1. Appendix A

Table S1 shows the nominal data of the motors selected in the study developed.

Table S1 Nominal values of induction motors.

Output Power (kW)	Voltage (V)	Current (A)	Speed (rpm)	Number of poles	Connection
0.04	220	0.35	2700	2	delta
0.25	415	0.7	1380	4	star
0.75	220	3.6	2870	2	delta
1.5	220	6.6	1420	4	delta
5.5	220	21	1425	4	star
7.5	660	8.48	2904	2	delta
15	400	28	1470	4	delta
22	400	41	2930	2	delta
30	400	55	1470	4	delta
45	400	81.5	1480	4	delta
75	400	134	1484	4	delta

2. Appendix B

By power motors category, differentiating between stator and rotor and by the metal used, the weight/power ratios have been approximated to a potential equation (B.1):

$$y = a \cdot x^b \tag{B.1}$$

Where:
y = weight/power ratio in kg.
x = motor output power in kW.
The coefficients a and b obtained in each case are shown in Table S2.

Table S2 Coefficients obtained for each metal in the different power categories.

Stator	Copper (conductors)		Steel (core)		Aluminium (cage)	
Power category	a	b	a	b	a	b
<0.75 kW	2.12	-0.43	3.78	-0.39	3.43	-0.43
0.75-7.5 kW	2.43	-0.51	4.8	-0.31	4.79	-0.62
7.5-75 kW	1.44	-0.25	7.96	-0.35	4.14	-0.41
Rotor	Aluminium (squirrel cage)		Steel (core)		Steel (axis)	
Power category	a	b	a	b	a	b
<0.75 kW	0.33	-0.41	1.73	-0.25	0.36	-0.29

| 0.75-7.5 kW | 0.44 | -0.49 | 2.68 | -0.49 | 0.59 | -0.36 |
| 7.5-75 kW | 0.21 | -0.14 | 1.46 | -0.04 | 0.71 | -0.26 |

3. Appendix C

This Appendix shows, in a simplified way, the procedure for calculating the quantities of metals in the different motors studied.

The sizing of electric motors is carried out based on much data collected from experience. The selection of different coefficients presents a high variability according to the design criteria that are prioritized.

Even so, the equations that can serve as a reference for the approximate calculation of each of the metals that make up each of the parts of the induction motors are included below, in the range of voltages and powers analyzed in this article. In all equations, SI units must be used.

Initially, the main dimensions of the motor are defined according to the nominal output power (P), which are the air gap diameter (D) and the length of the rotor (L), from:

$$D^2 \cdot L = \frac{P}{C \cdot n_s \cdot \cos \varphi} \tag{C.1}$$

$$C = 1.11 \cdot \pi^2 \cdot B_g \cdot q \cdot k_{ws} \cdot 10^{-3} \tag{C.2}$$

Where:
C = output coefficient of the motor.
n_s = synchronous speed (rev/s).
$\cos \varphi$ = power factor.
B_g = flux density in the air gap (0.5 ÷ 0.8 T).
q = specific electric loading (10000 ÷ 20000 A/m).
k_{ws} = stator winding factor (0.93 ÷ 0.98).
A dimensional relationship (D/L) is necessary to define (usually, between 0.6 ÷ 1).

3.1 Weight of Copper in the Stator ($W_{cu,s}$):

This weight is calculated from the volume ($Vol_{cu,s}$) and density (ρ_{cu}) of the copper:

$$W_{cu,s} = Vol_{cu,s} \cdot \rho_{cu} \tag{C.3}$$

$$Vol_{cu,s} = m_s \cdot N_s \cdot l_{Ns} \cdot s_{cu} \tag{C.4}$$

$$N_s = \frac{E}{4.44 \cdot f \cdot \varphi \cdot k_{ws}} \tag{C.5}$$

$$l_{Ns} = 2 \cdot \left[L + \left(1.3 \cdot \frac{\pi \cdot D}{2p} \right) \right] \tag{C.6}$$

$$\varphi = B_g \cdot s_g = B_g \cdot \frac{\pi \cdot D \cdot L}{2p \cdot \Psi} \tag{C.7}$$

$$s_{cu} = \frac{I_s}{\Delta_s} \qquad (C.\,8)$$

Where:

m_s = number of the stator phases.

N_s = number of the stator turns per phase.

l_{Ns} = length of the stator turn.

s_{cu} = surface of the stator wire.

$E \approx V$ = nominal voltage per phase.

f = frequency.

ϕ = flux per pole.

p = number of the pole pairs.

s_g = surface of the stator pole.

ψ = polar cover coefficient (0.6 ÷ 0.75).

I_s = stator nominal current per phase.

Δ_s = stator density current (5 ÷ 6 A/mm^2).

3.2 Weight of Steel Core in the Stator ($W_{fe,s}$):

This weight is calculated from the volume ($Vol_{fe,s}$) and density (ρ_{fe}) of the steel:

$$W_{fe,s} = Vol_{fe,s} \cdot \rho_{fe} \qquad (C.\,9)$$

$$Vol_{fe,s} = L \cdot \left[\left(\frac{\pi \cdot D_{ext,s}^2}{4} - \frac{\pi \cdot D^2}{4} \right) - \left(A_{slot,s} \cdot n_{s,s} \right) \right] \qquad (C.\,10)$$

$$A_{slot,s} = \frac{s_{cu}}{k_{cu}} \qquad (C.\,11)$$

Where:

$D_{ext,s}$ = exterior diameter of the stator ($D_{ext,s}/D$, between 1.6 ÷ 2)

$A_{slot,s}$ = surface of the stator slot

$n_{s,s}$ = number of the stator slots (12 ÷ 48, according to the motor power)

k_{cu} = slot utilization coefficient (0.35 ÷ 0.55)

3.3 Weight of Aluminium Cage in the Stator ($W_{al,s}$):

This weight is calculated from the volume ($Vol_{al,s}$) and density (ρ_{al}) of the aluminium:

$$W_{al,s} = Vol_{al,s} \cdot \rho_{al} \qquad (C.\,12)$$

$$Vol_{al,s} = L \cdot k_{al,cage} \cdot \left(\frac{\pi \cdot D_{cage}^2}{4} - \frac{\pi \cdot D_{ext,s}^2}{4} \right) \qquad (C.\,13)$$

$$D_{cage} = D_{ext,s} + \left(2 \cdot T_{cage} \right) \qquad (C.\,14)$$

Where:

D_{cage} = exterior diameter of the cage.
$k_{al, cage}$ = coefficient to include the volume of the cooling fins (3 ÷ 4).
T_{cage} = thickness of the cage (3 ÷ 6 mm).

3.4 Weight of Aluminium Squirrel Cage in the Rotor (Wal,r):

This weight is calculated from the volume ($Vol_{al,r}$) and density (ρ_{al}) of the aluminium:

$$W_{al,r} = Vol_{al,r} \cdot \rho_{al} \tag{C.15}$$

$$Vol_{al,r} = L \cdot A_{slot,r} \cdot n_{s,r} \cdot k_{rings} \tag{C.16}$$

$$A_{slot,r} = \frac{I_{br}}{\Delta_r} \tag{C.17}$$

$$I_{br} = \frac{I_r}{p} = \frac{I'_r \cdot r_{tI}}{p} \tag{C.18}$$

$$r_{tI} = \frac{N_s \cdot m_s \cdot k_{ws}}{N_r \cdot m_r \cdot k_{wr}} \tag{C.19}$$

Where:
$A_{slot,r}$ = surface of the rotor slot.
$n_{s,r}$ = number of the rotor slots (15 ÷ 40, according to the motor power).
k_{rings} = shorted rings coefficient (1.5 ÷ 2.5).
I_{br} = current in the rotor slot.
Δ_r = rotor density current (4 ÷ 6 A/mm^2).
I_r = current in the rotor.
I'_r = current in the rotor referred to the stator ≈ I_s.
r_{tI} = current transformation ratio.
m_r = number of the rotor phases = $n_{s,r}$/2p.
N_r = number of the rotor turns per phase = p.
k_{wr} = rotor winding factor ≈ 1.

3.5 Weight of Steel Core in the Rotor (Wfe,r):

This weight is calculated from the volume ($Vol_{fe,r}$) and density (ρ_{fe}) of the steel:

$$W_{fe,r} = Vol_{fe,r} \cdot \rho_{fe} \tag{C.20}$$

$$Vol_{fe,r} = L \cdot \left[\left(\frac{\pi \cdot D^2}{4} - \frac{\pi \cdot D^2_{axis}}{4} \right) - \left(A_{slot,r} \cdot n_{s,r} \right) \right] \tag{C.21}$$

Where:
D_{axis} = diameter of the axis (8 ÷ 70 mm, according to the motor power).

3.6 Weight of Steel Axis in the Rotor (Wfe,Axis):

This weight is calculated from the volume ($Vol_{fe,axis}$) and density (ρ_{fe}) of the steel:

$$W_{fe,axis} = Vol_{fe,axis} \cdot \rho_{fe} \qquad (C.22)$$

$$Vol_{fe,axis} = 2 \cdot L \cdot \frac{\pi \cdot D_{axis}^2}{4} \qquad (C.23)$$

3.7 Dimensioning Review by Simulation with the Finite Element Method:

This calculation procedure is being reviewed and adapted by simulation with finite elements. The freely available program FEMM (Finite Element Method Magnetic) has been used [1].

As an example, Figure S1 shows the simulation results carried out on the 1.5 kW motor studied. This simulation allows calculating and contrasting the magnetic flux per pole and the flux density in the air gap, using the geometry and the number of turns per phase established in the previous calculation.
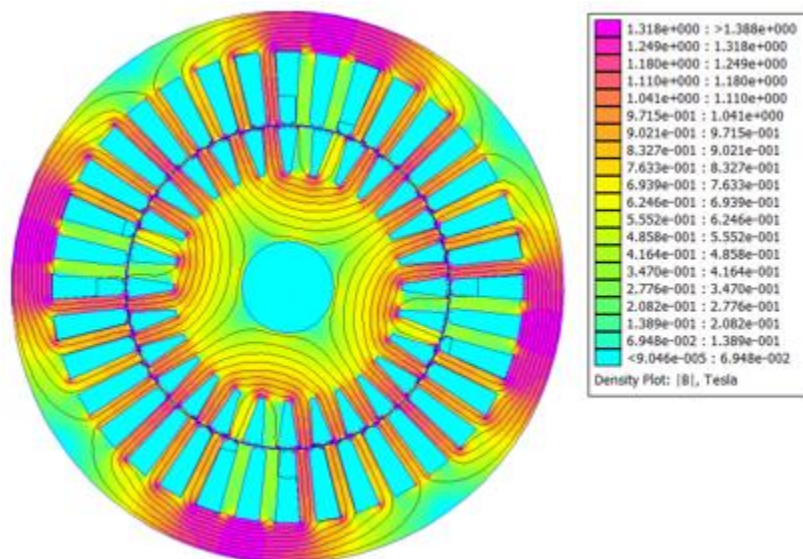

Figure S1 Finite Element Method Simulation (1.5 kW motor): Flux density map.

References

1. Meeker D. Finite element method magnetics: User's manual. 2015 [cited date 2023 April 12]. Available from: https://www.femm.info/Archives/doc/manual.pdf.