Theory and Design of Fractional–Slot Multilayer Windings

L. Alberti and N. Bianchi

Electric Drives Laboratory
Department of Electrical Engineering
University of Padova, Italy

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Outline

Fractional–slot windings

$$q = \frac{Q}{2p \cdot m} < 1 \qquad\qquad y_q = \frac{Q}{2p} \simeq 1$$

Well known and investigated advantages/applications:

- reduced mutual coupling among the phases
- reduced manufacturing costs
- reduced end–winding lengths
- fault–tolerant applications
- direct drive/low speed applications (high number of poles)
- low torque ripple (low periodicity between Q and p)
- wind power, automotive, fault tolerant drives,...

Drawbacks:

High MMF harmonic content,
including sub–harmonic ($\nu < p$)

Reduction of MMF harmonic:

Increasing the number of layer it is possible to reduce the harmonic content of the MMF

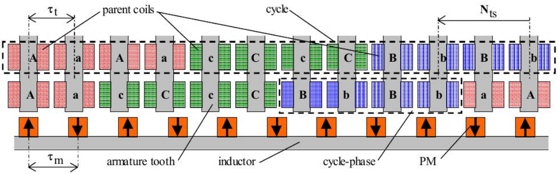
Example:

From 1–layer to 2–layer winding

It is possible to adopt more than 2 layers

Past work on multilayer windings

- Some example of multilayer winding (>2) have been presented
- "Di Gerlando, Ubaldini, Perini"
  ICEM 2004, *IEMDC 2005* (24/22)



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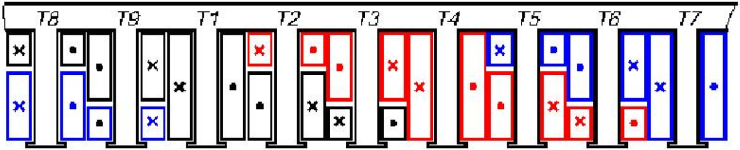
- “Cistelecan, Ferreira, Popescu”
  ICEM 2010, *ECCE 2010* (12/10 and 9/8)



Aim of this paper:

- to present the general theory of multilayer m–phase windings
- to give the rules to layout such a type of windings
- to discuss feasibility criteria and the convenience
- to consider the impact of multilayer windings on different type of machines (SPM, IPM and IM)

Machine periodicity

$t = GCD(Q, p)$

Number of spokes

Q/t (even or odd)

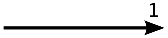
Angle between two spokes

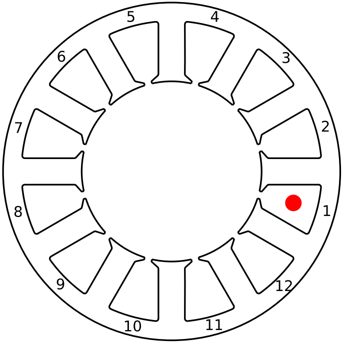
$\alpha_{ph} = 360\ t/Q \quad$ degrees

Sectors

The star of slots is divided in $2 \cdot m$ sectors, each of them spanning $360/(2\ m)$ degrees. Two opposite sectors are assigned to each phase.

Example: Layout of 2–layer winding (12–slot 10–pole)





$t = 1$ $\quad Q/t = 12$ even $\quad \alpha_s^e = 150$ deg

$\alpha_{ph} = 30$ deg $\quad y_q = round\Big(Q/(2p)\Big) = 1$

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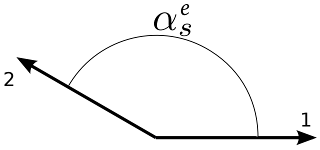

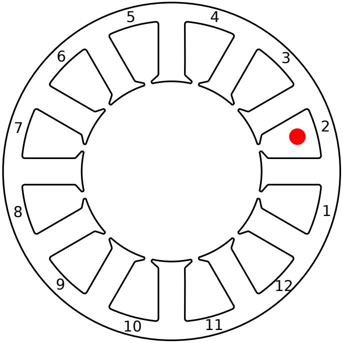

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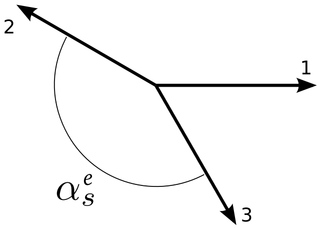

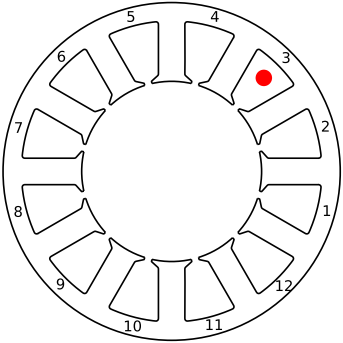

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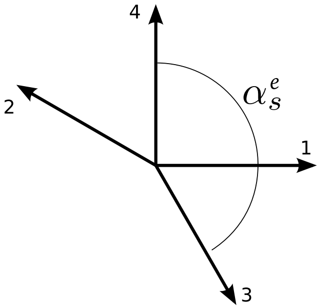

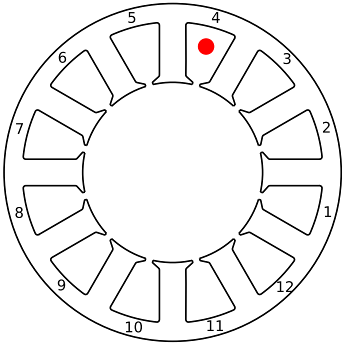

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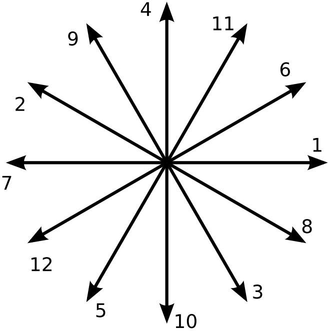

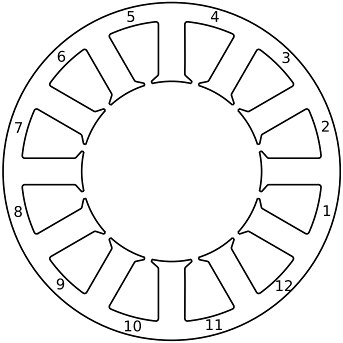

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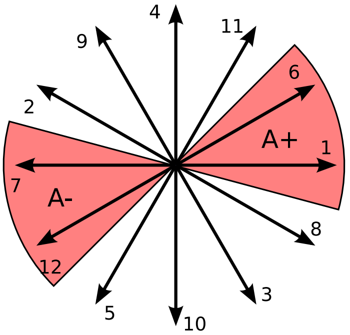

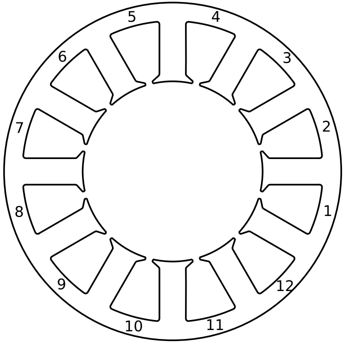

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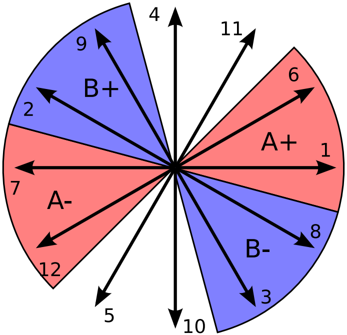

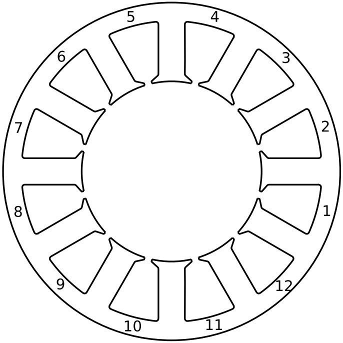

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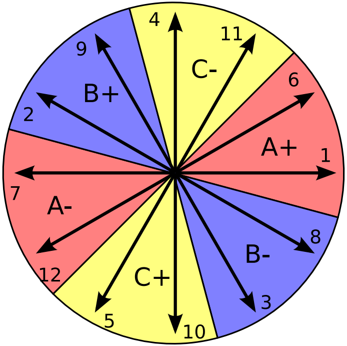

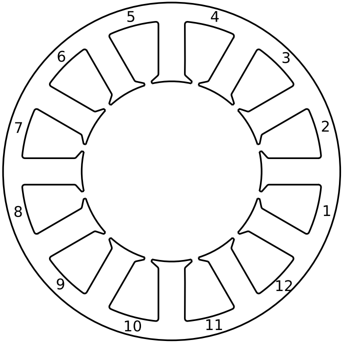

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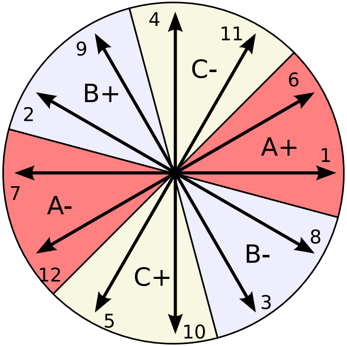

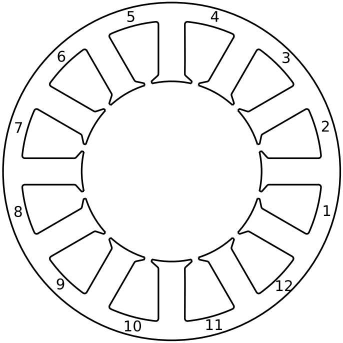

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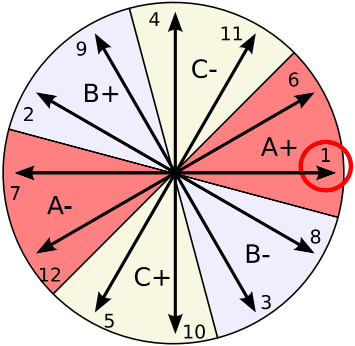

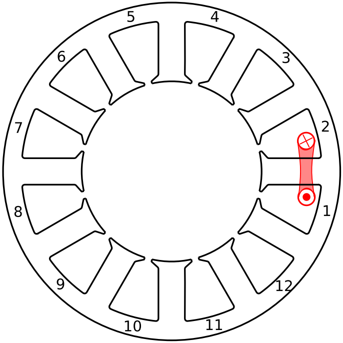

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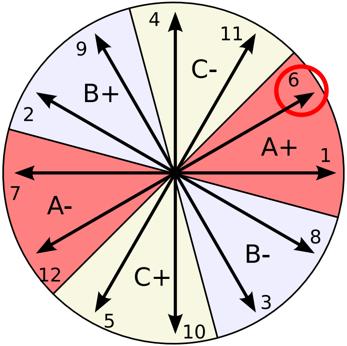

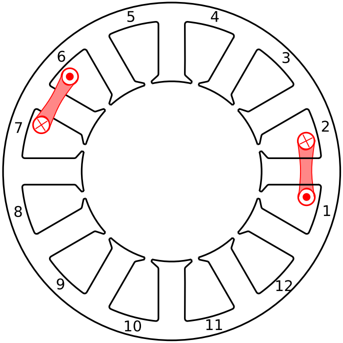

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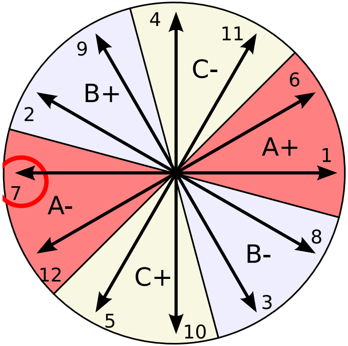

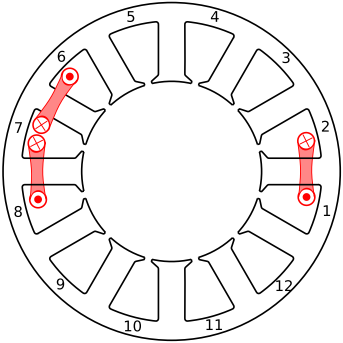

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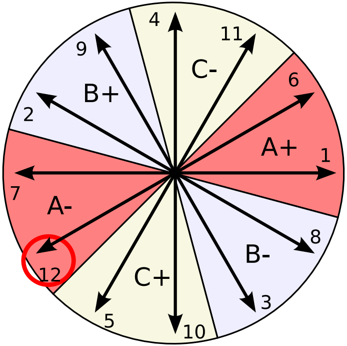

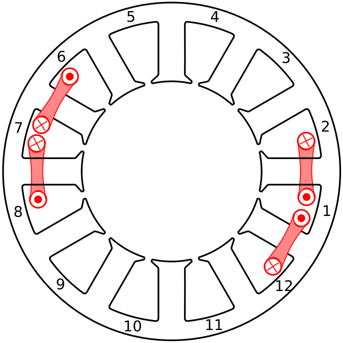

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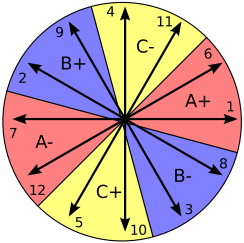

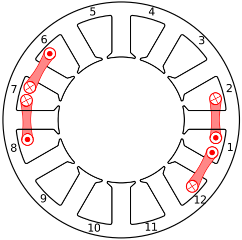

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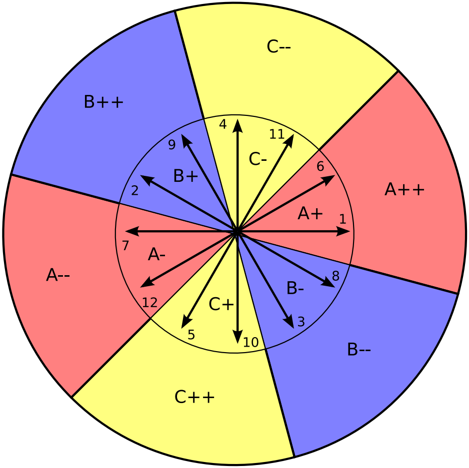

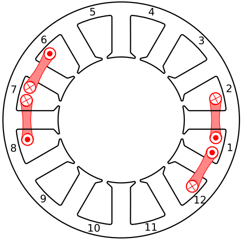

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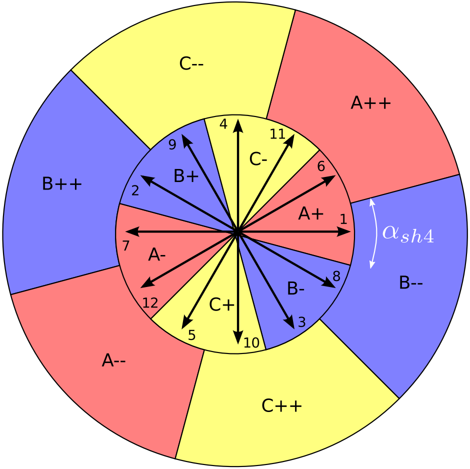

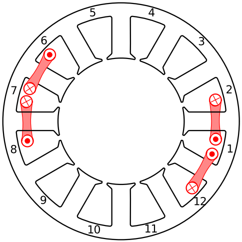

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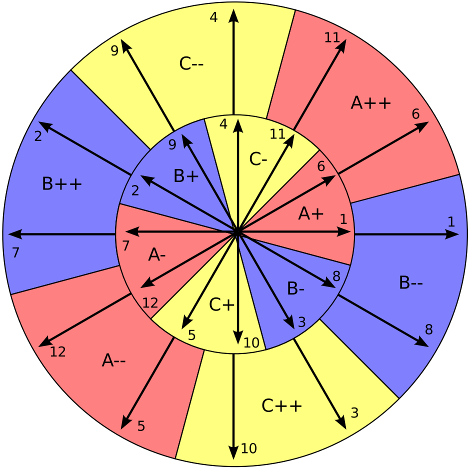

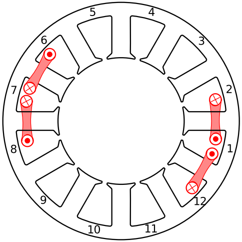

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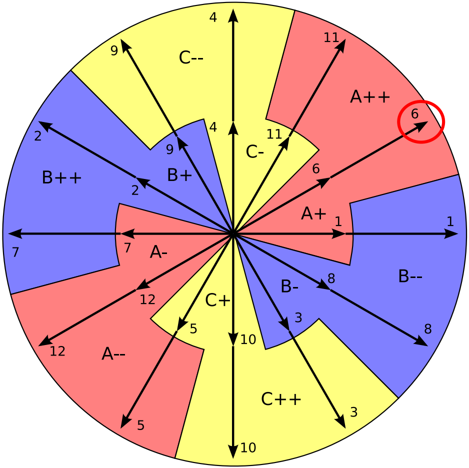

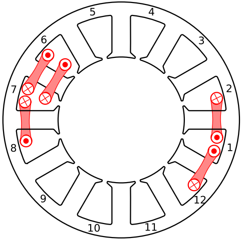

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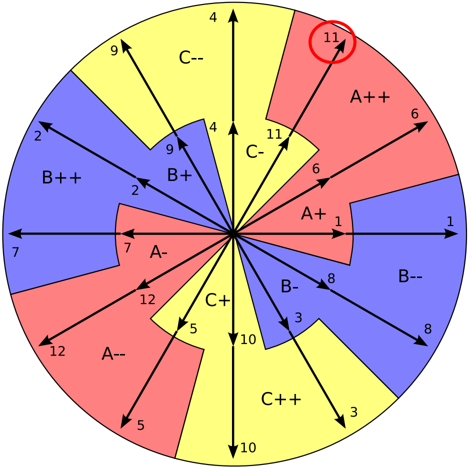

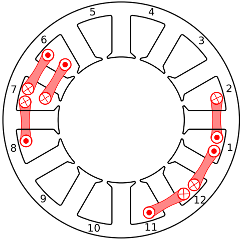

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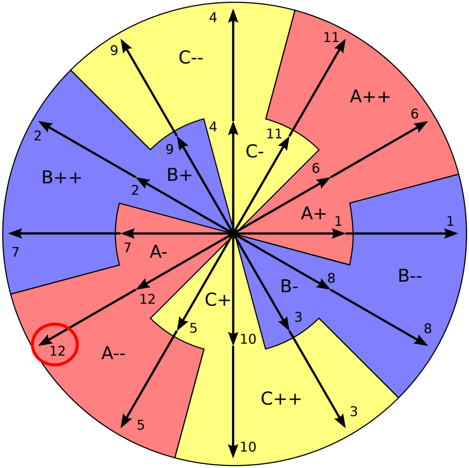

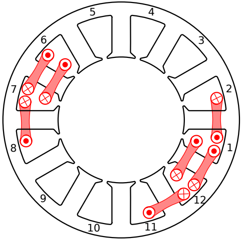

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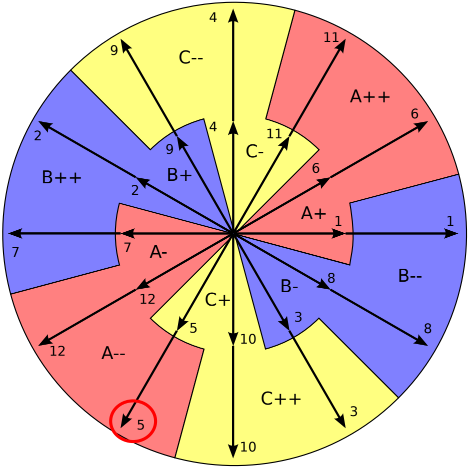

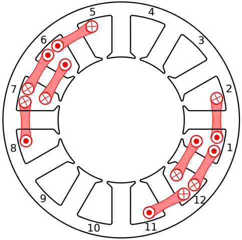

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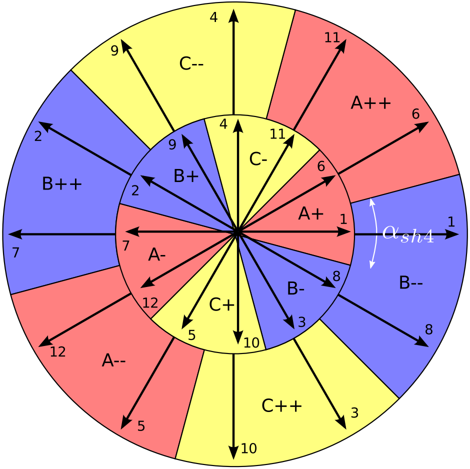
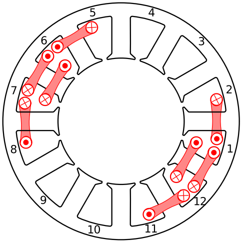
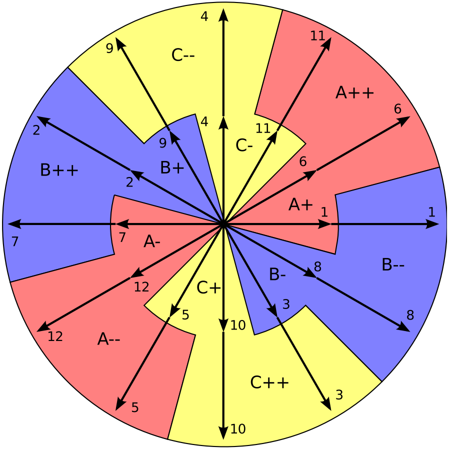




The selection of the shift angle α_{sh4} between the two sets of sectors is an additional degree of freedom in the winding design.

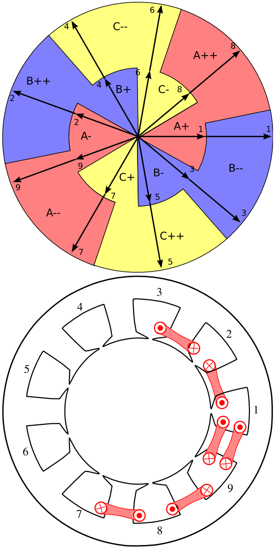
Various strategies:

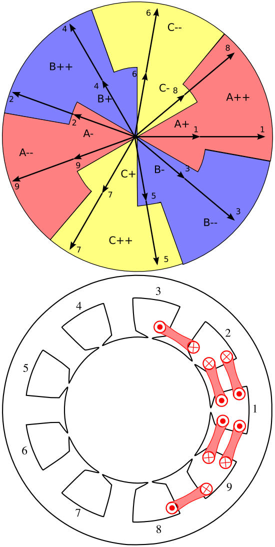
- to maximize the distribution factor for the main harmonic, the shift must be as small as possible.
- to minimize a specific MMF harmonic
- two distinct cases have to be considered depending on Q/t is an even or odd number.



All positive and negative sectors of all phases contains the same number of spokes.

Q/t odd (9–slot 8–pole)





solution i

$\alpha_{sh4} = \alpha_{ph}$

solution ii

$\alpha_{sh4} = \alpha_{ph}/2$

Reduction of the winding factor

$$k_{w4} = k_{w2} \cdot \frac{\sin \alpha_{sh4}}{2 \sin \frac{\alpha_{sh4}}{2}}$$

Table: Winding factors for 9–slot 8–pole windings

ν'	2–layer	4–layer *i*	4–layer *ii*
1	0.061	0.046	0.021
2	0.139	0.024	0.090
4	**0.945**	**0.888**	**0.931**
5	0.945	0.888	0.931
7	0.139	0.024	0.090
8	0.061	0.046	0.021
10	0.061	0.046	0.021
11	0.139	0.024	0.090

Geometrical feasibility

It is always possible to increase up to 4 the number of the coil sides in the slots.

Nevertheless the 4–layer windings are not convenient for every combinations of slots and poles.

In some cases the decreasing of the amplitude is the same for all the MMF space–harmonics and so to adopt a 4–layer winding makes no sense.

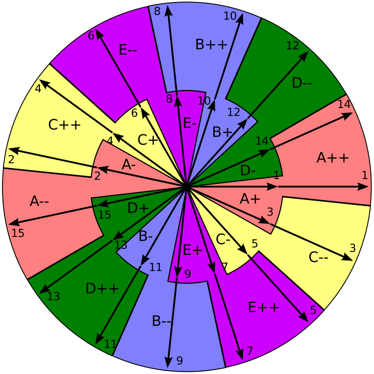
4–layer feasibility

it is necessary that each phase has at least two spokes in one sector of the star of slots, that is:

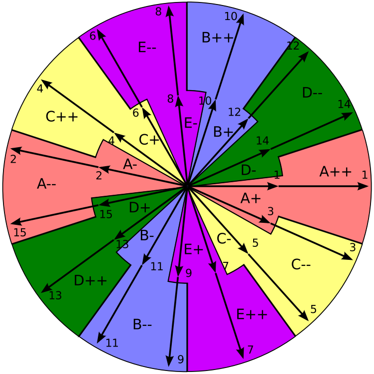
$Q/t > 2\ m$

5–phase example

4–layer	15–slot	14–pole	Q/t=15 (odd)



solution *i* with $\alpha_{sh4} = \alpha_{ph}$



solution *ii* with $\alpha_{sh4} = \alpha_{ph}/2$

Higher number of layers

The number of layers is not limited to 4 but it can be increased. Some examples are reported in bibliography

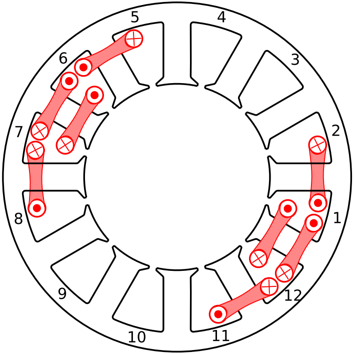
In general, to layout a l layer winding, $l/2$ set of 2 m sectors have to be considered in the star of slots.

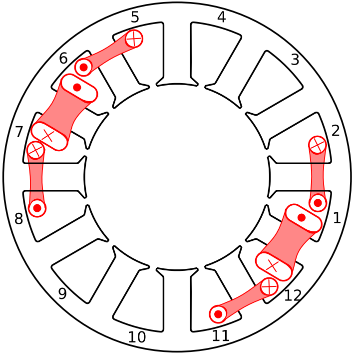
The winding cost increases with the number of layers. It is not convenient to consider high number of layers.

Winding optimization

It is possible "to optimize" the winding

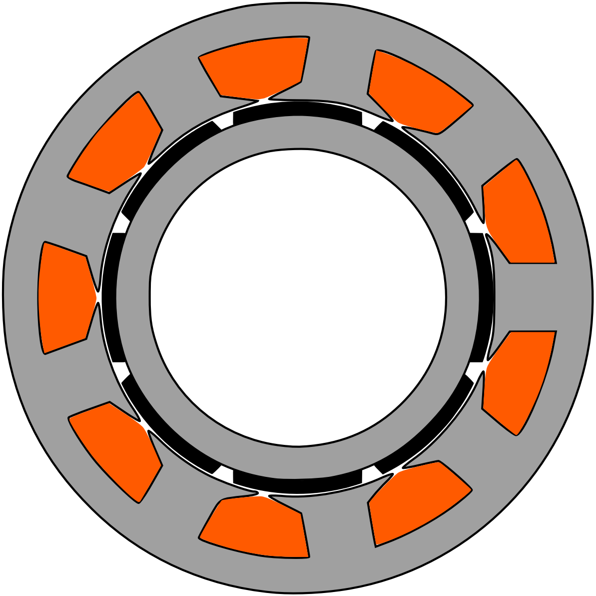
- to reduce the coils number (3 coil side per slots)
- to reduce/to eliminate a particular MMF harmonic





Outline

Example #1: 9–slot 8–pole SPM (SIM.)



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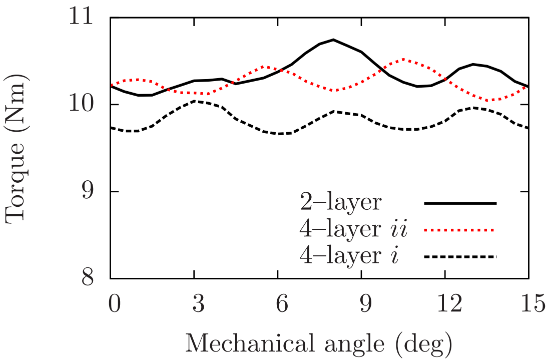
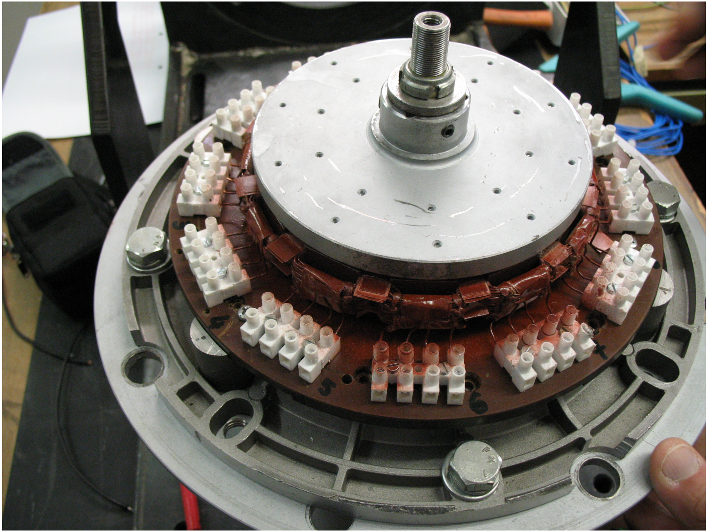
2	0.139	0.024	0.090
4	**0.945**	**0.888**	**0.931**
5	0.945	0.888	0.931
7	0.139	0.024	0.090
8	0.061	0.046	0.021
10	0.061	0.046	0.021
11	0.139	0.024	0.090



Configuration	Average torque (Nm)	Torque ripple %
2–layer	10.3	6.2
4–layer *i*	9.8	3.8
4–layer *ii*	10.3	4.6

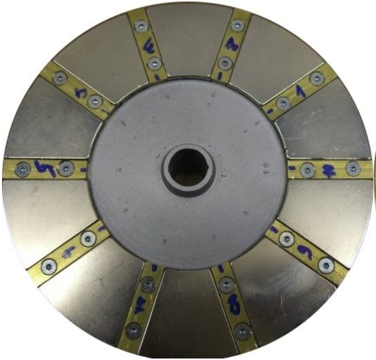
Example #2: 12–slot 10–pole SPM (TEST)

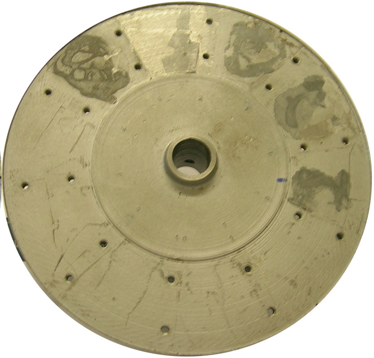
Tests have been carried out on an AxF SPM prototype available in our lab



Example #2: 12–slot 10–pole SPM (TEST)

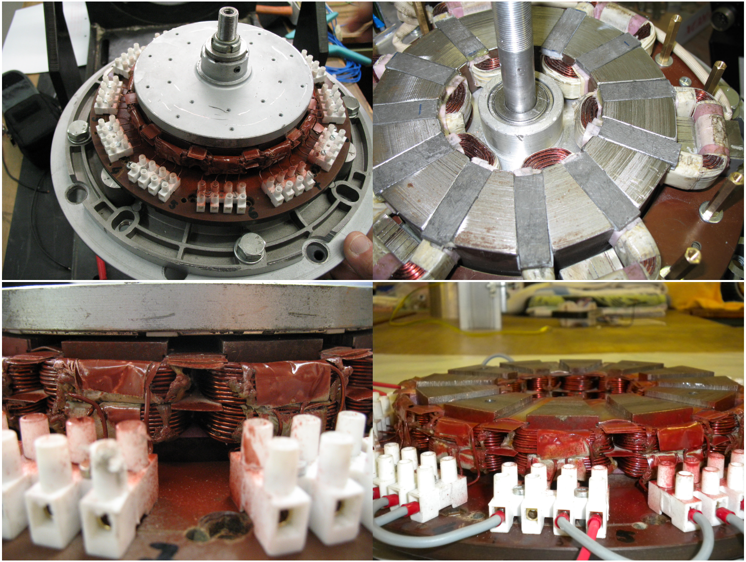
Different rotors





Example #2: 12–slot 10–pole SPM (TEST)

Different winding arrangements (1–, 2– and 4–layer)



BEMF (TEST)

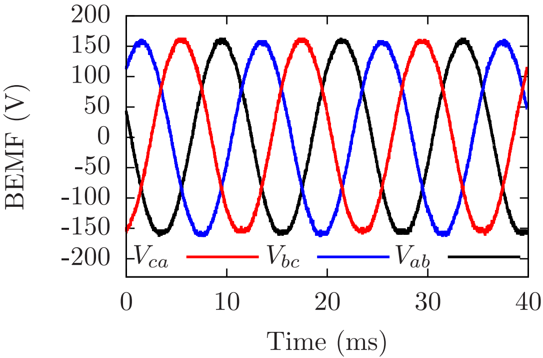
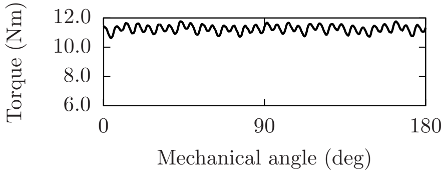


Table: Experimental result. Phase–to–phase BEMF (Vrms)

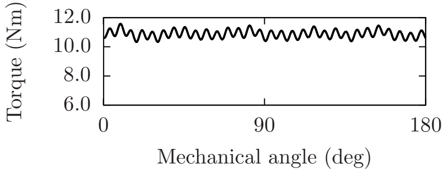
speed	1–layer	2–layer	4–layer
250 rpm	29.6	29.2	28.7
500 rpm	59.1	58.4	57.3
1000 rpm	114.6	113.7	109.3

Example #2: Torque ripple (TEST)

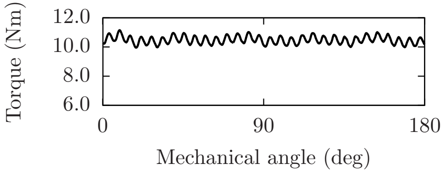
Load test at rated current ($\hat{I} = 8A$)



1–layer



2–layer

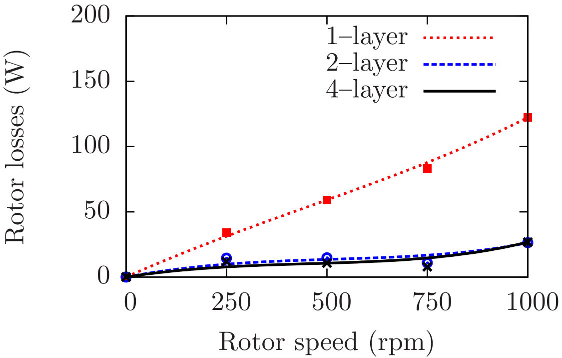


4–layer

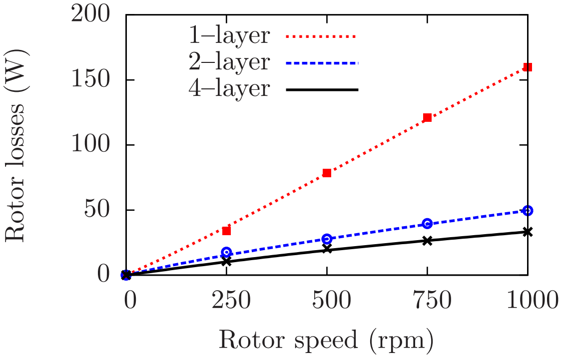
	1–layer	2–layer	4–layer
τ_{avg} (Nm)	11.25	10.88	10.48
$\Delta\tau$ (Nm)	1.18	1.28	1.23
$\Delta\tau$%	10.5	11.7	11.7
torque harmonic	torque harmonic amplitude % of mean value		
30	1.23	0.685	0.259
60	**2.57**	**2.93**	**2.79**
90	0.072	0.009	0.015
120	0.24	0.189	0.21

cogging: $Q \cdot \dfrac{2p}{HCF\{2p, Q\}} = 12 \cdot 5 = 60$

Measured rotor losses under load

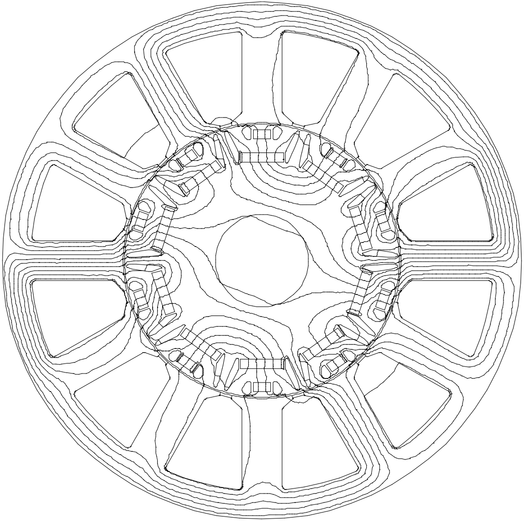


Measured rotor losses with iron disk (NO–PMs)



Example #3: IPM machine (SIM.)

A FS machine, characterized by 12 slots and 10 poles.



The motor is supplied with a peak current of 9 A on the maximum torque per Ampere trajectory.

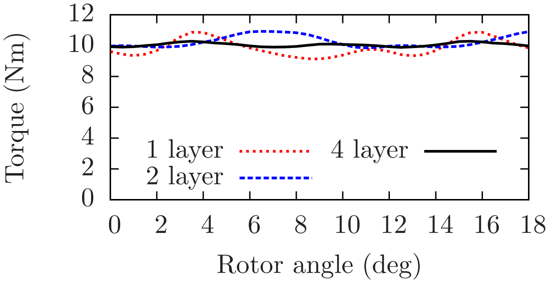


Table: FE simulations, IPM machine. Harmonic content of torque ripple for various number of winding layer. $\hat{I}$=9 A

	1–layer	2–layer	4–layer
τ_{avg} (Nm)	9.9	10.3	10.1
$\Delta\tau$ (Nm)	1.7	1.1	0.4
	(17.2%)	(10.7%)	(3.9%)

The adoption of multilayer windings in IPM machines is an effective solution to improve the torque characteristic.

- The general theory of multilayer *m*–phase winding has been presented.
- General rules to design such a type of windings have been given considering both feasibility and convenience for various combinations of slots and poles.
- Several examples and configurations have been included
- In particular:

4–layer winding in SPM machine:

- The torque ripple is not significantly reduced
- It is almost the same as the machine with 2– and 1–layer winding
- Only a slightly reduction of the rotor losses is found with respect to the 2–layer winding.

4–layer winding in IPM machine:

- The torque ripple results significantly reduced, especially at high current when the machine results heavily saturated
- such a winding should be adopted in applications where a very low torque ripple is mandatory

Related Papers by the Authors

- N. Bianchi, M. Dai Pré, L. Alberti, and E. Fornasiero, *Theory and Design of Fractional-Slot PM Machines*, Sponsored by the IEEE-IAS Electrical Machines Commitee, Ed. Padova: CLEUP (ISBN 978-88-6129-122-5), 2007.
- L. Alberti, E. Fornasiero, N. Bianchi, and S. Bolognani, "Rotor losses measurements in an axial flux permanent magnet machine," *IEEE Transactions on Energy Conversion*, vol. 26, no. 2, pp. 639 –645, june 2011.
- N. Bianchi and S. Bolognani, "Design techniques for reducing the cogging torque in surface-mounted PM motors," *IEEE Transactions on Industry Applications*, vol. 38, no. 5, pp. 1259–1265, Sep./Oct. 2002.

- L. Alberti, E. Fornasiero, and N. Bianchi, "Impact of the rotor yoke geometry on rotor losses in permanent magnet machines," in *Energy Conversion Congress and Exposition (ECCE), 2010 IEEE*, 2010, pp. 3486 –3492.
- E. Fornasiero, L. Alberti, N. Bianchi, and S. Bolognani, "Considerations on selecting fractional-slot windings," in *Energy Conversion Congress and Exposition (ECCE), 2010 IEEE*, 2010, pp. 1376 –1383.
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M. Barcaro, N. Bianchi, and F. Magnussen, "Analysis and tests of a dual three-phase 12-slot 10-pole permanent-magnet motor," *IEEE Transactions on Industry Applications*, vol. 46, no. 6, pp. 2355 –2362, 2010.

Thank you!!