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Chapter 1

ENERGY CONVERSION IN ELECTRIC DRIVES

1.1. ELECTRIC DRIVES - A DEFINITION

An electric drive is an industrial system which performs the conversion of electrical energy to mechanical energy (in motoring) or vice versa (in generator braking) for running various processes such as: production plants, transportation of people or goods, home appliances, pumps, air compressors, computer disc drives, robots, music or image players, etc.

About 50% of electrical energy is used in electric drives today.

Electric drives may run at constant speed (Figure 1.1) or at variable speed (Figure 1.2).

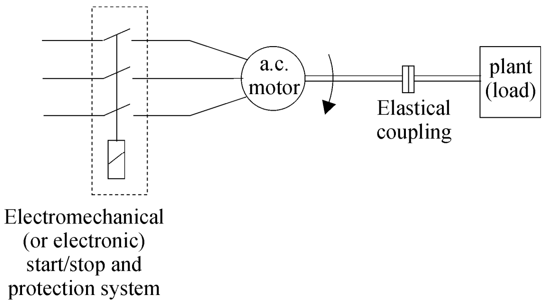

Figure 1.1. Constant speed electric drive

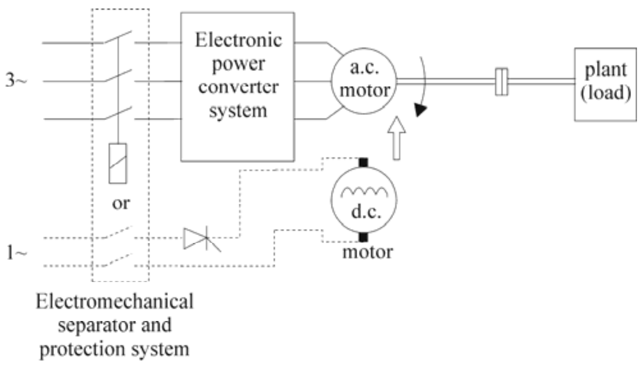

Figure 1.2. Variable speed electric drive

The constant speed electric drive contains the electric (alternating current) motor, the mechanical coupling, the mechanical load (plant) and the electromechanical (or electronic) start/stop and protection system. Today about (75-80)% of all electric drives still run at constant speed because there is not much need for speed control except for starting, stopping and protection.

However there is a smaller (20-25)% group of applications, with very fast annual expansion rate where the torque and speed must be varied to match the mechanical load.

A typical variable speed electric drive (Figure 1.2) contains, in addition, a power electronic converter (PEC) to produce energy conservation (in pumps, fans, etc.) through fast, robust and precise mechanical motion control as required by the application (machine tools, robots, computer-disk drives, transportation means, etc.)

Even though constant speed electric drives could constitute a subject for a practically oriented book, in this book we will refer only to variable speed electric drives which make use of power electronic converters (PECs). For brevity, however, we use the simple name of electric drives.

1.2. APPLICATION RANGE OF ELECTRIC DRIVES

A summary of the main industrial applications and power range of electric drives is shown in Figure 1.3.

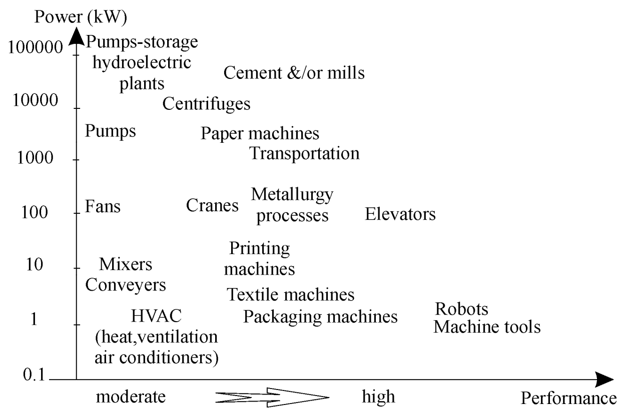

Figure 1.3. Electric drives-variable speed applications

Singular applications such as pumped-storage hydroelectric plants are now built for unit powers of 100MW or more. High performance means, in Figure 1.3, wide speed range, fast and precise response in speed, or position control.

Traditionally, for variable speed, DC brush motors have been used for decades [1] but AC motors [2,3] have been catching up lately (since 1990) as shown in Figure 1.4. This radical shift is mainly due to the rapid progress in power electronic converters for AC motors [4].

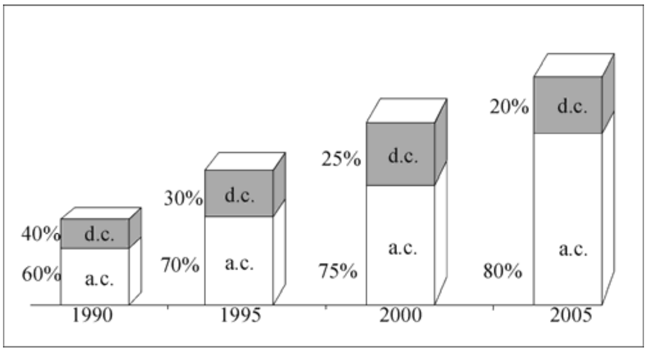

Figure 1.4. AC versus DC electric drives market dynamics

For variable speed, AC motors require both variable voltage amplitude and frequency while DC brush motors require only variable DC voltage. As the mechanical commutator of the motor does, the frequency changes itself.

AC motors are in many cases brushless and have a higher torque (power) density (Nm/kg or kW/kg) than DC brush motors and lower initial and maintenance costs. Today power electronic converters (PECs) for both d.c brush or brushless motors, for reversible speed applications, have comparable prices. The PEC costs are higher than the motor costs but this ratio (C) decreases as the power level increases

$$C = \frac{\text{PEC price}}{\text{a.c. motor price}} = 5 \div 2 \tag{1.1}$$

in general from the kW to MW power range. So what could justify introducing the PEC (Figure 1.2) which is more expensive than the motor?

In most applications the energy savings pay off the additional investment in the PEC in less than 5 years for applications with energy savings of only 25% for only a 1 to 3 speed variation ratio but 24 hours a day operation, above 10kW rated power level. The larger the power the lower the revenue period for a given energy savings percentage.

1.3. ENERGY SAVINGS PAY OFF RAPIDLY

Let us illustrate the energy savings potential pay off for the additional expenses in variable speed drives implied by the presence of the PEC system. Consider a real case when a motor pump system of 15kW works 300 days a year, 24 hours a day and pumps 1200m^3 of water per day. By on/off and throttling control only, the system uses 0.36kWh/m^3 of pumped water to keep the pressure rather constant for variable flow rate.

Adding a PEC, in the same conditions, the energy consumption is 0.28kWh/m^3 of pumped water, with a refined pressure control.

Let us consider that the cost of electrical energy is 8 cents/kWh.

The energy savings per year S is:

$$S = 1200 \cdot 300(0.36 - 0.28) \cdot \$0.08/\text{year} = \$2304/\text{year} \tag{1.2}$$

Now the costs of a 15kW PWM-PEC for an induction motor is less than \$8000. Thus, to a first approximation, only the energy savings pay off the extra investment in less than 4 years.

After this coarse calculation let us be more realistic and notice that the energy costs, interest rates and inflation rise slowly every year and taxes also lower to some extent the beneficial effect of energy saving through PEC, contributing to an increase in the revenue period.

Example 1.1. The revenue time.

Let us consider that S dollars (1.2) have been saved in the first year on energy losses through the introduction of a PEC system, and denote by i the interest rate and by i_p the power cost yearly increase.

Thus the effective interest rate per year i_E is

$$i_E = \frac{1+i}{1+i_p} - 1 \tag{1.3}$$

The net present value (NPV) of losses for an n-year period is

$$NPV = S \cdot \frac{(1+i_E)^n - 1}{i_E \cdot (1+i_E)} \tag{1.4}$$

We may now consider the influence of taxes and inflation on these savings

$$NPV^E = NPV_e + NPV_d \tag{1.5}$$

where NPV_e is the net present value of energy savings and NPV_d is the net present value of depreciation on premium investment (straight line depreciation is assumed). With T the tax range

$$NPV_e = NPV \cdot (1 - T) \tag{1.6}$$

$$NPV_d = \frac{NPV_e}{n} \cdot \frac{\left[(1+i)^n - 1\right]}{i \cdot (1+i)^n} \cdot T \tag{1.7}$$

With S = \$2304 as the first year savings, for a period of n = 5 years, with i = 10%, i_p = 5% and T = 40% we obtain gradually

from (1.3): $$i_E = \frac{1+0.1}{1+0.05} - 1 = 0.0476$$

from (1.4):
$$\text{NPV} = 2304 \cdot \frac{1.0476^5 - 1}{0.0476 \cdot 1.0476^5} = \$10047.7$$

from (1.6):
$$\text{NPV}_e = 10047.7 \cdot (1 - 0.4) = \$6028.6$$

from (1.7):
$$\text{NPV}_d = 6028.6 \cdot \frac{(1 + 0.1)^5 - 1}{0.1 \cdot (1 + 0.1)^5} \cdot 0.4 = \$1828.8$$

Finally the premium investment that can be expanded to achieve \$2034 energy savings in the first year for a period of 5 years is, from (1.5),

$$\text{NPV}^E = 6028.6 + 1828.8 \approx \$7857.$$

This is roughly \$8000 (the costs of the PEC), so more exact calculations have led to an increase of the revenue duration from 4 to 5 years.

Considering that lifetime of PEC drives is more than 10-15 years, the investment pays off well.

1.4. GLOBAL ENERGY SAVINGS THROUGH PEC DRIVES

So far the energy savings produced by the PEC in variable speed drives have been calculated for the drive only-PEC and motor.

If we consider the costs to produce and transport the saved electric energy to the consumer (drive) location, the rentability of energy savings increases dramatically. Figure 1.5 shows the energy flow from the power plant to the motor-pump system for constant speed operation and 10kW of useful power, when using throttling to control (reduce) the flow rate.

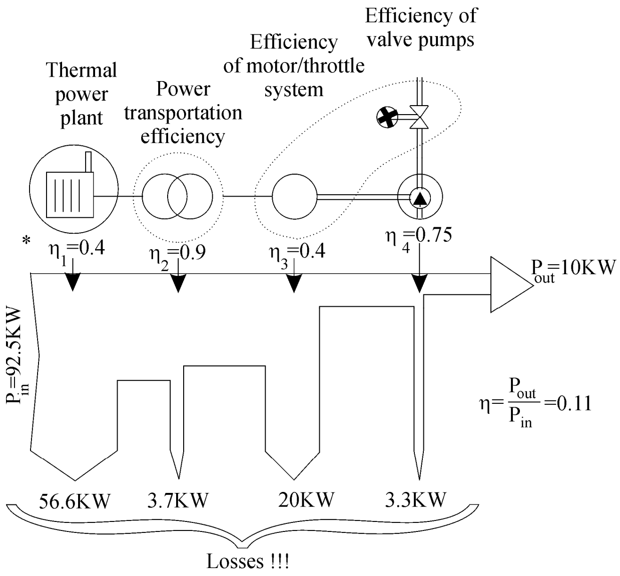

Figure 1.5. Primary energy consumption for throttle / motor / pump system

The total efficiency from the primary energy source is only 11%. This is poor energy utilization. When a PEC is introduced to produce the same useful power a much better energy utilization ratio is obtained (Figure 1.6).

The energy utilization factor (η) is doubled by the presence of PEC drives for variable speed. So, to the energy savings value in the drive, we should add the savings along the entire chain of energy conversion and distribution, from the power plants to the consumers.

Variable speed with PEC drives, applied today to 15-20% of all electric motor power in developed countries is expected to reach 30-40% by the year 2010, with an annual extension rate of 7-8%. If we add to this aspect the beneficial effects of motion control by PEC drives on the quality of products and manufacturing productivity, we get the picture of one of the top technologies of the near and distant future with large and dynamic markets worldwide (already 4 billion USD in 2004).

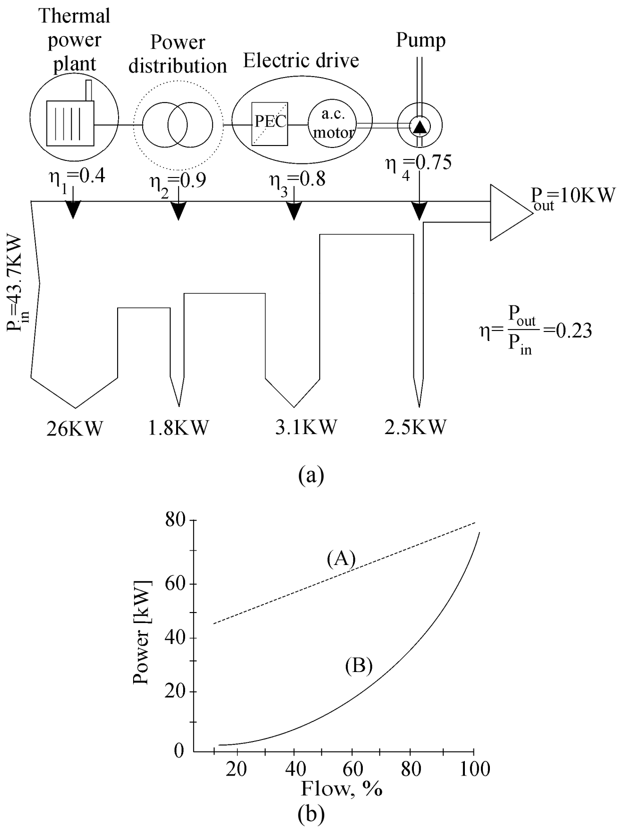

Figure 1.6. a) Primary energy consumption for PEC/motor/pump systems; b) Input power for a 73.6 KW pump motor (A) with output throttle value, (B) with variable voltage/frequency 100 KVA power electronics converter.

1.5. MOTOR/MECHANICAL LOAD MATCH

The role of electric drives is, in fact, to match the electric motor to the mechanical load and to the electrical power grid.

The mechanical load is described by shaft torque/speed or torque/time plus speed/time or position/time relationships.

1.5.1. Typical load torque/speed curves

Typical load torque/speed curves are shown in Figure 1.7. They give a strong indication of the variety of torque/speed characteristics. Along such curves the mechanical power required from the motor varies with speed.

The base speed (unity speed in Figure 1.7) corresponds to continuous duty rated torque (and power) and rated (maximum) voltage from the PEC.

$$\text{Power} = T_{load} \cdot \Omega_r \tag{1.8}$$

To match the required speed/torque (and power) envelope, the motor and PEC should be carefully chosen or designed. However, the motor to mechanical load match should be provided not only for steady state but also during transients such as drive acceleration, deceleration or short overload periods. The transients require higher torques, in general below base speed, and both the motor and the PEC have to be able to withstand it.

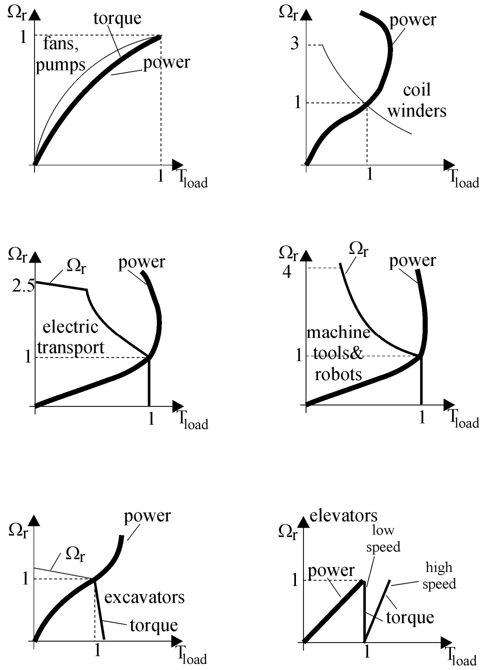

Figure 1.7. Typical load speed/torque, speed/power curves

1.6. MOTION/TIME PROFILE MATCH

For some applications such as robots and electric transportation for given load inertia and load torque/time, a certain position/time (and) or speed/time profile is required. An example is shown in Figure 1.8. There are acceleration, cruising and deceleration intervals. They are strong grounds for the design (sizing) of the electric drives. The torque varies with time and so does the motor current (and flux linkage level). The electric, magnetic and thermal loadings of the motor and the electric and thermal loading of the PEC are definite constraints in a drive specification.

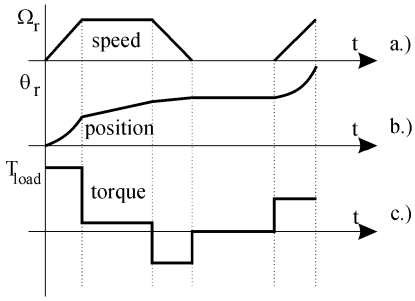

Figure 1.8. Motion/time profile:
a.) speed; b.) position; c.) required load torque.

Here is an illustrative example.

Example 1.2. The direct drive torque/time curve.

A direct drive has to provide a speed/time curve such as in Figure 1.9 against a constant load torque of T_L = 10Nm, for a motor load inertia J = 0.02 kgm^2.

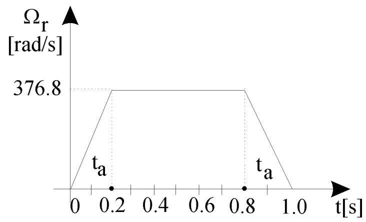

Figure 1.9. Required speed / time profile

Neglecting the mechanical losses lets us calculate the motor torque (T_e)/ time requirements.

The motion equation for a direct drive is

$$T_e(t) = J \cdot \dot{\Omega}_r(t) + T_L(t) \tag{1.9}$$

For the linear speed/time (acceleration-deceleration) zones the speed derivative is

$$\dot{\Omega}_r = \pm\frac{\Omega_{r\,max}}{t_a} = \pm\frac{376.8}{0.2} = \pm 1884 rad/s^2 \tag{1.10}$$

For the constant speed (cruising) zone $\dot{\Omega}_r$ = 0.0.

Consequently, the torque requirements from the motor for the three zones are:

$$T_e = \begin{cases} 1884 \cdot 0.02 + 10 = 37.68 + 10 = 47.68\text{Nm}; & \text{for } 0 \le t \le 0.2\text{s} \\ 0 + 10 = 10\text{Nm}; & \text{for } 0.2 \le t \le 0.8\text{s} \\ -1884 \cdot 0.02 + 10 = -37.68 + 10 = -27.68\text{Nm}; & \text{for } 0.8 \le t \le 1\text{s} \end{cases} \quad (1.11)$$

The motor torque/time requirements of (1.11) are shown in Figure 1.10.

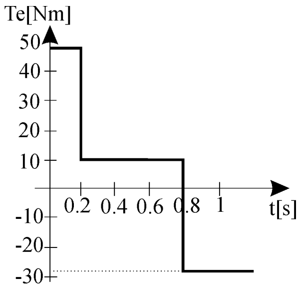

Figure 1.10. Motor torque/time requirements

It is known that a theoretical-sudden motor torque is not practical with a limited available source power. However, a quick torque variation is required.

Advanced PEC drives today manage a zero to rated torque ramping in only 1-5 ms. Lower values correspond to low powers (1kW), while higher values refer to larger powers (hundreds of kW or more). Many electric drives use a mechanical transmission for speed multiplication or for speed reduction by a ratio. The motor and load inertia are "coupled" through the mechanical transmission. Let us illustrate this aspect through a numerical example.

<u>Example 1.3.</u> Gear-box drive torque/time curve.

Let us consider an electric drive for an elevator with the data shown in Figure 1.11.

The motor rated speed n_n = 1550rpm. The efficiency of the gearing system is η = 0.8.

Let us calculate the total inertia (reduced to motor shaft), torque and power without and with counterweight.

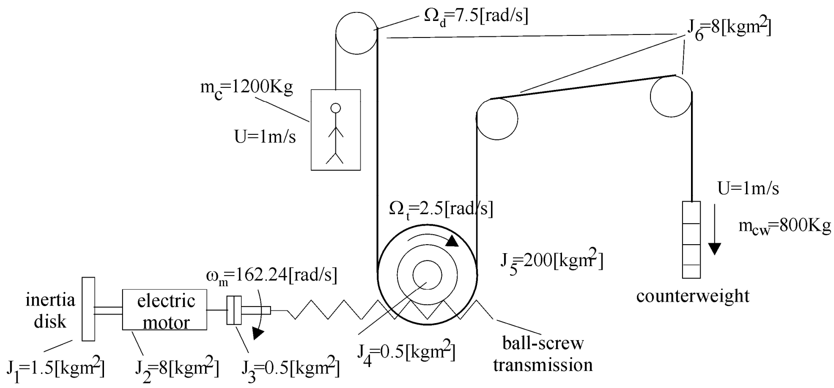

Figure 1.11. Elevator electric drive with multiple mechanical transmissions and counterweight

First the motor angular speed ω_m is

$$\omega_m = 2 \cdot \pi \cdot n_n = 2 \cdot \pi \cdot \frac{1550}{60} = 162.22 \text{ rad/s} \tag{1.12}$$

The gear ratios may be defined as speed ratios Ω_t / ω_m for J_4+J_5 and Ω_d / ω_m for J_6 (Figure 1.11).

Consequently the inertia of all rotating parts J_r, reduced to the motor shaft (Figure 1.11), is

$$J_r = J_1 + J_2 + J_3 + (J_4 + J_5) \cdot \frac{\Omega_t^2}{\omega_m^2} + J_6 \cdot \frac{\Omega_d^2}{\omega_m^2} =$$

$$= 15 + 8 + 2 + (0.5 + 200) \cdot \left(\frac{2.5}{162.22} \right)^2 + 8 \cdot \left(\frac{7.5}{162.22} \right)^2 = 25.062 \text{ kgm}^2 \tag{1.13}$$

For the cabin and the counterweight, the inertia reduced to motor shaft (J_e) is

$$J_e = (m_c + m_{cw}) \cdot \frac{u^2}{\omega_m^2} = (1200 + 800) \cdot \frac{1^2}{166.22^2} = 0.07238 \text{ kgm}^2 \tag{1.14}$$

Thus the total inertia J_t is

$$J_t = J_r + J_e = 25.062 + 0.07238 = 25.135 \text{ kgm}^2 \tag{1.15}$$

In absence of counterweight the law of energy conservation leads to

$$T_{em} \cdot \omega_m \cdot \eta = m_c \cdot g \cdot u \tag{1.16}$$

Consequently the motor torque, T_{em}, yields

$$T_{em} = \frac{1200 \cdot 9.81 \cdot 1}{162.22 \cdot 0.8} = 90.71\,\text{Nm} \tag{1.17}$$

The motor electromagnetic power P_{em} is

$$P_{em} = T_{em} \cdot \omega_m = 90.71 \cdot 162.22 = 14715\,\text{W} \tag{1.18}$$

On the other hand in the presence of a counterweight (1.16) the power balance becomes

$$T_{em}' \cdot \omega_m \cdot \eta = (m_c - m_{cw}) \cdot g \cdot u \tag{1.19}$$

$$T_{em}' = \frac{(1200 - 800) \cdot 9.81 \cdot 1}{162.22 \cdot 0.8} = 30.71\,\text{Nm} \tag{1.20}$$

So the motor electromagnetic P'_{em} is

$$P_{em}' = T_{em}' \cdot \omega_m = 30.71 \cdot 162.22 = 4905\,\text{W} \tag{1.21}$$

It should be noted that the counterweight alone produces a 3 to 1 reduction in motor electromagnetic power yielding important energy savings. On top of this, for the acceleration-deceleration periods, the PEC drive adds energy savings and produces soft starts and stops for a good ride quality. To do so in tall buildings, high speed quality elevators with up to 1/1000 motor speed variation (control) range are required. This is why in Figure 1.3 elevators are enlisted as high performance drives.

1.7. LOAD DYNAMICS AND STABILITY

Load dynamics in an electric drive with rigid mechanical coupling between motor and load is described by the equation

$$J_t \cdot \frac{d\Omega_r}{dt} = T_e - T_{friction} - T_{load} \tag{1.22}$$

where J_t is the total inertia of motor and load reduced to motor shaft, T_e is the motor electromagnetic torque, T_{load} is the actual load torque, and $T_{friction}$ is the total friction torque of the motor/transmission subsystem. The friction torque, $T_{friction}$, has quite a few components

$$T_{friction} = T_S + T_C + T_V + T_W \tag{1.23}$$

where T_S is the static friction torque (at zero speed); T_C is Coulomb friction torque (constant with speed); T_V is viscous friction torque (proportional to speed) and T_W is windage friction (including the ventilator braking torque, proportional to speed squared)

$$T_V = B' \cdot \Omega_r \tag{1.24}$$

$$T_W = C \cdot \Omega_r^{\,2} \tag{1.25}$$

The friction torque components are shown in Figure 1.12. Only to a first approximation we may write

$$T_{friction} = B \cdot \Omega_r \tag{1.26}$$

In this latter case (1.22) becomes

$$J \cdot \frac{d\Omega_r}{dt} = T_e - T_{load} - B \cdot \Omega_r \tag{1.27}$$

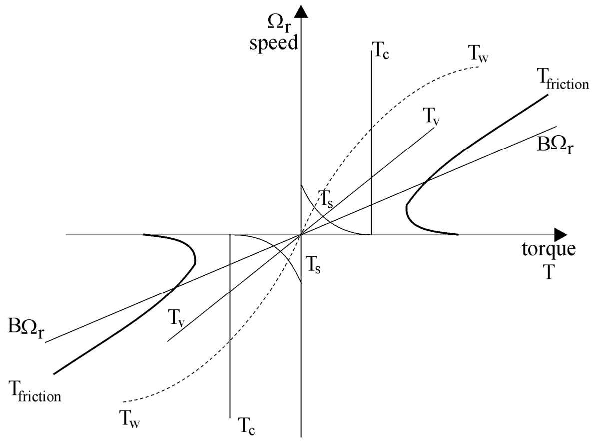

Figure 1.12. Components of friction torque, $T_{friction}$

If T_e and T_{load} are constant, the solution of (1.27) is

$$\Omega_r(t) = \Omega_{r\,final} + A \cdot e^{-t/\tau_m} \tag{1.28}$$

where $\Omega_{r\ final}$ is the final, steady state, speed and τ_m = J/B is the so-called mechanical time constant, and A is a constant to be determined from initial conditions. Equation (1.28) reflects a stable aperiodic response. As

$$\Omega_r = \frac{d\theta_r}{dt} \tag{1.29}$$

(1.27) becomes

$$J \cdot \frac{d^2\theta_r}{dt^2} + B \cdot \frac{d\theta_r}{dt} - T_e = -T_{load} \tag{1.30}$$

Clearly, for stable operation the transients in θ_r must die out. As B is generally small, stability is obtained if the motor torque T_e is of the form

$$T_e \approx -C_e \cdot \frac{d\theta_r}{dt}; \;\; C_e > 0 \tag{1.31}$$

or

$$T_e \approx -C_e \cdot \frac{d\theta_r}{dt} - C_i \cdot \theta_r; \;\; C_e, C_i > 0 \tag{1.32}$$

with (1.31)-(1.32), (1.30) becomes

$$J \cdot \frac{d^2\theta_r}{dt^2} + (B + C_e) \cdot \frac{d\theta_r}{dt} + C_i \cdot \theta_r = -T_{load} \tag{1.33}$$

Now it is evident that the θ_r transients will be stable.

Note: For the synchronous machine θ_r is in fact the angle between the e.m.f. and the terminal voltage, which is constant for steady state.

Let us see if the torque/speed curves of basic DC brush and AC motors satisfy (1.33). Typical torque/speed or torque/angle curves for these machines are shown in Figure 1.13.

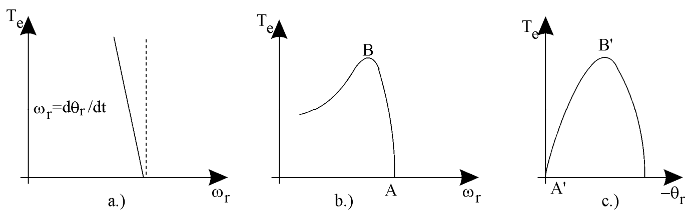

Figure 1.13. Mechanical characteristics: a) DC brush motor with separate excitation, b) induction motor, c) synchronous motor

Condition (1.13) is fulfilled by the DC brush motor as

$$-C_e = \frac{dT_e}{d\left(\frac{d\theta_r}{dt}\right)} < 0 \tag{1.34}$$

The torque decreases with speed steadily. For the induction motor (Figure 1.13b) only along the zone AB

$$\frac{dT_e}{d\omega_r} < 0 \tag{1.35}$$

Finally for the synchronous motor (Figure 1.13c) only along the zone A´B´

$$-C_i = \frac{dT_e}{d\theta_r} < 0 \tag{1.36}$$

The above discussion serves only to signal the problem of electric drive dynamics and stability. The presence of PECs frees the mechanical characteristics from the forms in Figure 1.13 obtained for constant voltage (and frequency). Consequently, stable response in position, speed, or torque may be artificially obtained through adequate control of voltage and frequency at the motor electrical terminals.

Two simple examples follow:

Example 1.4. DC brush motor drive stability.

A permanent magnet DC brush motor with the torque speed curve: $\Omega_r = 200.0 - 0.1 \cdot T_e$ drives a DC generator which supplies a resistive load such that the generator torque / speed equation is $\Omega_r = 2T_L$. We calculate the speed and torque for the steady state point and find out if that point is stable.

Solution:

Let us first draw the motor and load (generator) torque speed curves in Figure 1.14.

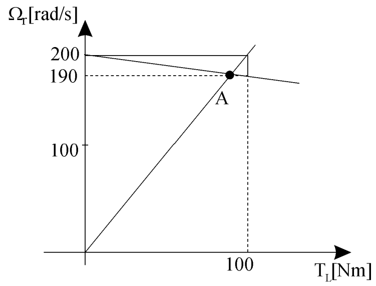

Figure 1.14. DC brush motor load match

The steady state point, A, corresponds to constant speed and B = 0 in (1.27). Simply, the motor torque counteracts the generator braking torque

$$T_L = T_e \tag{1.37}$$

Using the two torque speed curves we find

$$\Omega_{rA} = 200 - 0.1 \cdot \frac{\Omega_{rA}}{2} \tag{1.38}$$

and thus

$$\Omega_{rA} = \frac{200}{1 + 0.1/2} = 190.476 \text{ rad/s} \tag{1.39}$$

and

$$T_{eA} = T_{LA} = \frac{\Omega_{rA}}{2} = \frac{190.476}{2} = 95.238 \text{ Nm} \tag{1.40}$$

The static stability is met if

$$\left(\frac{\partial T_e}{\partial \Omega_r}\right)_A < \left(\frac{\partial T_L}{\partial \Omega_r}\right)_A \tag{1.41}$$

In our case from the two torque/speed curves

$$-10 < \frac{1}{2} \tag{1.42}$$

and thus, as expected, point A represents a situation of static equilibrium.

Example 1.5. Induction motor drive stability.
An induction motor has the torque speed curve given by

$$T_e = \frac{2T_{eK}}{\frac{S}{S_K} + \frac{S_K}{S}};\ S = \frac{\omega_1 - \omega_r}{\omega_1};\ S_K = 0.1;\ T_{eK} = 20\ \text{Nm} \tag{1.43}$$

where S - slip; ω_1 - primary frequency; ω_r - rotor electrical speed ($\omega_r = \Omega_r.p$; p - number of winding pole pairs). This motor drives a DC generator with a resistive load whose torque / speed curve is $T_L = C.\omega_r$. Neglecting the mechanical losses (B = 0) we decide to check out static stability conditions for T_e = 10Nm.
Solution:
Let us draw the two mechanical characteristics (Figure 1.15).

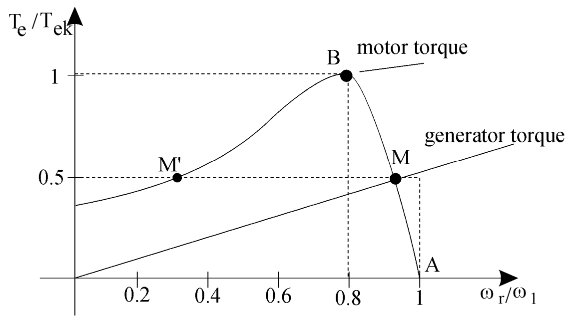

Figure 1.15. Induction motor / DC generator load

The slip value for T_e = 10Nm may be found from

$$10 = \frac{2 \cdot 20}{\frac{S}{0.2} + \frac{0.2}{S}} \tag{1.44}$$

The solutions of (1.44) are

$$S_1 = 0.0436;\ \text{point M in figure 1.15}$$

$$S_2 = 0.7464; \text{point M' in figure 1.15} \tag{1.45}$$

The static stability depends on the sign of $\partial T_e / \partial \omega_r$

$$\frac{\partial T_e}{\partial(\omega_r / \omega_1)} = \frac{-\partial T_e}{\partial S} = \frac{2T_e}{\left(\frac{S}{S_k} + \frac{S_K}{S}\right)^2} \cdot \left(\frac{1}{S_k} - \frac{S_K}{S^2}\right) \tag{1.46}$$

So for
$$S < S_K; \ \frac{\partial T_e}{\partial(\omega_r / \omega_1)} < 0; \ \text{stable zone} \tag{1.47}$$

and for
$$S > S_K; \ \frac{\partial T_e}{\partial(\omega_r / \omega_1)} > 0; \ \text{unstable zone} \tag{1.48}$$

As at point M $S_1 = 0.0536 < S_K = 0.2$, M corresponds (as expected) to static stability conditions while at point M´ $S_2 = 0.7464 > S_K = 0.2$; M´ is within the instability zone.

1.8. MULTIQUADRANT OPERATION

An electric drive may be required to provide for forward and reverse motion with rapid (regenerative) braking in both directions. Motor operation implies torque in the direction of motion. In regenerative braking the torque is opposite to the direction of motion, and the electric power flow in the motor is reversed also (negative). These possibilities are summarized in Table 1.1 and in Figure 1.16.

Table 1.1.

Mode of operation	Forward motoring	Forward regenerative braking	Reverse motoring	Reverse regenerative braking
Speed, ω_r	+	+	-	-
Torque, T_e	+	-	-	+
Electric power flow	+	-	+	-

Positive (+) electric power flow means electric power drawn from the PEC by the motor while negative (-) refers to electric power delivered by the motor (in the generator mode) to the PEC.

The PEC has to be designed to be able to handle this bi-directional power flow. In low and medium power PECs (up to hundreds of kW) with slow braking demands the generated power during the braking periods is interchanged with the strong filter capacitor of PEC or DC (dynamic) braking is being used.

For DC dynamic braking the kinetic energy of the motor-load system is converted to heat in the motor rotor. For fast and frequent generator brakings the PEC has to handle the generated power either by a controlled braking resistor or through bidirectional power flow. All these aspects will be discussed in some detail later in subsequent chapters.

For a fast speed response, modern variable speed drives may develop a maximum transient torque up to base speed ω_b and maximum transient power up to maximum speed, provided that both the motor and the PEC can handle these powers.

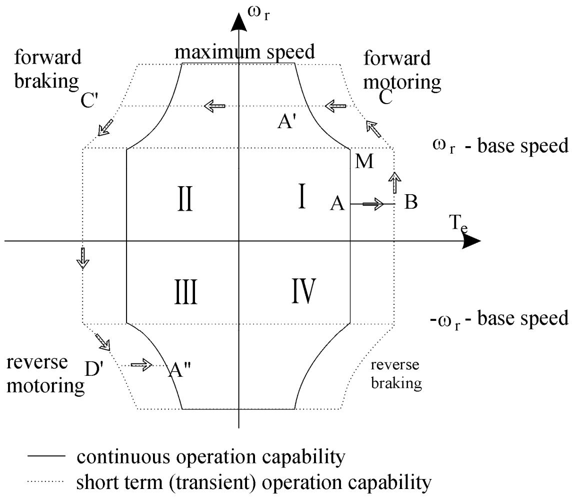

Figure 1.16. Electric drives with four quadrant operation

A rapid increase in speed from point A to point A´ (Figure 1.16) is managed along the ABCA´ path which remains in the first quadrant. A slow speed increase from A to A´ is performed along the path AMA´. For a speed reversal (from A to A´´ the trajectory goes along the path AA´C´D´ through the second quadrant (regenerative braking). Such speed transitions indicate the complexity of energy conversion and transfer between the motor, PEC and power source in a multiquadrant electric drive.

Note: So far we discussed only rotary motor electric drives. However for each rotary motor there is a linear counterpart. Torques and angular speeds will be replaced by thrust and linear speed, respectively, in linear motor drives [5]. Linear motor, however, are not treated in this book.

1.9. PERFORMANCE INDEXES

The electric drives performance indexes defined in what follows are divided into three main categories: energy conversion indexes, drive response indexes and costs and weight indexes.

Electric drives perform the conversion of electrical energy to mechanical energy or vice versa through the use of magnetic energy as a storage medium. A typical electric drive more detailed structure contains the following: an electric motor, a static power converter, feedback sensors (or observers) and a digital (or analog or hybrid) motion controller (Fig. 1.17)

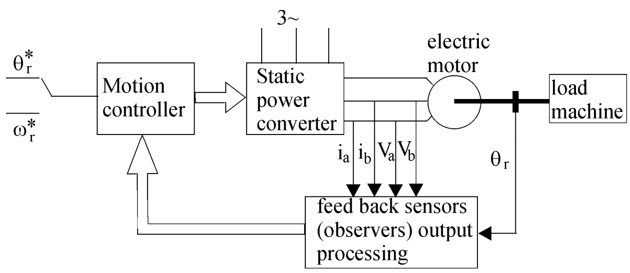

Figure 1.17. Electric drive basic topology

(a) Power efficiency (for steady state)

Energy conversion in an electric drive takes place both in the static power converter and in the electric motor. The energy flows from the static power converter to the electric machine in the motor regime (Fig. 1.18a), and vice versa for regenerative braking (Fig. 1.18b).

Energy conversion is accompanied by losses: conduction and commutation losses in the static power converter (p_{conv}), conduction, core, and mechanical losses in the motor (p_{mot}).

For steady state, the rating of energy conversion from electrical to mechanical or vice versa may be derived through the power efficiency η_p defined for the motor (η_{pm}) or for the drive (η_{pd}):

$$\eta_{pm} = \frac{P_{out}}{P_{out} + \sum p_{mot}} \tag{1.49}$$

$$\eta_{pd} = \frac{P_{out}}{P_{out} + \sum p_{mot} + \sum p_{conv}} \tag{1.50}$$

As speed is variable in electric drives, the power efficiency is relevant for base speed (ω_b), maximum speed (ω_{max}), and rated torque for these two situations.

Base speed ω_b is the speed for which full voltage is required to produce the peak design continuous operation torque T_{ek}. Above base speed the voltage remains constant and, in AC motors, only the frequency increases. In many servo drives $\omega_b = \omega_{max}$, that is, the peak torque T_{ek} is available up to maximum speed when the static power converter rating is defined for maximum rather than for base speed.

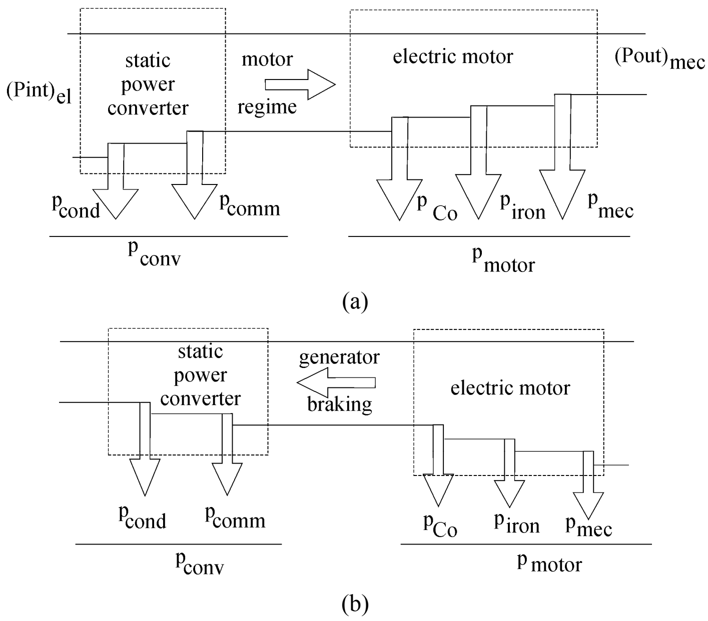

Figure 1.18. Energy conversion in electric drives;

a) motor regime, b) generator braking.

(b) Energy efficiency (for mechanical transients)

In some applications the variable speed drives undergo very frequent mechanical transients (speed and torque transients): hybrid and electric cars.

To assess the energy conversion efficiency for such cases the energy efficiency η_E for the motor (η_{Em}) and for the drive (η_{Ed}) are defined:

$$\eta_{Em} = \frac{W_{out}}{W_{out} + W_{motor}} \tag{1.51}$$

$$\eta_{Ed} = \frac{W_{out}}{W_{out} + W_{motor} + W_{conv}} \tag{1.52}$$

Where W_{out} is the output (useful) energy, W_{motor} are the motor total energy losses, and W_{conv} are the converter total energy losses.

The energy efficiency may be an important optimization criterion for the design of the drives (motor, converter and controller) with frequent mechanical transients (robotics, urban transit drives, etc.).

(c) Losses / torque [W/Nm] ratio.

A more flexible energy conversion index is the ratio between the motor losses and the motor torque. The W/Nm ratio may refer to motor winding power losses only. In this case the W/Nm ratio is most adequate for prolonged low speed operation, as the core losses at low speed are small.

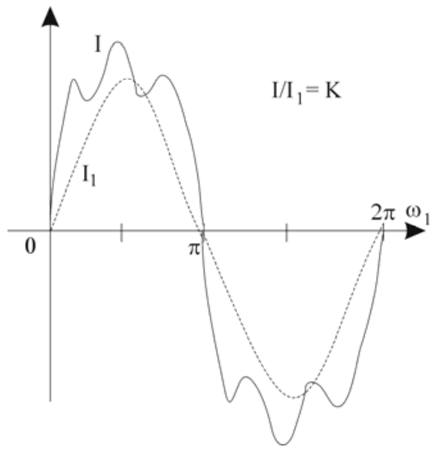

Figure 1.19. Alternating motor phase current in the field weakening zone (six-pulse inverter regime)

For high speed however, all losses in the motor have to be considered in the W/Nm, in order to assess the heating of the motor fairly.

(d) RSM kW/kVA ratio

The RSM kW/kVA ration for AC motors is in general computed for the fundamental components and represents, in fact, the displacement power factor DPF:

$$DPF = (kW / kVA)_{motor} = \frac{P_{in}}{3V_1 I_1} \tag{1.53}$$

For given torque, the higher the displacement power factor, the smaller the current drawn by the motor for given terminal voltage and frequency. The power factor DPF thus has considerable influence on stator winding losses, and finally on power efficiency.

(e) Peak kW/kVA ratio

As most variable speed servodrives make use of MOSFET or IGBT transistors, the static power converters are sized according to the peak current and voltage values.

For AC motors, at high speeds, in the weakening zone, the motor phase currents depart considerably from sinusoidal waveforms.

The active input power P_{in} is:

$$P_{in} = \frac{3}{\pi} V_0 I \frac{1}{K} DPF \tag{1.54}$$

WhereV_0 is the DC source voltage at the input of the power converter and I is the peak flat topped phase current; K is the ratio between the actual peak current and the peak value of the current fundamental (Fig. 1.19), in general $k \leq (1.1 - 1.15)$.

$$\text{peak } kW/kVA = \frac{P_{in}}{S_1} = \frac{3}{\pi} V_0 I \frac{1}{K} \frac{DPF}{6V_0 I} = \frac{DPF}{2\pi K} \tag{1.55}$$

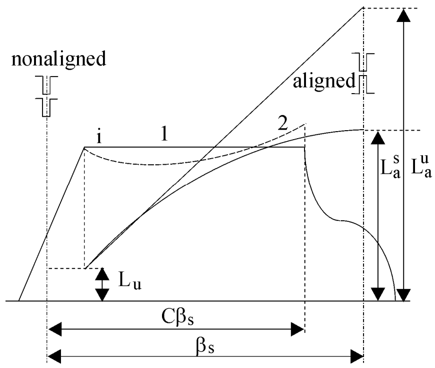

Figure 1.20. Current waveforms in a switched reluctance motor:

1-ideal (chopped) current; 2-actual current at full voltage (no chopping)

On the other hand, the switched reluctance motor (Chapter 12) has unipolar pulse currents with one phase working at a time (Fig. 1.20).

The same performance index may be defined for the switched reluctance motor [6] as:

$$\text{peak } kW/kVA = \frac{\beta_s N_r Q}{8\pi} \tag{1.56}$$

where β_s is the stator pole/stator pole pitch ratio ($\beta_s \cong 0.4$); N_r is number of rotor poles.

$$Q \approx C\left(2 - \frac{C}{s}\right) \tag{1.57}$$

where C is the ratio between the phase turn-on angle and the stator pole angle.

In general, at start (zero speed) C = 1 and decreases with speed (C ≅ 0.65 at base speed).

$$s = \frac{\lambda_u - 1}{\lambda_u \sigma - 1}; \;\; \lambda_u = \frac{L_a^u}{L_u} \approx (6 \div 10); \;\; \sigma = \frac{L_a^s}{L_a^u} = (0.3 \div 0.4) \tag{1.58}$$

L_u, L_a^u, L_a^s are the phase inductance values shown in Fig. 1.20.

The peak apparent power, S_1 is:

$$S = 2 \cdot m \cdot V_0 \cdot I \tag{1.59}$$

m is the number of phases (m = 3, 4 in general), V_0 is the DC source voltage; I – peak phase current value.

In the kW power range, the peak kW/kVA ratio is in the interval 0.55 - 0.65 for flat top ideal current, even with a considerable magnetic core saturation level (σ = (0.3 – 0.4)), suggesting a reasonable peak kVA in the static power converter rating [1].

(f) Peak torque / inertia ratio

As already mentioned, most electric drives provide the peak torque T_{ek} up to base electric speed ω_b only. In some servodrives the base speed is equal to maximum speed.

The ratio between the peak torque T_{ek} and the rotor inertia J represents the maximum ideal acceleration a_{max} (radian / sec^2) up to the base electric speed ω_b:

$$a_{max} = \frac{T_{ek}}{J} [rad/s^2] \tag{1.60}$$

Conversely, the time t_a required to reach the base speed ω_b under peak torque and no-load may be defined:

$$t_a = \frac{\omega_b / p}{a_{max}} = \omega_b \frac{J}{pT_{ek}} [ms]; p - \text{pole pairs} \tag{1.61}$$

Both, a_{max} and t_a tends to become catalogue data for high performance variable speed drives.

(g) Field weakening speed range (ω_{max}/ω_b)

Many applications require constant power over a wide range of speeds. For such applications the motor's full voltage is reached at base speed while above base speed the flux is gradually reduced to allow motoring torque.

The ratio between maximum and base speeds (ω_{max}/ω_b) is a performance index because it shows the capability of the drive to reach high speeds avoiding overheating.

Ratio ω_{max} / ω_b of 1.5 - 2 is characteristic for permanent magnet synchronous and induction motors. Higher values require special measures and traded converter and motor overrating.

(h) Variable speed ratio: $\omega_{max}/\omega_{min}$

The speed close loop control range, that is, $\omega_{max}/\omega_{min}$, is an indication of the drive capability to accommodate different applications.

Electric drives with $\omega_{max}/\omega_{min} > 200$ are considered to perform wide speed range control and require a position (or at least speed) feedback sensor for precision position (or speed) control.

On the other hand, when $20 < \omega_{max}/\omega_{min} < 200$ the speed range control is medium and the position and speed feedback signals for speed control are obtained through observers.

Speed errors of 2 to 3 % are allowable for such drives. As the motion (position and speed) sensor costs are important they should be replaced by motion observers but this is feasible only in applications with medium variable speed range.

For $\omega_{max}/\omega_{min} < 20$ open loop control with some speed overcompensation under load is applied with so called V/f AC drives. V/f AC drives are the most common as for fans and pumps applications they do the job properly at rather low costs (less than 200 USD / kVA).

(i) Torque rise time (t_{Tek})

In fast response drives it is important to provide for fast torque variation. Torque transients depend on speed, motor parameters, converter type, input voltage level, and method of control.

As, inevitably, the torque rise time decreases with speed due to increased back e.m.f., it seems that the rise time of torque from zero to T_{ek}, t_{Tek}, with the flux linkage already present in the machine, at zero speed, may constitute a reliable performance index.

In fast response drives t_{Tek} is in the range of 2-6 ms. For AC (brushless) motor drives such fast torque response is obtained through the field orientation (transvector) control of induction, PM- synchronous, and synchronous reluctance motors.

(k) Torque ripple ratio ($\Delta T_e/T_{erated}$)

The pulsations in torque depend on motor type, parameters, and also on torque control strategy. They may be assessed through the ratio of torque ripple peak to rated torque ($\Delta T_e/T_{erated}$). The rated torque is defined here as the steady-state continuous torque at base speed. The rated torque pulsations influence the torque, speed and position control precision, vibrations and noise. Consequently, they should be as low as possible in a trade off between performance and costs.

(l) Thermal limitation (ϑ_{motor})

Direct drives for position or wide speed range are in direct mechanical contact with the load (machine tools, for example). In order to avoid mechanical deformations in the shaft of the load, in such cases, the temperature of the motor ϑ_{motor} should be [7]:

$$\vartheta_{motor} < 20^0 C + \vartheta_{ambient} \tag{1.62}$$

This is a serious limitation in motor design.

For most drives the motor temperature is limited by the electric insulation class (B, E or F).

(m) Noise level, L_{noise} (dB)

The noise radiated by a variable speed drive is due to both the motor and the static power converter. The noise level accepted depends on the application. As an example, for machine tools, [2]:

$$L_{noise} \approx 70 + 20\log(P_n / P_{n0}); \;\; P_{n0} = 1kW; \;\; P_n = (1 \div 10)kW \tag{1.63}$$

where P_n is the rated power of the motor.

(n) Motion control precision and robustness

Motion control means torque, speed and position close loop control.

Torque control is the most demanding, as the torque feedback sensor should account for the core losses. In general, motion control precision may be measured as torque, speed or position error:

$$\Delta T_e; \Delta\omega_r(rpm); \Delta\theta_r(^0) \tag{1.64}$$

The torque error is defined in relative values and the speed error in rpm, while the position error is given in degrees.

For speed and position control, the torque loop is present, sometimes as a current limiter.

Robustness of control is defined as the sensitivity of the drive response (in torque, speed, position) with respect to motor parameters, inertia, and load torque variations. It is the degree of immunity of the drive response to drive parameters detuning.

Between robustness and quickness of speed control there is a conflict in the sense that, for robustness, available quickness of response has to be partially sacrificed.

Advanced motion controllers such as self-tuning, model reference, or variable structure, fuzzy reasoning controllers are proposed to increase response robustness.

Robustness indexes could be defined as: torque error (ΔT_e), for a given parameter detuning ΔP_{ar} ($\Delta T_e / \Delta P_{ar}$), or speed rise time ratio from zero to base speed for J and 2J, respectively, or for zero and rated load torque.

(o) Dynamic stiffness

Dynamic stiffness is the ratio between perturbation torque ($\Delta T_{perturbation}$) and controlled variable error (Δx) versus frequency of torque perturbation. It is a kind of dynamic robustness to torque perturbations:

$$DS = \frac{\Delta T_{perturbation}}{\Delta x}$$

(p) Specific costs and weights

The overall costs C_{total} of an electric drive may be considered as a cost criterion:

$$C_{total} = C_{equip} + C_{loss} + C_{maint} \tag{1.65}$$

where:

C_{equip} is the cost of motor, converter, sensors, and of controller;

C_{loss} is the capitalized energy loss cost of the drive over its lifetime;

C_{maint} is the maintenance cost.

The relative importance of C_{loss} increases with drive power (or torque) and should be accounted for in any computation attempt of total cost break down.

In the equipment cost C_{equip}, the cost of motor, static power converter, sensors (observers), and motion controllers have a relative importance depending notably on the motor power, with the motor cost's importance increasing with power level. Here the net present worth cost (including inflation, premium on investments dynamics) for the foreseeable life of the drive is to be considered.

The specific weights are considered also as performance criteria:

$$\text{motor specific weight} = \frac{\text{peak torque}}{\text{weight}}, [\text{Nm/Kg}] \tag{1.66}$$

$$\text{converter specific weight} = \frac{\text{peak apparent power}}{\text{weight}}, [\text{kVA/Kg}] \tag{1.67}$$

The first weight criterion (1.66) is a strong comparison criterion between different motors for drives. The second refers, from the same point of view, to the static power converter since the peak apparent power is a design criterion for the MOSFET or IGBT PWM inverters, widely applied to servodrives. For thyristor inverters the RMS apparent power should be considered, instead of peak apparent power.

1.10. SUMMARY

- Modern electric drives perform electrical to mechanical energy conversion at variable speeds. They contain power electronic converters (PEC) which modify the voltage (and frequency) with high efficiency. [9 - 11]
- The introduction of PECs in electric drives (15 – 20 % of all drives in 2004) is justified by energy savings or process control (productivity and quality) performance.
- DC brush motor-PEC drives are now more and more replaced by AC motor-PEC drives as the motors are more rugged, less expensive for about the same PEC costs and comparative performance, especially for reversible motion control applications.
- Energy savings with PEC drives provide a revenue period of 5 years or less from 10 kW up while global energy savings (from the power plant to the application site) are spectacular.
- Motor torque has to match the load torque during steady state while stable transients are produced by closed loop motion control in PEC drives. Load dynamics and stability are priority issues in PEC drives.
- PEC drives provide, in general, motoring in both directions of motion. Also, they are capable of fast regenerative braking in both directions of motion, provided the PEC can retrieve the generated power back to the power source. When this is not possible, for slow dynamics (braking), the energy is dumped into the motor rotor or in an external, controlled, braking resistor attached to the PEC.
- The PECs have a limited voltage ceiling V_b for which the motor produces continuous rated power P_b at the so-called base speed ω_b.
- Most PEC drives can work above ω_b for constant power P_b (and constant voltage V_b) up to $\omega_{max} = (2\text{-}4)\ \omega_b$.
- A set of coherent / practical energy conversion, drive response quality and cost / weight performance for modern (power electronics) electric drives has been introduced.

1.11. PROBLEMS

1.1. A PEC drive saves S = \$500 of energy in the first year of operation. For a 4 year (n = 4) money return period calculate the price of PEC investment if the interest rate i = 8%, the energy costs yearly raise i_p = 4% and the tax range T = 35%.

1.2. Calculate the global power requirements for 100kW of useful (mechanical) power of an electric drive at 60% of rated speed if the power plant efficiency is η_1 = 40%, energy transportation is η_2 = 90% for two cases:

1.3. with a conventional drive at η_{34} = 60% total efficiency;

1.4. with a PEC drive at η'_{34}= 85% total efficiency.

1.5. An electric drive uses a mechanical transmission between the motor and load with a reduction ratio a = 1/10. The motor inertia J_m = 0.02kgm^2 while the load-transmission inertia J_L = 2kgm^2. Mechanical losses are neglected and the load torque T_L = 200Nm. For the speed/time curve in Figure 1.9, calculate the motor torque requirements after reducing the load inertia to motor shaft.

1.6. The base speed and power of a PEC AC motor drive are ω_b = 367 rad/s and P_b = 100kW. The motor has 4 poles (2p = 4). Calculate the motor torque T_{eb} at base speed and power and the torque for constant power P_b for ω_{max} = 3ω_b. What is the torque value and sign for generator braking at ω_b and delivering P_b with zero motor losses?

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