In The Name of God The Most Compassionate, The Most Merciful

Brushless PM Machines

Design, Optimization and Analysis

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Fundamental definitions

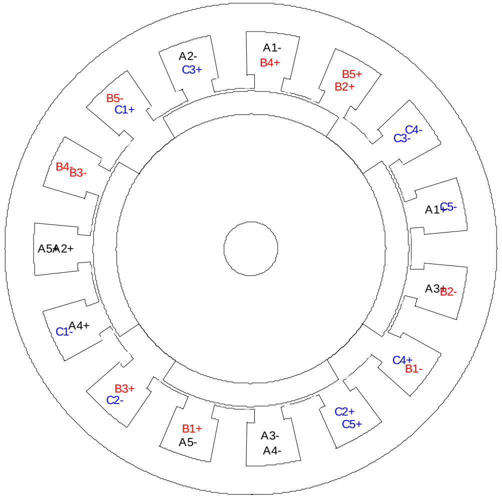
Concentrated vs. distributed winding

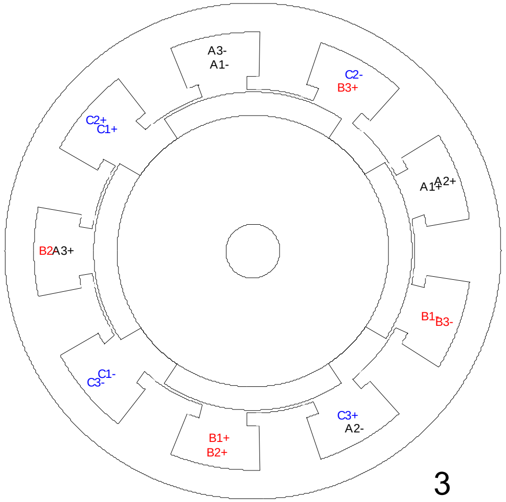
- **Number of slots per pole per phase** $N_{spp} = \dfrac{N_s}{2pq}$

  where N_s is the number of slots, *p* is the number of pole pairs and *q* is the number of phases.

- If $N_{spp} \geq 1$ the winding is **distributed**

- If $N_{spp} < 1$ the winding is **concentrated**



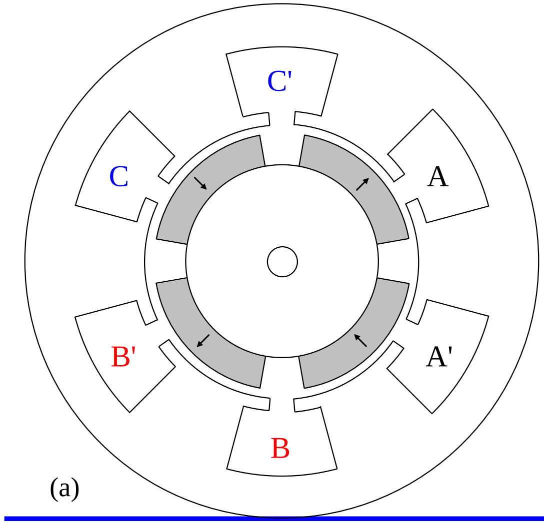


Winding

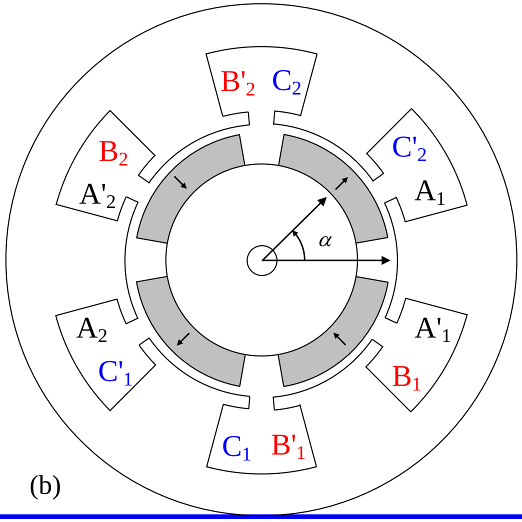
Fundamental definitions

Overlapping vs. non-overlapping windings

- **Non-overlapping**: each coil is wound around a single stator tooth.
  - Alternate teeth wound (Single-layer slots) (a)
  - All teeth wound (double-layer slots) (b)
- **Overlapping**: each coil spans almost a pole pitch. (c)



(a)



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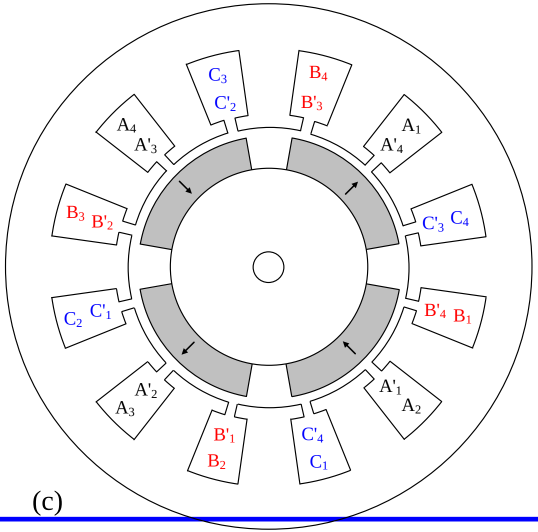


(c)

Winding

Fundamental definitions

Overlapping vs. non-overlapping windings

Advantages of non-overlapping over overlapping windings:

- **Shorter end turn** winding
- Easier **manufacturability**
- More **fault tolerant**, less probability of turn-to-turn short circuit fault.

Integral vs. fractional

In the case of slotted motors another classification is defined as either ***integral*** or ***fractional*** number of slots per pole per phase. Fractional slot structures reduce the cogging torque.

Winding

Fundamental definitions

Winding factors: pitch and distribution factors

- **Pitch factor** for the *n*-th harmonic is expressed as

$$k_{pn} = \sin\left(\frac{n\pi\theta_c}{2\theta_p}\right) = \sin\left(\frac{n\theta_c}{2}\right)$$

where θ_c is the coil pitch and θ_p is the pole pitch both in electrical measures.

- **Distribution factor** for the *n*-th harmonic is represented as

$$k_{dn} = \frac{\sin\left(\frac{nm\theta_s}{2}\right)}{m\sin\left(\frac{n\theta_s}{2}\right)}$$

where $\theta_s = \frac{2\pi p}{N_s}$ is the electrical angle between two adjacent slots and *m* is the number of slots in each phase belt.

Winding

Hints

- Winding should **maximize** the **electromagnetic torque** and **minimize** the **torque ripple**.

- The **number of coils** must be a **multiple** number of **phases**.

- The **number of slots** should be a **multiple** number of **phases** for **double-layer** motors. In general $N_s = kq*2/N_l$ where q is the number of phases and N_l is the number of layers.

- The **number of slots** must be **even** for **single-layer** windings.

- The **number of poles** must be **even**.

Winding

Hints

- The **number of poles** **cannot** be equal to the **number of slots**.
- The ***phase offset*** in slots number should be an integer value using

$$K_0 = \frac{N_s}{qp}(1 + k\,q) \qquad k = 0, 1, 2, \ldots, p-1$$

- In inner rotor motors the **number of poles** is usually **lower** than the **number of slots**.
- In outer rotor motors, it is usual to have **higher number of poles** than the **number of slots**.
- The magnetic **flux linked with each coil** needs to be **maximized** which means the induced back-EMF is maximized.
- The **phase winding** should be **balanced**.

Winding

Procedure to find 3-phase layout

1. Select the **number of pole-pairs**, p. It must be an integer number.
2. Select the **number of layers** for each slot, N_l. It must be an integer number, normally 1 or 2.
3. Based on the number of pole-pairs and number of layers, select a proper **number of slots**, N_s.
   - Number of slots should be a **multiple** **number of phases** for double-layer winding. In general it should be a multiple number of $q*2/N_l$.
   - Number of slots should be **even for single layer** winding.
   - The number of slots **cannot** be equal to the number of poles and more generally

$$N_s \neq (q-1)^k 2p \qquad k = 0, 1, 2, \ldots$$

   - There should be a possibility for **balanced** winding.

Winding

Procedure to find 3-phase layout

4. Select between ***overlapping*** and ***non-overlapping*** windings.
5. Find **coil pitch** in slot number, *S*, using the following expression

$$S = \begin{cases} 1 & \text{for} \quad \text{non}-\text{overlapping} \\ \max\left(\text{floor}\left(\dfrac{N_s}{2p}\right),1\right) & \text{for} \quad \text{overlapping} \end{cases}$$

In the case of **single layer** windings, S should be an **odd** number. If the above expressions results in an even number then $S=S$-1.

Winding

Procedure to find 3-phase layout

6. Calculate **phase offset** (the offset between two adjacent phases) in terms of slots number, K_0 using the following expression

$$K_0 = \frac{N_s}{qp}\left(1+qk\right) \qquad k = 0,1,2,\ldots,p-1$$

Normally the **first integer value** of K_0 is selected as phase offset. In the case **single layer** winding, phase offset should be an **even** number; therefore the first integer even value is selected as phase offset. Note that if **no integer value** can be found from the above expression, it means the number of **poles/slots** combination is not **valid** for a balanced winding.

Winding

Procedure to find 3-phase layout

7. Based on the coil pitch and phase offset the **winding layout** is presented in the following format:

Coil numbers (*i*)	**1**	**2**	• • •	***i***	• • •	$\frac{N_s N_l}{2}$
Coil angles (θ_i^{coil})	0	$\frac{2\theta_s}{N_l}$	• • •	$\frac{2\theta_s}{N_l}(i-1)$	• • •	$\theta_s\left(N_s-\frac{2}{N_l}\right)$
In-slot (N_i^{in})	1	$1+\frac{2}{N_l}$	• • •	$1+\frac{2}{N_l}(i-1)$	• • •	$1+N_s-\frac{2}{N_l}$
Out-slot (N_i^{out})	$1+S$	$1+\frac{2}{N_l}+S$	• • •	$N_i^{in}+S$	• • •	$1+N_s-\frac{2}{N_l}+S$

where $\theta_s = 360\,p/N_s$ is the slot pitch angle in electrical degrees.

Winding

Procedure to find 3-phase layout

8. **Modify winding layout table** by bringing the coil angles in the range of -180 and 180 and the out-slot between 1 and N_s:

$$\theta_i^{coil} = rem(\theta_i^{coil} + 180, 360) - 180$$

$$N_i^{out} = rem(N_i^{out}, N_s)$$

where *rem* is the remainder function. If N_i^{out} is zero after applying the remainder function, the zero should be replaced by N_s.

Winding

Procedure to find 3-phase layout

9. For those coils where their coil angles are **greater than 90** degrees or **less than -90 degrees**, the **coil direction is reversed** (swap N_i^{in} and N_i^{out}) and the **coil angles are added by -180 or 180** respectively. By this step, the coil angles are brought within -90 and 90 degrees.

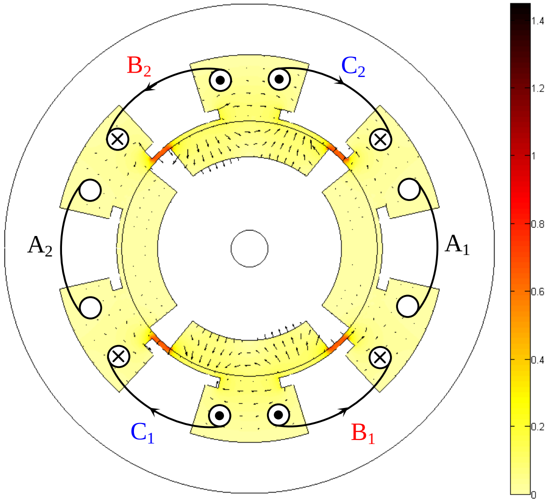
$$\begin{cases} N_i^{in} \leftrightarrow N_i^{out} & if \quad \theta_i^{coil} > 90 \\ N_i^{in} \leftrightarrow N_i^{out} & if \quad \theta_i^{coil} < -90 \end{cases}$$

$$\theta_i^{coil} = \begin{cases} \theta_i^{coil} - 180 & if \quad \theta_i^{coil} > 90 \\ \theta_i^{coil} + 180 & if \quad \theta_i^{coil} < -90 \end{cases}$$

Winding

Procedure to find 3-phase layout

10. Find out **each coil is related to which phase**. To do so, the coils with **coil angles closest to 0** with **minimum total spread** will be selected for the **first phase**. For each coil from first phase there is a corresponding coil for the next phase using the phase offset. This process will be repeated to find the coils of all phases.



Winding

Example 1

Assume a 3-phase machine with

1. **Four poles** (2-pole-pair)
2. **Double layer** slots
3. **15 slots**
4. **Overlapping** winding.

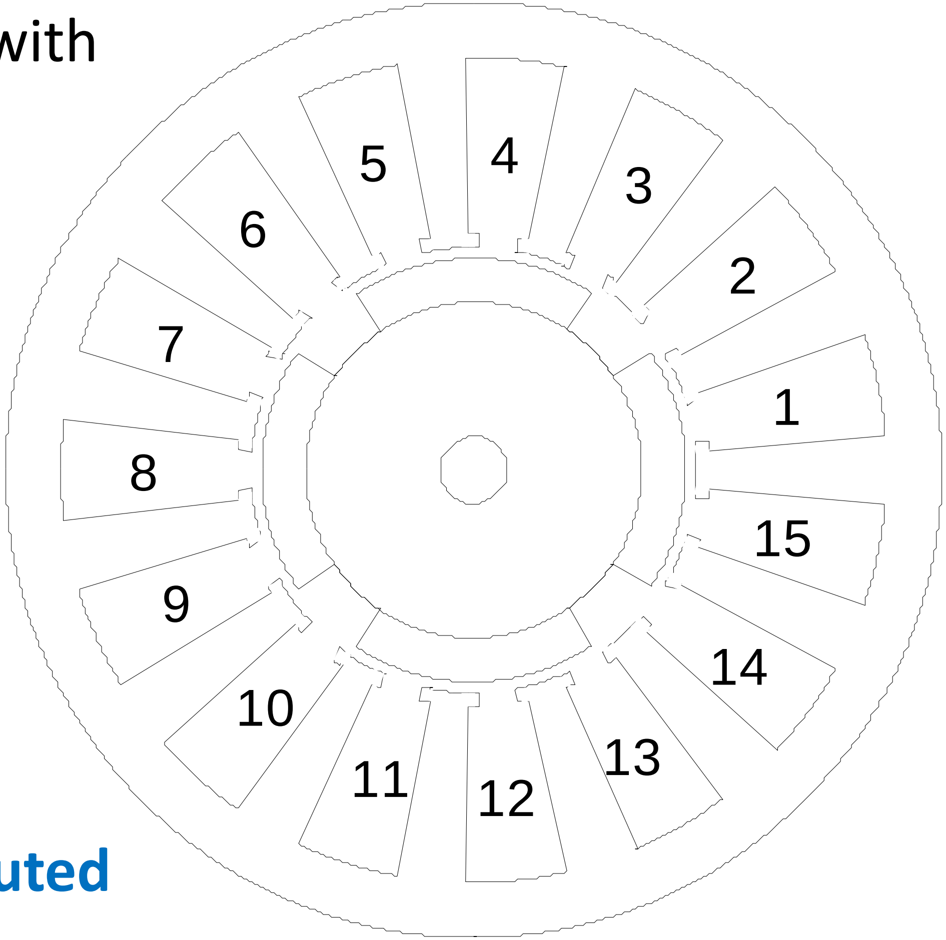
$q = 3$

$p = 2$

$N_l = 2$

$N_s = 15$

$N_{spp} = \frac{N_s}{2qp} = 1.25 \geq 1$ => **Distributed**



Winding

Example 1

5. Coil pitch calculation

$$S = \max\left(\operatorname{floor}\left(\frac{N_s}{2p} \right), 1 \right) = \max\left(\operatorname{floor}\left(\frac{15}{4} \right), 1 \right) = 3$$

6. Phase offset calculation

$$\begin{aligned} K_0 &= \frac{N_s}{qp}(1+qk) \qquad\qquad k = 0, 1, 2, \ldots, p-1 \\ &= \frac{15}{3\times 2}(1+3k) \\ &= 10 \qquad\qquad\qquad for \quad k = 1 \end{aligned}$$

Winding

Example 1

7. Winding layout

Coil Numbers	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Coil angles	0	48	96	144	192	240	288	336	384	432	480	528	576	624	672
In-slot coil	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Out-slot coil	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

Coil angles: $\frac{2\theta_s}{N_l}(i-1)$ In-slot: $1+\frac{2}{N_l}(i-1)$ Out-slot: $N_i^{in}+S$

where $\theta_s = 360\,p/N_s = 48, \qquad N_l = 2, \qquad S = 3$

Winding

Example 1

8. Modifying winding layout

Coil Numbers	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Coil angles	0	48	96	144	**-168**	**-120**	**-72**	**-24**	**24**	**72**	**120**	**168**	**-144**	**-96**	**-48**
In-slot coil	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Out-slot coil	4	5	6	7	8	9	10	11	12	13	14	15	**1**	**2**	**3**

$$\theta_i^{coil} = rem(\theta_i^{coil} + 180, 360) - 180$$

$$N_i^{out} = rem(N_i^{out}, N_s)$$

Winding

Example 1

9. Modifying winding layout

Coil Numbers	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Coil angles	0	48	**-84**	**-36**	**12**	**60**	-72	-24	24	72	**-60**	**-12**	**36**	**84**	-48
In-slot coil	1	2	**6**	**7**	**8**	**9**	7	8	9	10	**14**	**15**	**1**	**2**	15
Out-slot coil	4	5	**3**	**4**	**5**	**6**	10	11	12	13	**11**	**12**	**13**	**14**	3

$$\theta_i^{coil} = \begin{cases} \theta_i^{coil} - 180 & \& \quad N_i^{in} \leftrightarrow N_i^{out} \quad \text{if} \quad \theta_i^{coil} > 90 \\ \theta_i^{coil} + 180 & \& \quad N_i^{in} \leftrightarrow N_i^{out} \quad \text{if} \quad \theta_i^{coil} < -90 \end{cases}$$

Winding

Example 1

10. Find out the coils of each phase (5 coils per phase)

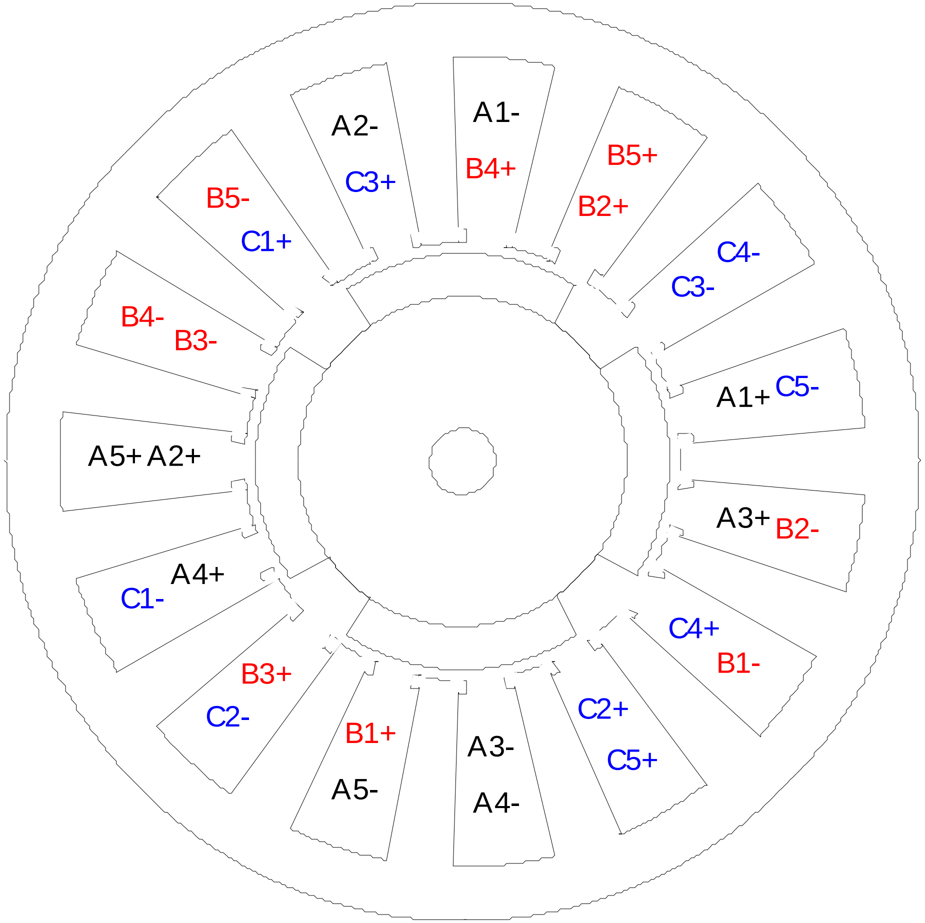
Coil Numbers	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Coil angles	0	48	-84	-36	12	60	-72	-24	24	72	-60	-12	36	84	-48
In-slot coil	1	2	6	7	8	9	7	8	9	10	14	15	1	2	15
Out-slot coil	4	5	3	4	5	6	10	11	12	13	11	12	13	14	3
Phase	A1	C3	B5	B4	A2	C1	B3	A5	A4	C2	B1	A3	C5	C4	B2

Winding

Example 1

Plot the winding topology

Slots	Phase A	Phase B	Phase C
1	In		Out
2			Out & Out
3		In & In	
4	Out	In	
5	Out		In
6		Out	In
7		Out & Out	
8	In & In		
9	In		Out
10		In	Out
11	Out	In	
12	Out & Out		
13			In & In
14		Out	In
15	In	Out	



Winding

Valid pole/slot combinations for **2-phase** machines

Slots	8	12	16	20	24	28	32	36	40	44	48
Poles	2	2	2	2	2	2	2	2	2	2	2
	6	10	4	6	4	6	4	6	4	6	4
			6	14	6	10	6	10	6	10	6
			10		10	18	8	14	10	14	8
			12		18	22	10	22	12	18	10
			14		20		12	26	14		12
							14	30	26		14
							20		28		18
							22		30		20
							24		34		30
							26				34
							28				36
											38
											40
											42

Winding

Valid pole/slot combinations for **3-phase** machines

Slots	**3**	**6**	**9**	**12**	**15**	**18**	**21**	**24**	**27**	**30**	**33**	**36**	**39**	**42**	**45**	**48**
Poles	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
			6	8	10	6	8	8	6	8	8	6	8	8	6	8
			8	10		8	14	10	8	10	10	8	10	10	8	10
			12	18		12	16	16	10	20	14	10	14	14	10	14
						14		20	12	22	20	12	16	16	12	16
						16			18	26	22	14	26	26	14	20
									20		26	16	28	32	16	32
									22		28	22	32	34	20	34
									24			24	34		28	38
												26			30	40
												28			32	
												30			34	
												32			38	
															40	

Winding

Valid pole/slot combinations for **4-phase** machines

Slots	8	16	24	32	40	48
Poles	2	2	2	2	2	2
	4	4	6	4	6	4
		6	10	6	10	6
		10	18	8	14	10
		12		10	26	12
		14		12	30	14
				14	34	18
				20		20
				22		30
				24		334
				26		36
				28		38
						40

Winding

Valid pole/slot combinations for **5-phase** machines

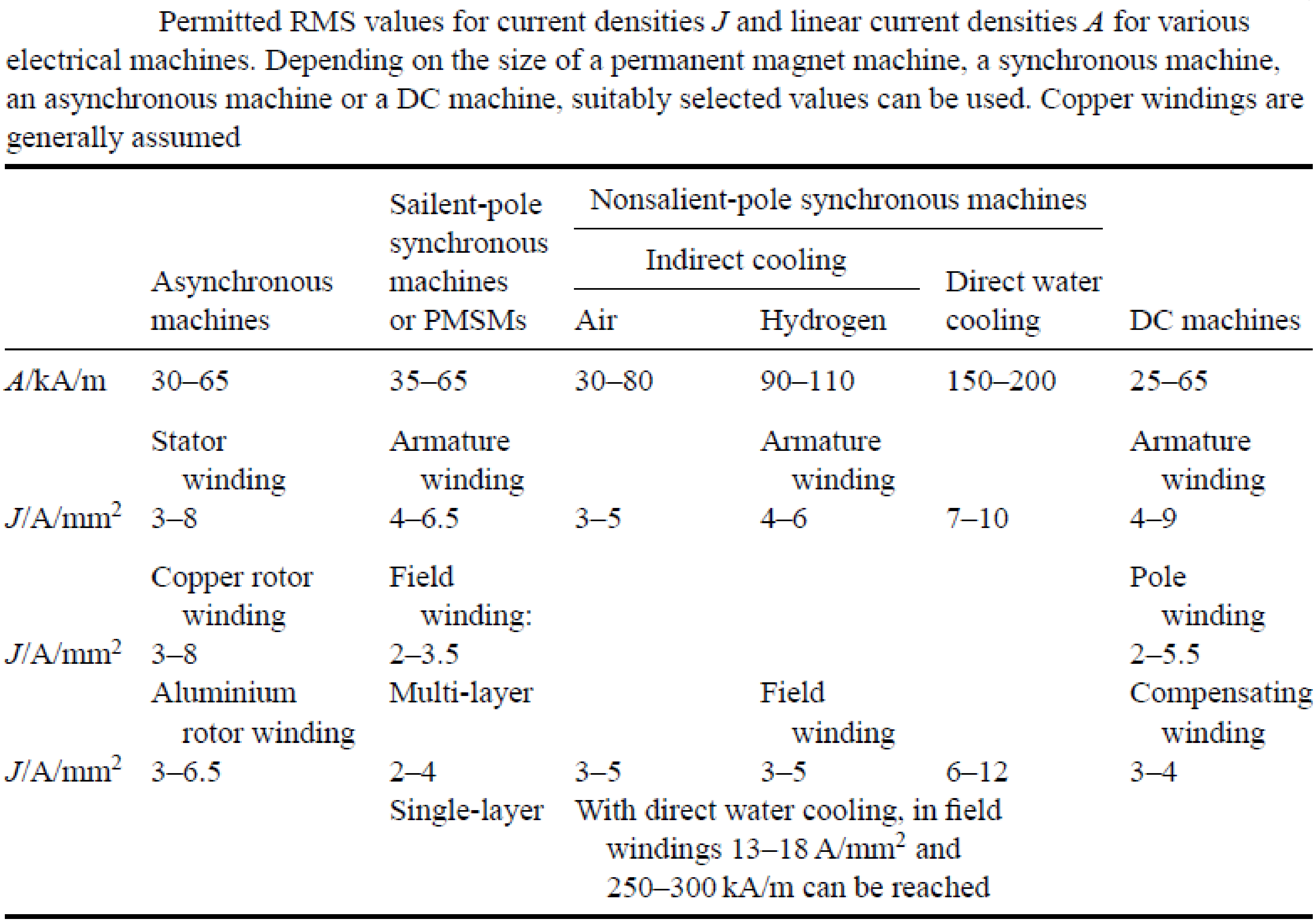
Slots	5	10	15	20	25	30	35	40	45
Poles	2	2	2	2	2	2	2	2	2
	4	4	4	4	4	4	4	4	4
		6	6	6	6	6	6	6	6
		8	12	8	8	8	8	8	8
				12	10	12	12	12	12
				14	16	18	14	14	14
				16	18	22	22	16	16
					20	24	24	24	18
					22	26	26	26	28
							28	28	32
								32	34
								34	36

Winding

Valid pole/slot combinations for **6-phase** machines

Slots	**12**	**24**	**36**
Poles	2	2	2
	10	4	6
		10	10
		20	14
			22
			26
			30

Permitted Current Density



Permitted RMS values for current densities J and linear current densities A for various electrical machines. Depending on the size of a permanent magnet machine, a synchronous machine, an asynchronous machine or a DC machine, suitably selected values can be used. Copper windings are generally assumed

	Asynchronous machines	Sailent-pole synchronous machines or PMSMs	Nonsalient-pole synchronous machines			DC machines
			Indirect cooling		Direct water cooling	
			Air	Hydrogen		
A/kA/m	30–65	35–65	30–80	90–110	150–200	25–65
	Stator winding	Armature winding		Armature winding		Armature winding
$J/\mathrm{A/mm^2}$	3–8	4–6.5	3–5	4–6	7–10	4–9
	Copper rotor winding	Field winding:				Pole winding
$J/\mathrm{A/mm^2}$	3–8	2–3.5				2–5.5
	Aluminium rotor winding	Multi-layer		Field winding		Compensating winding
$J/\mathrm{A/mm^2}$	3–6.5	2–4	3–5	3–5	6–12	3–4
		Single-layer	With direct water cooling, in field windings 13–18 A/mm^2 and 250–300 kA/m can be reached			