EE4502: Electric Drives & Control

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Learning Objectives and Outcomes

- Learning Objectives:
  - Understand about Electric Drive System.
  - Different components of an electric drive system.
  - Understand different types of drive systems and why Electric Drive amongst those preferred?
  - Understand the rational behind using variable or adjustable speed drive (VSD/ASD) system and why it is preferred?
  - Concept of energy conservation using VSD/ASD.
  - Electric drive a dynamic system.
  - Closed-loop operation.
  - Electric drive specifications.
- Learning outcome
  - You should be able to explain an electric drive system and how ASD/VSD is used for energy efficiency improvement in various industrial applications.

Introduction to Electric Drives

- **Electrical Machines** are electro-mechanical *energy converters* that convert:
  - ➢ electrical energy → mechanical energy (motors)
  - ➢ mechanical energy → electrical energy (generators)
- This process of energy conversion is called **electro-mechanical energy conversion**.

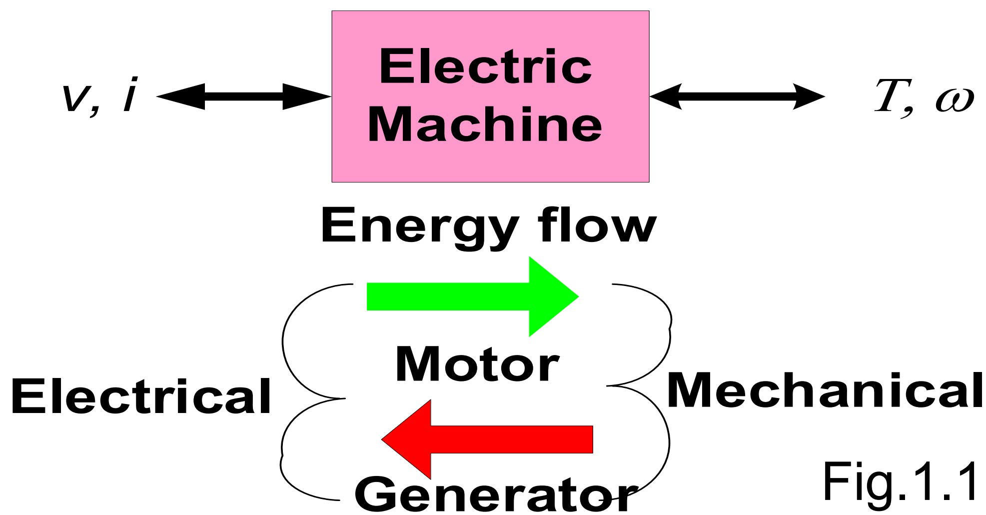
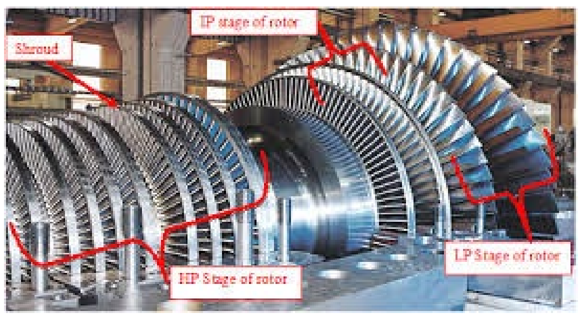


Fig.1.1: Electric machine

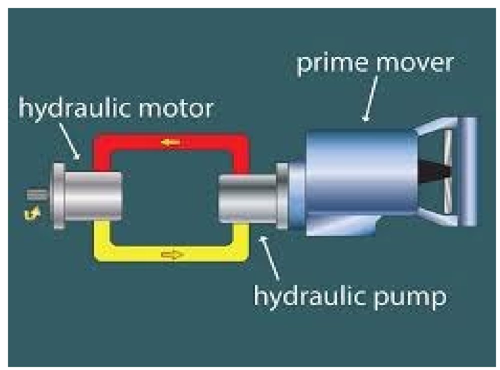
- Mechanical energy is used widely wherever physical activities are involved e.g. transporting people or goods.
- For any physical activity some form of motion is involved either in rotational or in translational (linear) form.
- **Motion control** is required for automation starting from home automation to office automation and leading to industrial automation.

- **Systems** employed for motion control are called **drives**.
- Drives are of different types and may employ different types of prime mover (that provides mechanical energy):
  - petrol/diesel engines in automobiles;
  - gas/steam turbines in power plants;
  - hydraulic actuators in earth digging apparatus and
  - electric motors in PMDs/EVs/HEVs/SMRT/LRT

for supplying mechanical energy to perform a given task.



Prime mover – Steam Turbine



- Drives employing electric motors as actuators/prime mover are called **electric drives**.

What is an Electric-Motor Drive System?

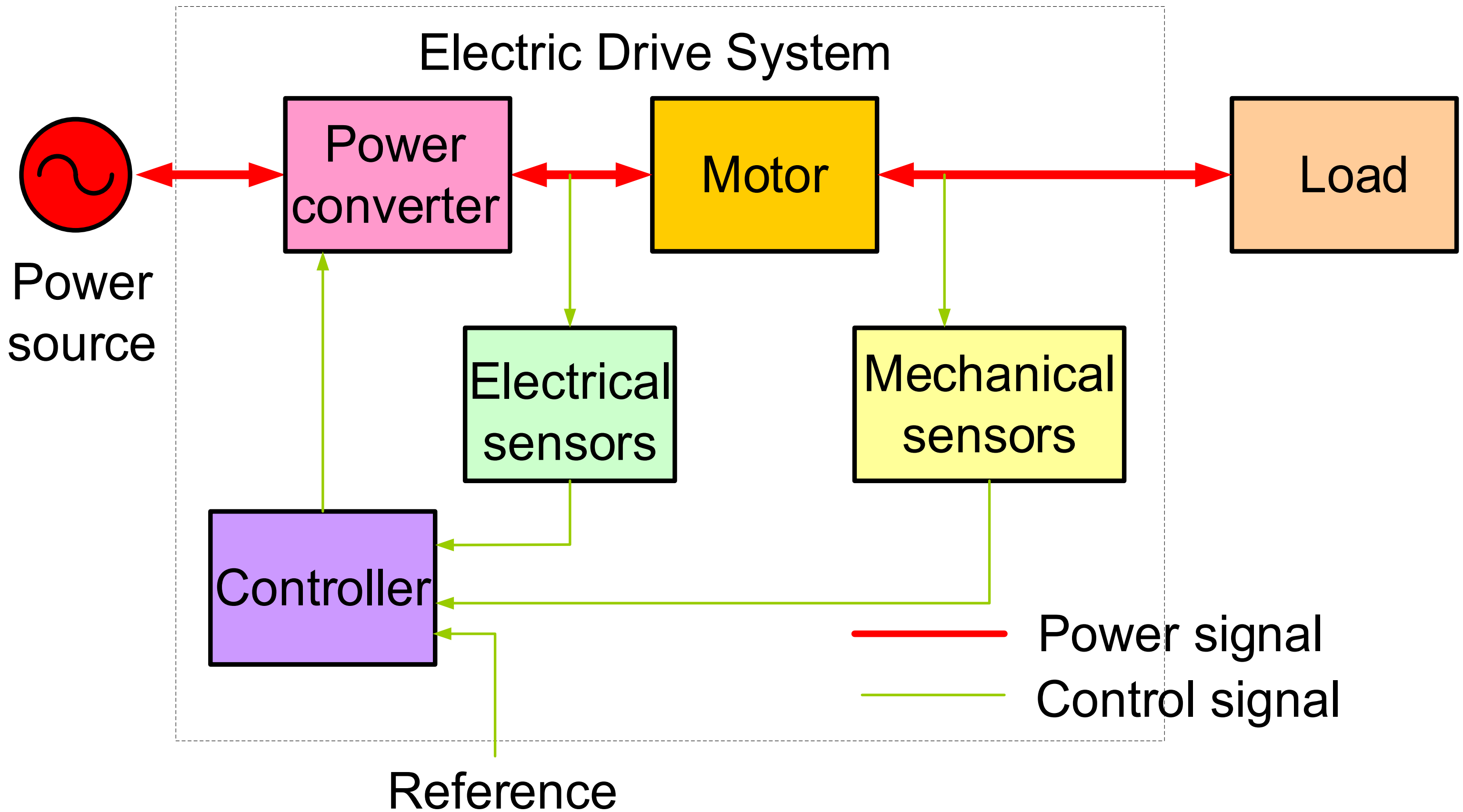


Figure 1.2: Electric drive system

- It is a "**system**" involving many different components as shown in Fig. 1.2 and the main role of electric drive system is – *efficient conversion* of electric energy to mechanical energy or vice-versa.

World Market & Growth Rate

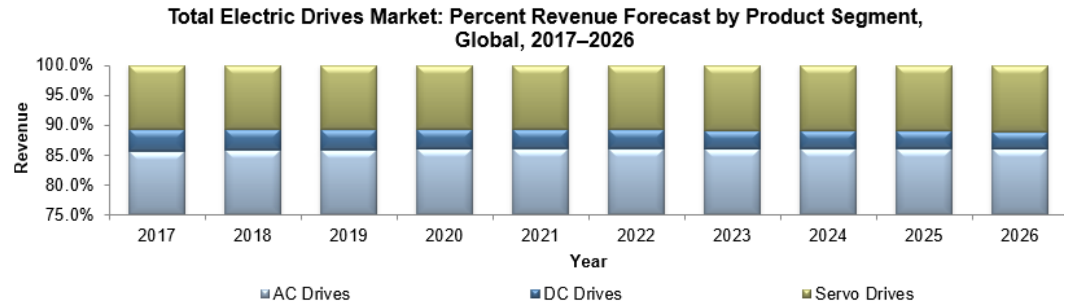
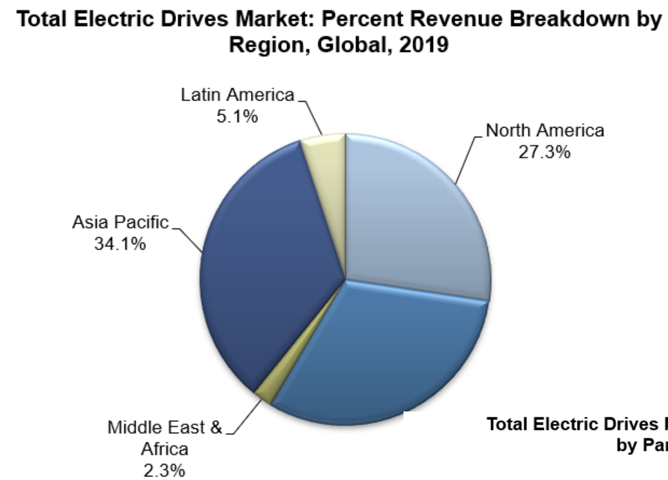


Fig.1.3



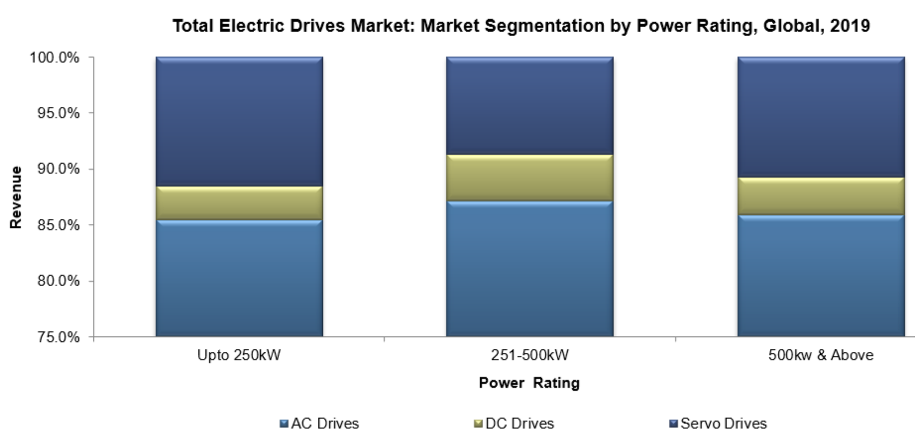
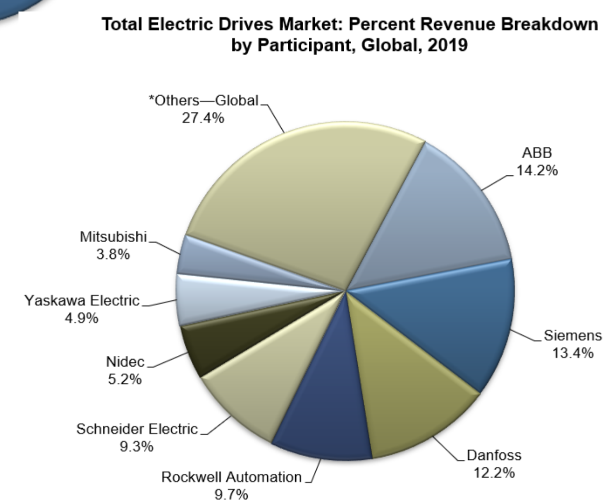


Fig.1.4



Why Electric Drives are Preferred?

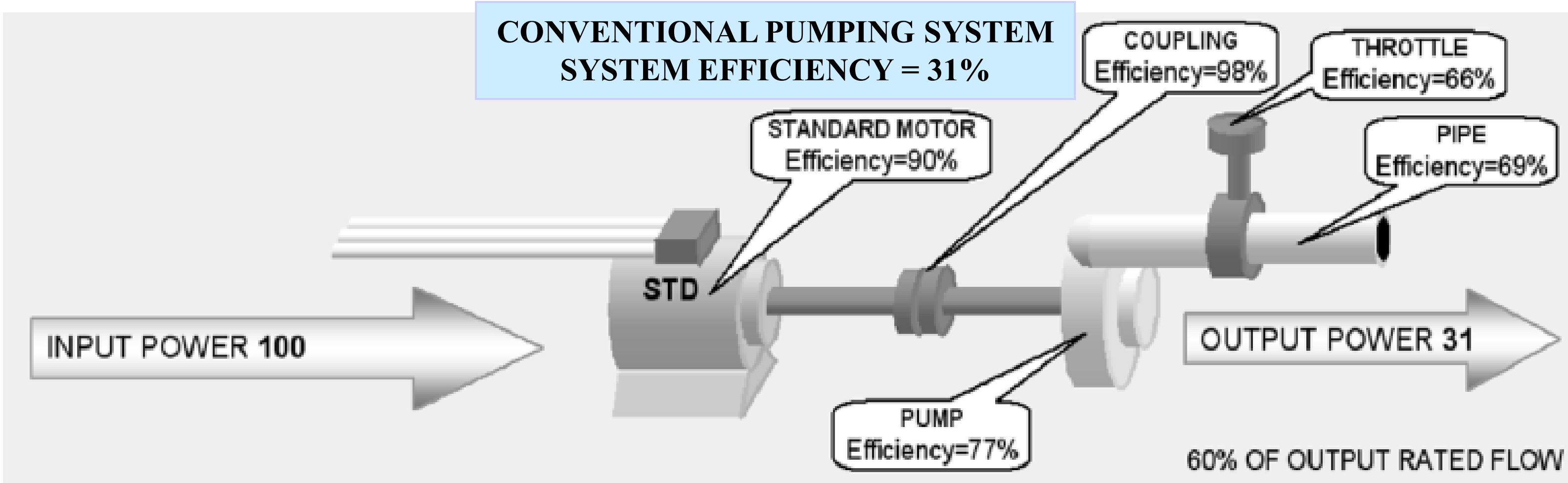
- **Advantages** :
  - they are available in any power from fraction of a watt in micro-motors (bacteria driven micro-motor) to MW (> 10^6 W) in driving pumps; (Siemen's Electric Drives Video)
  - they cover a wide range of power and speed: ~ 100 MW for rolling mill to > 80,000 rpm for centrifuge and spindle drives;
  - modern electric drives can be operated in any type of environment starting from radioactive to mines to semi-submersible drives for pumps for oil-gas extraction;
  - they produce very little noise (EVs) as compared to their counterparts (ICEs);
  - they can be operated almost instantaneously;

- ➢ they have much higher overall efficiency > 85% (for power > 2 kW);
- ➢ modern drives require almost no maintenance;
- ➢ they can be easily controlled and their characteristics (torque-speed) can be easily altered to meet the load demand and
- ➢ they can be operated indefinitely in all the four quadrants of the torque-speed plane.

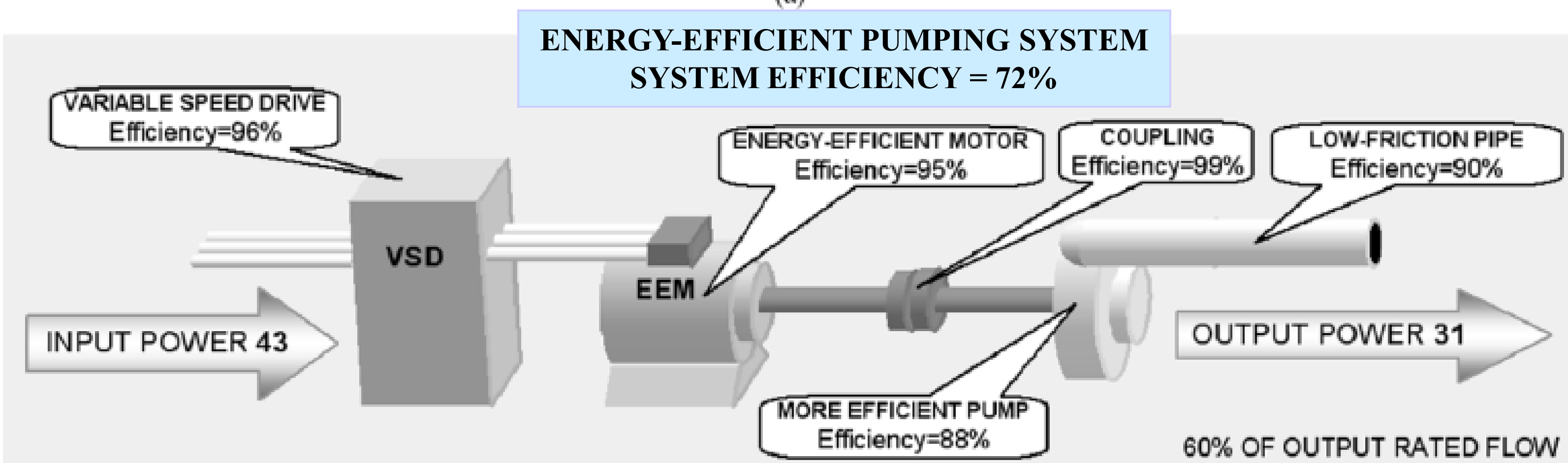
- **Disadvantages** are:
  - ✓ they require continuous supply of electric power, and
  - ✓ due to magnetic saturation and thermal problem they provide a lower power-weight ratio.

- Most of the electric drives run at constant speed e.g. escalator, travellators, hard-disk drive etc.
- Some specific applications e.g. PSA quay crane drives, reversing rolling mill drives, traction drives, servo drives require variable speed as well as variable load (torque) operation.
- **Why variable speed drive operation is needed**?
  - o needed by the process (regulating the flow of water(pumps) or air (fans))
  - o energy saving aspect (pumps, fans and air-conditioners)
  - o improvement in product quality (air-conditioners – precise temp. control)
- As of today only about 20-25% of electric drives are of variable speed type but the trend is to increase the use of variable speed drives for energy savings for environmental concerns.

- # Energy Savings:
  - In centrifugal pumps and fans driven by constant-speed motors, automatic throttle valves or other mechanical means such as dampers are used to vary the flow rate.
  - If variable speed drives (VSD) are used, the motor speed can be controlled electronically to vary the flow rate resulting in significant electric energy savings.
  - In a pump
    - Volume of flow (Q) is **directly** proportional to the motor speed, ω_m
    - Pressure head (H) is proportional to **square** of the motor speed, ω_m^2
    - Input power ($P_{in} = H \times Q$) is proportional to the **cube** of the motor speed, ω_m^3
  - If flow rate, Q is reduced by 50% then the motor speed, ω_m is reduced to 50%, resulting in pressure head dropping to ($(1/2)^2$ = 25%) leading to input power, P_{in} required is only $(1/2)^3$ ~ 12.5% of that required for 100% flow rate.



(a)



(b)

Fig.1.5 3. Two pumping systems with same output. (a) Conventional system. (b) Energy-efficient pumping system combining efficient technologies.

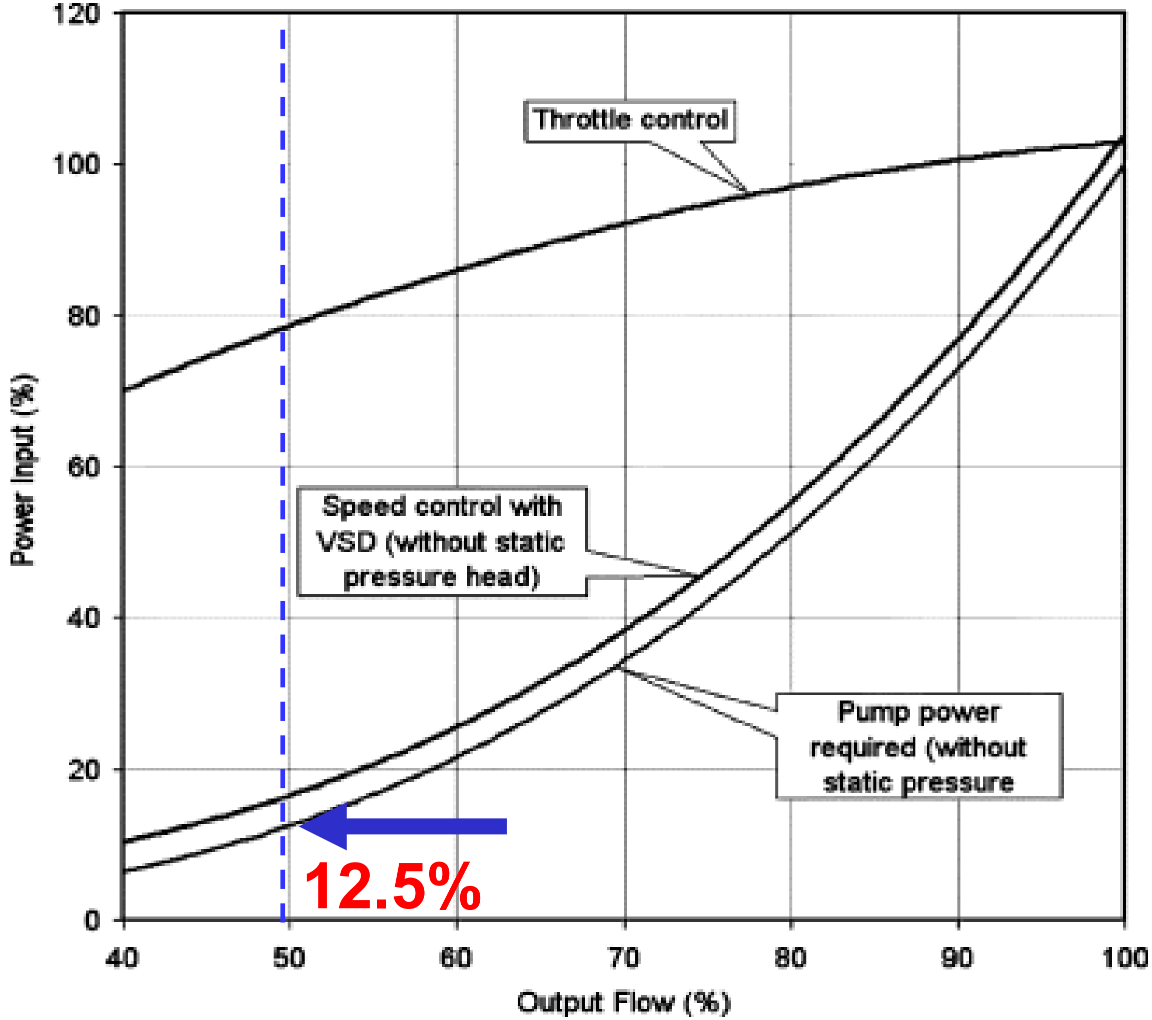


Fig.1.6 Input power for different flow control methods for a centrifugal pump

Typical Applications

- Process industry – pumps, fans, compressors
- Heating and air-conditioning – blowers, chiller plant
- Paper & Steel industry – hoist, rollers
- Transportation – PMDs, elevators, trains, automobiles, more and more electric aircrafts, full electric or hybrid ship propulsion…
- Food industry – conveyer, fans
- Oil, Gas, Mining – compressors, pumps, cranes, thruster drive for oil-rig platforms…
- Residential – heat pumps, freezers, washing machine, grinders, food processors, air-conditioners, hair drier, HDD, DVD/VCD…

Energy Conservation in Pumps

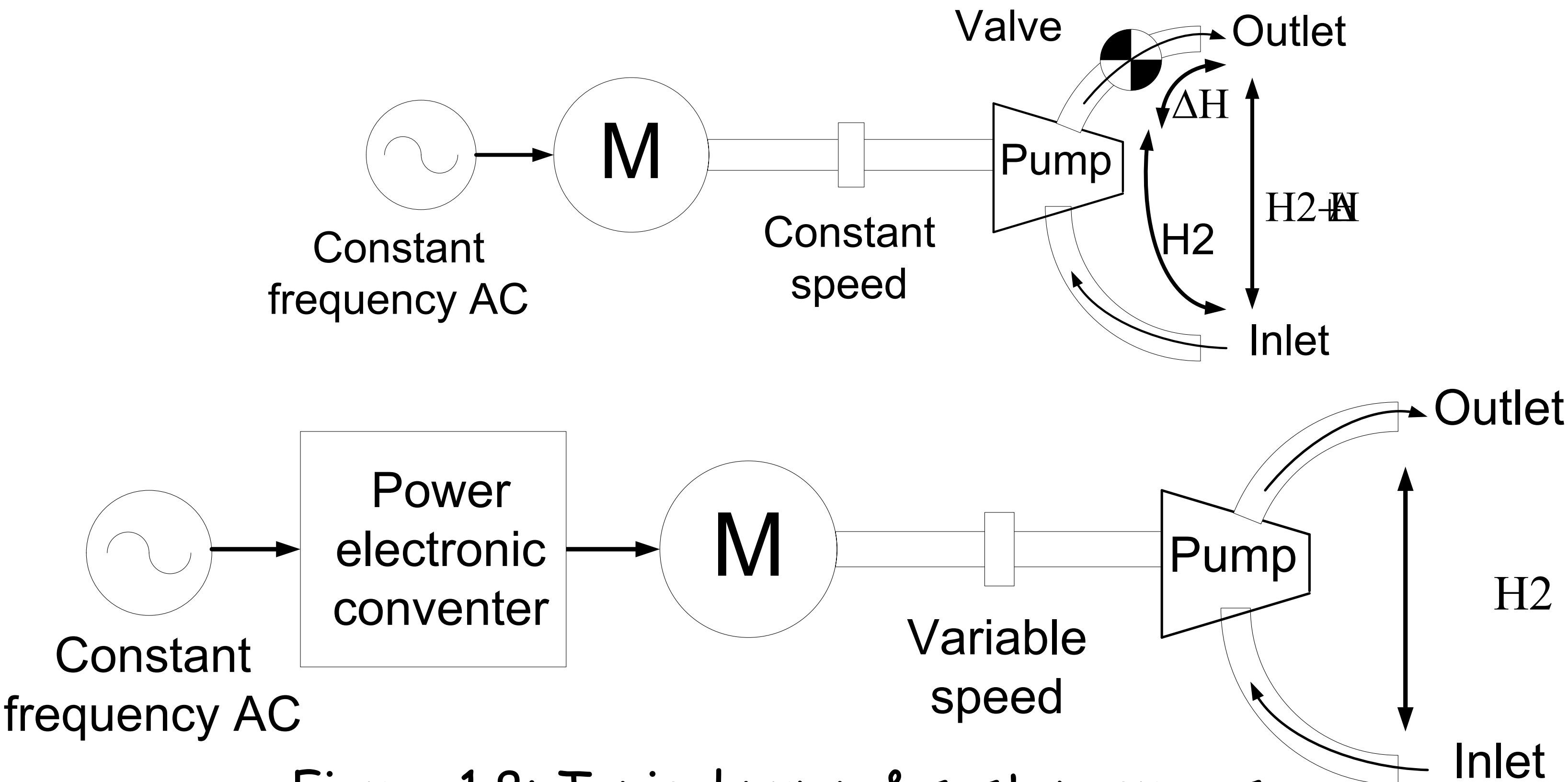


Figure 1.8: Typical pump & system curves.

- Throttling introduces an additional pressure head drop, *ΔH* across the throttle valve.
- Adjustable speed drives (ASD) reduces pump speed to match the load requirement.

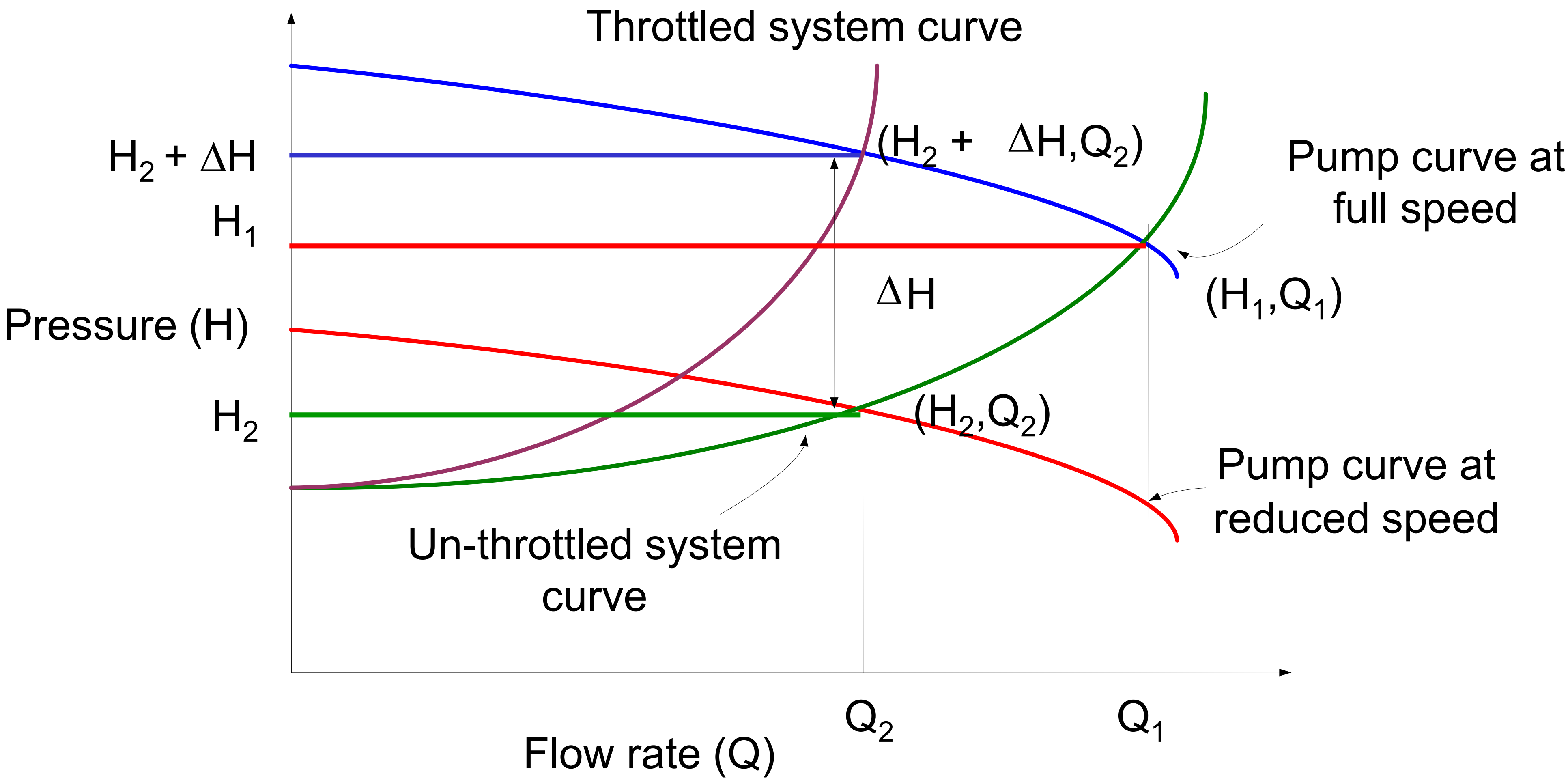
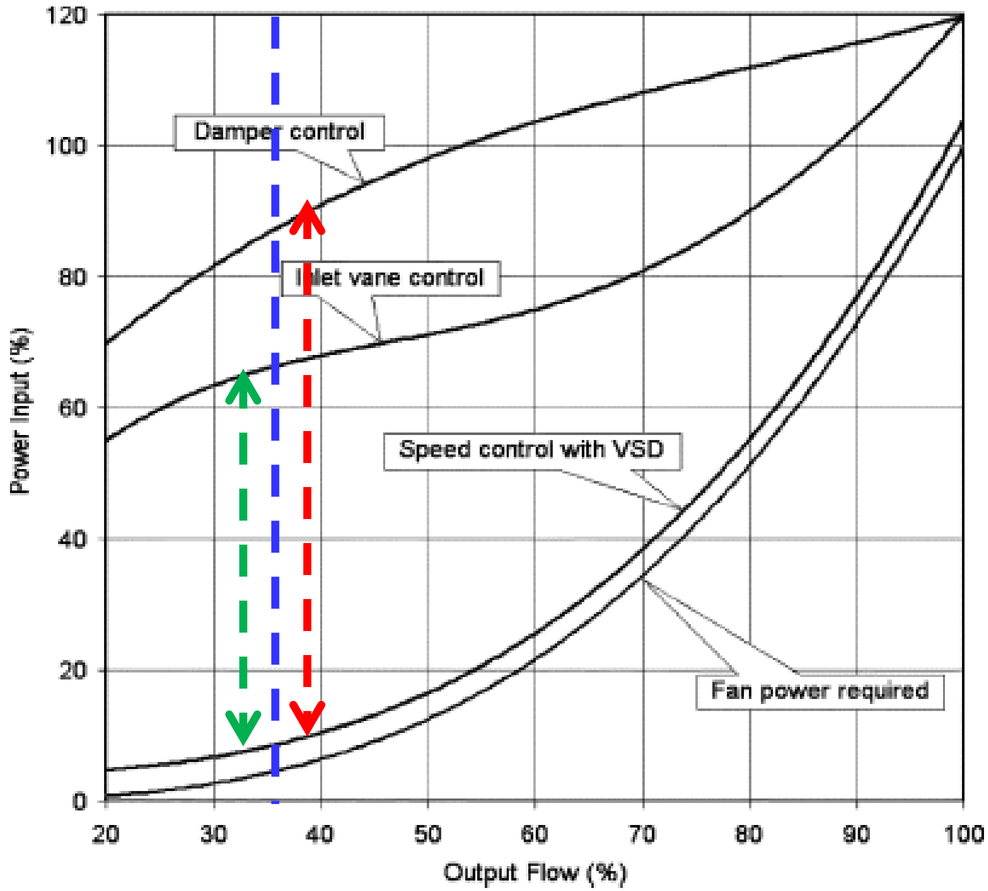


Figure 1.8(b): Typical pump & system curves.

Energy Conservation in Blower Systems



https://www.youtube.com/watch?v=H8nEFMsxKjQ

Figure 1.9: Power consumption in a blower

❑ Large amount of energy is wasted by throttling the air flow using either a damper or inlet vane control versus using ASD .

Hybrid Electric Vehicles

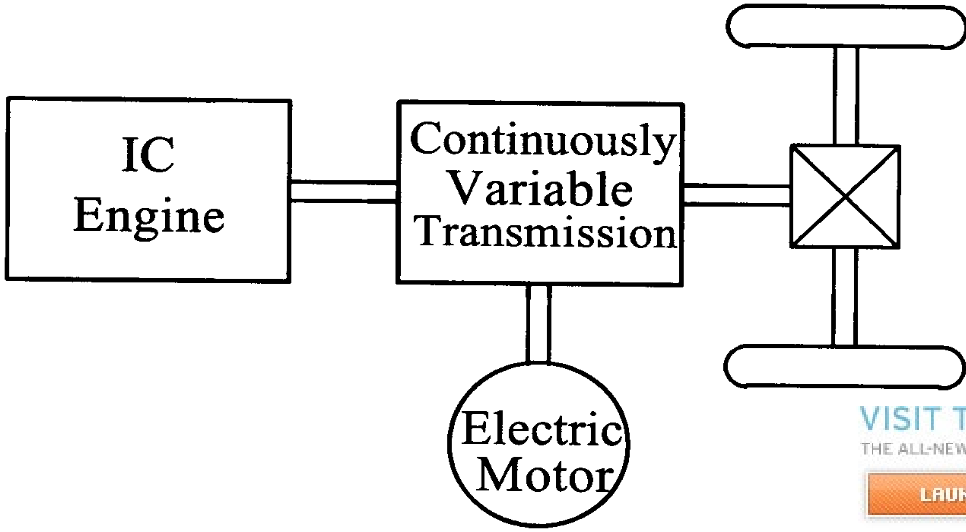


Figure 1.10: Hybrid electric vehicle

♣ Hybrid EV reduces fuel consumption by more than 50% as compared to internal-combustion-engine (ICE) vehicles.

Energy in Transportation Sector

- Most of the present transportation system is not sustainable – dependence on fossil fuel.
- There is a need for an evolving paradigm shift (electrification) in the transportation sector towards more efficient, more reliable, safer, smarter, and high-performance vehicles that are more environmentally friendly.
- Electrification can be applied to both propulsion and non-propulsion systems.

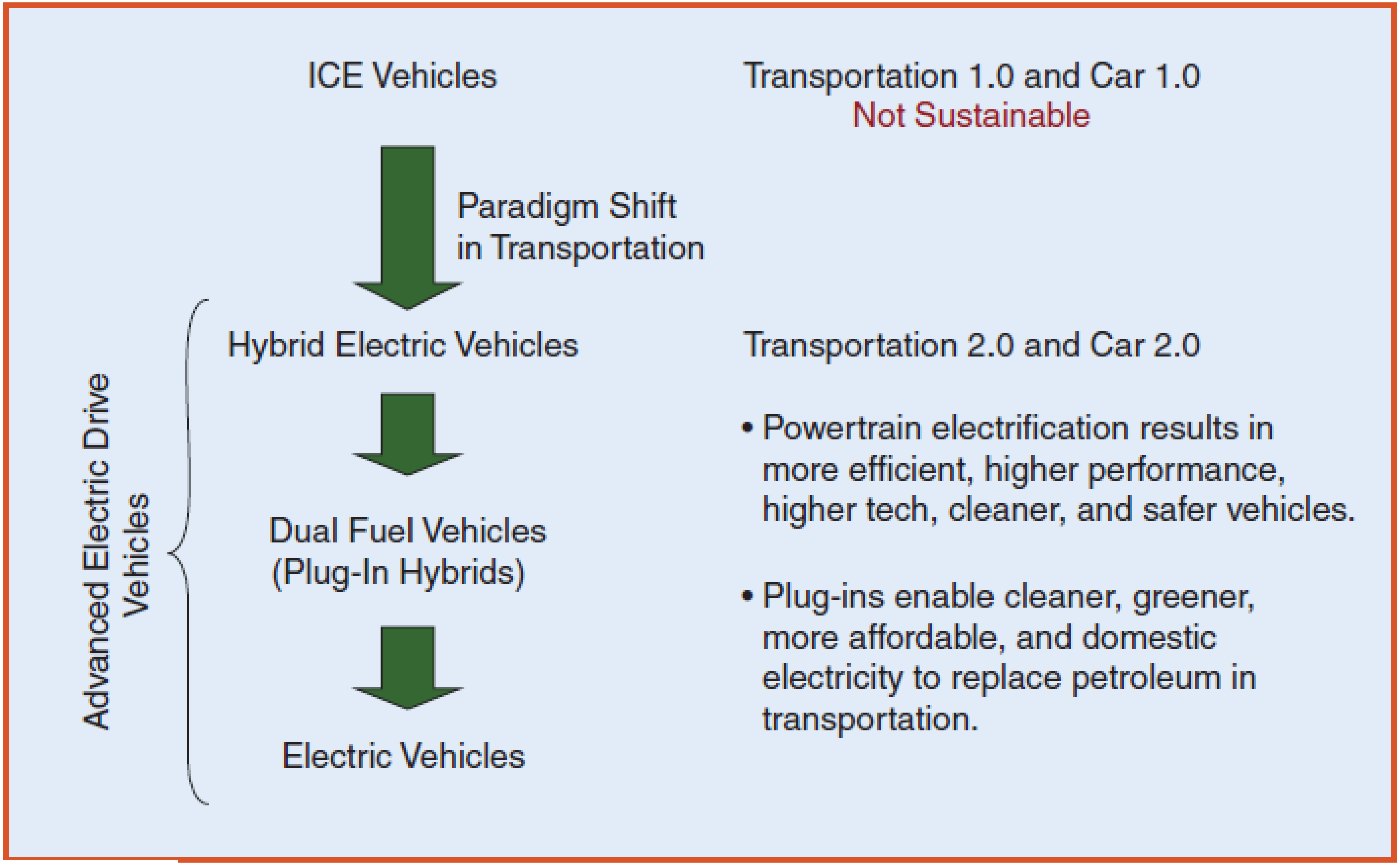


Fig. 1.11 The paradigm shift in transportation, from ICE vehicles to advanced electric-drive vehicles.

HEVs: Establishing the Paradigm Shift

- HEVs can be series, parallel or series-parallel.

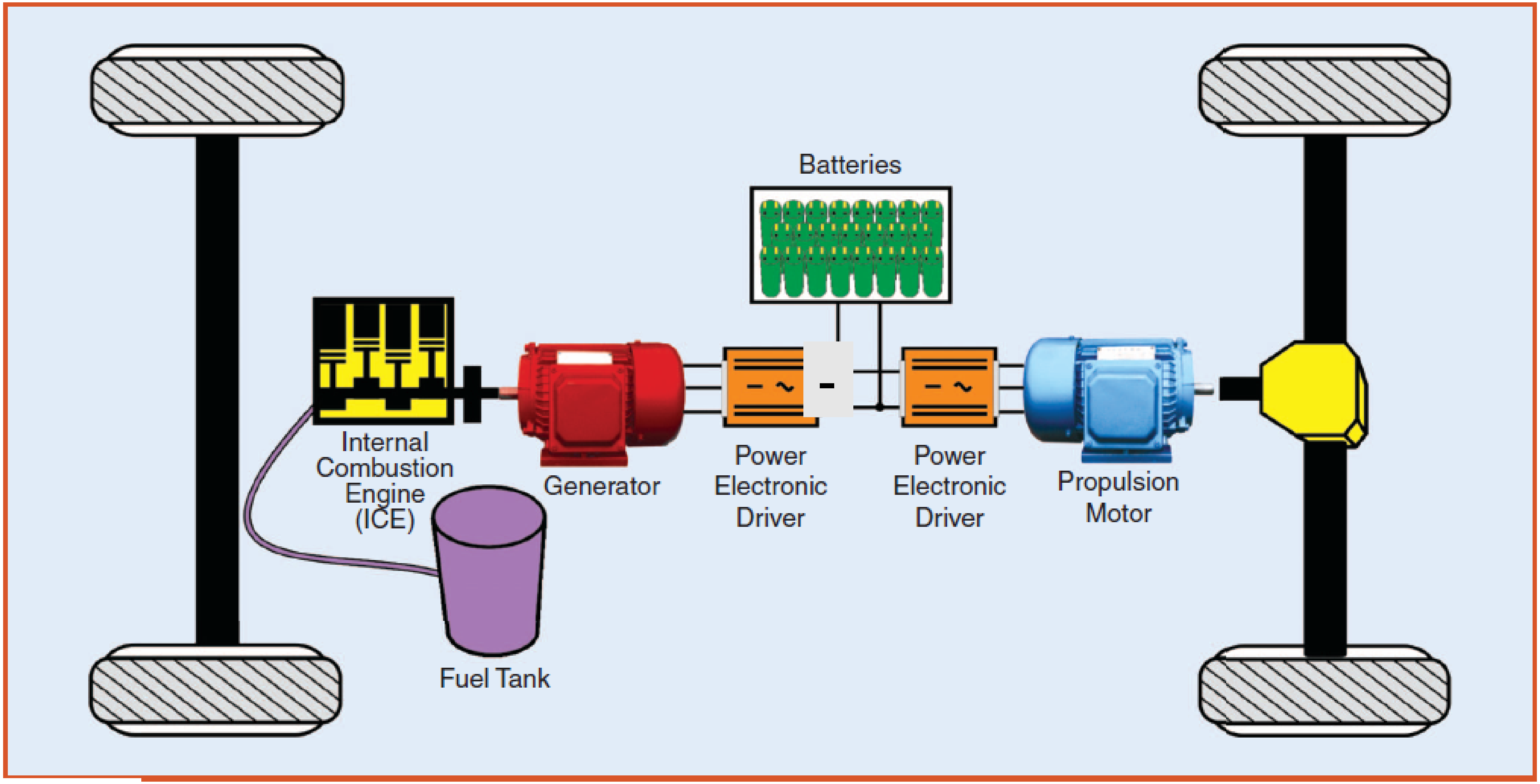


Fig. 1.12 A hybrid electric vehicle with a series hybrid power train.

- In parallel hybrid both ICE and motor share power.

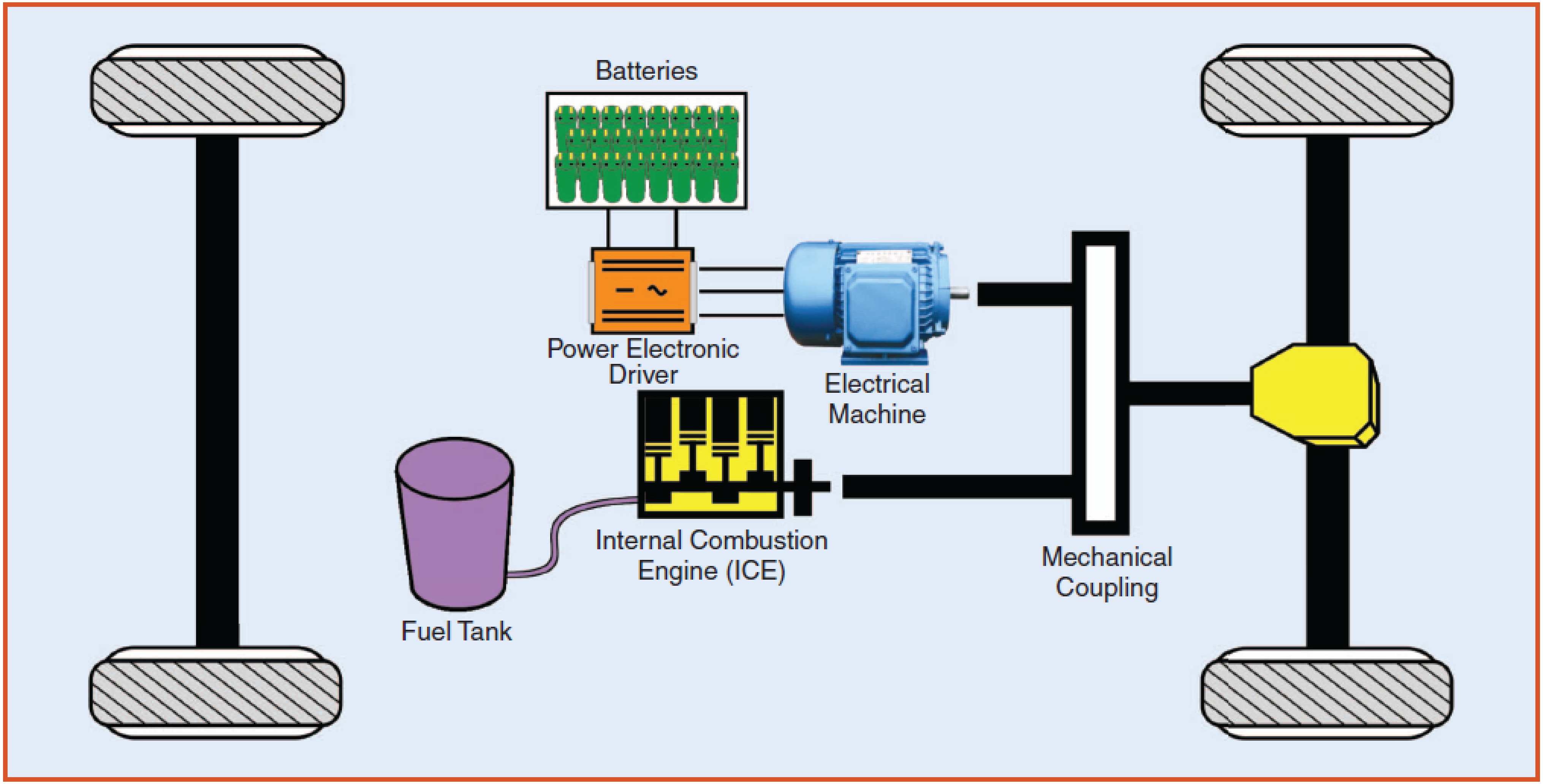


Fig. 1.13 A hybrid electric vehicle with a parallel hybrid power train.

- In series-parallel hybrid two electrical machines are used and they provide both series as well as parallel paths.

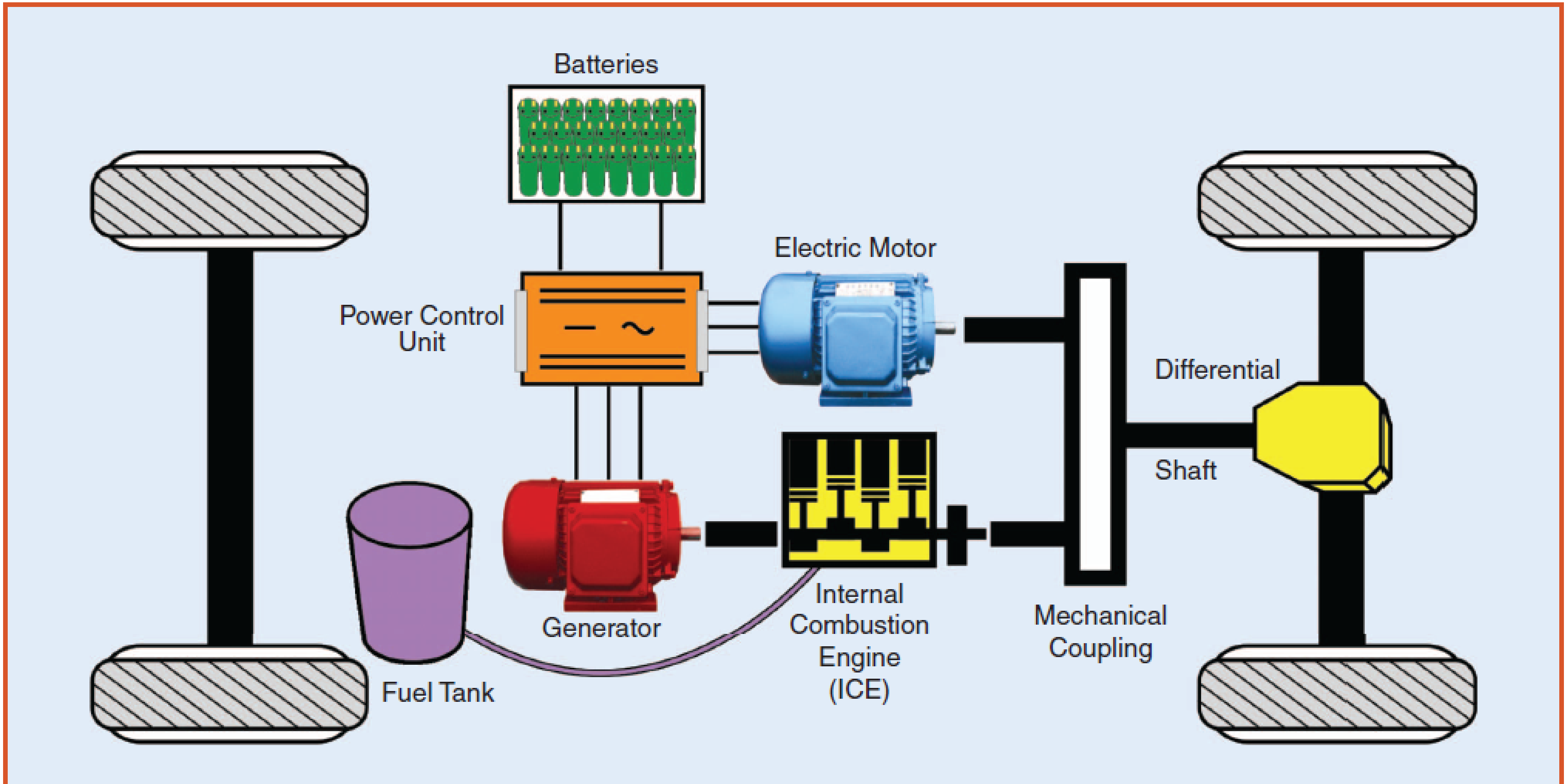


Fig. 1.14 A hybrid electric vehicle with a series-parallel hybrid power train.

- HEVs whether series or parallel provides the following benefits:
  1. Electric propulsion motors are more efficient and faster than mechanical, hydraulic, and pneumatic systems.
  2. The internal combustion engine can be operated at a higher-efficiency operating region because of the flexibility provided by the electric propulsion system.
  3. Hybridization enables vehicles to take advantage of regenerative braking.

PHEVs: Giving Momentum to the Paradigm Shift

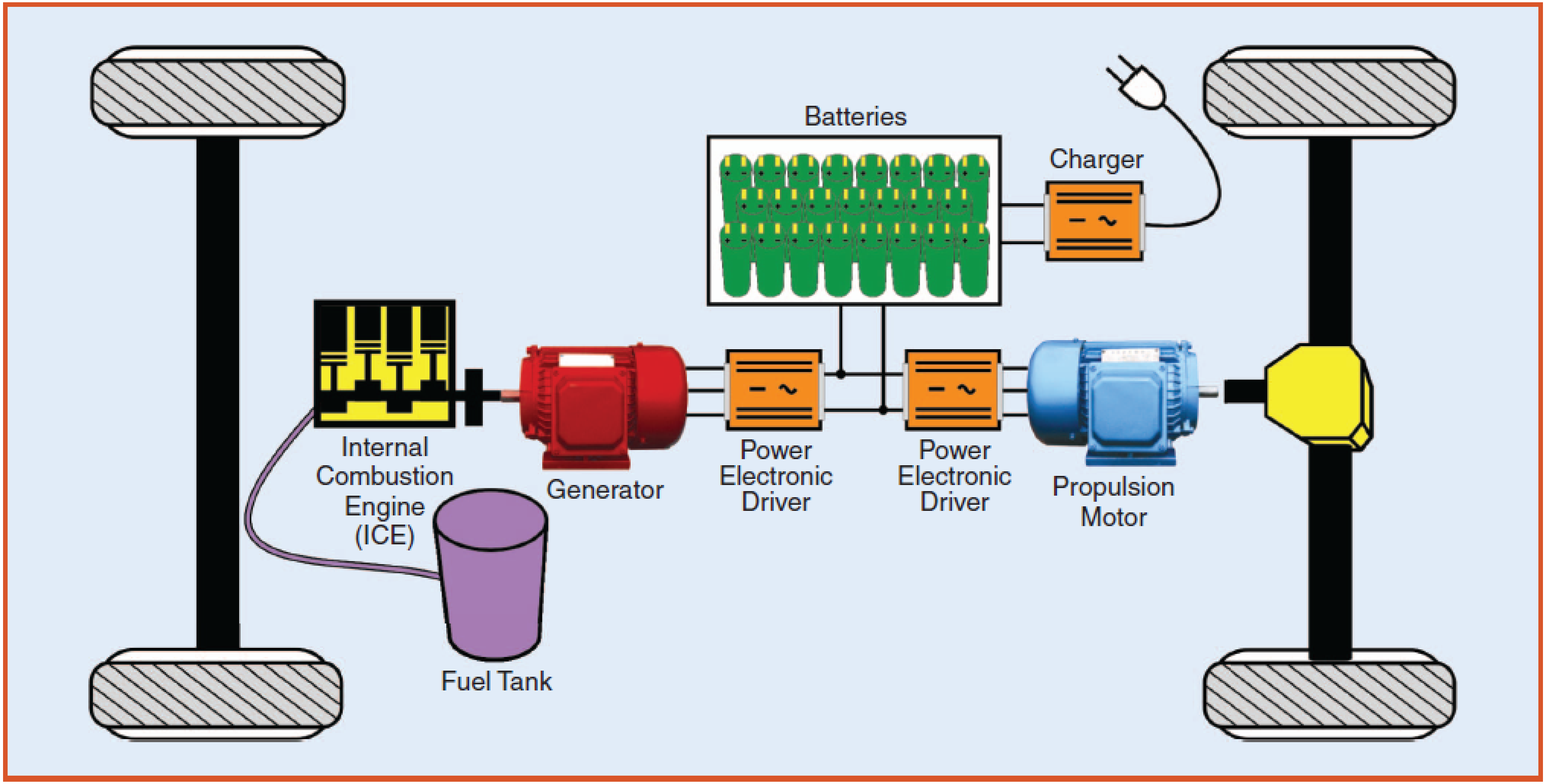


Fig. 1.15 A plug-in hybrid electric vehicle with a series hybrid power train.

- PHEVs have a high-energy-density storage system that can be externally charged; they can run solely on electric power longer than regular hybrids, resulting in better fuel economy.
- PHEVs improve the utilization of utility power because their batteries are typically recharged overnight.
- The energy storage system can be charged on-board the vehicle or externally through the utility grid, thus increasing the vehicle's range when operating in all-electric mode.

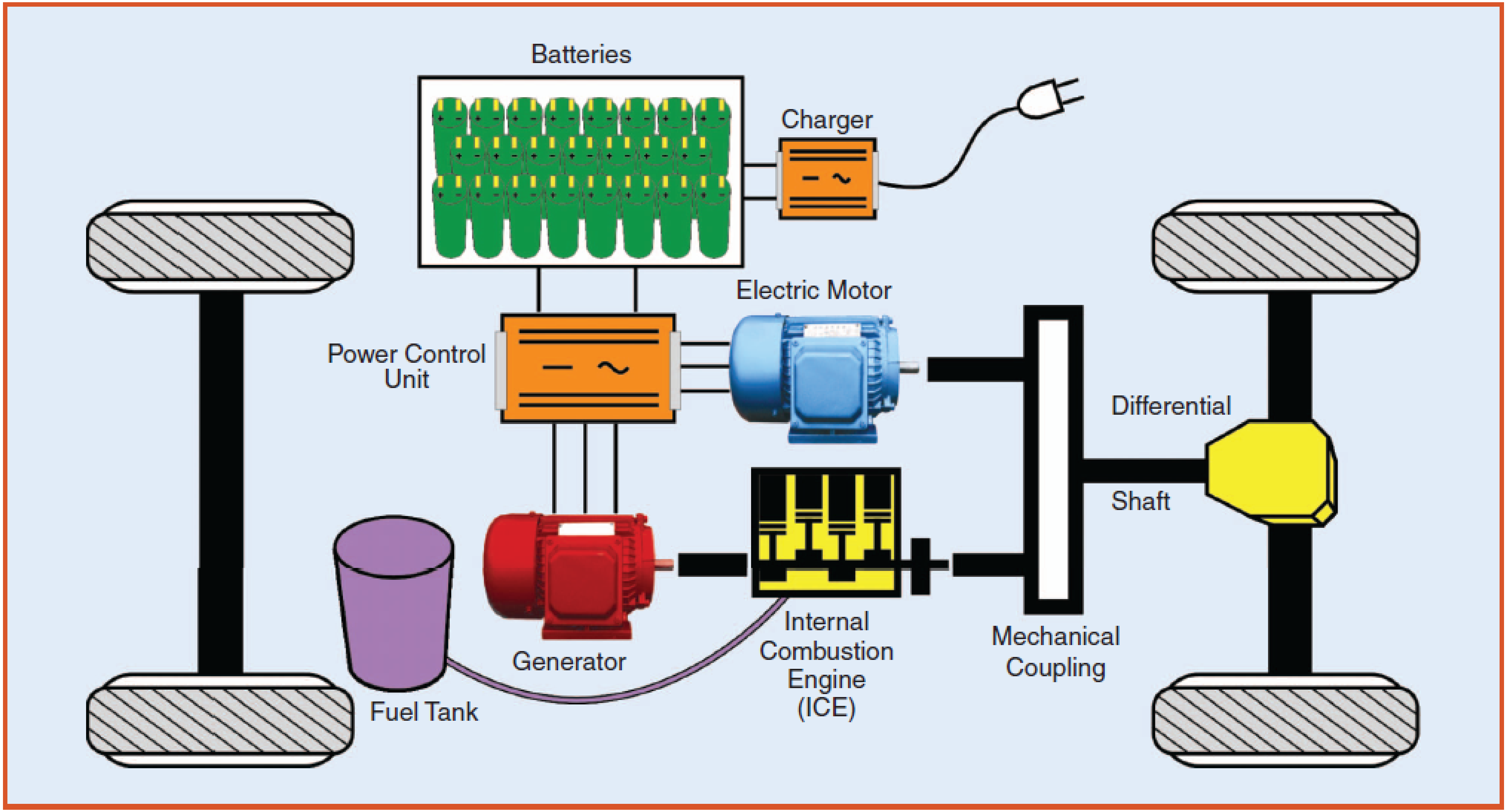


Fig. 1.16 A plug-in hybrid electric vehicle with a series-parallel hybrid power train.

EVs: Completing the Paradigm Shift

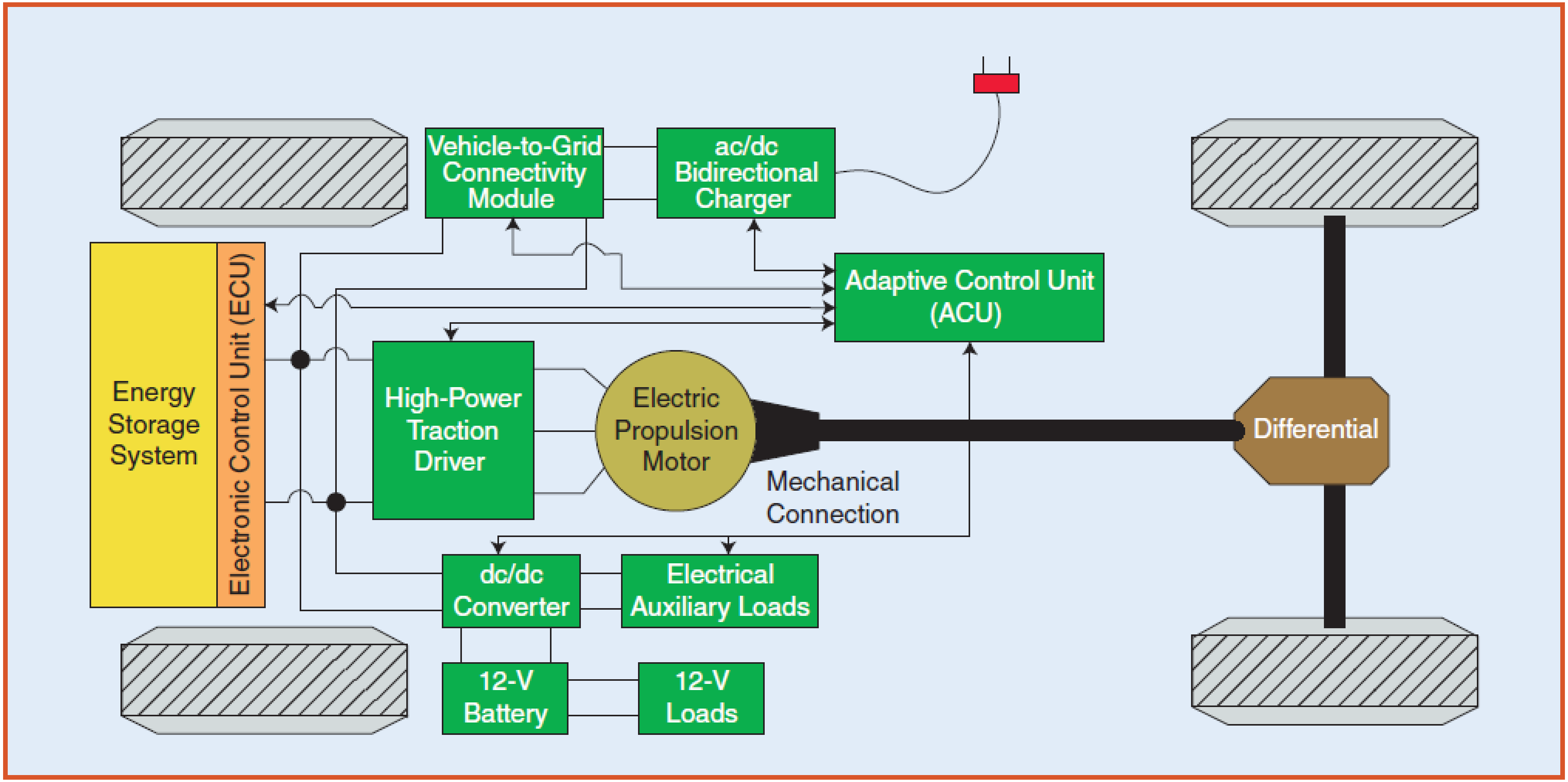


Fig. 1.17 An all-electric power train with the ACU designed by HEVT.

Electric Ship Propulsion System

- Motivation for electric propulsion system is:
  - to conserve fuel in ships that must operate over a wide speed range;
  - need to implement applications where the non-propulsion power requirements are very high and
  - integration of power system with propulsion system.

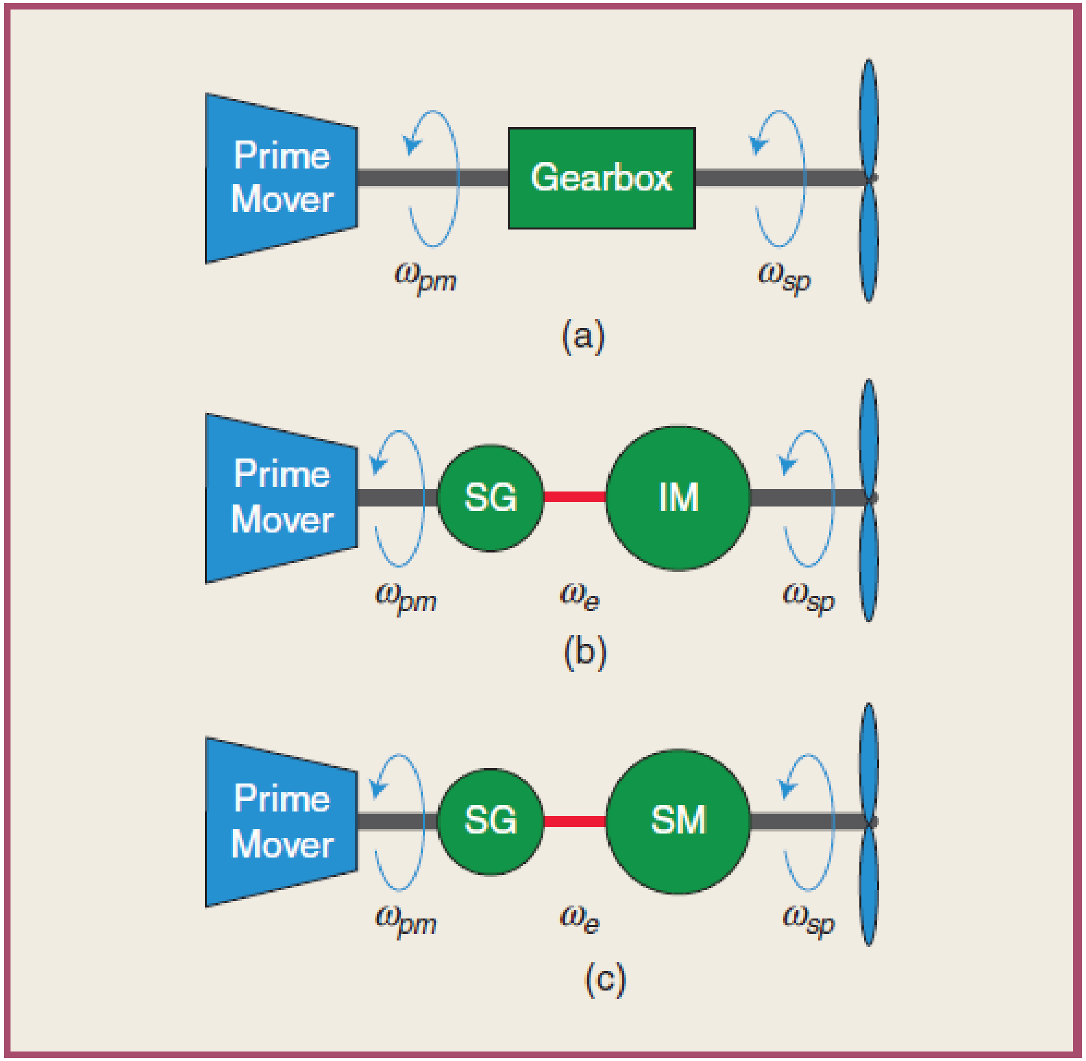


figure 1. Early ship propulsion systems: (a) mechanical drive propulsion, (b) induction motor propulsion, and (c) Fig. 1.18 ɪs motor propulsion.

SG – Synchronous generator

IM – Induction motor

SM – Synchronous motor

- Size of IM & SM > SG
- $P_{SG,\ IM,\ SM}$ – Number of poles

$$\omega_e = \omega_{pm} \times \frac{P_{SG}}{2},$$

$$\omega_e = \omega_{sp} \times \frac{P_{IMorSM}}{2},$$

$$\frac{\omega_{sp}}{\omega_{pm}} = \frac{P_{SG}}{P_{IM\ or\ SM}}$$

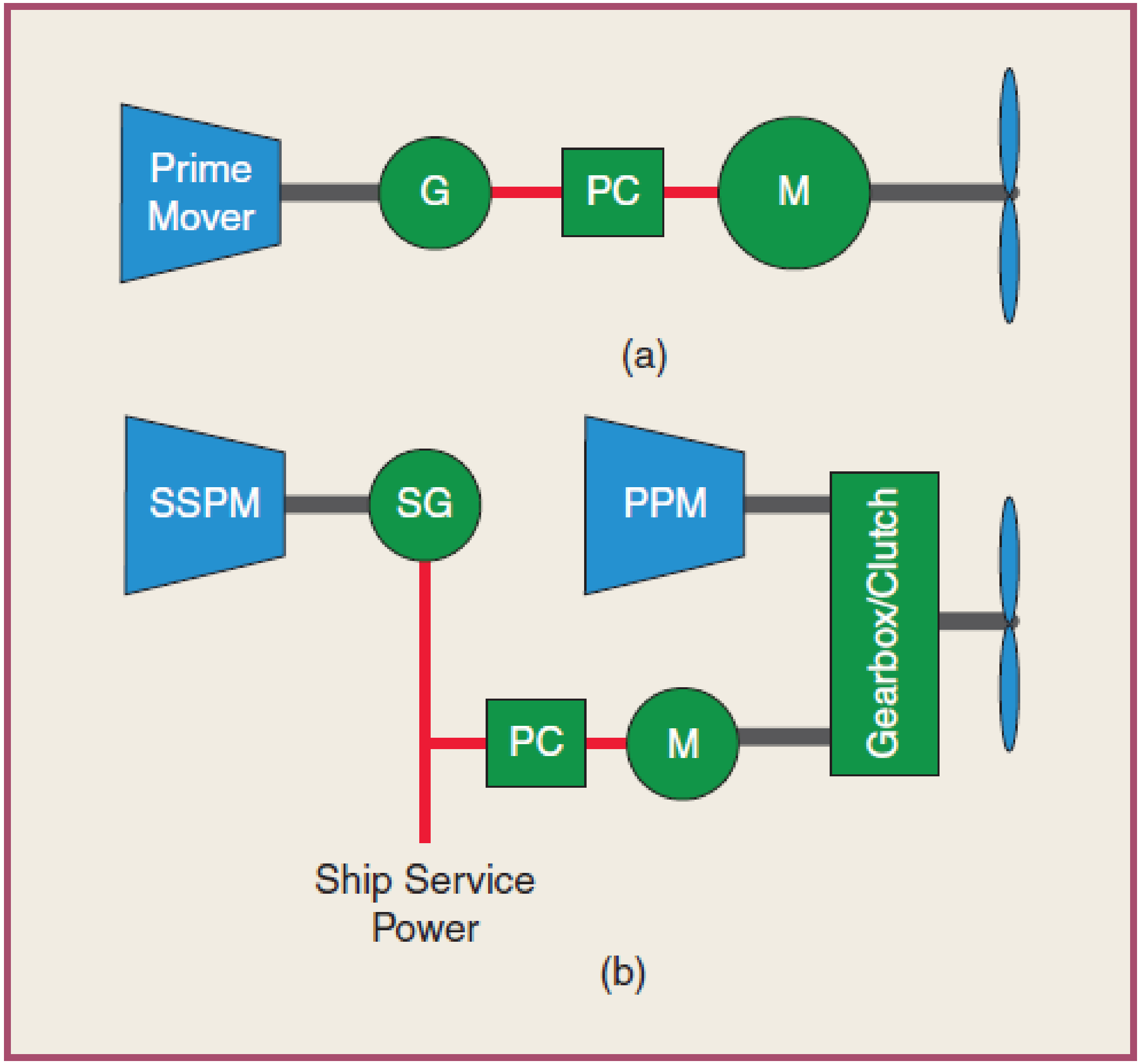


Fig. 1.19 Contemporary ship propulsion systems: (a) full electric and (b) hybrid electric.

G – Generator
M – Motor
PC – Power Converter
PM – Prime Mover
SSPM – Ship Service PM
PPM – Propulsion PM

- The power converter (PC) in full-electric and hybrid-electric drive decouples the generator's electrical frequency, ω_e from that of the motor and hence the propeller, ω_{sp}.
- Besides fuel efficiency and shipboard power, a secondary advantage of electric ship technology is the architectural freedom it offers the ship designer, since it is no longer necessary to have the prime mover aligned with the ship's propellers.

Electric Aircraft Systems

- Large transport airplanes require several MWs of power, and employ fully autonomous power generation, management and distribution systems powering flight-critical systems and functions.

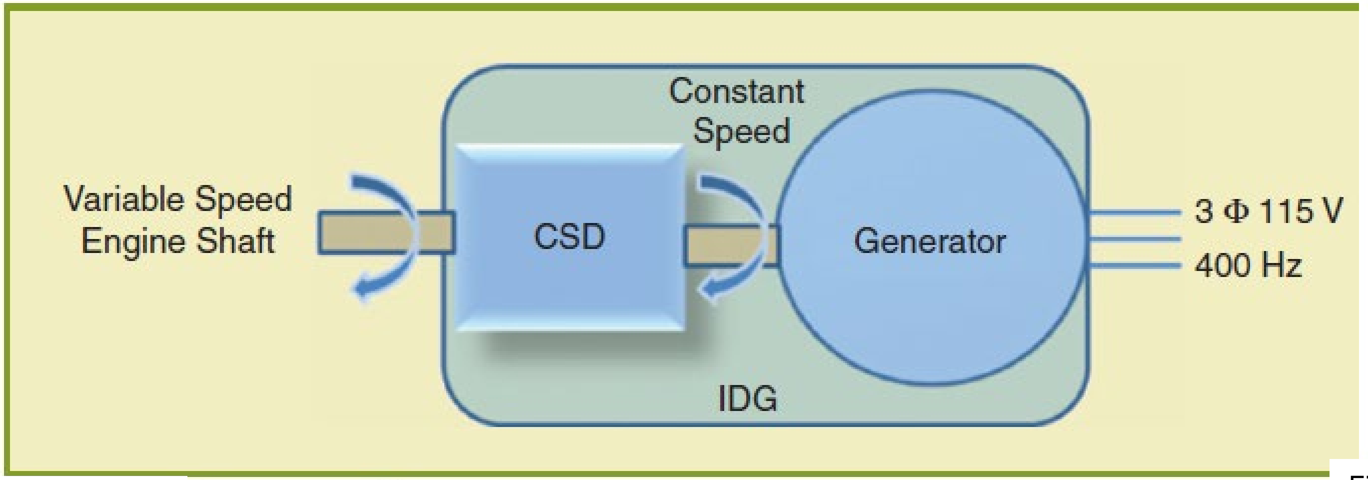


Fig. 1.20 The CSD and IDG concept.

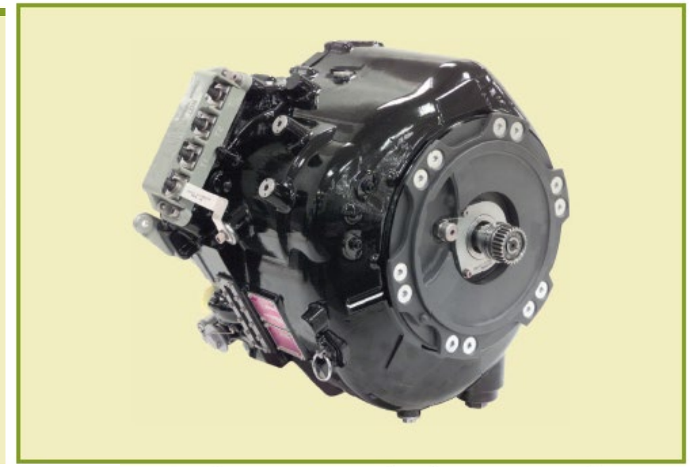


Fig. 1.21 . A 120-kVA IDG. (Used with permission from Hamilton Sundstrand.)

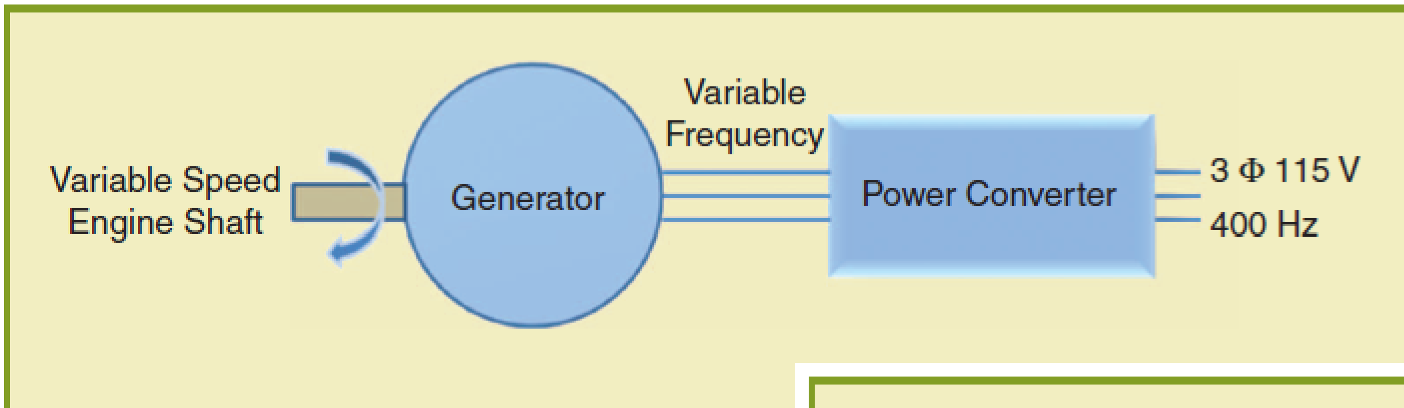


Fig. 1.22 The VSCF concept.

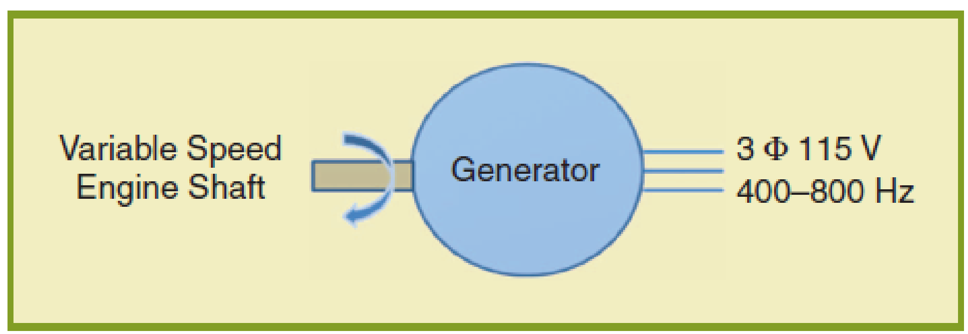
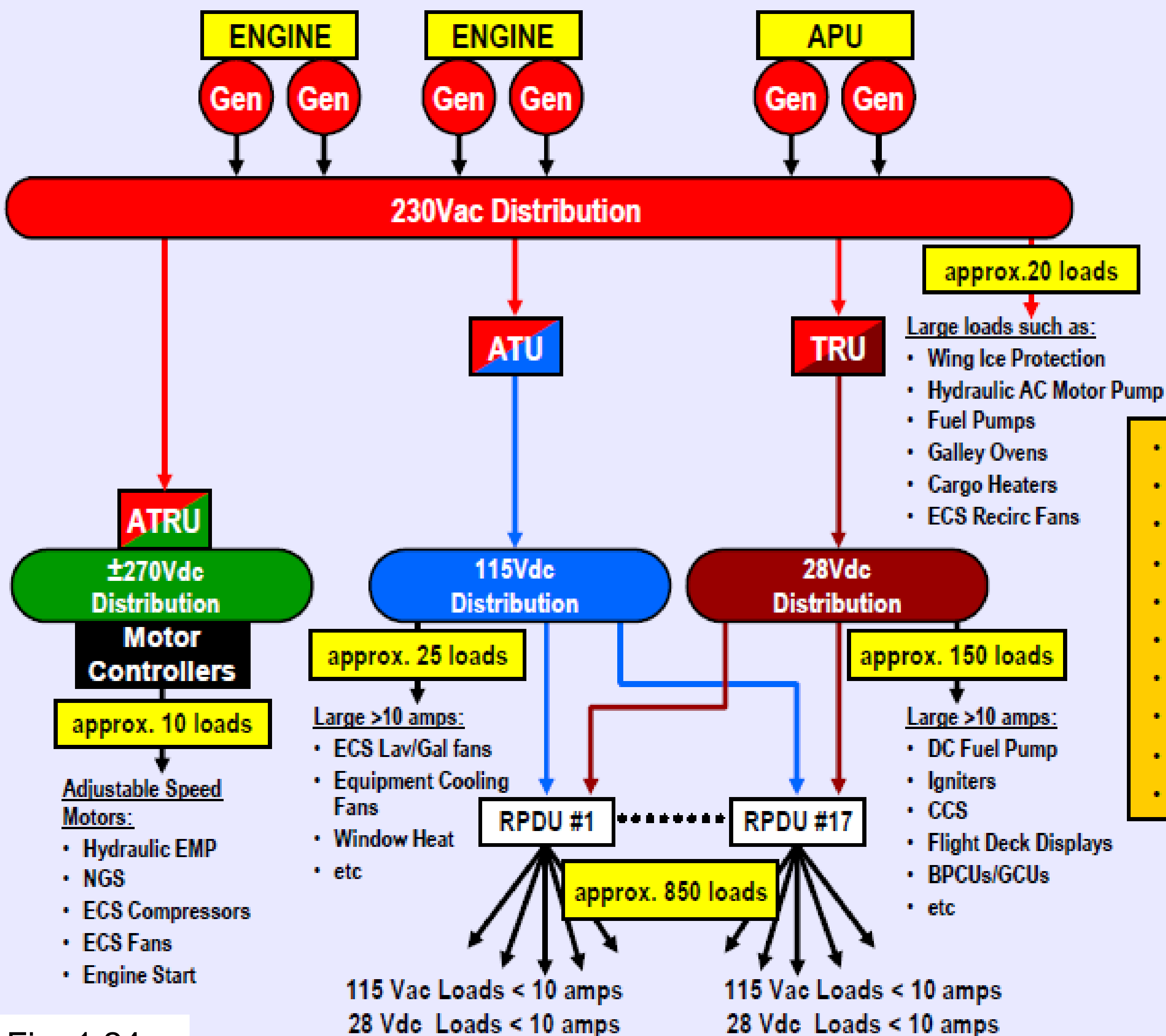


Fig. 1.23 A variable-speed VF generator.

Electrical Systems Overview



- ATRU – Auto Transformer Rectifier Unit
- ATU – Auto Transformer Unit
- TRU – Transformer Rectifier Unit
- NGS – Nitrogen Generating System
- EMP – Electric Motor Pump
- ECS – Environmental Control System
- RPDU – Remote Power Distribution Unit
- CCS – Common Core System
- BPCU – Bus Power Control Unit
- GCU – Generator Control Unit

Fig. 1.24

- Some new airplanes have been designed with variable-frequency (VF) systems running at 400 – 800 Hz, taking into account engine’s wide speed range from take-off to idle speeds.
- The concept of VF system is to shift the frequency conversion stage to the load.
- Electric power is supplied from different sources to the loads by the electrical power management and distribution system, which is composed of primary and secondary power distribution systems producing three-phase AC at 230 V or 115 V and 28 V DC power.

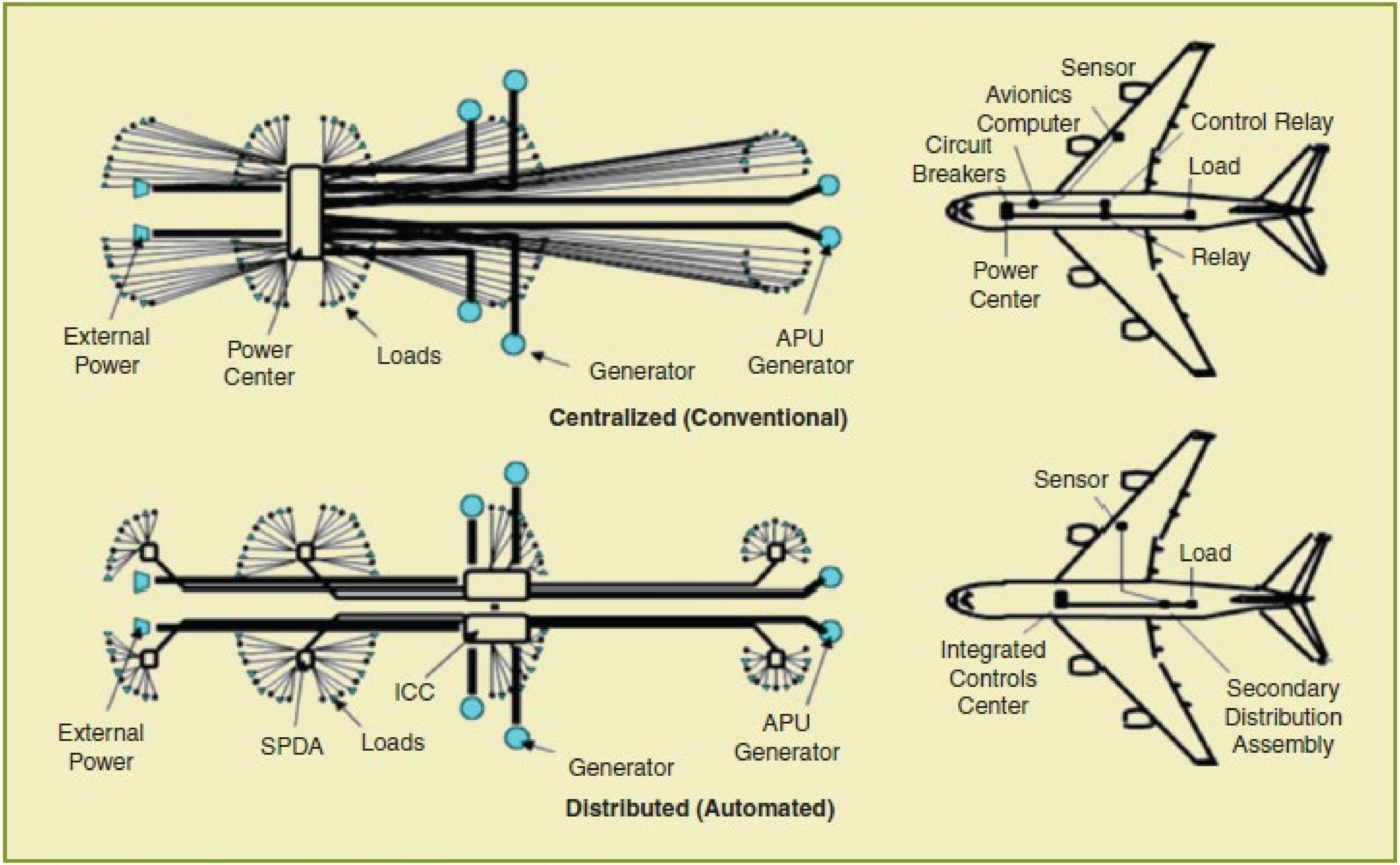


Fig. 1.25 The secondary power distribution system.

Harnessing Wind Energy

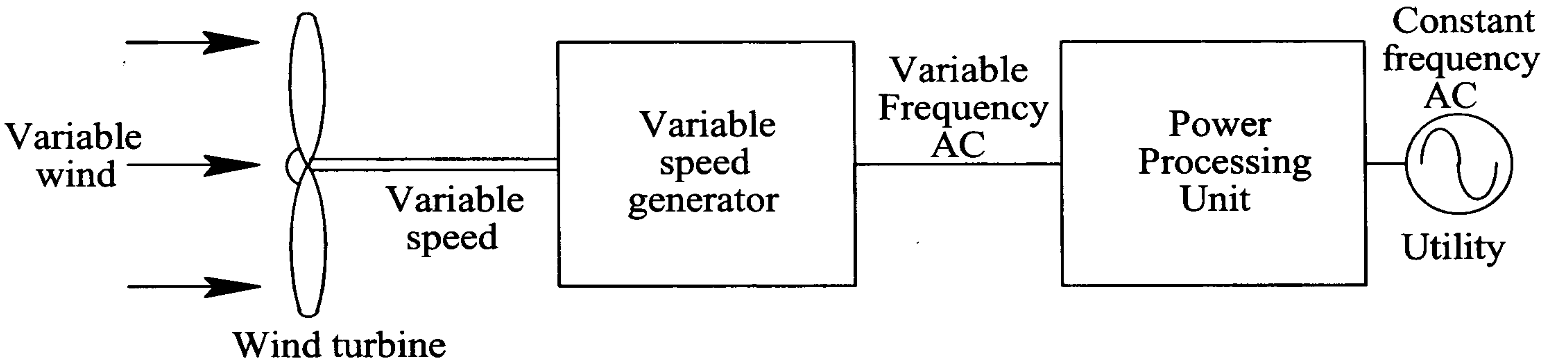


Figure 1.26: Electric drive for wind generator

Cost Benefits of AC Drives

- Consider a motor below 2.2 kW.

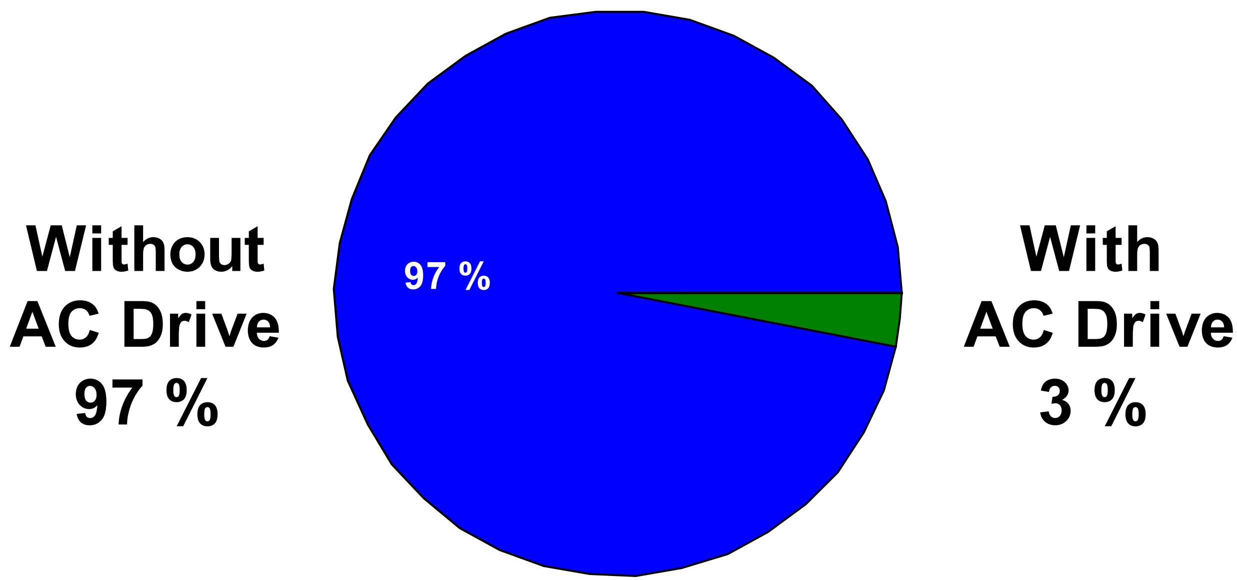


Fig.1.27: **AC motors with and without AC drive**

- The cost benefits are reviewed, with the cost divided into investment, installation and operational costs.

- To make a proper cost comparison with different control methods we choose pumping as an example.
- Direct-on-line (DOL) starting.

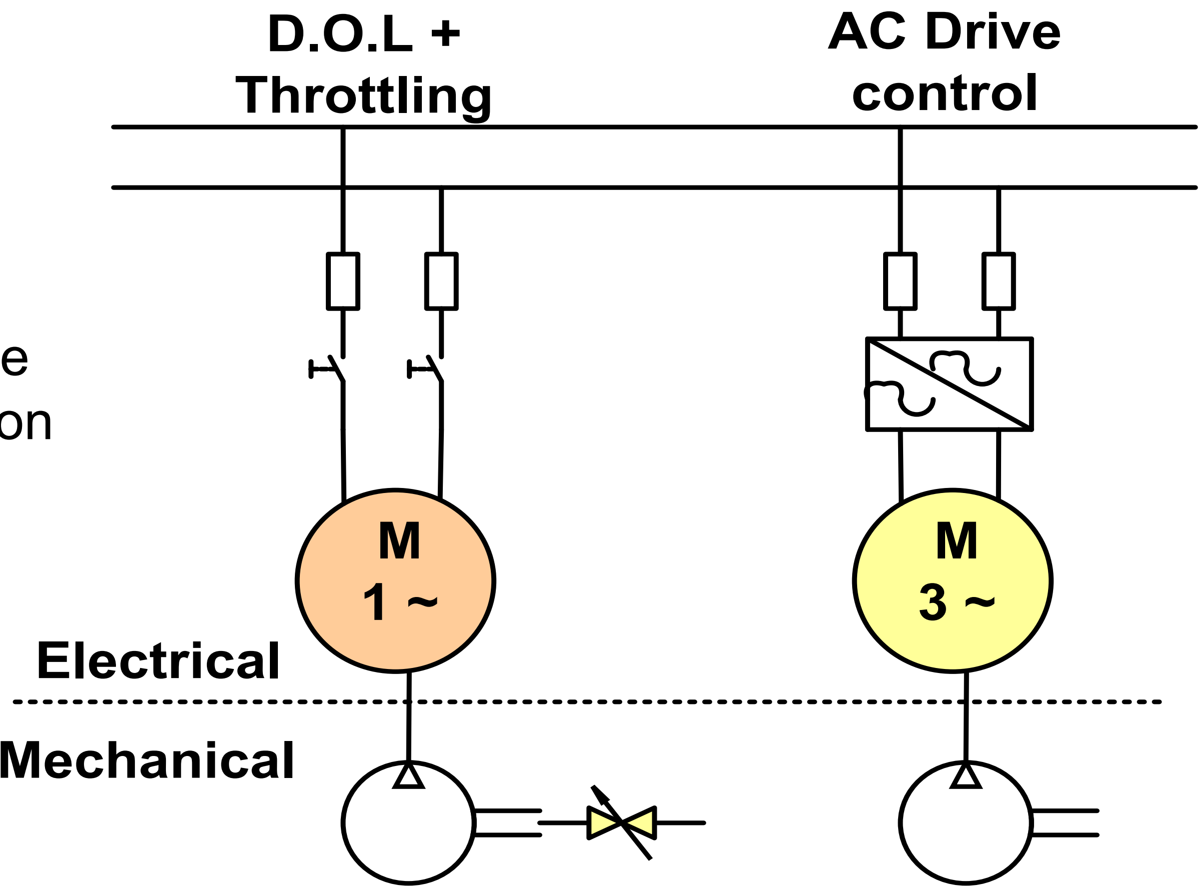
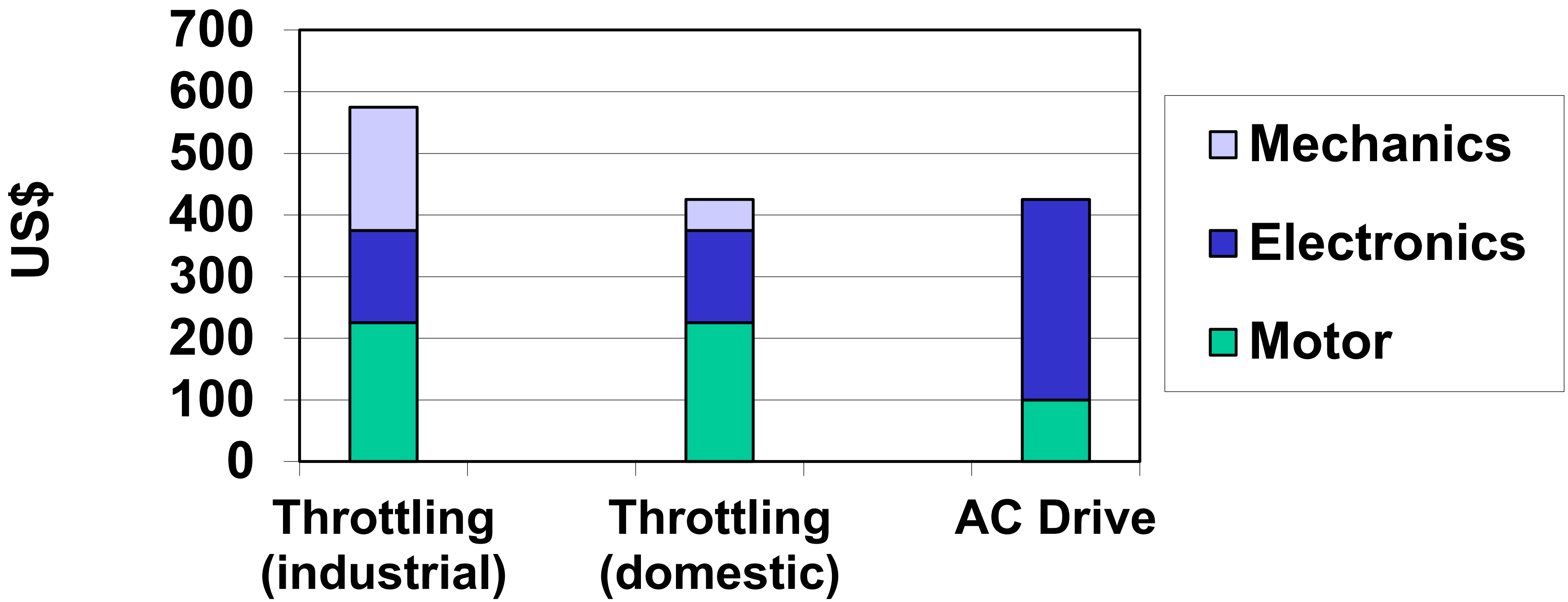


Fig.1.28: Electric drive for pumping application

- In throttling we need fuses, contactors and reactors on electrical side and valves on mechanical side.
- In AC drive control, no mechanical control component is needed as control is done on electrical side only.
- With AC drive control we can make use of 3-phase AC motor (cheaper!!) even with single-phase supply.
- Whereas with throttling, we have no choice but to use single-phase induction motors (IM) which is more expensive.

Conventional methods	AC drive
- both electrical & mechanical parts	- all in one
- many electrical parts	- only one electrical component
- mechanical parts need regular maintenance	- no mechanical parts, no wear and tear
- mechanical control is energy consuming	- Electrical control is – energy saving

Investment Cost



- Stricter industrial requirements increase mechanics cost.
- Motor cost for AC drive is cheaper due to three-phase motor.

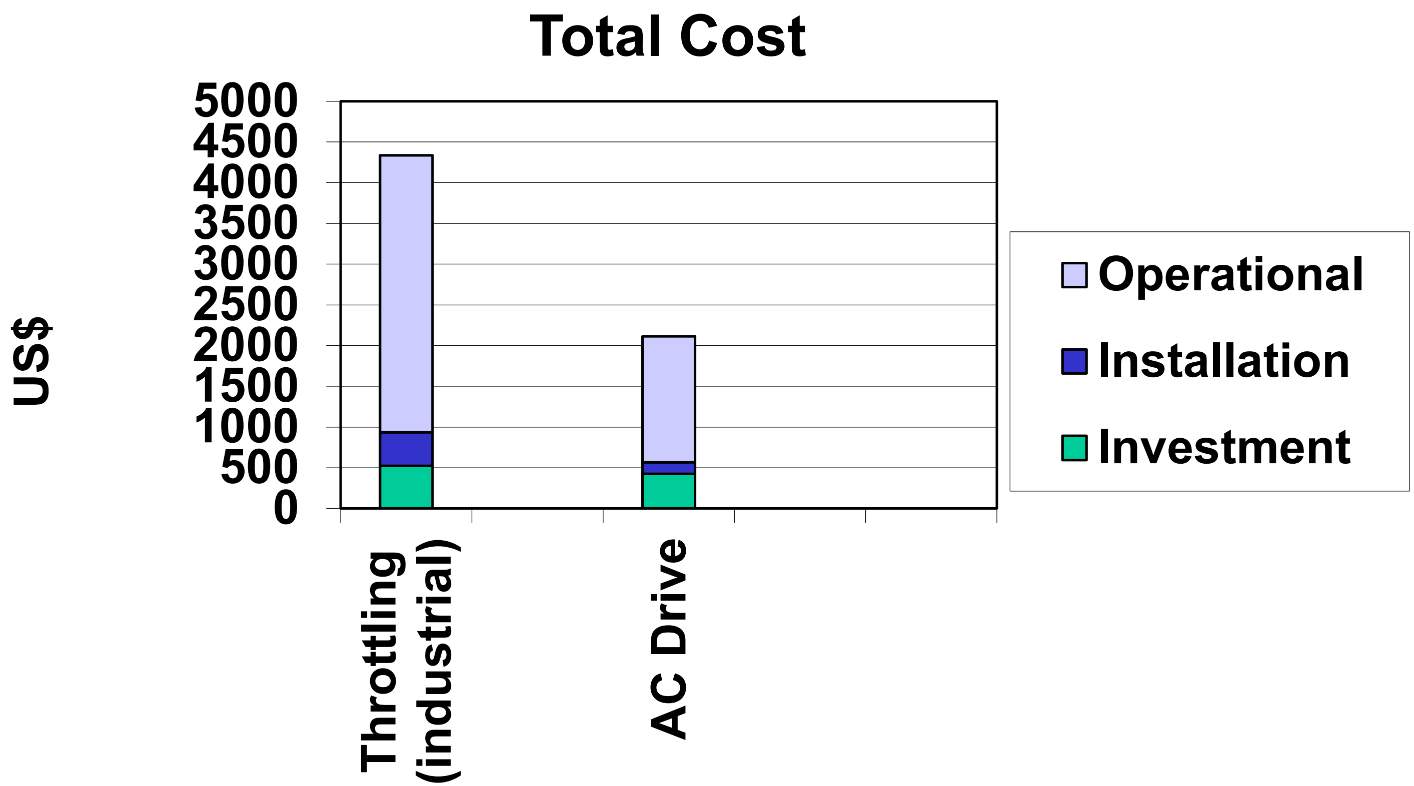
- Installation Costs:

	Throttling	**AC Drive**
Installation material	20 US$	10 US$
Installation work	5 h x 65 US$ = 325 US$	1 h x 65 US$ = 65 US$
Commissioning work	1 h x 65 US$ = 65 US$	1 h x 65 US$ = 65 US$
Total	410 US$	140 US$
Savings in installation : 270 US$		

- **Operational costs:**

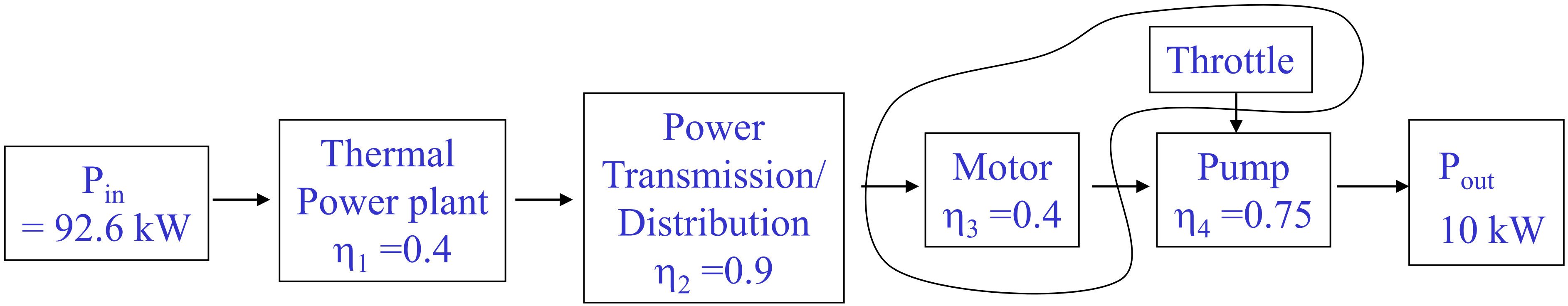
	Throttling	AC Drive with 50% saving
Power required	0.75 kW	0.37 kW
Annual energy 4000 hrs/year	3000 kWh	1500 kWh
Annual energy cost with 0.1 US$/kWh	300 US$	150 US$
Maintenance/year	40 US$	5 US$
Total cost/year	340 US$	155 US$
Savings in operational cost: 185 US$!!		

- Total cost for 10 years of operation



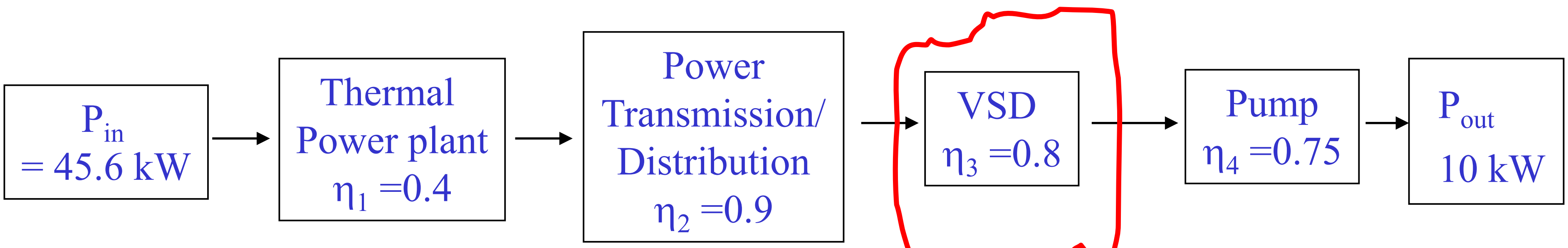
- Conventional method would be twice as expensive as AC drive option.

- If we consider the cost to produce and transport energy to the consumer's location then savings would increase further.



$$\eta = P_{out}/P_{in} = 0.11$$

Fig.1.29 Primary energy consumption for throttle/motor/pump system



$$\eta = P_{out}/P_{in} = 0.22$$

Fig.1.30 Primary energy consumption for VSD/motor/pump system

Multi-disciplinary Nature of Electric Drives

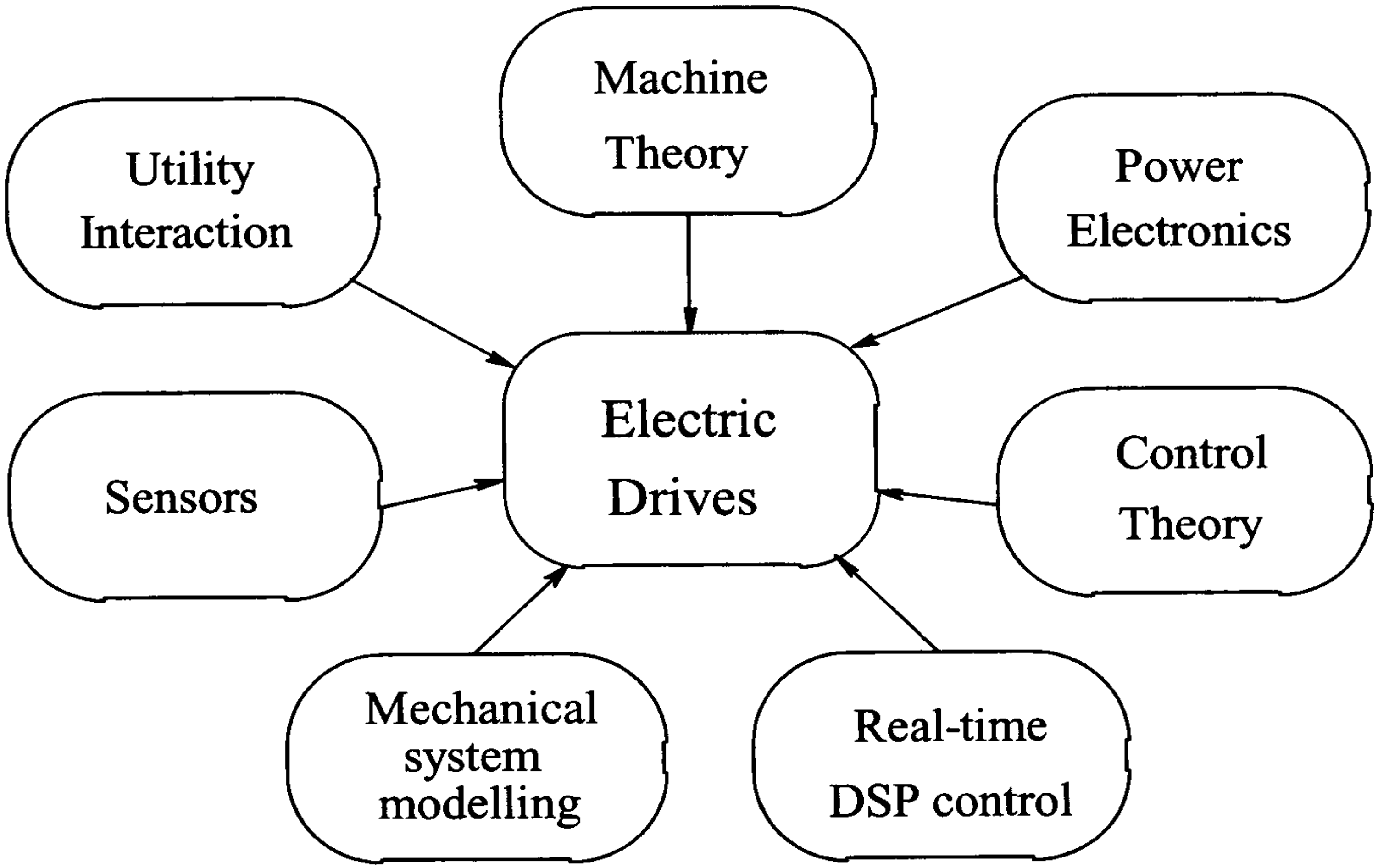


Figure 1.31: Multi-disciplinary nature of electric drives.

Dynamics of Motor and Load System

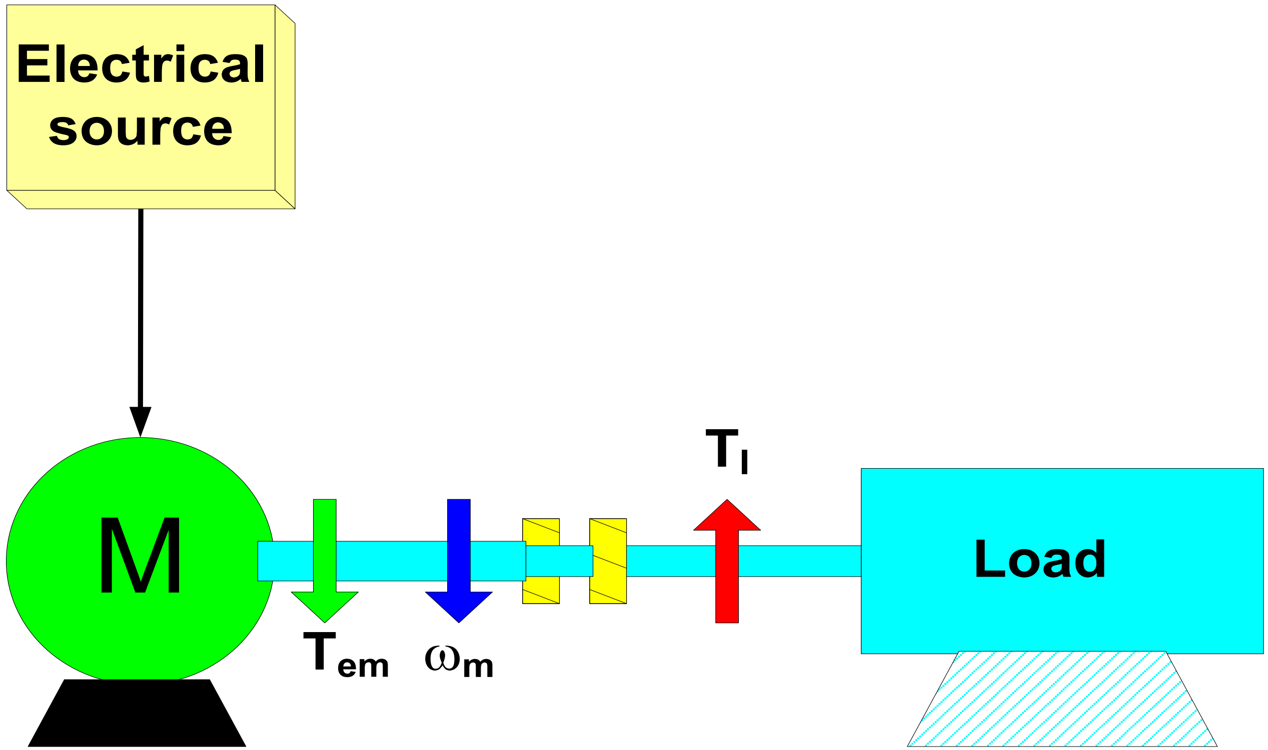


Figure 1.32: Basic considerations (a) motor-load system.

- The basic equation of motion is:

$$T_{em} \text{ or } T_m = T_l + J\frac{d\omega_m}{dt} \quad (1.1)$$

- ➢ T_{em} *or* T_m – electromagnetic torque produced by the electric motor
- ➢ T_l – load torque, J – moment of inertia of the drive system

- Three different operating conditions are possible (Fig.1.32(b)):

at location(a): $T_{em,a} > T_{l,a} \rightarrow \frac{d\omega_m}{dt} > 0$ – acceleration

at location(b): $T_{em,b} < T_{l,b} \rightarrow \frac{d\omega_m}{dt} < 0$ – deceleration

at location(c): $T_{em,c} = T_{l,c} \rightarrow \frac{d\omega_m}{dt} = 0 \rightarrow$ constant speed

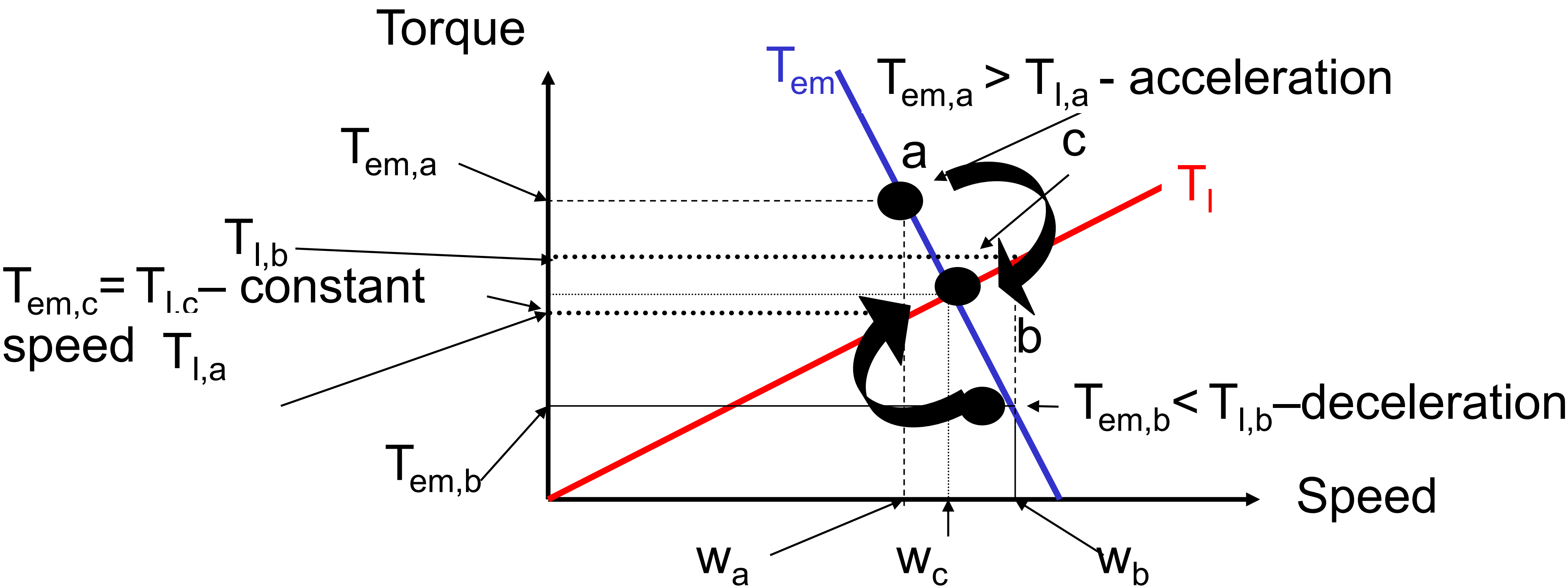


Figure 1.32: Basic considerations (b) motor-load torque-speed characteristics

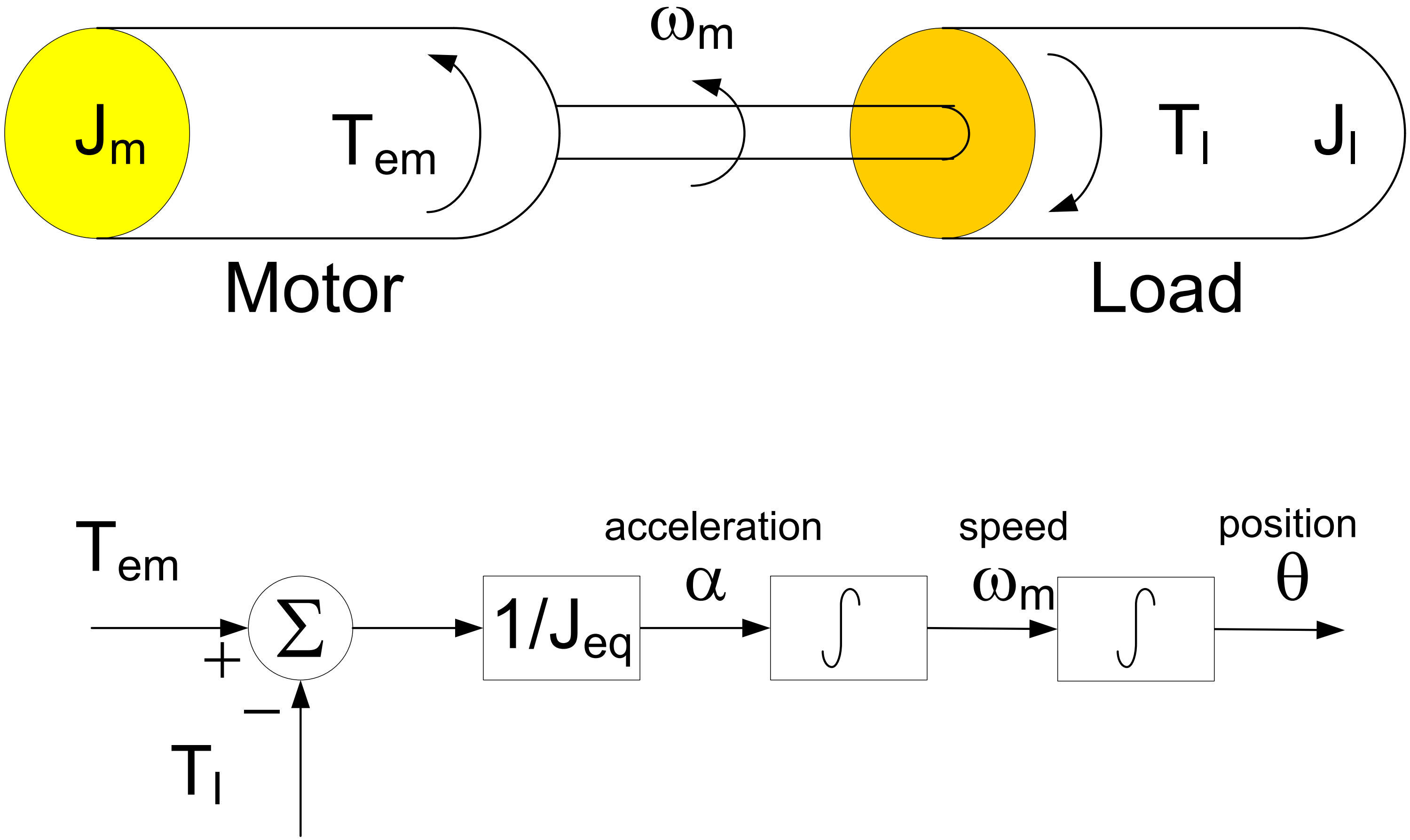


Figure 1.33: Basic considerations (a) motor-load system and (b) transfer function based electric-drive system.

$$\text{Accelaration, } \alpha = \frac{d\omega_m}{dt} = \frac{1}{(J_m + J_l)}(T_{em} - T_l) = \frac{T_{net}}{J_{eq}}$$

$$where \;\; T_{net} = (T_{em} - T_l) \;\; and \;\; J_{eq} = (J_m + J_l)$$

$$\text{Speed, } \omega_m(t) = \omega_m(0) + \int_0^t \alpha(\tau)\, d\tau$$

$$\text{Position, } \theta(t) = \theta(0) + \int_0^t \omega_m(\tau)\, d\tau$$

$$\text{Power, } P_{em} = T_{em} \times \omega_m ; P_l = T_l \times \omega_m$$

$$\text{Kinetic Energy (KE), } W = \frac{1}{2} J_{eq} \omega_m^2$$

- The operating point of an electric drive system is decided by the intersection of load and motor torque-speed characteristics.
- To vary the operating speed, either the load or the motor torque-speed characteristic has to be altered.
- We have no control on the load torque-speed characteristic **(why?)** , but the motor torque-speed characteristic can be altered by controlling the input electric power.
- Most efficient way of controlling electric power is by using **power semiconductor converter** as shown in Fig. 1.2.
- Role of power converter is efficient conversion of utility's input electric power to a form that is required by the load - motor.

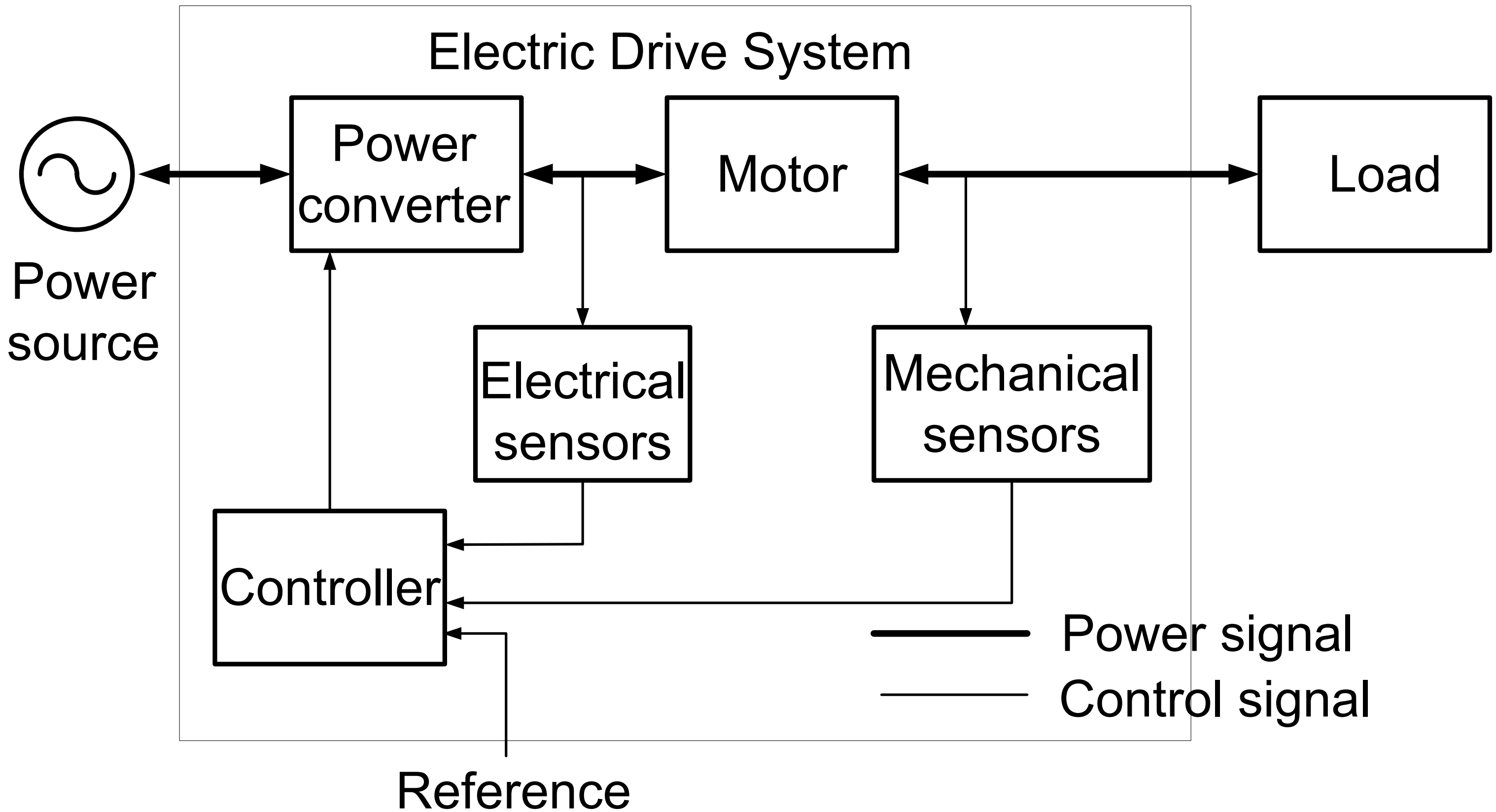


Figure 1.2: Electric drive system

Components of Load Torque

- Load torque T_l can be further subdivided into following categories:
  - **Frictional torque**: is present at the motor shaft and also at various parts of the load and is *directly proportional to the motor speed, (ω_m);*
  - **Windage torque**: stand-still wind in the air medium generates an opposing torque when the motor rotates and is proportional to the *square of the motor speed, (ω_m^2);*
  - **Mechanical torque**: is required to do the useful work. This torque depends on the nature of the load - might be *independent or function of the motor speed.*

Frictional Torque

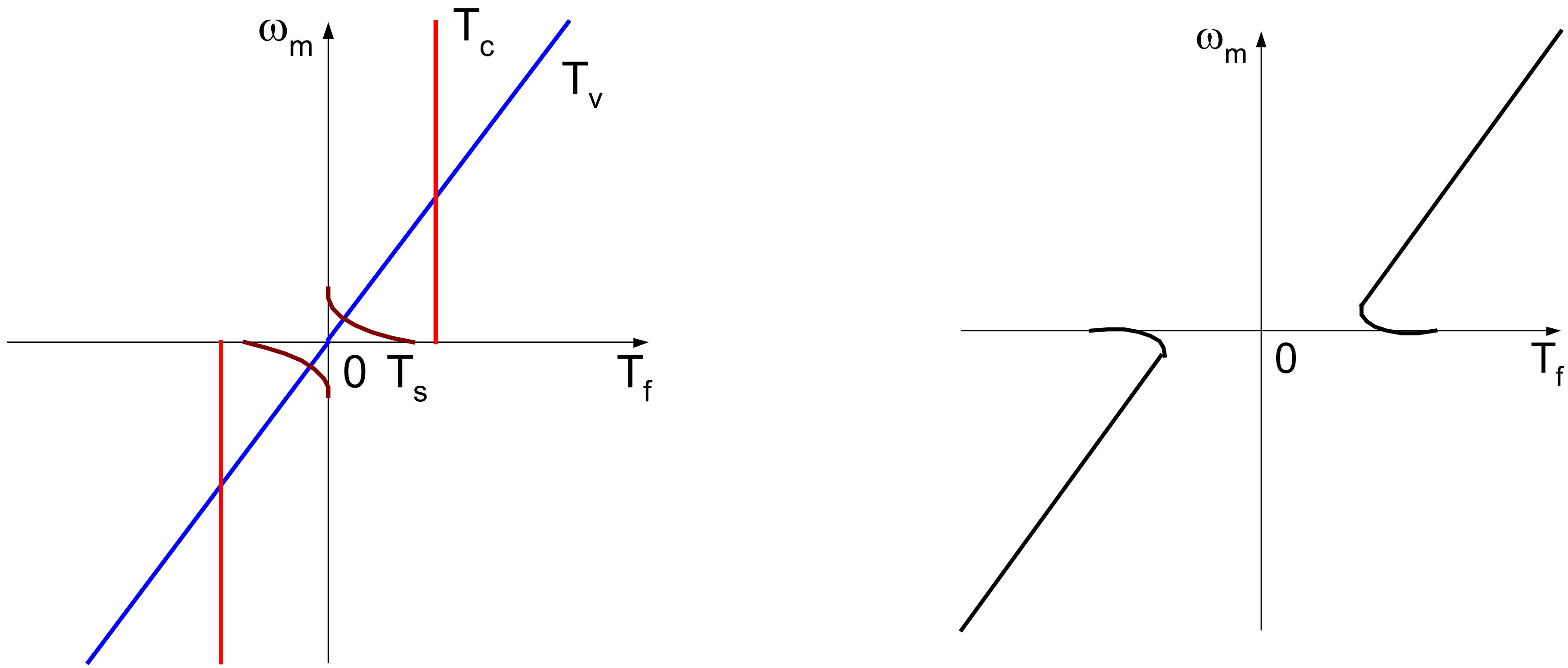


Figure 1.34: Components of frictional torque.

$$T_{fric.} = T_S + T_V + T_C \approx T_V (= B\omega_m) \quad (1.2)$$

$T_S - static\ friction, T_V - viscous\ friction, T_C - Columb\ friction$

$B - coefficient\ of\ friction$

http://en.wikipedia.org/wiki/Friction

- Load torque equation can be written as:

$$T_l = T_{mech.} + B\omega_m + C\omega_m^2 \quad (1.3)$$

- For many applications $(C\omega_m{}^2) << T_{mech}$ and hence windage torque can be neglected or incorporated by suitably updating the value of the coefficient of friction, *B*.

$$T_l = T_{mech.} + B\omega_m \quad (1.3(a))$$

- **Dynamic torque**: $J(d\omega_m/dt)$ is developed only during the *transient condition* and used to overcome the inertial torque of the drive system.

- The final equation of motion can be written as:

$$\boxed{T_m = T_{mech} + B\omega_m + J\frac{d\omega m}{dt} \quad (1.4)}$$

Different Types of Mechanical Load Torque

(a) **Constant-torque load** - independent of operating speed, ω_m.

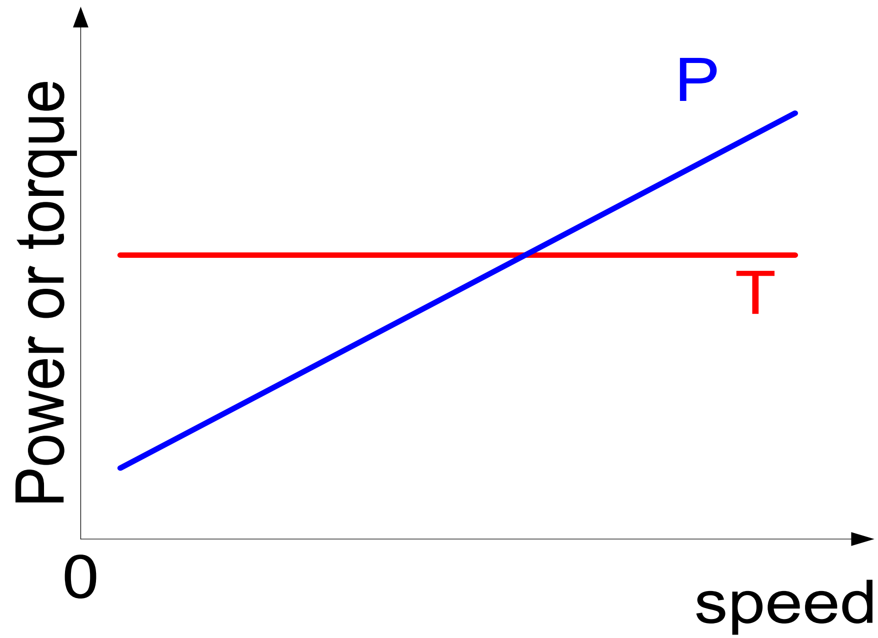


Figure 1.35: Typical torque and power curves in a constant torque application.

- Examples: ball mill for grinding ore, compressor operating against constant pressure, elevator operating at constant velocity and drum-type hoist.

Fan or Centrifugal Pump

- Load torque varies as the square of the speed. $T_l = k\omega_m^2$.

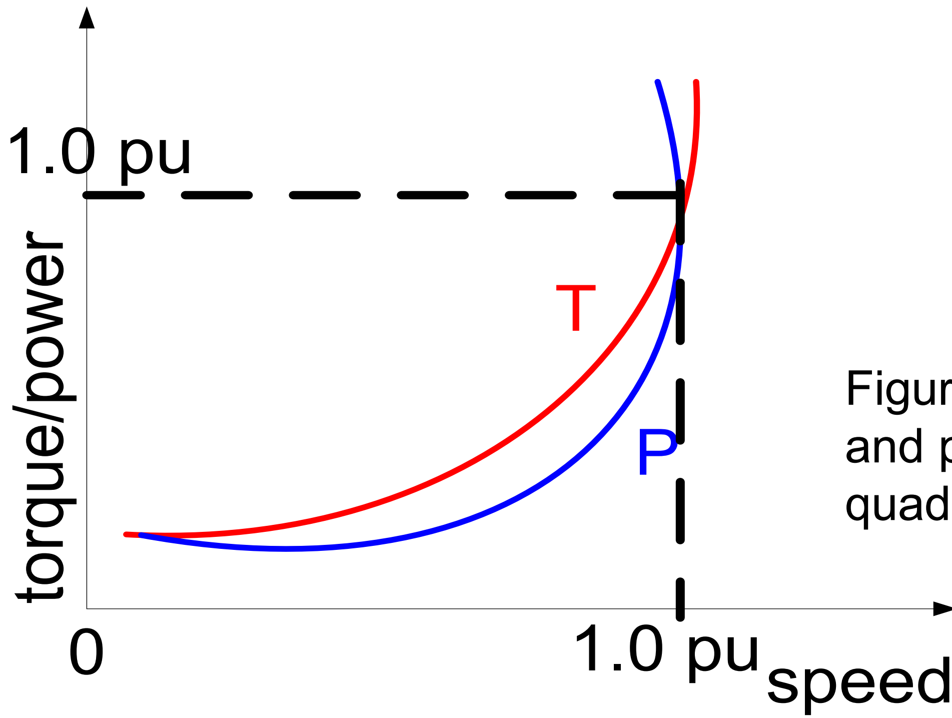


Figure 1.36: Typical torque and power curves in a quadratic torque application.

- Typical applications are centrifugal pumps and fans.

Constant Power Drive

- Paper rolling mill requires: constant strip tension, *f* and at constant velocity, *v* leads to constant output power requirement.

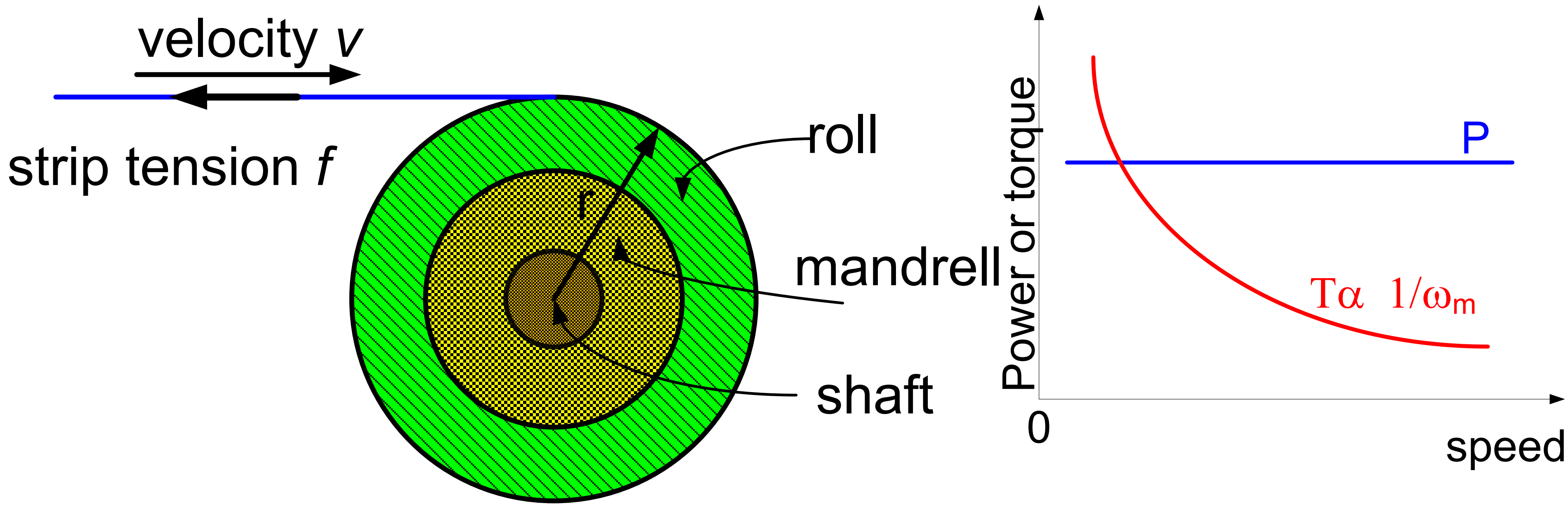


Figure 1.37: Constant power drive (a) paper roll on mandrel and (b) torque-speed characteristics.

$$P = T_l \times \omega_m = (f \times r) \times \left(\frac{v}{r}\right) = f \times v = \text{constant} \quad (1.5)$$

Transportation Drive

Orian VII Hybrid Electric Bus

Toyota Camry Hybrid 2007

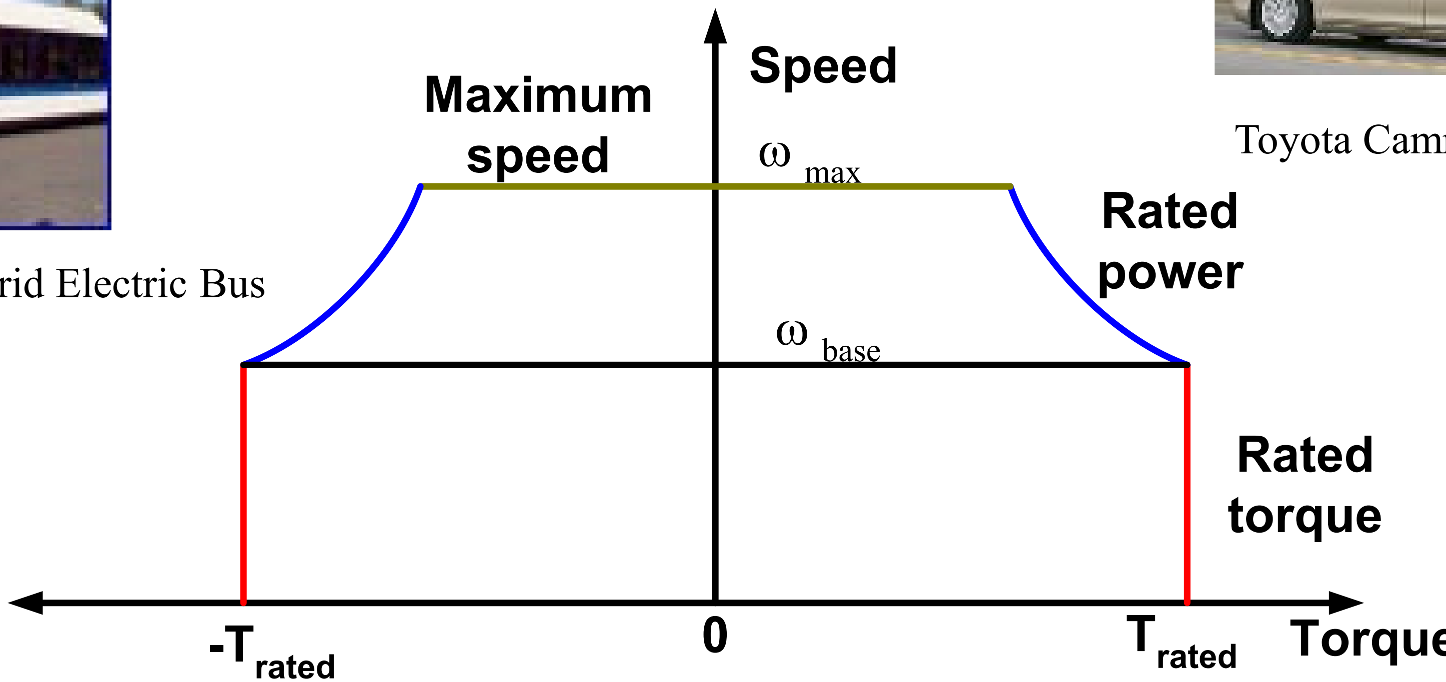


Figure 1.38: Envelopes of speed and torque for traction load.

- Examples: subway trains (MRT, LRT), street cars, golf-carts, EVs etc.

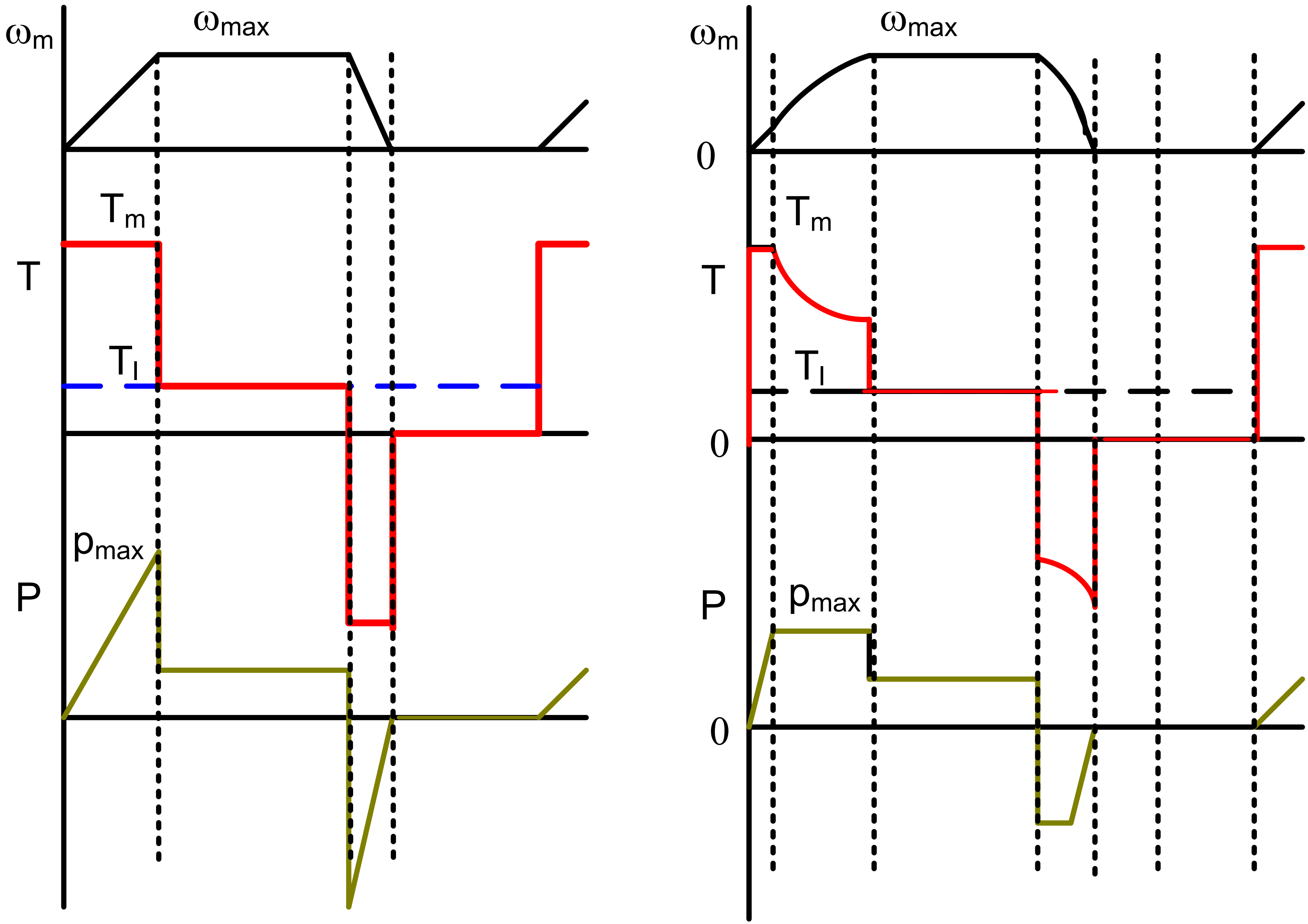


Fig. 1.39: (a) Ideal and (b) optimised torque and speed envelopes for traction load.

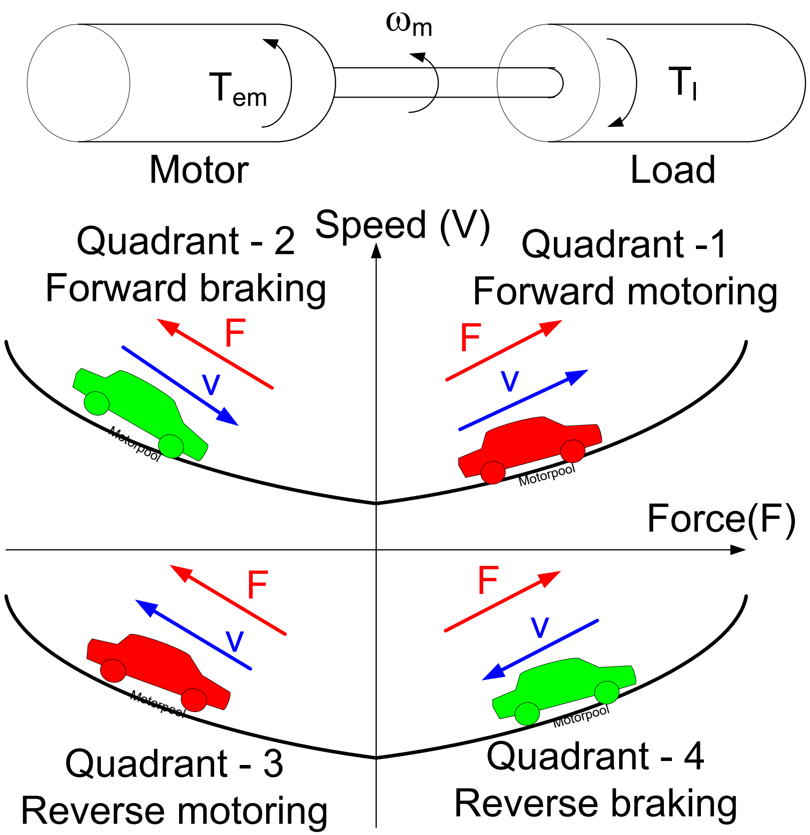
Braking in Electric Drives

- For any electrical drive application braking is essential due to:
  - long time to stop the motor – mains supply switched off
  - emergency condition – MRT, lifts etc.
  - accurate positioning of load – lift, machine tools
  - driving active loads – hoist applications
- Braking can be achieved by using mechanical means or by electrical means.
- Mechanical brakes are subjected to wear and tear and therefore not preferred.
- Electrical braking is maintenance free and therefore preferred.

- In electrical braking kinetic energy is converted into electrical energy and is fed back to the supply and therefore is more efficient (regenerative braking) and preferred.

- Electrical braking can be classified into:
  - **Dynamic braking:** Motor acts as a generator and generated electric energy is dissipated as heat in externally connected resistor.
  - **Regenerative braking:** generated electrical energy is fed back to the mains supply thereby increasing the system efficiency.

Multi-quadrant operation



- Quadrant - I,
  $F > 0, V > 0, P = F \times V > 0$
- Quadrant - II,
  $F < 0, V > 0, P = F \times V < 0$
- Quadrant - III,
  $F < 0, V < 0, P = F \times V > 0$
- Quadrant - IV,
  $F > 0, V < 0, P = F \times V < 0$

- Quadrant - I,
  $T_{em} > 0, \omega_m > 0, P = T_{em} \times \omega_m > 0$
- Quadrant - II,
  $T_{em} < 0, \omega_m > 0, P = T_{em} \times \omega_m < 0$
- Quadrant - III,
  $T_{em} < 0, \omega_m < 0, P = T_{em} \times \omega_m > 0$
- Quadrant - IV,
  $T_{em} > 0, \omega_m < 0, P = T_{em} \times \omega_m < 0$

Figure 1.40 (a): Four quadrant operation of a drive.

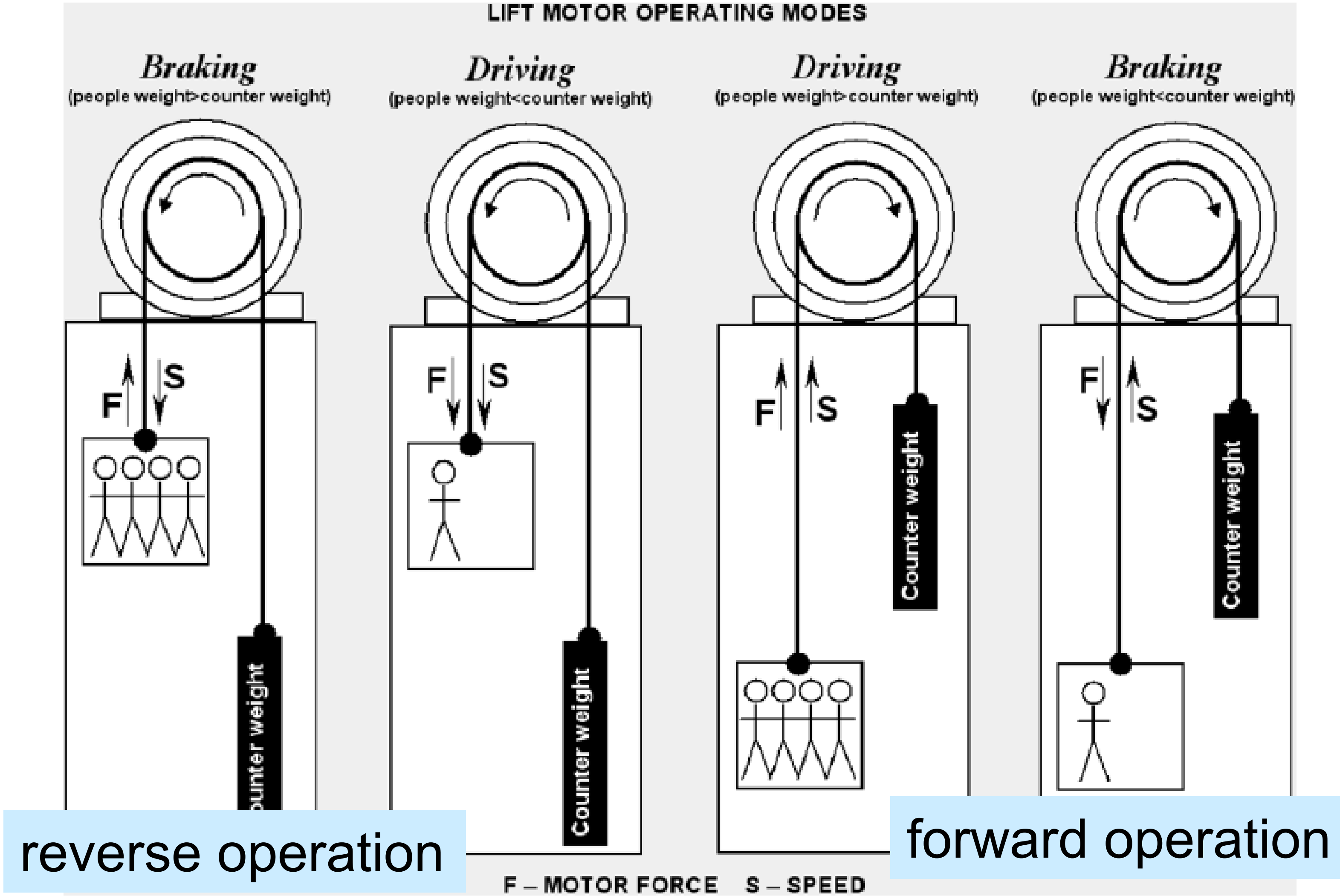


Figure 1.41: Four quadrant operation of a drive.

- VSDs with regenerative capability allows braking energy to be injected back to the source/grid with significant energy savings.

Steady–state Stability

- How do we determine whether a given operating point on the torque-speed plane is stable or not?
- Any operating point in the torque-speed plane is said to be in stable equilibrium "if any disturbance is introduced to the drive system, the operating point deviated from its original position should restore back to the original equilibrium point".
- Conditions for stability can be derived mathematically as follows:

- Assume initially the drive is operating at a stable equilibrium speed of ω_m and motor & load torques are T_{em} and T_l respectively.
- A disturbance causes the operating point to move to a new location where the new value of the torque and motor speed be $T_{em} + \Delta T_{em}$, $T_l + \Delta T_l$ and $\omega_m + \Delta \omega_m$.
- At the original operating point (before disturbance) we have

$$-T_{em} + T_l + J\frac{d\omega_m}{dt} = 0 \quad (1.6)$$

- At the new operating point, we have

$$-(T_{em} + \Delta T_{em}) + (T_l + \Delta T_l) + J\frac{d(\omega_m + \Delta\omega_m)}{dt} = 0 \quad (1.7)$$

- Rearranging eqns. 1.6 and 1.7 we get

$$-\Delta T_{em} + \Delta T_l + J\frac{d\Delta\omega_m}{dt} = 0 \qquad (1.8)$$

- Linearizing around the operating point, we have

$$\Delta T_{em} = \left(\frac{dT_{em}}{d\omega_m}\right)\Delta\omega_m \text{ and } \Delta T_l = \left(\frac{dT_l}{d\omega_m}\right)\Delta\omega_m \qquad (1.9)$$

- From eqns. (1.8) and (1.9) we have,

$$\frac{d(\Delta\omega_m)}{dt} + \frac{1}{J}\left[\frac{dT_l}{d\omega_m} - \frac{dT_{em}}{d\omega_m}\right](\Delta\omega_m) = 0 \qquad (1.10)$$

- If at $t = 0$ the initial deviation in speed is $\Delta\omega m_0$ then the solution of eqn. 1.10 is:

$$\Delta\omega_m = (\Delta\omega_m)_0 \, e^{-\frac{1}{J}\left[\frac{dT_l}{d\omega_m} - \frac{dT_{em}}{d\omega_m}\right]t} \qquad (1.11)$$

- Any equilibrium point is said to be stable if $\Delta\,\omega_m \to 0$ as $t \to \infty$, so the **necessary condition for stability** is:

$$\left[\frac{dT_l}{d\omega_m} - \frac{dT_{em}}{d\omega_m}\right] > 0 \qquad (1.12)$$

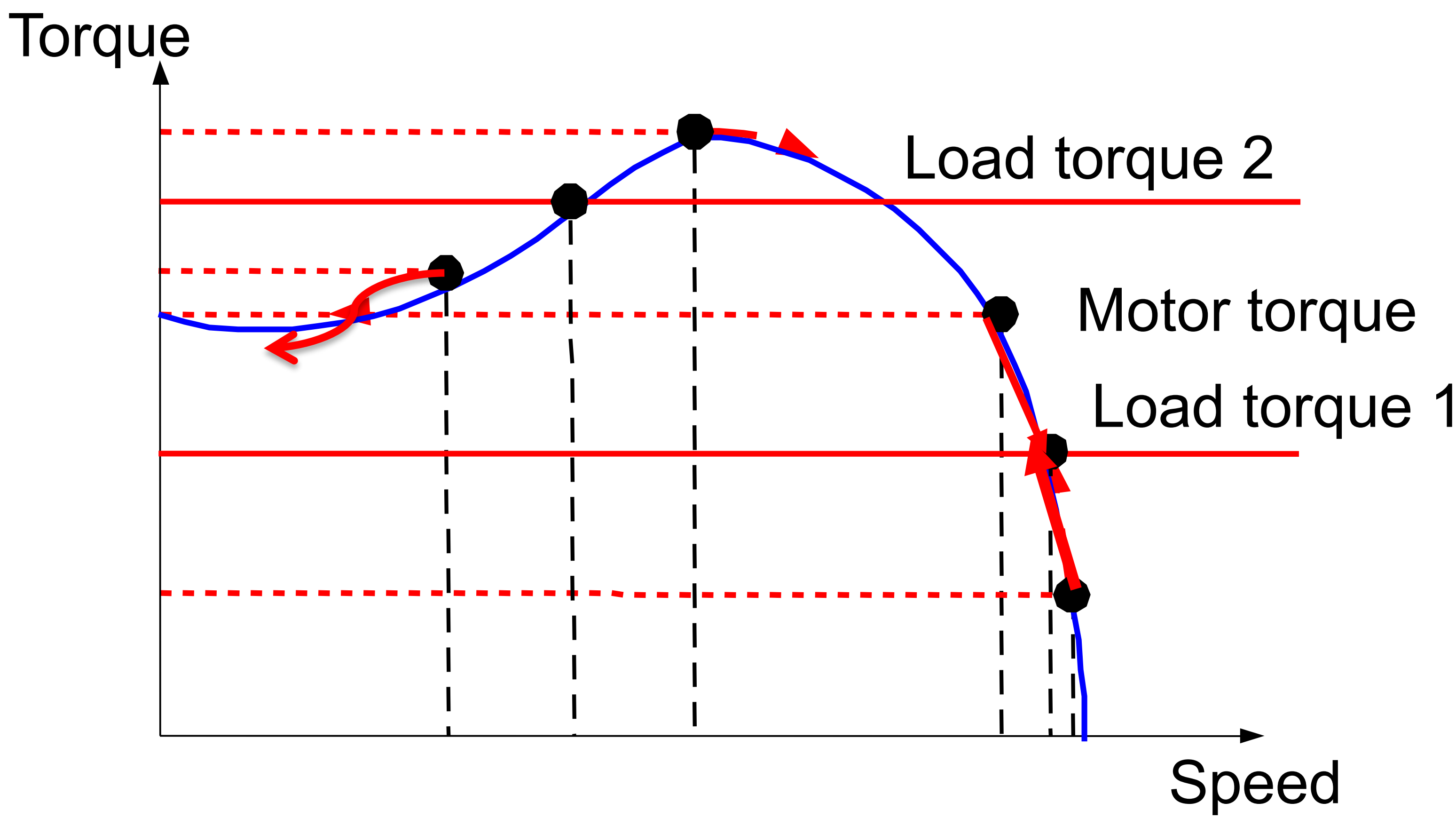


Figure 1.42: Steady-state stability of equilibrium points.

Example 1: A motor having a suitable circuit develops a torque given by the relationship $T_m = a \ \omega_m + b$ where a and b are positive real constants.

This motor is used to drive a load whose torque is expressed as $T_l = c\omega_m^2 + d$ where c and d are some other positive real constants.

The total inertia of the rotating masses is J.

a) Determine the relations amongst the constants a, b, c and d in order that the motor can start together with the load and have equilibrium operating speeds?

b) Calculate the equilibrium speed(s).

c) Will the drive be stable at the equilibrium speed(s) as calculated in part(b)?

Solution: At steady-state:

$$T_m = T_l$$
$$a\omega_m + b = c\omega_m^2 + d$$
$$c\omega_m^2 - a\omega_m + (d-b) = 0$$
$$\omega_{m,A} = \frac{a + \sqrt{a^2 - 4c(d-b)}}{2c}, \omega_{m,B} = \frac{a - \sqrt{a^2 - 4c(d-b)}}{2c}$$

$$1. At\ \omega_m = 0, T_m > T_l \Rightarrow b > d,$$
$$2. [a^2 - 4c(d-b)] > 0 \Rightarrow [a^2 > 4c(d-b)]$$
$$\frac{dT_l}{d\omega_m} > \frac{dT_m}{d\omega_m} \Rightarrow 2c\omega_m > a,$$
$$2c\omega_{m,A} = \left(a + \sqrt{a^2 - 4c(d-b)}\right) > a \Rightarrow stable$$
$$2c\omega_{m,B} = \left(a - \sqrt{a^2 - 4c(d-b)}\right) \ngtr a \Rightarrow unstable$$

Power Converters for Electric Drives

- Industrial drives commonly use:
  - dc motors,
  - induction motors, and
  - synchronous motors.
- AC (induction and synchronous) motors require variable frequency and variable voltage ac supply.
- DC motors require variable voltage dc supply.
- Supply voltage available is either fixed voltage dc or fixed voltage and fixed frequency ac supply.

Converters	Conversion Function	Applications
1. Controlled rectifiers	AC to variable DC	Control of DC, IM and SM
2. Choppers	Fixed Voltage dc to variable voltage dc	Control of DC and IM
3. AC voltage controllers	Fixed voltage ac to variable voltage ac at same supply frequency	Control of IM
4. Inverters	DC to fixed or variable voltage and variable frequency ac	Control of IM and SM

- VSDs may use either one or more of the above mentioned converters.

Continuous and Transient Ratings of Motors

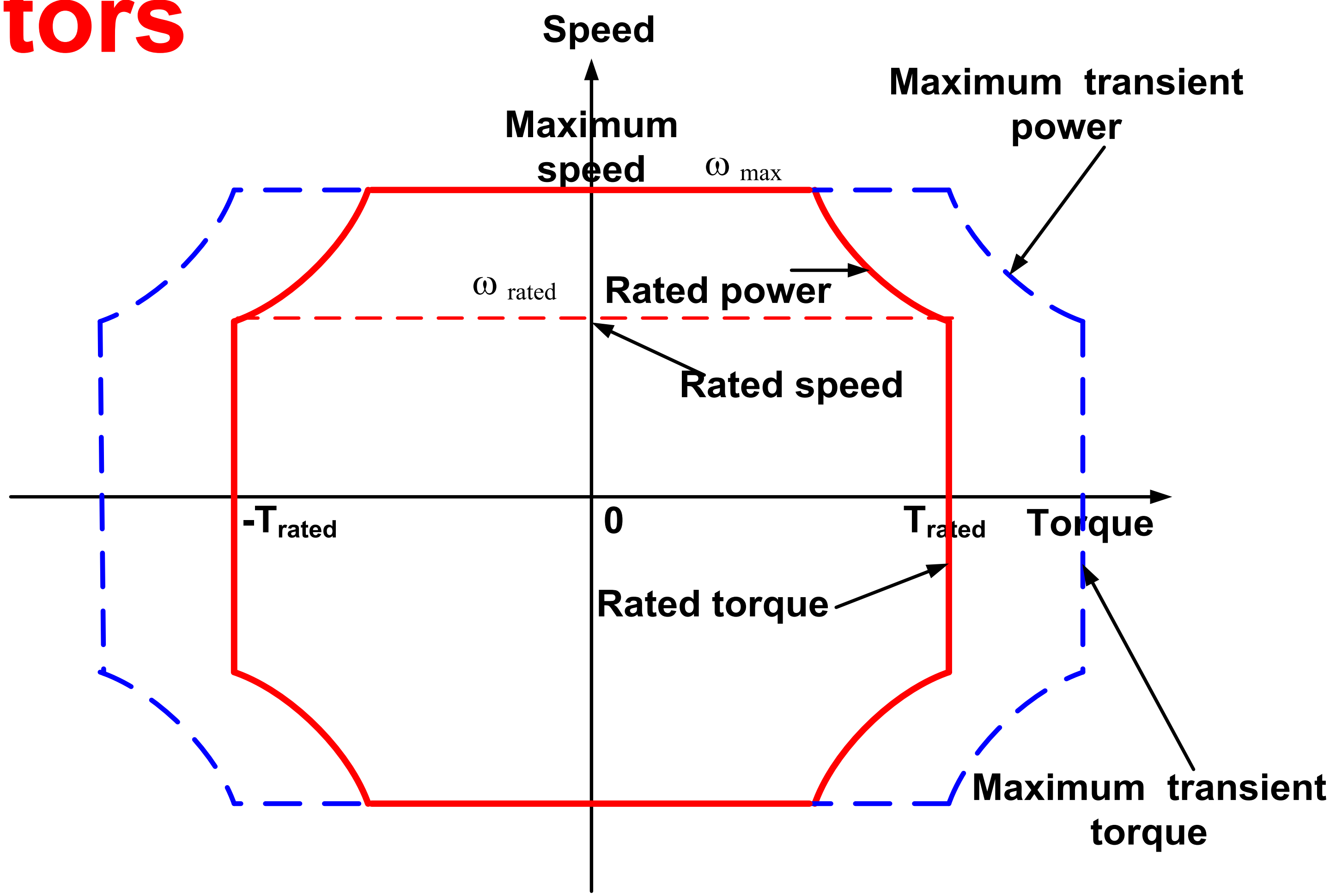


Figure 1.43: Rated and transient, torque, speed and power limitations of drives in four quadrants

Continuous and Transient Ratings of Power Converters

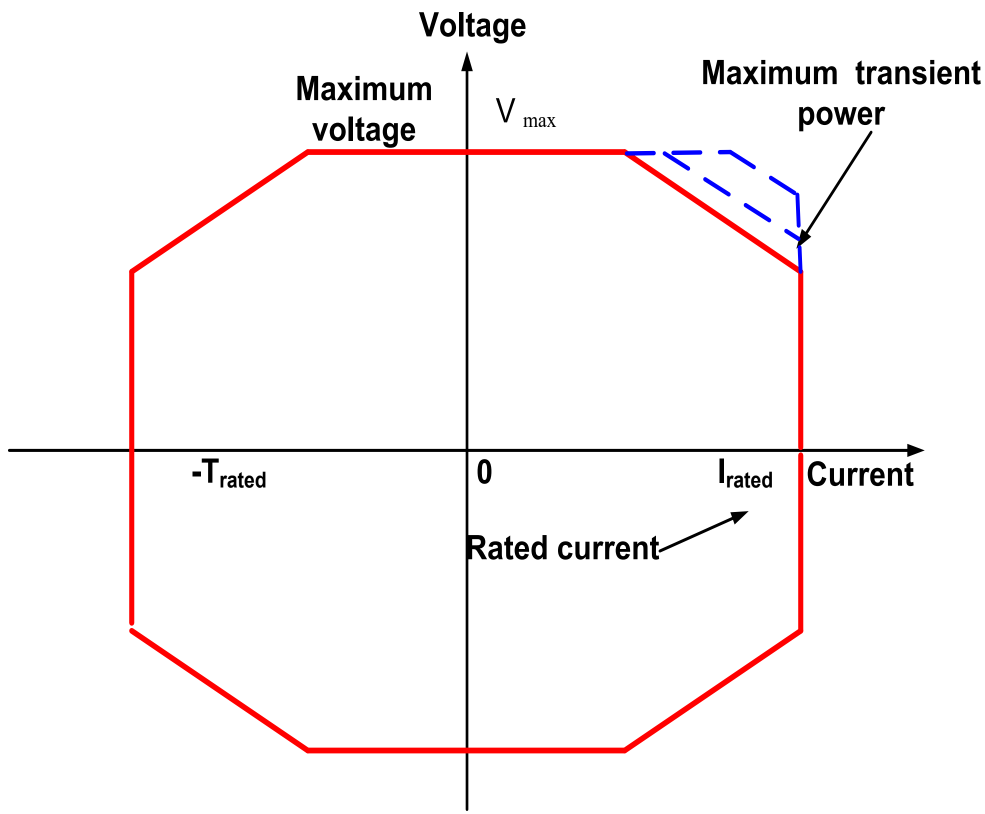


Figure 1.44: Rated and transient, torque, speed and power limitations of drives in four quadrants

Harmonics and Power Factor

- All power semiconductor converters produce harmonics in their output voltages and currents.
- Harmonic currents do not contribute to output power but significantly increase the losses in the motor due to high rms current - motor needs to be **de-rated** for safe operation.
- Power converters draw harmonic current from the input supply side which adversely affect the performance of other sensitive loads connected to the same utility supply.

- **Advantages of Power Semiconductor Converters**
  - high efficiency;
  - fast response;
  - control flexibility;
  - easy maintenance;
  - high reliability;
  - low weight and volume;
  - and less noisy.
- Advantages in using Power Semiconductor Converter outweigh the disadvantages and hence are widely used in replacing conventional power controller such as magnetic amplifiers, mercury arc rectifiers, resistors etc.

Different Modes of Operation

- An electric drive operates in either of the following three modes:
  - Steady-state,
  - Acceleration and
  - Deceleration.

Speed Increase

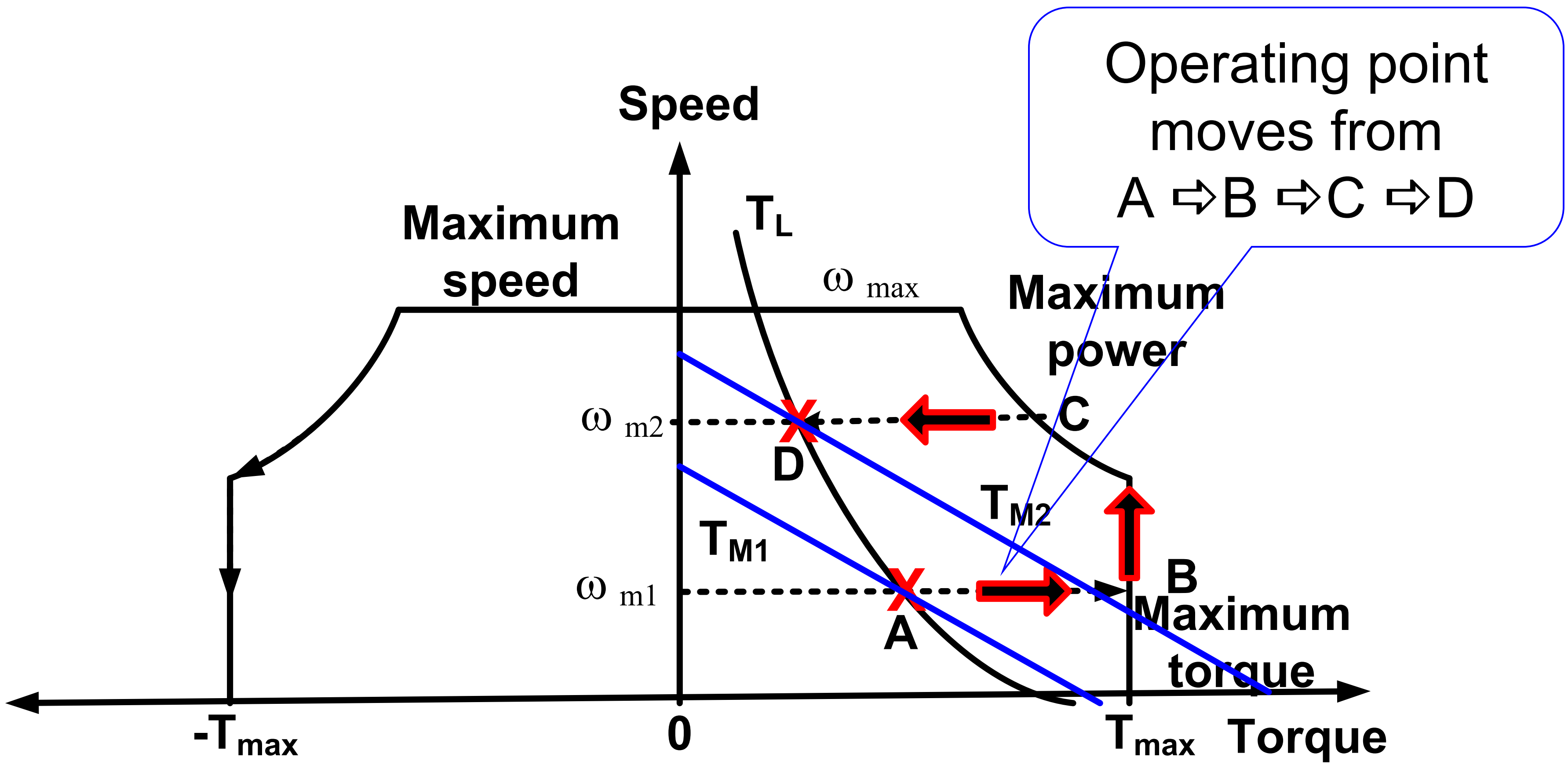


Figure 1.45: Speed transition: (a) speed increase

Speed Reduction

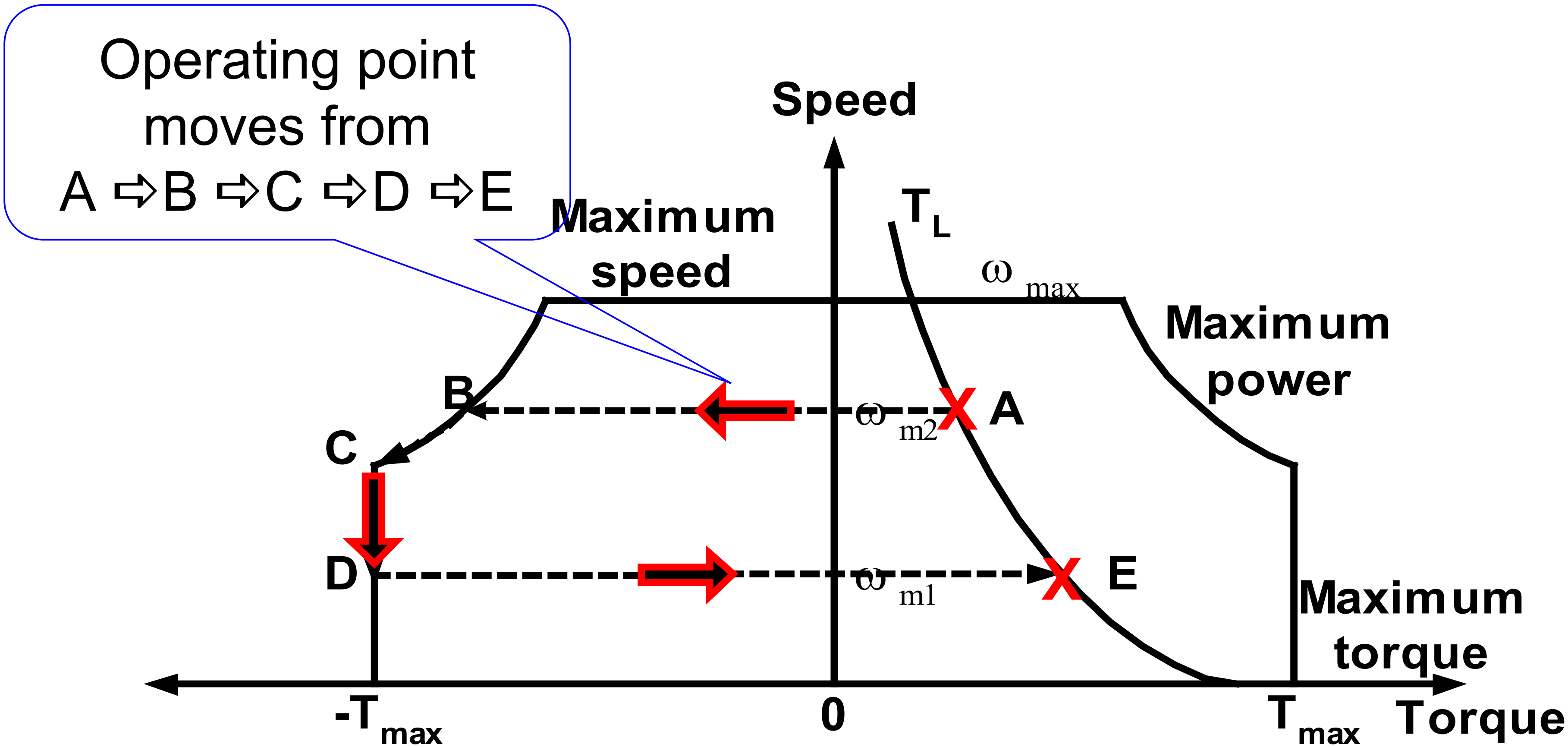


Figure 1.46: Speed transition: (a) speed reduction

Speed Reversal

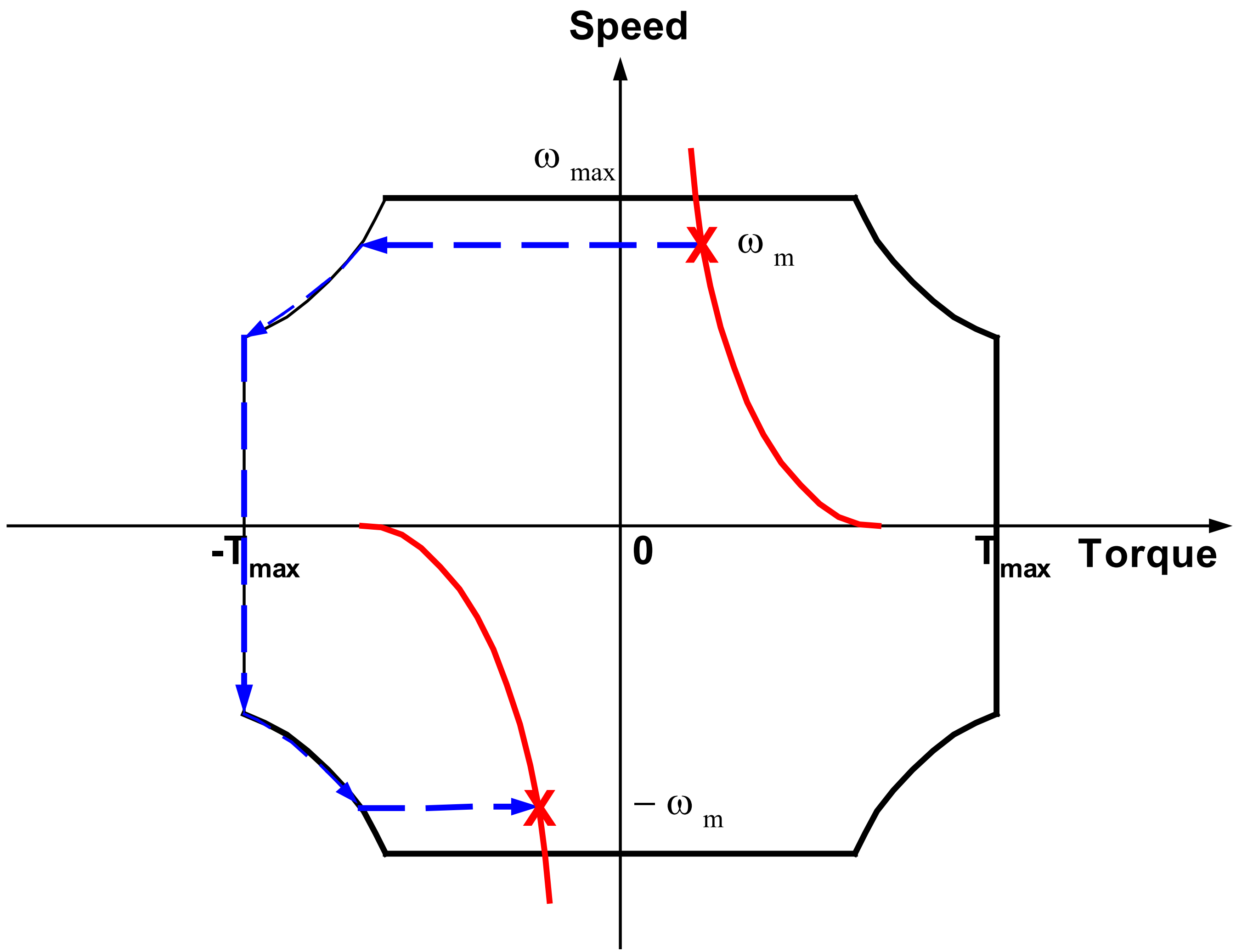


Figure 1.47: Speed transition: (c) speed reversal

Speed Reduction using Single-Quadrant Converter

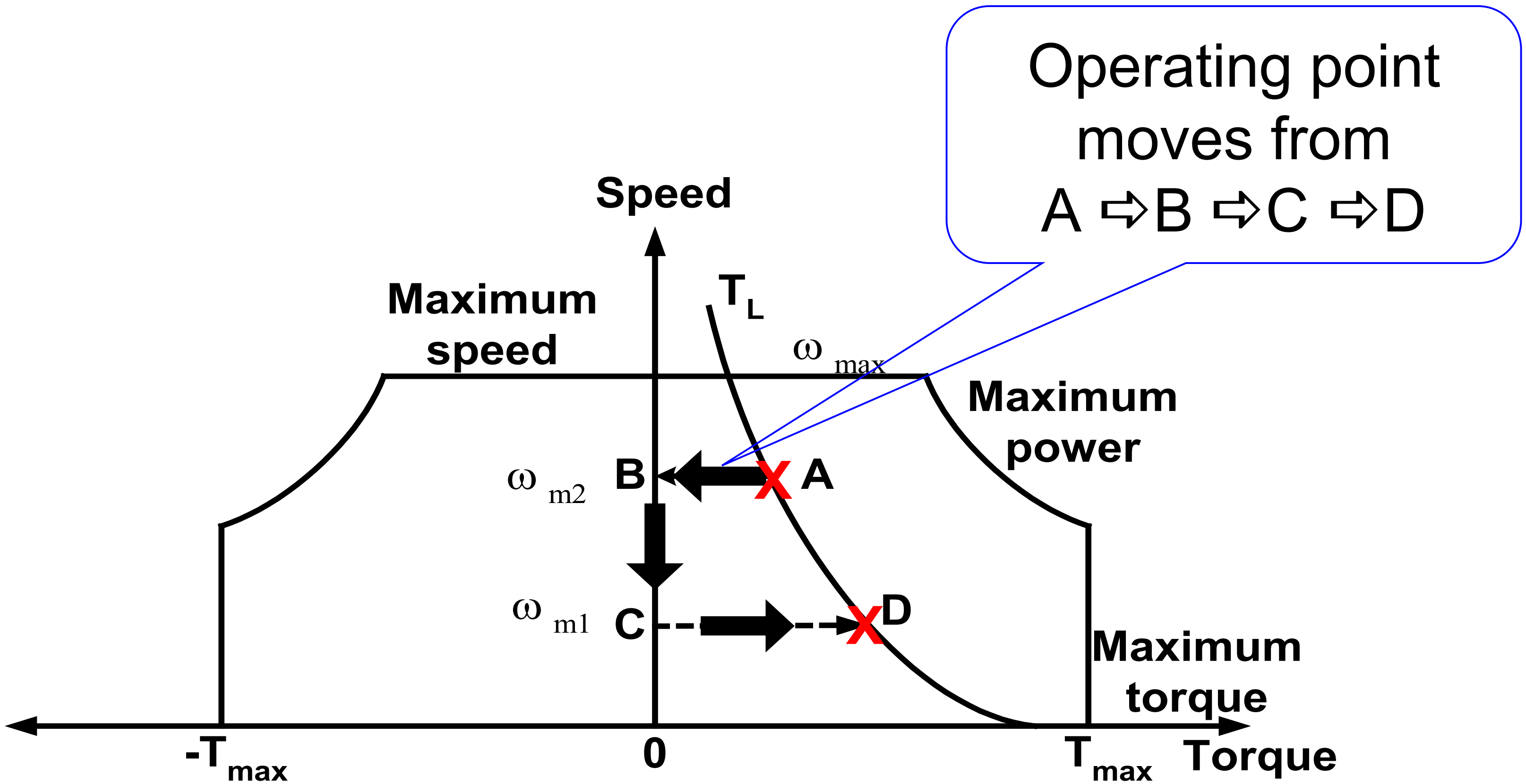


Figure 1.48: Speed transition: (d) speed reduction with single-quadrant converter

Electromechanical System in Transient State

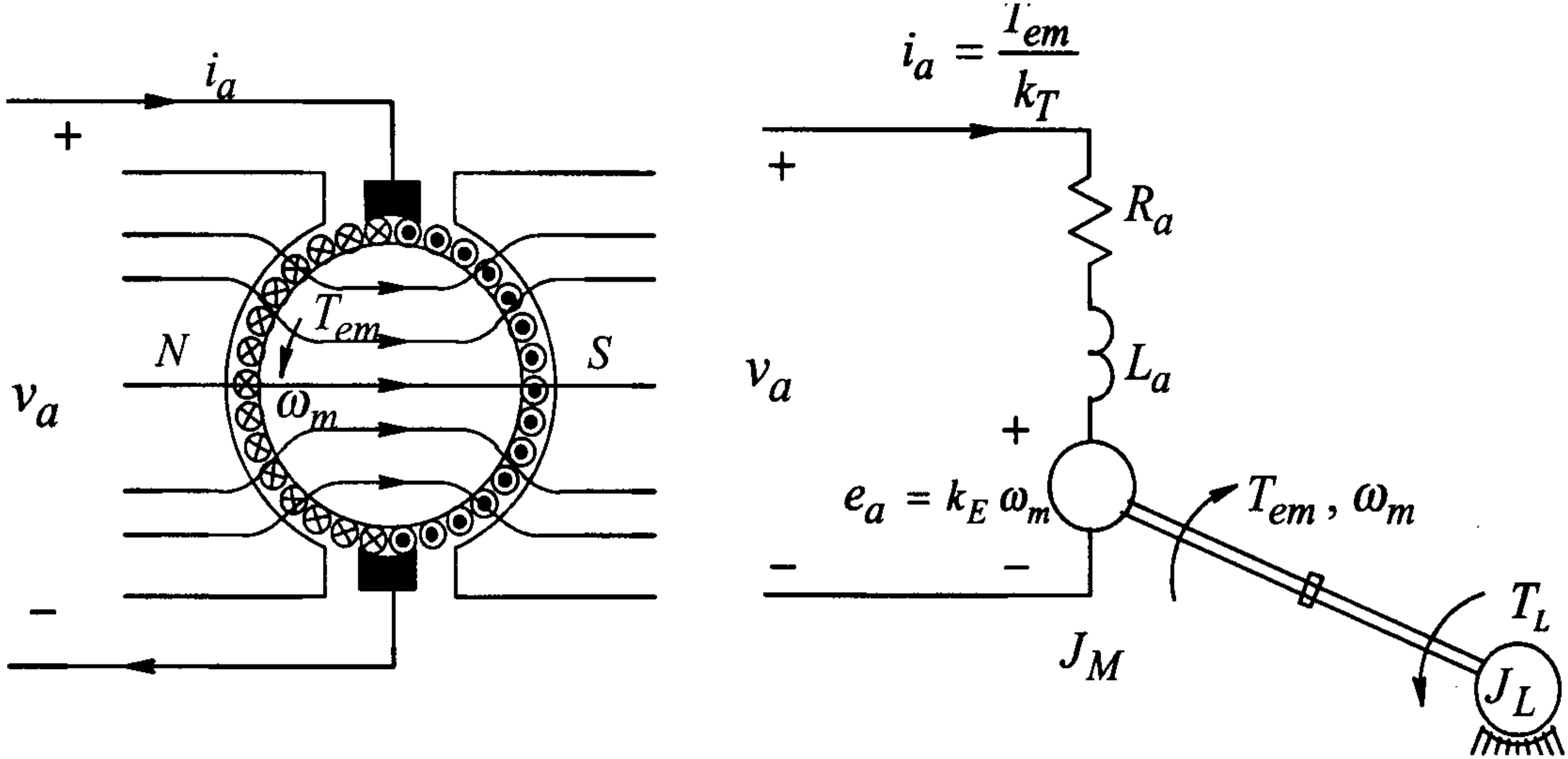


Figure 1.49: Steady-state equivalent circuit of the armature of a dc motor drive.

- Basic steady-state equations applicable to all dc motors are:

$$E_a = (k_e\varphi)\,\omega_m = k_E\omega_m,$$
$$V_a = E_a + I_a R_a,$$
$$T_{em} = (k_e\varphi)I_a = k_T I_a \Rightarrow k_E = k_T$$

- Basic dynamic equations are:

$$e_a = (k_e\varphi)\omega_m = k_E\omega_m$$
$$v_a = e_a + i_a R_a + L_a\frac{di_a}{dt}$$
$$T_{em} = (k_e\varphi)i_a = k_T i_a$$
$$\frac{d\omega_m}{dt} = \frac{1}{J_{eq}}(T_{em} - T_L)$$

- For a DC machine

$$T_m = k\varphi i_a = k_T i_a = k_T\left(\frac{V - k_E\omega_m}{R_a}\right) = \frac{(k_T = k_E)V}{R_a} - \frac{(k_E)^2\omega_m}{R_a}$$

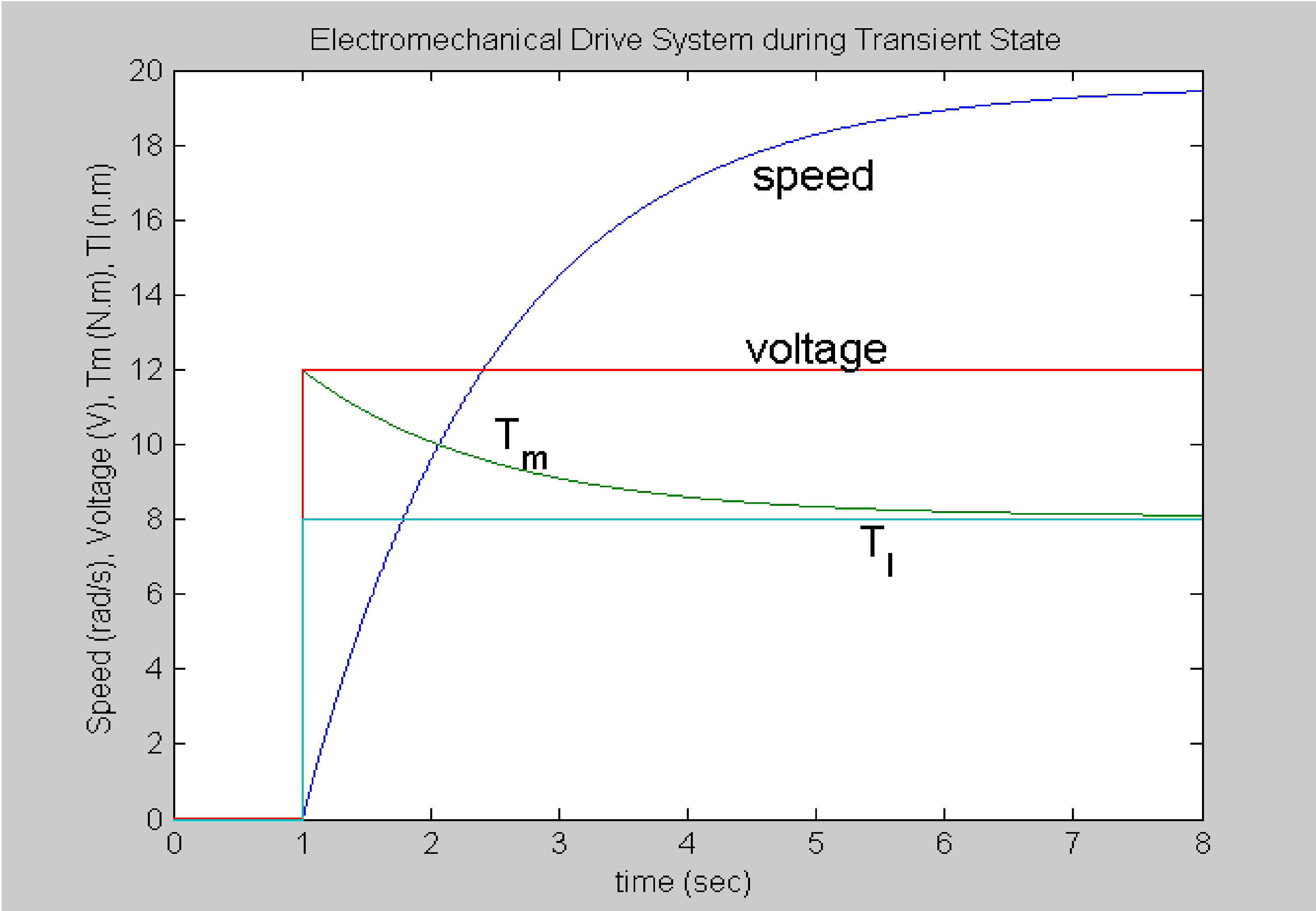
$$T_m\left[=\left\{\frac{k_E V}{R_a} - \frac{(k_E)^2\omega_m}{R_a}\right\}\right] = T_l + J\frac{d\omega_m}{dt}$$

$$\frac{JR_a}{(k_E)^2}\frac{d\omega_m}{dt} + \omega_m = \left(\frac{V}{k_E} - \frac{R_a T_l}{(k_E)^2}\right)(=\omega_{ss})$$

$$\tau_m\frac{d\omega_m}{dt} + \omega_m = \omega_{ss}$$

$$\omega_m(t) = \omega_{ss}\left(1 - e^{-t/\tau_m}\right) + \omega_{mo}e^{-t/\tau_m} \quad (1.13)$$

where $\tau_m = JR_a/(k_e)^2$ – mechanical time constant, ω_{mo} – initial speed at $t = 0$ and ω_{ss} – final steady-state speed.



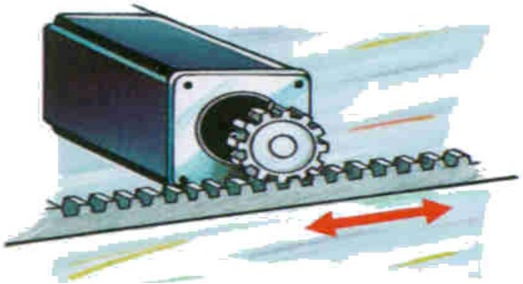
Electromechanical Drive System during Transient State
speed
voltage
T_m
T_l
Speed (rad/s), Voltage (V), Tm (N.m), Tl (n.m)
time (sec)
0
2
4
6
8
10
12
14
16
18
20
0
1
2
3
4
5
6
7
8

Equivalent Values of Drive Parameters

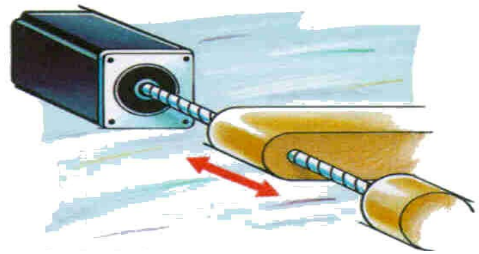
- Loads may be connected to the motor shaft through different mechanism e.g. directly coupled *or* through gear box.

- Coupling is required when
  - a rotating motor is driving a load which requires linear motion;
  - motor is preferred to be operated at higher speeds than required by the load;
  - the axis of rotation needs to be changed

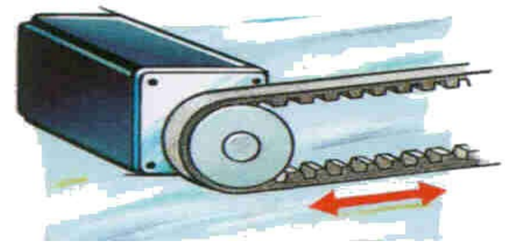
State of the Art: Mechanical Coupling



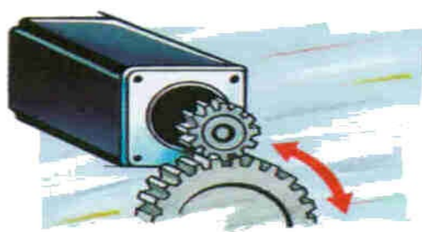
Rack and Pinion



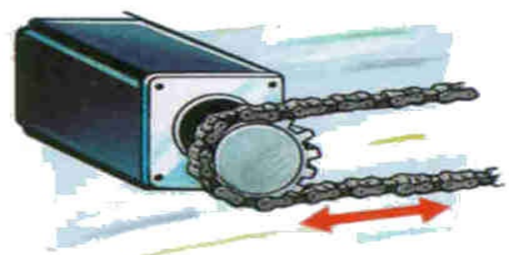
Spindle



Belt



Gear

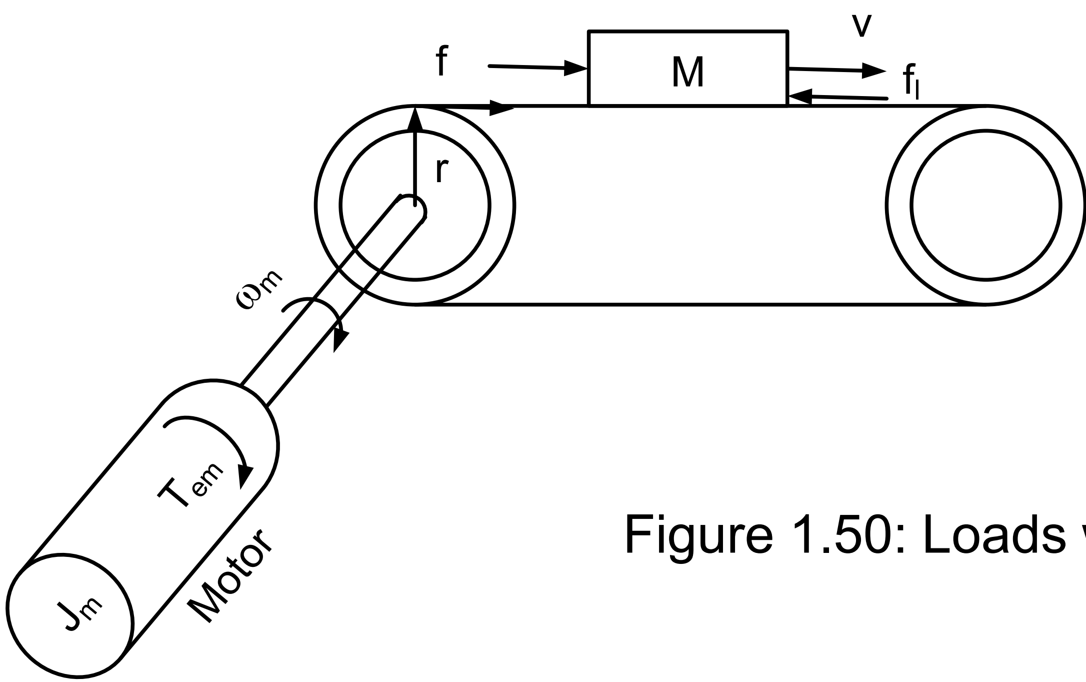


Chain

Prof. Dr. -Ing. J. M. Pacas, University of Siegen
Prof. Dr. -Ing. R. M. Kennel, Wuppertal University

- Different parts of the drive system may have different speeds as well as different types of motion e.g. rotational *or* translational motion.
- Need to calculate equivalent moment of inertia, J_{eq} and also equivalent torque, T_{eq} all referred to the motor shaft in order to determine the power rating of the motor.

Conversion between linear and rotary systems



J_m – motor inertia
M – mass of load
r – pulley radius

Figure 1.50: Loads with translational motion

Loads with Rotational Motion

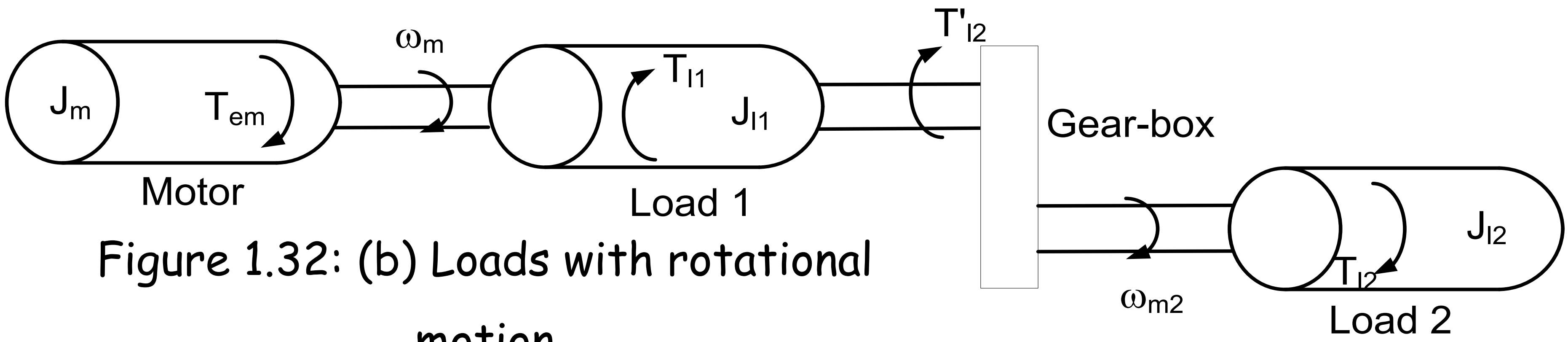


Figure 1.32: (b) Loads with rotational motion

- Assuming no power loss in the gear-box, negligible mass :

$$T'_{l2} \times \omega_m = T_{l2} \times \omega_{m2} \text{ (no power loss)}$$

$$\frac{\omega_{m2}}{\omega_m} = \frac{T'_{l2}}{T_{l2}} = a = \frac{1}{a'} \text{ (1.14) } (a - \text{gear}-\text{box ratio})$$

- If transmission energy losses are neglected then the kinetic energy due to the equivalent inertia must be the same as K.E. of various rotating parts taken together.
- Let J_{eq} be the equivalent inertia then we have

$$\frac{1}{2}J_{eq}{\omega_m}^2 = \frac{1}{2}(J_m + J_{l1}){\omega_m}^2 + \frac{1}{2}J_{l2}{\omega_{m2}}^2$$

$$J_{eq} = (J_m + J_{l1}) + \left(\frac{\omega_{m2}}{\omega_m} = a\right)^2 J_{l2}$$

$$J_{eq} = (J_m + J_{l1}) + a^2 J_{l2} \quad (1.15)$$

- Let T_l be the equivalent load referred to the motor shaft and efficiency of gear-box be η_1 then based on power equivalence we have

$$T_l \times \omega_m = T_{l1} \times \omega_m + \frac{T_{l2} \times \omega_{m2}}{\eta_1}$$

$$T_l = T_{l1} + \left(\frac{\omega_{m2}}{\omega_m}\right)\frac{T_{l2}}{\eta_1} = T_{l1} + a \times \frac{T_{l2}}{\eta_1} \qquad (1.16)$$

Loads with Rotational and Translational Motion

- Loads with rotational as well as translational motion

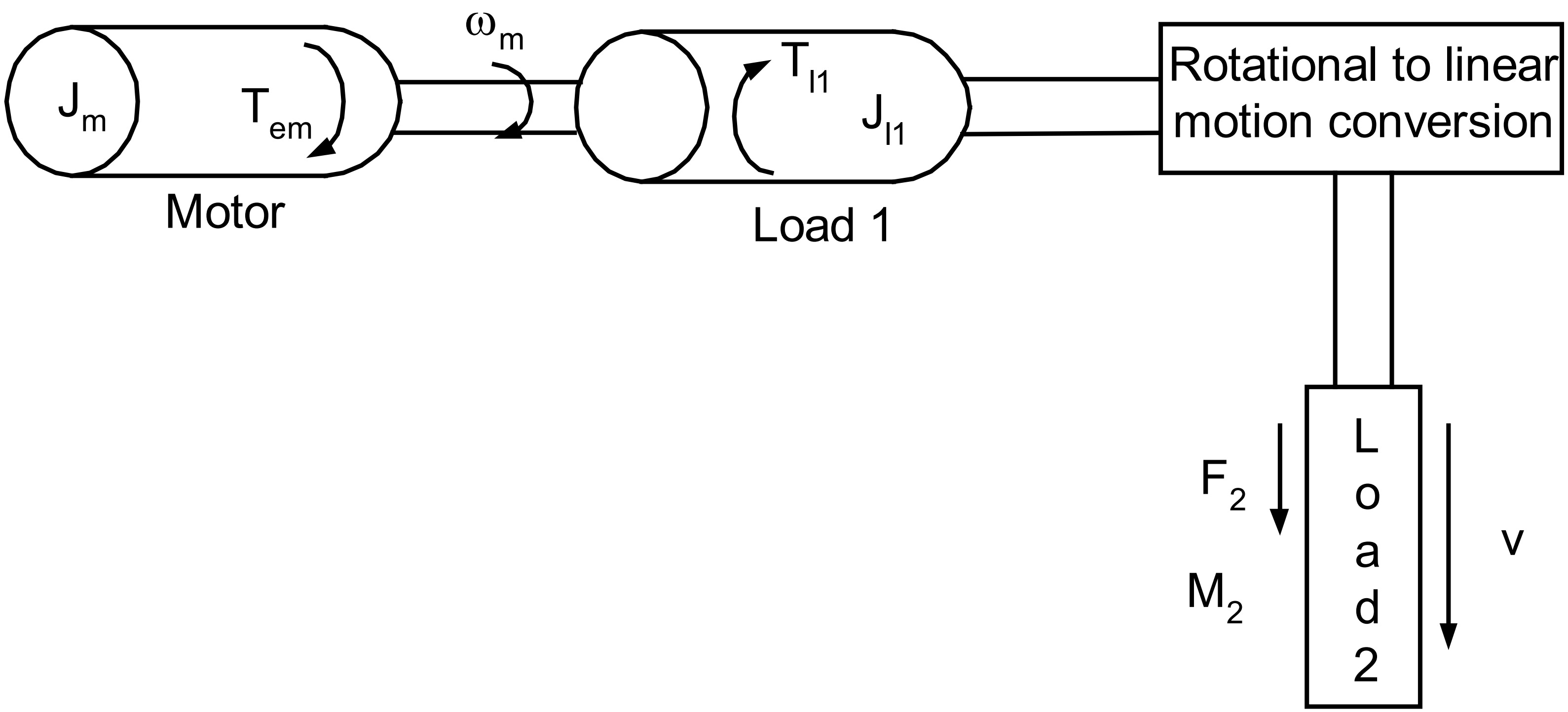


Figure 1.52: (c) loads with rotational and translational motion

- If the transmission energy losses are neglected then the K.E. due to the equivalent inertia "J_{eq}" must be the same as the K.E. of various moving parts. Thus, we have

$$\frac{1}{2} J_{eq} {\omega_m}^2 = \frac{1}{2} (J_{l1} + J_m) {\omega_m}^2 + \frac{1}{2} M_2 v^2$$

$$J_{eq} = (J_{l1} + J_m) + \left(\frac{v}{\omega_m}\right)^2 M_2 \quad (1.17)$$

- Similarly, power output at the motor shaft must be equal to the total power delivered at different loads.

$$T_l \times \omega_m = T_{l1} \times \omega_m + \frac{F_2 \times v}{\eta_2} \; (\eta_2 - \text{efficiency of converter})$$

$$T_l = T_{l1} + \left(\frac{F_2}{\eta_2}\right) \times \left(\frac{v}{\omega_m}\right) \quad (1.18)$$

Example 2:

An electric motor drives two loads: one has rotational motion and is coupled to the motor shaft through a speed reduction gear-box with teeth ratio of $a = 0.1$ and an efficiency of $\eta_1 = 0.9$. The load has a moment of inertia (M.I) of 10 Kg.m^2 and torque of 10 N.m.

The other load has translational motion and consists of 1000 kg. weight to be lifted up at a uniform speed of 1.5 m/s. The coupling between this motor and load has an efficiency of $\eta_2 = 0.85$.

The motor has an inertia of 0.2 kg.m^2 and runs at a constant speed of 1420 rpm. Determine the equivalent inertia referred to the motor shaft and the power developed by the motor.

Solution:

$$J = J_m + \left(\frac{v_1}{\omega_m}\right)^2 M_1 + a^2 J_2$$

$$= 0.2 + \left(\frac{1.5m/\sec}{\frac{2\pi}{60}(1420rpm)}\right)^2 (1000) + (0.1)^2 \times 10$$

$$= 0.4107 kg.m^2$$

$$T_l = \left(\frac{F_2}{\eta_2}\right) \times \left(\frac{v}{\omega_m}\right) + \frac{a_1 T_{l1}}{\eta_1}$$

$$= \frac{1000 \times 9.81}{0.85} \frac{1.5m/\sec}{\frac{2\pi}{60}(1420rpm)} + \frac{0.1 \times 10}{0.9}$$

$$= 117.53 N.m$$

$$P_{out} = T_l \times \omega_m = 117.53 N.m \times \left(\frac{2\pi}{60} \times 1420rpm\right) = 17.5kW$$

Closed-loop Control of Electric Drives

- Many applications require precise control of motor torque, speed and position.
- Open-loop control alone is not sufficient to meet high-performance demand – there is a need for closed-loop feedback control.

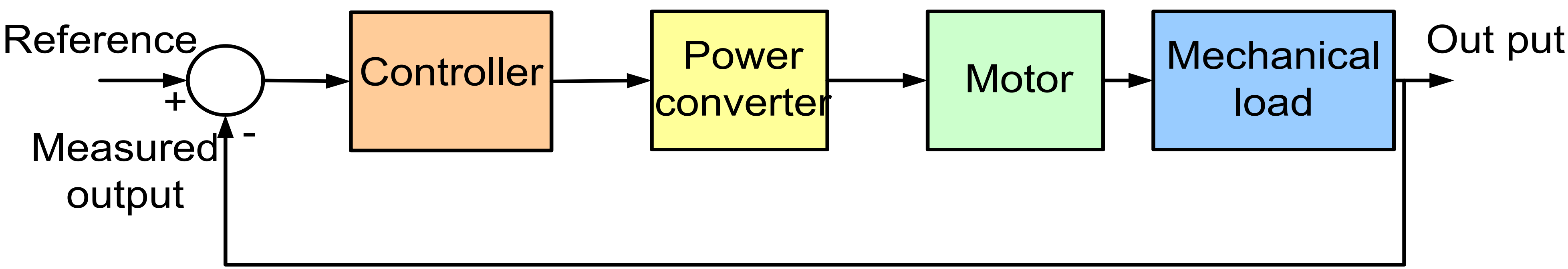


Figure 1.53: Feedback controlled drive.

- Feedback control
  - makes the system insensitive to disturbances (such as load disturbance, supply voltage disturbance etc.) and parameter variation
- The control objectives are to have :
  - zero steady-state error
  - Good dynamic response under transient conditions
    - fast
    - with little overshoot

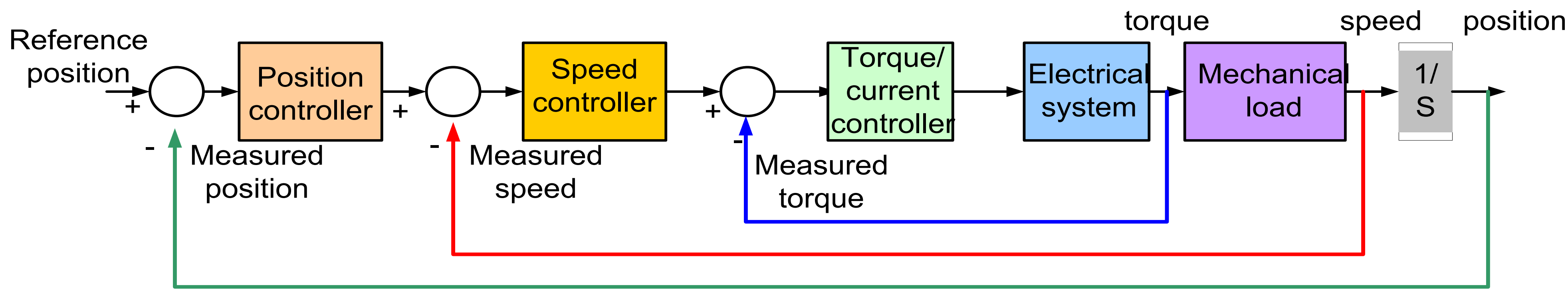


Figure 1.54: Cascaded control of motor drive.

- Cascaded structure is preferred because:
  - it is most flexible
  - each loop can be designed and tuned independently
- Bandwidth (BW) of control loops increases from outer loop towards inner loop:
  - Torque/current loop - fastest
  - Speed loop – slower
  - Position loop - slowest

Drive Specifications

- The purpose of the electric drive is to drive the load which may be a given machinery, in such a manner that the load is able to accomplish the task assigned to it.
- Therefore, the drive specifications are usually decided by the load requirements.
- The load requirements can be divided into three different categories namely:
  - Requirements related to transient operations;
  - Requirements related to normal operations and
  - Requirements related to location and environment.

Requirements related to transient operations –

1. Nature and range of torque:
   - How dose the load torque vary with different speed settings?
   - Dose the machines started/stopped/reversed frequently?
2. What is the inertia – low or high?
3. How much time is allowed for transient operations?
4. Is smooth acceleration or deceleration necessary?
5. Is it required to have quick stop or reversal in emergency?
6. Are these operations to be done automatically or manually?

- Requirements related to normal operation

1. Nature and range of the load torque and power.
2. Is it to be operated at one speed or at few discrete speeds?
3. Is variable speed operation required? If so what is the speed range and whether speed to be controlled in a stepless manner or at few discrete points only?
4. What is the permissible regulation of the speed?
5. Will the load be overhauling at any part of the cycle? Will it be supplying a substantial amount of energy or a small amount of energy during overhauling?

- Requirements related to location and environment –
  - Does the location allows easy access for maintenance?
  - Is it going to operated in an environment where there is substantial dust, flammable gasses etc.?
  - Is it going to submerged in water or any liquid?
  - Is it going to be placed under protective shed or in open air?
- In practice, it is found that more than one motor drive can meet the load requirements. In that case, the one which is best in terms of cost, reliability, maintenance needs, efficient is chosen.

Summary

- Principles of Electro-mechanical Energy Conversion
- Electric Drive System and its components
- Why Variable Speed Drive is required?
- Dynamics of motor-load system
- Components of load torque and characteristics of various types of load
- Need for braking in electric drives and various types of electrical braking mechanism
- Study of stability of Electric Drive System
- Power Converters for electric drives
- Different modes of operation of an electric drive system
- Transient operation of drive system
- Closed-loop operation of electric drive system
- Drive specifications

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