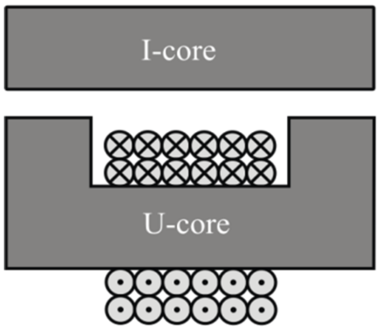
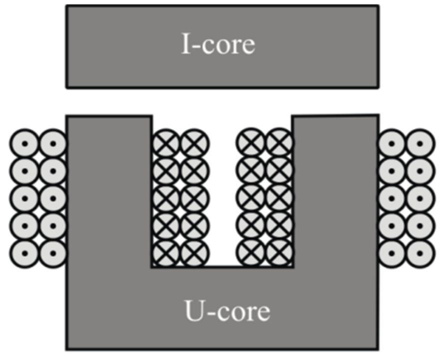
Power Magnetic Devices: A Multi-Objective Design Approach

Chapter 3: Introduction to Inductor Design

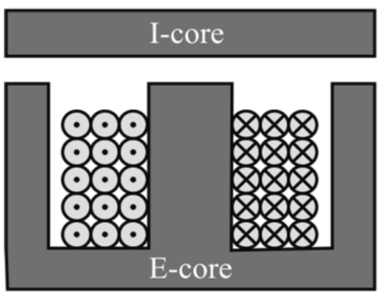
3.1 Common Inductor Architectures



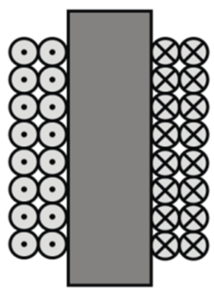
(a) UI-core

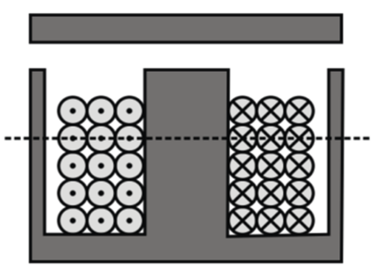


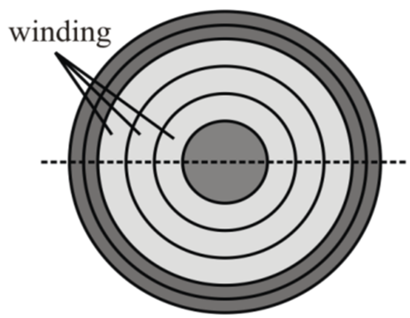
(b) alternate UI-core



(c) EI-core


(d) solenoid


(e) bobbin core cross section



(f) bobbin core (bottom piece from above)

3.2 DC Coil Resistance

- Resistance of coil

$$R = \frac{V_{cl} N^2}{k_{pf} A_{cl}^2 \sigma}$$

- Packing factor

$$k_{pf} = \frac{A_{cd}}{A_{cl}}$$

3.2 DC Coil Resistance

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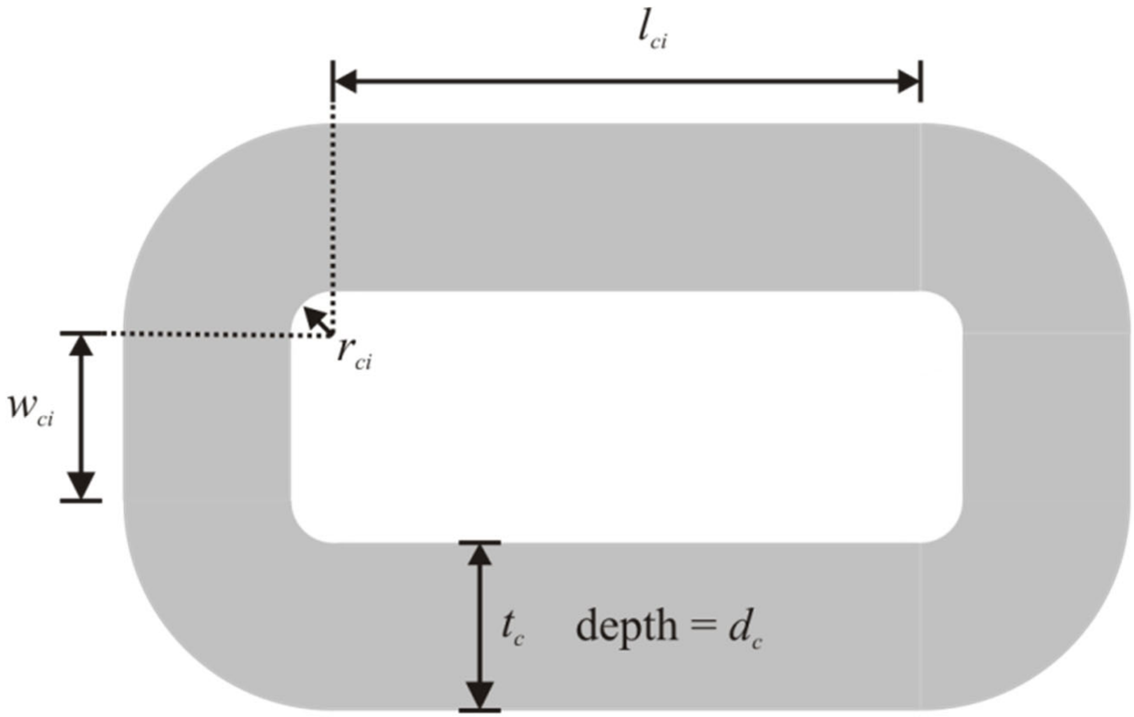
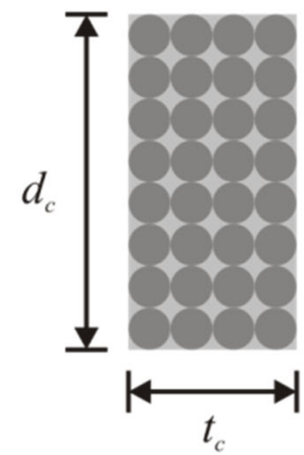


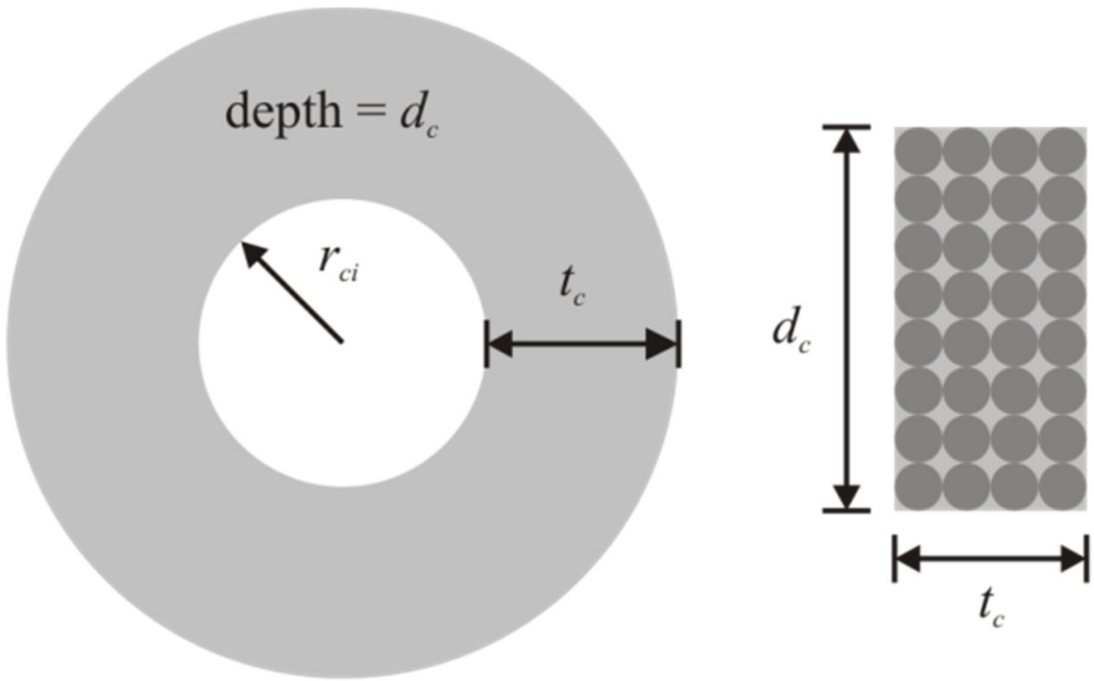
(a) top view of coil



(b) coil cross section

$$V_{cl} = d_c\left(\pi(t_c + r_{ci})^2 - \pi r_{ci}^2 + (2l_{ci} + 2w_{ci})t_c\right) \quad A_{cl} = t_c d_c$$

3.2 DC Coil Resistance

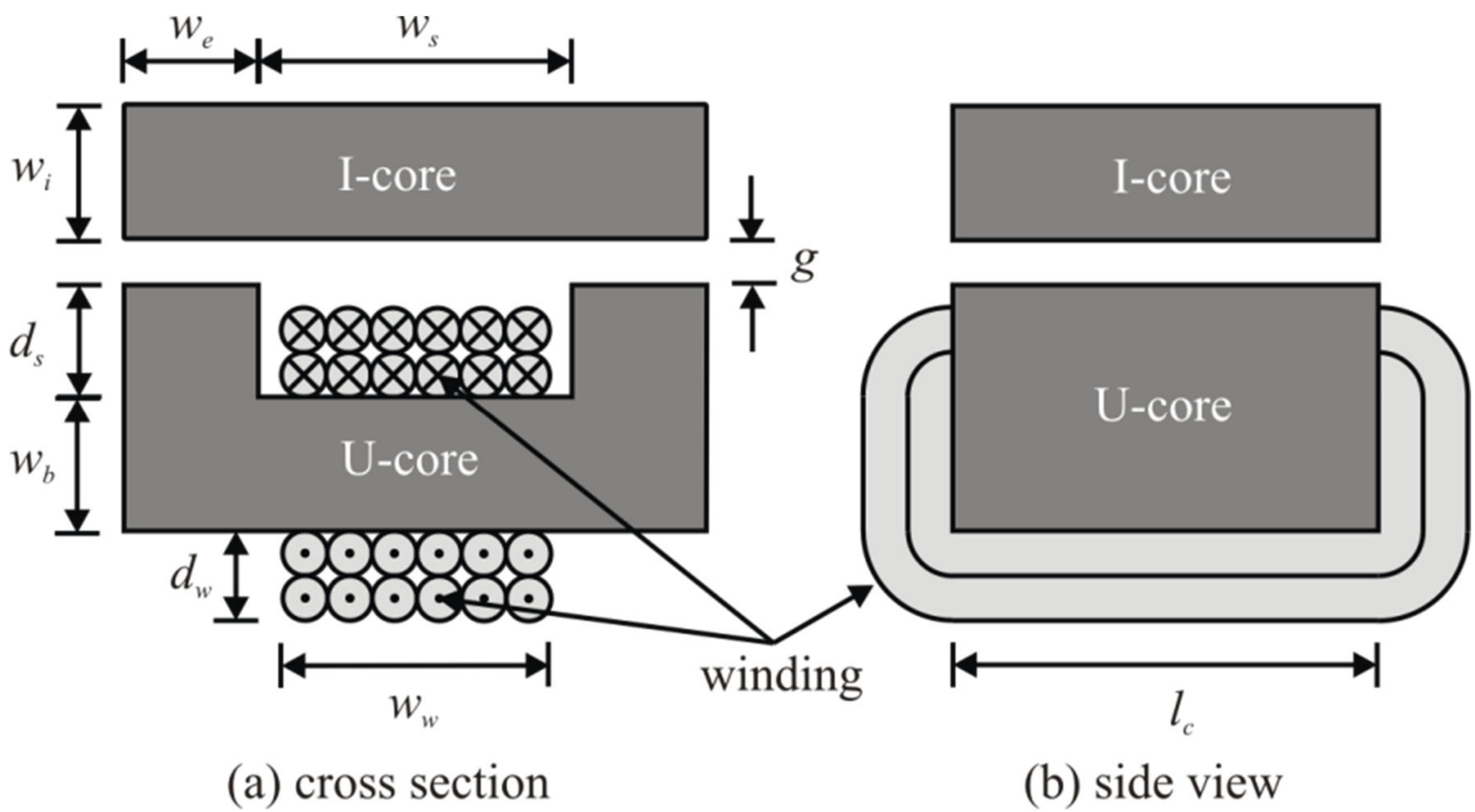


(a) top view of coil (b) cross section of coil

$$V_{cl} = \pi d_c \left((t_c + r_{ci})^2 - r_{ci}^2 \right) \qquad A_{cl} = t_c d_c$$

3.3 DC Inductor Design

- Design space



$$\boldsymbol{\theta} = [T_{cr}\ T_{cd}\ g\ l_c\ w_e\ r_{ie}\ r_{be}\ a^*\ N^*\ N_w^*\ N_d^*\ c_w\ c_d]^T$$

3.3 DC Inductor Design

- Widths

$$w_i = r_{ie} w_e$$

$$w_b = r_{be} w_e$$

- Conductors

$$a = \text{round}_{WG}(a^*)$$

$$r_c = \sqrt{\frac{a}{\pi}}$$

$$N = \text{round}(N^*)$$

3.3 DC Inductor Design

- Coil layout

$$N_w = \text{round}(N_w^*)$$

$$N_d = \text{round}(N_d^*)$$

$$w_w = 2 r_c k_b N_w$$

$$d_w = 2 r_c k_b N_d$$

- More geometry

$$w_s = w_w + 2 c_w$$

$$d_s = d_w + c_d$$

3.3 DC Inductor Design

- Mass and volumes

$$M_{cr} = \rho_{cr}\left((w_b + w_i)(w_s + 2w_e) + 2d_s w_e\right)l_c$$

$$V_{cl} = w_w\left(\pi d_w^2 + \left(2l_c + 2w_b\right)d_w\right)$$

$$k_{pf} = \frac{Na}{d_w w_w}$$

$$V_{cd} = k_{pf} V_{cl}$$

$$M_{cd} = \rho_{cd} V_{cd}$$

3.3 DC Inductor Design

- Total mass

$$M_L = M_{cr} + M_{cd}$$

- Loss

$$A_{cl} = d_w w_w$$

$$R = \frac{V_{cl} N^2}{k_{pf} d_w^2 w_w^2 \sigma_{cd}}$$

$$P_L = R i_{dc0}^2$$

3.3 DC Inductor Design

- Constraints

$$c_1 = \mathrm{gte}(N_d N_w, N)$$

$$c_2 = \mathrm{lte}(k_{pf}, k_{pf,mx})$$

$$J = \frac{i_{dc0}}{a}$$

$$c_3 = \mathrm{lte}(J, J_{mx})$$

3.3 DC Inductor Design

- More constraints

$$h_L = d_w + w_b + d_s + g + w_i$$

$$w_L = 2w_e + w_s$$

$$l_L = 2d_w + l_c$$

$$\alpha_L = \frac{\max(h_L, w_L, l_L)}{\min(h_L, w_L, l_L)}$$

$$c_4 = \text{lte}(\alpha_L, \alpha_{mx})$$

3.3 DC Inductor Design

- Even more constraints

$$c_5 = \text{lte}(M_L, M_{Lmxa})$$

$$c_6 = \text{lte}(P_L, P_{Lmxa})$$

$$L_{inc} = \frac{\lambda|_{i_{dc0}+\Delta i} - \lambda|_{i_{dc0}-\Delta i}}{2\Delta i}$$

$$c_7 =$$

$$c_8 = \text{gte}(L_{inc}, L_{mn})$$

3.3 DC Inductor Design

- A final constraint

$$r_\Phi = \left| \frac{N\Phi_3 \big|_{i=i_{dc0}+\Delta i}}{\lambda \big|_{i=i_{dc0}+\Delta i}} \right|$$

$$c_9 = \mathrm{gte}(r_\Phi, r_{\Phi rq})$$

3.3 DC Inductor Design

- Pseudo-code for fitness function

calculate M_L , P_L

calculate constraints c_1 through c_6

$C_S = c_1 + c_2 + c_3 + c_4 + c_5 + c_6$

$C_I = 6$

if ($C_S < C_I$)

$$\mathbf{f} = \varepsilon\left(\frac{C_s - C}{C}\right)\begin{bmatrix}1\\1\end{bmatrix}$$

return

end

construct MEC and calculate c_7 , c_8 , and c_9

$C_s = C_I + c_7 + c_8 + c_9$

$C_I = C_I + 1$

if ($C_S < C_I$)

$$\mathbf{f} = \varepsilon\left(\frac{C_s - C}{C}\right)\begin{bmatrix}1\\1\end{bmatrix}$$

return

end

$$\mathbf{f} = \begin{bmatrix}\dfrac{1}{M_L}\\ \dfrac{1}{P_L}\end{bmatrix}$$

return

3.4 Case Study

- Specifications

Table 3.4-1 Inductor specifications.

Symbol	Description	Value
i_{dc0}	nominal dc operating current	10 A
L_{rqi}	required incremental inductance at nominal current	5 mH
J_{mxa}	Maximum allowed current density at nominal current	7.6 MA/m^2
α_{mxa}	maximum allowed aspect ratio	3
M_{Lmxa}	maximum allowed mass	5 kg
P_{Lmxa}	maximum allowed loss at nominal current	100 W
k_{pf-mxa}	maximum allowed packing factor	0.7
k_b	winding build factor	1.05
Δi	perturbation in current for inductance calculation	0.1 A
$r_{\Phi rq}$	minimum required magnetizing flux ratio	0.9

3.4 Case Study

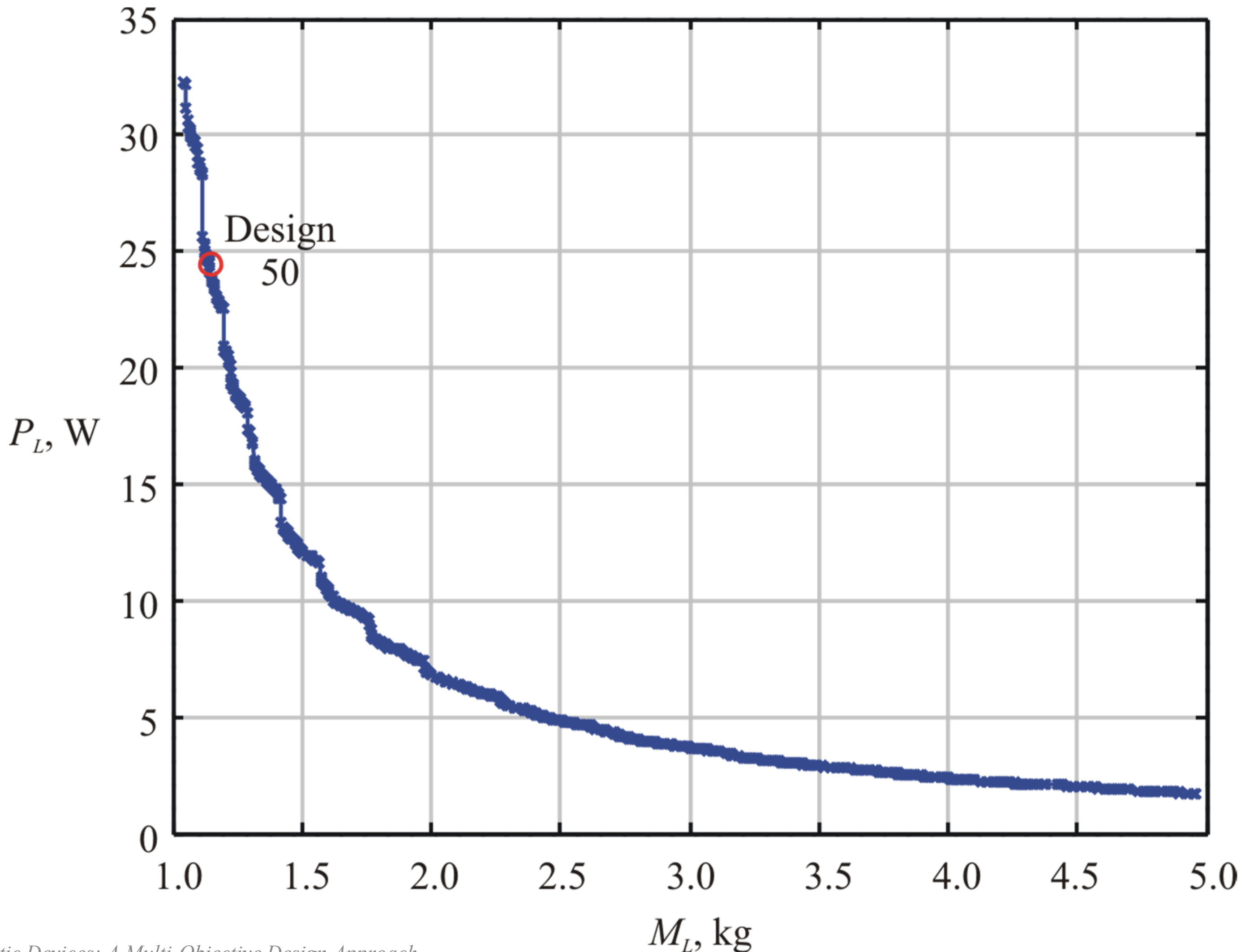
- Design space

Table 3.4-2 Design space.

Par.	Description	Min.	Max.	Enc.	Gene
T_{cr}	Core material	1	5	int	1
T_{cd}	Conductor material	1	2	int	2
g	Air gap (m)	10^{-4}	10^{-2}	log	3
l_c	Core length	10^{-2}	1	log	4
w_e	U-core end width (m)	$2\cdot10^{-3}$	10^{-1}	log	5
r_{ie}	w_i to w_e ratio	0.5	1.5	lin	6
r_{be}	w_b to w_e ratio	0.5	1.5	lin	7
a_c	Cross sectional conductor area (m^2)	10^{-9}	10^{-4}	log	8
N^*	Desired number of turns	1	10^3	log	9
N_w^*	Desired slot width in conductors	1	10^3	log	10
N_d^*	Desired slot depth in conductors	1	10^3	log	11
c_w	Slot clearance in width (m)	10^{-6}	10^{-2}	log	12
c_d	Slot clearance in depth (m)	10^{-6}	10^{-2}	log	13

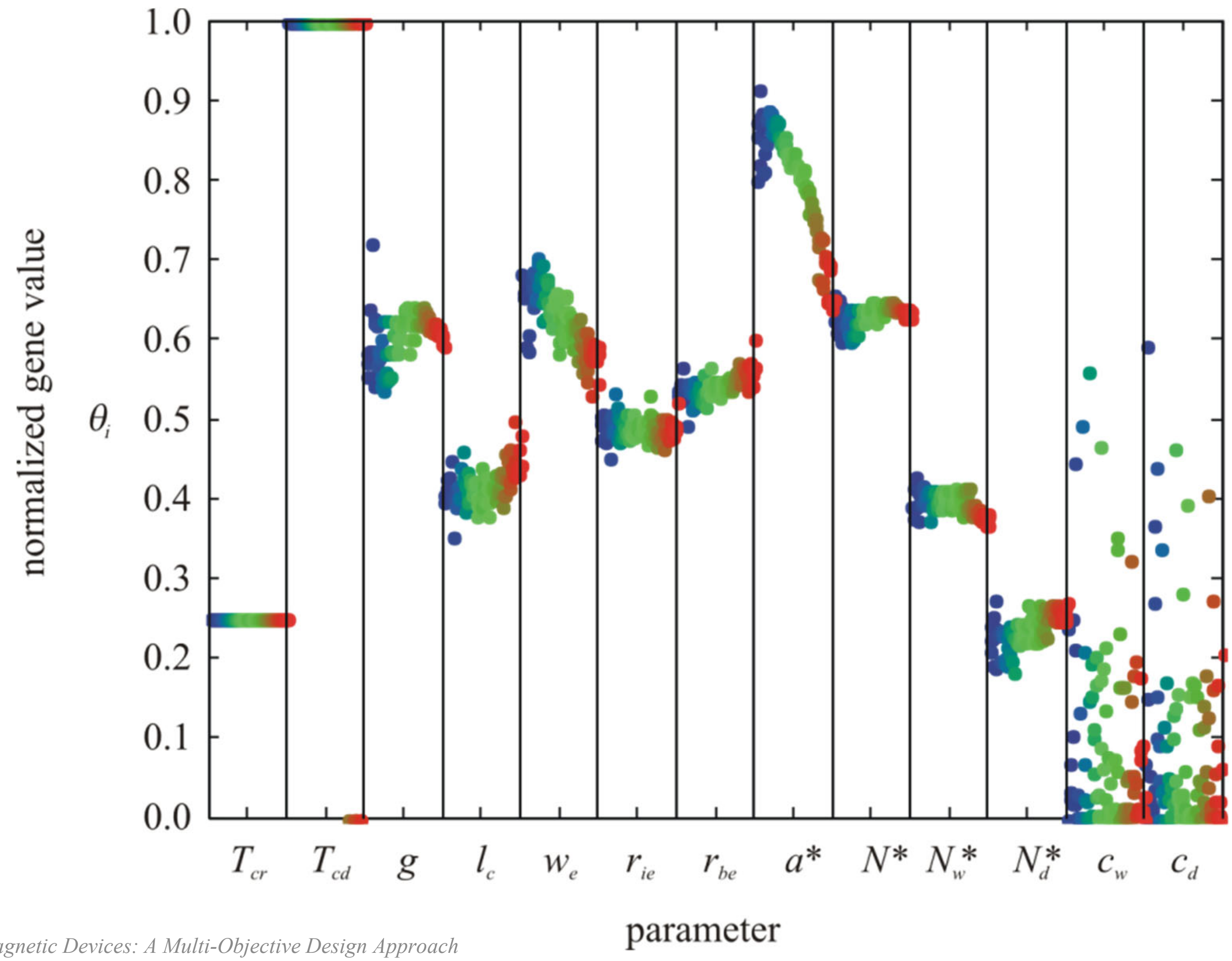
3.4 Case Study

- Pareto-optimal front



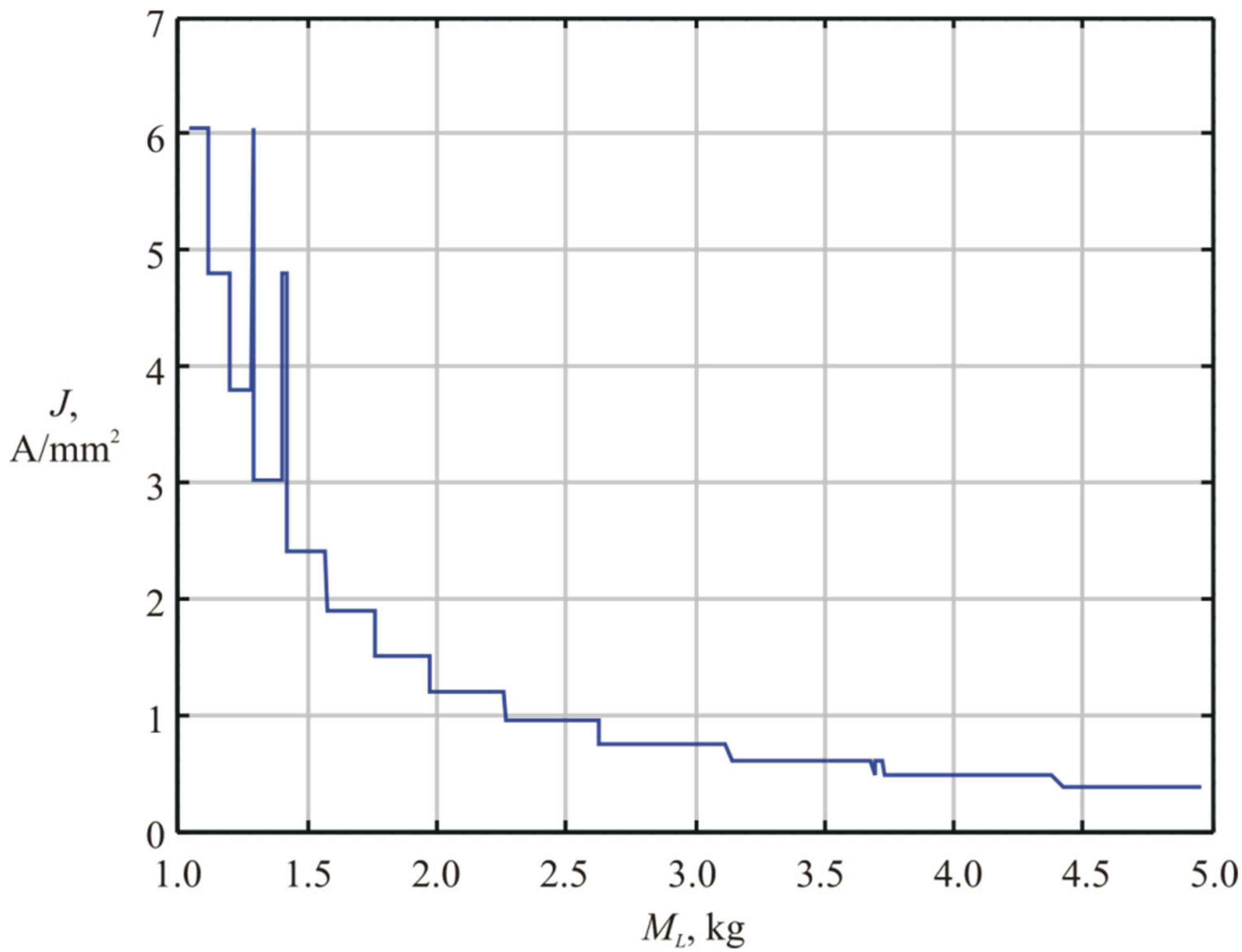
3.4 Case Study

- Population distribution (sorted by first objective)



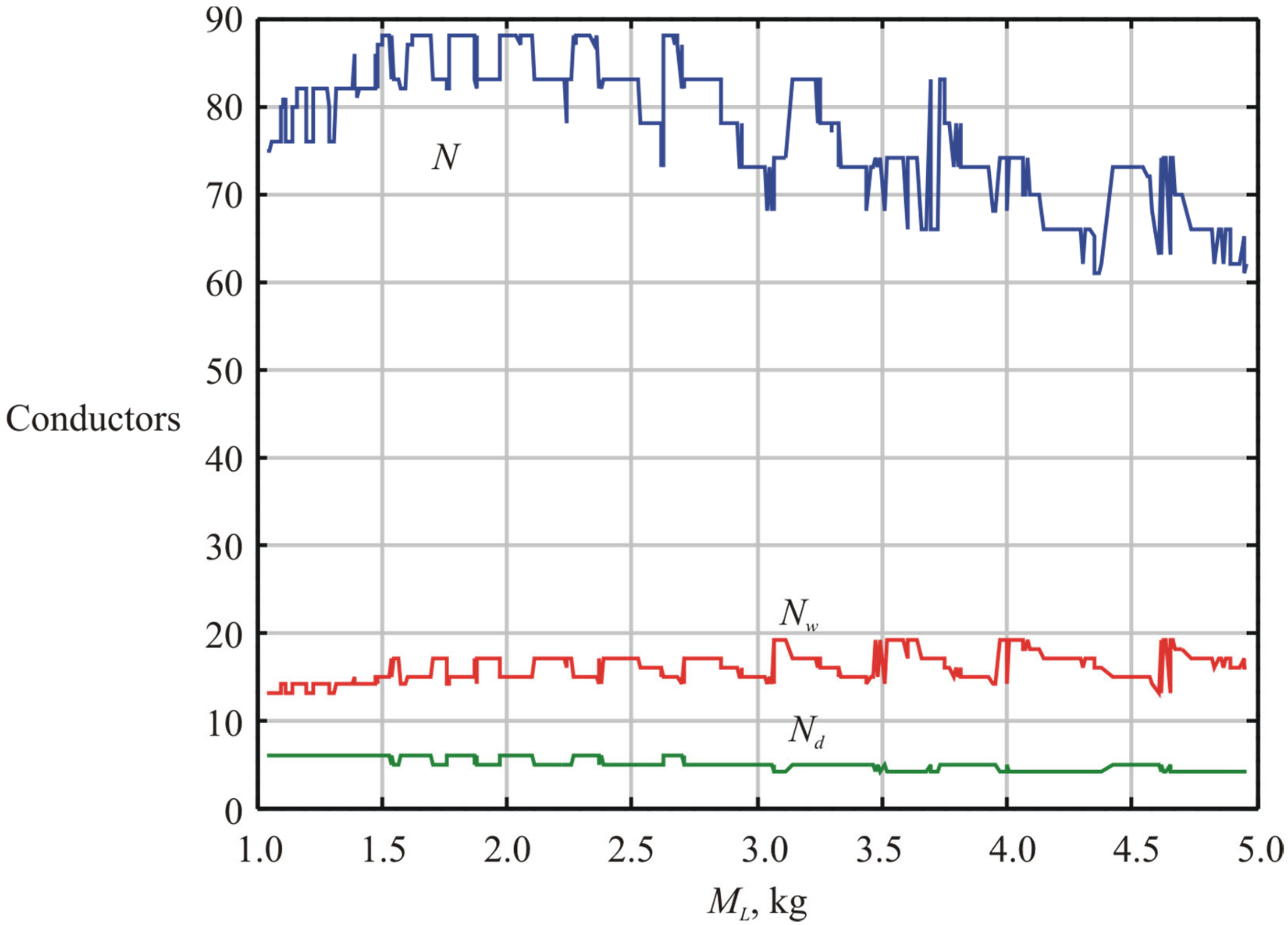
3.4 Case Study

- Current density



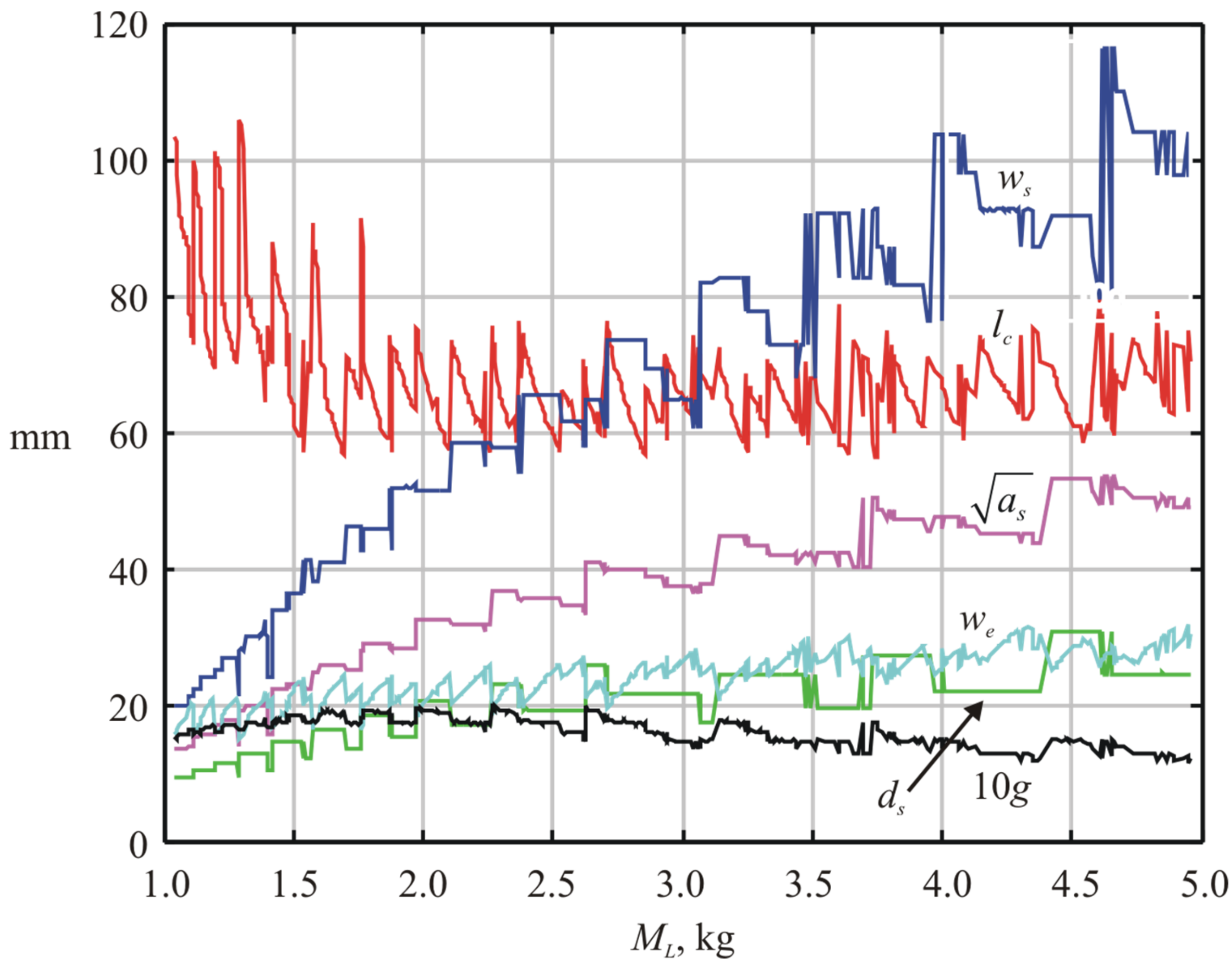
3.4 Case Study

- Conductor count



3.4 Case Study

- Dimensions



3.4 Case Study

- Design 50

Table 3.4-3 Design 50 data.

UI Core Data	Winding Data	Metrics
Material = MN60LL	Material = Aluminum	M_L = 1.14 kg
w_e = 1.72 cm	AWG = 14	P_L = 24.5 W
w_i = 1.67 cm	a_c = 2.08 mm^2	J = 4.80 A/mm^2
w_b = 1.82 cm	N = 76	L_{inc} = 5.00 mH
w_s =2.22 cm	N_w = 13	R_L = 245 mΩ
d_s = 1.03 cm	N_d = 6	h_L = 5.69 cm
l_c = 9.24 cm	d_w = 1.03 cm	w_L = 5.66 cm
M_{cr} = 1.03 kg	w_w = 2.22 cm	l_L = 11.3 cm
g=1.58 mm	M_{cd} = 0.108 kg