MINISTRY OF INDUSTRY AND TRADE

EU - VIET NAM SUSTAINABLE ENERGY TRANSITION PROGRAMME (SETP)

Global Gateway

Funded by the European Union

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)

TRAINING PROGRAMME
MOTOR SYSTEMS OPTIMISATION

Ha Noi, 25 - 26/09/2025

AGENDA

Training on Motor Systems Optimisation (MSO)
25 - 26 September 2025

Adonis Hotel - 55 Quang Trung Street, Hai Ba Trung Ward, Ha Noi

Day 1

Time	Contents	Speakers
8.00-8.30	Registration and welcome	
8.30-8.40	Opening speech	Representative of IEEP PO
8.40-10.00	**Part 1: Overview of Motor Systems in Industry** - Importance of electric motors in industrial energy consumption - Common types of motors and their applications - Overview of energy losses in drive systems	International Expert
10.00-10.15	**Tea-break**	
10.15-12.00	**Part 2: Operating Principles and Efficiency of Electric Motors** - Motor efficiency and efficiency classes (IE1--IE4) - Losses in motors and the impact of load - Performance curves and efficiency vs. load	International Expert
12.00-13.15	**Lunch at the hotel**	
13.15-15.00	**Part 3: Components of the Drive System** - Pumps, fans, compressors -- relationship with motors - Impact of load, transmission system, control - System performance curves and operating points	International Expert
15.00-15.15	**Tea-break**	
15.15-16.45	**Part 4: Motor System Performance Analysis** - Key performance indicators: percent load, load deviation, power consumption - How to collect and analyze operational data - Practice: Interpreting measurement results and identifying savings opportunities	International Expert

Day 2

Time	Contents	Speakers
8.00-8.30	Registration	
8.30-9.00	Q&A and recap of Day 1	International Expert
9.00-10.00	**Part 5: Introduction and Installation of the MSO Tool Software** - Purpose and structure of the MSO Tool - Software interface and main modules	International Expert
10.00-10.15	**Tea-break**	
10.15-12.00	**Part 6: Detailed Analysis with MSO Tool** - Practice: Entering technical specifications and measurement data - Determining load, efficiency, losses - Assessing energy saving potential	International Expert
12.00-13.15	**Lunch at the hotel**	All the class
13.15-15.00	**Part 7: Proposing System Optimization Solutions** - Replacing with high-efficiency motors - Application of Variable Speed Drives (VSD/VFD) - Optimizing the drive system and maintenance	International Expert
15.00-15.15	**Tea-break**	
15.15-16.30	**Part 8: Comprehensive Practical Exercise (Case Study)** - Analyzing a real-world motor system - Practicing using the MSO Tool to propose solutions - Calculating investment costs and savings benefits	International Expert
16:30 – 16:45	**Part 9: Wrap-up Session** - Key takeaways & notes for practical implementation - Suggested support tools: MEASUR, MotorMaster+, VSD toolkit - Course evaluation and feedback	International Expert IEEP Project Office

Motor Systems Optimisation

User Training

(Presented by: Siraj Williams)

Welcome …

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

Acknowledgements

UNIDO

- Marco Matteini, Vienna

Original authors

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

Course Objectives

Why are we here?

Learn from each other and share experiences and knowledge

Gain understanding of the fundamentals of motor driven systems

Learn structured methodologies for assessing and optimising motor driven systems

Course Outline – User Training

1. Overview of UNIDO
2. Introduction to MSO
3. The Systems Approach
4. Motor Technologies
5. Motor Standards
6. New Motor Selection
7. Motor Operating and Control
8. Pumps
9. Fans
10. Compressed Air
11. Other Applications
12. Power Quality & Power Factor
13. Mechanical Transmissions
14. Maintenance and Repair
15. Conducting an MSO Assessment
16. Software Tools
17. Development of MSO Business Case
18. eMobility and Smart Grids
19. MSO Training Guideline

Section 1

Overview of UNIDO

UNIDO SDG's

Objectives of the UNIDO IEE Programme

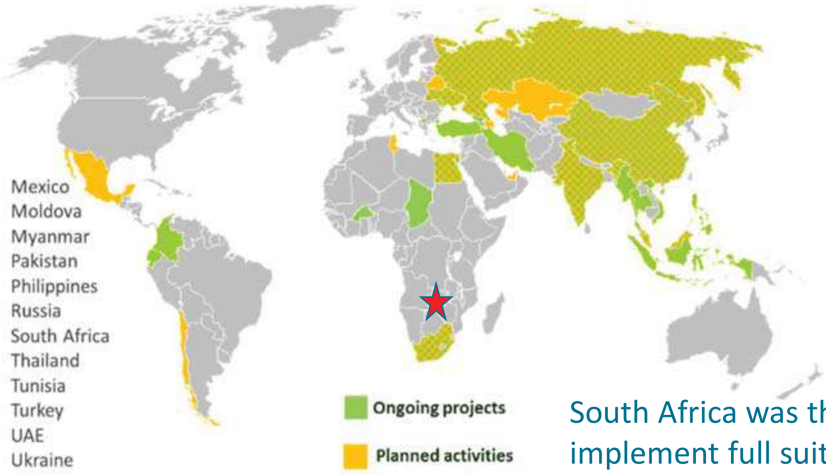
Work together with counterparts, stakeholders and partners to:

- **Strengthen policy** and regulatory frameworks for better & sustainable EE performance in industry
- **Accelerate adoption** and wide dissemination of IEE best-available practices and technologies
- **Save energy** and reduce GHG emission of the industrial sector
- **Integrate EE** in industry daily business practices for sustainable increased productivity and competitiveness

UNIDO Industrial Energy Efficiency Portfolio

30 Countries

Armenia
Belarus
Burkina Faso
Chad
Chile
China
Colombia
Ecuador
Egypt
Georgia
Kazakhstan
India
Indonesia
Iran
Macedonia
Malaysia
Maldives
Mexico
Moldova
Myanmar
Pakistan
Philippines
Russia
South Africa
Thailand
Tunisia
Turkey
UAE
Ukraine
Viet Nam



South Africa was the first country to implement full suite of projects offered

Impact of UNIDO-GEF EnMS-ISO 50001- ESO Programme

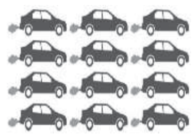
7,500 GWh of final energy savings =

Annual energy consumption of 1,230,000 EU households

OR

5 years energy production of 400 1 MW wind turbines

OR



CO_2 emissions of 1,875,000 middle class cars (running 12,500 km per year)

- Organization-wide energy savings in first 1-2 years range from 4% to 15%, with little or no capital investments

- Cumulative cost savings of beneficiary companies estimated to exceed ***USD 250 mio*** without considering non-energy benefits
- Direct GHG emission reductions of more than ***4.8 million*** **tCO_2**
- Sustainable pipeline of IEE investments generated

Section 2

Introduction to MSO

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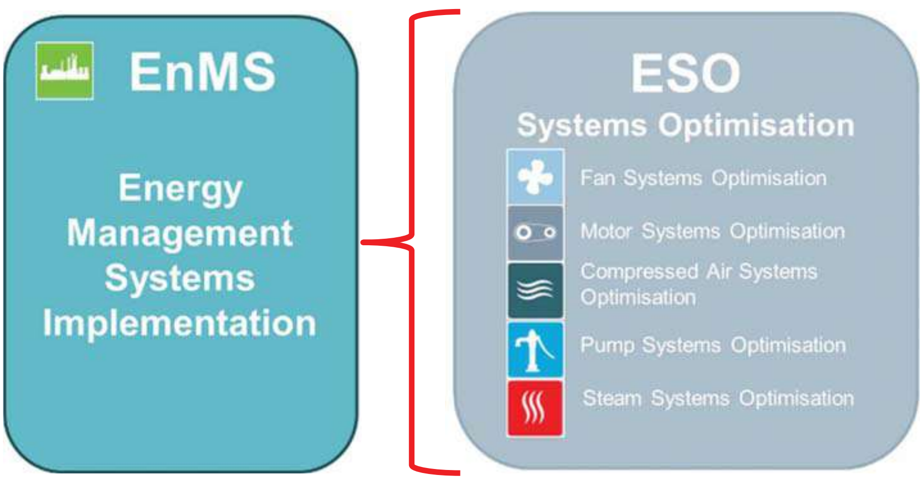
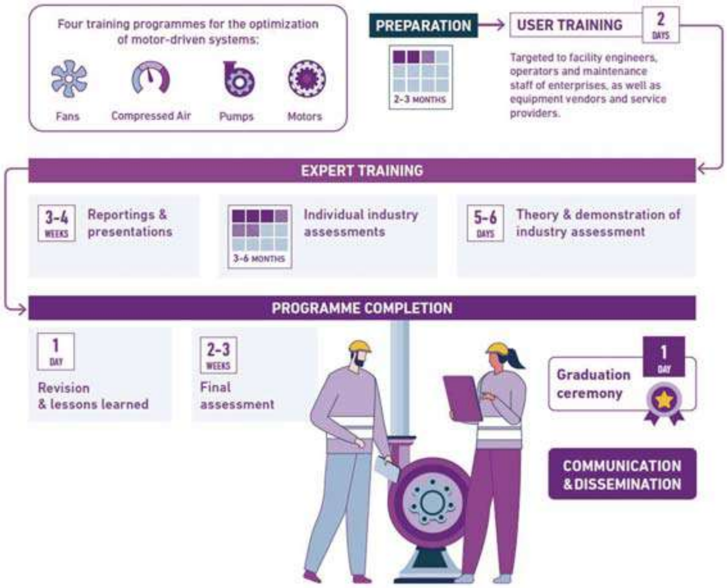
Relation between EnMS and ESO’s



The MSO Training Cycle

Key elements:

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



Why do we use motors?

to drive some mechanical application…

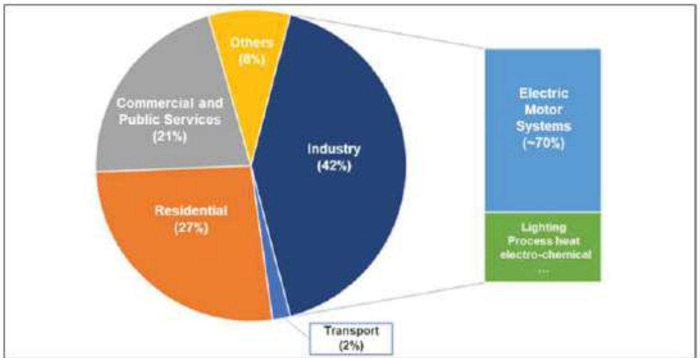
(always connected to something to create movement to do “work”)

BUT…

- Motors cost money to install and maintain

- Motors consume energy of which there is currently limited supply

Why do we focus on electric motors?

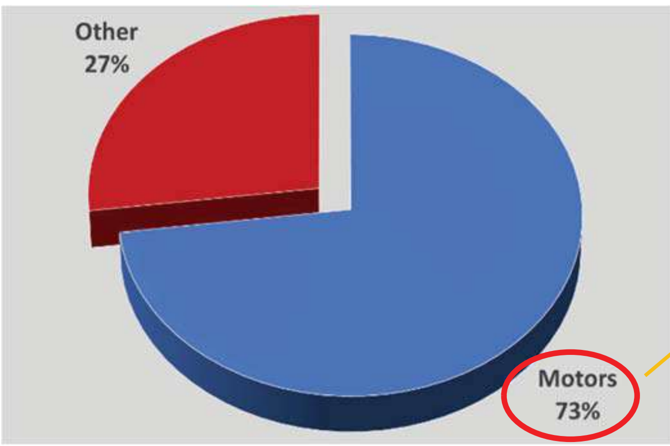


Industry	9566 TWh
Transport	420 TWh
Residential	6072 TWh
Commercial and public services	4849 TWh
Others (agriculture and fishing)	1940 TWh
Total:	**22,847 TWh**

IEA (2019):

- 53% of the electricity worldwide is used in electric motor systems (12,100 TWh)
- Representing emissions of 6 Gton CO_2eq

Electric Motors in Industry

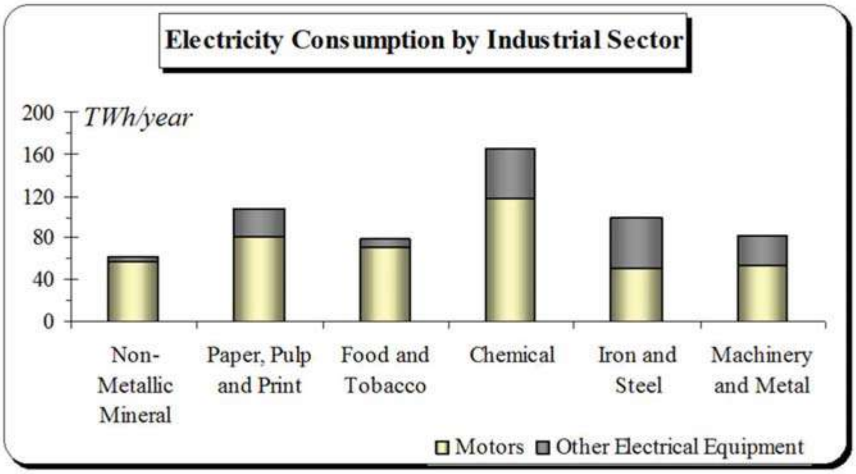


Motors 73%

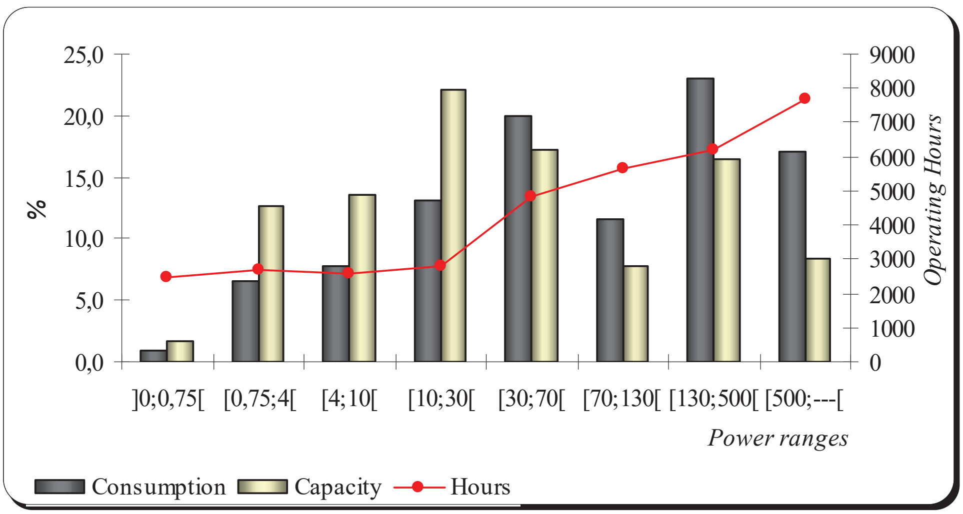
Electricity Consumption in the European Union Industrial Sector
Source: ISR – University of Coimbra (2012)

Electric Motors in Industry

Motor Systems Electricity Consumption by Industrial Sector (2000)

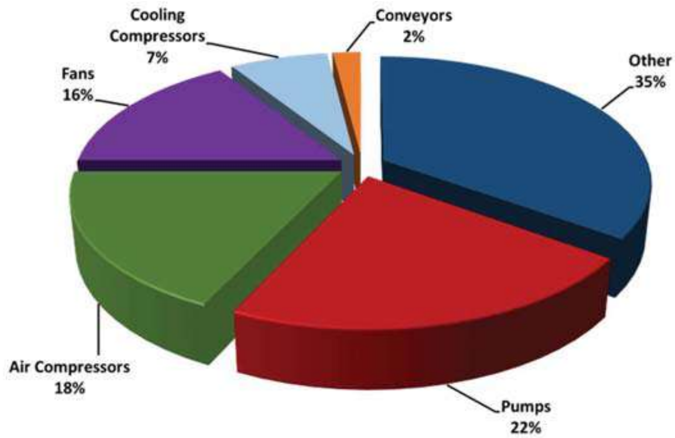


Motor Systems Electricity Consumption by Motor Size



Motor Systems Electricity Consumption by Application

Pumps, fans and air compressors make up 56% of industrial applications



Electricity Consumption in the European Union Industrial Sector
Source: ISR – University of Coimbra (2012)

MSO Objectives

Why are we here?

- Motor systems in industrial and commercial environments can in most cases be **optimised**
- Improvements in energy performance will lead to **reduction** in energy costs

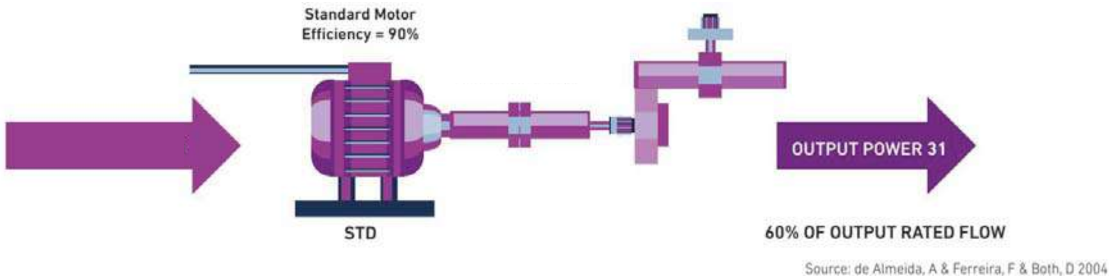
Review and Discussion

- Why are we interested in motor system optimisation?
- Which mechanical loads are the most common applications of motors?

Section 3

Motors: The Systems Approach

Case Study: Electric motor in a pump application



- The motor is operating at full speed and driving the pump.
- The pump is providing fluid to the production process.
- The process requires 31 units of power.
- The throttle is used to control the volume of the flow to 60% of the maximum pump output and is manually controlled by an operator.
- The motor is 90% efficient.

How efficient is the **system**?

Efficiency of an Electric Motor System

Motor:

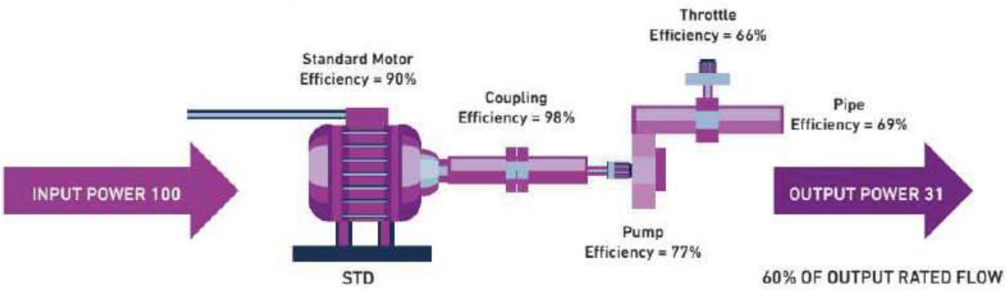
$$\eta_{MOTOR} = \frac{P_{OUTPUT\ (USEFUL)}}{P_{INPUT}} = \frac{P_{SHAFT}}{P_{ELECTRICAL}} \qquad (where\ P_{SHAFT} = T \cdot \omega)$$

System:

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

Where,
η – efficiency; P – Power; T – Torque; ω – rotational speed; VSD – Variable Speed Drive

Case Study: Electric motor in a pump application



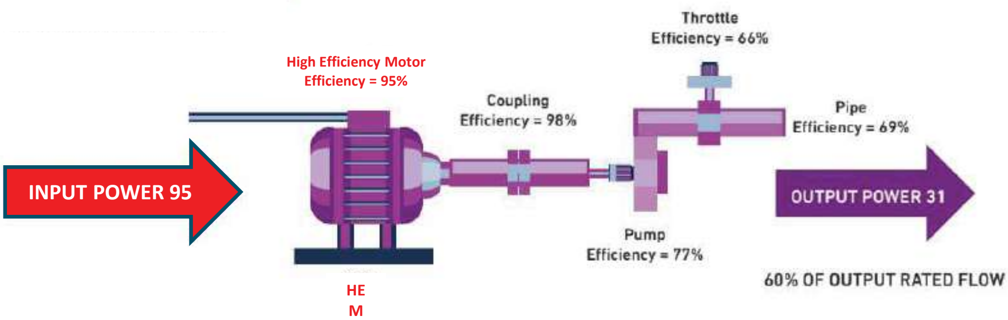
System efficiency is the product of the efficiencies of the individual components

- Efficiency (η) = $\eta_{motor} * \eta_{coupling} * \eta_{pump} * \eta_{throttle} * \eta_{pipe}$

  = 90% * 98% * 77% * 66% * 69% = **31%**

Is this acceptable?

Case Study: Improving motor efficiency only

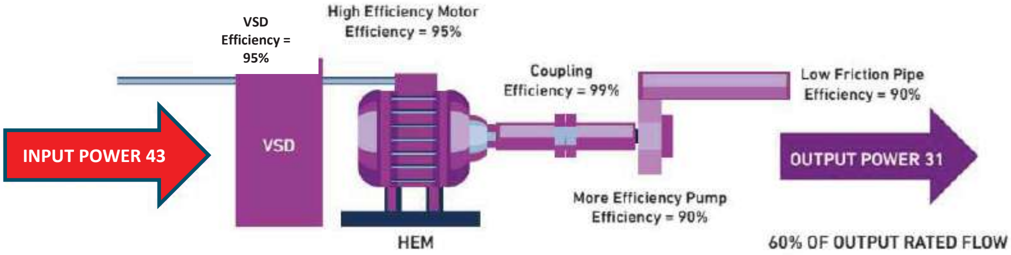


New Efficiency (η) = $\eta_{motor} * \eta_{coupling} * \eta_{pump} * \eta_{throttle} * \eta_{pipe}$

= 95% * 98% * 77% * 66% * 69% = **32.6%**

Is this acceptable?

Case Study: Improving all system components



- Replace throttle control with VSD
- Install high efficiency motor
- Improve transmission coupling
- Install more efficient pump
- Install low friction piping

New System Efficiency (η) = **72%**

We have created a virtual power station worth 57 power units!

Optimisation: Using the Systems Approach

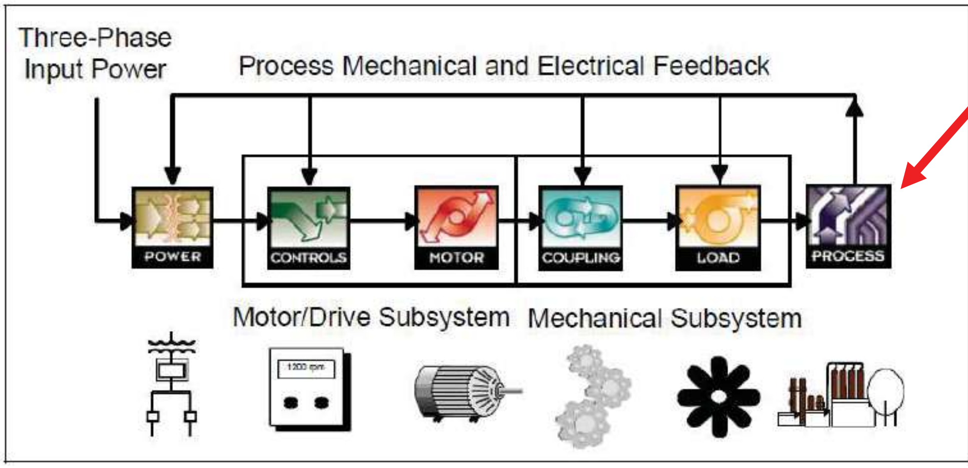
- Using the system approach, savings of between 5-40 % may often be realised.
- At component level, replacing the motor with a more efficient one only, will usually yield about 1-4 %.

Where do we start?

- Review load requirement first
- Review complete system and identify low cost opportunities within the system
- Lastly, review the motor and motor drive for the system

The Electric Motor System

Start Here

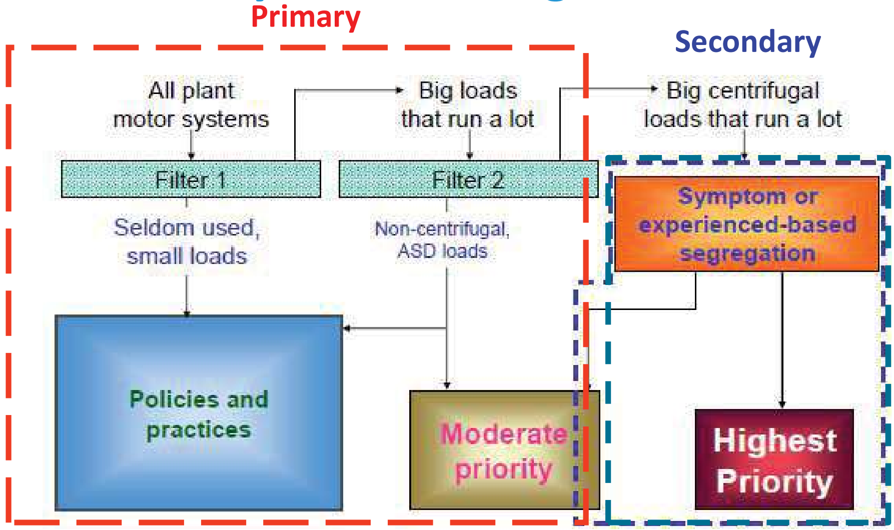


Pick the Top 20 Motor Systems

Ideally end up with a list of 10-20 motor systems to look at

Allow 30 - 60 minutes per system for review and prioritisation

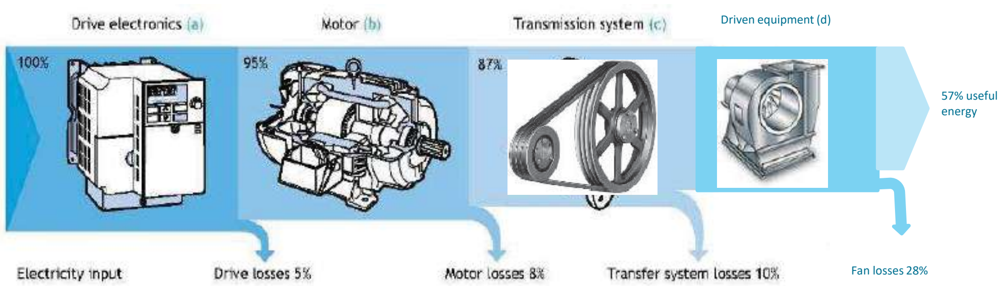
Primary & Secondary Prescreening



Slide Courtesy of Oak Ridge National Laboratory

Motor System Analysis: Start with the end use…

Start at the process where the final energy is required and work backwards towards the source



Energy losses occur at each stage. Identify the losses and look for the best opportunities to improve

Ask the Big Questions

1. What is the system trying to achieve?
2. What are the settings – how were these settings determined?
3. Is it the best way of doing it?
4. Do we really need it all the time?

Conduct a Motor System Review

- Determine the type of motor and load application
- Determine the system requirements
- Establish the operating hours and costs
- Calculate the annual cost of operation
- Check on the method of operation and management
- Draft a system diagram showing all components
- Determine the motor control method
- Establish where any inefficiencies may occur
- Calculate the losses where possible
- Estimate the possible savings

Remember… use the systems approach

An efficient electric motor and the use of variable speed drives is of little value if pipes are blocked in a pump system, or if there are leaks in a compressed air system. Similarly, if a motor is idly running and not providing a mechanical end use benefit, then energy will be wasted, regardless of the equipment's efficiency rating.

System optimization approaches address the entire motor system, from the power supply to the mechanical controls and everything in between. A motor is considered just one of many opportunities for optimization.

It is very common to identify a setting or operational control that can reduce the requirement for energy in the production process, thereby improving the energy efficiency of the motor system.

Review and Discussion

- Why use the systems approach?
- Give some benefits of using the systems approach?
- How do we calculate system efficiency?
- Where do we start?
- How do we decide which motor systems to optimise?

Section 4

Motor Technologies

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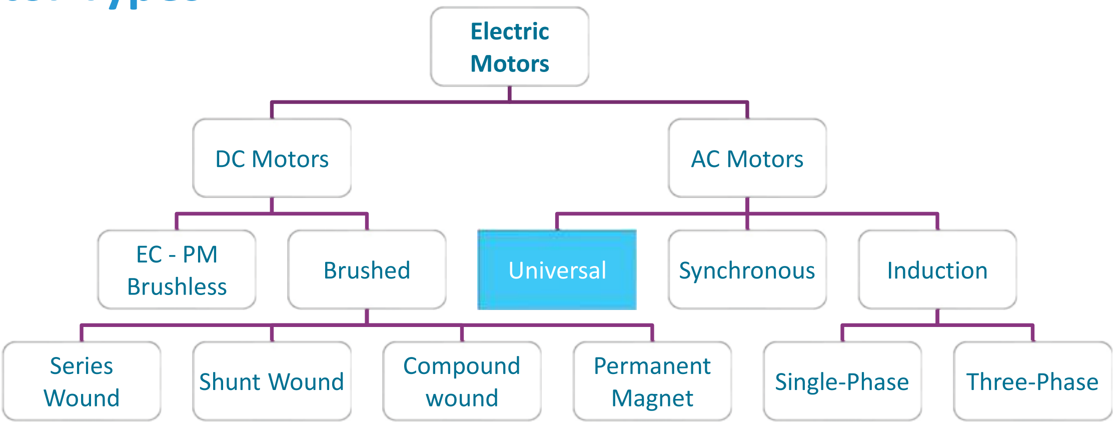
Operating Principles

All motors have two basic parts:

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

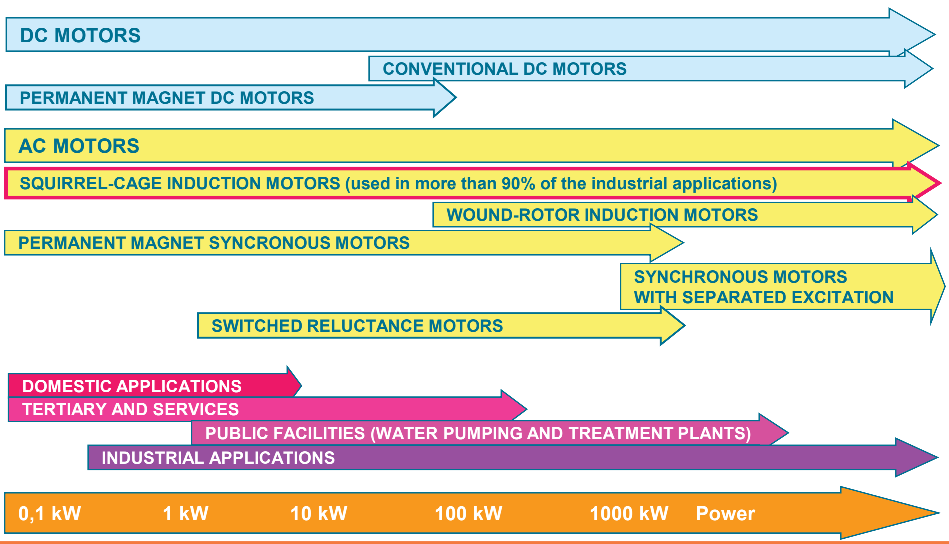
The design and fabrication of these two components determines the classification and characteristics of the motor.

Motor Types



EC – Electronically Commutated
PM – Permanent Magnet

Motor Types and Applications



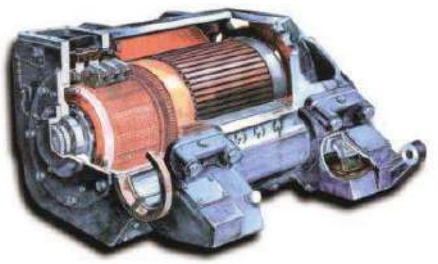
DC Motors

Types

- Brushed with stator winding
- Brushed with PM stator
- Brushless (new technology)

Characteristics:

- Simple to control
- High maintenance requirements
- Poor reliability (brush failure)



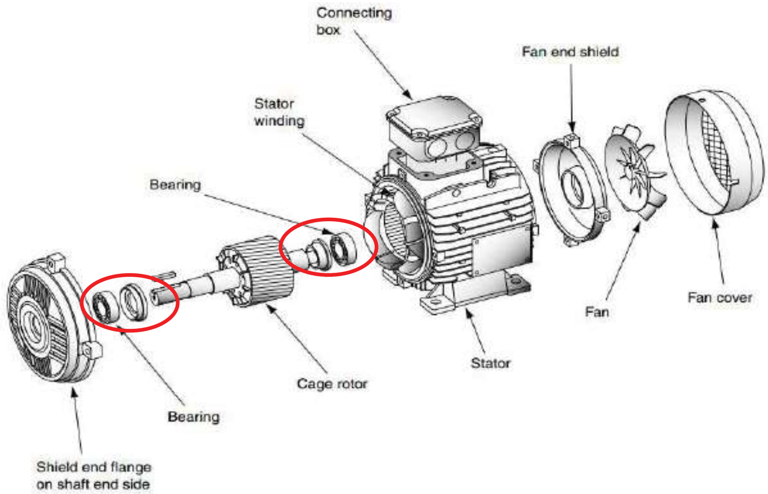
Brushed DC motor with stator winding

Squirrel-Cage Induction Motors

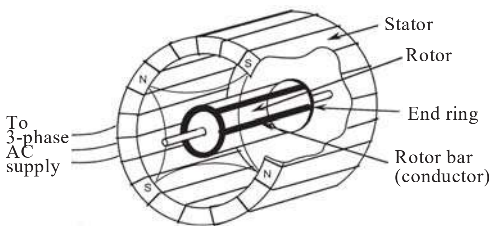
Used in more than 90% of electric motor systems;

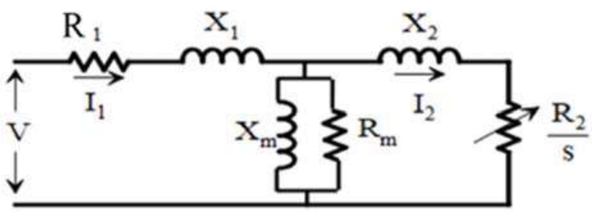
- Good efficiency and high realibility (reduced maintenance);
- Low cost (when compared to other motor types);
- Easy to control, when fed by Variable Speed Drives (VSDs).

Squirrel-Cage Induction Motors



Squirrel-Cage Induction Motors





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

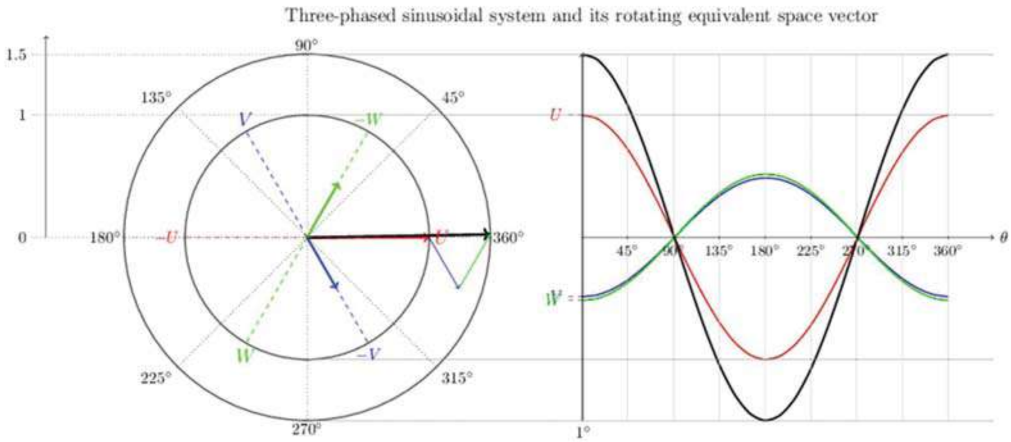
Xm = Magnetising Reactance
Rm = Magnetising Resistance

s = Slip = $(\omega_s - \omega_{rotor}) / \omega_s$

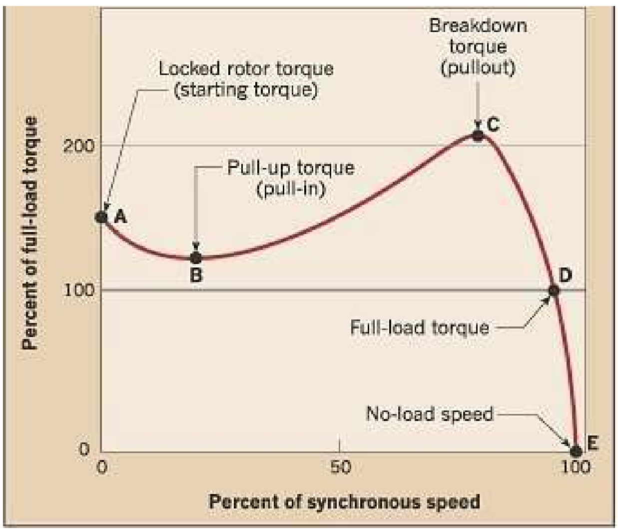
ω_s *= Synchronous Speed (rad/s)*

ω_{rotor} *= Rotor Speed (rad/s)*

Rotating Magnetic Field



Typical Torque-speed Curve - AC Induction Motor



Energy Efficient Induction Motors

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

Motor Losses

Electrical losses

(also called Joule losses) are expressed by I^2R, and consequently increase rapidly with the motor load. Electrical losses appear as heat generated by electric resistance to current flowing in the stator windings and in the rotor conductor bars and end rings.

Magnetic losses

occur in the steel laminations of the stator and rotor. They are due to hysteresis and eddy currents, increasing approximately with the square of the magnetic flux-density.

Mechanical losses

are due to friction in the bearings, ventilation and windage losses.

Stray load losses

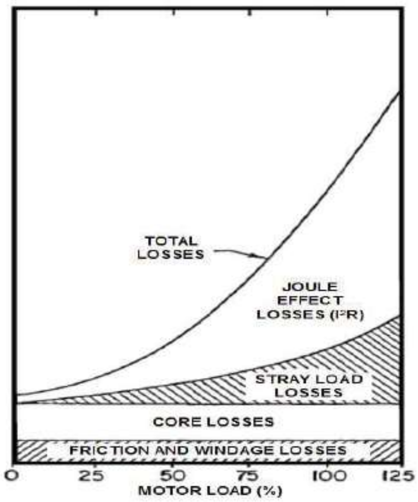
are due to leakage flux, harmonics of the air gap flux density, non-uniform and inter-bar currents distribution, mechanical imperfections in the air gap, and irregularities in the air gap flux density.

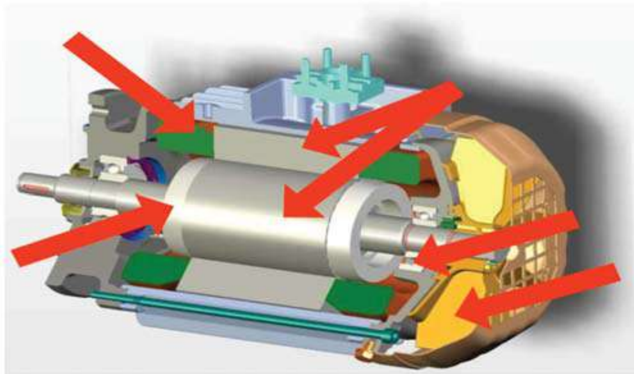
The brush contact losses (only for motors with brushes)

result from the voltage drop between the brushes and the commutator, as well as include additional friction losses.

I - current; R – electric resistance

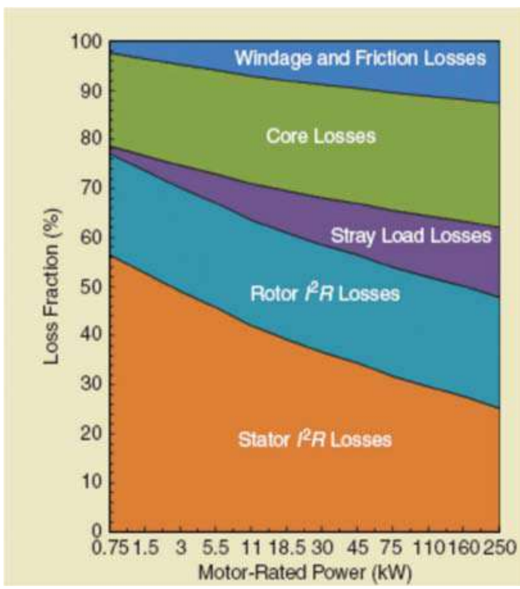
Motor Losses vs Motor Load





Motor Losses Vs. Motor Power

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



Permanent Magnet Synchronous Motors (PMSM)

Also called:

Brushless DC Motors (BLDC)	Electronically Commutated Motors (ECM)	PMSM is preferred

Motor behavior similar to DC motors, but have no brushes

- Stator design similar to induction motors (3 phase stator winding
- Rotating permanent magnet in the rotor
- Powering of the 3 phases according to rotor position

- Synchronous operation, eliminates electric and magnetic losses in the rotor – a typical reduction of 20% of the motor losses
- May become more attractive: cost reduction is likely with cheaper magnets and mass production

Permanent Magnet Synchronous Motors (PMSM)

Main advantages

- Excellent torque-speed curve (e.g. may allow direct drive)
- Excellent dynamic response
- High efficiency and reliability → low maintenance
- Longer lifetime
- Low accoustical noise
- High speed capability
- High torque/volume ratio or high power density.

Main disadvantages

- High cost and there is always the necessity of a controller (VSD).

LSPM Motors

LSPM = Line start permanent magnet motors

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

Interchangeable with induction motors (same output x frame ratio)

**alloy of neodymium, iron and boron

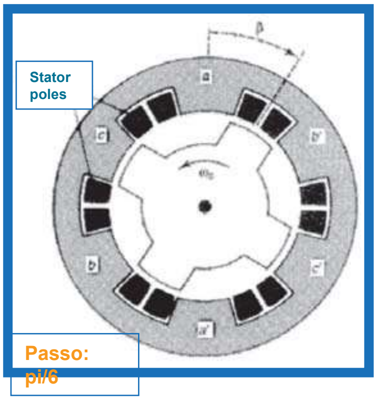
Switched Reluctance Motors (SR)

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

Switched Reluctance Motors

STATOR: 6 POLES (3 PHASES)

ROTOR: 4 POLES



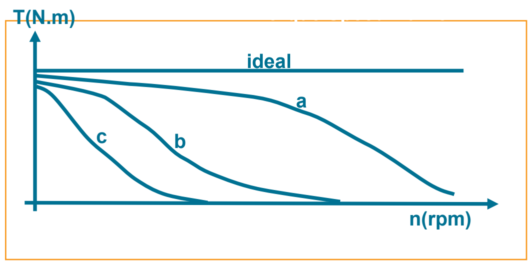
STATOR: 8 POLES

ROTOR: 6 POLES

Switched Reluctance Motors

APPLICATIONS UP TO 75 kW:

- High speed centrifugal machines
- Compressors
- Washing machines
- Vacuum cleaners
- Vacuum pumps
- HVAC**
- Variable-speed drive systems
- Machine-tools
- Automation
- Traction, etc.



Source: ISR – University of Coimbra

** Heating, Ventilation, Air Conditioning

Switched Reluctance Motors

Main advantages

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

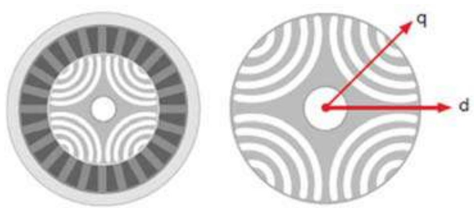
Main disadvantages

- Ripple torque and high acoustical noise due to the high vibration level – research is made to improve these aspects.
- The controller (drive) is always necessary

Synchronous Reluctance Motors

IE5 synchronous reluctance motors (SynRM) reduce losses up to 40% compared to IE3 induction motors

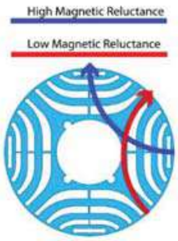
Stator similar to AC 3 phase Induction Motor



The torque produced by a synchronous reluctance motor is proportional to the difference between the inductances on the d- and q-axes: the greater this difference, the greater the torque production. Synchronous reluctance motors are therefore designed with magnetically conductive material, iron, in the d-axis and magnetically insulating material, air, in the q-axis.

Synchronous Reluctance Motors – Operating Principle

Stator similar to induction motor creating a rotating field. The rotor will create torque whenever there is a magnetic field present in the air gap that is not aligned with the rotor.



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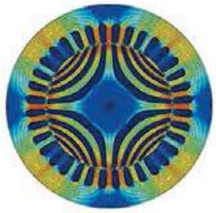
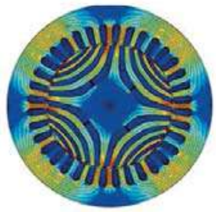


b)



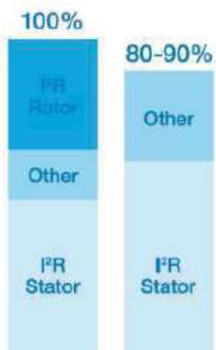
c)

a) rotor areas of high and low reluctance
b) the rotor is aligned with the magnetic field so no torque is produced;
c) the rotor is not aligned with the magnetic field and (counter-clockwise) torque is produced

(Source: Oemer and ABB)

The new rotor has neither magnets nor windings, and thus suffers virtually no power losses – which makes it uniquely cool.

Synchronous Reluctance Motors



Traditional induction motor

Losses

High output SynRM motor

Source: ABB

Synchronous Reluctance Motors

Advantages

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

Disadvantages

- Low power factor
- Torque ripple

Review and Discussion

- Why is the most common type of motor in industrial operations?
- Mention some losses internal to an electric motor.
- What is the latest type of motor that offers IE5 level energy efficiency?

Section 5

Motor Standards

63

Key Efficiency Test and Related Standards

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

IEC 60034-2-1 (Edition 2.0:2014): Standard methods for determining losses and efficiency from tests	This standard establishes methods of determining efficiencies from tests, and also specifies methods of obtaining specific losses. It applies to DC machines and to AC synchronous and inductions machines of all sizes within the scope of IEC 60034-1.
IEC 60034-31 (Edition 1.0: 2010): Guide for the selection and application of energy-efficient motors including variable-speed applications	The standard gives technical guidelines for the application of energy-efficient motors in constant-speed and variable-speed applications. It does not cover aspects of a pure commercial nature.

IEC - International Electrotechnical Commission

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).

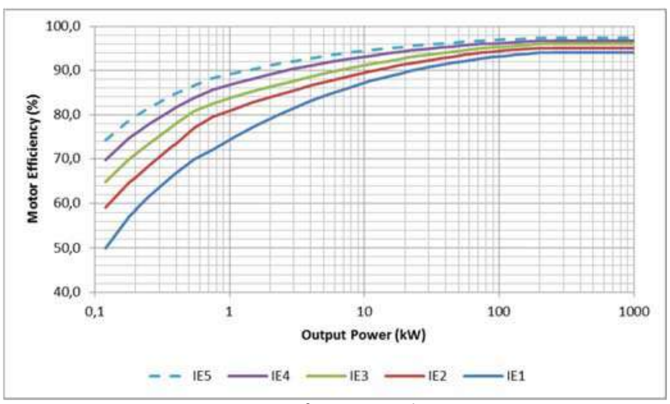
Four efficiency classes

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

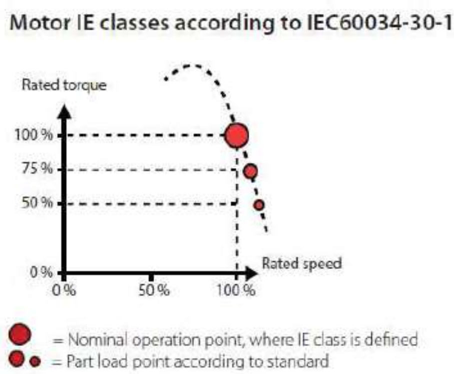
IE5: only presented in the form of an informative annex (Annex A). It is the goal to reduce the losses of IE5 by some 20 % relative to IE4.

Efficiency Classification – IEC 60034-30-1

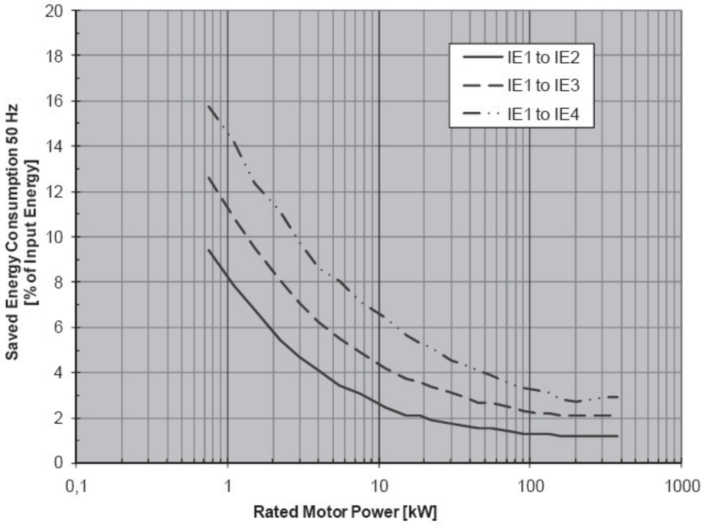
Harmonization of efficiency classification standards in the World – IEC 60034-30-1



Curves for 50 Hz 4pole motors

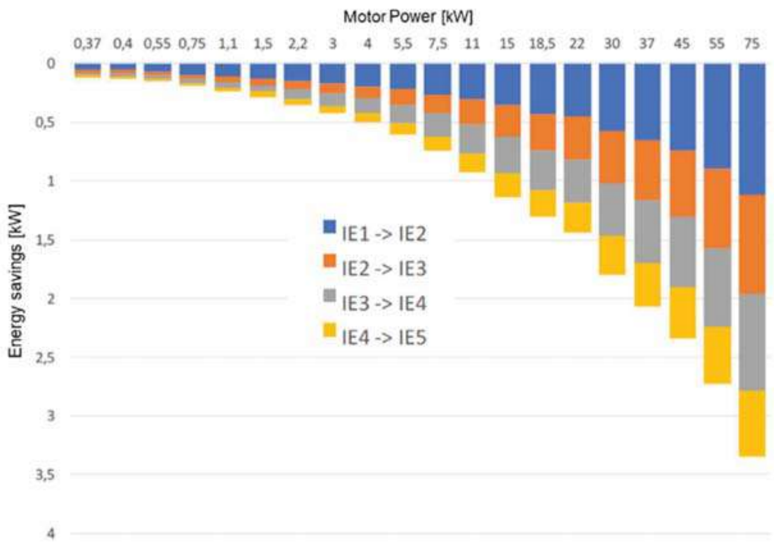


Energy Savings



Potential energy savings by improvement of efficiency-classes

Energy Savings in Motor Losses from Class to Class



Milestones in the Evolution of Electric Motor Efficiency Classes

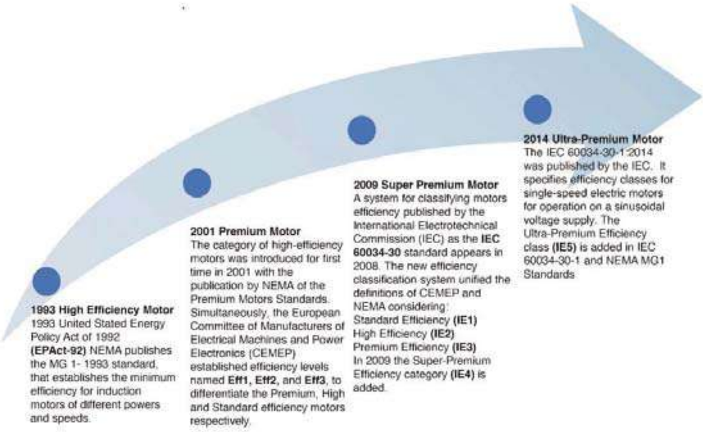
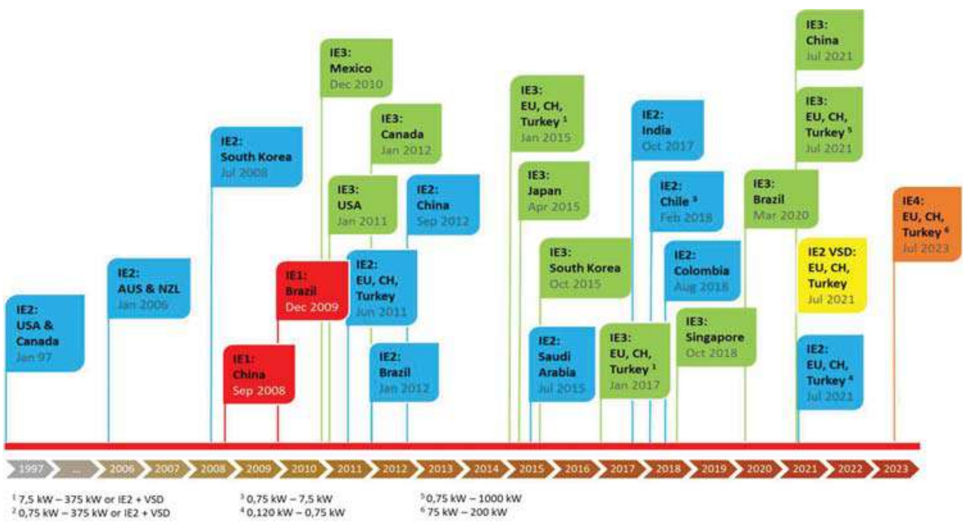


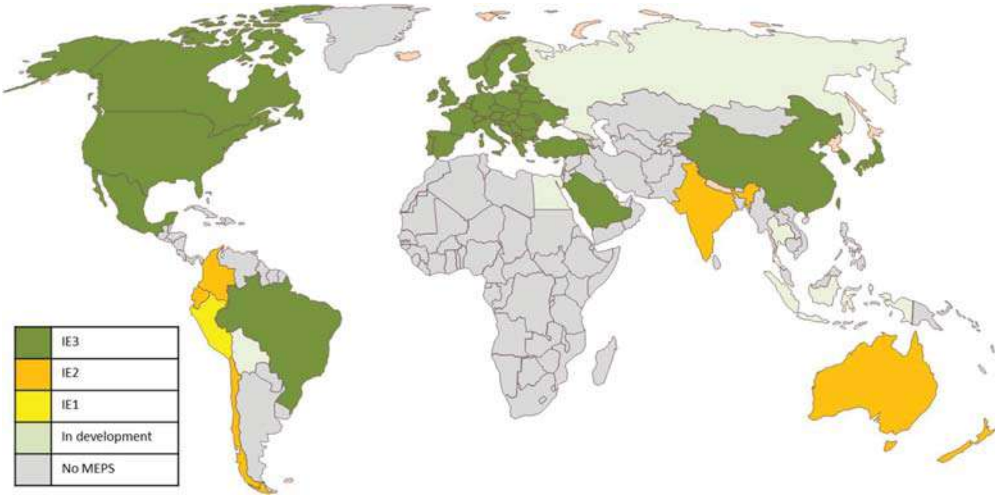
Figure 1. Milestones in the evolution of electric motor efficiency classes since the 1990s.

Source. Identification of Technoeconomic Opportunities with the Use of Premium Efficiency Motors as Alternative for Developing Countries, Energies · October 2020

Motor Standards Around the World



Motor MEPS in the World



Motor MEPS in Vietnam

- TCVN7540-1:2013 - Three-phase squirrel-cage induction motors - Part 1: Energy efficiency (TCVN 7540-1:2013 - Động cơ điện không đồng bộ ba pha rôto lồng sóc - Phần 1: Hiệu suất năng lượng)
- According to this document minimum IE2 became compulsory from Jan 2015. IE3 is recommended but not required by law (voluntary).
- Updated in 2023 to confirm IE2 as minimum standard, with IE3 and IE4 recommended (under Decision 14/2023/QĐ-TTg effective 15 July 2023)

Impact of Energy Efficiency Policies on Motor Market

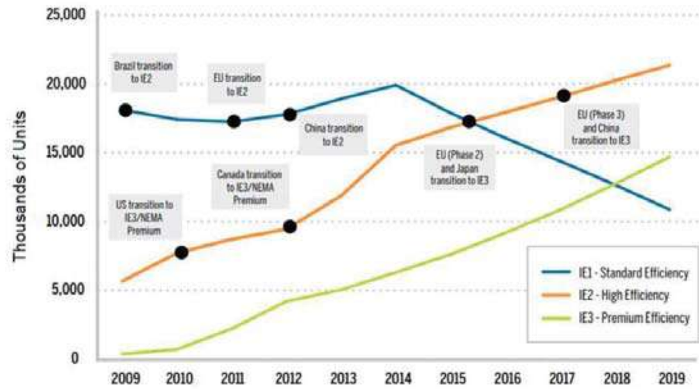


Figure 2. Impact of energy efficiency policies on the sales of more efficient electric motors. Reproduced from [12], 4E Energy-Efficient End-use Equipment: November 2015.

Source: IHS, 2015

Review and Discussion

- Why do we need motor standards?
- What MEPS are applicable to Viet Nam?

Section 6

New Motor Selection

Selecting Appropriate Motor for Application

Factors to be used

- The mechanical requirements of the driven load
- Motor efficiency classification
- The electrical distribution system
- Physical and environmental considerations
- The evaluation of these characteristics should enable the user to select the most suitable type of motor for the application (AC or DC; single-phase; three-phase; power; mounting arrangement, etc)

DC Motor Selection

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

DC Motor Selection

Disadvantages of DC motors:

- High initial cost
- Increased operation and maintenance cost due to presence of commutator and brush gear
- Cannot operate in explosive and hazard conditions due to sparking occur at brush (risk in commutation failure)

- AC motors with similar control capabilities are taking over

Single-phase Motor Selection

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

Synchronous Motor Selection

Speed

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

Lower Operating Costs

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

Power Factor Correction

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

Induction Motor Selection

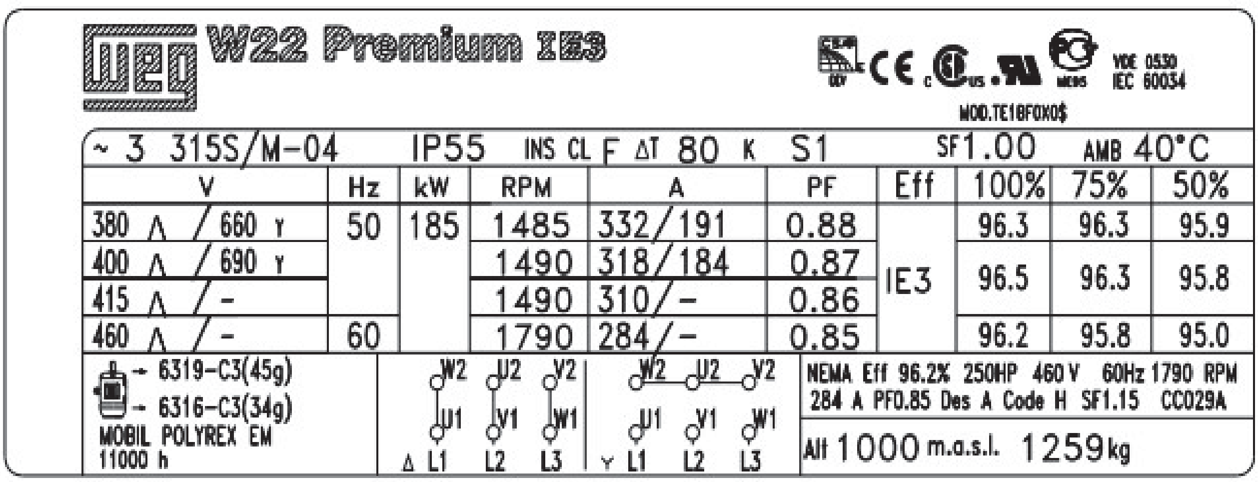
IEC 60034-12 (2002) and NEMA MG-1 (2011)

IEC Design N

IEC Design H

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

Induction Motor Label

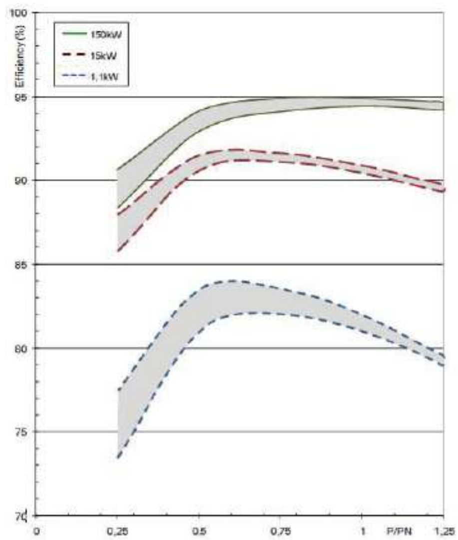


Motor Load

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

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

Motor Efficiency vs Motor Load



IEC 60034-31

Motor Selection Operational Criteria

Frequency of starting and stopping

- For frequent starts, ensure winding and core temperature do not exceed motor rating (Duty types as defined in IEC 60034-1)

Starting torque requirement

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

Acceleration restrictions

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

Operating Temperature

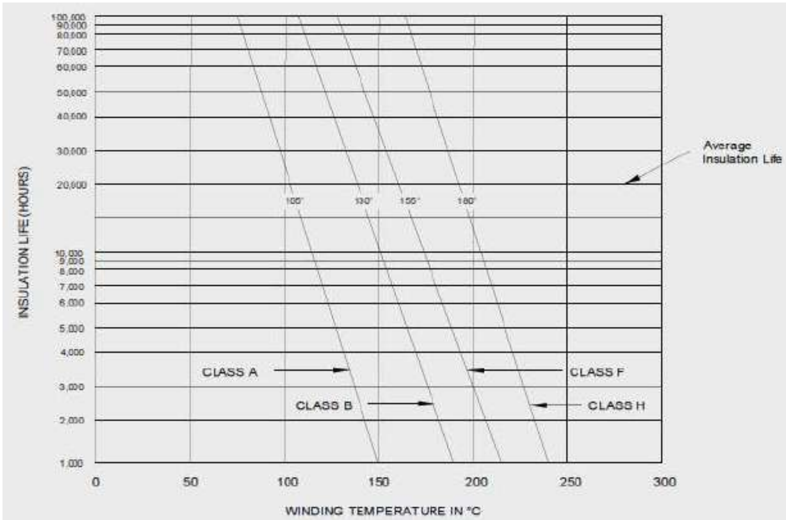
The standard IEC 60085 gives the maximum operation temperature for each thermal class

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

Ambient temperature → is the temperature of the air surrounding the motor.

Maximum operation temperature → is the maximum permissible hot spot temperature of a winding (rated temperature of the insulation system)

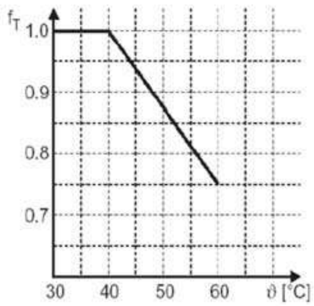
Insulation Life vs Temperature

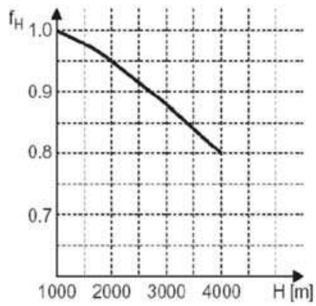


Service Factor

- Motor service factor is an indication of the ability to exceed the mechanical power output rating on a sustained basis. A service factor greater than 1.0 allows a margin for peak power demand without selecting the next larger motor size.
- E.g. A 10 kW motor operating under rated conditions with a 1.15 service factor should be able to deliver 11.5 kW without exceeding the NEMA allowable temperature rise for its insulation system.
- A motor operating continuously at a service factor greater than 1 will have a reduced life expectancy (insulation and bearings).
- Motor efficiency is usually reduced during operation at the service factor rating.

Motor Derating

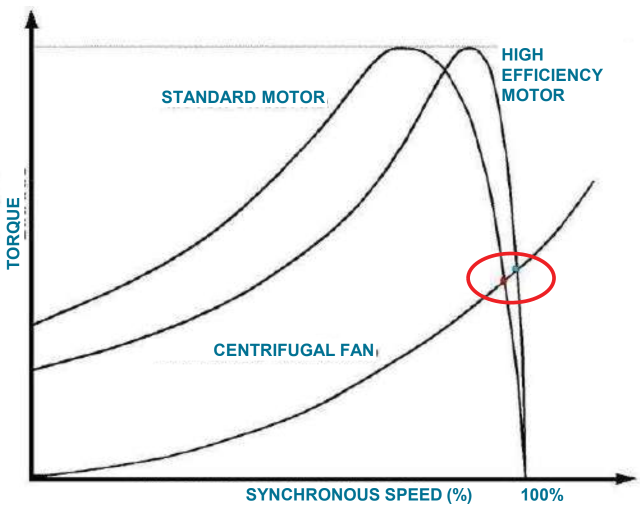




- For temperatures above 40° C and below 60° C
- For altitudes above 1000m

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

Match Higher Efficiency Motor Operating Speed



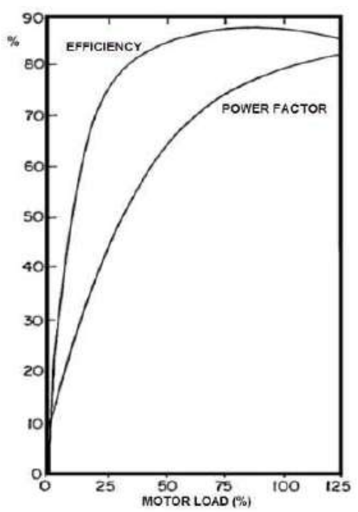
- The higher efficiency motor has a different torque speed curve
- The new intersection point with the system curve represents the operating point
- Notice that the speed is now slightly faster than the original
- If not adjusted, the process could possibly be out of specification and the energy consumption might actually increase

Motor Sizing

Properly Size the Motor for your Application

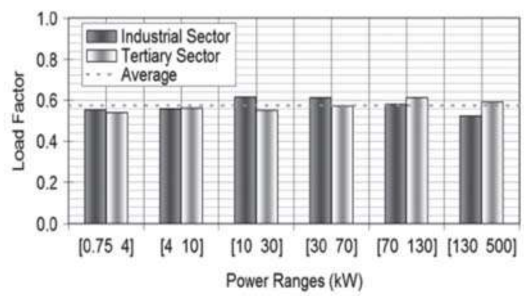
- Motor efficiency is fairly constant down to approximately 50% of rated load, below which it drops off quickly. Care should be exercised in leaving an adequate but not excessive safety margin.
- The motor should be sized for the peak load expected.
- Oversized motors can significantly increase costs since all electrical components must be sized to the motor rating.
- Due to the low temperature utilization of more efficient motors their overload capacity is typically higher when compared to standard motors.

Oversizing



Disadvantages:

- Higher capital cost (motor and command and protection equipment)
- Lower motor efficiency and power factor;



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

Energy Saving Strategies

Choose a Replacement Before a Motor Fails

- Sometimes in trying to get a motor back into service as quickly as possible, decisions are made that satisfy the short-term goal but negatively impact long-term efficiency and motor life.

- When conducting this evaluation it may often be more beneficial to replace working motors with properly sized more efficient ones.

Energy Saving Strategies

Match Motor Operating Speeds:

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

- For most rotating machinery, power consumption is proportional to the cube of the rotational speed.

For example:

- increasing operating speed by 2% can increase the power required to drive the system by 8%.
- This can easily offset the savings expected by the replacement of a motor with a more efficient one.

Review and Discussion

- Mention some characteristics that need to be defined for specifying a new motor.
- What is the typical insulation class for standard induction motors today?
- What is the relation between temperature and motor life?

Section 7

Motor Operating and Control

Motor Torque and Speed

Operating characteristics of electric motors are defined in terms of the **speed** of rotation as well as the **torque** produced on the output shaft of the motor.

$$Torque\,[N.m] = \frac{Power\,[W]}{speed\,[rad/s]}$$

$$Torque\,[N.m] = \frac{Power\,[W]}{2\pi \times speed\,[rps]}$$

$$Torque\,[N.m] = \frac{Power\,[W]}{2\pi \times speed\,[rpm]/60}$$

- *f = frequency (in Hz)*
- *n = Rotations per minute (rpm)*
- *ω = Angular Speed (radians/s)*

Note** ω = 2πf

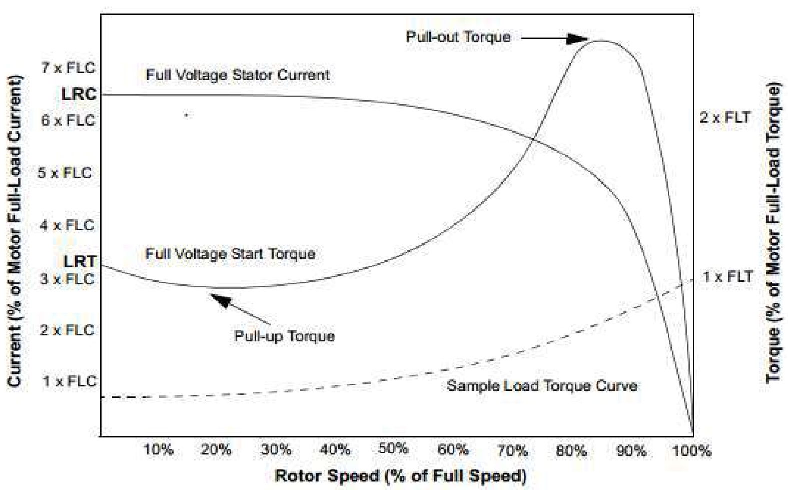
Speed and Slip in Induction Motors

$$synchronous\ speed\,[rpm] = \frac{frequency\ of\ the\ applied\ voltage\,[Hz] \times 60}{number\ of\ pole\ pairs}$$

$$slip\,[rpm] = Synchronous\ speed\,[rpm] - running\ speed\,[rpm]$$

$$slip\,[\%] = \frac{Synchronous\ speed - running\ speed}{Synchronous\ speed} \times 100$$

Typical Torque-Speed Curve of 3ph AC Induction Motor



LRC –Locked Rotor Current,
LRT- Locked Rotor Torque,
FLC- Full Load Current,
FLT- Full Load Torque

Torque Definitions

Starting torque

- The torque produced at zero speed. If the motor is to turn a load that is difficult to start (a high inertia load) one would choose a motor with high starting torque.

Pull-up torque

- The minimum torque produced during acceleration from standstill to operating speed.
- This may be critical for an application that needs power to go through some temporary barriers before achieving the working level output.

Full load torque (also **braking torque)**

- The torque produced at full load speed that gives the rated output of the motor.
- At this point the torque times the speed equals the nameplate power rating.

Breakdown torque

- The maximum torque that the motor can produce before stalling.

Load Characteristics

There are three basic types of loads in terms of T=f(w):

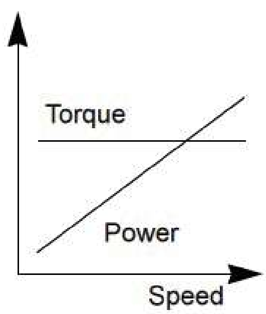
- Variable torque
- Constant torque
- Constant horsepower

In terms load variation the loads can be:

- Cyclic
- Constant

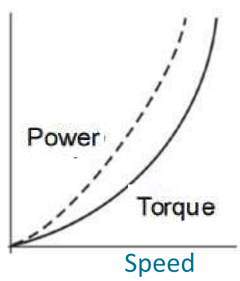
Types of Loads

Constant Torque / Variable Speed



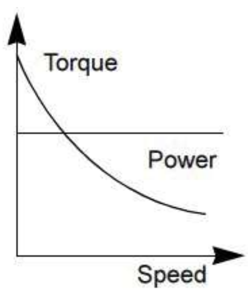
screw compressors, conveyors and feeders

Variable Torque / Variable Speed



centrifugal pumps, fans

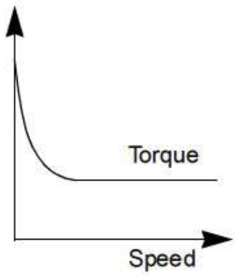
Variable Torque / Constant Power



Traction drives, winders, rolling mills

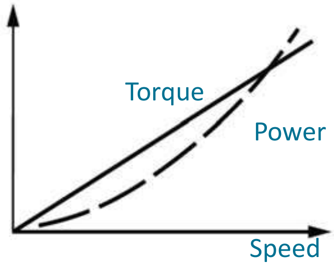
Types of Loads

High Starting Breakaway Torque / Constant Torque



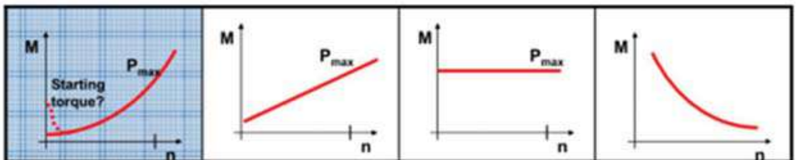
Extruders, screw pumps

Linear Torque / Power ~ n^2



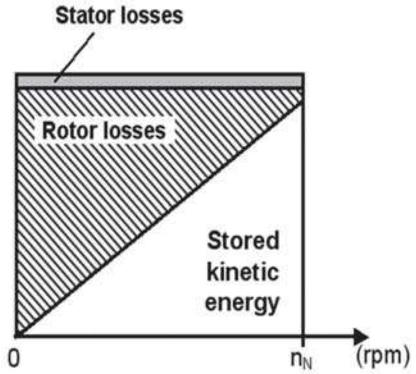
Calenders with viscous friction coupling, mixers, eddy current brakes

Why do we need to control speed?

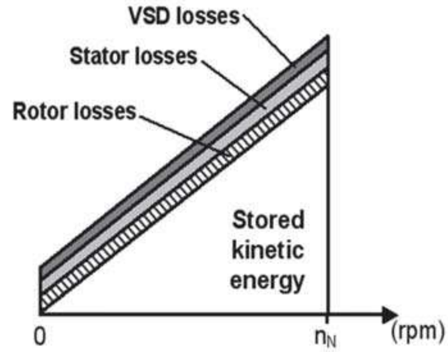


$M \sim n^2$	$M \sim n$	M = const	M = 1/n
Pumps Fans Blowers Compressors Turbo compressors	Calander drives (calandering to smooth and emboss) Paper machines Plastic making and finishing machines	Feed drives Positioning drive Elevators, cranes Extruders, mixers Reciprocating and screw compressors	Winders Main spindle for machine tools Mixers, crushers, saws, coilers
VT	VT / CT	CT	CT
Without encoder	Without encoder / With encoder	With encoder	With encoder

Motor Starting – Energy Consumption



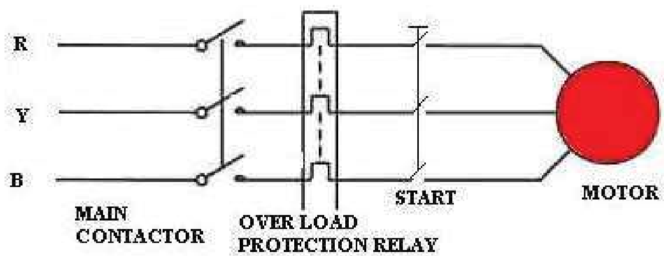
Standard DOL Motor



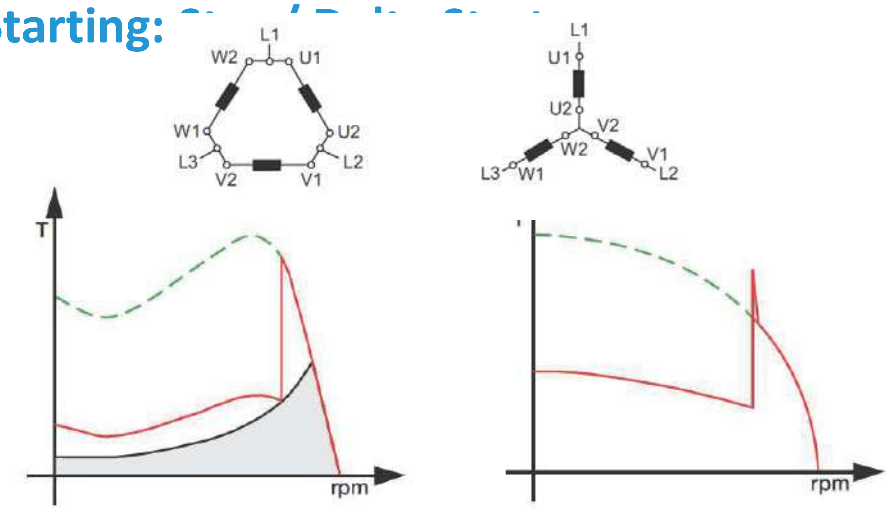
Variable Speed Drive

Motor Starting: Direct On line (DOL)

Direct on line (DOL) starting is the simplest and most economical way to start an induction motor, but it causes a considerable starting current, typically 5 to 7 times the rated current.



Motor Starting:

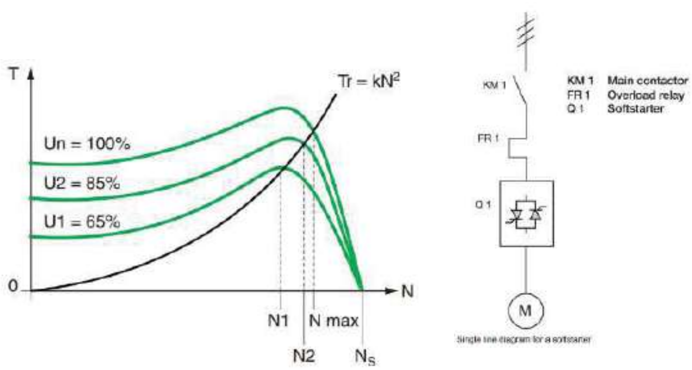


Torque/speed curve at Star-Delta start

Current curve at Star-Delta start

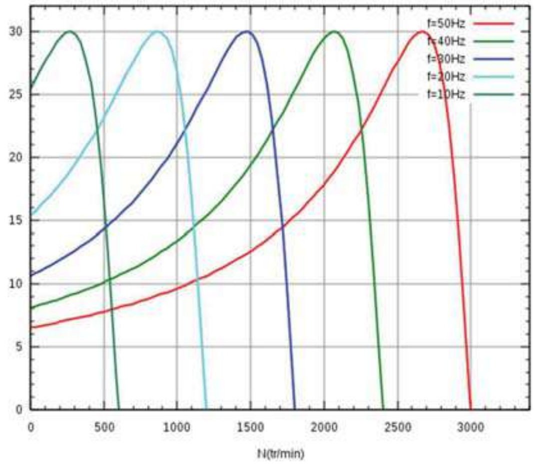
Motor Starting: Soft Starter

- Voltage control device that applies a much lower than normal voltage to the motor to limit the starting current.
- As the motor starts moving slowly, the voltage is increased in steps until the motor has reached its operating speed
- Also has the ability to soft stop which is especially useful for conveyors and certain pumps

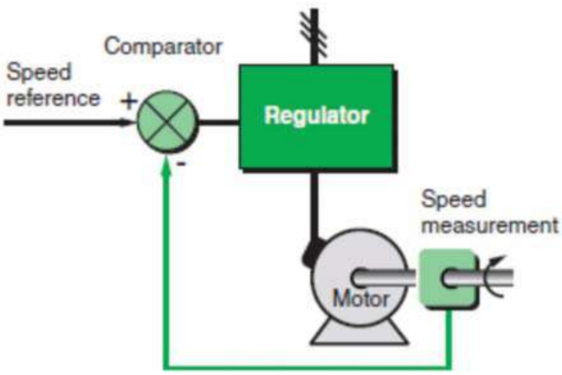


Motor Starting: Variable Speed Drive (VSD)

- Control device that applies a change in frequency to control the speed
- During start up it operates similar to a soft starter by limiting the voltage during start up
- Also called variable frequency drives (VFD) and adjustable speed drives (ASD)



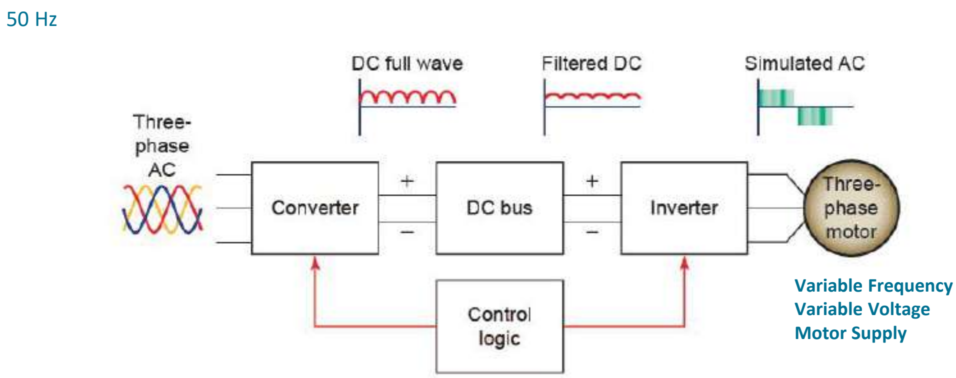
Principle of Speed Regulation



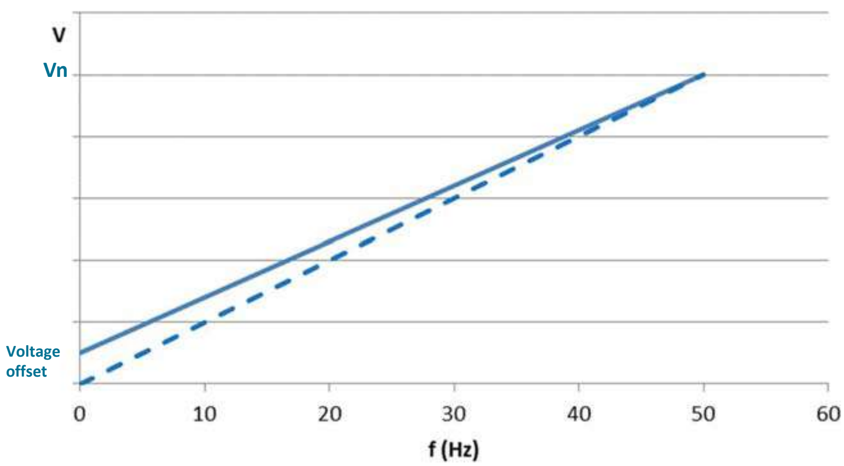
- VSD enable closed loop feedback control where speed can be controlled more precisely.
- In many cases this improves production quality and sometimes even production volume

Variable Speed Drive (VSD)

- Also called a variable frequency drive (VFD)



Voltage Variation with Frequency



Advantages of VSDs

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

Possible Disadvantages of VSDs

- Inject harmonic distortion in the network
- Voltage spikes leading to failure of insulation in windings of old motors
- Bearing current leading to premature failure
- Introduce a new element in the system (could affect total system reliability)
- May require additional cooling

Review & Discussion

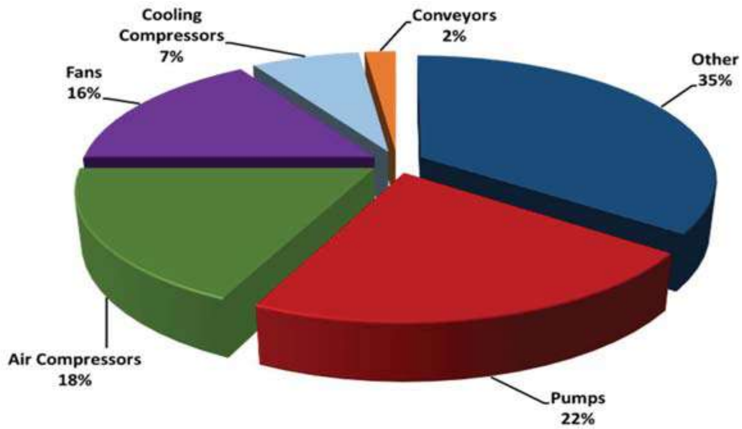
- Why do we need motor control?
- What methods are available for motor speed control?
- What methods are available for starting and stopping motors?

Section 8

Motor Mechanical Load: Pumps

Motor Systems Electricity Consumption by Application

Pumps, fans and air compressors make up 56% of industrial applications



Electricity Consumption in the European Union Industrial Sector
Source: ISR – University of Coimbra (2012)

Industrial Pump Applications

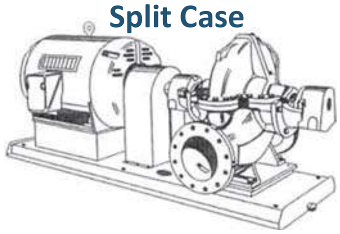
Task	Application example
Take, Transport	Crude oil, Chemicals, Water in pipelines
Circulate, Transfer	Circuits of heating and cooling systems in buildings, Cooling and lubrication systems in machine technology
Fill, Drain	Bottling plants, draining of sewage sludge containers
Portion, Dose	Analysis technology, Chemical industry, Injection of fuel into oil burners and combustion engines
Pressure boosting, power transmission	Industrial water supply in multi-storey buildings, Pressure- and material testing in machine- and plant construction, Water jet cutting, Hydraulic drives

Pump Types

- **Pump Types**
  - **Roto-Dynamic Pumps** (Centrifugal)
    - End Suction
    - Split Case
    - Vertical Turbine
    - Special Pumps
      - Jet Pumps
      - Vortex Pumps
      - Regenerative turbines
  - **Displacement Pumps**
    - Reciprocating
      - Piston
      - Diaphragm
    - Rotary
      - Peristaltic
      - Progressive Cavity
      - Multiple Gear-Lobe

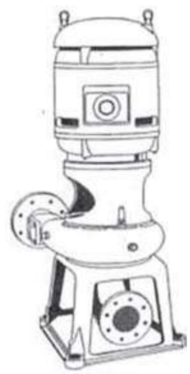
Examples of Centrifugal Pump Types

Split Case



Submersible

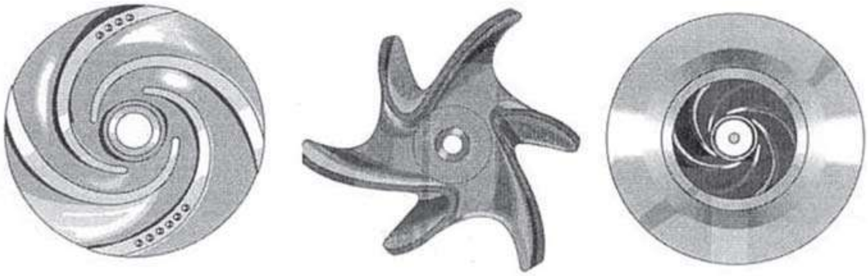
End Suction



Vertical, close coupled

Figures courtesy of ACR Publications

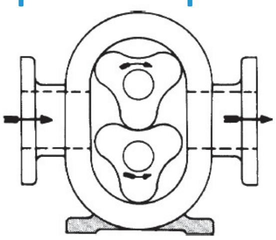
Centrifugal Impellers



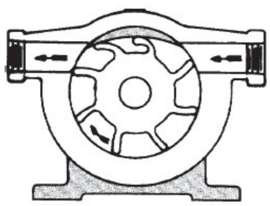
Semi-open Open Closed

Figures courtesy of ACR Publications

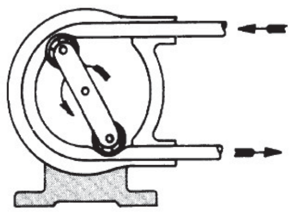
Examples of Displacement Pumps



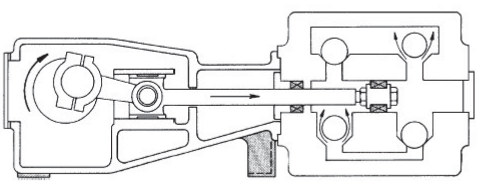
Rotary Lobe



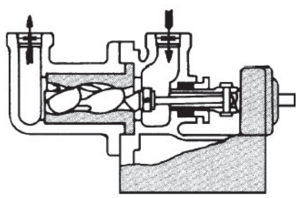
Flexible Vane



Flexible Tube



Horizontal Piston



Screw Pump

Figures courtesy of Hydraulic Institute

Two Types of Pumping Loads

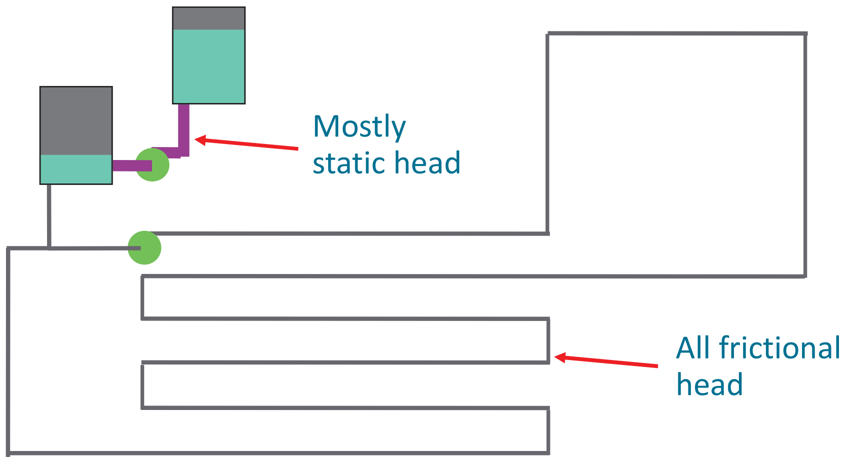
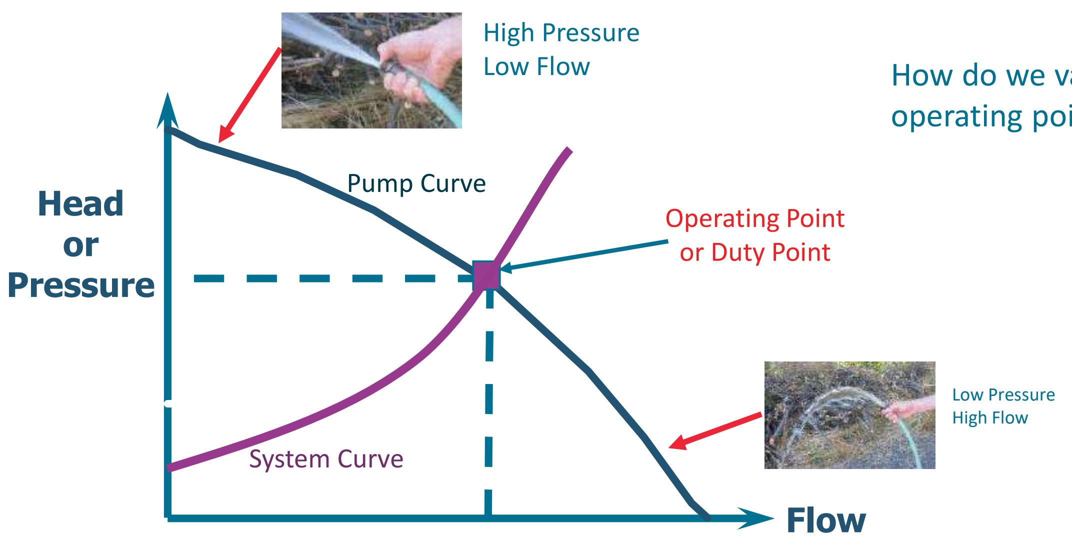


Figure Courtesy of Oak Ridge National Laboratory

Pump Basics – Pressure Flow Relationship



How do we vary the operating point?

Pump Fluid (Hydraulic) Power

Function: to transfer a fluid from one point of a plant to another

$$P_{fluid} = \frac{Flow\left(\frac{l}{s}\right) * Head(m) * Density}{102} = kW$$

$$P_{elec} = \frac{P_{fluid}}{\eta_{system}} \qquad \eta_{system} = \eta_{motor} * \eta_{trans} * \eta_{pump}$$

Where:

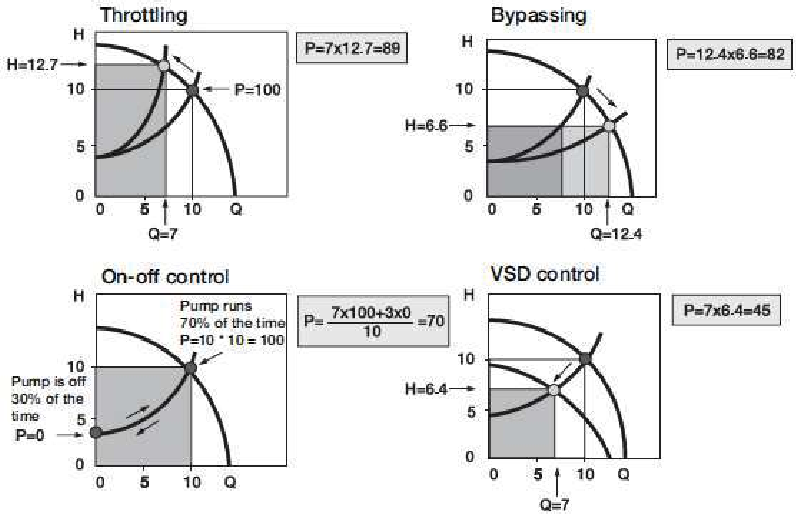
Density is 1 for water

η_{system} is the efficiency for the whole pump system

Traditional Control Methods

1. Bypass Lines
   - Bypass allow the fluid to flow around or past the production or system component, when the fluid flow is not required.
2. On Off Control
   - Fluid flow is controlled by switching pumps on and off . This often requires a multi pump arrangement.
3. Throttle Valves
   - A throttle valve restricts the fluid flow so that less fluid can flow through the pump, and also creating a pressure drop across the valve
4. Multispeed Pumps
   - Pumps that have been fitted two speed motors that can switch between speeds depending on the fluid flow required.
5. Impeller Trimming
   - For specific process speed requirements the pump impeller may be trimmed in order to redefine the operating point of the pump more efficiently
6. Pump Speed Control
   - Fluid flow is controlled by the actual speed of the pump and includes:
     a) Mechanical (gears, belts, fluid couplings)
     b) Electrical (VSDs)

Traditional Pump Control Methods



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

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

Affinity Laws for Pumps

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

Relation between

- Pump 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

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

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

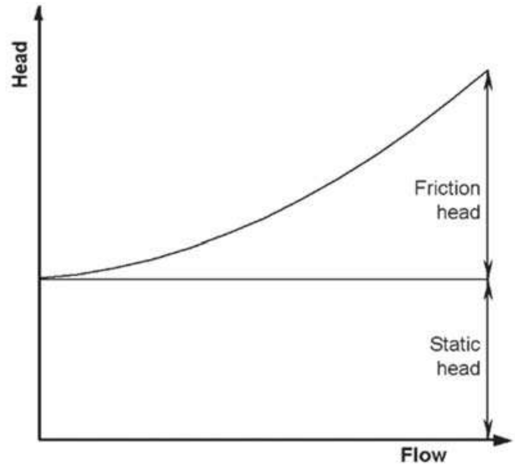
$$P_{new} = P_{old} * \left(\frac{D_{new}}{D_{old}}\right)^3$$

Centrifugal Pumps

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

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

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

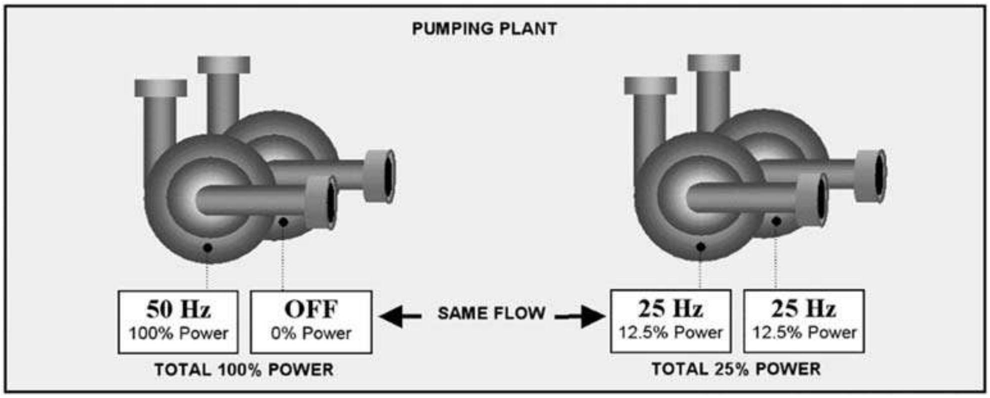


Pump Systems – Energy Strategies (Motor Side)

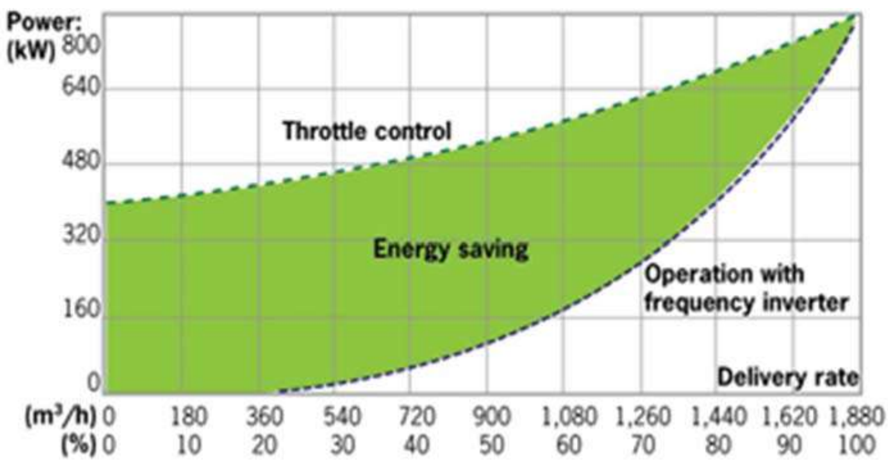
- Operating pump motors at correct voltage
- Minimising power quality disturbances at the motor electrical input
- Replacing traditional mechanical flow control (throttle, bypass, on-off) with VSD technology
- Replace motor, transmission or pump with higher efficiency models.
- Impeller trimming for some fixed speed applications

Example

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



Example



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

Pump Systems – Energy Strategies (Load Side)

Operations:
- Reduce run time
- Reduce flow rate
- Reduce head

Maintenance
- Repair leaks
- Remove / reduce pipe restrictions in flow
- Replace / repair impellers that have become eroded

Design
- Redesign piping to minimize head loss
- The suction inlet design should ensure that flow approaching the inlet is uniform and steady
- A straight run of suction pipe of at least eight diameters in length immediately prior to the pump suction flange is recommended

Review & Discussion

- What are the two basic types of pumps?
- Mention some methods of flow control for pumps.
- Why are centrifugal pumps using mechanical flow control a good opportunity for energy savings?
- What are the affinity laws?
- Which types of pumps are these laws applicable to?

Section 9

Motor Mechanical Load: Fans

Fan Basics: What do fans do?

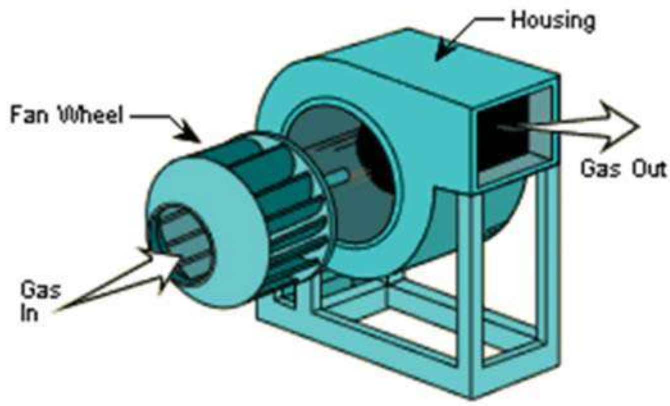
Function: Transfer air or gas (fluid) from one point of a plant to another

NOTE: In engineering terms we consider air as a fluid. So any movement of air by a fan is considered as "fluid" flow. In this respect fluid flow of a gas in a fan is mathematically very similar to fluid flow of a liquid in a pump

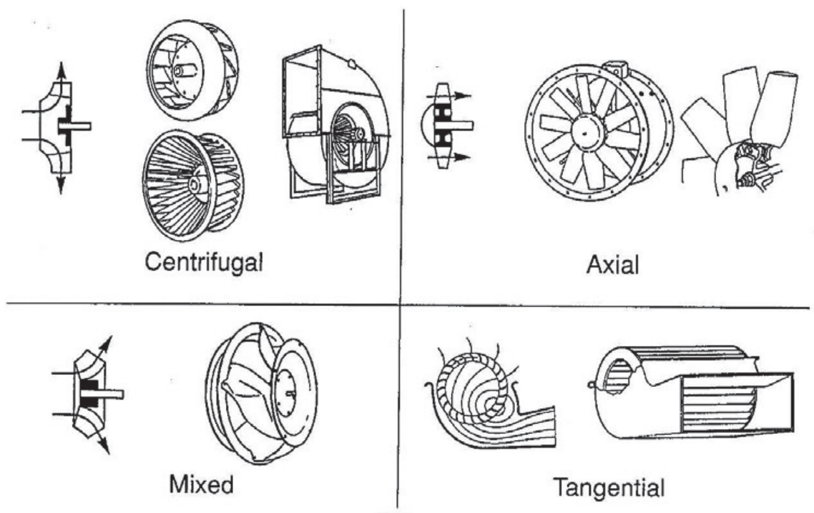
Why are fans shaped differently?

Performance is determined by many

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



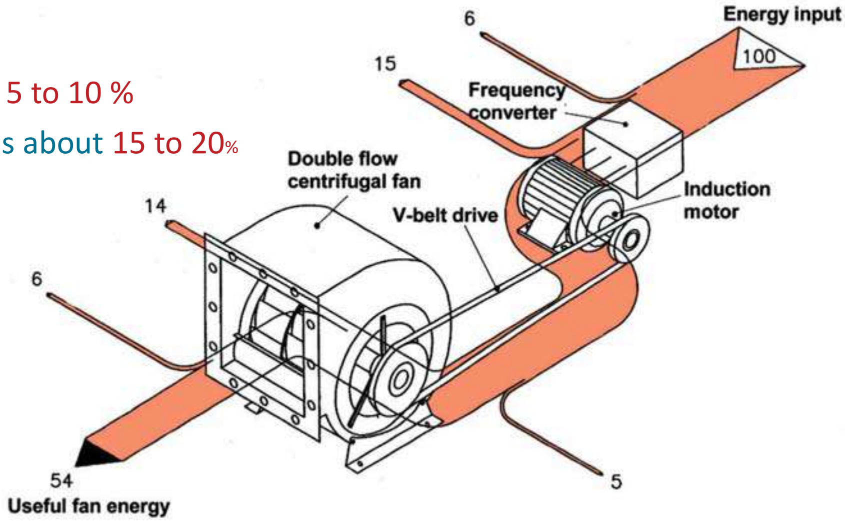
Types of Fans



Fan Systems

Systems approach:

- Fan Saving Potential is about 5 to 10 %
- Fan System Saving Potential is about 15 to 20%



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Traditional Control Methods

1. On Off Control
   - Fluid flow is controlled by switching fans on and off . This often requires a multi fan arrangement.
2. Inlet and Outlet Dampers
   - A valve positioned before or after the fan restricts the fluid flow so that less fluid flows through the fan, and also creating a pressure drop across the damper
3. Variable Inlet Guide Vanes
   - Variable pitch vanes that control the direction and volume of flow a the inlet to the fan.
4. Multispeed Fans
   - Fans that have been fitted with two speed motors that can switch between speeds depending on the fluid flow required.
5. Impeller Trimming
   - For specific process speed requirements the fan impeller may be trimmed in order to redefine the operating point of the pump more efficiently
6. Fan Speed Control
   - Fluid flow is controlled by the actual speed of the fan and includes:
     a) Mechanical (gears, belts, fluid couplings)
     b) Electrical (VSDs

Fan Dampers

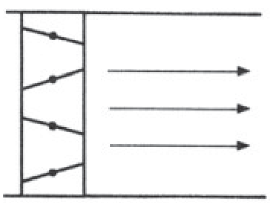
- Designers tend to oversize fans for safety.
- The system then needs to be balanced (if it is) with dampers.
- A damper that is always mostly or partly closed is an indicator of a good optimization opportunity.

Location for dampers

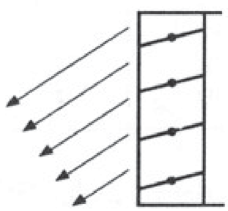
- Inlet louvre damper is most common
- Outlet dampers also common but much less efficient
- Or dampers located somewhere else in the system

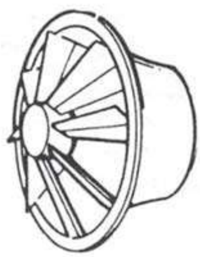
Damper Types (for flow control)

Opposed Blade

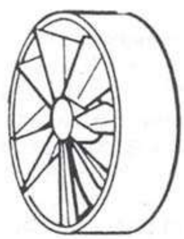


Parallel Blade



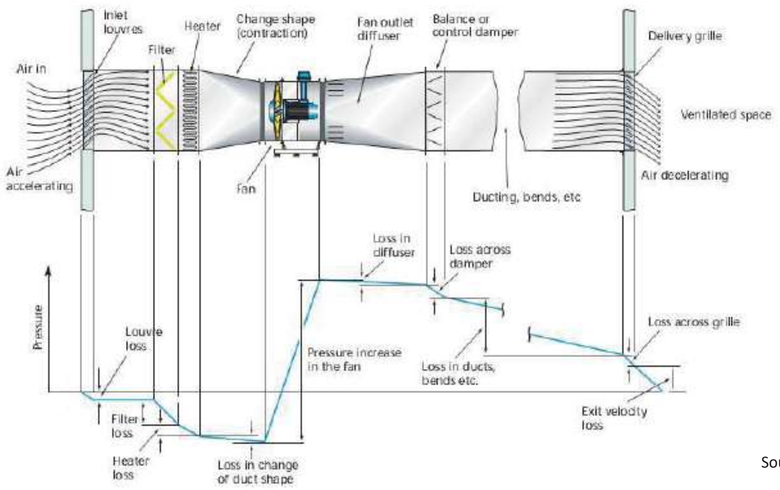


CONE TYPE VARIABLE INLET VANES



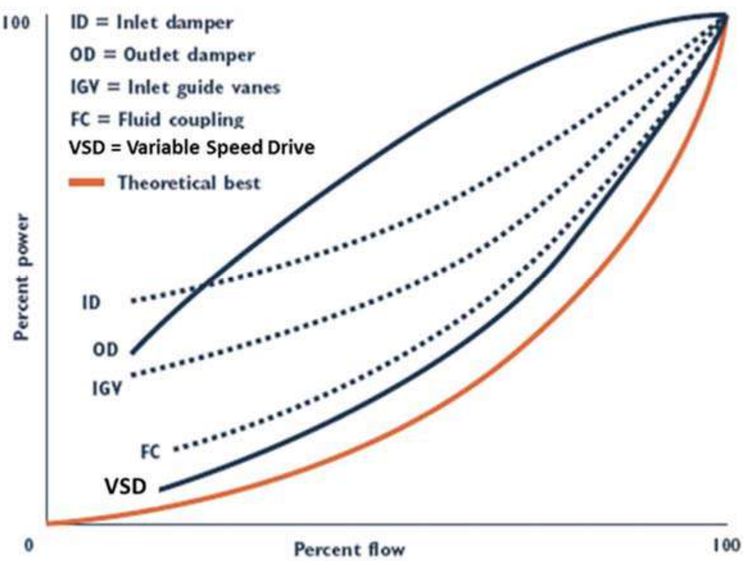
CYLINDRICAL TYPE VARIABLE INLET VANES

Losses Across a Typical Fan System



Source: CIBSE Fan Application Guide

Fan Control Methods at Partial Load



Fluid Power of Fan

Function: to transfer air or gas (fluid) from one point of a plant to another

$$P_{fluid} = \frac{Flow\left(\frac{m^3}{s}\right) * Head(Pa) * Compressibility\ Factor}{1000} = kW_{fluid}$$

$$P_{elec} = \frac{P_{fluid}}{\eta_{motor} * \eta_{trans} * \eta_{pump/fan}} = \eta_{system}$$

Where:

Compressibility Factor is 0.96 to 1 depending on pressure

η_{system} is the efficiency of the pump/fan system

Spotting Potential Fan Savings

Look for

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

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

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

Fan Systems – Energy Strategies (Motor Side)

- Operating fan motors at correct voltage
- Minimising power quality disturbances at the motor electrical input
- Replacing traditional mechanical flow control (damper, bypass, on-off) with VSD technologies
- Replace motor, transmission, or fan with higher efficiency models
- Changing fan type or changing impeller type to match load requirements
- Impeller trimming for some fixed speed applications

Fan Systems – Energy Strategies (Load Side)

Operations:

- Reduce run time
- Reduce flow rate
- Reduce head

Maintenance

- Repair leaks (especially in connections and flexible ducting)
- Ensure dampers are operating and set correctly
- Remove / reduce ducting restrictions - causes of high system resistance in ducting include dirty screens, filters and coils
- Obstructions at fan **inlets** and outlets disrupt the flow, causing turbulence

Design

- Redesign piping to minimize head loss
- The suction inlet design should ensure that flow approaching the inlet is uniform and steady
- Elbows located directly on fan inlets increase losses and are to be avoided

Review & Discussion

- Mention some methods of flow control for fans?
- What opportunities are good for fan system optimisation questions?

Section 10

Motor Mechanical Load: Compressed Air

150

Why use compressed air in industry?

Power

As an energy source to perform work

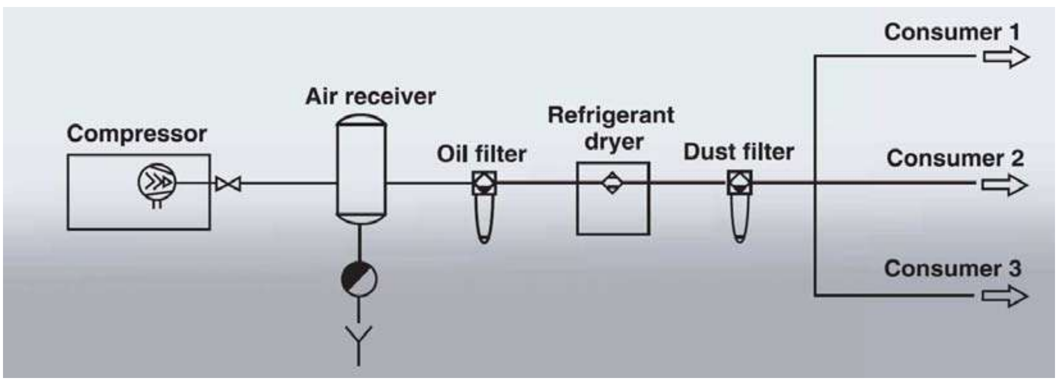
Process

Air becomes part of a process

Control

To stop, start or regulate the operation of a machine

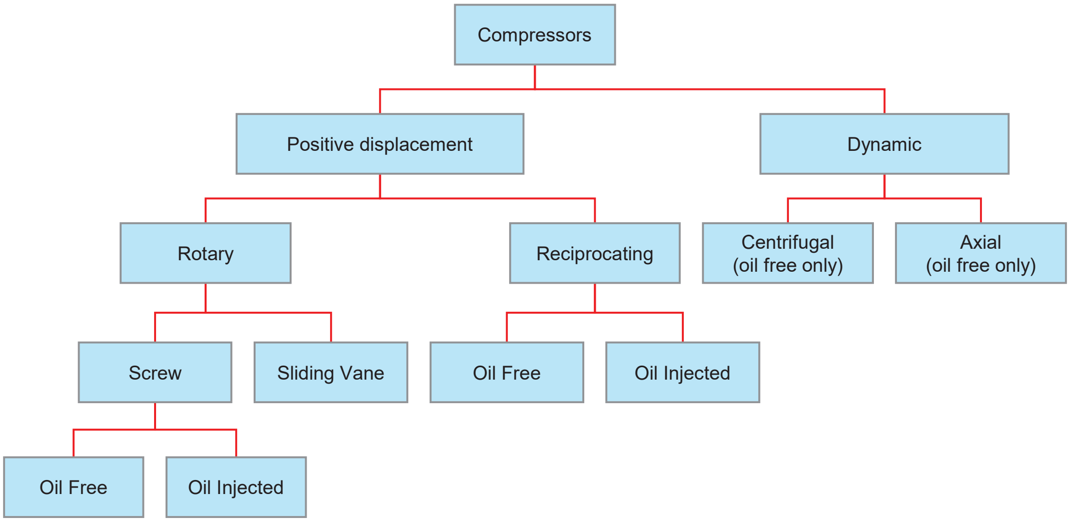
Typical Compressed Air System



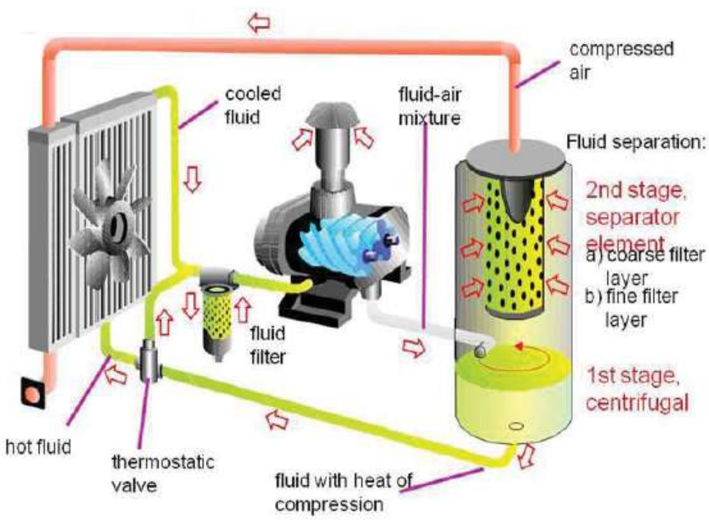
Where does the energy come from?

What drives the compressor?

The Compressor Family



Oil Injected Screw Compressors



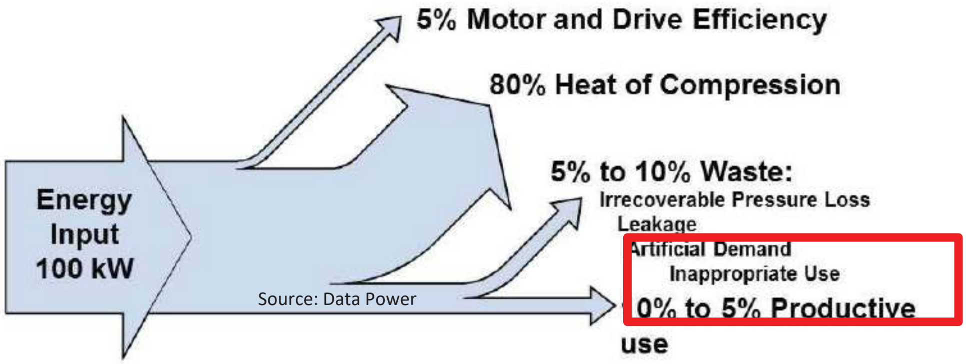
Why compressed air offers rich pickings?

Most compressed air systems are initially designed with:

- The assumption that "more" is better, where supply is concerned
- Little or no thought is given to system efficiency
- There is no plan for increases or decreases in system demand
- Purchase the lowest initial capital cost system
- An initial demand very different from how things have evolved

And··· they also need regular maintenance

Compressed Air Energy Conversion

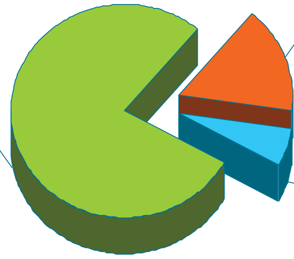


- Approximately 15% of the electrical input energy is converted into compressed air energy, a ratio of ~7 to 1.
- Effectively compressed air energy **costs 7 times as much as electricity**!

Compressed Air Systems

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

Assumptions:
- Power 110 kW
- Equipment life 15 years
- Operating hours 4000 h/year
- Electricity price 0.05US$/kWh



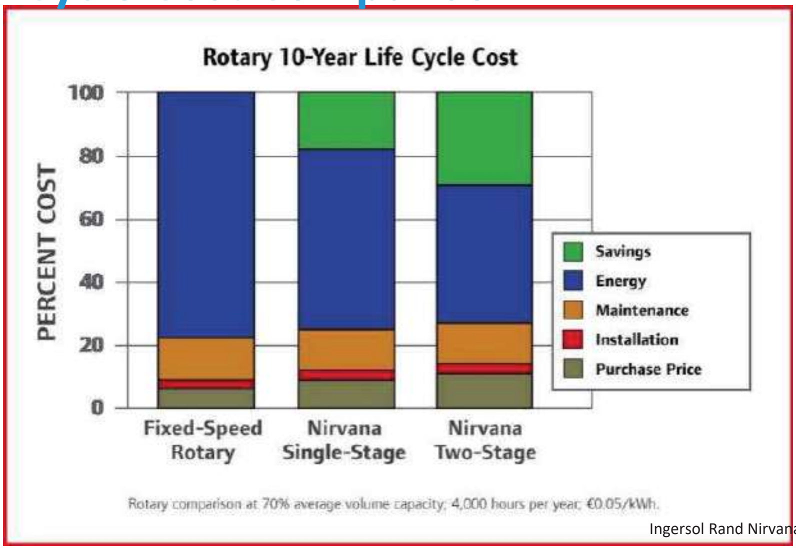
The delivered price of compressed air/kWh is approximately 7 to 10 times the electricity price

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:	182.5 kW (fully loaded), 58 kW (unloaded)
Flow:	30.3 m^3 / min
Specific Power:	6.02 kW / m^3/m
Energy Cost:	kW x hours x rate
Energy Cost :	$ 130,000 per year

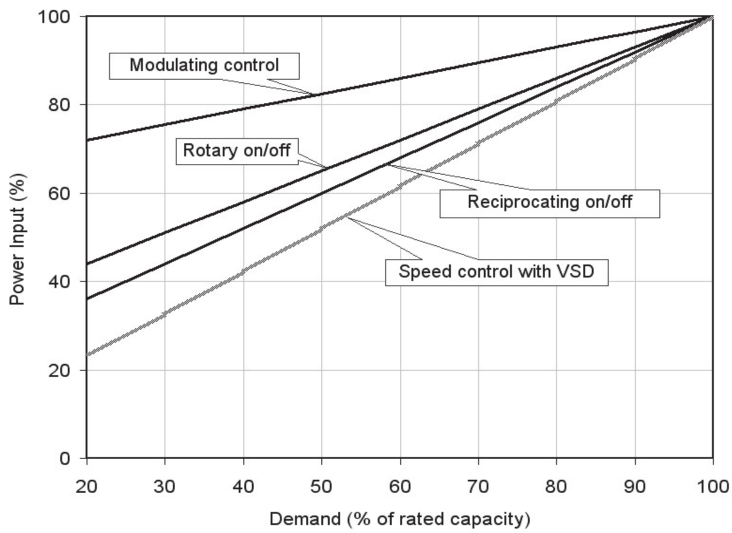
Compare with Purchase Price = $ 126,000

Life Cycle Cost Comparison



Ingersol Rand Nirvana Variable Speed Air Compressor

Compressor Control Methods

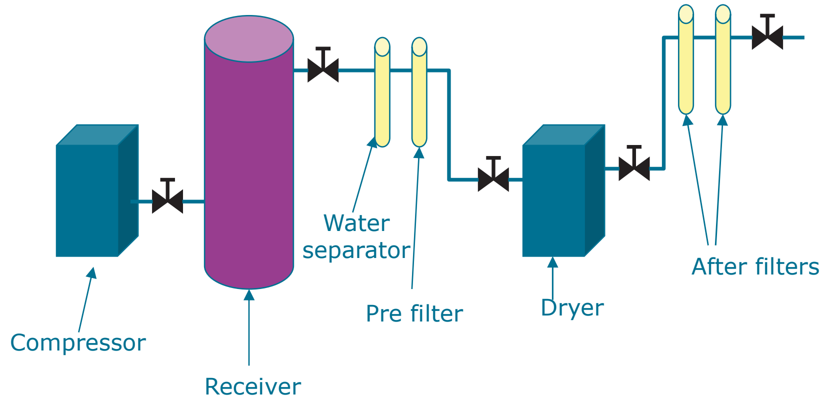


Energy can be saved by using a VSD on a rotary screw air compressor, but low cost energy savings are often found in the application of compressed air in the plant

Compressed Air Treatment Systems

Reduces water, dust and oil in the delivered air

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



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

Compressed Air Systems – Energy Strategies

- Leakage is the largest single waste of energy associated with compressed air usage.
- Consider alternate methods for low-pressure applications such as agitation, part ejection, cleaning, cooling and fume removal – this can be effectively done at greatly reduced cost by blowers or air amplifiers.
- Use the lowest system pressure possible - every 1bar increase in system pressure requires an additional 7% power.
- Pipe pressure loss is proportional to pipe length and inversely proportional to diameter - Keep air velocities below 9 m/s.

Compressed Air Systems – Energy Strategies

- Install intakes in locations providing the cleanest, driest and coolest air possible – outdoors if possible.
- Compressors charge the system to the preset pressure and maintain it by various methods including recirculation, venting, stop/start and speed control with variable speed drives - optimize the control to meet requirements.
- Choose filter systems with the lowest pressure drop.
- Compressor systems give off high volumes of low-grade waste heat, which can be used efficiently by some industrial processes, boiler feed water, heating or ventilation systems.

Leakage Losses

Hole Diameter	Air Consumption at 6 bar (g) (m3/min)		Power Loss (kW)	
	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 6mm leak requires an extra 12 kW, and costs over USD 10,000 per year in power plus additional service on the compressed air equipment.

One continuous audible leak (±2mm) will require an extra 1.5 kW and will cost **ZAR 20,000** per year!

Relative Savings for Various Opportunities

Measure	% systems where it's typically applicable	Typical savings range
Centralised Control Integration on Multiple Compressor Systems	75%	12% - 57%
Engineered controlled storage volume	30%	8% - 28%
Waste Heat Recovery	13%	19% - 65%
Compressor conditions: Improved cooling, drying, filtering	20%	1% - 4%
Distribution network improvement	35%	4% - 18%
Artificial demand	65%	5% - 13%
Inappropriate uses	38%	5% - 32%
Manage air leakages	70%	8% - 25%
Condensate practices	33%	2% - 41%

Source : Williams, A. 2018

Review & Discussion

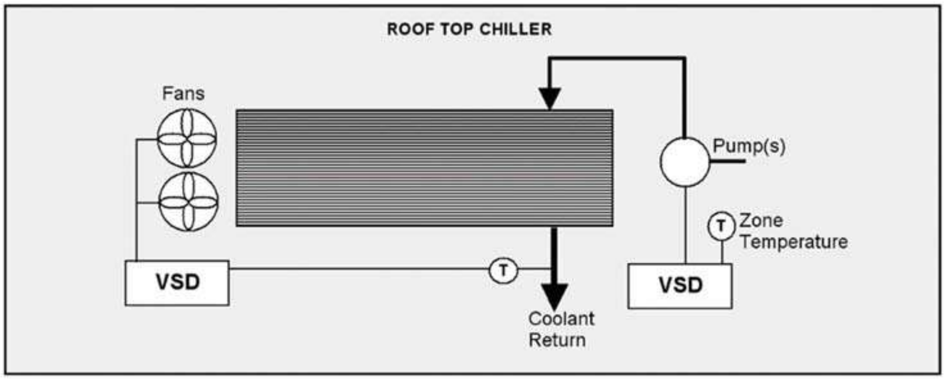
- What percentage of input energy is typically converted to compressed air energy?
- What is the most common type of air compressor in industrial facilities?
- What is first opportunity that should be addressed for compressed air optimisation?

Section 11

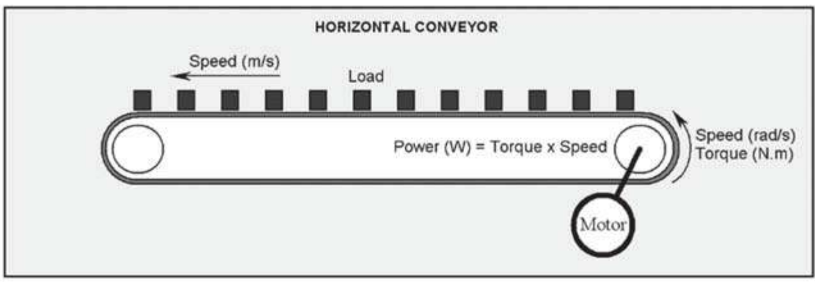
Motor Mechanical Load: Other VSD Applications

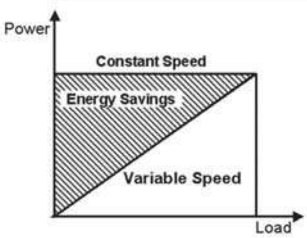
Chiller VSD Application

Application of VSDs on a roof top chiller



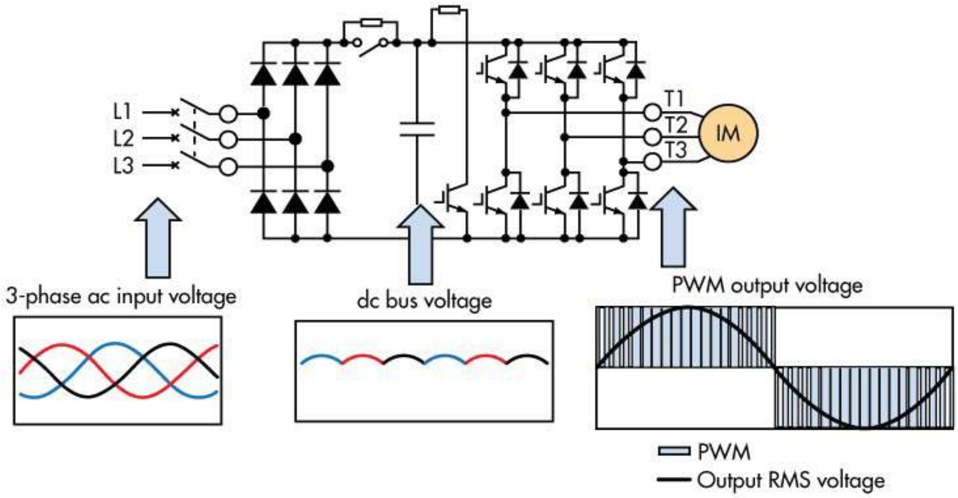
VSDs in Conveyors





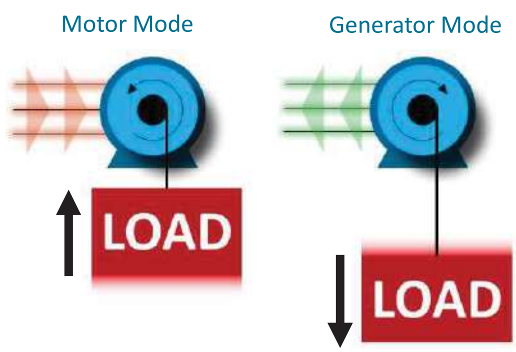
Energy savings in a conveyor using speed control, are in relation to the typical constant speed

Variable Speed Drive



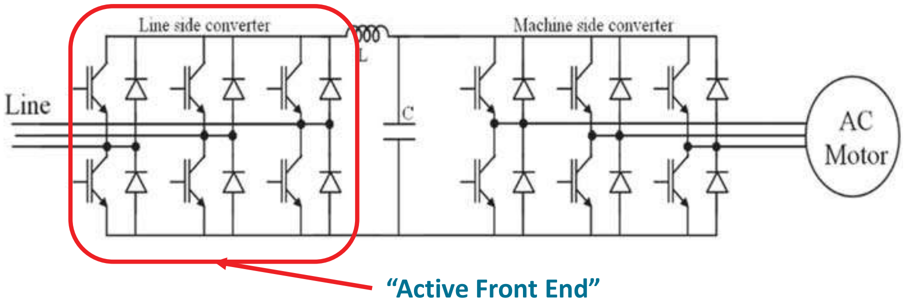
Regeneration Using Electric Motors

- Regeneration represents a good opportunity for energy saving in many applications of material handling loads.
- The opportunity for regeneration exists where the mechanical load is driving the motor.
- A VSD with an active front end is required to allow for energy to flow in the reverse direction, i.e. from the motor (acting as a generator) to the electrical supply network.

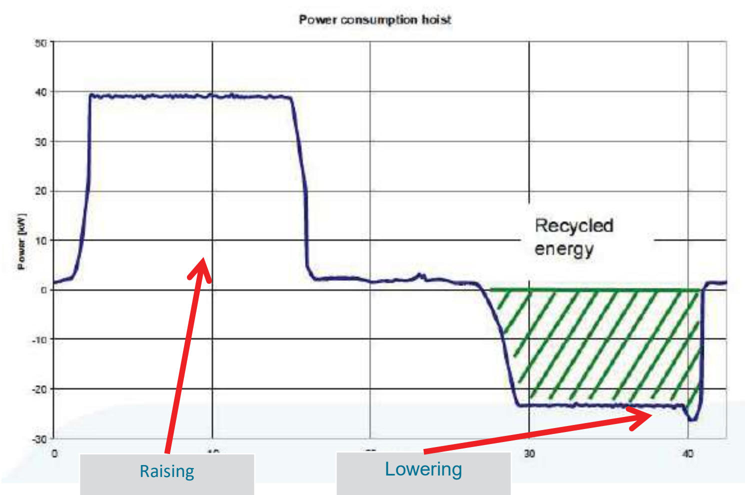


VSD with Bidirectional Power Flow

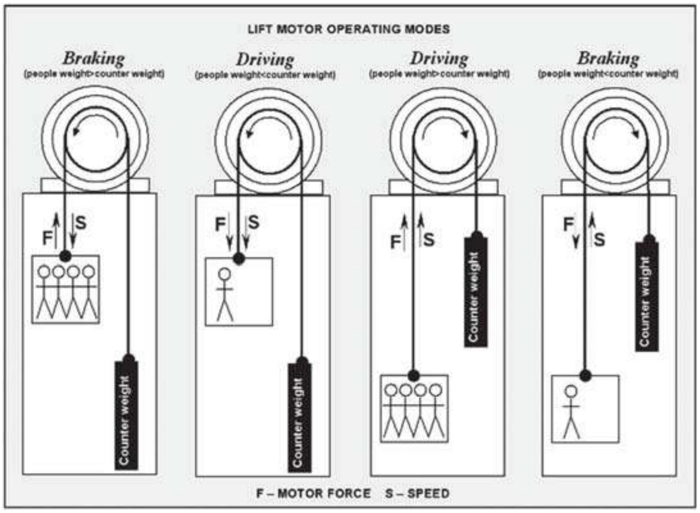
- Four quadrant drive control allows for regenration of electrical energy from the motor when operating in generating mode



Recycled Energy from Hoist (Y-axis)



VSDs in Lifts



Common Energy Saving VSD Applications

1

Centrifugal pumps, fans and compressors in which torque increases with the square of the rotating speed of the motor
The electric power sharply increases with the speed (up to the cube) and a small adaptation to the process need can lead to large savings

2

Conveyors, escalators, hoists, cranes and similar types of equipment where the torque is more or less independent from speed
The cost and energy efficiency benefits are smaller compared to the first group of applications because the change of input power is only linear with the speed. Regenerative braking can lead to additional savings

Common Energy Saving VSD Applications

3

Changes in load and speed can benefit from a VSD in other ways like process control, soft starting and stopping, as well as the requirement of an especially high starting torque or of regenerative braking

The cost and energy efficiency benefits are small compared to the first two groups. VSDs allow for voltage optimization to improve motor efficiency if the torque changes

4

Motion Control – AC drives can now provide high performance torque/speed control, similar to motor servo drives

Benefits of VSD Applications

- Large energy & cost savings (20% – 70% possible)

Better match of machine to process requirements

- Increased flexibility
- Better process control
- Better throughput

- Better start & stop control
- Reduced starting currents
- Reduced stresses on the system = reduced maintenance & longer life

Practical Considerations of VSD's

Do not use when

- Cost savings are not financially viable
- Little opportunity to reduce speed
- Little variation in process demand
- Associated equipment does not allow speed changes
- A large static head exists in a pumping system
- If other equipment is sensitive to harmonics

Practical Considerations of VSDs

Installation

Adequate physical space to install drive

Adequate cooling, no dust, humidity

Ensure suitable cabling & electrical filtering

Ensure adequate electrical insulation in the motor

Correct commissioning procedures

Review & Discussion

- What is the ratio of savings for a conveyor that is reduced to half speed using a VSD?
- What special type of drive is necessary for a motor to be able to provide generation as well?
- When should we not use a VSD?

Section 12

Power Quality & Power Factor

Definition of Power Quality

From a **quality perspective**:

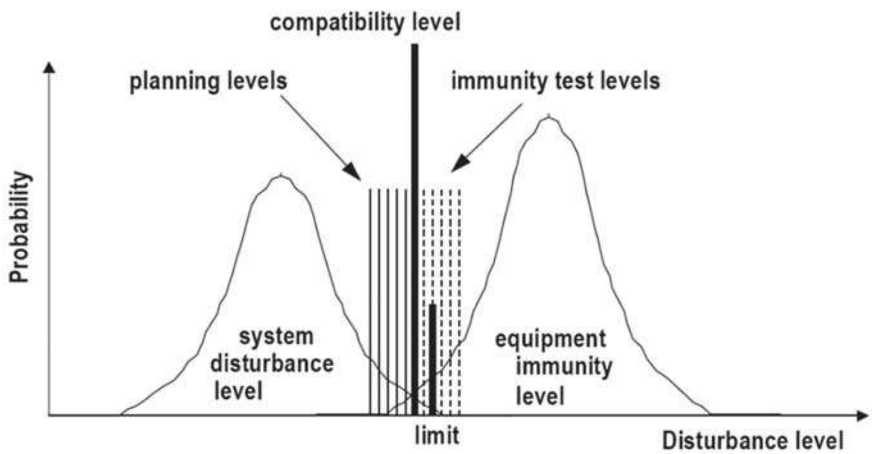
- may be defined as the measurement, analysis, and improvement of the bus voltage to maintain a sinusoidal waveform at rated voltage and frequency[1]

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]

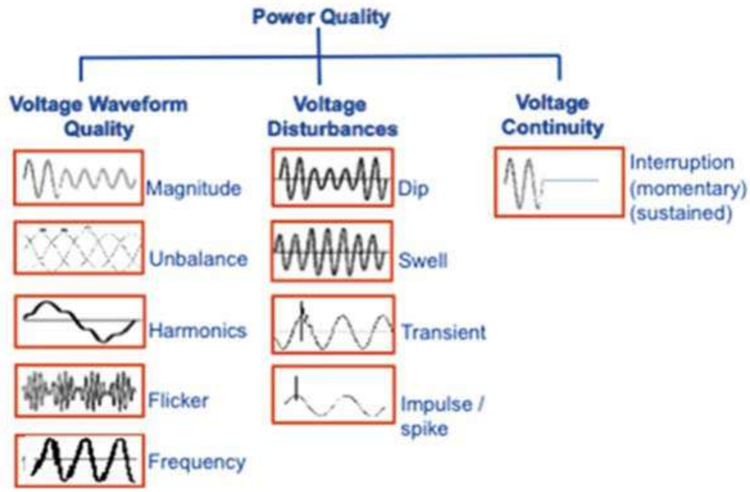
1. Masoum et al. Power quality in Power systems and electrical machines
2. International Electroctechnical Commission (IEC)

Electromagnetic Compatibility



Source: UNIDO Power Quality Course: South Africa 2020

Types of Power Quality Occurrences

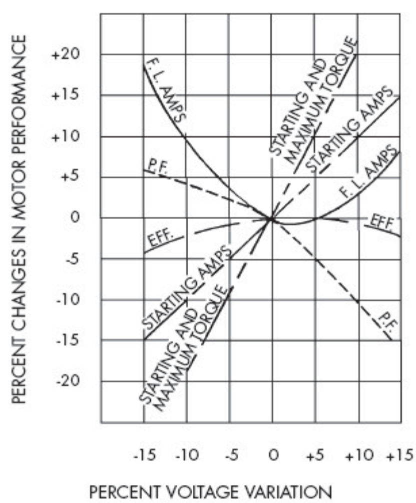


Source: Eskom Power Quality Course Notes

Voltage Variation Effect on Motor Performance

Maintain Voltage Levels

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



Calculation of Voltage Unbalance

True voltage unbalance

Requires Fortescue Transform

$$\% \ VU = \frac{Negative\ sequence\ voltage\ component}{Positive\ sequence\ voltage\ component} \times 100$$

Estimated voltage unbalance

Good for values below 10% unbalance

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

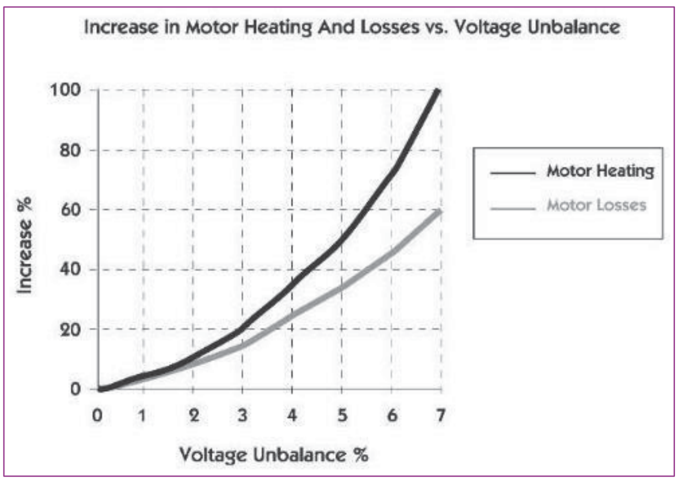
ANSI/NEMA Standard MG1-1993 (USA)

Voltage Unbalance on Motors

Effect of unbalanced voltage on winding temperature.

The increase is equal to two times the square of the unbalance %.

Increase = 2 x (unbalance %)^2



Source: www.pumpsandsystems.com

Class Exercise (10min)

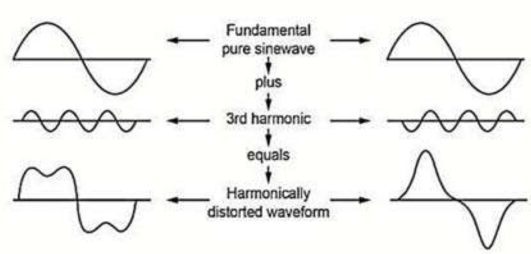
- Assume a 250 kW motor operated at 75 % load, 8000 hours per year at a 2,5% voltage unbalance

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

- Calculate the savings if corrective action was taken to improve unbalance to 1%
- What would happen to the operating temperature?

Harmonics

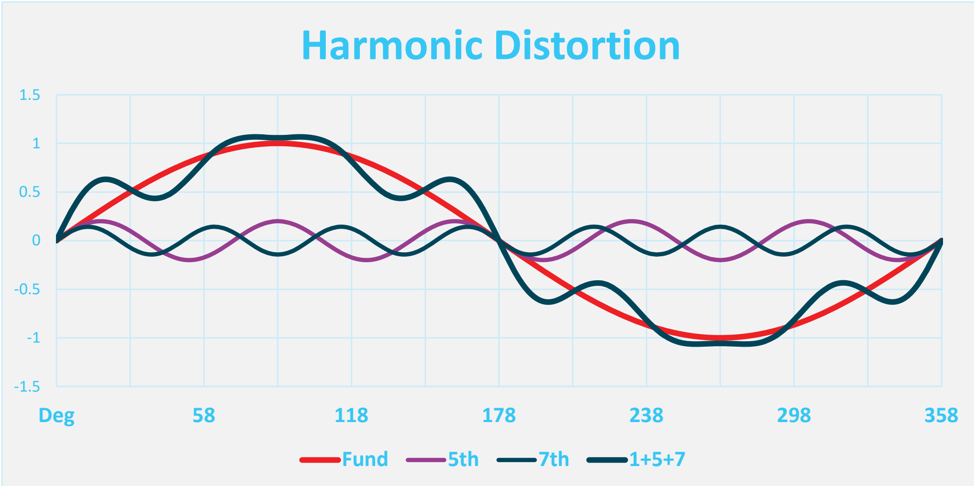
- Harmonics are waveforms with a frequency that is a full multiple (1,2,3 etc.) of the original waveform, called the **fundamental waveform.**
- When harmonics combine with the fundamental waveform, the new summated waveform is one that is distorted.



Frequency = 50 Hz

Frequency =3 x 50 Hz = 150 Hz
(3^{rd} harmonic)

Distortion of the Fundamental Wave



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

What causes harmonics?

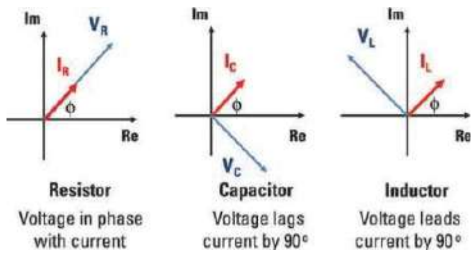
- Harmonics and harmonic distortion are caused by the presence of non-linear loads

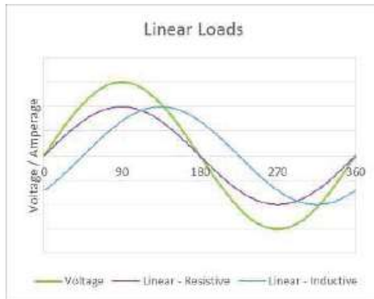
Sources of non-linear loads

- Welding machines, arc furnaces, induction furnaces
- Power electronics like variable speed drives (VSD), soft starters, power inverters, other electronics like PLCs, computers, servers, fax machines
- Control gear from lighting (fluorescent lamps, HID lamps), appliances like refrigerators, microwaves, television screens

Linear Loads

- Pure resistive, inductive and capacitive loads are all linear
- The voltage is proportional to the current
- Incandescent lighting, heating loads, motors

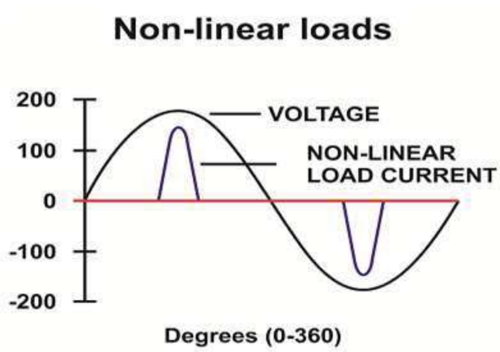




Non Linear Loads

- Loads that do not exhibit a constant impedance during the sinusoidal cycle
- The voltage is not proportional to the current

- Computers
- Photocopiers
- Lighting dimmers
- VSDs
- Arc furnaces
- Welding machines
- UPS
- Battery chargers



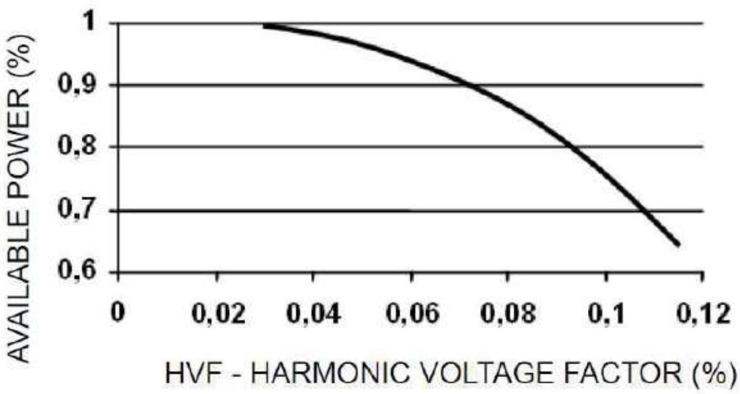
Effect of Harmonics on Network

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.

Harmonic Voltage Factor



Derating due to extra heating caused by harmonics

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

Mitigation of Harmonics

- Add linear loads to the system
- Remove non-linear loads, if possible
- Reconfigure network to limit influence of harmonics
- Install power transformers with 12 pulse drive systems
- Install harmonic filters

Power Factor

From an energy efficiency perspective:

Power Factor (*pf*)

is a ratio that indicates how much of the power supplied or generated can be used to perform useful work in a specific electrical system.

Partial Load *pf* of Induction Motors

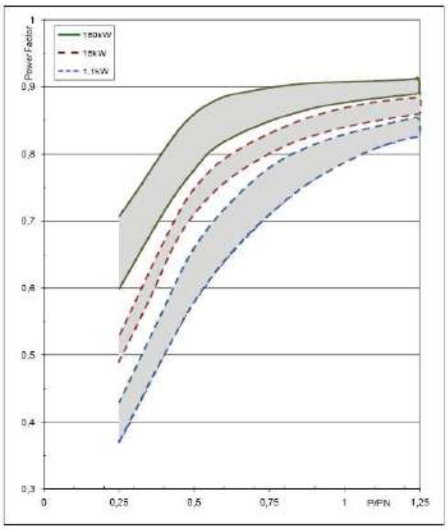
- Workhorse of industry
- 70% of all industrial electrical loads are motors
- 90% of all electrical motors in industry are induction motors
- Poor part load power factor
- Most motors in industry operate at part load

Motor Load Variation	
Motor Load	**Typical pf**
0%	17%
25%	55%
50%	73%
75%	80%
Full Load	84%
125%	86%

Oversized Motors and Power Factor

Maintain High Power Factor:

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



Typical Power Factor vs Motor Load
Source: IEC 60034-31

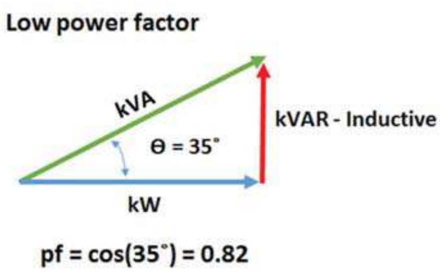
Why improve power factor?

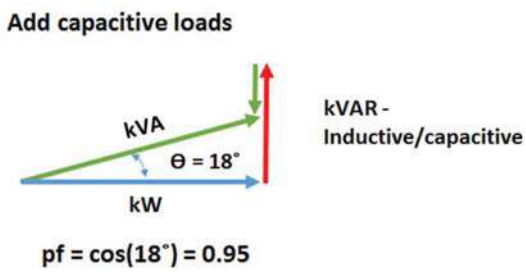
Improving a poor or low power factor:

- Can reduce the peak maximum demand and consequently, the overall cost of electrical supply
- Could reduce the probability of paying a penalty for a poor overall power factor
- Could increase the system capacity
- Could reduce the system losses
- Could improve the overall voltage level
- Could result in longer life cycle for motors by running cooler and more efficiently

Improving the Power Factor

- Most reactive components are **inductive**.
- Improve the power factor by **adding capacitance to the system**.
- This reduces the phase angle.





Harmonics and *pf*

- With linear loads the power factor is only related to the **50Hz** sinusoidal wave
- With non-linear loads the waveforms of the harmonics also need to be included, as each will have its own power factor
- The new **total power factor** will be a summation of the fundamental **+** the power factors of the harmonics
- The **50Hz** power factor is called the **displacement power factor**
- The power factor adjustments due to the harmonic wave distortion is called **distortion power factor**
- For non-linear loads the total power factor is **less** than the displacement power factor

Harmonics in Future

Harmonics will only increase in industry as more companies use sophisticated electronics to control the production machinery.

The development of a suitable harmonic strategic plan could be result in significant future savings and reduction in loss of production.

Power Quality Costs

Direct costs

- Some utilities charge a penalty for excessive reactive power (kVAr)
- Reactive power is unused power that increases peak power and its costs
- Damage in the equipment
- Loss of production and raw material
- Salary costs during non-productive period
- Restarting costs

Indirect costs

- Inability to accomplish deadlines
- Loss of future orders

Power Quality - Mitigation

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

SOURCE:
Schneider Electric

Review & Discussion

- What is a harmonic in power quality terms?
- How does voltage unbalance contribute to the motor performance?

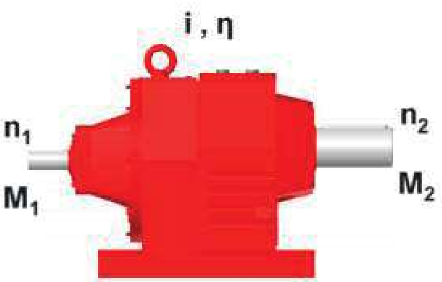
Section 13

Mechanical Transmissions: Gears & Belts

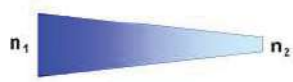
Mechanical Transmissions

- Used to transmit the required torque to a different point of use
- Match the mechanical load requirements to the load: they convert the input provided by a motor into output of lower RPM and correspondingly higher torque or vice-versa
- Transmission equipment including shafts, belts, chains, and gears should be properly installed and maintained
- High efficiency transmission equipment such as helical gears and synchronous belts should be used where applicable

Mechanical Transmissions - Gears



Reduce Speed



$$n_2 = \frac{n_1}{i}$$

Multiply Torque

$$M_2 = M_1 \times i \times \eta$$

Mechanical Transmissions - Gears

- Used for low speed, high torque loads

Several types:

  - Helicoidal
  - Spur
  - Conic
  - Screw.

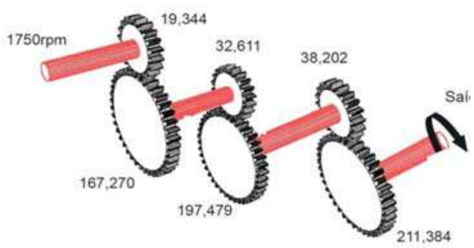
- Losses are related to the friction of gears and bearings, windage and lubricating viscosity

Mechanical Transmissions – Worm Gears

- Worm gears have typical efficiency between 50 & 85% (depending on the transmission ratio, speed, lubricant, and temperature)

Mechanical Transmissions – Helicoidal Gears

- Helicoidal and conic gears have typical efficiency of 98-98.5 % per stage (1.5-2% loss per stage)



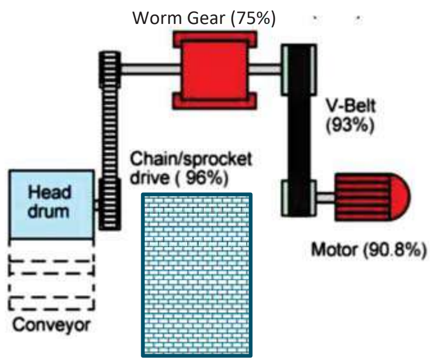
Worked Example

System Efficiency:

$$\eta = \eta_{motor} * \eta_{belt} * \eta_{worm} * \eta_{chain}$$

$= 0.908 * 0.93 * 0.75 * 0.96$

$= 60.8\ \%$



Power Transfer

Input electrical power	= 16.5 kW (measured)
Mechanical power to the conveyor	= 16.5 * 0.608 = 9.1 kW
Transmission power loss	= 7.4 kW

Mechanical Transmissions - Belts

- 1/3rd of all transmission applications use belts
- Belts offer high flexibility of the motor in relation to the load, and speed adjustment possibility

Several types:

  - V-belts (with and without cogs)
  - flat belts,
  - synchronous belts

- The V-belt is the most widely used, with an efficiency of 90-96% (depending on the elasticity, tension, slip, and alignment)

- If the tension is excessive → accelerated wear of the belts and bearings
- if the tension is too little → the slip and losses increase

- The most efficient types are the flat and the synchronous belts. The synchronous belt has an efficiency of about 98-99%

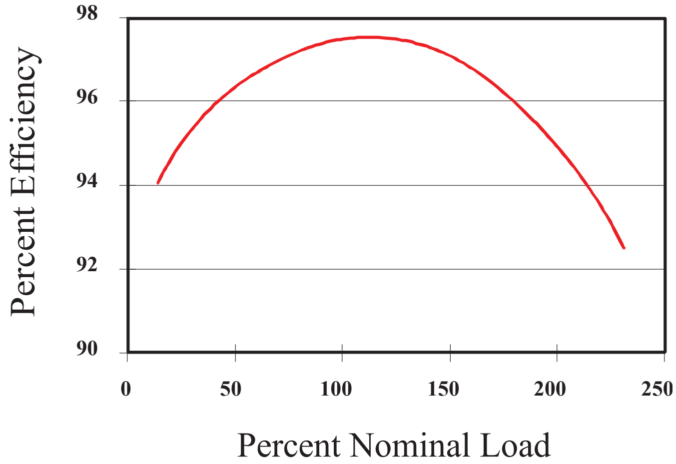
Mechanical Transmissions - Belts

- Because V-belts operate on the friction principle, multiplied by the mechanical advantage of the wedging principle, proper tensioning of v-belts is the single most important factor necessary for long, satisfactory operation.

The alignment is very important!

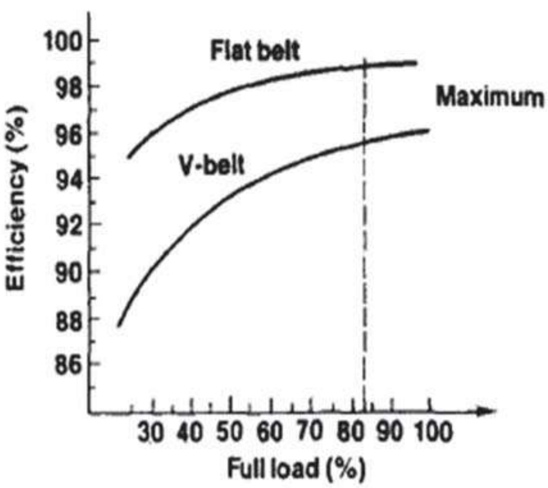
- Too little tension will result in slippage, causing rapid belt and sheave wear, and loss of productivity.
- Too much tension can result in excessive stress on belts, bearings, and shafts and reduced efficiency.

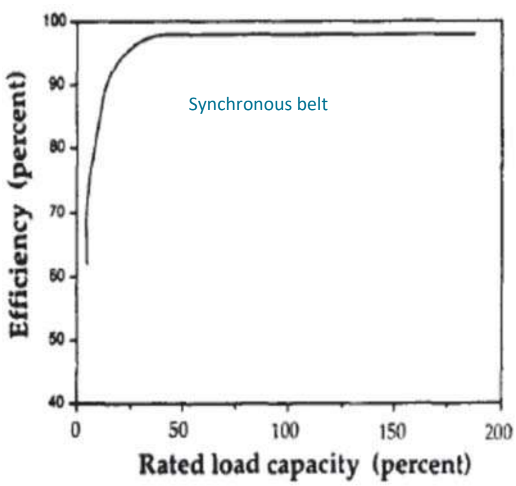
Mechanical Transmissions - Belts



Efficiency Curve for a typical toothed V-belt

Mechanical Transmissions - Belts





Mechanical Transmissions - Belts

Comparison of the Main Characteristics of Belt Drives

	Typical Efficiency Range (%)	Suitable for Shock Loads	Periodic Mainte-nance Required	Change of Pulleys Required	Special Features
V-belts	90-98	Yes	Yes	No	Low first cost
Cogged-V-belts	95-98	Yes	Yes	No	Easy to retrofit Reduced slip
Synchro-nous Belts	97-99	No	No	Yes, with higher cost	Low-medium speed applications. No slip. Noisy

Worked Example

A continuously operating 75kW supply-air fan motor (93% efficient) operates at an average load of 75% and consumes 530,000 kWh annually.

What are the annual energy and cost savings if a 93% efficient (η_1) V-belt is replaced with a 98% efficient (η_2) synchronous belt?

(Electricity is priced at USD 0.37/kWh)**

Energy Savings
= Annual Energy Use x (1 – η_1/η_2)
= 530,000 kWh/year x (1 – 93/98)
= 27,000 kWh/year

Annual Cost Savings
= 27,000 kWh x LKR 37/kWh
= USD 9 990 / year

Direct Coupling

- Best whenever possible for simplicity, lower maintenance and higher efficiency.
- New types of motors and especially new drives make this option more feasible nowadays.

- If properly aligned, the efficiency is high (99%)
- If not properly aligned, both motor efficiency and bearing lifetime will be decreased
- Can only be used where motor speed is close to speed required for load

Review & Discussion

- What are the main functions of transmissions?
- What are the basic types of transmissions?

Section 14

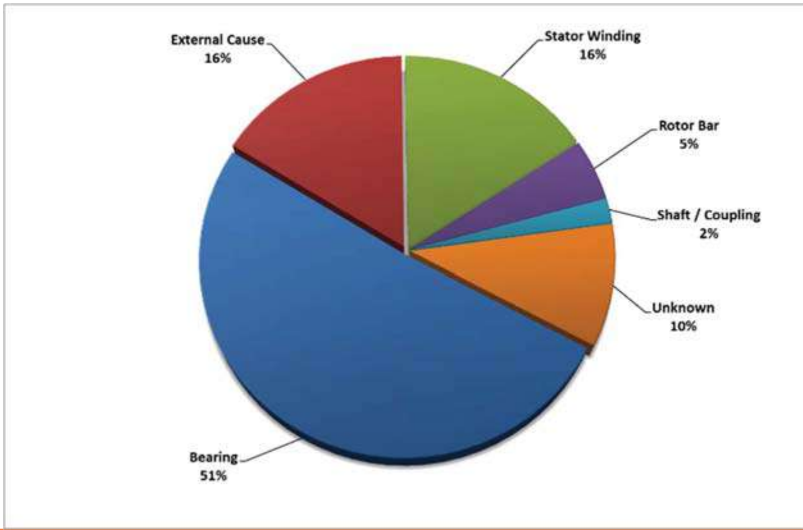
Maintenance & Repair

Why do motors fail?

Problems arising from:

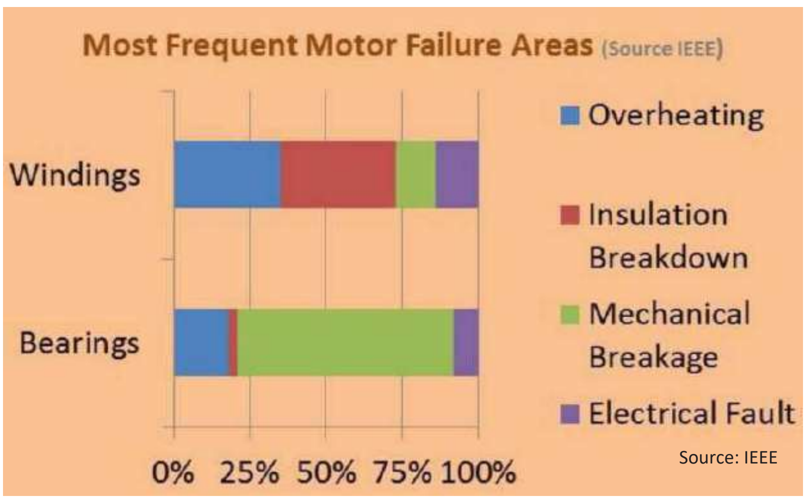
- Poor specification
- Incorrect installation
- Operating under abnormal ambient conditions
- Poor power quality
- Poor maintenance
- External mechanical damage

Failure by Motor Component

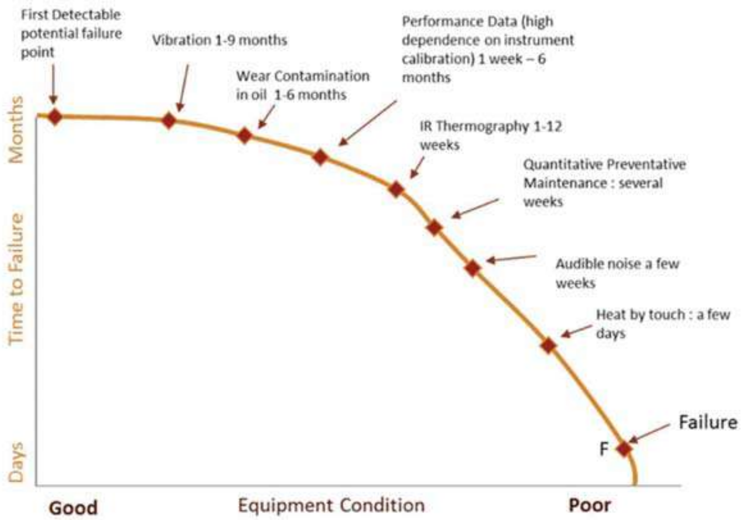


Source: EASA

Common Motor Failure Modes



Motor Failure Potential



Source: EASA

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

Linking Energy and Maintenance

- Maintenance problems represent an energy loss – and are an indicator of a saving opportunity.
- Regular maintenance checks also yield information on energy efficiency.
- Can you use the maintenance database for storing energy use information on?
- Maintenance projects always get priority over energy saving projects!

Where Better Maintenance Saves Energy

Shaft alignment	Lubrication	Dirt removal
Ventilation	Voltage balance	Harmonic filtering

Conditions Affecting Motor Performance/Reliability

Frequent starts and stops

- Can cause premature motor failure

Environmental conditions

- Poor cooling due to high ambient temperatures
- Partially clogged motor vents
- Dirty/wet application

Voltage unbalance or under/over voltage

- Creates additional heat
- Increases motor internal losses
- Motor is derated for high voltage unbalance Frequent starts and stops

Operating in the service factor

- NEMA recommends that motors should be derated when operating in the service factor

Energy Saving Maintenance Checklist

- Ensure motors, VSDs and related equipment are clean, free from dust & debris
- Ensure adequate cooling and ventilation can take place
- Inspect motor & equipment mountings for tightness and alignment
- Examine drive belts, check for:
  - Wear, correct seating on pulleys
  - Alignment of belts & pulleys
  - Correct tension
- Make lubrication checks – check for sufficient lubrication, no leaks
- Listen to noise – listen for tell tale sounds of problems (operators will recognise changes from the norm)
- Electrical supply - check voltages are within tolerance, and phases are balanced

Repair or Replace?

Decision is dependent on	• **Reparability** • **Downtime** • **Finance** • **Expected life**
Do we consider	• **Energy efficiency** • **Life cycle cost (LCC) or** • **Total cost of ownership (TCO)**

Why Repair a Motor?

- Repairing an old motor is usually a lower cost "up front" option, and so is the default. As a "rule of thumb", it may be 2/3rds the cost of a new one, but this varies.
- The maintenance engineer does not reap the future energy savings from buying a new and more efficient motor, and so opts for the lower up front cost option.
- Repairers would rather repair rather than replace, as there is more profit in this. (Although they will soon lose business if pushing uneconomic repairs).

In the absence of any accreditation scheme, you are on your own

Things to look for:

Stocks

- Do they have adequate spares inventories?
- Do they have a good range of wire gauges?

Winding removal

- Do they have an oven in good condition with good controls?

Quality control

- What evidence is there of quality control system?

Motor testing

- What tests do they do on repaired motors?

Personnel

- What experience do their staff have?

Stator Core – Burn Out Temperature

This is a critical part of the repair function.

Burnout temperature must be closely controlled

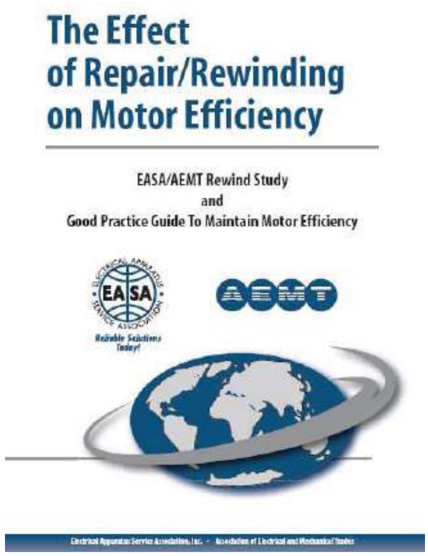
- **< 360°C** → The core may not be clean, requiring additional cleaning and risk of mechanical damage
- **360 to 370°C** → Ideal temperature
- **> 400°C** → Can damage inorganic interlaminar insulation

Source: Reliance Electric

Quality Repair Procedures

- Avoid damage to the stator core when removing old windings
- Rewind with the correct wire gauge, number of turns and insulation
- Use the correct cooling fan
- Use the right bearings and lubricate correctly

In the UK,(80%+) undertaken are done to this code (with other motors really being beyond technically satisfactory repair)



Review & Discussion

- What is the most common type of motor failure?
- Why is the burnout temperature for a motor repair oven so important?
- Mention some techniques that can be used to predict motor failure.

Section 15

Conducting an MSO Assessment

Why Motor Systems Energy Assessments?

Why do we need it?

- Energy cost money
- Equipment costs money
- Reducing operating costs will improve profits for the same volume of production
- Opportunities for saving DO exist

What benefits?

- Save money
- Cultural behavioural shift (management more willing to spend on energy projects, operational staff become accustomed to reducing waste)

Why Motor System Energy Assessments?

70 % → of industrial electric load is consumed by motor systems

Opportunities to reduce energy use include:

- Old control technologies
- Changing operating conditions
- Varying production needs

Although system efficiency can be around 60% or higher,
→ it often falls below 50% and even as low as 15%-20%

Benefits of Motor System Optimization

- Energy Savings / cost reduction
- Peak power reduction
- Improved operational reliability and control
- Ability to increase production without requiring additional, and possibly constrained, energy supply
- CO_2 emission reduction
- Avoidance of capital expenditures through greater utilization of existing equipment assets
- Recognition as a "green company"

Benefits of Motor System Management

Increased Productivity	Improved Reliability	Reduced Costs
Greater control over process requirements	Scheduled downtime instead of breakdown maintenance	More efficient operation
Flexibility in meeting production requirements	Longer production runs between maintenance outages	Reduced maintenance costs
Reduced scrap and rework	Longer equipment life	Lower unit cost

Effective motor system management develops synergies between preventive and predictive maintenance programs, equipment operation and process productivity to establish a repair/replace policy based on a commitment to energy-efficient equipment selection and operation.

Benefits of Energy Efficiency for Emerging Economies

Improved energy efficiency provides a variety of befits of particular importance for emerging economics and developing countries as they seek to exploit their resource base to reduce poverty and support sustainable growth:

Access: energy efficiency can help countries to expand access, effectively enabling them to supply power to more people through the existing energy infrastructure

Development /growth: energy efficiency has a variety of positive impacts that support economic growth, for example by improving industrial productivity & reducing fuel import bill

Affordability/poverty alleviation: energy efficiency can increase the affordability of energy services for poorer families by reducing the per-unit cost of lighting, heating, refrigeration and other services

Local pollution: energy efficiency (both supply side and end-use) can help to reduce the need for generation and lower associated emissions – while supporting economic growth

Climate change resilience: by reducing the need for energy infrastructure, energy efficiency the amount of energy assists exposed to extreme weather events

Source-IEA, 2014

Information, Behavioural, Organizational and Market Barriers to MSO and energy efficiency

- K — Companies have limited knowledge and access to information about new and existing energy saving technologies.
- K — Companies may perceive technical and operational risks of implementing energy efficiency projects due to unfamiliarity with energy-reducing technologies and practices relative to core business projects.
- O — Professional and functional boundaries within the organisation limit the collaboration required to identify and support energy efficiency
- P — Energy prices and taxes are subsidised in some countries in the industrial sector; therefore, companies may not pay the full cost of their energy use and have less incentive to reduce consumption.

K Knowledge   O Organization   P Policy

Financial Barriers to MSO and energy efficiency

- K/ F — Investments in energy efficiency projects do not meet financial criteria within companies (especially in countries where interest rates are high).
- P/ F — Companies lack access to capital.
- K/ F — Investments impose too high a risk due to lack of familiarity with energy-savings projects relative to core business projects and difficulty in predicting future energy prices.
- O/ F — Businesses like to use capital and resources to grow and expand their business. When they want to reduce costs, they want to do so without spending too much capital. Companies will often only fund projects with an 18-month to two-year payback or less, unless it has a productivity or growth outcome as well.

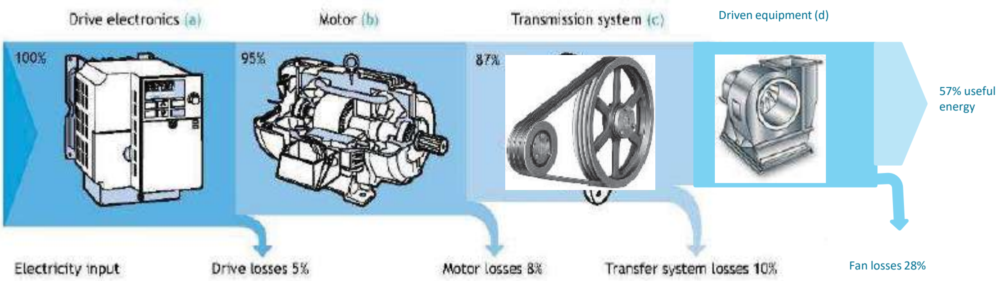
K/F Knowledge /Financial   O/ F Organization /Financial   O/ F Policy/ Financial

Recall from yesterday: Where do we start?

1. List of all motor systems
2. Prioritise a list of 10 – 20 systems
3. Review each motor system
   a. Start with the end use
   b. Ask the big questions

Recall from yesterday: Start with the end use…

Start at the process where the final energy is required and work backwards towards the source



Energy losses occur at each stage. Identify the losses and look for the best opportunities to improve

Recall from yesterday: Ask the Big Questions

1. What is the system trying to achieve?
2. What are the settings – how were these settings determined?
3. Is it the best way of doing it?
4. Do we really need it all the time?

Recall from yesterday: Motor System Review

- Determine the type of motor and load application
- Determine the system requirements
- Establish the operating hours and costs
- Calculate the annual cost of operation
- Check on the method of operation and management
- Draft a system diagram showing all components
- Determine the motor control method
- Establish where any inefficiencies may occur
- Calculate the losses where possible
- Estimate the possible savings

What Actions Can Be Taken?

Switch off options	Motor upgrades
System optimisation	VSD opportunities

Identify systems that could do with more in depth investigation – Pumps, fans, compressed air

Opportunities: Switch Off

When

- Tea breaks
- Out of hours
- Review switch on/off times
- Time switches / BMS controls
- Tool changes
- Between batches

Beware of

Switching frequency limits – motors can only be switched on and off a certain number of times per hour

How to Switch Off

Manually via

- Education

Automatically via

- Timers
- Thermostats
- Interlocks
- Load sensors
- Process control

Opportunities: Motor Upgrades

Develop a Motor Management Policy to enable a systematic approach to motor upgrades

Look for

- Large motors that run all the time
- Motor that fail often or tend to have short life cycles
- Motors running much less than full load (< 50%)

Opportunities: Transmissions

Look for

- Loose transmission belts
- Motor shaft alignment problems
- Motor bearing failures
- Oil leaks under gearbox or transmission

Listen for

- Noisy gearboxes
- Screeching pulleys

Opportunities: VSDs

Look for

- Pumps and fans driving processes and loads with variable demand
- Motors running much less than full load
- Closed loop systems with low static head
- Existing system with parallel equipment (eg multiple pumps in a cooling system)

Consider

- Review of existing operating parameters for systems
- Installation of new motors to enable VSD control

Worked Example: VSD Saving Opportunity

Existing pumping system:

- Motor runs at 2900 rpm, Electrical power in: 22 kW, Pressure: 4 bar
- Opportunity to reduce flow rate by 15%

- New speed (rpm): 2900 x 0.85 = 2465 rpm
- New pressure (bar): 4 x $(0.85)^2$ = 4 x 0.72 = 2.9 Bar
- New power (kW): 22 x $(0.85)^3$ = 22 x 0.614 = 13.5 kW

- Discount saving by 5% to account for additional losses due to VSD
- Savings potential = ((22kW – 13.5kW) x 95%) = 8.075 kW

- ***Conclude:*** 15% flow (speed) reduction = 37% power reduction

Conducting a Site Visit

Pre-Assessment Checks:

- Check all pre-visit information
- Check everyone still available
- Check attitudes – does everyone want you there, who is showing you around?
- Check motivations – what are their problems, what is going to make them invest?
- Safety requirements (PPE and induction)
- Keys and access to areas

Conducting a Site Visit

Listen to

- Plant operators
- Maintenance staff
- Quality control staff
- Cleaning staff
- Procurement
- Management

Where to look FIRST

- Large equipment with high and frequent usage
- Equipment that fail often and result in long down times
- Systems with varying duties or outputs
- Auxiliary equipment that is not critical to the production process
- Problem equipment and systems with high failure rates

Where NOT to look

Every plant is different, but you will probably find that these are not very lucrative areas for saving:

Process equipment	(Value of throughput too high and plant already fine tuned for the process)
Critical processes	(Risk of unexpected problems unacceptable)
Small equipment	(Energy use too small to justify detailed investigation or implementation)
Equipment scheduled for replacement	(Financial payback unattractive)

Existing Data

- Plant data - allow for undocumented changes, actual operating conditions
- Instruments - are they believable?
- Energy use - what exactly is being measured?
- Maintenance history

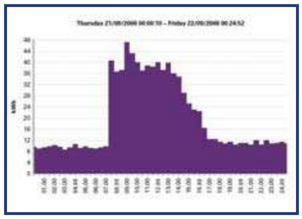
Can waste a lot of time, but may just contain a gem. Trying to answer the above questions can yield a lot of information!

Data Analysis

Meter readings + Driving factors → Analysis

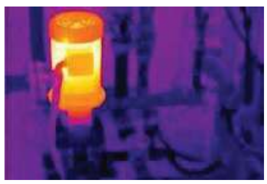




Measurement

- Power data logger
- Infrared camera
- Clamp ammeter
- Vibration meter




How detailed should your recommendations be?

- Your main objective is to identify and give an outline financial justification for energy saving opportunities
- Distinguish those jobs that can be designed and implemented in house, and those that require outside assistance
- The Motor Systems Energy Assessment sets the scene for a more detailed technical design and investment programme

Estimation of Motor Load

Estimation of approximate load based on of motor speed and voltage

Name plate data

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

Measured data

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

Estimation of Motor Load

Based on speed Measurement:

Synchronous speed

= 60 x 50/2

= 1500 rpm

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

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

Slip = Synchronous Speed – Measured speed
= 1500 – 1460
= 40 rpm

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

Estimation of Motor Load

Based on Current Measurement:

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

$$Load\ (\%) = \frac{415 \times 33}{400 \times 55} = 0.623\ \ (62.3\%)$$

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

Review and Discussion

- Why do we need motor systems energy assessments?
- What type of opportunities should we look for?
- Where should we look?
- How do we prioritise the systems we should assess?

Section 16

Software tools

Software Tools

Demonstration of MEASUR

- Motor tools
- Motor system analysis

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

Free download available from US Department of Energy

Section 17

Development of an MSO Business Case

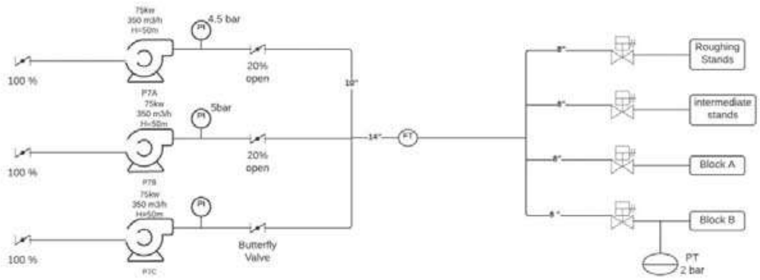
Business Case Reports

Key elements of a business case report:

- Executive summary
- Objectives of study
- Plant process overview
- Plant electricity network and costs
- Motor system selection
- Motor system overview
- Measurements and findings
- Analysis of motor system results
- Energy saving opportunities
- Opportunities summary
- Recommendations

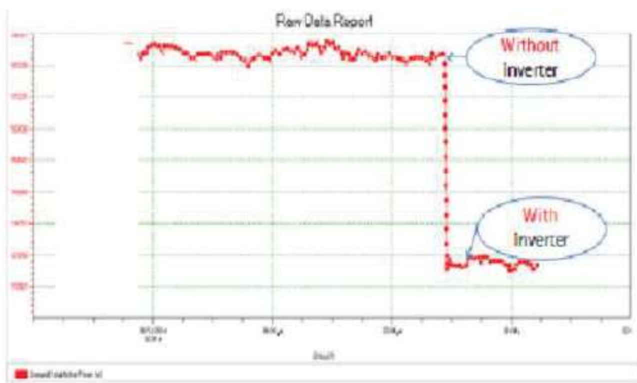
Motor System Overview

- Overview of motor system being assessed
- Simple block diagram
- Include process parameters
- Construct energy balance
- Identify opportunities along the energy supply chain



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.



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

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 (ZAR)	300,000	80,000	460,000	3,000	20,000
Saving per year (ZAR)	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

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)

Need tools to help with these choices

Some Financial Choices

Two motors are the same size (power rating)

- One costs USD 300 000 and the other USD 250 000

Which one should you buy?

Two compressors:

- One costs USD 500 000 to buy and USD 200 000 p.a. to operate
- The other USD 700 000 to buy and USD 150 000 p.a. to operate

Which is best?

Simple Payback (SPB)

SPB = Initial Cost / Annual Savings

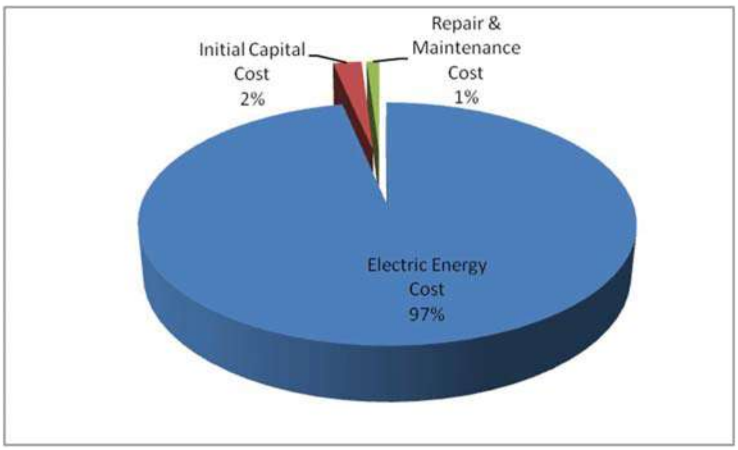
- Usually organisations have a limit e.g. only opportunities with a payback of less than 2 years will be considered
- Called "simple" because it does not take into consideration the effects of inflation, taxes and the cost of capital

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.

Why use Life Cycle Costing?



11 kW IE3 Motor
4000 operating hours per year,
15 years life cycle
0.0754 €/kWh

Source: ISR – University of Coimbra

Why good projects don't happen?

Energy Efficiency is perceived as:

- Discretionary
- Less important because it is regarded as small scale
- Technically risky
- Optional, with no legal drivers
- Costly

What do decision makers want to see?

Some common problems:

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

Selling It! - Summary

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

Review and Discussion

- How do we show savings in a business case?
- Why use life cycle costing?

Section 18

eMobility

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Electric Vehicles (EV) and Sustainable Development

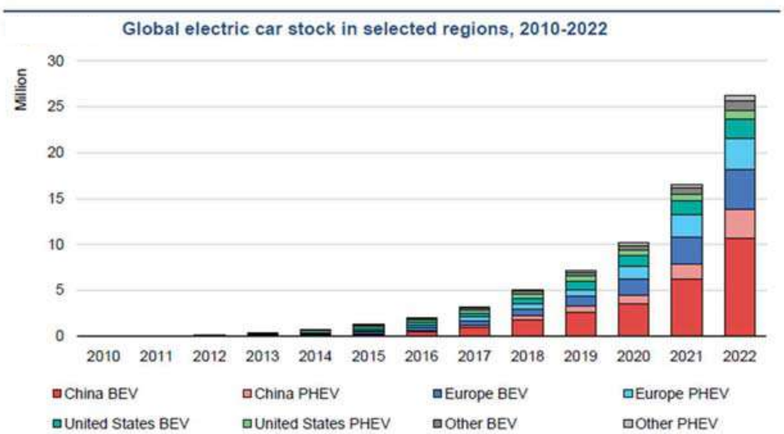
Electric mobility deals with means of transportation (two-wheel vehicles, cars, trucks, buses, trains, ships, airplanes) in which electricity is used to supply electric motors to provide, partially or totally, the mechanical power required to produce motion.

- **E--mobility a key solution for sustainable transport**
- Electricity as a fuel leads to more sustainable transport:
  - Reducing CO_2 emissions
  - Improving air quality
  - Increasing energy efficiency
  - Reducing oil dependence
- Environmental performance of EVs will further improve due to commitment to carbon-neutral electricity by 2050

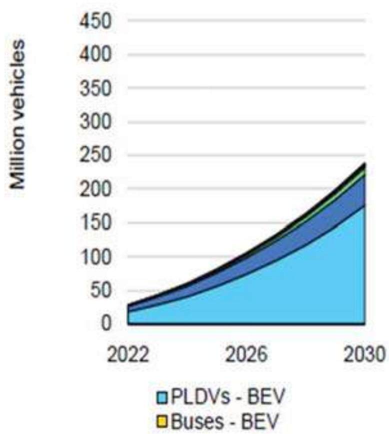
Electric Mobility – Not a new thing!

1900 Lohner Porsche car with electric motors integrated into the wheels (Wienkötter, 2018).

Global Electric Car Stock



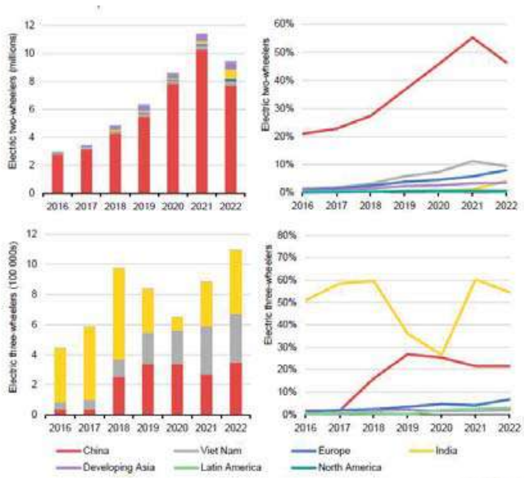
2010 - 2022



FORECAST

(Source – IEA, 2023)

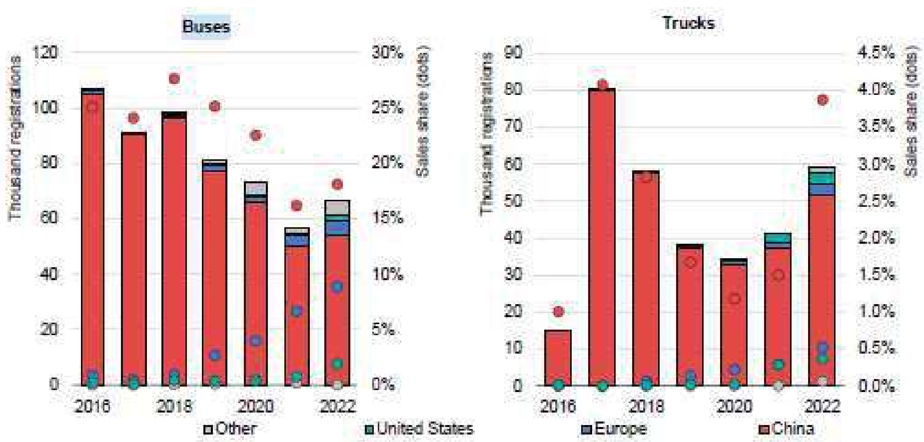
Global Sales of Electric 2 and 3 Wheeler Vehicles



(Source – IEA, 2023)

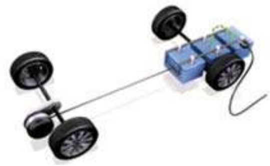
MINISTRY OF INDUSTRY AND TRADE
Global Gateway
UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

Global Sales of Electric Buses and Trucks



(Source – IEA, 2023)

Electric Vehicle Architecture



Hybrid Electric Vehicle (HEV)

- Integration of an electric motor/generator (MG) connected to a controller and battery, in parallel with the Internal Combustion Engine ICE.

Plug in Hybrid Electric Vehicle (PHEV)

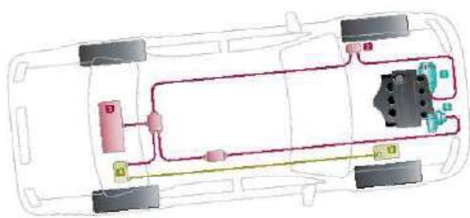
- Capable of being recharged from the grid.
- Can be driven in an exclusively electric mode with good dynamic performance

Battery Electric Vehicle (BEV)

- Equipped with a recharge system on board, a large capacity battery with values already reaching 100 kWh in some models, controllers and one or more electric motors per vehicle, axle or wheel.
- No Internal Combustion Engine

Mild Hybrid Vehicles

1. Electric Starter Generator
2. AC/DC converter
3. 48 volt lithium ion battery
4. DC/DC Converter
5. 12 volt lead acid battery
6. Electrical supercharger

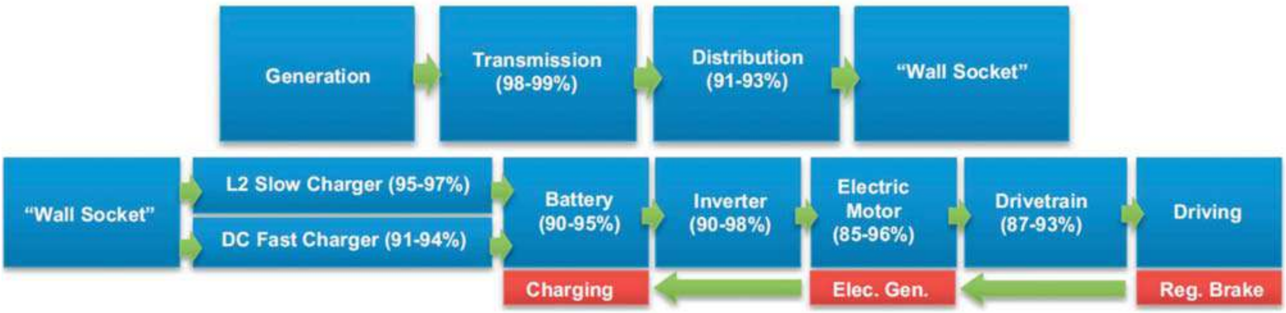


10 kW (or higher) starter motor/generator:

- It can boost the engine to increase the vehicle's acceleration performance and manage engine load to reduce fuel consumption (motoring).
- when the vehicle is cruising or decelerating/stopping the starter generator can recover electrical energy back to the battery (generating).

The electric supercharger eliminates the turbo lag limitation of the traditional turbocharger. Its primary purpose is to increase the air/fuel mixture density that goes into the cylinder of the engine.

Energy Efficiency of EVs



Range of efficiency of the different components in the energy path of an EV

Comparison of EV Motor Technologies

Characteristics	Motor type		
	IM	PM	SynRM
Power density	Medium	Very high	High
Efficiency	Medium	Very high	High
Controllability	Very high	High	Medium
Reliability	Very high	High	Very high
Technological maturity	Very high	High	High
Cost	Very low	High	Low

The Future of EV Recharge Stations

Electric Buses

Cities around the world are introducing electric buses (e-buses), driven by growing concerns on air quality, CO_2 emissions and potential operational cost savings.

Electric Buses

Beyond improvements in air quality, there are other factors that will further help to push the adoption of e-buses:

- Lower total costs of ownership (TCO): in a growing number of configurations the e-buses have lower TCO than comparable diesel or compressed natural gas (CNG) buses. Operational savings were one of the more important arguments supporting e-buses introduction in many cities.
- Noise reduction and reduced downtime: e-buses run more quietly than diesel or CNG buses, which reduce noise pollution. E-buses also require almost no maintenance.
- Industrial policy considerations: some governments may see an opportunity to build a domestic industry around the electrification of transport. Job creation linked to e-bus production and setting up a charging infrastructure can be a very positive argument for e-buses.

Electric Buses – Made in Uganda

A good example for other countries to follow

Carrying Capacity:	90 (49 seated, 41 standing)
Maximum Motor Power:	245 kW
Torque:	3,300 Nm
Range on single charge:	300 km
Battery bank energy capacity:	301 kWh

Review and Discussion

- Any questions?

Section 19

Smart Grids and Demand Response

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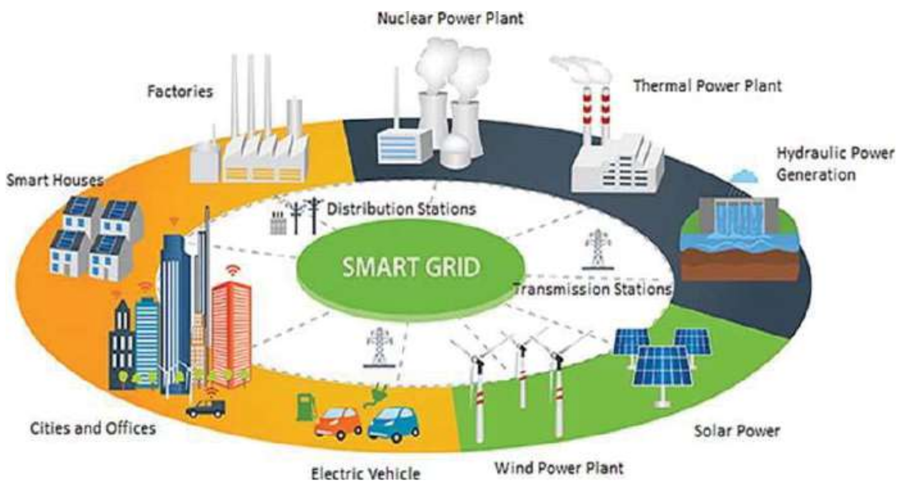
Smart Grids Definition

- **A smart grid is an electricity network that uses digital and other advanced technologies** to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users.

- Smart grids coordinate the needs and capabilities of all generators, grid operators, end users and electricity market stakeholders **to operate all parts of the system as efficiently as possible, minimising costs and environmental impacts while maximising system reliability, resilience, flexibility and stability**.

Smart Grids

Optimal integration of thermal power plants, renewable energies, energy storage and flexible loads



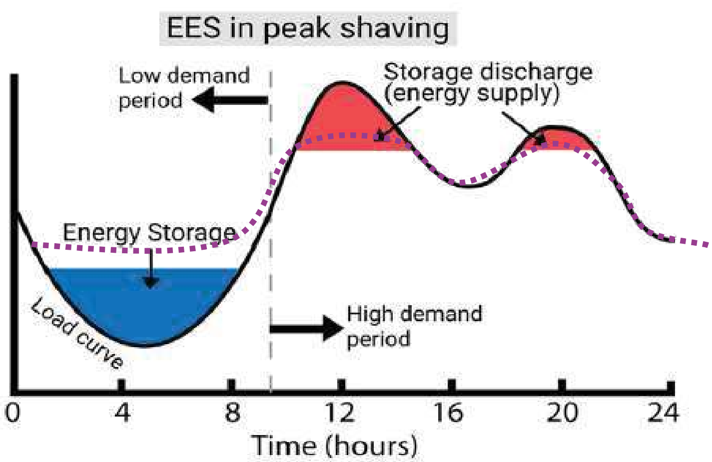
Importance of Demand Flexibility

FUNDAMENTAL VALUE DRIVERS OF DEMAND FLEXIBILITY

CATEGORY	DEMAND FLEXIBILITY CAPABILITY	GRID VALUE	CUSTOMER VALUE
Capacity	Can reduce the grid's peak load and flatten the aggregate demand profile of customers	Avoided generation, transmission, and distribution investment; grid losses; and equipment degradation	Under rates that price peak demand (e.g., demand charges), lowers customer bills
Energy	Can shift load from high-price to low-price times	Avoided production from high-marginal-cost resources	Under rates that provide time-varying pricing (e.g., time-of-use or real-time pricing), lowers customer bills
Renewable energy integration	Can reshape load profiles to match renewable energy production profiles better (e.g., rooftop PV)	Mitigated renewable integration challenges (e.g., ramping, minimum load)	Under rates that incentivize on-site consumption (e.g., reduced PV export compensation), lowers customer bills

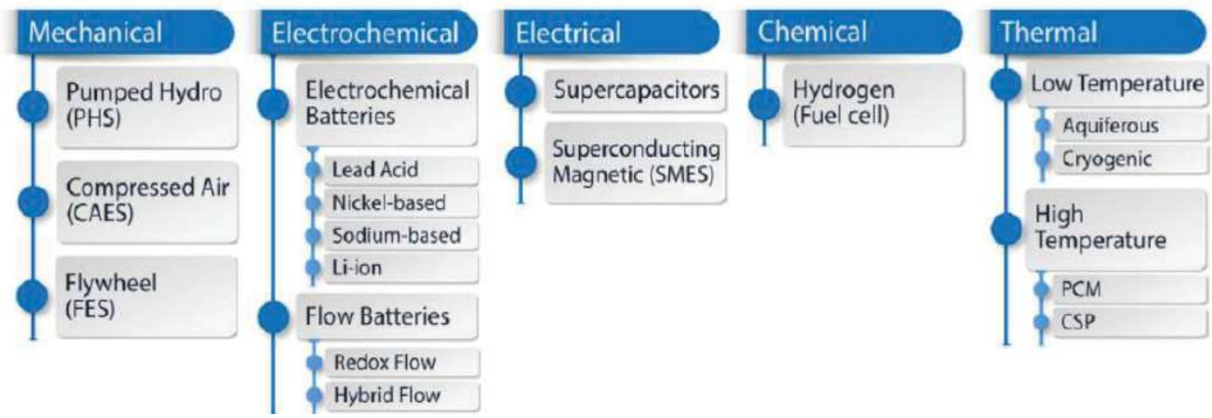
Essential for the integration of intermittent renewable generation (Solar PV + Wind)

Energy Storage for Load Profile Peak Shaving



- Storage can be achieved with electricity or through a service, like cold storage, water supply storage, materials processing in industry, etc.
- Result is a aflatter more regular demand profile with lower overall peak demands

Types of Energy Storage



Large Flexible Motor Loads

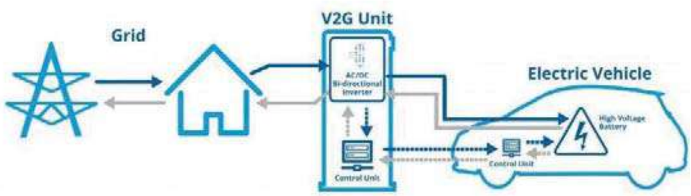
- Materials processing in industry (e.g. cement mills, mining industry)
- Refrigeration wharehouses
- Air conditioning loads with cool storage
- Large data centres
- Irrigation, namely to take advantage of solar power
- Sea water desalination, namely to take advantage of solar power, using water reservoirs
- **Electric vehicles (cars, buses, trucks) – charging can me made off-peak or with solar electricity**

EVs and the Smart Power System

- EV has the potential of providing flexibility as mobile load and source of energy storage
- Renewables may be complementary to electric vehicle charging
- Mass-market EV electrification requires an intelligent connection between the vehicle and the grid
- Smart charging is a cornerstone in the smart grid development benefiting the power system, EV drivers, consumers & society

Vehicle to Grid (V2G)

- Electric Vehicles can put their battery at the service of the balance between the generation and demand, functioning as a buffer that stores energy when there is generation surplus in the grid and the releases when there is a deficit, in an operation mode called Vehicle to Grid (V2G).
- Each EV will actively contribute to the stabilization of the electrical grid and the further penetration of renewable energy sources.



Source: CENEX

Review & Discussion

- Any questions?

Section 20

MSO Training Guideline

The MSO Training Cycle

The MSO Expert Training Programme

Why should people attend?

- Save the company money
- Personal skills development
- Internationally accepted assessment methodology
- Accredited qualification

What can people expect?

- Structured training programme
- Combination of class room and mentored experiential learning
- Practical individual assessment with full support from international trainers

What is required of participants?

- Interest in energy systems with appropriate background
- Access to a suitable site for practical experiential learning
- Total of 15 days spread over 8 months

Who should attend?

- Engineers and practitioners intending to become motor system assessment practitioners
- Persons who would like to become motor system trainers

MSO Certification Options

Attendance Certificate

- For participants who are interested in motors and would like to increase their knowledge in motor systems
- Attendance of at least 75% of total course

Expert Certificate

- For participants who intend to become active practitioners in the assessment of motor systems
- For participants who would also like to become motor systems trainers and facilitators

MSO Expert Certificate

Requirements:

- Attend the User training (2 day).
- Write and pass the User training class test achieving at least 70%.
- Attend the Expert training (5 day).
- Actively participate in the class discussions, practical demonstrations and presentations.
- Complete an individual MSO assessment at an industrial plant.
- Attend progress webinars as arranged wilst conducting the MSO assessment.
- 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.

MSO Trainers and Facilitators

Purpose

- To enable continued transfer of knowledge
- Local capacity building for self sustainability

Requirements

- **Training skills** – ability to engage and communicate with participants in a learning environment
- **Knowledge** – of subject matter, ability to think critically, analyse challenges and synthesise solutions
- **Attitude** – professional conduct and behaviour couple with ethics and values regarded by UNIDO

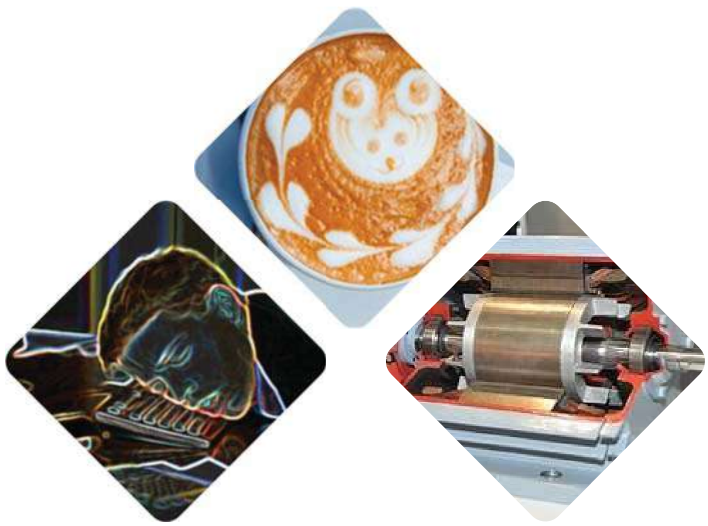
Any Questions?

Next Step: Start your own MSO journey

- At your plant or place of work or home
- Develop a list of motor systems & quantify energy consumption
- Identify the process / production requirements for each system
- Identify and implement suitable opportunities
- Make savings
- Consider your suitability to join expert programme

End of MSO User Training

Thank you for your participation



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