Chapter 14

MOTOR SPECIFICATIONS AND DESIGN PRINCIPLES

14.1 INTRODUCTION

Induction motors are used to drive loads in various industries for powers from less than 100W to 10MW and more per unit. Speeds encountered go up to tens of thousands of rpm.

There are two distinct ways to supply an induction motor to drive a load:

- Constant voltage and frequency (constant V and f) – power grid connection;
- Variable voltage and frequency – PWM static converter connection

The load is represented by its shaft torque–speed curve (envelope).

There are a few basic types of loads. Some require only constant speed (constant V and f supply) and others request variable speed (variable V and f supply).

In principle, the design specifications of the induction motor for constant and variable speed, respectively, are different from each other. Also, an existing motor, that was designed for constant V and f supply may, at some point in time, be supplied from variable V and f supply for variable speed.

It is thus necessary to lay out the specifications for constant and variable V and f supply and check if the existing motor is the right choice for variable speed. Selecting an induction motor for the two cases requires special care.

Design principles are common to both constant and variable speed. However, for the latter case, because different specifications with machine special design constraints, or geometrical aspects (rotor slot geometry, for example) lead to different final configurations. That is, induction motors designed for PWM static converter supplies are different.

It seems that in the near future more and more IMs will be designed and fabricated for variable speed applications.

14.2 TYPICAL LOAD SHAFT TORQUE/SPEED ENVELOPES

Load shaft torque/speed envelopes may be placed in the first quadrant or in 2, 3, 4 quadrants (Figure 14.1a,b).

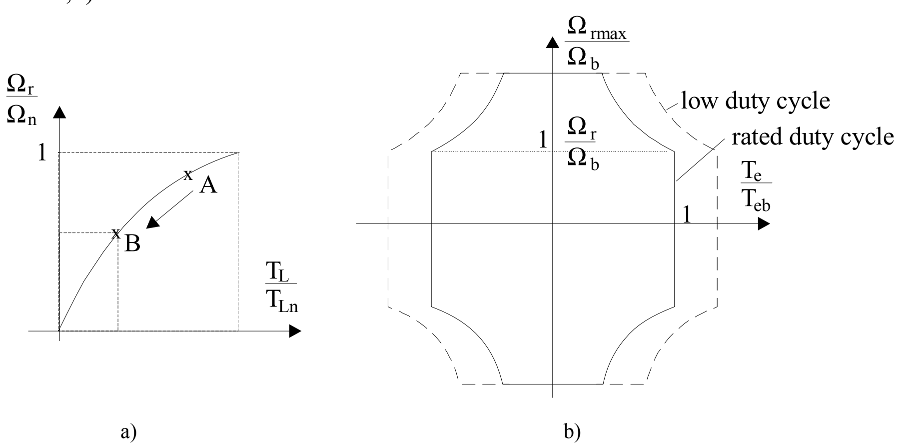

Figure 14.1 Single a) and multiquadrant b) load speed/torque envelopes

Constant V and f fed induction motors may be used only for single quadrant load torque/speed curves.

In modern applications (high performance machine tools, robots, elevators) multiquadrant operation is required. In such cases only variable V and f (PWM static converter) fed IMs are adequate.

Even in single quadrant applications variable speed may be required (from point A to point B in Figure 14.1a) in order to reduce energy consumption for lower speeds, by supplying the IM through a PWM static converter at variable V and f (Figure 14.2).

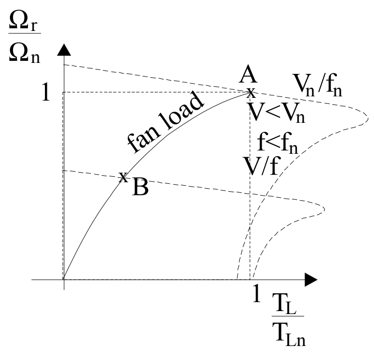

Figure 14.2 Variable V/f for variable speed in single quadrant operation

The load torque/speed curves may be classified into 3 main categories

- Squared torque: (centrifugal pumps, fans, mixers, etc.)

$$T_L = T_{Ln}\left(\frac{\Omega_r}{\Omega_n}\right)^2 \tag{14.1}$$

- Constant torque: (conveyors, rollertables, elevators, extruders, cement kilns, etc.)

$$T_L = T_{Ln} = \text{constant} \tag{14.2}$$

- Constant power

$$\begin{aligned} T &= T_{Lb} \ \text{ for } \ \Omega_r \le \Omega_b \\ T &= T_{Lb}\frac{\Omega_b}{\Omega_r} \ \text{ for } \ \Omega_r > \Omega_b \end{aligned} \tag{14.3}$$

A generic view of the torque/speed envelopes for the three basic loads is shown in Figure 14.3.

The load torque/speed curves of Figure 14.3 show a marked diversity and, especially, the power/speed curves indicate that the induction motor capability to meet them depends on the motor torque/speed envelope and on the temperature rise for the rated load duty-cycle.

There are two main limitations concerning the torque/speed envelope deliverable by the induction motor. The first one is the mechanical characteristic of the induction machine itself and the second is the temperature rise.

For a general purpose design induction motor, when used with variable V and f supply, the torque/speed envelope for continuous duty cycle is shown in Figure 14.4 for self ventilation (ventilator on shaft) and separate ventilator (constant speed ventilator), respectively.

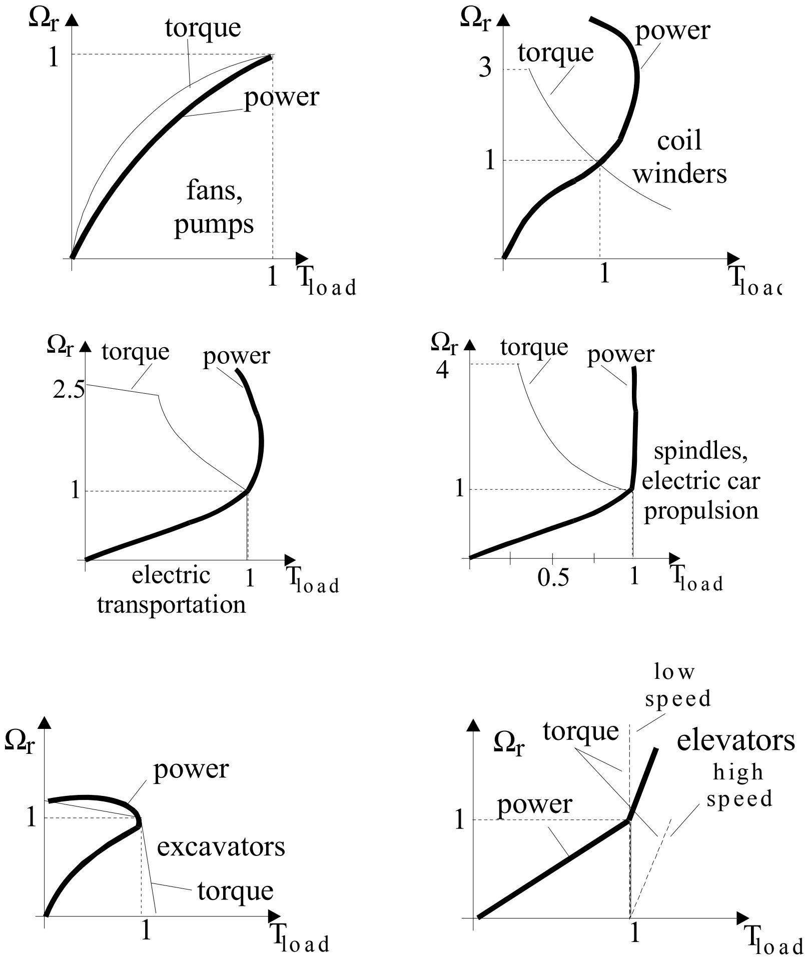

Figure 14.3 Typical load speed/torque curves (first quadrant shown)

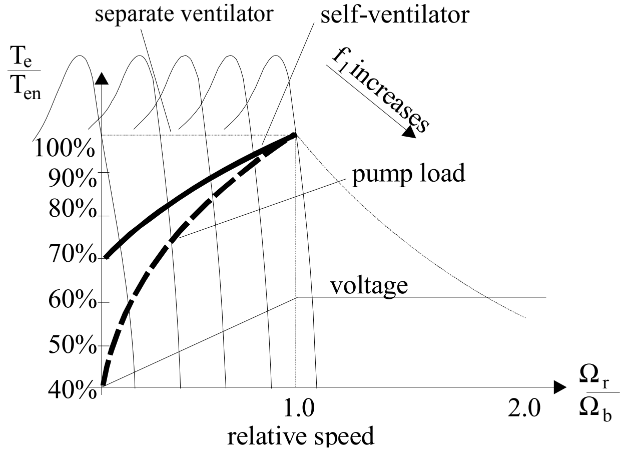

Figure 14.4 Standard induction motor torque/speed envelope for variable V and f supply

Sustained operation at large torque levels and low speed is admitted only with separate (constant speed) ventilator cooling. The decrease of torque with speed reduction is caused by temperature constraints.

As seen from Figure 14.4, the quadratic torque load (pumps, ventilators torque/speed curve) falls below the motor torque/speed envelope under rated speed (torque). For such applications only self-ventilated IM design is required.

Not so for servodrives (machine tools, etc) where sustained operation at low speed and rated torque is necessary.

A standard motor capable of producing the extended speed/torque of Figure 14.4 has to be fed through a variable V and f source (a PWM static converter) whose voltage and frequency has to vary with speed as on Figure 14.5.

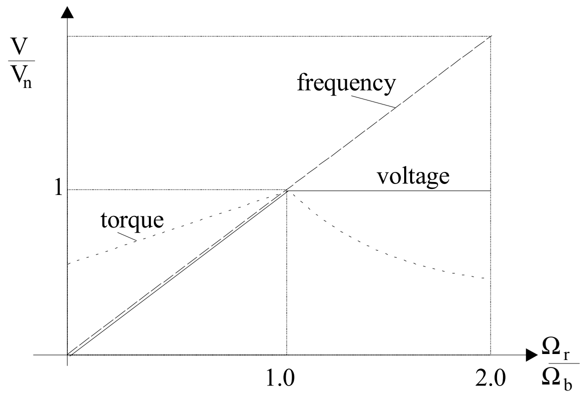

Figure 14.5 Voltage and frequency versus speed

The voltage ceiling of the inverter is reached at base speed Ω_b. Above Ω_b constant voltage is applied for increasing frequency. How to manage the IM flux linkage (rotor flux) to yield the maximum speed/torque envelope is a key point in designing an IM for variable speed.

14.3 DERATING DUE TO VOLTAGE TIME HARMONICS

Derating is required when an induction motor designed for sinusoidal voltage and constant frequency is supplied from a power grid which has a notable voltage harmonic content due to increasing use of PWM static converters for other motors or due to its supply from similar static power converters. In both cases the time harmonic content of motor input voltages is the cause of additional winding and core losses (as shown in Chapter 11). Such additional losses for rated power (and speed) would mean higher than rated temperature rise of windings and frame. To maintain the rated design temperature rise, the motor rating has to be reduced.

The rise of switching frequency in recent years for PWM static power converters for low and medium power IMs has led to a significant reduction of voltage time harmonic content at motor terminals. Consequently, the derating has been reduced. NEMA 30.01.2 suggests derating the induction motor as a function of harmonic voltage factor (HVF), Figure 14.6.

Reducing the HVF via power filters (active or passive) becomes thus a priority as the variable speed drives extension becomes more and more important.

In a similar way, when IMs designed for sinewave power source are fed from IGBT PWM voltage source inverters, typical for induction motors now up to 2MW (as of today), a certain derating is required as additional winding and core losses due to voltage harmonics occur.

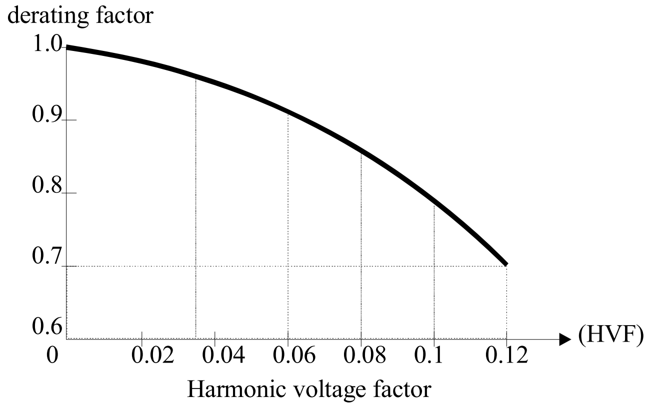

Figure 14.6 Derating for harmonic content of standard motors operating on sinewave power with harmonic content

This derating is not yet standardized, but it should be more important when power increases as the switching frequency decreases. A value of 10% derating for such a situation is now common practice.

When using an IM fed from a sinewave power source with line voltage V_L through a PWM converter, the motor terminal voltage is somewhat reduced with respect to V_L due to various voltage drops in the rectifier and inverter power switches, etc.

The reduction factor is 5 to 10% depending on the PWM strategy in the converter.

14.4 VOLTAGE AND FREQUENCY VARIATION

When matching an induction motor to a load a certain supply voltage reduction has to be allowed for which the motor is still capable to produce rated power for a small temperature rise over rated value. A value of voltage variation of ±10% of rated value at rated frequency is considered appropriate (NEMA 12.44).

Also, a ±5% frequency variation at rated voltage is considered acceptable. A combined 10% sum of absolute values, with a frequency variation of less than 5%, has to be also handled successfully. As expected in such conditions, the motor rated speed efficiency and power factor, for rated power will be slightly different from rated label values.

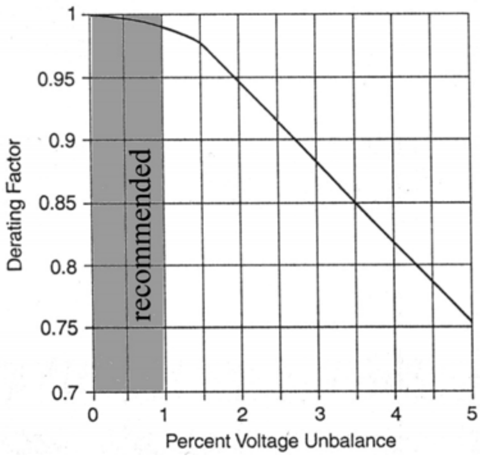

Figure 14.7 Derating due to voltage unbalance in %

Through their negative sequence, unbalanced voltages may produce, additional winding stator and rotor losses. In general a 1% unbalance in voltages would produce a 6 to 10% unbalance in phase currents.

The additional winding losses occurring this way would cause notable temperature increases unless the IM is derated (NEMA, Figure 14.7). A limit of 1% in voltage unbalance is recommended for medium and large power motors.

14.5 SPECIFYING INDUCTION MOTORS FOR CONSTANT V AND f

Key information pertaining to motor performance, construction, and operating conditions is provided for end users' consideration when specifying induction motors.

National (NEMA in USA [1]) and international (IEC in Europe) standards deal with such issues, to provide harmonisation between manufacturers and users worldwide.

Table 14.1 summarizes most important headings and the corresponding NEMA section.

Table 14.1. NEMA standards for 3 phase IMs (with cage rotors)

Heading	NEMA section
Nameplate markings	NEMA MG – 1 10.40
Terminal markings	NEMA MG – 1 2.60
NEMA size starters	
NEMA enclosure types	
Frame dimensions	NEMA MG – 1 11
Frame assignments	NEMA MG – 1 10
Full load current	NEC Table 430 – 150
Voltage	NEMA MG – 1 12.44, 14.35
Impact of voltage, frequency variation	
Code letter	NEMA MG – 1 10.37
Starting	NEMA MG – 1 12.44, 54
Design letter and torque	NEMA MG – 1 12
Winding temperature	NEMA MG – 1 12.43
Motor efficiency	NEMA MG – 12 – 10
Vibration	NEMA MG – 17
Testing	NEMA MG – 112, 55, 20, 49 / IEEE-112B
Harmonics	NEMA MG – 1 30
Inverter applications	NEMA MG – 1, 30, 31

Among these numerous specifications, which show the complexity of IM design, nameplate markings are of utmost importance.

The following data are given on the nameplate:

a. Designation of manufacturer's motor type and frame
b. kW (HP) output
c. Time rating
d. Maximum ambient temperature
e. Insulation system
f. RPM at rated load
g. Frequency
h. Number of phases
i. Rated load amperes
j. Line voltage
k. Locked-rotor amperes or code letter for locked-rotor kVA per HP for motor ½ HP or more
l. Design letter (A, B, C, D)
m. Nominal efficiency
n. Service factor load if other than 1.0

o. Service factor amperes when service factor exceeds 1.15
p. Over-temperature protection followed by a type number, when over-temperature device is used
q. Information on dual voltage and frequency operation option

Table 14.2. 460V, 4 pole, open frame design B performance NEMA defined performance

Appendix II: 460 V, 4 Pole, Open Frame, Design B Motors—Comparison of NEMA Defined Performance

HP	Full Load Amperes (FLA) per NEC Table 430-150	Maximum Locked Rotor Amperes (LRA) per NEMA MG 1, Tables 12.35 and 12.35A		Ratio: LRA/FLA		Nominal Full Load Efficiencies (%) per NEMA MG 1, Tables 12-10 and 12-11 (open 4 pole)		Efficiency Ratio: Design E/ Design B	Minimum Locked Rotor Torque (%) per NEMA MG 1, Tables 12-2 and 12.38.4		Minimum Breakdown Torque (%) per NEMA MG 1, Tables 12.39.1 and 12.39.3		Minimum Pull-up Torque (%) per NEMA MG 1, Tables 12.40.1 and 12.40.3	
	Designs B and E	Design B	Design E	Design B	Design E	Design B*	Design E		Design B	Design E	Design B	Design E	Design B	Design E
3	4.8	32	37	6.7	7.7	86.5	89.5	1.04	215	180	250	200	150	120
5	7.6	46	61	6.1	8.0	87.5	90.2	1.03	185	170	225	200	130	120
7 ½	11	64	92	5.8	8.4	88.5	91.0	1.03	175	160	215	200	120	110
10	14	81	113	5.8	8.1	89.5	91.7	1.03	165	160	200	200	115	110
15	21	116	169	5.5	8.0	91.0	92.4	1.02	160	150	200	200	110	110
20	27	145	225	5.4	8.3	91.0	93.0	1.02	150	150	200	200	105	110
25	34	183	281	5.4	8.3	91.7	93.6	1.02	150	140	200	190	105	100
30	40	218	337	5.5	8.4	92.4	94.1	1.02	150	140	200	190	105	100
40	52	290	412	5.6	7.9	93.0	94.5	1.02	140	130	200	190	100	100
50	65	363	515	5.6	8.0	93.0	95.4	1.03	140	130	200	190	100	100
60	77	435	618	5.6	7.5	93.6	95.4	1.02	140	120	200	180	100	90
75	96	543	723	5.7	7.6	94.1	95.4	1.01	140	120	200	180	100	90
100	124	725	937	5.8	7.5	94.1	95.4	1.01	125	110	200	180	100	80
125	156	908	1171	5.8	7.8	94.5	95.4	1.01	110	110	200	180	100	80
150	180	1085	1405	6.0	7.8	95.0	95.8	1.01	110	100	200	170	100	80
200	240	1450	1873	6.0	7.8	95.0	95.8	1.01	100	100	200	170	90	80
250	302	1825	2344	6.0	7.8	95.4	96.2	1.01	80	90	175	170	75	70
300	361	2200	2809	6.1	7.8	95.4	96.2	1.01	80	90	175	170	75	70
350	414	2550	3277	6.2	7.9	95.4	96.5	1.01	80	75	175	160	75	60
400	477	2900	3745	6.1	7.9	95.4	96.5	1.01	80	75	175	160	75	60
450	515	3250	4214	6.3	8.2	95.8	96.8	1.01	80	75	175	160	75	60
500	590	3625	4682	6.1	7.9	95.8	96.8	1.01	80	75	175	160	75	60

* - Applies to induction motors labeled "Premium Efficiency" or "Energy Efficient" ; design E was abandoned in 2000, but the comparison holds

Rated power factor does not appear on NEMA nameplates, but is does so according to most European standards.

Efficiency is perhaps the most important specification of an electric motor as the cost of energy per year even in an 1kW motor is notably higher than the motor initial cost. Also, a 1% increase in efficiency saves energy whose costs in 3 to 4 years cover the initial extra motor costs.

Standard and high efficiency IM classes have been defined and standardized by now worldwide. As expected, high efficiency (class E) induction motors have higher efficiency than standard motors but their size, initial cost and locked-rotor current are higher. This latter aspect places an additional burden on the local power grid when feeding the motor upon direct starting. If softstarting or inverter operation is used, the higher starting current does not have any effect on the local power grid rating. NEMA defines specific efficiency levels for design B IMs (Table 14.2).

On the other hand, EU established three classes EFF1, EFF2, EFF3 of efficiencies, giving the manufacturers an incentive to qualify for the higher classes (Table 14.2).

The torque/speed curves reveal, for constant V/f fed IMs, additional specifications such as starting torque, pull-up, and breaking torque for the five classes (letters: A, B, C, D design) of induction motors (Figure 14.8).

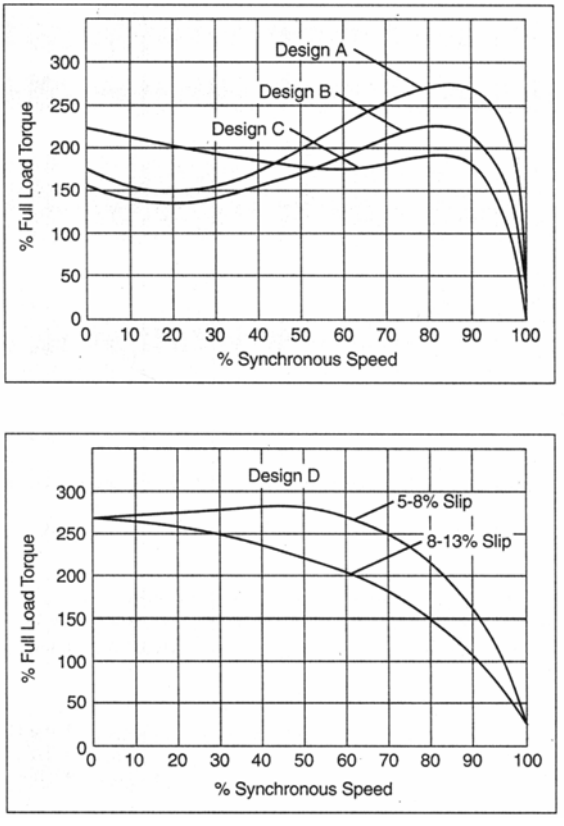

Figure 14.8 NEMA designs A, B, C, and D (b) torque/speed curves

The performance characteristics of the B, C, D designs are summarized in Table 14.3 from NEMA Table 2.1 with their typical applications.

Table 14.3. Motor designs (after NEMA Table 2.1) and EU

Classification	Locked rotor torque (% rated load torque)	Breakdown torque (% rated load torque)	Locked rotor current (% rated load current)	Slip %	Typical applications	Rel. η
Design B Normal locked rotor torque and normal locked rotor current	70 – 275*	175 – 300*	600 - 700	0.5 – 5	Fans, blowers, centrifugal pumps and compressors, motor – generator sets, etc., where starting torque requirements are relatively low	Medium or high
Design C High locked rotor torque and normal locked rotor current	200 – 250*	190 – 225*	600 - 700	1 – 5	Conveyors, crushers, stirring machines, agitators, reciprocating pumps and compressors, etc., where starting under load is required	Medium
Design D High locked rotor torque and high slip	275	275	600 – 700		High peak loads with or without fly wheels, such as punch presses, shears, elevators, extractors, winches, hoists, oil – well pumping and wire – drawing machines	Medium

Note – Design A motor performance characteristics are similar to those for Design B except that the locked rotor starting current is higher than the values shown in the table above
* Higher values are for motors having lower horsepower ratings

IEC60034-30 EuP Directive 2005/32/EC	Europe (50Hz) CEMEP Voluntary agreement	US (60Hz) EPAct	Other similar local regulations for example in countries like:
IE1 Standard efficiency	Comparable to EFF2	Below standard efficiency	AS in Australia NBR in Brazil GB/T in China IS in India JIS in Japan MEPS in Korea
IE2 High efficiency	Comparable to EFF1	Identical to NEMA Energy efficiency / EPACT	
IE3 Premium efficiency	Extrapolated IE2 with 10 to 15% lower losses	Identical to NEMA Premium efficiency	

14.6 MATCHING IMs TO VARIABLE SPEED/TORQUE LOADS

As IMs are, in general, designed for 60(50) Hz, when used for variable speed, with variable V and f supply, they operate at variable frequency. Below the rated frequency, the machine is capable of full flux linkage, while above that, flux weakening occurs.

For given load speed and load torque, with variable V and f supply we may use IMs with $2p_1 = 2, 4, 6$. Each of them, however, works at a different (distinct) frequency.

Figures 14.9 shows the case of quadratic torque (pump) load with the speed range of 0 to 2000 rpm, load of 150 kW at 2000 rpm, 400 V, 50 Hz (network). Two different motors are used: one of 2 poles and one of 4 poles.

At 2000 rpm the 2 pole IM works at 33.33 Hz – with full flux, while the 4 pole IM operates at 66.66Hz in the flux-weakening zone. Which of the two motors is used is decided by the motor costs. Note however, that the absolute torque (in Nm) of the motor has to be the same in both cases.

For a constant torque load (extruder) with the speed range of 300 to 1100 rpm, 50 kW at 1200 rpm (network: 400 V, 50 Hz) two motors compete. One, of 4 pole, will work at 40 Hz and one, of 6 pole, operating at 60 Hz (Figure 14.10).

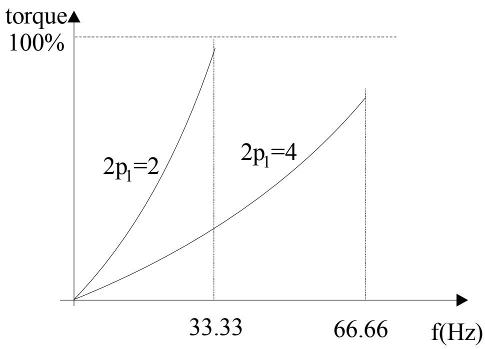

Figure 14.9 Torque versus motor frequency (and speed) pump load

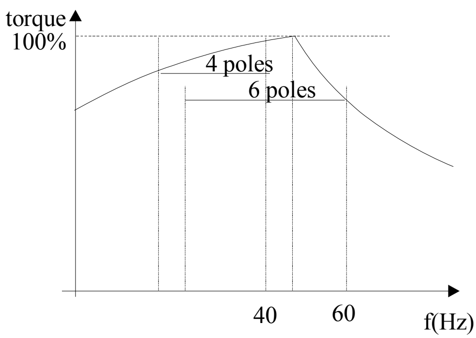

Figure 14.10 Torque versus motor frequency (and speed): constant torque load

Again, both motors scan satisfy the specifications for the entire speed range as the load torque is below the available motor torque. Again the torque in Nm is the same for both motors and the choice between the two motors is given by motor costs and total losses.

While starting torque and current are severe design constraints for IMs designed for constant V and f supply, they are not for variable V and f supply.

Skin effect is important for constant V and f supply as it reduces the starting current and increases the starting torque. In contrast to this, for variable V and f suply, skin effect is to be reduced, especially for high performance speed control systems.

Breakdown torque may become a much more important design factor for variable V and f supply, when a large speed zone for constant power is required. A spindle drive or an electric car drive may require more than 4 to 1 constant power speed range (Figure 14.11).

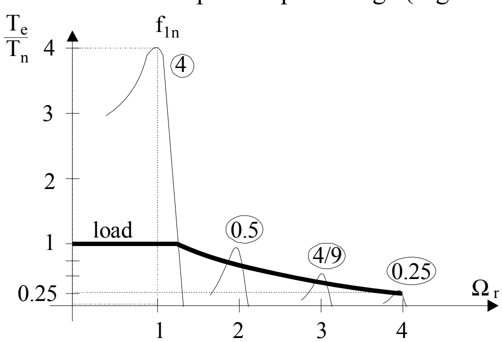

Figure 14.11 Induction motor torque/speed curves for various values of frequency and a 4/1 constant power speed range

The peak torque of IM is approximately

$$T_{ek} \approx 3\left(\frac{V_{phn}}{2\pi f_{1n}}\right)^2\left(\frac{f_{1n}}{f_1}\right)^2 \frac{p_1}{2L_{sc}} = T_{ekf_{1n}}\left(\frac{f_{1n}}{f_1}\right)^2 \tag{14.4}$$

The peak torque for constant (rated) voltage is inversely proportional to frequency squared. To produce a 4/1 constant power speed range, the peak torque has to be 4 times the rated torque. Only in this case, the motor may produce at $f_{1max} = 4f_{1n}$, 25% of rated torque.

Consequently, if the load maximum torque is equal to the rated torque, then at $4f_{1n}$ the rated power is still produced.

In reality, a breakdown torque of 400% is hardly practical. However, efforts to reduce the short-circuit leakage inductance (L_{sc}) have led up to 300% breakdown torque.

So there are two solutions to provide the required load torque/speed envelope: increase the motor rating (size) and costs or to increase the flux (voltage) level in the machine by switching form star to delta connection (or by reducing the number of turns per phase by switching off part of stator coils).

The above rationale was intended to suggest some basic factors that guide the IM design.

Relating the specifications to a dedicated machine geometry is the object of design (or dimensioning). This enterprise might be as well called sizing the IM.

Because there are many geometrical parameters and their relationships to specifications (performance) are in general nonlinear, the design process is so complicated that it is still a combination of art and science, based solidly on existing experience (motors) with tested (proven) performance. In the process of designing an induction motor, we will define hereby a few design factors, features, and sizing principles.

14.7 DESIGN FACTORS

Factors that influence notably the induction machine design are as follows:

- *Costs*

  Costs in most cases, the overriding consideration in IM design. But how do we define costs? It may be the costs of active materials with or without the fabrication costs. Fabrication costs depend on machine size, materials available or not in stock, manufacturing technologies, and man-power costs.

  The costs of capitalized losses per entire motor active life surpass quite a few times the initial motor costs. So loss reduction (through higher efficiency or via variable V and f supply) pays off generously. This explains the rapid expansion of variable speed drives with IMs worldwide.

  Finally, maintenance costs are also important but not predominant. We may now define the global costs of an IM as

$$\begin{aligned}\text{Global costs} &= \text{material costs} + \text{fabrication \& selling costs} + \\ &+ \text{losses capitalised costs} + \text{maintenance costs}\end{aligned} \tag{14.5}$$

  Global costs are also a fundamental issue when we have to choose between repairing an old motor or replacing it with a new motor (with higher efficiency and corresponding initial costs).

- *Material limitations*

  The main materials used in IM fabrication are magnetic-steel laminations, copper and aluminum for windings, and insulation materials for windings in slots.

Their costs are commensurate with performance. Progress in magnetic and insulation materials has been continuous. Such new improved materials drastically affect the IM design (geometry), performance (efficiency), and costs.

Flux density, B(T), losses (W/kg) in magnetic materials, current density J (A/mm^2) in conductors and dielectric rigidity E (V/m) and thermal conductivity of insulation materials are key factors in IM design.

➢ *Standard specifications*

IM materials (lamination thickness, conductor diameter), performance indexes (efficiency, power factor, starting torque, starting current, breakdown torque), temperature by insulation class, frame sizes, shaft height, cooling types, service classes, protection classes, etc., are specified in national (or international) standards (NEMA, IEEE, IEC, EU, etc.) to facilitate globalization in using induction motors for various applications. They limit, to some extent, the designer's options, but provide solutions that are widely accepted and economically sound.

➢ *Special factors*

In special applications, special specifications–such as minimum weight and maximum reliability in aircraft applications–become the main concern. Transportation applications require ease of maintaining, high reliability, and good efficiency. Circulating water home pumps require low noise, highly reliable induction motors.

Large compressors have large inertia rotors and thus motor heating during frequent starts is severe. Consequently, maximum starting torque/current becomes the objective function.

14.8 DESIGN FEATURES

The major issues in designing an IM may be divided into 5 areas: electrical, dielectric, magnetic, thermal and mechanical.

➢ *Electrical design*

To supply the IM, the supply voltage, frequency, and number of phases are specified. From this data and the minimum power factor and a target efficiency, the phase connection (start or delta), winding type, number of poles, slot numbers, and winding factors are calculated. Current densities (or current sheets) are imposed.

➢ *Magnetic design*

Based on output coefficients, power, speed, number of poles, and type of cooling, the rotor diameter is calculated. Then, based on a specific current loading (in A/m) and airgap flux density, the stack length is determined.

Fixing the flux densities in various parts of the magnetic circuit with given current densities and slot mmfs, the slot sizing, core height, and external stator diameter D_{out} are all calculated. After choosing D_{out}, which is standardized, the stack length is modified until the initial current density in slot is secured.

It is evident that sizing the stator and rotor core may be done many ways based on various criteria.

➢ *Insulation design*

Insulation material and its thickness, be it slot/core insulation, conductor insulation, end connection insulation, or terminal leads insulation depends on machine voltage insulation class and the environment in which the motor operates.

There are low line voltage 400V/50Hz, 230V/60Hz, 460V/60Hz 690V/60Hz or less or high voltage machines (2.3kV/60Hz, 4kV/50Hz, 6kV/50Hz). When PWM converter fed IMs are used, care must be exercised in reducing the voltage stress on the first 20% of phase coils or to enforce their insulation or to use random wound coils.

- *Thermal design*

  Extracting the heat caused by losses from the IM is imperative to keep the windings, core, and frame temperatures within safe limits. Depending on application or power level, various types of cooling are used. Air cooling is predominant but stator water cooling of high speed IMs (above 10,000rpm) is frequently used. Calculating the loss and temperature distribution and of the cooling system represents the thermal design.
- *Mechanical design*

  Mechanical design refers to critical rotating speed, noise and vibration modes, mechanical stress in the shaft, and its deformation, displacement, bearings design, inertia calculation, and forces on the winding end coils during most severe current transients.

We mention here the output coefficient as an experience, proven theoretical approach to a tentative internal stator (stator bore) diameter calculation. The standard output coefficient is $D_{is}^2 \cdot L$ where D_{is} is the stator bore diameter and L, the stack length.

Besides elaborating on $D_{is}^2 \cdot L$, we introduce the rotor tangential stress σ_{tan} (in N/cm^2), that is, the tangential force at rotor surface at rated and peak torque.

This specific force criterion may be used also for linear motors. It turns out that σ_{tan} varies from 0.2 to 0.3N/cm^2 for hundred watt IMs to less than 3 to 4 N/cm^2 for large IMs. Not so for the output coefficient $D_{is}^2 \cdot L$, which is related to rotor volume and thus increases steadily with torque (and power).

14.9 THE OUTPUT COEFFICIENT DESIGN CONCEPT

To calculate the relationship between the $D_{is}^2 \cdot L$ and the machine power and performance, we start by calculating the airgap apparent power S_g,

$$S_{gap} = 3E_1 I_{1n} \tag{14.6}$$

where E_1 is the airgap emf per phase and I_{1n} rated current (RMS values).

Based on the phasor diagram with zero stator resistance ($R_s = 0$), Figure 14.12:

$$\underline{I}_{1n} R_s - \underline{V}_{1n} = \underline{E}_1 - jX_{ls}\underline{I}_{1n} \tag{14.7}$$

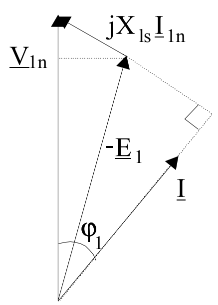

Figure 14.12 Simplified phasor diagram

Or

$$K_E = \frac{E_1}{V_{1n}} \approx 1 - x_{ls} \cdot \sin\varphi_1 \tag{14.8}$$

with

$$x_{ls} = \frac{X_{ls} I_{1n}}{V_{1n}} \tag{14.9}$$

The p.u. value of stator leakage reactance increases with pole pairs p_1 and so does $\sin\varphi_1$ (power factor decreases when p_1 increases).

$$K_E \approx 0.98 - 0.005 \cdot p_1 \tag{14.10}$$

Also, the input apparent power S_{1n} is

$$S_{1n} = 3V_{1n}I_{1n} = \frac{P_n}{\eta_n \cos\varphi_{1n}} \tag{14.11}$$

where P_n is the rated output power and η_n and $\cos\varphi_{1n}$ are the assigned values of rated efficiency and power factor based on past experience.

Typical values of efficiency have been given in Table 14.3 for Design B (NEMA). Each manufacturer has its own set of data.

Efficiency increases with power and decreases with the number of poles. Efficiency of wound rotor IMs is slightly larger than that of cage rotor IMs of same power and speed because the rotor windings are made of copper and the total additional load (stray) losses are lower.

As efficiency is defined with stray losses p_{stray} of 0.5(1.0)% of rated power in Europe (still!) and with the latter (p_{stray}) measured in direct load tests in USA, differences in actual losses (in IMs of same power and nameplate efficiency) of even more than 20% may be encountered when motors fabricated in Europe are compared with those made in USA.

Anyway, the assigned value of efficiency is only a starting point for design as iterations are performed until best performance is obtained.

The power factor also increases with power and decreases with the number of pole pairs with values slightly smaller than corresponding efficiency for existing motors. More data on initial efficiency and power factor data will be given in subsequent chapters on design methodologies.

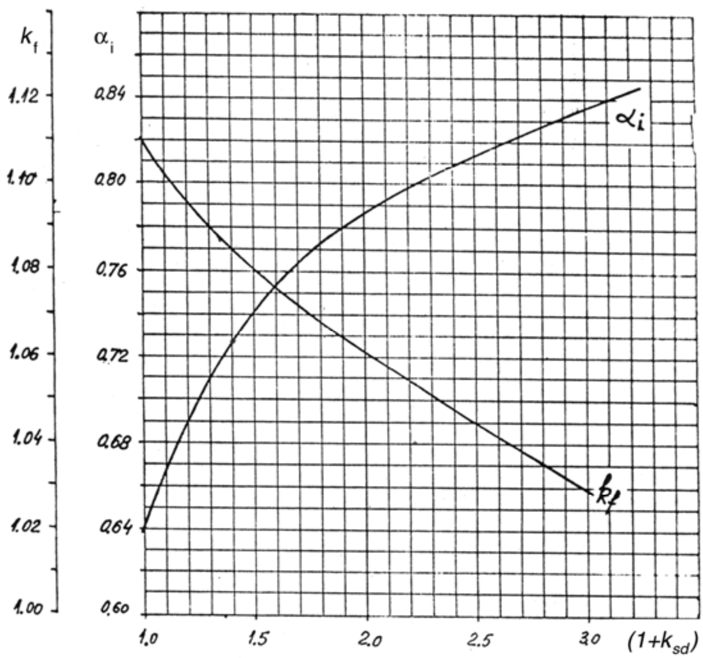

Figure 14.13 Form factor K_f and flux density shape factor α_i versus teeth saturation

The emf E_1 may be written as a function of airgap pole flux ϕ,

$$E_1 = 4f_1K_fW_1K_{w1}\phi \tag{14.12}$$

Where f_1 is frequency, $1.11 > K_f > 1.02$ form factor (dependent on teeth saturation) (Figure 14.13), W_1 is turns per phase, and K_{w1} is winding factor, ϕ pole flux.

$$\phi = \alpha_i\tau LB_g \tag{14.13}$$

where α_i is flux density shape factor dependent on the magnetic saturation coefficient of teeth (Figure 14.13) and B_g is flux density in the airgap. The pole pitch τ is

$$\tau = \frac{\pi D_{is}}{2p_1};\ n_1 = \frac{f_1}{p_1} \tag{14.14}$$

Finally, S_{gap} is

$$S_{gap} = K_f\alpha_iK_{w1}\pi^2D_{is}^{\ 2}L\frac{n_1}{60}A_1B_g \tag{14.15}$$

with A_1 the specific stator current load A_1 (A/m),

$$A_1 = \frac{6W_1I_{1n}}{\pi D_{is}} \tag{14.16}$$

We might separate the volume utilization factor C_0 (Esson's constant) as

$$C_0 = K_f\alpha_iK_{w1}\pi^2A_1B_g = \frac{60S_{gap}}{D_{is}^{\ 2}Ln_1} \tag{14.17}$$

C_0 is not in fact a constant as both the values of A_1(A/m) and airgap flux density (B_g) increase with machine torque and with the number of pole pairs.

The $D_{is}^{2}\cdot L$ output coefficient may be calculated from (14.17) with S_{gap} from (14.6) and (14.11).

$$D_{is}^{\ 2}L = \frac{1}{C_0}\frac{60}{n_1}\frac{K_EP_n}{\eta_n\cos\varphi_{1n}} \tag{14.18}$$

Typical values of C_0 as a function S_{gap} with pole pairs p_1 as parameter for low power IMs is given in Figure 14.14.

The $D_{is}^{2}\cdot L$ (internal) output constant (proportional to rotor core volume) is, in fact, almost proportional to machine rated shaft torque. Torque production requires apparently less volume as the pole pairs number p_1 increases, C_0 increases with p_1 (Figure 14.14).

It is standard to assign also a value λ to the stack length to pole pitch ratio

$$\lambda = \frac{L}{\tau} = \frac{2Lp_1}{\pi D_{is}};\ 0.6 < \lambda < 3.0 \tag{14.19}$$

The stator bore diameter may now be calculated from (14.18) with (14.19).

$$D_{is} = \sqrt[3]{\frac{2p_1}{\pi\lambda}\frac{1}{C_0}\frac{p_1}{f_1}\frac{K_EP_n}{\eta_n\cos\varphi_{1n}}} \tag{14.20}$$

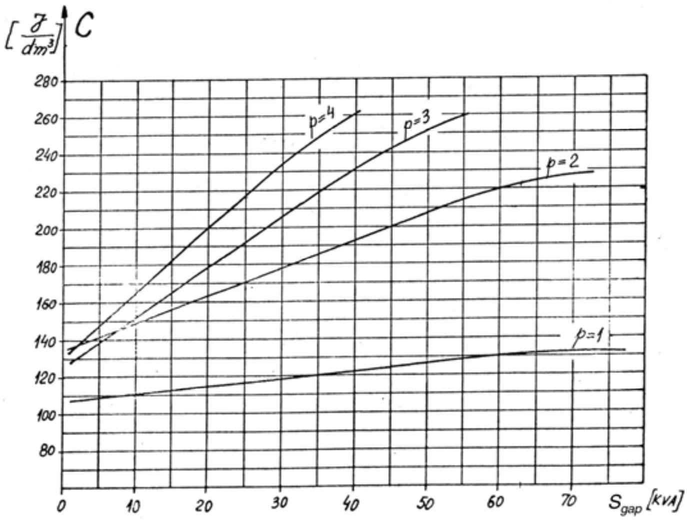

Figure 14.14 Esson's "constant" C_0 versus S_{gap} (airgap apparent power)

This is a standard design formula. However it does not say enough on the machine total volume (weight). Moreover, in many designs, the stator external (frame internal) diameters are standardized.

A similar (external) output coefficient $D_{out}^2 \cdot L$ may be derived if we first adopt a design current density $J_{con}(A/m^2)$ and consider the slot fill factor (with conductors), K_{fill} = 0.4 to 0.6, given together with the tooth and stator back iron flux densities B_{ts} and B_{cs}.

With the airgap flux and tooth flux densities B_g and B_{ts} considered known, the stator slot height h_s is approximately

$$h_s = \frac{6W_1I_n}{\frac{B_g}{B_{ts}} j_{con} K_{fill}} \frac{1}{\pi D_{is}} = \frac{A_1}{\frac{B_g}{B_{ts}} j_{con} K_{fill}} \tag{14.21}$$

Now the core radial height h_{cs} is

$$h_{cs} = \frac{\phi}{2LB_{cs}} = \frac{\alpha_i}{2}\left(\frac{\pi D_{is}}{2p_1}\right)\frac{B_g}{B_{cs}} \tag{14.22}$$

The outer stator diameter D_{out} is

$$D_{out} = D_{is} + 2(h_s + h_{cs}) \tag{14.23}$$

We may replace D_{is} from (14.23) in $D_{is}^2 \cdot L$ with h_s and h_{cs} from (14.21) and (14.22).

$$D_{is}^2 L = D_{out}^2 L \cdot f_0(D_{is}) \tag{14.24}$$

$$f_0(D_{is}) = \frac{1}{\left[1 + \frac{2(h_s + h_{cs})}{D_{is}}\right]^2} \tag{14.25}$$

And, finally,

$$f_0(D_{is}) = \frac{1}{\left[1 + \frac{2A_1B_{ts}}{j_{con}K_{fill}B_gD_{is}} + \frac{\alpha_i}{2}\frac{\pi}{p_1}\frac{B_g}{B_{cs}}\right]^2} \tag{14.26}$$

From (14.24),

$$D_{out}^2L = \frac{D_{is}^2L}{f_0(D_{is})} = \frac{1}{C_0f_0(D_{is})}\frac{p_1}{f_1}\frac{K_EP_n}{\eta_n\cos\varphi_{1n}} \tag{14.27}$$

As

$$L = \lambda\frac{\pi D_{is}}{2p_1} \tag{14.28}$$

$$D_{out} = \sqrt{\frac{2p_1^2}{\pi\lambda C_0f_1}\frac{K_EP_n}{\eta_n\cos\varphi_{1n}}\frac{1}{D_{is}f_0(D_{is})}} \tag{14.29}$$

Although (14.29) through the function $[D_{is}f_0(D_{is})]^{-1}$ suggests that a minimum D_{out} may be obtained for given λ, B_g/B_{co}, B_g/B_t, j_{con}, and A_1, it seems to us more practical to use (14.29) to find the outer stator diameter D_{out} after the stator bore diameter was obtained from (14.20). Now if this value is not a standard one and a standard frame is a must, the aspect ratio λ is modified until D_{out} matches a standardized value.

The specific current loading A_1 depends on pole pitch τ and number of poles on D_{is}, once a certain cooling system (current density) is adopted.

In general, it increases with D_{is} from values of less than 10^3A/m for $D_{is} = 4\cdot10^{-2}$m to 45,000A/m for $D_{is} = 0.4$m and $2p_1 = 2$ poles. Smaller values are common for larger number of poles and same stator bore diameter.

On the other hand, the design current density j_{con} varies in the interval $j_{con} = (3.5$ to $8.0)\cdot10^6$A/m^2 for axial or axial-radial air cooling. Higher values are designated to high speed IMs (lower pole pair numbers p_1) or for liquid cooling. While A_1 varies along such a large span and the slot height h_s to slot width b_s ratio is limited to K_{aspect}=(3 to 6), to limit the slot leakage inductance, using A_1 may be avoided by calculating slot height h_s as

$$h_s = K_{aspect}b_s = K_{aspect}\frac{\pi D_{is}}{N_s}\left(1 - \frac{b_t}{\tau_{slot}}\right) = K_{aspect}\frac{\pi D_{is}}{N_s}\left(1 - \frac{B_g}{B_{ts}}\right) \tag{14.30}$$

Higher values of aspect ratios are typical to larger motors.

This way, D_{out}^2L is

$$D_{out}^2L = \frac{1}{C_0}\frac{P_1}{f_1}\frac{K_EP_n}{\eta_n\cos\varphi_{1n}}\left[1 + \frac{2K_{aspect}\pi}{N_s}\left(1 - \frac{B_g}{B_{ts}}\right) + \frac{\alpha_i}{2}\frac{\pi}{p_1}\frac{B_g}{B_{cs}}\right]^2 \tag{14.31}$$

Also,

$$\frac{D_{out}}{D_{is}} \approx 1 + \frac{2K_{aspect}\pi}{N_s}\left(1 - \frac{B_g}{B_{ts}}\right) + \frac{\alpha_i}{2}\frac{\pi}{p_1}\frac{B_g}{B_{cs}} \tag{14.32}$$

To start, we may calculate D_{is}/D_{out} as a function of only pole pairs p_1 if B_g/B_{ts} = ct and B_g/B_{cs} = ct, with K_{aspect} and N_s (slots/stator) also assigned corresponding values (Table 14.4).

Table 14.4. Outer to inner stator diameter ratios

$2p_1$	2	4	6	8	≥ 10
$\frac{D_{out}}{D_{is}}$	1.65 – 1.69	1.46 – 1.49	1.37 – 1.40	1.27 – 1.30	1.24 – 1.26

The stack aspect ratio λ is assigned an initial value in a rather large interval: 0.6 to 3.

In general, longer stacks, allowing for a smaller stator bore diameter (for given torque) lead to shorter stator winding end connections, lower winding losses, and lower inertia, but the temperature rise along the stack length may become important. An optimal value of λ is highly dependent on IM design specifications and the objective function taken into consideration. There are applications with space shape constraints that prevent the using of a long motor.

Example 14.1 Output coefficient

Let us consider a 55 kW, 50 Hz, 400 V, $2p_1 = 4$ induction motor whose assigned (initial) rated efficiency and power factor are $\eta_n = 0.92$, $\cos\varphi_n = 0.92$.

Let us determine the stator internal and external diameters D_{out} and D_{is} for $\lambda = L/\tau = 1.5$.

Solution

The emf coefficient K_E (14.10) is: $K_E = 0.98 – 0.005\cdot 2 = 0.97$

The airgap apparent power S_{gap} (14.3) is

$$S_{gap} = 3K_E V_1 I_{1n} = K_E \frac{P_n}{\cos\varphi_n \eta_n} = \frac{0.97\cdot 55\cdot 10^3}{0.92\cdot 0.92} = 63.03\cdot 10^3\,\text{VA}$$

Esson's constant C_0 is obtained from Figure 14.14 for $p_1 = 2$ and $S_{gap} = 63.03\cdot 10^3$VA: $C_0 = 222\cdot 10^3$J/m^3.

For an airgap flux density $B_g = 0.8$T, $K_{w1} = 0.955$, $\alpha_i = 0.74$, $K_f = 1.08$ (teeth saturation coefficient $1 + K_{st} = 1.5$, Figure 4.13). The specific current loading A_1 is (14.17).

$$A_1 = \frac{C_0}{K_f \alpha_i K_{w1} \pi^2 B_g} = \frac{222\cdot 10^3}{1.08\cdot 0.74\cdot 0.955\cdot 0.8\pi^2} = 36.876\cdot 10^3\,\text{A/m}$$

with λ = 1.5 from (14.20) the stator internal diameter D_{is} is obtained.

$$D_{is} = \sqrt[3]{\frac{2\cdot 2}{2\cdot 1.5}\cdot\frac{1}{222\cdot 10^3}\cdot\frac{2}{50}\cdot 63.03\cdot 10^3} = 0.2477\text{m}$$

The stator stack length L (14.19) is

$$L = \lambda\frac{\pi D_{is}}{2p_1} = \frac{1.5\cdot\pi\cdot 0.2477}{2\cdot 2} = 0.2917\text{m}$$

with $j_{con} = 6\cdot 10^6$A/m, $K_{fill} = 0.5$, $B_{ts} = B_{cs} = 1.6$T, the stator slot height h_s is (14.21).

$$h_s = \frac{36.876\cdot 10^3}{\frac{0.8}{1.6}\cdot 6\cdot 10^6\cdot 0.5} = 24.584\cdot 10^{-3}\text{m}$$

The stator back iron height h_{cs} (14.22) is

$$h_{cs} = \frac{\alpha_i}{2}\frac{\pi D_{is}}{2p_1}\frac{B_g}{B_{cs}} = \frac{0.74\cdot\pi\cdot 0.2477}{2\cdot 2\cdot 2}\cdot\frac{0.8}{1.6} \approx 36\cdot 10^{-3}\,m$$

The external stator diameter D_{out} becomes

$$D_{out} = D_{is} + 2(h_{cs} + h_s) = 0.2477 + 2(0.024584 + 0.036) = 0.3688m$$

With N_s = 48 slots/stator and a slot aspect ratio K_{aspect} = 3.03, the value of slot height h_s (14.30) is

$$h_s = K_{aspect}\frac{\pi D_{is}}{N_s}\left(1 - \frac{B_g}{B_{ts}}\right) = 3.03\pi\frac{0.2477}{48}\left(1 - \frac{0.8}{1.6}\right) = 0.0246m$$

About the same value of h_s as above has been obtained. It is interesting to calculate the approximate value of the specific tangential force σ_{tan}.

$$\sigma_{tan} \approx \frac{P_n}{\pi D_{is}\left(\frac{D_{is}}{2}\right)L}\frac{p_1}{2\pi f_1} = \frac{55\cdot 10^3}{\frac{\pi}{2}\cdot 0.2917\cdot 0.2477^2}\cdot\frac{2}{2\pi 50} =$$
$$= 1.246\cdot 10^4\,N/m^2 = 1.246N/cm^2$$

This is not a high value and the moderate-low slot aspect ratio $K_{aspect} = h_s/b_s = 3.03$ is a clear indication of this situation.

Apparently the machine stator internal diameter may be reduced by increasing A_1 (in fact, C_0 is Esson's constant). For same λ, the stack length will be reduced, while the stator external diameter will also be slightly reduced (the back iron height h_{cs} decreases and the slot height increases).

Given the simplicity of the above analytical approach further speculations on better (eventually optimized) designs are considered inappropriate here.

14.10 THE ROTOR TANGENTIAL STRESS DESIGN CONCEPT

The rotor tangential stress $\sigma_{tan}(N/m^2)$ may be calculated from the motor torque T_e.

$$\sigma_{tan} = \frac{T_{en}\cdot 2}{(\pi D_{is}L)\cdot D_{is}}\left(N/m^2\right) \quad (14.33)$$

The electromagnetic torque T_{en} is approximately

$$T_{en} \approx \frac{p_1 P_n\left(1 + \frac{p_{mec}}{P_n}\right)}{2\pi f_1(1 - S_n)} \quad (14.34)$$

P_n is rated motor power; S_n = rated slip.

The rated slip is less than 2 to 3% for most induction motors and the mechanical losses are in general around 1% of rated power.

$$T_{en} \approx \frac{p_1 P_n\cdot 1.01}{2\pi f_1 0.98} = 0.1641\cdot P_n\frac{p_1}{f_1} \quad (14.35)$$

Choosing σ_{tan} in the interval 0.2 to 5N/cm^2 or 2,000 to 50,000N/m^2, we may use (14.33) directly, with $\lambda = \frac{2p_1L}{\pi D_{is}}$, to determine the internal stator diameter.

$$D_{is} = \sqrt[3]{\frac{4p_1}{\pi^2\lambda\sigma_{tan}}\left(0.1641\cdot P_n\cdot\frac{p_1}{f_1}\right)} \tag{14.36}$$

No apparent need occurs to adopt at this stage efficiency and power factor values for rated load.

We may now adopt the no-load value of airgap flux density B_{g0},

$$B_{g0} = \frac{\mu_0 3\sqrt{2}W_1K_{w1}I_0}{\pi p_1K_cg(1+K_s)} \tag{14.37}$$

where the no-load current I_0 and the number of turns/phase W_1 are unknown and the airgap g, Carter's coefficient K_c and saturation factor K_s are assigned pertinent values.

$$\begin{aligned} g &\approx \left(0.1+0.02\sqrt[3]{P_n}\right)\cdot 10^{-3}\,[m];\quad \text{for } P_1 = 1 \\ g &\approx \left(0.1+0.012\sqrt[3]{P_n}\right)\cdot 10^{-3}\,[m];\quad \text{for } P_1 \geq 2 \end{aligned} \tag{14.38}$$

Typical values of airgap are 0.35, 0.4, 0.45, 0.5, 0.55 …mm, etc. Also, $K_c \approx (1.15 - 1.35)$ for semiclosed slots and $K_c = 1.5 - 1.7$ for open stator slots (large power induction motors). The saturation factor is typically $K_s = 0.3 - 0.5$ for $p_1 \geq 2$ and larger for $2p_1 = 2$.

The airgap flux density B_g is

$$\begin{aligned} B_g &= (0.5-0.7)T \quad \text{for } 2p_1 = 2 \\ B_g &= (0.65-0.75)T \quad \text{for } 2p_1 = 4 \\ B_g &= (0.7-0.8)T \quad \text{for } 2p_1 = 6 \\ B_g &= (0.75-0.85)T \quad \text{for } 2p_1 = 8 \end{aligned} \tag{14.39}$$

The larger values correspond to larger motors.

The product, W_1I_0, is thus obtained from (14.37). The number of turns W_1 may be calculated from the emf E_1 ((14.12) and (14.13)).

$$W_1 = \frac{E_1}{4f_1K_fK_{w1}\phi} = \frac{E_1 2p_1}{4f_1K_fK_{w1}\alpha_i\pi D_{is}LB_g} \tag{14.40}$$

with W_1I_0 and W_1 known, the no-load (magnetization) current I_0 may be obtained. The airgap active power P_{gap} is

$$P_{gap} = T_{en}\frac{2\pi f_1}{p_1} = 3K_EV_1I_T \tag{14.41}$$

where I_T is the stator current torque component (in phase with E_1). With I_T determined from (14.41), we may now calculate the stator rated current I_{1n}.

$$I_{1n} \approx \sqrt{I_0^{\,2} + I_T^{\,2}} \tag{14.42}$$

The rotor bar current (for a cage rotor) I_b is

$$I_b \approx \frac{2mW_1K_{w1}I_T}{N_r} \tag{14.43}$$

N_r – number of rotor slots, m – number of stator phases.

We may now check the product $\eta_n\cos\varphi_{1n}$.

$$\eta_n \cos\varphi_n = \frac{P_n}{3V_1I_{1n}} < 1 \tag{14.44}$$

The linear current loading A_1 may be also checked,

$$A_1 = \frac{2mW_1I_{1n}}{\pi D_{is}} \tag{14.45}$$

and eventually compared with data from existing similar motors.

With all these data available, the sizing of stator and rotor slots and their windings is feasible. Then the machine reactances and resistances and the steady-state performance may be calculated. Knowing the motor geometry and the loss breakdown, the thermal aspects (design) may be approached. Finally, if the temperature rise or other performance are not satisfactory, the design process is repeated.

Given the complexity of such an enterprise, some coherent methodologies are in order. They will be developed in subsequent chapters.

Example 14.2 Tangential stress

Let us consider the motor data of Example 14.1, adopt $\sigma_{tan} = 1.5\cdot10^4 N/m^2$, and determine the values of D_{is}, L, W_1, I_0, I_{1n}, $\eta_n\cos\varphi_n$.

Solution

With $p_1 = 2$, $P_n = 55$ kW, $f_1 = 50$ Hz, $\lambda = 1.5$, from (14.36),

$$D_{is} = \sqrt[3]{\frac{4\cdot2\cdot0.1641\cdot55\cdot10^3\cdot2}{\pi^2 1.5\cdot1.5\cdot10^4\cdot50}} = 0.2352\text{m}$$

The stack length L is

$$L = \lambda\frac{\pi D_{is}}{2p_1} = 1.5\frac{\pi\cdot0.2352}{2\cdot2} = 0.277\text{m}$$

with $B_g = 0.8$ T, $K_f = 1.08$, $\alpha_i = 0.74$, $K_{w1} = 0.955$, $K_E = 0.97$, and from (14.40), the number of turns per phase W_1 is

$$W_1 = \frac{0.97\cdot\left(\frac{400}{\sqrt{3}}\right)\cdot2\cdot2}{4\cdot50\cdot1.08\cdot0.955\cdot0.74\cdot\pi\cdot0.2352\cdot0.277\cdot0.8} = 36\text{turns/phase}$$

The rated electromagnetic torque T_{en} (14.35) is

$$T_{en} = 0.1641\cdot P_n\frac{p_1}{f_1} = 0.1641\cdot55\cdot10^3\cdot\frac{2}{50} = 361.02\text{Nm}$$

Now, from (14.41) the torque current component I_T is

$$I_T = \frac{T_{en} \cdot 2\pi f_1}{3K_E V_1 p_1} = \frac{361.02 \cdot 2\pi 50}{3 \cdot 0.97 \cdot \frac{400}{\sqrt{3}} \cdot 2} = 84.24A$$

The magnetization current I_0 is obtained from (14.37).

$$I_0 = \frac{B_{g0}\pi p_1 K_c g(1+K_s)}{\mu_0 3\sqrt{2} W_1 K_{w1}} = \frac{0.8 \cdot \pi \cdot 2 \cdot 1.25 \cdot 0.55 \cdot (1+0.5) \cdot 10^{-3}}{1.256 \cdot 10^{-6} \cdot 36 \cdot 0.955 \cdot 3\sqrt{2}} = 28.36A$$

The airgap g (14.38) is

$$g = \left(0.1 + 0.012\sqrt[3]{55000}\right) \cdot 10^{-3} = 0.55 \cdot 10^{-3} m$$

The stator rated current I_{1n} is

$$I_{1n} = \sqrt{I_0^2 + I_T^2} = \sqrt{28.36^2 + 84.24^2} = 88.887A$$

$$\eta_n \cos\varphi_{1n} = \frac{P_n}{3V_1 I_{1n}} = \frac{55 \cdot 10^3}{3 \cdot \frac{400}{\sqrt{3}} \cdot 88.887} = 0.894$$

This corresponds to a rather high (say) $\eta_n = \cos\varphi_{1n} = 0.9455$.

Note that these values appear at design starting, before all the losses in the machine have been assessed. They provide a design start without Esson's (output) constant which changed continuously over the last decade as material quality and cooling systems improved steadily.

14.11 SUMMARY

- Mechanical loads are characterized by torque/speed curves.
- Single quadrant and multiquadrant load torque/speed curves are typical.
- Constant V and f supply IMs are suitable only for constant speed single quadrant loads.
- For single and multiquadrant variable speed loads variable V and f supply IMs are required. They result in energy savings commensurable with speed control range.
- Three load torque/speed curves are typical: quadratic torque/speed (pumps), constant torque (elevators) and constant power (machine tool, spindles, traction, etc.).
- The standard IM design torque/speed envelope, to match the load, includes two regions: below and above base speed Ω_b. For base speed full voltage, full torque, is delivered at rated service cycle and rated temperature rise.
- With self ventilation the machine overtemperature leads to torque reduction with speed reduction. For constant torque below base speed, separate (constant speed) ventilation is required.
- Above base speed, with constant voltage and increasing frequency, the torque available decreases and so does the flux linkage in the machine.
- A 2/1 constant power speed range (from Ω_b to $2\Omega_b$) is typical with standard IM designs at constant voltage.

- When an induction motor designed for sine wave power is faced with a notable harmonic content in the power grid due to presence of power electronic equipments nearby, it has to be derated. In general a harmonic voltage factor (HVF) of less of 3% is considered harmless (Figure 14.6).
- A standard sine wave IM, when fed from a PWM voltage source inverter due to the additional (time harmonics) core and winding losses, has to be derated. A derating of 10% is considered acceptable with today's IGBT converters.
- Further on, the presence of a static power converter leads to a 5% voltage reduction at motor terminals with respect to the power grid voltage.
- Finally, an additional derating occurs due to unbalanced power grid voltage. The derating is significant for voltage unbalance above 2% (Figure 14.7).
- Induction motor specifications for constant V and f motors are lined up in pertinent standards. Nameplate markings refer to a miryad of specifications for the user's convenience.
- Efficiency is the most important nameplate marking as the cost of losses per year is about 30 to 40% of initial motor costs.
- Standard and high efficiency motors are now available. EU regulations refer to high efficiency thresholds (Table 14.3).
- Designs A, B, C, and D reveal through their torque speed curves, the starting, pull-up, and breakdown torques which are important factors in most constant V and f supply IMs.
- Matching a constant V and f IM to a load refers to equality of load and motor torque at rated speed and lower load torque below rated speed.
- For variable speed drives, two pole pairs count motors at two different frequencies, one below base speed (full flux zone) and one above base speed (flux weakening, constant voltage zone) may be used.
- For constant power large speed ranges $\Omega_{max}/\Omega_b > 3$, very large breakdown torque designs are required (above 300%). Alternatively, the voltage per phase is increased above base speed by star/delta connection or a larger torque (larger size) IM is chosen.
- Design of an IM means sizing the motor for given specifications of power, supply parameters and load torque/speed envelope.
- Main design factors are: costs of active materials, fabrication and selling, capitalized losses capitalized costs, maintenance costs, material limitations (magnetic, electric, dielectric, thermal, and mechanical) and special application specifications.
- The IM design features 5 issues:
    - Electric design
    - Dielectric design
    - Magnetic design
    - Thermal design
    - Mechanical design
- IM sizing is both a science and an art based on prior experience.
- D_{is}^2L output coefficient design concept has gained widespread acceptance due to Esson's output constant and, with efficiency and power factor known, the stator bore diameter D_{is}, may be calculated for given power, speed and stack length L per pitch τ ratio λ given.
- Further on, with given stator winding current density, airgap, stator teeth and back core flux densities B_g, B_{ts}, B_{cs}, the outer stator diameter is obtained. Based on this data, the stator/rotor slot sizing, wire gauge, machine parameters, performance, losses, and temperatures may be approached. Such a complex enterprise requires coherent methodologies, to be developed in subsequent chapters.

- The rotor tangential stress, $\sigma_{tan} = (0.2 - 4)$ N/cm^2, is defined as a more general design concept valid for both rotary and linear induction motors. This way there is no need to assign initial values to efficiency and power factor to perform the complete design (sizing) process.
- More on design principles in [4–7].

14.12 REFERENCES

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