual flow required.
- All discharge valves are throttled to approx. 60% open.
- Discharge header very well designed, but leaks detected in discharge piping network.
- Pumps were installed in 1963, 1982 and 2009, with different efficiencies.
- Power factor correction installed in 2017, improving from 0.7 to 0.98.

Case 6 - Analysis

Item	Actual water consumption m^3/hr	Observations
CDU- 1	*500*	*Using Portable F.M.*
CDU-2	*570*	*Design*
VDU	*385*	*Estimated 60% Design*
1/2 MILLION	*245*	*Using Portable F.M.*
TOTAL Distillation units	***1700***	
Reformer complex	***1200***	*Flow Indicator(note 2)*
Coker complex	***2800***	*Estimated 70% Design*
Total	***5700***	

- Actual cooling requirements were determined.
- This allowed the energy team to adjust the sea water pump output to match the requirements.

Case 6 - Outcome

System	Saving Opportunity	Annual Energy Savings [kWh p.a.]	Financial Savings [EGP p.a.]	Investment [EGP]	Payback [years]
Sea Water Pumps	1. Discharge Valves Opening Adjustment	750,000	530,000	0	0
	2. Run only one Pump during Units Outages	2,730,000	1,900,000	0	0
	3. Using New Efficient Smaller Pumps	1,480,000	1,000,000	8,000,000	8
	4. Replacing Manual Valves by Motorized	518,000	366,000	3,000,000	9

- Opportunity 1 and 2 implemented at no cost.
- Total cost saving of EGP2,430,000 (equivalent to 3,480,000 kWh) per year.
- Opportunities 3 and 4 will be considered when replacing the 2 old pumps (from 1963).

Case 6 - Lessons Learned

Measurement and understanding of load requirements are essential to the successful outcome of an optimisation project.

The MSO methodology can provide good support to deploy a culture of improvement, especially in old companies with high resistance to change.

Review & Discussion

05. Compressed Air

Electric Motor Applications

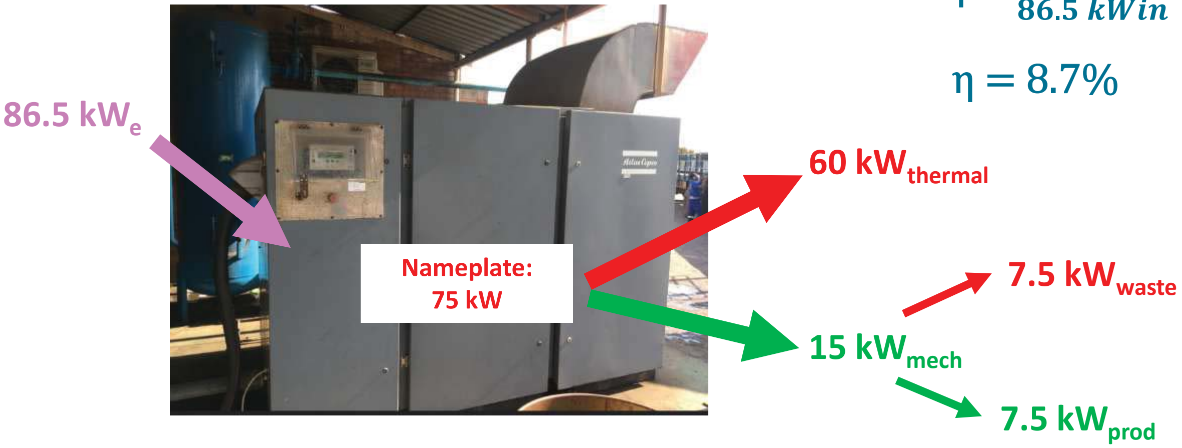
Review of User Training

- 80% of input energy lost as heat
- Compressed air costs 7 times as much as electricity
- Purchase compressors based on life cycle cost, not initial price
- Operation of oil injected screw compressor

Compressed Air Energy Conversion

$$\eta = \frac{7.5\ kWout}{86.5\ kWin}$$

$$\eta = 8.7\%$$



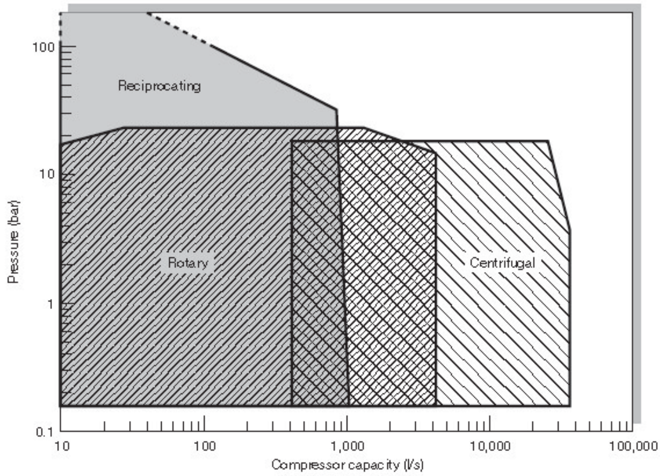
Compressed air is THE most expensive source of energy

Typical Compressor Operating Cost

Item:	Typical 160 kW air cooled screw compressor
Duty:	Fully loaded at 7.5 bar, 4,200 hr/y, Unloaded 4,000 hr/y
Rate:	$ 0.13 / kWh
Power at full load:	182.5 kW
Flow:	30.3 m^3 / m
Specific Power:	6.02 kW / m^3/m
Energy Cost:	kW x hours x rate
Energy Cost :	$ 134,000 per year

Compare with Purchase Price = $ 126,000

Compressor Range Chart



Range of Efficiencies

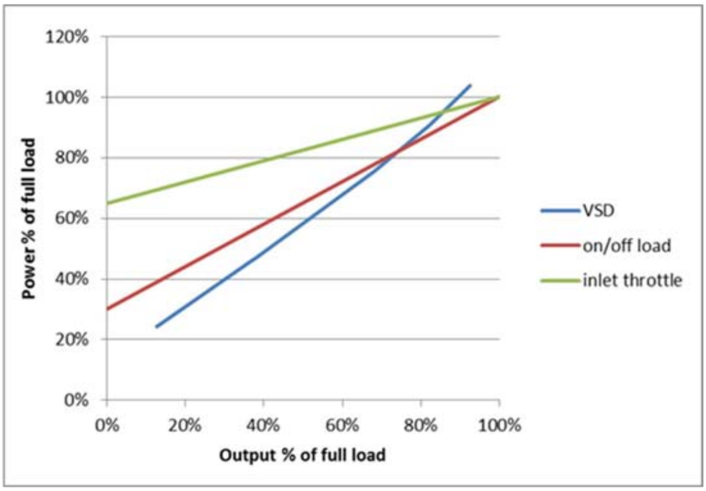
Good **rule of thumb** when assessing if the compressor is appropriate for the size of the installation

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**

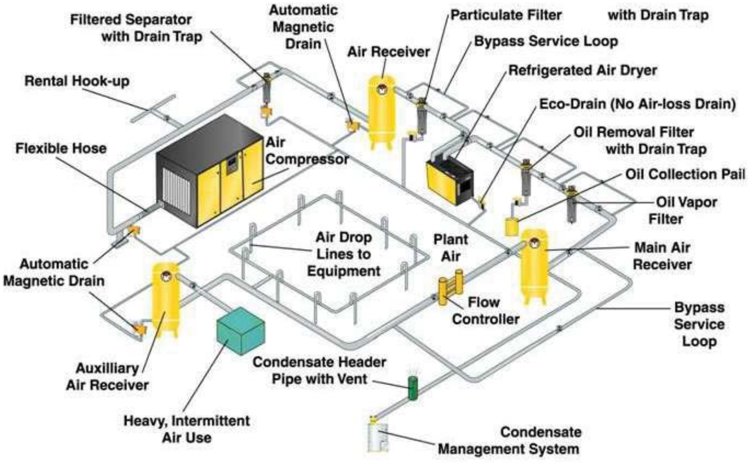
Variable Speed Control

- Better part load performance
- More accurate pressure tracking
- No gearbox
- BUT higher full load energy consumption
- NOT suitable for base load supply

Control of Positive Displacement Air Compressors



Typical Compressed Air System

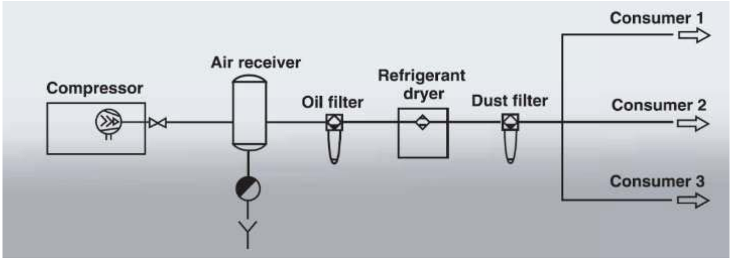


Assessment of Compressed Air Systems

- 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!

Optimisation of Compressed Air



1. Use less air
2. Optimise generation and compressor control
3. Improve quality of air to process
4. Recover energy from heat of compression

Use Less Air

1. Eliminate leaks
2. Isolate equipment when not used
3. Eliminate inappropriate uses
4. Reduce artificial demand




Leakage Losses

	Air Consumption at 6 bar (g) (m3/min)		Power Loss (kW)	
Hole Diameter	sharp orifice 0.61 coefficient	rounded orifice 0.97 coefficient	Shaft Power 6.2 kW / m^3/min.	Package Power 7.1 kW / m^3/min.
1mm	0,040	0,064	0,25 to 0,40	0,28 to 0,45
2mm	0,16	0,25	0,62 to 1,5	1,1 to 1,8
3mm	0,35	0,56	2,2 to 3,1	2,5 to 4,0
4mm	0,63	1,00	3,9 to 6,2	4,5 to 7,1
6mm	1,42	2,26	8,8 to 14,0	10,0 to 16,0

At USD 0.10/kWh, a 6 mm leak costs over USD 90,000 per year in power plus additional service on the compressed air equipment.

One audible leak (±3mm) will cost USD 12,000 per year!

Estimating Amount of Leakage

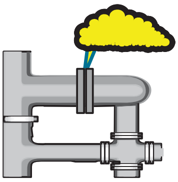
- Start the compressor when there are no demands on the system (when all the compressor operated end-use equipment is turned off).

$$\text{Leakage } (\%) = [(T \times 100)/(T+t)]$$

T – On Time
t – Off Time

Managing Air Leaks

- Not practical to eliminate ALL air leaks
- Should not be more than 10% of the mean production demand in a normal factory
- Typical industrial installations will have between 15% and 50% leakage rates (over 80% measured on one occasion)
- Conduct leakage rate test no load running decay time or data logging
- Leaks come back but seldom in the same place
- Regular on-going leakage campaigns must be conducted



Isolate Equipment When Not in Use

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 / sections

Inappropriate Use 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

NB – Offer an alternative

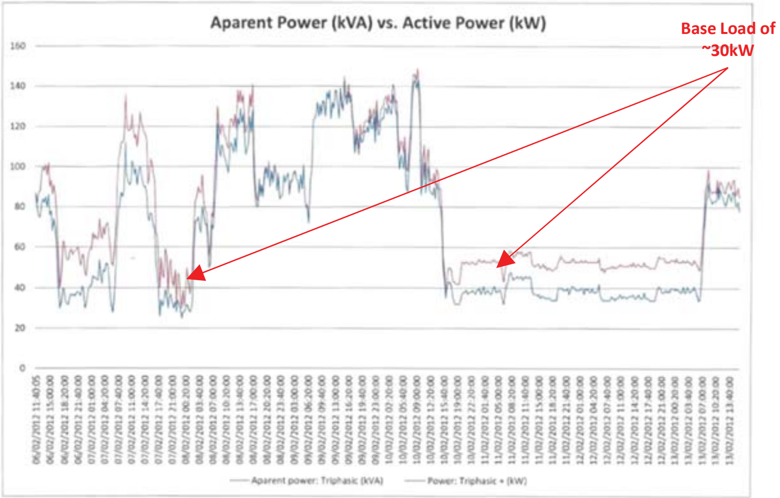
Blowing

- 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

Optimise Compressor Control

- Demand profile
- Pressure profile
- Compressor control
- Improve air treatment
- Use air receivers optimally

Demand Profile



Weekly Load Profile – Plating Plant

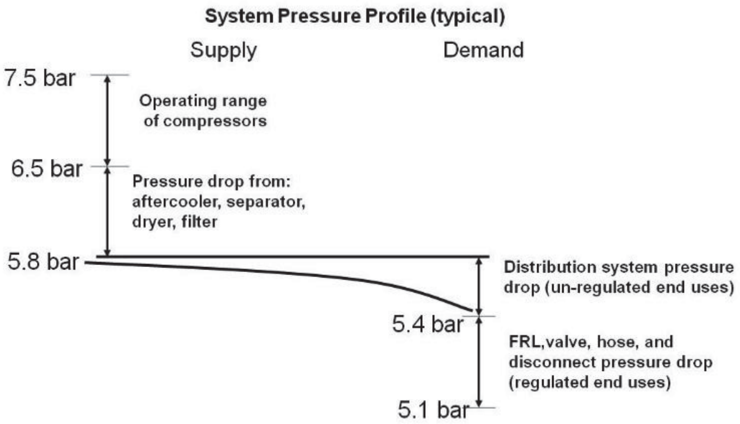
Can be used to:

- Identify opportunities for improvement
- Identify losses
- Determine compressor sizing requirements

Pressure Profile

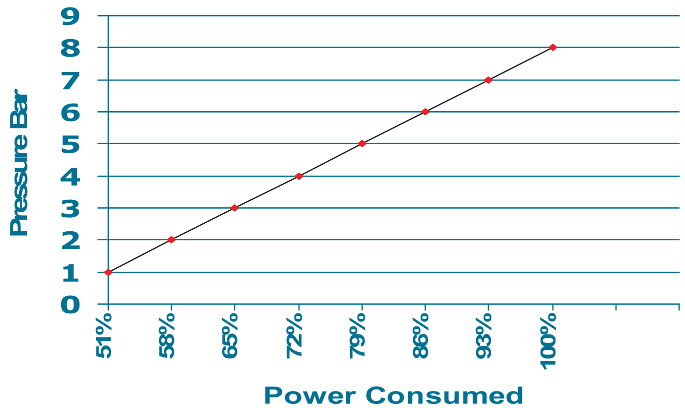
Pressure loss due to:

- Excessive filtration
- Small bore tubing or kinks
- Small fittings causing local restrictions



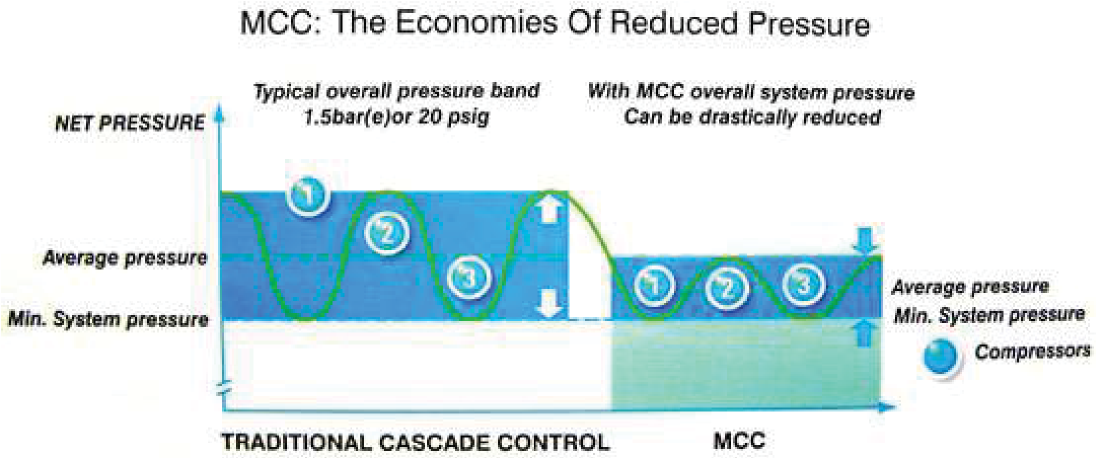
Optimise System Pressure

- Reduce system pressure = Reduced energy cost



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

Multiple Compressor Controllers

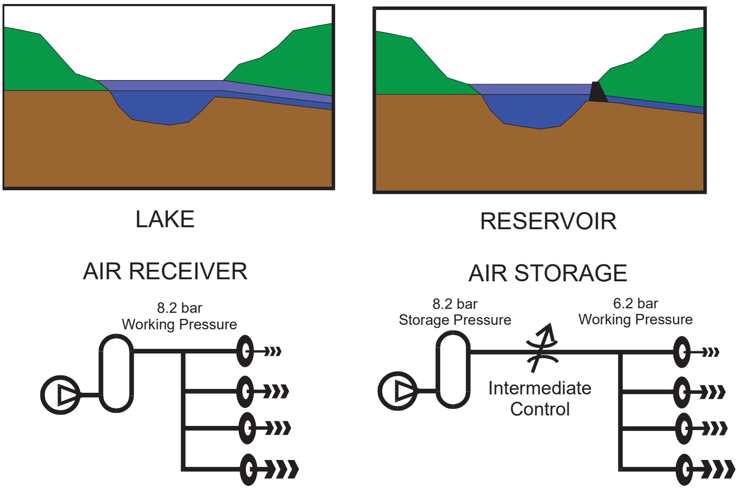


Atlas Copco Electronikon Multiple Compressor Controller

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

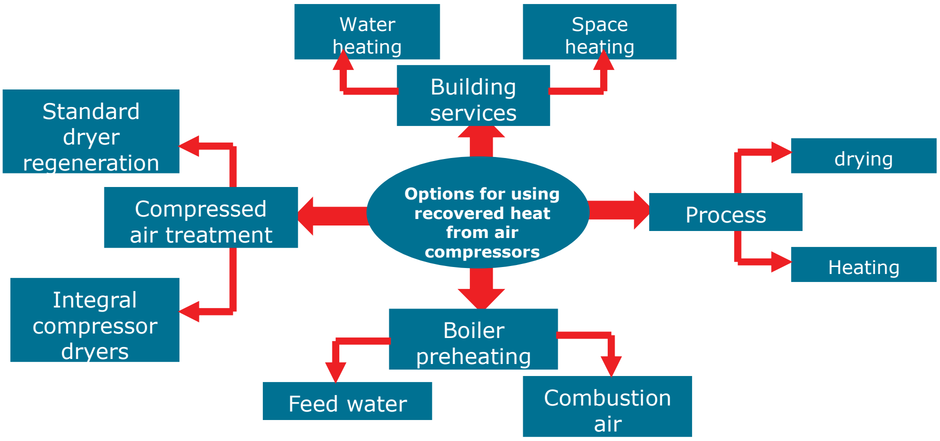
Storage: Lake – vs – Reservoir



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.

Options for Heat Recovery



Review & Discussion

MINISTRY OF INDUSTRY AND TRADE
Global Gateway
Funded by the European Union
UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

06. MSO Cases

Electric Motor Applications

MEASUR (Software tool)

https://www.energy.gov/eere/iedo/iedo-software-tools

https://www.energy.gov/eere/amo/measur

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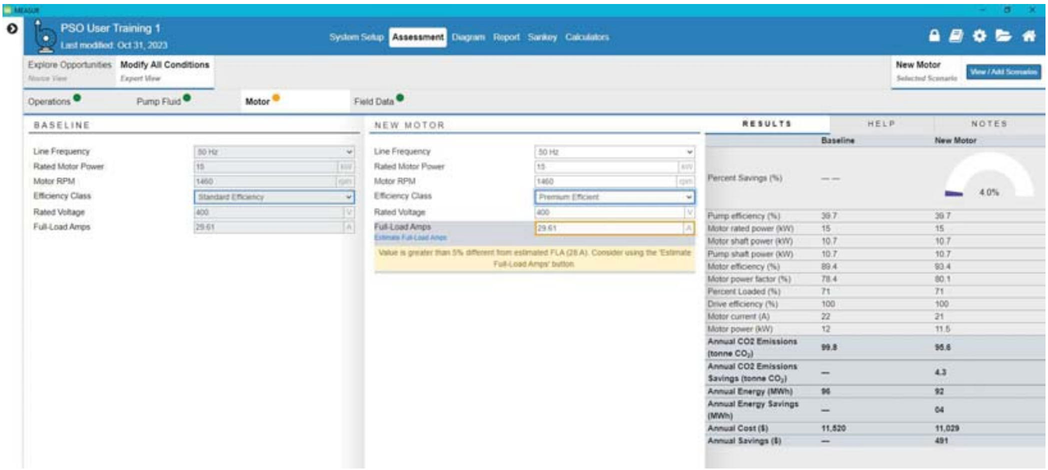
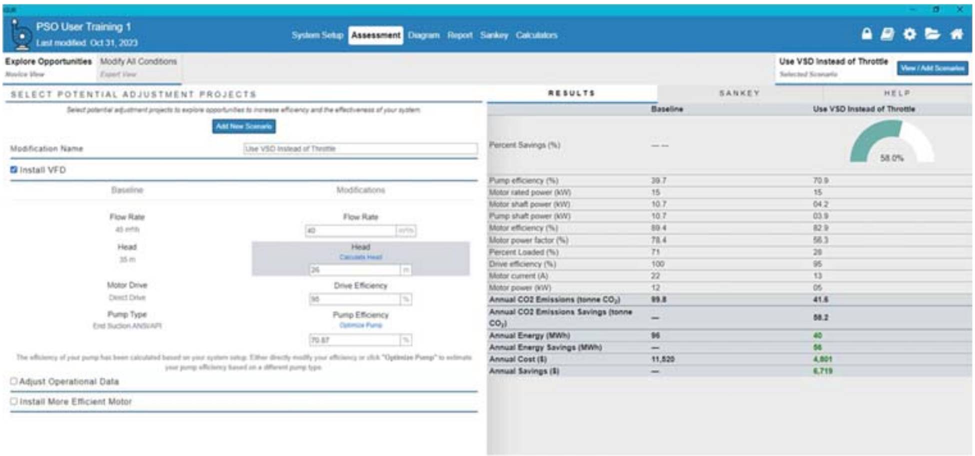
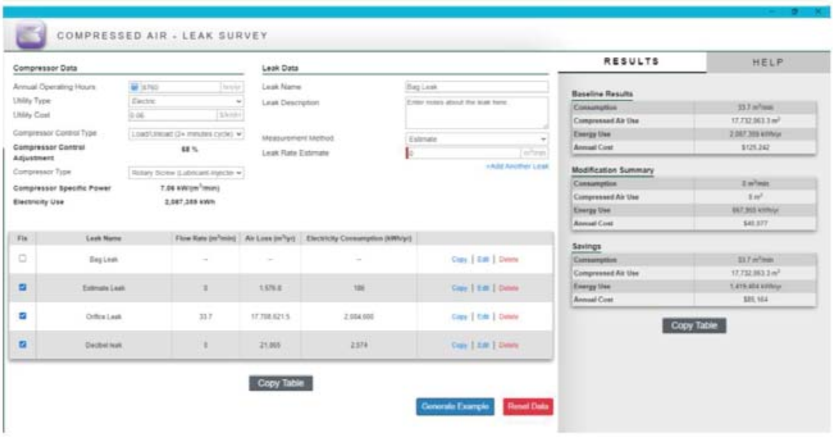
MEASUR Example – High Efficiency Motor



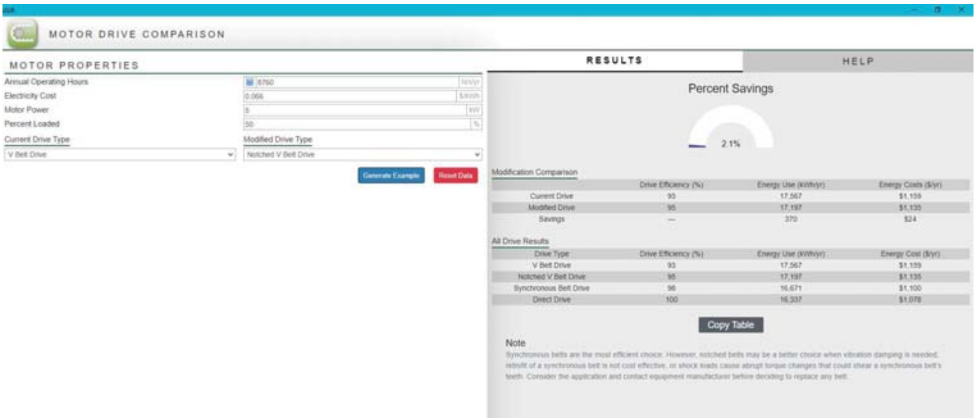
MEASUR Example: VSD on a Pump



MEASUR Example: Compressed Air Leak Survey



MEASUR Example: Transmission Belt Upgrade



DISCLAIMER

This document was developed within the framework of the project "Accelerating energy efficiency in large industries through energy management systems, system optimization and the promotion and adoption of energy efficiency in small and medium-sized enterprises (IEEP)", funded by the European Union (EU), managed by the Ministry of Industry and Trade (MOIT), and implemented by the United Nations Industrial Development Organization (UNIDO). The content of this document is the sole responsibility of the Project and does not necessarily reflect the views of any individual or organization.

THANK YOU

End of Day 1

Thank you for your participation!

See you tomorrow!

MINISTRY OF INDUSTRY AND TRADE

EU - VIETNAM SUSTAINABLE ENERGY TRANSITION PROGRAMME (SETP)

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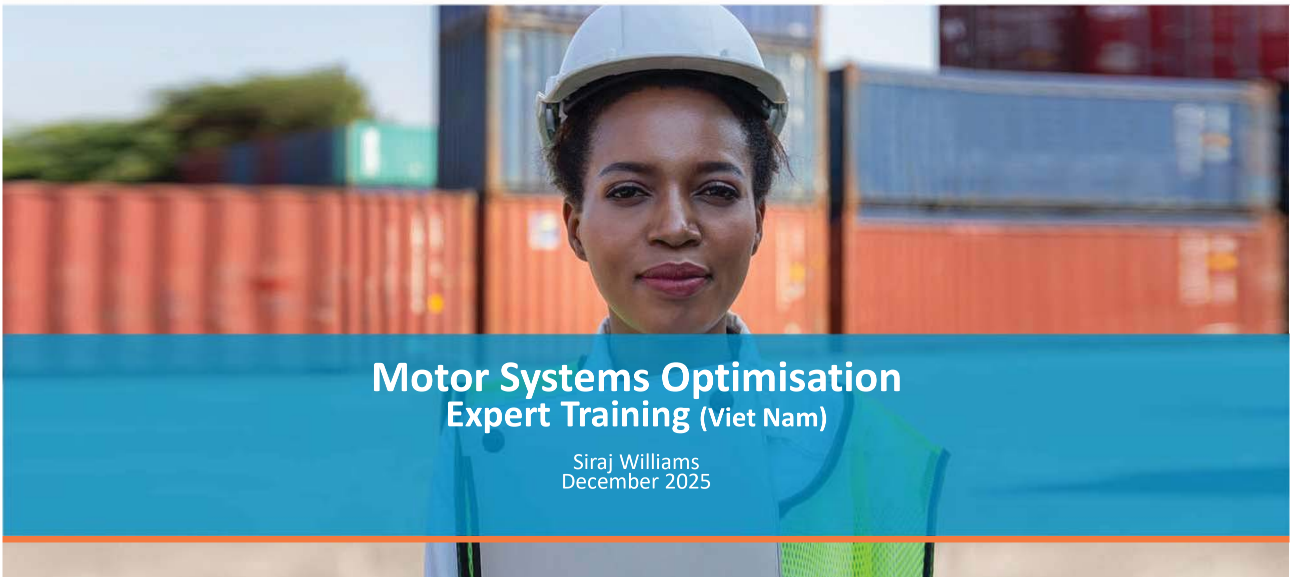


Motor Systems Optimisation
Expert Training (Viet Nam)

Siraj Williams
December 2025

Review of Day 1

- Any questions?
- Any comments?

Agenda Day 2 – In Class Session

Day 2 - Classroom				
08h30	Review of Day 1 (Q&A)	1	3	3
08h45	Power Quality	4	29	26
10h00	TEA			
10h15	Maintenance & Repair	30	55	26
10h55	MSO Assignment Report	56	75	20
11h30	Intro to Project Finance	76	92	17
12h00	Lunch			
13h15	Cases: Project Finance	93	93	1
13h45	Demonstration of Measurement Tools	94	98	5
15h00	TEA			
15h15	Demonstration of Measurement Tools	99	100	2
15h45	Site Visit Preparation	101	104	4
16h15	Next Steps	105	108	4
16h30	End of Day	109	109	1

07. Power Quality

Electric Motor Assessment

Review of User Training

Definition of Power Quality

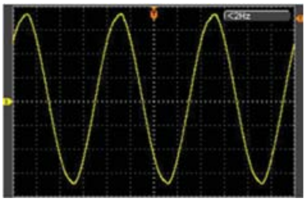
From a **quality perspective**:

- may be defined as the measurement, analysis, and improvement of the bus voltage to maintain a sinusoidal waveform at rated voltage and frequency[1]

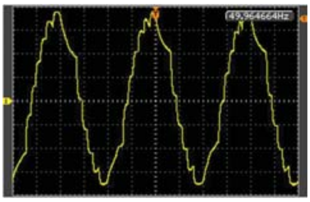
When viewed from a **compatibility perspective**:

- the ability of an equipment or system to function satisfactorily in its electromagnetic (EM) environment (immunity) without introducing intolerable electromagnetic disturbances to anything in that environment (emission)[2]

At generator

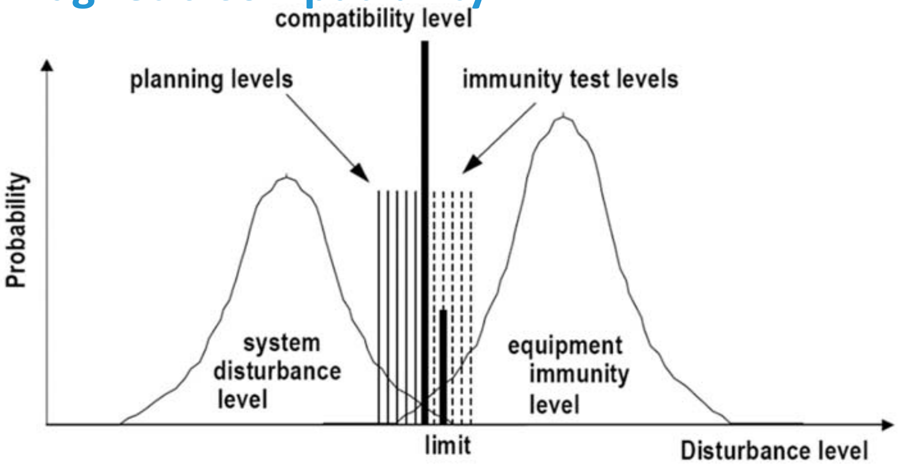


At point of use



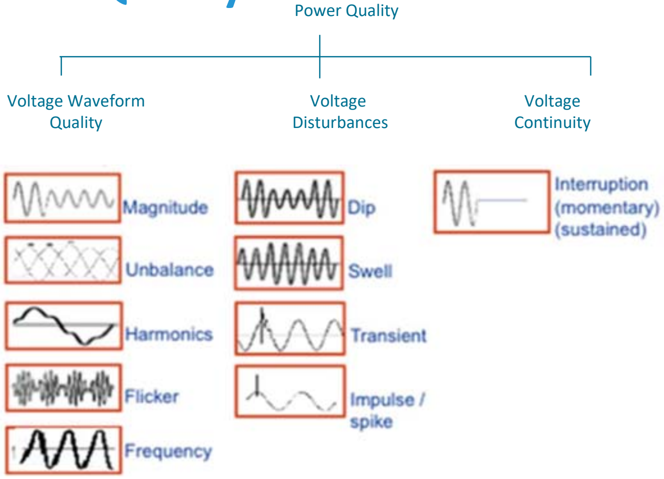
1. Masoum et al. Power quality in Power systems and electrical machines
2. International Electroctechnical Commission (IEC)

Electromagnetic Compatibility



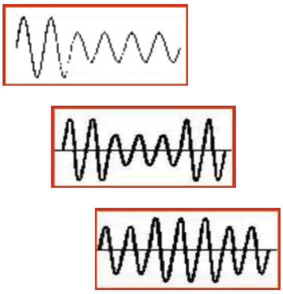
Source: UNIDO Power Quality Course: South Africa 2020

Types of Power Quality Occurrences



Source: Eskom Power Quality Course Notes

Voltage Magnitude



Steady state voltage not close to nominal voltage

- System voltage regulation

Short reduction in voltage magnitude (dip / sag)

- Momentary short circuits – birds, lightning, other causes
- Start up of very large motors
- Operation of large intermittent loads (eg arc furnaces)
- Energisation of power transformers

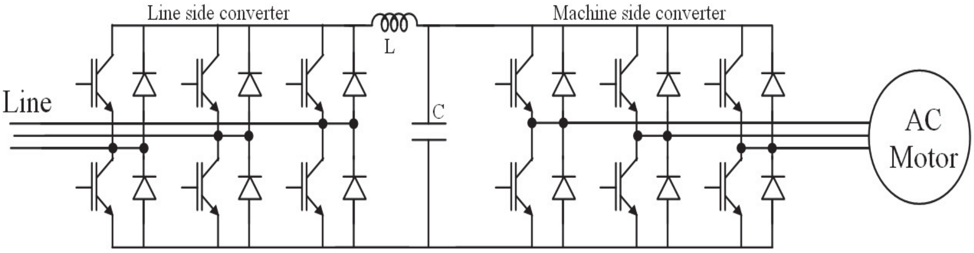
Short increase in voltage magnitude (swell)

- Sudden loss of large load
- Sudden increase in generation

Effect on motor systems

- Change in torque speed characteristic
- May cause extra heating reducing life span
- Reduction in motor efficiency

Active Rectifier VSD Front End



- Also called a bi-directional drive or regenerative drive
- 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.

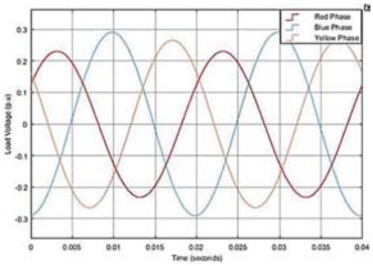
Disadvantages:

- 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.

Voltage Unbalance

Caused by

- Unbalanced 3 phase loads
- Unequal transformer tap changer settings
- Large single phase loads
- Open delta connected transformers and loads
- Unequal impedance in transmission and distribution conductors
- Inter winding short in one phase of a motor winding



Effect on motor systems

- Overheating of motor, reducing lifespan
- Loss of motor performance
- Reduction in efficiency

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Voltage Unbalance Limits – Viet Nam

Based on …

From a motor perspective, NEMA recommends that unbalance at the motor terminals should not exceed **1%.** Unbalanced voltage at motor terminals can cause phase current unbalance of **6 to 10** times the voltage unbalance.

Voltage Unbalance 2 (good approximation for values below 10%)

$$\% \, LVUR = \frac{\max voltage\ deveiation\ from\ the\ average\ line\ voltage}{average\ line\ voltage} \times 100$$

National Electrical Manufacturers Association (USA)

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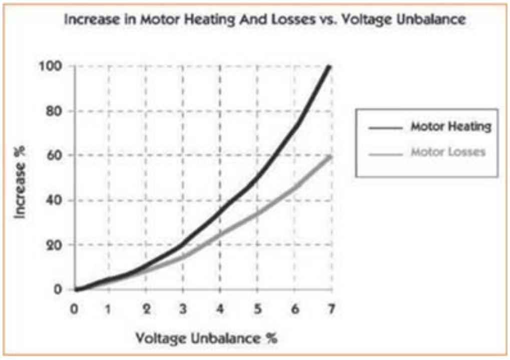
Effects of Unbalance on Motor Systems

CORRECT UNBALANCE AS MUCH AS PRACTICAL

- An unbalanced system causes extra heating in the motor windings
- Motor has to be derated to reduce the probability of premature failure
- Effect of unbalanced voltage on winding temperature:

Temp Rise = 2 x (unbalance %)^2



Source: www.pumpsandsystems.com

Total Harmonic Distortion (THD)

Total harmonic distortion is the magnitude of the harmonic distortion in a system.

$$THD = \frac{\sqrt{{V_2}^2 + {V_3}^2 + {V_4}^2 + \ldots\ldots + {V_N}^2}}{V_1} \times 100$$

Where:

- *n* is the harmonic number
- *n=1* is the fundamental frequency of the ideal waveform

Voltage Harmonic Distortion Limits (Vietnam)

Maximum allowable voltage harmonic distortion

Voltage level	Total Harmonic Distortion (THD)	Individual deformation
500kV, 220kV	3.0%	Not specified
110 kV	3.0%	1.5%
Medium voltage	5.0%	3.0%
Low voltage	8.0%	5.0%

Also have current limits at low voltage:

- *20% if load <50kW*
- *12% if load >50 kW*

REF: Circular 05_2025_TT-BCT-642994

Effect of Harmonics on Network

Harmonics cause more current to be used to do the same work. This adds energy cost, require more expensive wiring or causes overheating and damage.

Higher frequency harmonics cause additional core losses in motors resulting in energy losses, additional energy cost and overheating of the motor core.

Higher frequency harmonics could also interfere with communication frequencies and highly sensitive electronics like avionics and medical equipment.

Excessive heating of transformers and associated equipment, and damage to power factor correction capacitors..

How Harmonics Affect Motor Systems

Generation of system harmonics caused by invert fed motors

5th, 11th, 17th.

- Called negative sequence harmonics
- Cause a torque in the opposite direction to normal motor rotation resulting in a reduction in motor performance

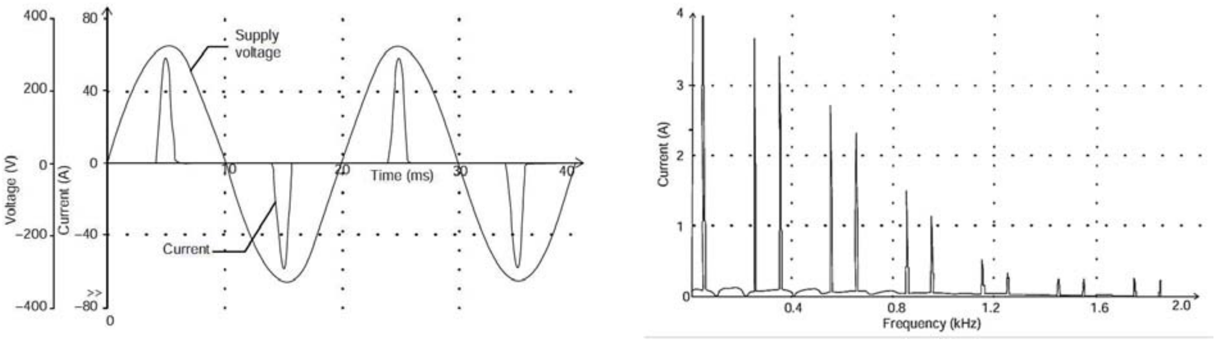
7th, 13th, 19th..

- Called positive sequence harmonics
- Cause a pulsing torque out of sequence with normal motor rotation increasing heating and losses

3rd, 9th, 15th ...

- Called zero sequence (triplen) harmonics
- In unbalanced systems will cause currents to flow in the neutral conducor of earthed systems causing dstortion of the voltage magnitudes of the phases

Harmonic Generation within VSDs



Typical input current waveform for a 1.5 kW three-phase drive and corresponding harmonic spectrum (only 1 phase shown)

Harmonics - Remedial Actions

- Change point of connection of identified electrical equipment
- Where possible, use 3ph drives instead of 1ph drives
- Install additional inductance
- Change the size of DC smoothing capacitor
- Use harmonic filters
- Use a drive with an active input converter
- Use 12 pulse drives

Harmonics - Remedial Actions

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.

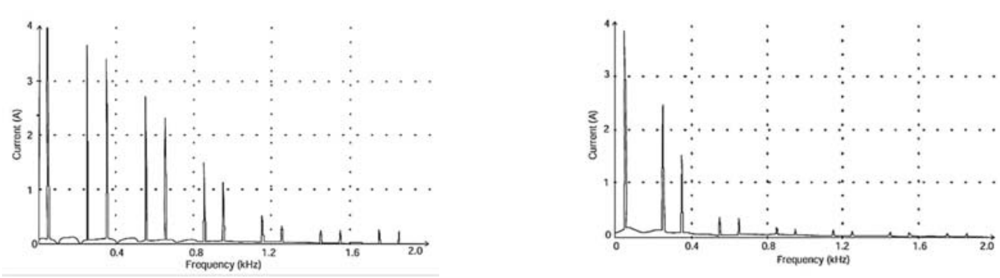
Use three-phase drives where possible

- 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 5th and 7^{th} harmonics are also reduced by three-phase drives.

Harmonics - Remedial Actions

Install 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 DC inductance internally, but useful reductions can also be obtained with large drives.



Harmonic spectrum for 1.5kW 3ph drive WITH and WITHOUT a 2% input inductor.

Harmonics - Remedial Actions

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.

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.

Harmonics - Remedial Action

Use a drive with an active input converter

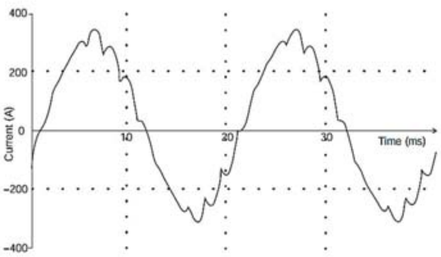
- An active input converter using PWM generates negligible harmonic current, as well as permitting the return of power from the load to the supply.

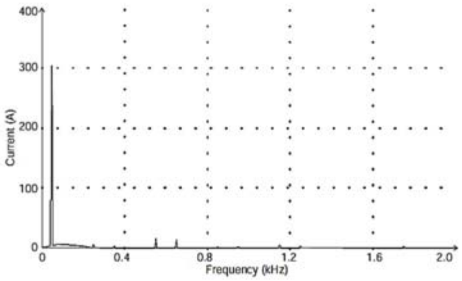
Use a higher pulse number (12 pulse or higher)

- 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).

Harmonics - Remedial Actions

Use a higher pulse number (12 pulse or higher) drive





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

Typical Harmonic Currents

Harmonic current levels for standard 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.

Costs of Power Quality

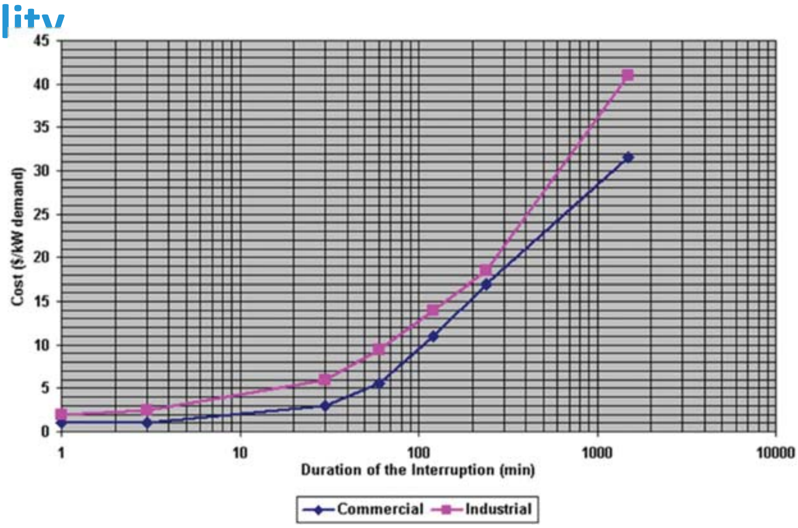
Cost of momentary interruption of 1 minute duration in $/kW demand

	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

Source: Electrotek Concepts

Cost of Power Quality

Costs of an event rises exponentially as duration increases



Review & Discussion

08. Maintenance and Repair

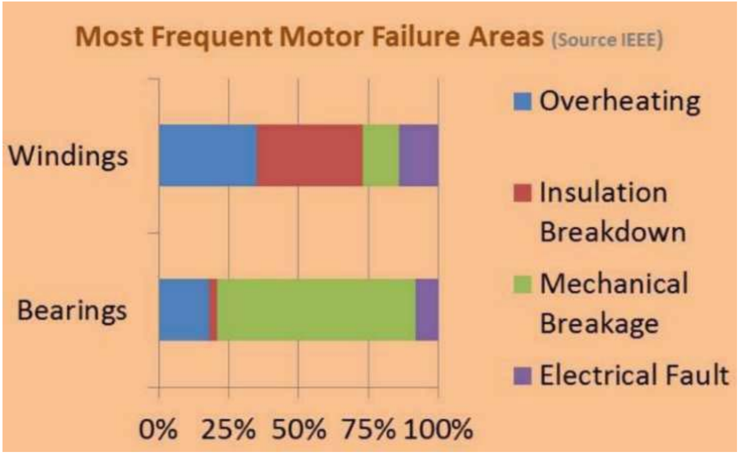
Electric Motor Assessment

Discussed Topics

- Why motors fail?
- Most common failures
- Motor rewinder requirements

Common Motor Failure Modes

Failure Cause	%
Bearings	51
Windings	16
External	16
Other	17



Source: IEEE

Prevention of Failures

- It is usually easier to prevent a motor from failing than it is to repair or replace it.
- Failures often result in production loss – this is usually large in comparison to the motor cost

Where do we start with prevention?

- Commissioning practices
- Operating conditions
- Power quality
- Maintenance and inspection

Condition Monitoring Techniques

Thermal Imaging	Vibration analysis	Shock Pulse Analysis

How?

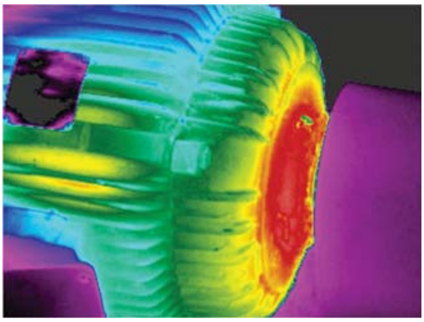
- Define acceptable limits for operation
- Include a maintenance plan to manage
- Record a history and trend over time

Thermal Imaging

Look for

- Hot spots in windings
- Over-heated bearings
- Over-heated terminal connections

Island Thermal Imaging

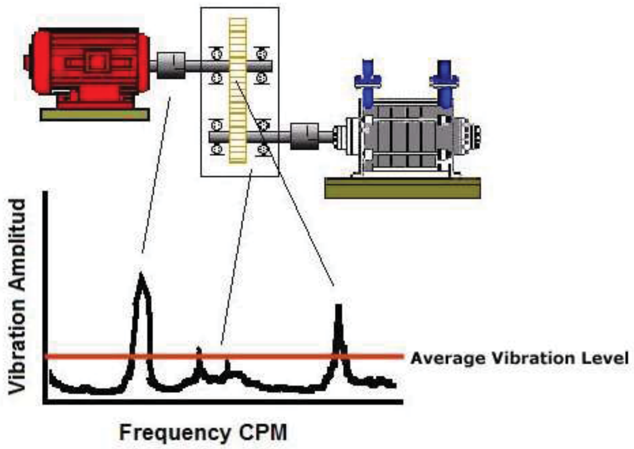


Note

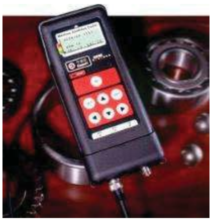
- Understand thermography to interpret results
- Regular surveys (in house or external)
- Trending equipment over time

Vibration Analysis

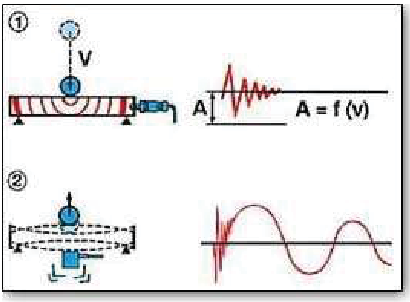
- Improvement on listening
- Identify different components by their frequency
- Best to trend over time
- For SMEs, call in outside help



Shock Pulse Vibration



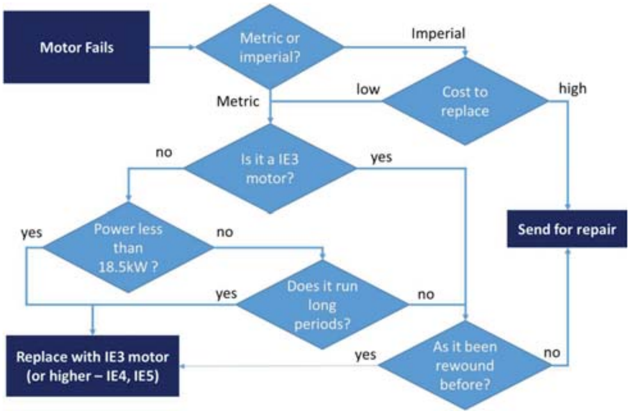
- Ideal for condition monitoring of bearings
- Can measure **lubrication** (regular or "carpet" level) and
- **Damage** (peak values) – like hitting a pothole.
- Rpm should be entered in order to adjust for speed.
- Budget $3-5kUS. Its best for looking at changes over time.
- Can be done in house.



Example of a Repair/Replace decision chart

This involves several key questions relating to what happens when a motor fails:

- ✓ Efficiency
- ✓ Size
- ✓ Running hours
- ✓ Past rewind history
- ✓ Metric / Imperial
- ✓ Other costs to change



Note that bearing replacement does not figure in this.

Source: ABB Motors – others produce similar diagrams

Worked Example

- **Economic Analysis – High Efficiency IE3 or IE4 Motors versus Repair or Retrofit of Old Standard Motors:**

1 - When a motor fails

2 - New application

3 - Retrofit of an existing operating motor

- Motor power and load -75 kW, 8400 hours/year, 70% load
- Electricity price US$ 0,1/kWh
- Efficiency of IE3 motor – 95%
- Efficiency of old motor – 91% (assume IE0 for motors more than 20 years old)

Exercise (Repair vs Replace with IE3 or IE4)

DATA REQUIRED:

- Efficiency of new IE3 motor – 95%
- Efficiency of new IE4 motor – 96%
- Efficiency of old motor – 91% (assume IE0 for motors more than 15 years old)

- Cost of new 75 kW IE3 motor – US$4500
- Cost of new 75kW IE4 motor: US$5625
- Cost of repair of old 75 kW motor – US$1500 (good repair – no additional losses)

- Lifetime of new efficient motor – 20 years

Savings & Payback

$$Electricity\ Savings\ [kWh/year] = Hr \times LF \times \left(\frac{P}{\eta_1} - \frac{P}{\eta_2}\right)$$

$$Simple\ Payback = \frac{Cost\ difference\ of\ new\ motor\ (\text{US\$})}{Energy\ Savings(kWh/year) \times Electricity\ Cost(\text{US\$}/kWh)}$$

Hr – Number of Operating Hours per year
LF – Load Factor
P – Motor Mechanical Output Power
η_1 – Standard or Old Motor Efficiency
η_2 – More Efficient Motor Efficiency

Electricity Savings (Repair vs. Replace with IE3)

$$Electricity\ Savings\ [kWh/year] = Hr \times LF \times \left(\frac{P}{\eta_1} - \frac{P}{\eta_2}\right)$$

$$Electricity\ Savings\ [kWh/year] = 8400 \times 0{,}70 \times \left(\frac{75}{91} - \frac{75}{95}\right)$$

$$Electricity\ Savings\ [kWh/year] = \mathbf{20\ 404\ kWh/year}$$

Payback

$$Simple\ Payback = \frac{Cost\ difference\ of\ new\ motor\ (\text{US\$})}{Energy\ Savings(kWh/year) \times Electricity\ Cost(\text{US\$}/kWh)}$$

$$Simple\ Payback = \frac{4500\ - 1500}{20\,404\ \times 0{,}1}$$

$$Simple\ Payback = \frac{3000}{2040} = \mathbf{1,47\ year}$$

Exercise (Repair vs Replace with IE4)

- Replacement with IE4 motor instead of IE3
  - Efficiency of IE4 motor: 96%
  - Price of IE4 motor: US$5625

Electricity Savings

$$Electricity\ Savings\ [kWh/year] = Hr \times LF \times \left(\frac{P}{\eta_1} - \frac{P}{\eta_2}\right)$$

$$Electricity\ Savings\ [kWh/year] = 8400 \times 0{,}70 \times \left(\frac{75}{0{,}91} - \frac{75}{0{,}96}\right)$$

$$Electricity\ Savings\ [kWh/year] = \mathbf{25\ 387\ \boldsymbol{kWh/year}}$$

Payback

$$Simple\ Payback = \frac{Cost\ difference\ of\ new\ motor\ (\text{US\$})}{Energy\ Savings(kWh/year) \times Electricity\ Cost(\text{US\$}/kWh)}$$

$$Simple\ Payback = \frac{5625\ - 1500}{25\ 387\ \times 0{,}1}$$

$$Simple\ Payback = \frac{4125}{2\ 539} = \mathbf{1,6\ year}$$

Savings & Return on Investment (Repair vs Replace with IE3)

$$Electricity\ Savings\ [kWh/year] = Hr \times LF \times \left(\frac{P}{\eta_1} - \frac{P}{\eta_2}\right)$$

$$Return\ on\ Investment = \frac{Energy\ Savings(kWh/year) \times Electricity\ Cost\left(\frac{US\$}{kWh}\right) \times Lifetime(years)}{Cost\ difference\ of\ new\ motor\ (US\$)}$$

Hr – Number of Operating Hours per year
LF – Load Factor
P – Motor Mechanical Output Power
η_1 *– Standard or Old Motor Efficiency*
η_2 *– More Efficient Motor Efficiency*

Return on Investment

$$Return\ on\ Investment = \frac{Energy\ Savings(kWh/year) \times Electricity\ Cost\left(\frac{US\$}{kWh}\right) \times Lifetime(years)}{Cost\ difference\ of\ new\ motor\ (US\$)}$$

$$Return\ on\ Investment = \frac{20\,404 \times 0{,}1 \times 20}{4500 - 1500}$$

$$Return\ on\ Investment = \frac{40800}{3000} = \mathbf{13.6\ x\ 100\%}$$

Exercise

- **New installation: Decision between IE4 motor instead of IE3**
  - Efficiency of IE3 motor: 95%
  - Efficiency of IE4 motor: 96%
  - Price of IE3 motor: US$4500
  - Price of IE4 motor: US$5625

Electricity Savings

$$Electricity\ Savings\ [kWh/year] = Hr \times LF \times \left(\frac{P}{\eta_1} - \frac{P}{\eta_2}\right)$$

$$Electricity\ Savings\ [kWh/year] = 8400 \times 0{,}70 \times \left(\frac{75}{95} - \frac{75}{96}\right)$$

$$Electricity\ Savings\ [kWh/year] = \mathbf{4835\ kWh/year}$$

Payback

$$Simple\ Payback = \frac{Cost\ difference\ of\ new\ motor\ (\text{US\$})}{Energy\ Savings(kWh/year) \times Electricity\ Cost(\text{US\$}/kWh)}$$

$$Simple\ Payback = \frac{5625\ - 4500}{4835\ \times 0{,}1}$$

$$Simple\ Payback = \frac{1125}{483{,}5} = \mathbf{2,3\ year}$$

Exercise (Retrofit existing operating motor with IE3)

- Replacement with IE3 motor
  - Efficiency of IE3 motor: 95%
  - Price of IE3 motor: US$4500
  - Terminal value of old motor: US$500

Electricity Savings

$$Electricity\ Savings\ [kWh/year] = Hr \times LF \times \left(\frac{P}{\eta_1} - \frac{P}{\eta_2}\right)$$

$$Electricity\ Savings\ [kWh/year] = 8400 \times 0{,}70 \times \left(\frac{75}{91} - \frac{75}{95}\right)$$

$$Electricity\ Savings\ [kWh/year] = \mathbf{20\ 404\ kWh/year}$$

Payback

$$Simple\ Payback = \frac{Cost\ difference\ of\ new\ motor\ (\text{US\$})}{Energy\ Savings(kWh/year) \times Electricity\ Cost(\text{US\$}/kWh)}$$

$$Simple\ Payback = \frac{4000}{20\ 404\ \times 0{,}1}$$

$$Simple\ Payback = \frac{4000}{2040} = \mathbf{2\ year}$$

Review & Discussion

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09. MSO Assignment Report

Electric Motor Assessments

Discussed Topics

1. Business case report

2. Financial evaluation of MSO cases

✓ Basic types of evaluation
✓ Time value of money
✓ NPV and LCC

Table of Contents of MSO report

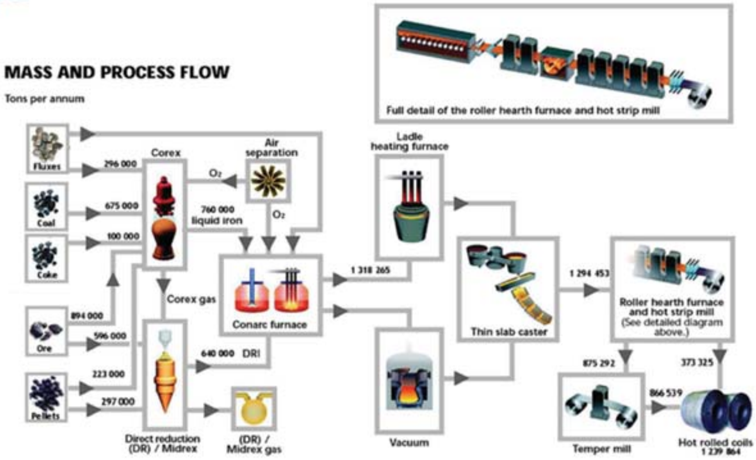
- Executive Summary
- Introduction
- Objectives of study
- Overview of Plant
- Initial MSO assessment
  - Reason for selecting motor system
  - Status quo
  - System diagram
  - Baseline energy consumption
- Detailed MSO Assessment
  - Process requirements
  - Mechanical load characteristics
  - Transmission characteristics
  - Motor and motor control characteristics
  - Power quality
- Measurement and Analysis
  - Measurement plan
  - Measurement data and analysis
  - Other data collected and analysis
- Opportunities identified
  - Opportunity 1
  - Opportunity 2
- Recommendations
- Which opportunities are recommended
- Appendices

Objective of Study

- Important to state what the purpose of the study is (feasibility, business case, process or equipment audit)
- Methodology of assessment (why, who, what, where, when, how)
- Expected outcomes

Plant Process Overview

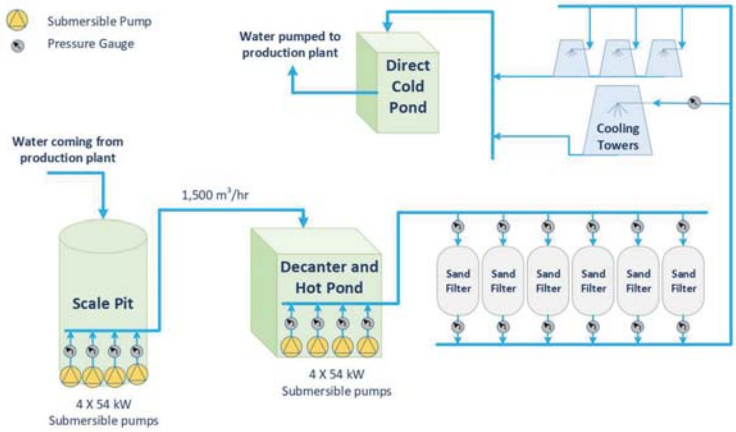
- Overview of plant production
- Simple bock diagram
- Key parameters for energy
- Pie chart or bar chart of SEUs if available



SOURCE: www.arcelormittalsa.com

Motor System Overview

- Simple bock diagram of motor system being assessed
- Operating parameters for production
- Pie chart or bar chart of SEUs if available



Plant Electrical Network and Costs

- Overall plant energy consumption
- Major energy drivers if available
- Simplified single line layout
- Highlight the motor system to be assessed

Motor System Selection

- An explanation of how the motor system was chosen and why
- Usually with a list of the major motors at the plant

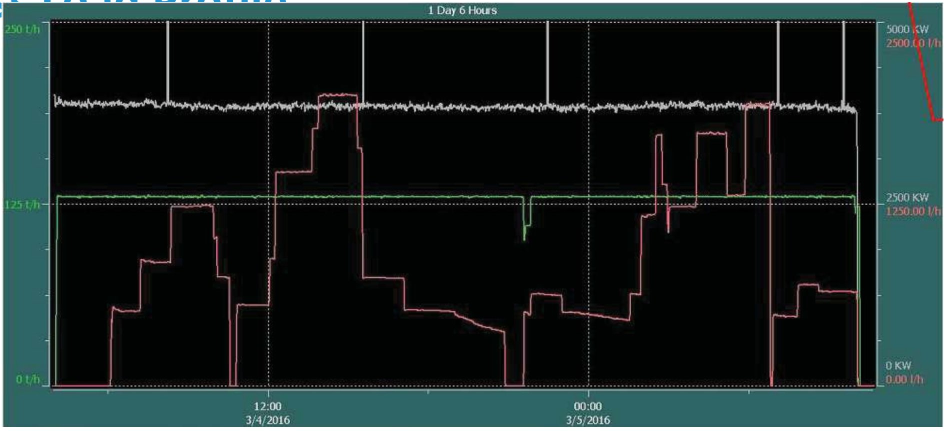
Major Motor List

	Plant System	Motor Application	No of Motors	Rated Power	total
1	Refrigiration A300	OLD Comp. NH3	5	300	1500
2	Refrigiration A300	NEW Comp. NH3	4	330	1320
3	Refrigiration B08	Comp. NH3	3	400	1200
4	air compressors	air comp motor	4	135	540
5	air compressors	air comp motor	2	250	500
6	Refrigiration A300	5 ºC pump	4	75	300
7	air dryer	Compr. Air dryer	3	90	270
8	Amenity Chillerno.1	Chiller Comp no. 2	2	104	208
9	B08 colling tunnel 1	Cooling cell from 1 to 12	12	17	204
10	B08 colling tunnel 2	Cooling cell from 1 to 12	12	17	204
11	process(UHT3.4.5)	UHT3.4.5	1	200	200
12	Amenity Chillerno.1	Chiller Comp no. 1	2	90	180
13	process(UHT3.4.5)	UHT3.4.5	1	160	160
14	process	MP1	1	132	132
15	Amenity Chillerno.1	Chiller Comp no. 3	2	63	126
16	Refrigiration A300	OLD Evap. Cond fan	4	30	120
17	Refrigiration B08	MPG Secondary Pumps	3	37	111
18	process(UHT3.4.5)	UHT3.4.5	6	18.5	111
19	process(UHT2)	UHT2	1	110	110
20	process(UHT3.4.5)	UHT3.4.5	1	110	110
21	process	CIP 4	7	15	105
22	air dryer	Compr. Air dryer	1	104	104

Measurements and Findings

- Measurement of existing energy parameters
- Operating conditions of load and process
- Set points and specifications of load and process

Process Load Profile

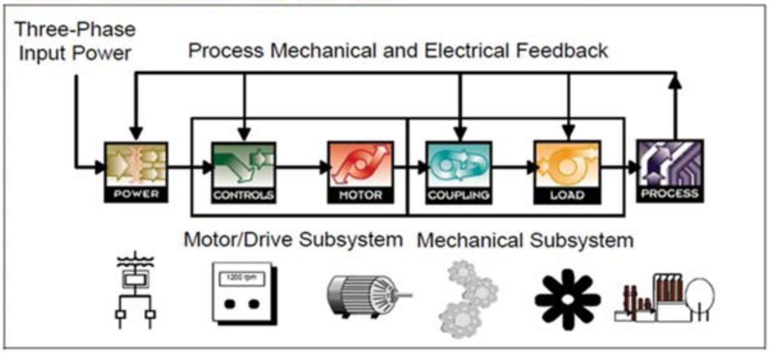


Provide a suitable explanation of the load profile.

Analysis

- Must include baseline (initial energy consumption) calculation
- Must include an analysis of all elements of the motor system
- Include any assumptions (eg. costs, operating parameters) that were used to calculate energy consumption.

Analysis of the Motor System



All elements of the system should be investigated and analysed.

Analysis of the Motor S

Good example of graphic to show potential savings results using MEASUR

	Baseline	Potential
Percent Savings (%)	— —	29.0%
Pump efficiency (%)	56.7	81.2
Motor rated power (kW)	54	54
Motor shaft power (kW)	46.5	34.1
Pump shaft power (kW)	46.5	34.1
Motor efficiency (%)	91.2	94.6
Motor power factor (%)	84.9	81.5
Percent Loaded (%)	86	63
Drive efficiency (%)	100	100
Motor current (amps)	91	67
Motor power (kW)	51	36
Annual Energy (MWh)	337	238
Annual Energy Savings (MWh)	—	98.9

Energy Savings Opportunities

- After analysis and identification of opportunities
- Quantify each opportunity (energy savings)
- Rank the opportunities using a risk matrix relevant to your organization
- Summary table or diagram to highlight key numbers and options

Risk Matrix for Opportunities

- An example of a simple risk matrix for opportunities. The actual energy and cost savings could be included in the matrix.
- The risk column may be expanded to include for example, production risk, financial risk, overall business risk.

Sr.	Proposal Description	Implementation Cost	Implementation Time	Payback Time	Risk
1	Medium voltage drives	Very high	Very high	Medium	No Risk
2	Enhanced Soft starter	high	Very high	Medium	Low
3	Switching ON/OFF	No Cost	Immediately	Immediately	Very High
4	Optimizing the operation control	No Cost	Immediately	Immediately	No Risk

Opportunities Summary

- After analysis and identification of opportunities
- Summary table or diagram to highlight key numbers and options
- Good to remind the reader of all the opportunities in a table on one page

Good Opportunities Summary

Criteria	Efficiency Improvement	Switching ON / OFF	Fan Speed Control	Adjusting Fan angle	Power Factor Correction
Implementation Methodology	Replacement the existing low efficiency oversized motor (190 KW) by new IE4 high efficiency motor (160 KW) **Cost:** Purchasing the new motor	Modifying the control circuit to add the automatic operation mode and installing soft starter to reduce the effect of repeated starting on the motor and mechanical parts **Cost:** Purchasing the soft starter & circuit modification	Installing variable frequency drive and modifying the control circuit to perform the fan variable speed operation **Cost:** Purchasing the VFD, new motor (compatible with VFD operation) & circuit modification	Adjusting the fan blade angle to be 8.9 during the six months with higher ambient temperature and to be 7.9 during the six months with lower ambient temperature **Cost:** Manpower cost	Installing power factor correction capacitor bank with 90 KVAR reactive power **Cost:** Purchasing the capacitor bank and installing it.
Implementation Cost (LE)	**300,000**	**80,000**	**460,000**	**3,000**	**20,000**
Saving per year (LE)	**6,384**	**82,313.1**	**116,826.89**	**11,970**	**1,191.92**
Payback Period (Year)	**47**	**0.97**	**3.94**	**0.25**	**16.78**

Recommendations

- From the list of opportunities, recommend which ones will be implemented and in which order.
- If opportunities will not be implemented or will be delayed, explain why.

Review & Discussion

- Any questions?

10. Introduction to Project Finance

Electric Motor Assessments

Financial Evaluation of MSO Projects

Basic types of evaluation	Time value of money	NPV and LCC

What is financial appraisal?

All organisations…

Need to control spending

- Current spending (expenses)
- Capital spending (investment)

Need to make choices of where to spend

- Spend; Yes or No?
- Choose between options for investment in savings project
- Choose between options using life cycle cost (LCC)

Simple Payback (SPB)

SPB = Initial Cost / Annual Savings

Usually organisations have a limit e.g. only opportunities with a payback of less than 2 years will be considered

Called "simple" because it does not take into consideration the effects of inflation, taxes and the cost of capital

Simple Payback (SPB)

Advantages:

- Simple and quick
- Good starting point to rank projects
- Useful as a quick estimate
- Can be used for low cost opportunities

Disadvantages:

- Too simple for large or critical projects that require a detailed analysis
- Does not account for inflation, discount rates
- Does not account for life cycle costs

Time Value of Money

If I offer you the choice of USD 10,000 now or USD 1,250 p.a. for 10 years

which would you choose?

Option 1:

You spend both forms of payment upon receipt

Option 2:

You invest both forms of payment at 11% interest pa and 22% inflation

Inflation and Interest

- Due to inflation, money is worth less in future than it is now.
- Assuming 22% inflation, then USD 10,000 now is worth USD 7,800 in one years time.
- Investing money in a bank, the nominal value of the money grows at the interest rate.
- Assuming an interest rate of 11%, USD 1000 will be USD 1110 at the end of the year.
- But due to inflation that USD 1110 will only have the buying power of USD 865.

Discount rate (or hurdle rate)

Need to know discount rate

- This is the return the organisation will decide to invest at
- Sometimes increased for more risky projects
- Related to the cost the organisation incurs in raising the capital
- Weighted average cost of capital (WACC) (debt and equity)
- Usually your accountant will know the discount rate
- Assuming the money is available

Net Present Value (NPV)

- The value now of a future amount of money
- USD 100 in 1 year at 22% inflation has a present value of USD 78

NPV is the value now of a future stream of cash flows

- Negative cash flows are outgoing
- Positive cash flows are incoming
- In energy terms, we invest in a project now to make a saving in energy in future
- We may include maintenance and repair costs
- We may have a scrap / salvage value at the end

Net Present Value (NPV)

$$PV = \frac{FV}{(1+i)^n}$$

Where

- *PV is the present value of all incoming cash flows*
- *FV is the sum of all cash flows*
- *i* is the discount rate
- *n* is the number of periods

$$NPV = PV - INV$$

NPV → is the present value

INV → is the initial investment

If NPV > 0 then it is profitable

It is viable if:

- If you have the money
- It is the best NPV available
- It is practical and will not affect production

Worked Example

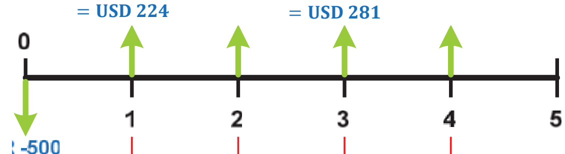
USD1000 investment and USD200 savings for 4 years at a 22% discount rate. Savings increase at 12% p.a.

$200 * (1.12)^1 = \text{USD } 224$

$200 * (1.12)^2 = \text{USD } 251$

$200 * (1.12)^3 = \text{USD } 281$

$200 * (1.12)^4 = \text{USD } 315$



$$\frac{-500}{(1.22)^0} = \text{USD } -500$$

$$\frac{224.00}{(1.22)^1} = \text{USD } 184$$

$$\frac{251}{(1.22)^2} = \text{USD } 169$$

$$\frac{281}{(1.22)^3} = \text{USD } 155$$

$$\frac{315}{(1.22)^4} = \text{USD } 142$$

NPV = USD 150

Positive cash flow (incoming e.g. savings)
Negative cash flow (outgoing e.g. investments)

Internal Rate of Return (IRR)

- Very similar to NPV
- Doesn’ t use discount rate, but calculates a rate of return (IRR) based on the projected cash flows
- The IRR is then compared with the discount rate (or the company hurdle rate, or with the IRR of other projects)
- If IRR = discount rate, then NPV = 0
- If IRR > discount rate, then NPV > 0

IRR = indicator of the efficiency of yield (%)
NPV = indicator of the magnitude of investment return (EGP)

NPV and IRR C

Financial Benefits of an investment				
Year 0	- 500		Discount Rate	22%
Year 1	224		Savings Inflation	12%
Year 2	251			
Year 3	281			
Year 4	315			
Year 5				
Year 6				
Year 7				
Year 8				
Year 9			**NPV**	**R 148.96**
Year 10			**IRR**	**36%**

Life Cycle Cost (LCC)

- LCC is used to compare which of 2 or more projects will have a lower total cost over its life cycle.
- All cash flows are negative because they are expenditures.
- In comparison, NPV is used to compare which of 2 or more projects will yield a better return.

Life Cycle Cost (LCC)

Example

Buy a fixed speed pump for USD 5,000 and annual running costs of USD 7,000	**OR**	Buy a variable speed pump for USD 10,000 and annual running costs of USD 3,000

Life Cycle Cost (LCC) – UNIDO Tool

Life Cycle Costing (LCC)				
	Option 1	Option 2		
Cost	-5,000	-10,000	Interest/Discount	22%
Year 1	-7,000	-3,000	Savings Inflation	12%
Year 2	-7,840	-3,360		
Year 3	-8,781	-3,763		
Year 4	-9,834	-4,215		
Year 5	-11,015	-4,721		
Year 6	-12,336	-5,287		
Year 7	-13,817	-5,921		
Year 8	-15,475	-6,632		
Year 9	-17,332	-7,428		
Year 10	-19,412	-8,319		
LCC	**LE 45,237**	**LE 27,244**		

Review & Discussion

- Any questions?

Case Studies: Project Finance

- Example of NPV
- Example of LCC

11. Measurements

Electric Motor Assessments

Discussion & Demonstration

- Demonstration of Instruments

Power Quality and Energy Loggers

Power data logger with basic quality of supply analysis

General Data Loggers

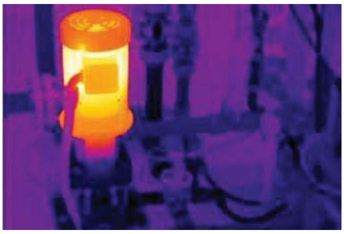
Data logger with typical transducers

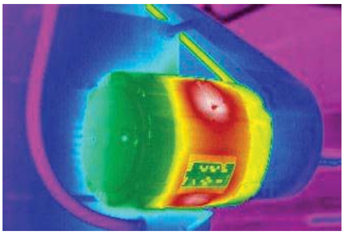




Hand Held Ammeter


Thermal Imaging Camera





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Motor Assessment Devices

Tachometer

Environmental Monitor

On/Off Data Logger

12. Site Visit

Electric Motor Assessments

Site Programme - Objectives

Gain some practical experience on how to conduct a motor system assessment

- Plant overview
- MSO systems overview
- Conducting an MSO assessment
- Measurement and data collection
- Analysis of data collection
- Development of opportunities and recommendations

Site Visit - Programme

Day 3 - Site Visit - Xuong Giang Paper	
08h30	Welcome and Introduction
09h00	Plant Overview & Welcome by Top Management
09h30	Safety Briefing
09h40	Training Objectives & Split into Groups
10h00	TEA
10h15	Review of Motor Systems
11h00	Site Visit - First inspection of the system
12h00	LUNCH
13h15	Motor System Assessment Session 1
14h00	Motor System Assessment Session 2
15h00	TEA
15h15	Motor System Assessment Session 3
16h00	Analysis of observations and data
16h30	End of day

Day 4 - Host Plant - Xuong Giang Paper	
08h30	Opening Discussion (Q&A)
08h45	Analysis of observations and data
10h00	TEA
10h15	Summarise findings & observations
12h00	LUNCH
13h15	Opportunities for each motor system
14h00	Presentation of findngs & opportunities
15h00	TEA
15h15	Feedback to Management
16h00	Next steps - Assignments & Webinars
16h30	End of day

Site Visit

Please remember:

- Safety shoes
- Obey the instructions of Xuong Giang Paper personnel at all times
- No wandering off on your own
- No photos without permission

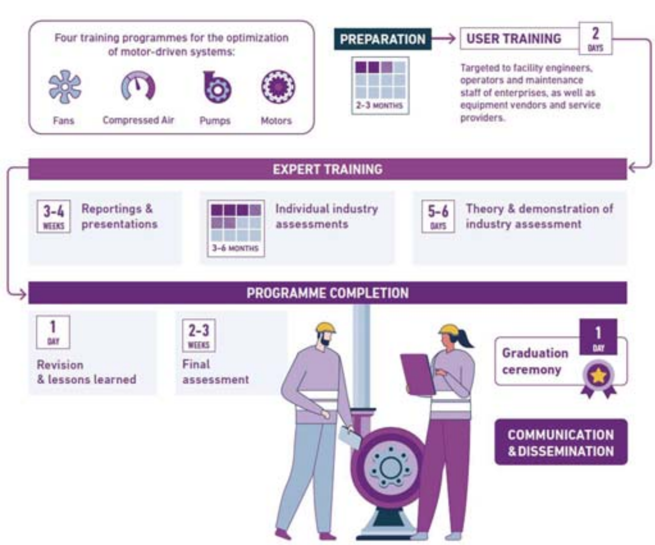
13. MSO Next Steps

Certification

The MSO Training Cycle

Key components:

1. User Training Class
2. Expert Training Class
3. Individual industry assessment
4. Final examination



MSO Expert Certificate

Requirements:

- Attend the User training (2 day).
- Write and pass the User training class test achieving at least 70%.
- Aattend the Expert training (5 day).
- Actively participate in the class discussions, practical demonstrations, and presentations.
- Complete an individual MSO assessment at a plant.
- Attend progress webinars as arranged.
- Write and pass a final examination based on the coursework covered, obtaining a minimum pass mark of 70%.
- Obtain an overall final pass mark of 70% based on the individual report, final examination and class participation.

What happens next?

	MSO Expert Schedule	Date
1	Assign groups and confirm system to be assessed	
2	MSO Assignment Webinar 1	
3	MSO Assignment Webinar 2	
4	Submission of Assignment Report (First draft)	
5	Submission of Assessment Report (Final version)	
6	Final Examination	
7	Graduation	

DISCLAIMER

This document was developed within the framework of the project "Accelerating energy efficiency in large industries through energy management systems, system optimization and the promotion and adoption of energy efficiency in small and medium-sized enterprises (IEEP)", funded by the European Union (EU), managed by the Ministry of Industry and Trade (MOIT), and implemented by the United Nations Industrial Development Organization (UNIDO). The content of this document is the sole responsibility of the Project and does not necessarily reflect the views of any individual or organization.

THANK YOU!

End of Course

Thank you for your participation!

Please complete the course evaluation!