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Different Possibilities of Multiphase Drives Functioning in Constant Power Region

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Laboratory of Electrical Engineering and Power Electronics (L2EP), Lille, France

OUTLINE

I. Introduction & Context

II. Three-phase Drives Vs Multiphase Ones

III. Multiphase - Possibility at High Speed (Constant Power Region)

1. Pole Changing
2. Different Stator Winding Connections

IV. Conclusion

Introduction & Context

Hybrid and Full electric automotive applications

Electrical machines requirements

- High efficiency
- Low cost
- High torque density
- Easy manufacturing

rotor with ***PM***

Stator with tooth concentrated winding

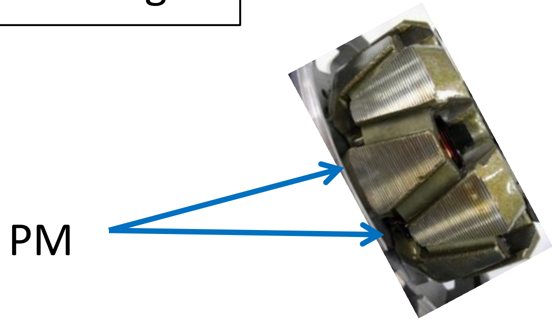
Fault tolerance capability or low voltage (48V)

Number of phases > 3

Wide speed range

- Dahlander circuit
- Winding configuration
- Saliency ratio

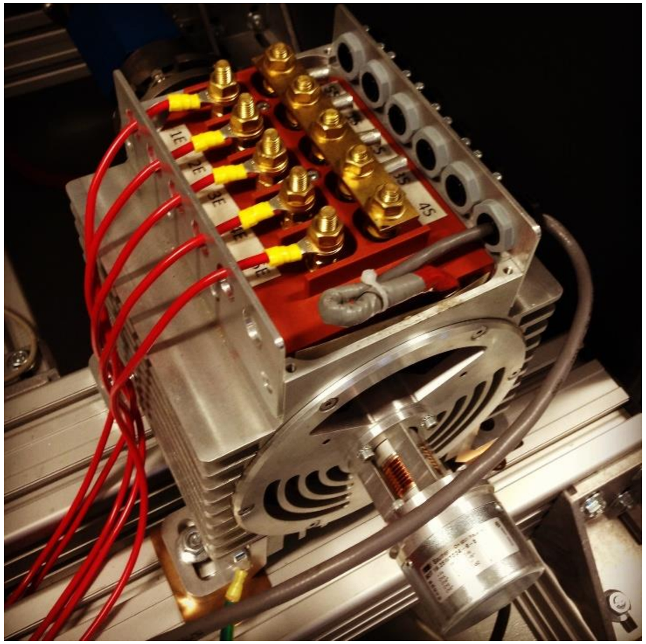
Electronic pole commutation



Introduction & Context

Advantages of 5-phase machines
(PM + Tooth concentrated windings)

- **Acceptable current/phase** for low voltage high power (48V/15kW):
  - ✓ **No transistor** in parallel
  - ✓ **Smaller cables** leading to an easy connection
- **Additional degrees of freedom** for vector control
  - ✓ **Improving constant power** functionality
  - ✓ **High torque quality** with non-sinusoidal currents
  - ✓ Increase **fault-tolerance capabilities**



MHYGALE Project, L2EP Laboratory, Lille, France

F. Scuiller, H. Zahr, and E. Semail, "Maximum Reachable Torque, Power and Speed for Five-Phase SPM Machine With Low Armature Reaction," *IEEE Transactions on Energy Conversion,* vol. 31, pp. 959-969, 2016.

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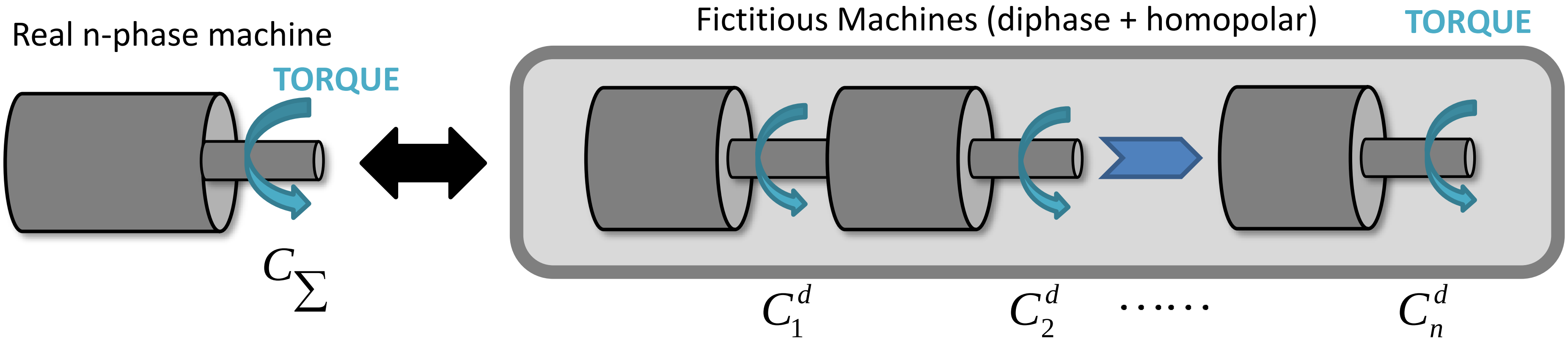
Multiphase Decomposition Theory

GENERALIZED VECTORIAL FORMALISM THEORY

In the **new base**, the voltage and electromagnetic torque are expressed as:

$$\vec{v} = \sum_{k=1}^{n} \vec{v}_k^{\,d} = \sum_{k=1}^{n} \left(R_s \vec{i}_k^{\,d} + \Lambda_k \frac{d\vec{i}_k^{\,d}}{dt} + \vec{e}_k^{\,d} \right) \qquad C_{\sum} = \sum_{k=1}^{n} C_k^d = \sum_{k=1}^{n} \frac{\vec{e}_k^{\,d} \cdot \vec{i}_k^{\,d}}{\Omega}$$



Real n-phase machine

TORQUE

$C_{\sum}$

Fictitious Machines (diphase + homopolar)

TORQUE

C_1^d C_2^d …… C_n^d

Shape of the back-EMF
(sinusoidal/trapezoidal or others)

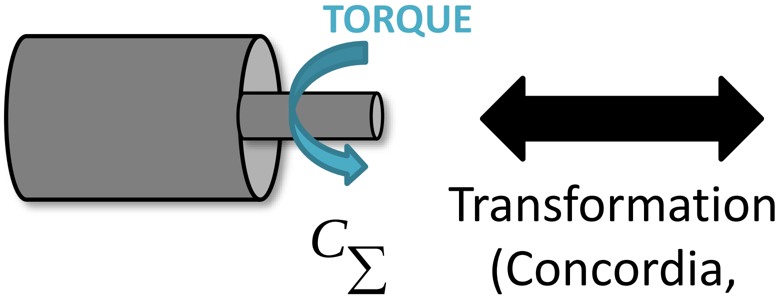
Leads to

Fictitious machines

Multiphase Decomposition Theory

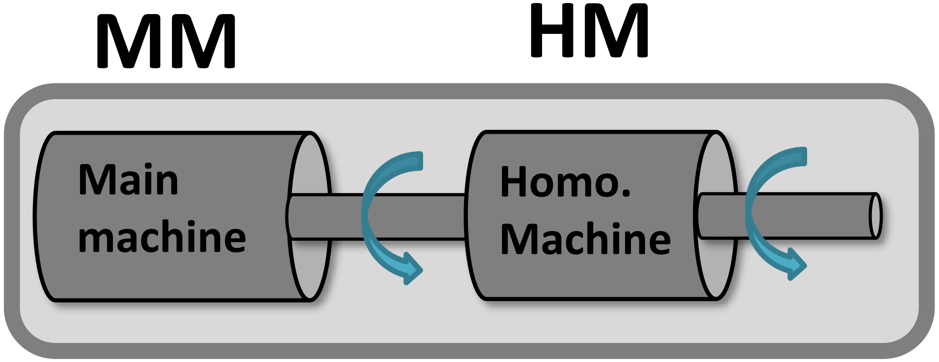
3-phase PMSM

Real 3-phase machine



Transformation (Concordia, Clarke, etc.)

Fictitious Machines (1 diphase + 1 homopolar)



h = 1, 5, 7, 11,…
$h \neq 3k$

h = 3, 6, 9, …
$h = 3k$

h : odd harmonic rank
(even harmonics are ignored)

Main machine (MM) : diphase ($\Lambda_1 = \Lambda_2$)
Homo. Machine: monophase (Λ_0)

Λ_i Eigenvalues
of inductance matrix

Notes

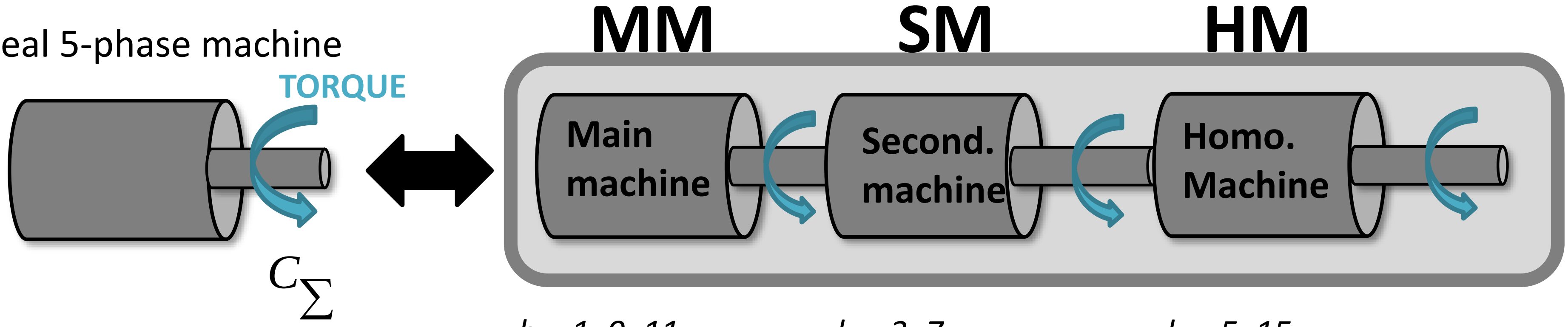
- Wye connection: current of homopolar machine **$i_0=0$** **$C_0=0$**

- All **harmonics**, different from 3*k, are **regrouped** in the **main machine** and **INTERACT** between them (currents (time) and back-EMFs (space))

Multiphase Decomposition Theory

5-phase PMSM

Fictitious Machines (2 diphase + 1 homopolar)



MM	SM	HM
h = 1, 9, 11,…	*h = 3, 7, …*	*h = 5, 15, …*
h=5k ± 1	*h=5k ± 2*	*h=5k*

h : harmonic rank of the back-EMF

\+ : direct rotating vector

\- : inverse rotating vector

Main machine (MM) : diphase ($\Lambda_1 = \Lambda_2$)
Second. Machine (SM): diphase ($\Lambda_3 = \Lambda_4$)
Homo. Machine: monophase (Λ_0)

Notes

- Wye connection: current of homopolar machine
  i_0=0 **C_0=0**

\- **Separation** of some **harmonics** into two **decoupled frames** ➡ **Interesting point**

E. Semail, A. Bouscayrol, and J. P. Hautier, “Vectorial formalism for analysis and design of polyphase synchronous machines,” *European Physical Journal-Applied Physics*, vol. 22, pp. 207-220, Jun. 2003.

Multiphase Decomposition Theory

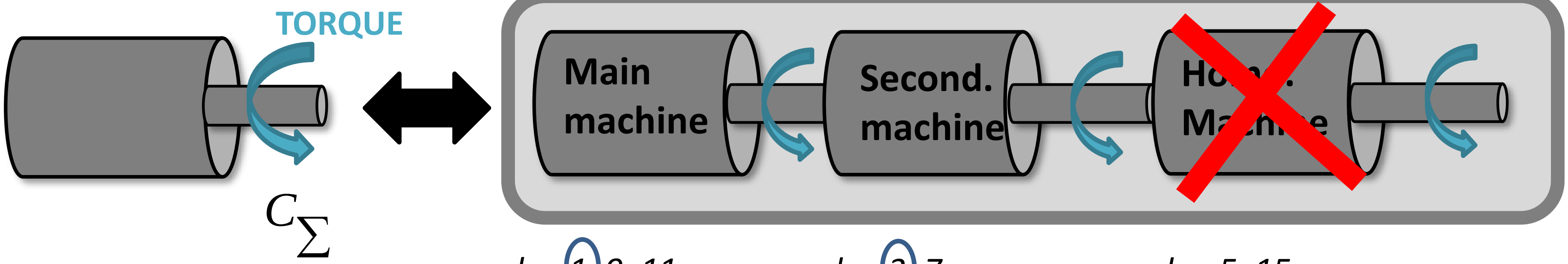
5-phase PMSM

MM : 1st harmonic
SM : 3th harmonic

Torque can be created by injecting the 1st and the 3th harmonic of currents

Real 5-phase machine

Fictitious Machines (2 diphase + 1 homopolar)



h = 1, 9, 11,… → **p** pairs of poles

h = 3, 7, … → **3p** pairs of poles

h = 5, 15, …
h=5*k*

Classical solutions:

- **Secondary** machine **torque** contribution is between **10% and 25%**
- **Weak secondary machine**→ Low Torque

New solution

« Bi-harmonic » machine

Enhance SM, so **MM** and **SM** have the **same torque** contribution

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Lille

1. Pole Changing

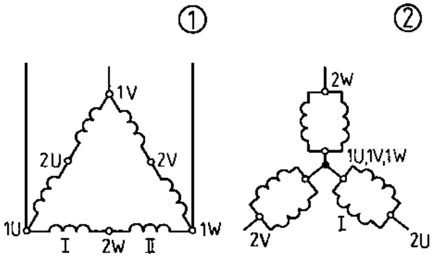
Multiphase machine

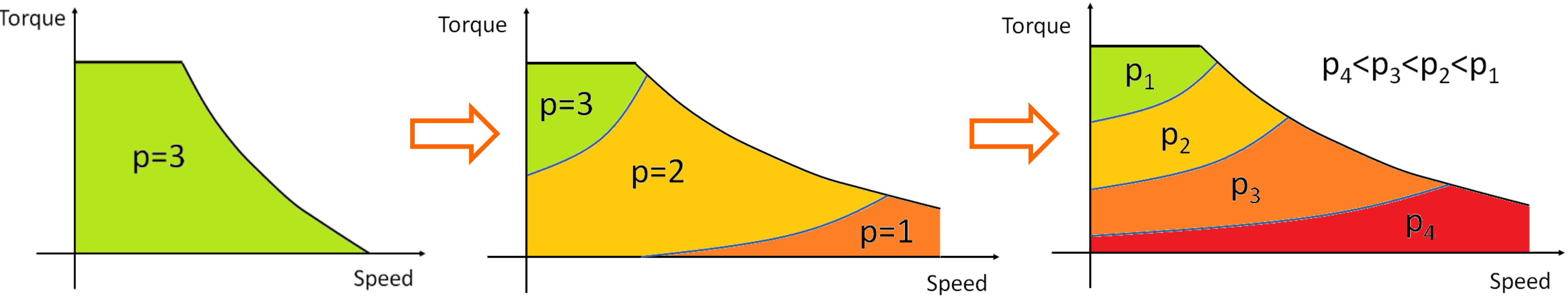
Mechanical commutations of windings (Dahlander)

$$n = \frac{120f}{p}\ \text{(rpm)}$$

Change number of pole pairs **electronically**

[1] for induction motors,
[2] for 5-phase PMSM





Electronic pole changing with multiphase machines to extend the speed range

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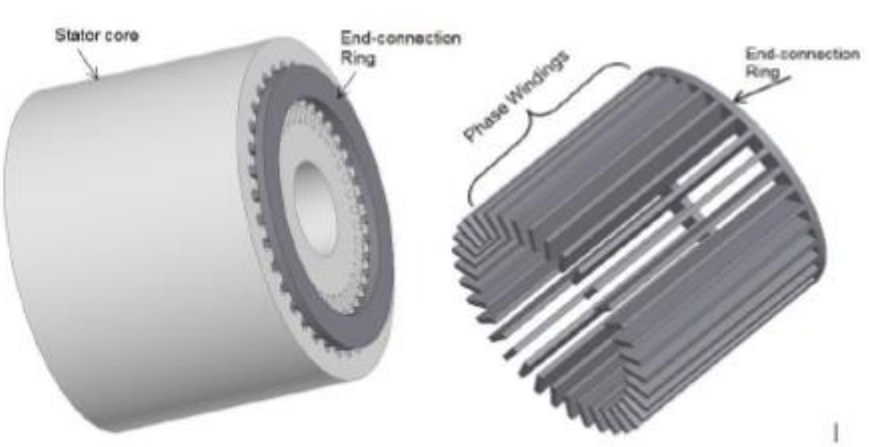
[1] G. Dajaku, F. Bachheibl, A. Patzak, and D. Gerling, "Intelligent stator cage winding for automotive traction electric machines," EVS28 International Electric Vehicle Symposium and Exhibition, Korea, 5/2015.

[2] J. Gong, H. Zahr, E. Semail, M. Trabelsi, B. Aslan, and F. Scuiller, "Design Considerations of Five-Phase Machine with Double p/3p Polarity," IEEE Transactions on Energy Conversion, pp. 1-1, 2018.

1. Pole Changing

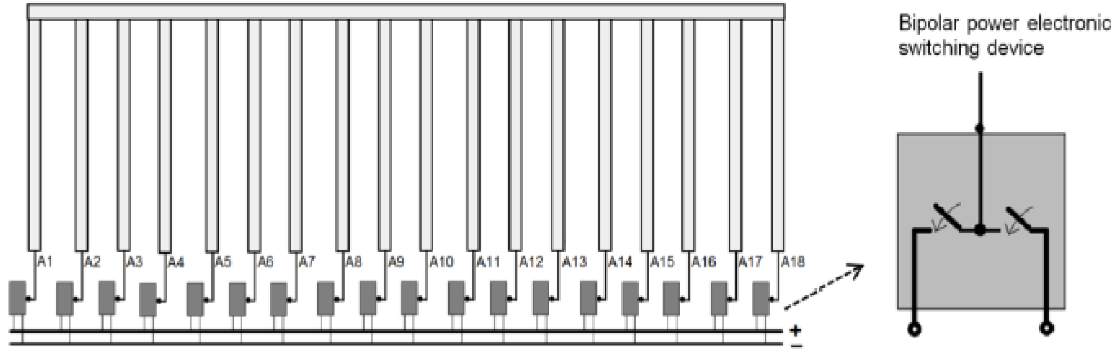
ISCAD : Intelligent Stator Cage Drive

Stator cage winding

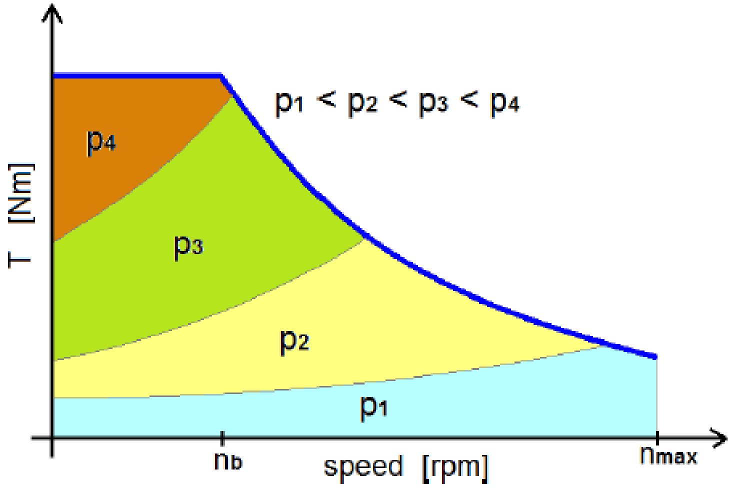


- Intelligent Stator → Each slot is one phase
- Modification (by controlling 60 legs) of Slot/pole according to operating points for maximizing the efficiency
- High fault-tolerant capability
- Double-polarity possibility to increase the performance

The m-phase stator winding supplied with multiphase inverter



60 stator slots/ 73 rotor slots (Induction machine)

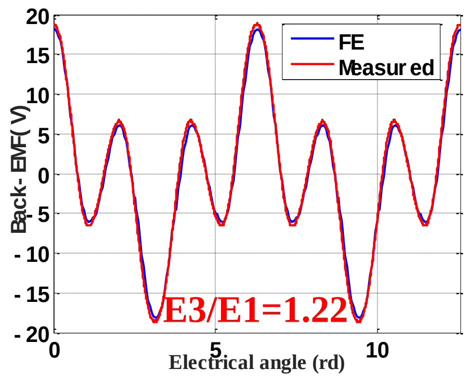


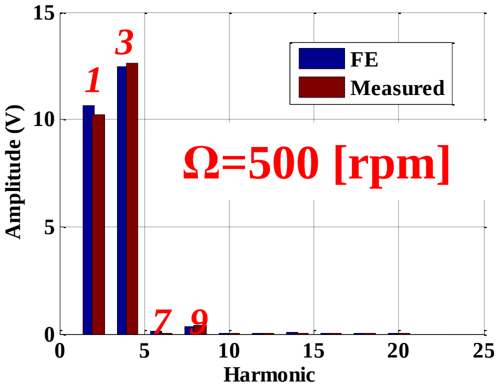
[1] G. Dajaku, F. Bachheibl, A. Patzak, and D. Gerling, “Intelligent stator cage winding for automotive traction electric machines,” EVS28 International Electric Vehicle Symposium and Exhibition, Korea, 5/2015.

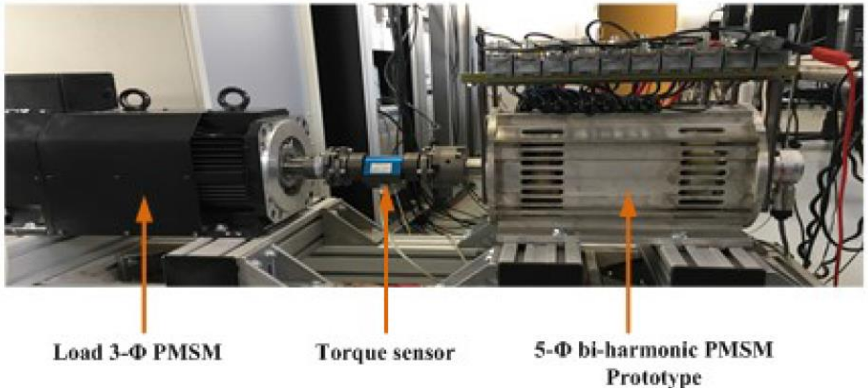
1. Pole Changing

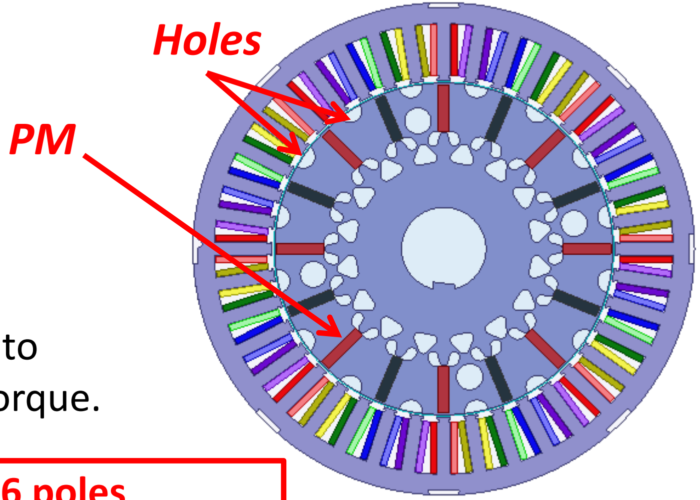
Structure with interior magnets

- Redistribution of flux between 1st & 3rd harmonic
- Introducing holes between poles

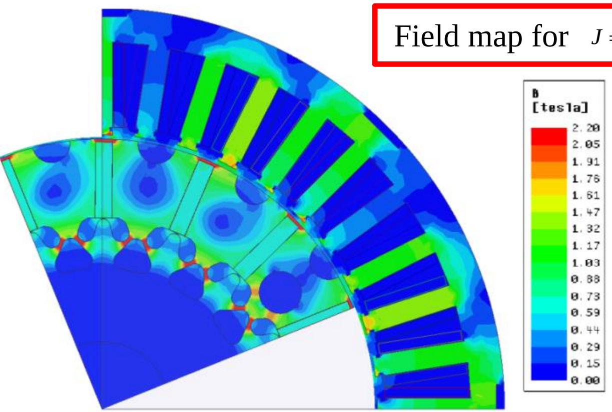








Equivalent potentiality between the **1st** and the **3rd** harmonic to produce torque→ **two degrees of freedom** for control of the torque.



Field map for $J = 10A/mm^2$

40 slots / 16 poles
bi-harmonic machine
(½ slot per pole per phase) [3][4]

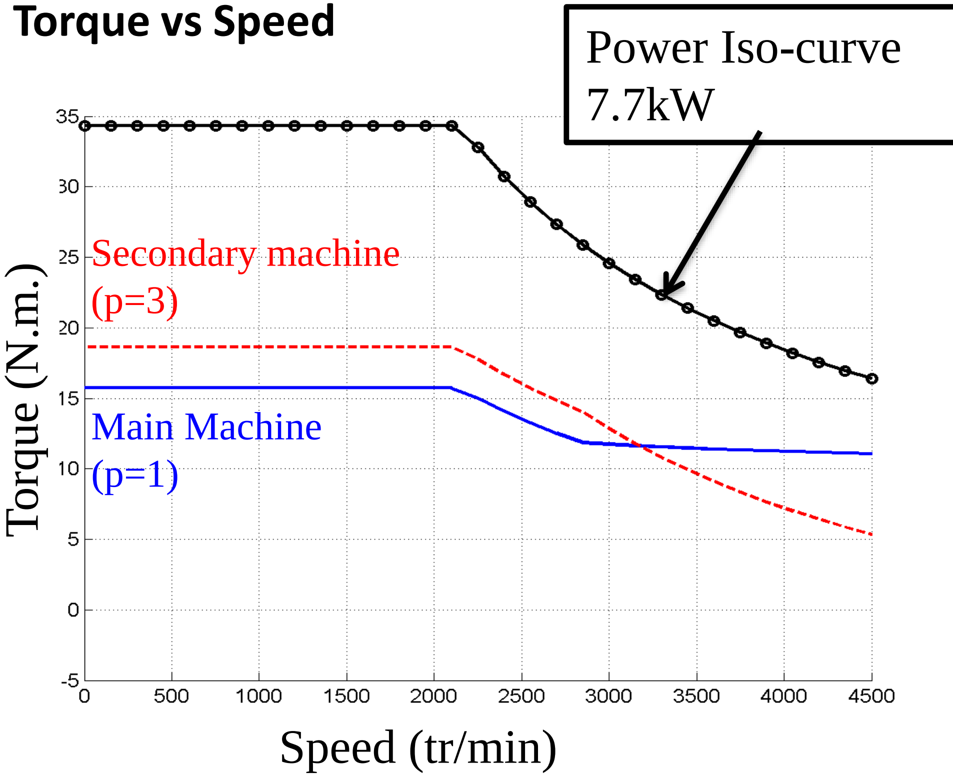
[3] H. Zahr, J. Gong, E. Semail and F. Sculller, "Comparison of Optimized Control Strategies of a High-Speed Traction Machine with Five Phases and Bi-harmonic Electromotive Force," *Energies* 2016, Vol. 9, No. 12, pp. 1-19.

[4] B. Aslan and E. Semail, "New 5-phase concentrated winding machine with bi-harmonic rotor for automotive application," *2014 International Conference on Electrical Machines (ICEM)*, Berlin, 2014, pp. 2114-2119

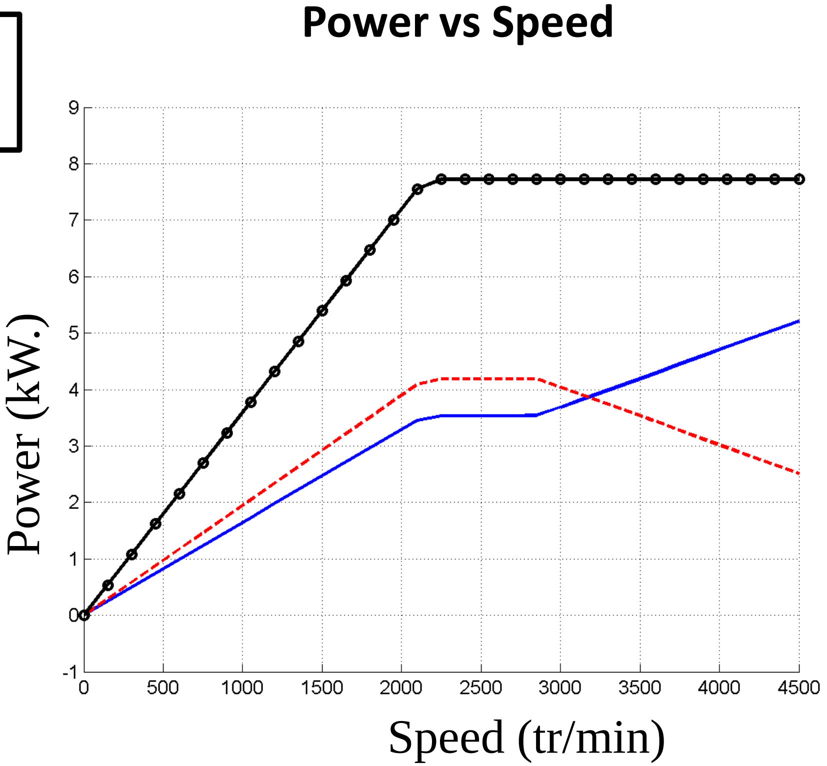
1. Pole Changing

MTPA strategy and **Constraint** on **Voltage** at High Speed

Torque vs Speed



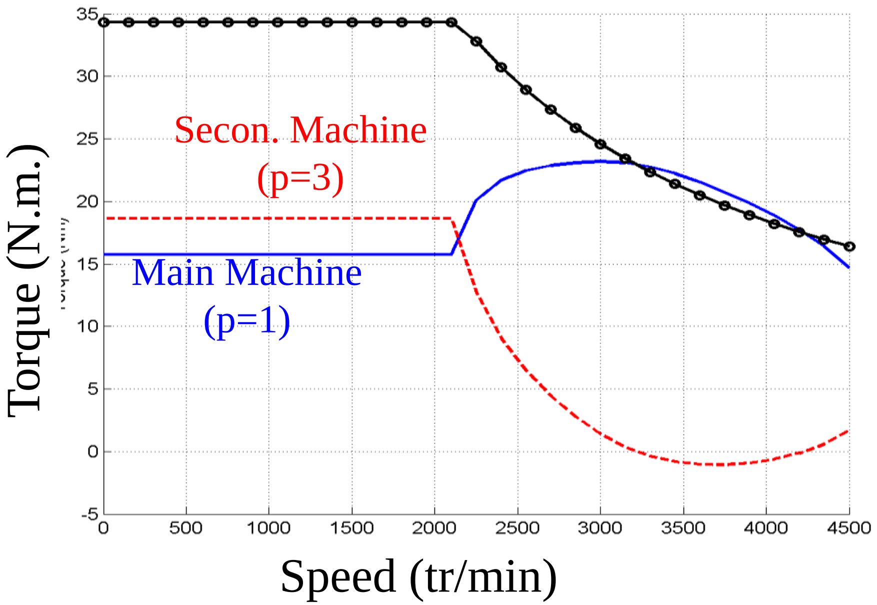
Power vs Speed



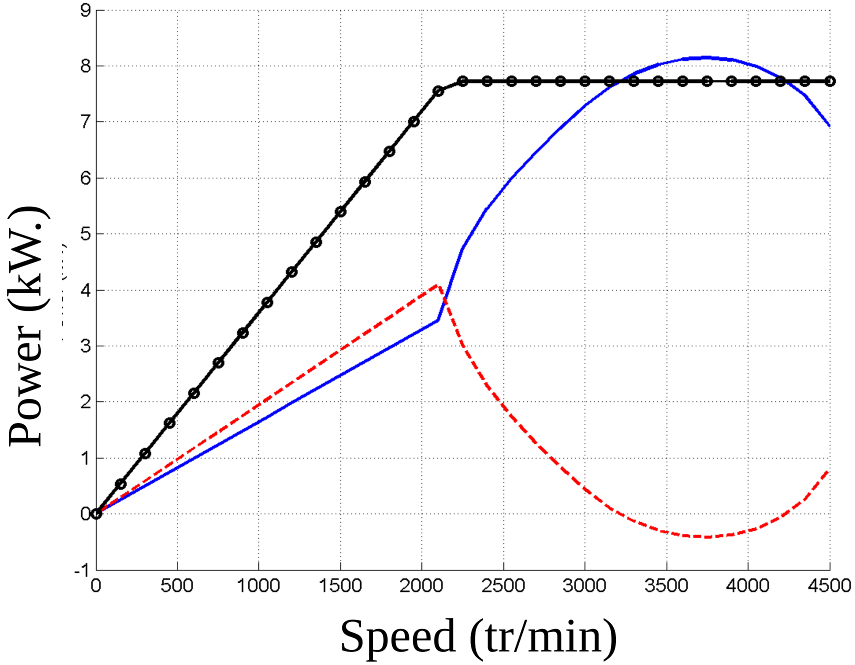
1. Pole Changing

Maximum Torque Per Primary Machine (MTPPM)

Torque Vs Speed



Power Vs Speed



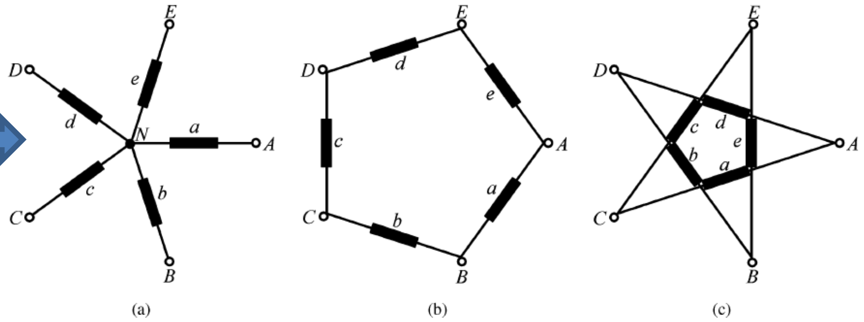
Second. **Machine** is operating as a **generator** for keeping the **voltage under limit**

Functioning at **high speed** is very **different** with **three-phase** drives since there are **more degrees of freedom**

2. Different Stator Winding Connections

N-phase machine → (N+1)/2 configurations

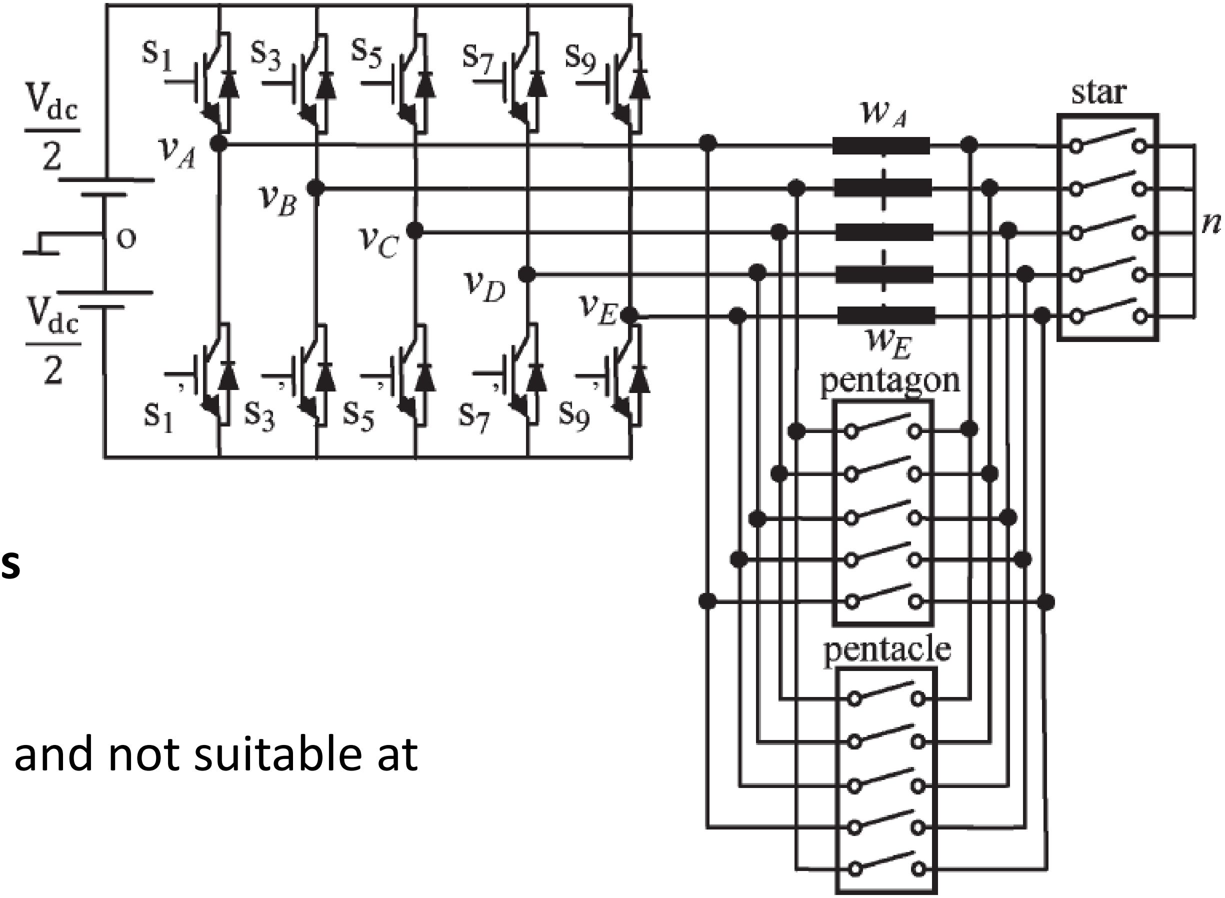
Number of phases	Possibilities of stator configuration
3	2 : Wye and Delta
5	3: Wye, Pentagon and Pentacle
:	:
N	(N+1)/2



(a) (b) (c)

D. Dujic, M. Jones, and E. Levi, "Analysis of Output Current-Ripple RMS in Multiphase Drives Using Polygon Approach," *IEEE Trans. on Power Electronics*, vol. 25, no. 7, pp. 1838-1849, 2010.

2. Different Stator Winding Connections

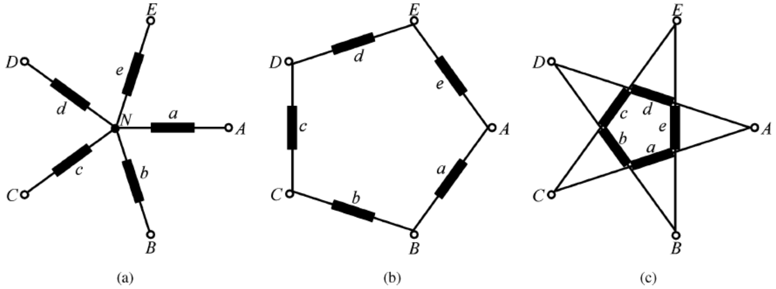


Magnetic Contactors

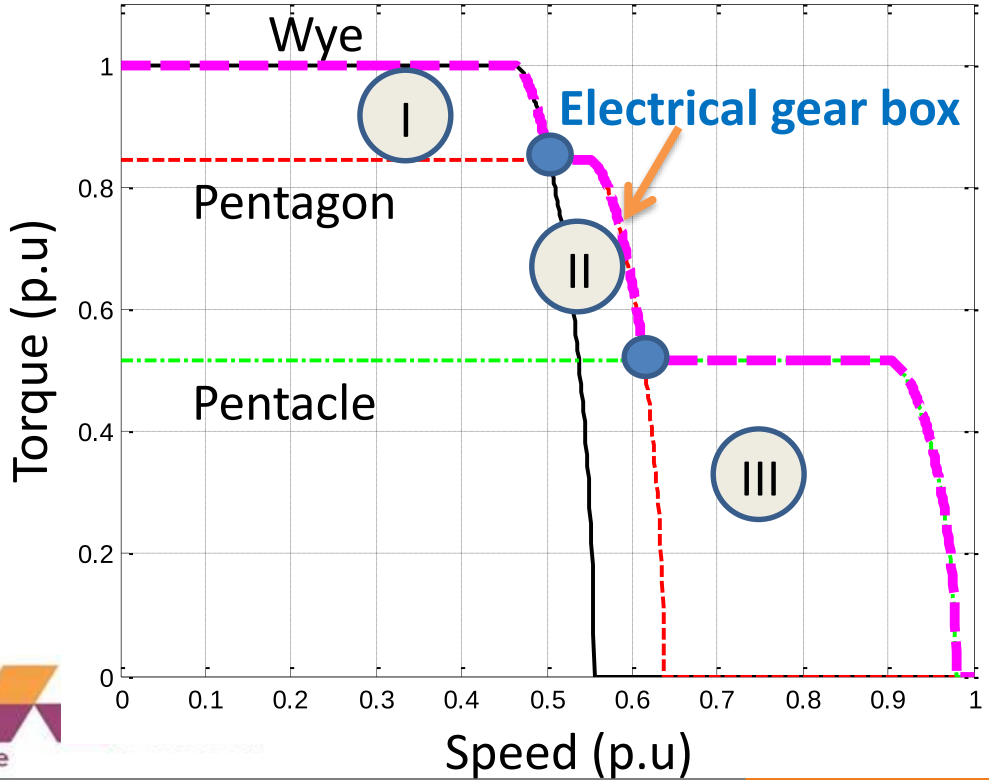
- Time delay
- Bulky
- “Hard” switching and not suitable at high speed

S. Sadeghi, L. Guo, H. A. Toliyat and L. Parsa, “Wide Operational Speed Range of Five-Phase Permanent Magnet Machines by Using Different Stator Winding Configurations”, *IEEE Trans. Industrial Electronics*, Vol. 59, No. 6, 2012.

2. Different Stator Winding Connections



|Va|=Vm |Va|=**1,2***Vm |Va|=**1,9***Vm



Objective

⇩

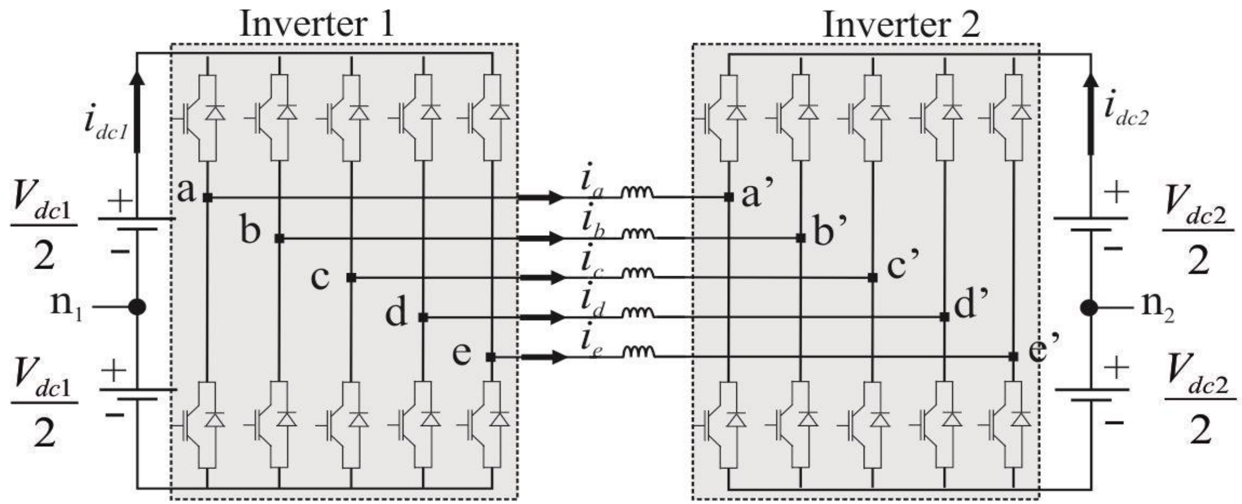
Electrical Gear Box (EGB)

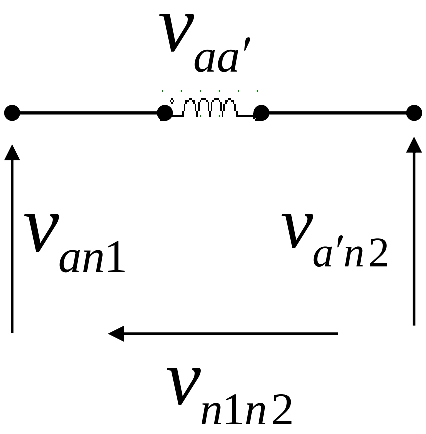
How we can **change** these stator **configurations** by **power electronics control** ?

⇩

5-phase open-end winding structure

2. Different Stator Winding Connections





$$\mathbf{v}_{abcde} = \mathbf{v}_{abcde-INV1} - \mathbf{v}_{abcde-INV2} + \mathbf{v}_{abcde-n_1n_2}$$

where

$$\mathbf{v}_{abcde} = \left[v_{aa'} \quad v_{bb'} \quad v_{cc'} \quad v_{dd'} \quad v_{ee'}\right]^T$$

$$\mathbf{v}_{abcde-INV1} = \left[v_{an_1} \quad v_{bn_1} \quad v_{cn_1} \quad v_{dn_1} \quad v_{en_1}\right]^T$$

$$\mathbf{v}_{abcde-INV2} = \left[v_{a'n_2} \quad v_{b'n_2} \quad v_{c'n_2} \quad v_{d'n_2} \quad v_{e'n_2}\right]^T$$

$$\mathbf{v}_{abcde-n_1n_2} = \left[v_{n_1n_2} \quad v_{n_1n_2} \quad v_{n_1n_2} \quad v_{n_1n_2} \quad v_{n_1n_2}\right]^T$$

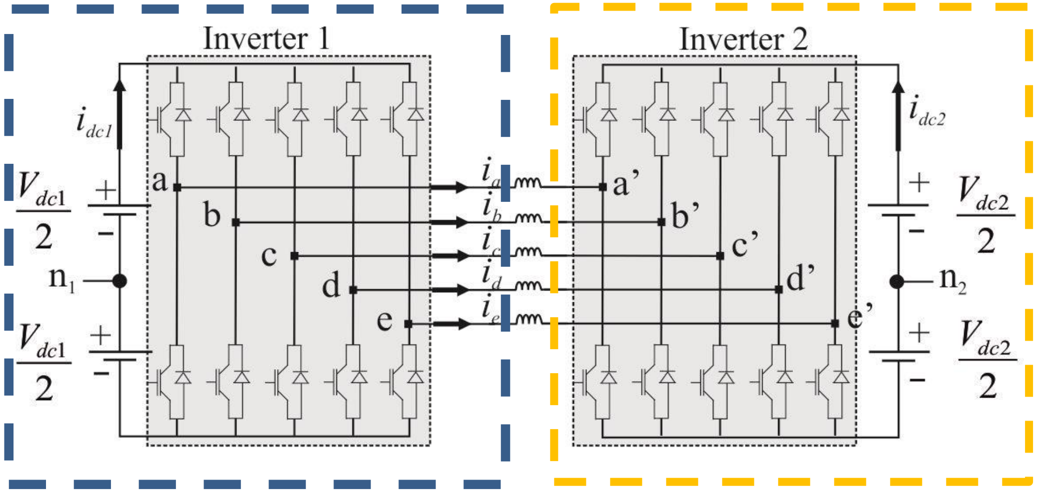
Hypothesis : Sinusoidal and balanced phase voltages:

$$\mathbf{v}_{abcde} = \mathbf{A} \cdot \left(\mathbf{v}_{abcde-INV1} - \mathbf{v}_{abcde-INV2}\right)$$

where

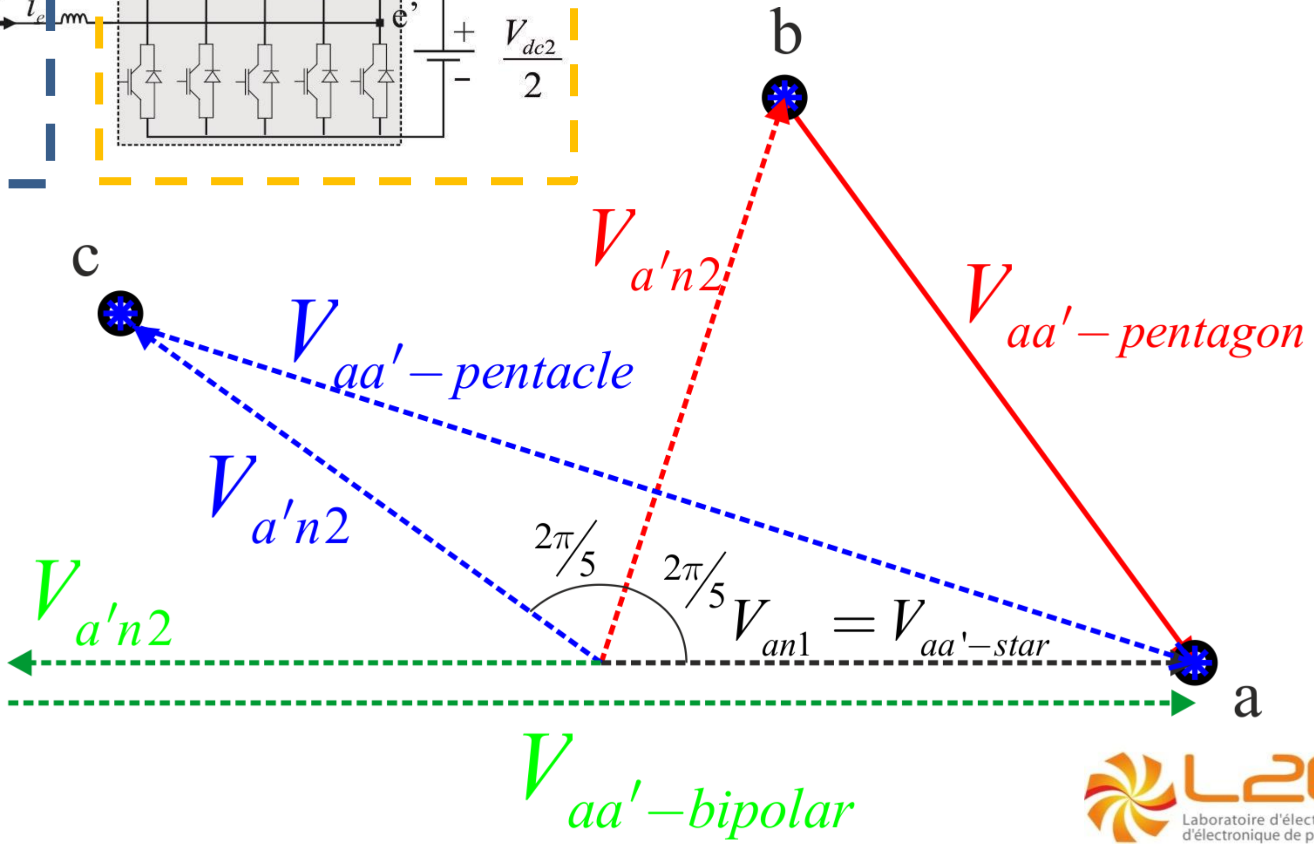
$$\mathbf{A} = \frac{1}{5}\begin{bmatrix} 4 & -1 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & -1 & 4 & -1 & -1 \\ -1 & -1 & -1 & 4 & -1 \\ -1 & -1 & -1 & -1 & 4 \end{bmatrix}.$$

2. Different Stator Winding Connections



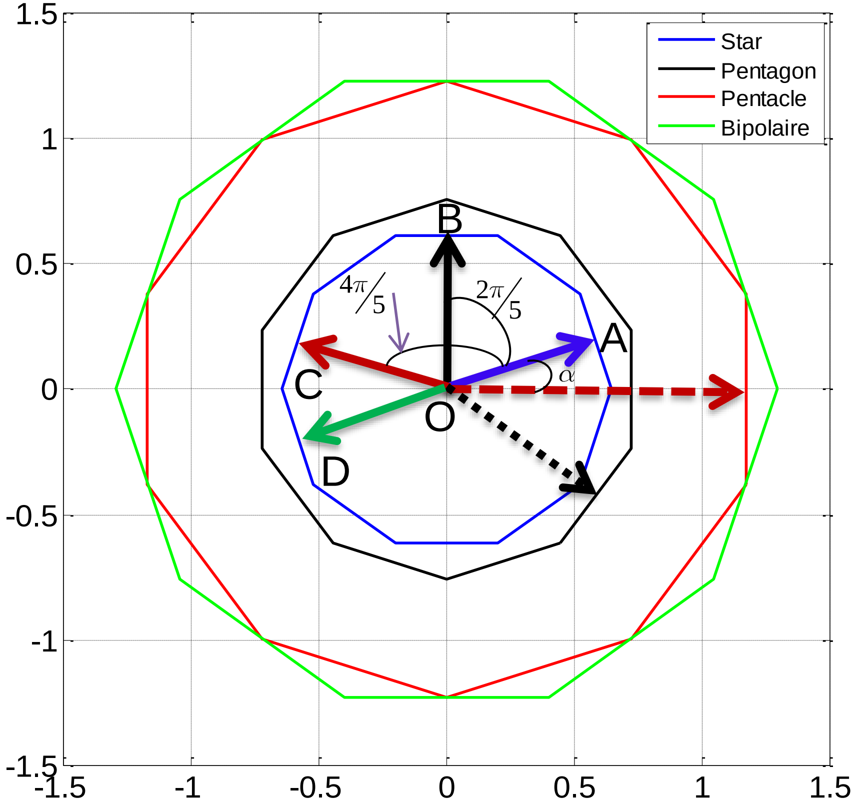
$$\mathbf{v}_{abcde} = \mathbf{A}\cdot\ \mathbf{v}_{abcde-INV1} - \mathbf{v}_{abcde-INV2}$$

For phase a:



2. Different Stator Winding Connections

$\alpha_1 - \beta_1$ frame of voltage



Wye-Connection

$V_{INV-1} = V^{*}\,\underline{|\alpha}$ $\qquad V_{INV-2} = 0$

Pentagon Connection:

$$V_{INV-1} = V^{*}\,\underline{|\alpha} \qquad V_{INV-2} = V^{*}\,\underline{\left|\alpha + \frac{2\pi}{5}\right.}$$

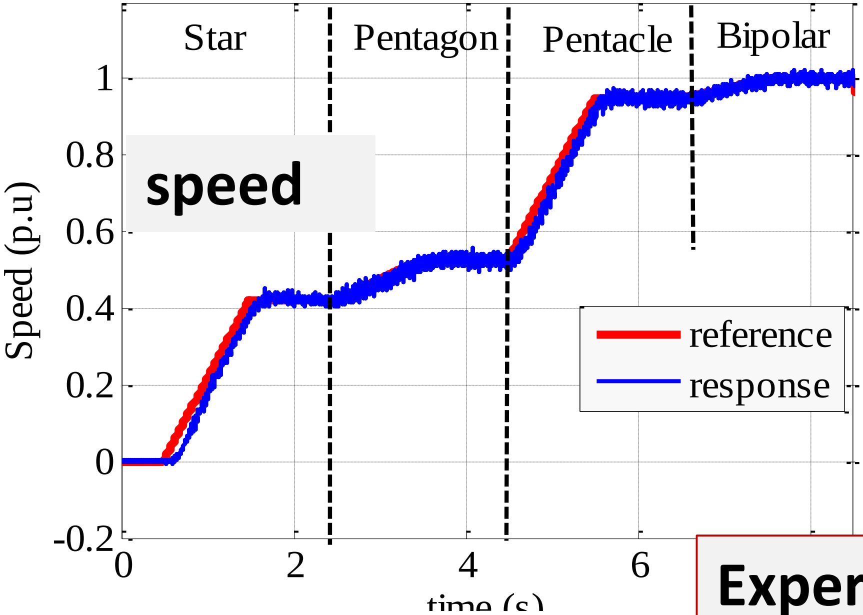
Pentacle Connection:

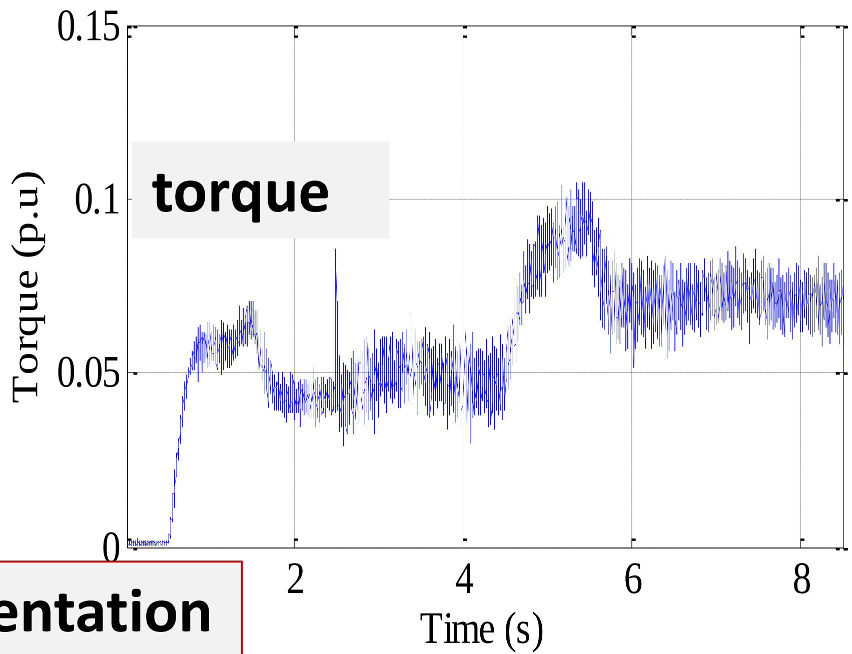
$$V_{INV-1} = V^{*}\,\underline{|\alpha} \qquad V_{INV-2} = V^{*}\,\underline{\left|\alpha + \frac{4\pi}{5}\right.}$$

Bipolaire Connection :

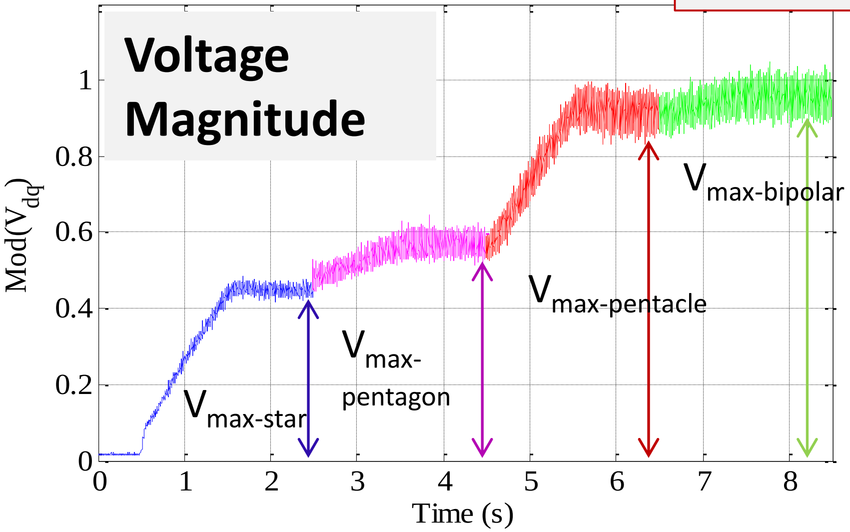
$$V_{INV-1} = V^{*}\,\underline{|\alpha} \qquad V_{INV-2} = V^{*}\,\underline{|\alpha + \pi}$$

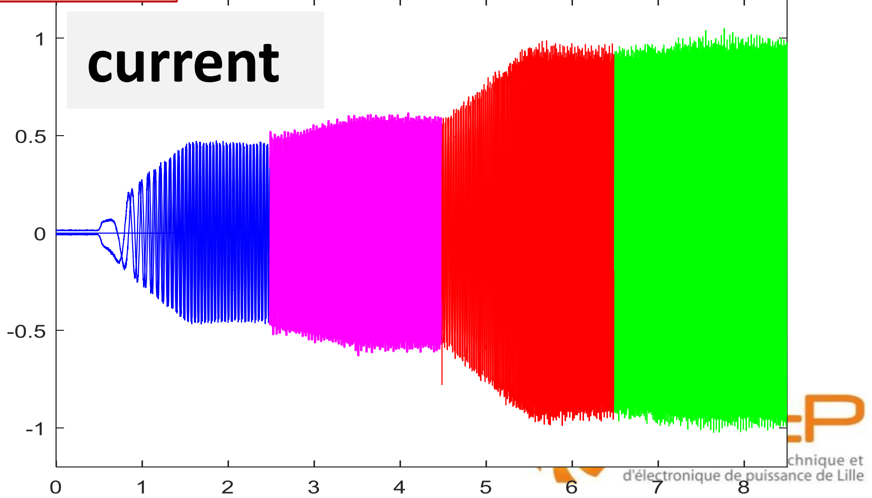
2. Different Stator Winding Connections





Experimentation





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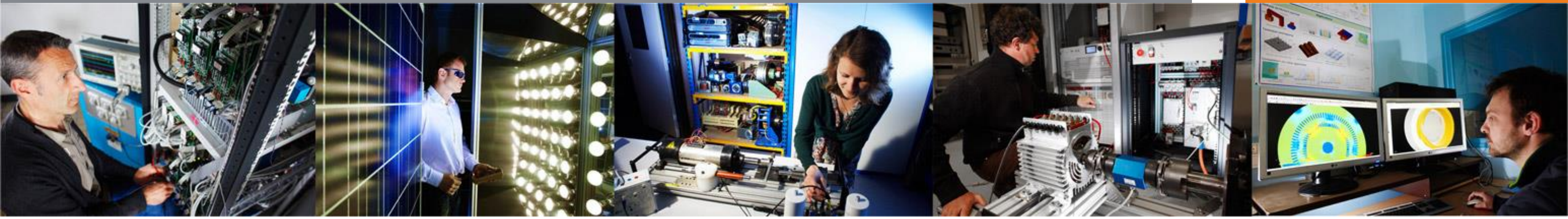
IV. Conclusion

Conclusion

- ✓ Properties of multiphase machines have been presented
- ✓ Different possibilities of multiphase drives for functioning at high speed
- ✓ Validation

Multiphase Drive Experimental Platform of L2EP Lab., Lille, France.
Two 7-phase generators, **Two 5-phase PMSM** drives, **Two 6-phase PMSM** drives;
Power Supplies and Electronic Loads: 5 to 15 kW 12V, 48V to 500 V;
Rapid prototyping control: **Dspace** 1005, 1006, **MicroLabox**, **Opal–RT**



Thank you for your attention

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Laboratoire d'électrotechnique et
d'électronique de puissance de Lille

ARTS
ET MÉTIERS
ParisTech
Lille

II. Bi-harmonic machine Design: Stator

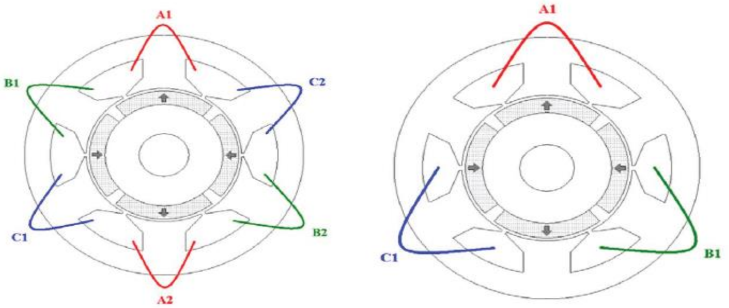
Tooth-Coil concentrated winding are used .

Advantages

➢Shorter end-windings →more useful copper → more efficient machine.

➢Higher filling factor: 20% more

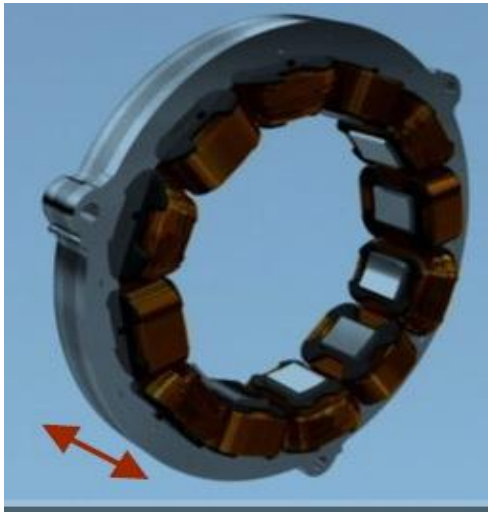
➢Simpler winding structure (easy manufacturing, maintenance, and recycling).



Solution for high frequencies:
Combinations family with Spp= 0,5 slot per pole and per phase.:Low MMF harmonic content, Less undesied effects(noise, PM losses).

Winding topology: (slot/pole combinaison):

Bad choice of slot/pole combinaison→MMF with a lot of MMF harmful harmonics and sub-harmonics and mechanical vibration→Rotor eddy current losses can be induced espicially at high frequencies→Demagnitization of magnets is possible.

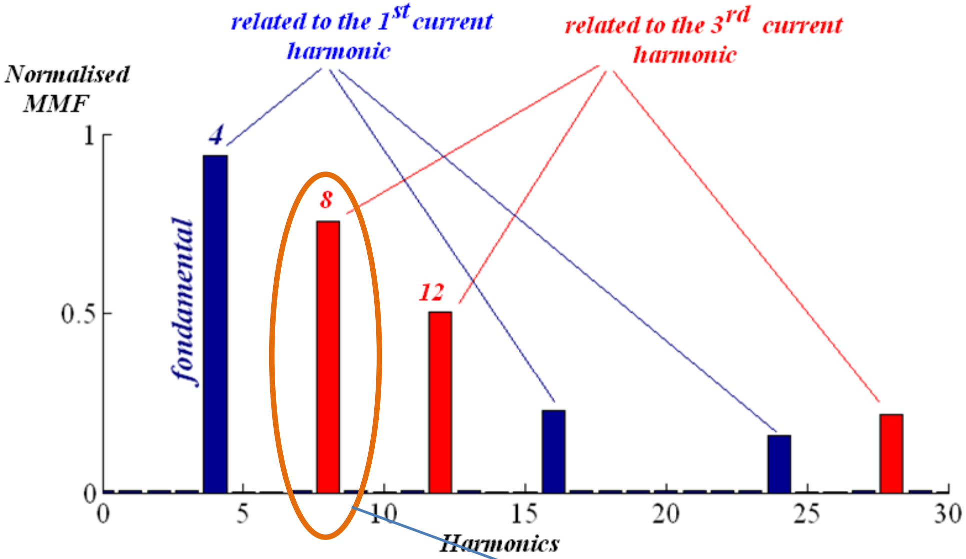


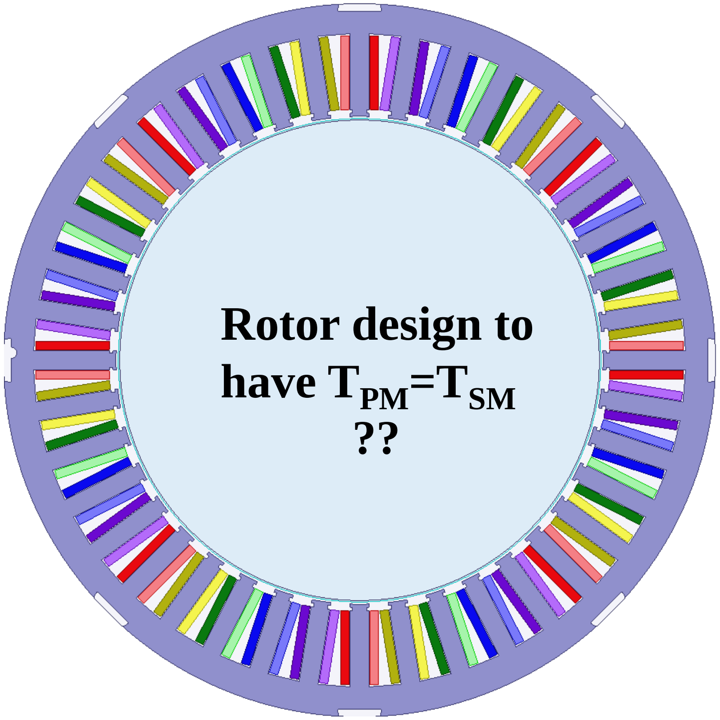
3-Phase
12 slots / 8 poles 2010 TOYOTA Prius Generator

II. Bi-harmonic machine Design: Stator

5-Phase combination: **40** slots / **16** poles (½ slot per pole per phase)

- Low level of parasitic effects (with 1st harmonic)





Rotor design to have $T_{PM}=T_{SM}$??

- Weak 1st harmonic winding factor $(\xi_w)_1 = 0.588$
- High 3rd harmonic winding factor $(\xi_w)_3 = 0.95$

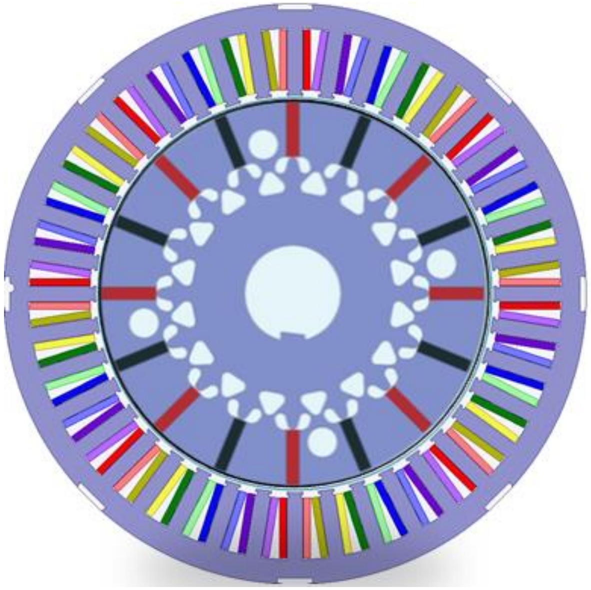
Possible Weak points:

→small winding factor of first harmonic.

→one subharmonic (8) when supplied with 3 harmonic.

II. Bi-harmonic machine Design: Rotor

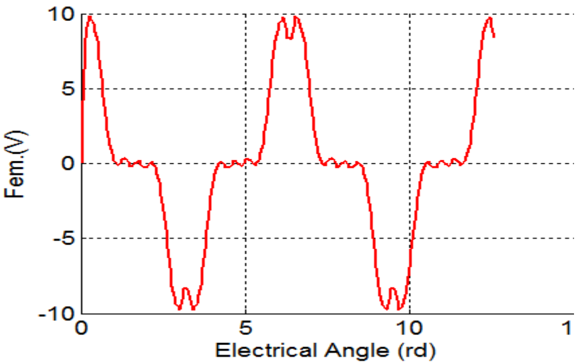
Structure with interior magnets is used.

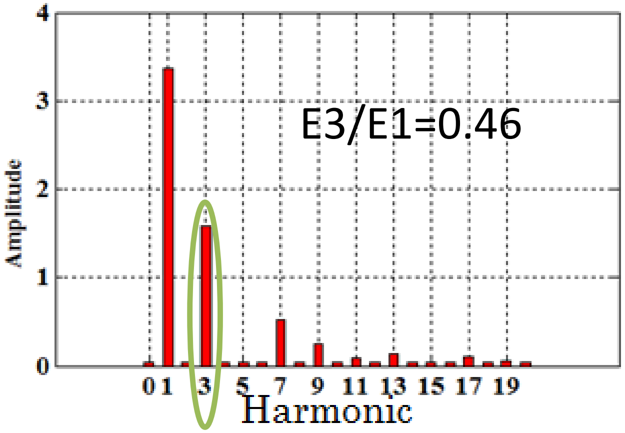


Advantages

- ➢flux concentration which boosts torque and improve torque density.
- ➢Large flux weakening area due to the possibility to obtain higher value of L_d
- ➢Reluctant torque in addition to torque from Permanent Magnet, which improve machine compactness.

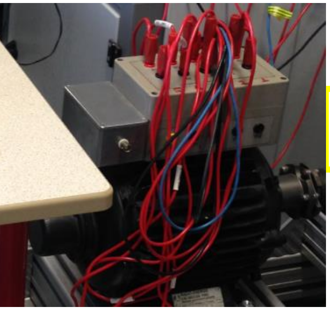
Extra protection of magnets from the MMF harmonics
→ Low magnet losses expected in this machine.





Low potentiality of the third harmonic to produce torque
→ TO MODIFY THE ROTOR TO OVERCOME THIS

EXPERIMENTAL RESULTS



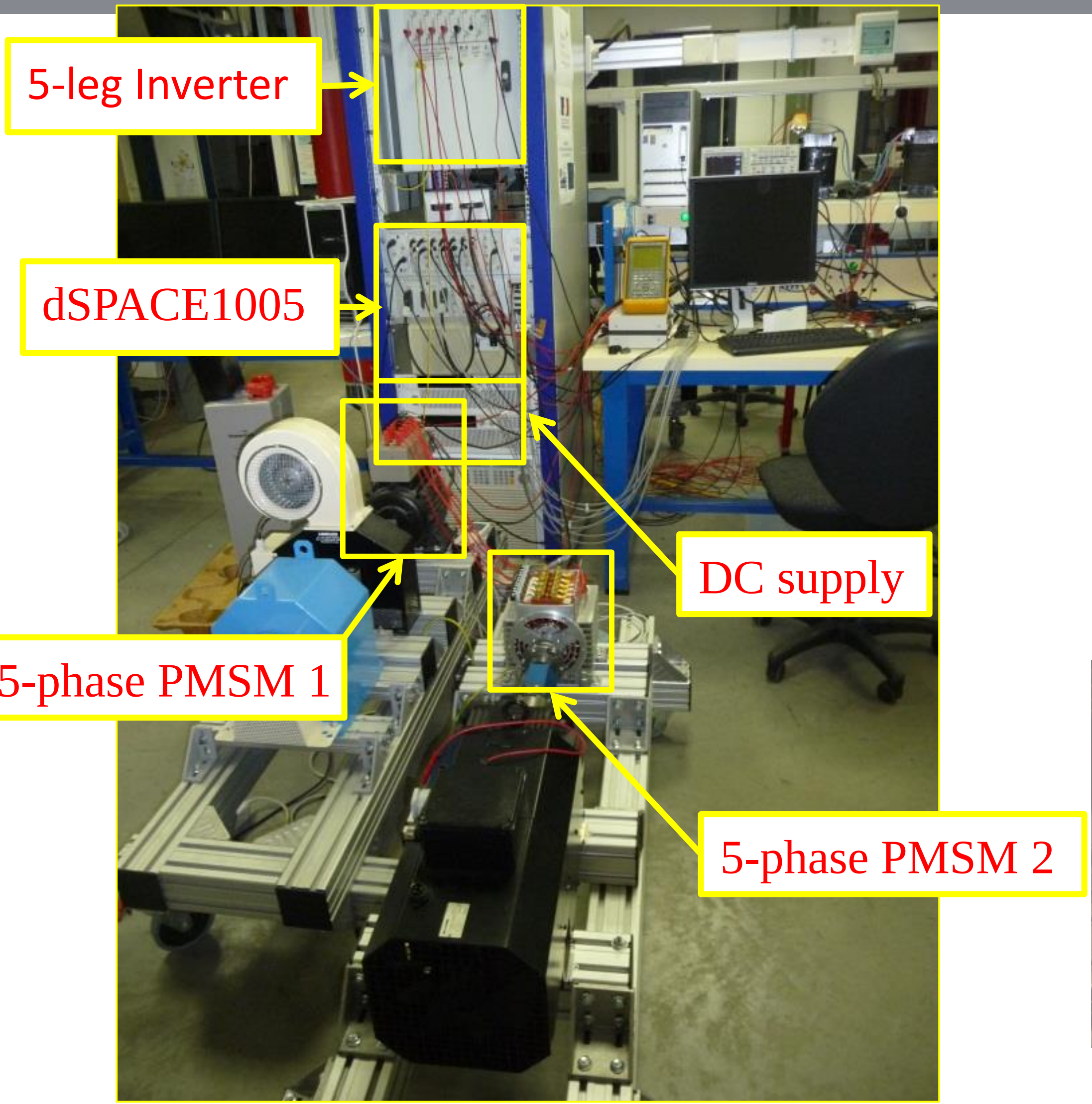
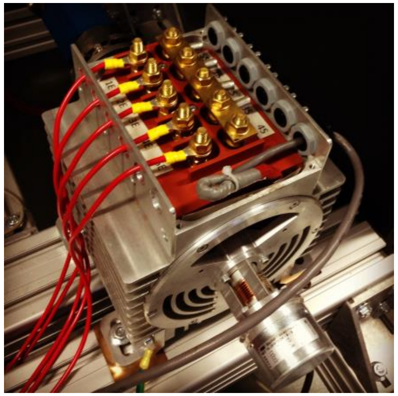
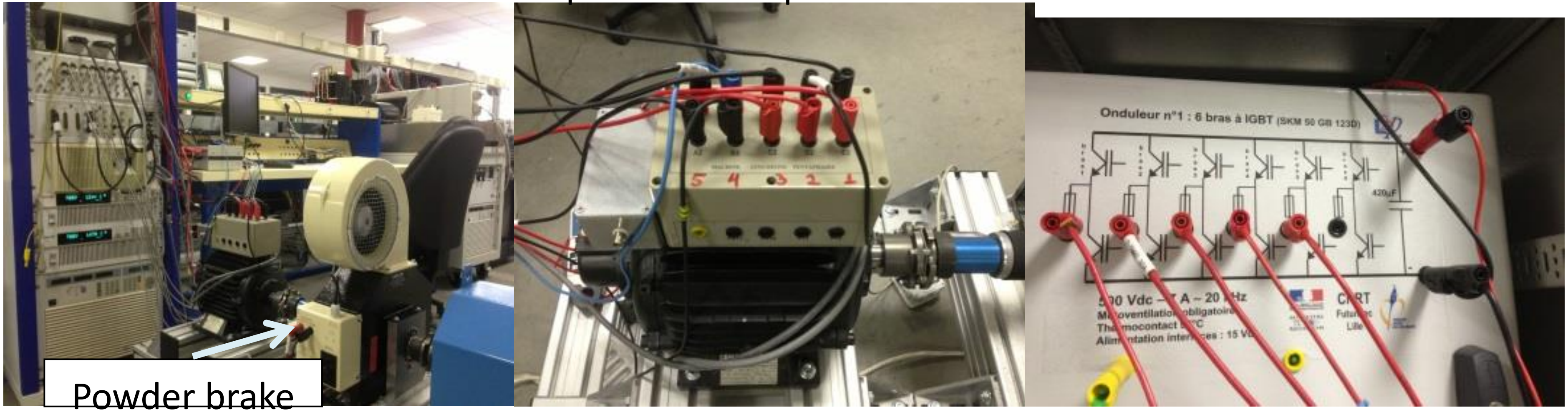


Fig. 1. Laboratory experimental test-bench





dSPACE and 2 DC sources

Open-end five-phase machine

Five-bridge inverter (one side)

Laboratory experimental platform setup

5-phase machine parameters

Phase resistance: R=2.24 Ω

Inductance : L_{1d}=3.2 mH

Inductance L_{1q}=3.2 mH

Inductance L_{3d}=0.9 mH

Inductance L_{3q}=0.9 mH

$k_{emf-1} = E_1/\Omega = 0.32\ (\mathrm{V.s.rad}^{-1})$

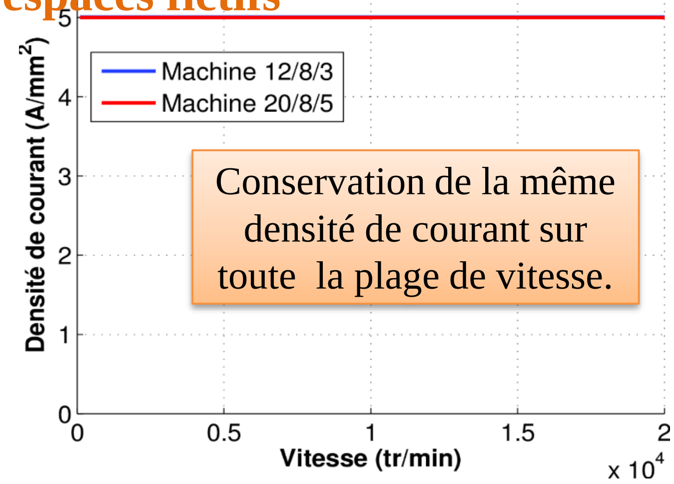
Maximum torque $T_{em\text{-}max}$ = 20 N.m

Maximum speed $\Omega_{max} = 2500$rpm

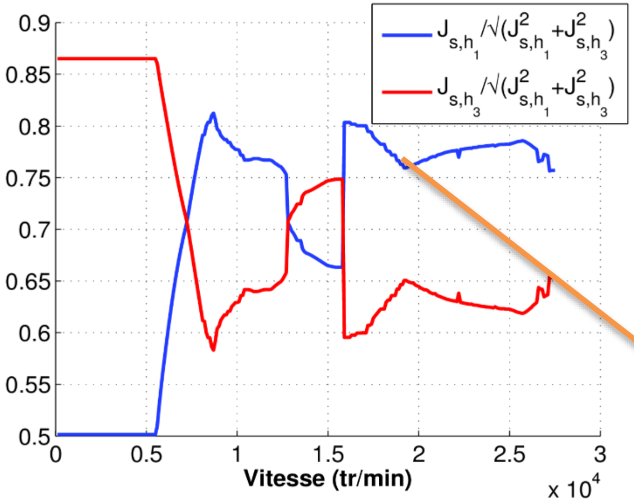
Bus voltage V_{bus}=70 V

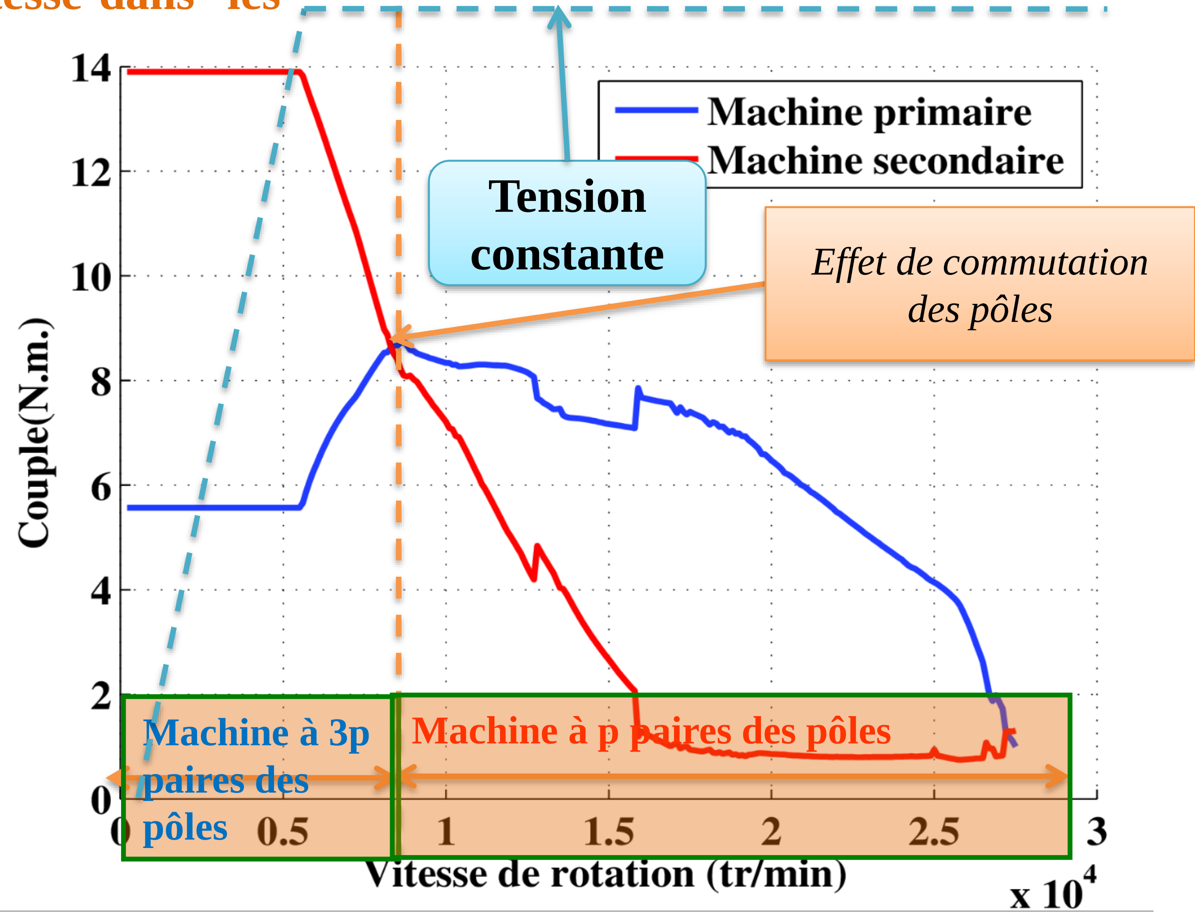
Maximum phase current I_{max}=15 A

V.B.3. Caractéristiques couple /vitesse dans les espaces fictifs



Conservation de la même densité de courant sur toute la plage de vitesse.





Tension constante

Effet de commutation des pôles

Machine à 3p paires des pôles

Machine à p paires des pôles

Contrairement au défluxage classique des machines triphasées, on agit sur la répartition de courant entre les machines fictives.

Multiphase Decomposition Theory

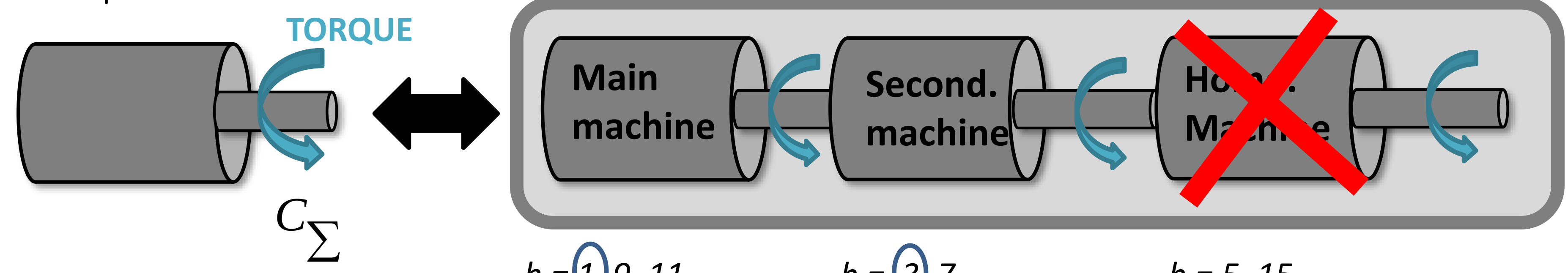
5-phase PMSM

MM : 1st harmonic
SM : 3th harmonic

Torque can be **created** by injecting the **1st** and the **3th** harmonic of **currents**

Real 5-phase machine

Fictitious Machines (2 diphase + 1 homopolar)

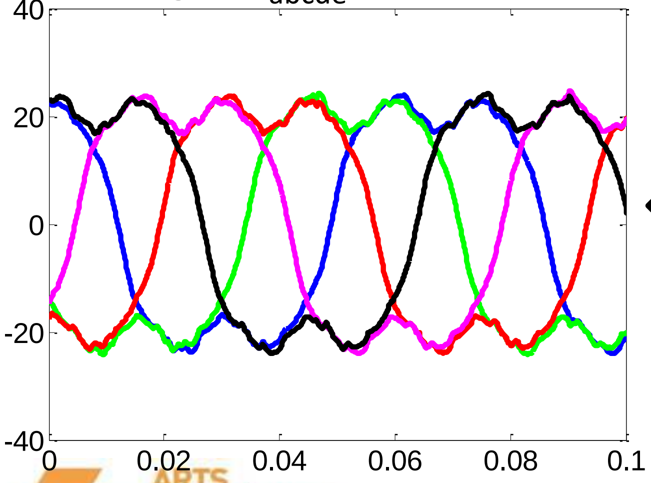


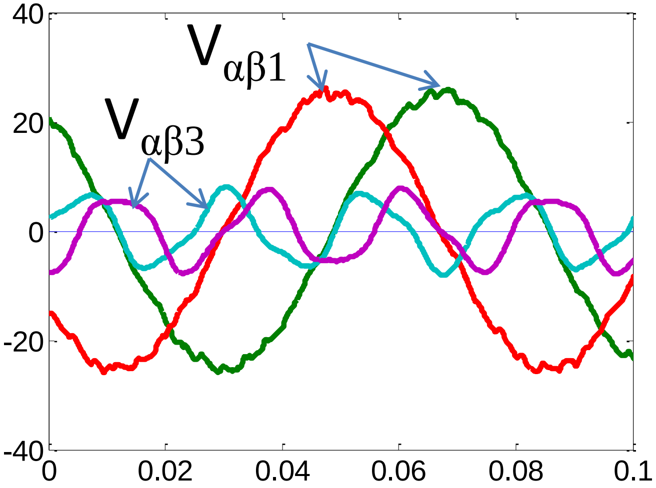
h = 1, 9, 11,…
h=5*k* ± 1

h = 3, 7,
h=5*k* ± 2

h = 5, 15, …
h=5*k*

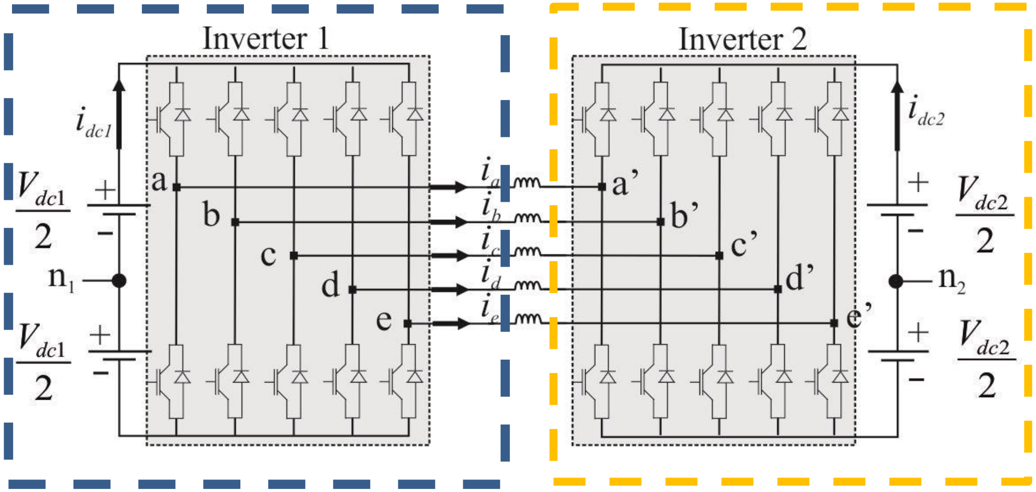
Voltages V_{abcde}





Voltages in decoupled base

2. Different Stator Winding Connections



For all configurations,
the ***1st Inverter*** is
controlled as :

$$\mathbf{v}_{abcde-INV1} = \begin{bmatrix} v_{an_1} & v_{bn_1} & v_{cn_1} & v_{dn_1} & v_{en_1} \end{bmatrix}^T = V\left[\sin\theta \quad \cdots \quad \sin\left(\theta - \frac{8\pi}{5}\right)\right]^T$$

For ***the 2nd Inverter***:

WYE $\mathbf{v}_{abcde-INV2} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T \quad (1)$

PENTAGON $\mathbf{v}_{abcde-INV2} = \begin{bmatrix} v_{bn_1} & v_{cn_1} & v_{dn_1} & v_{en_1} & v_{an_1} \end{bmatrix}^T \quad (2)$

PENTACLE $\mathbf{v}_{abcde-INV2} = \begin{bmatrix} v_{cn_1} & v_{dn_1} & v_{en_1} & v_{an_1} & v_{bn_1} \end{bmatrix}^T \quad (3)$

BIPOLAR $\mathbf{v}_{abcde-INV2} = -\begin{bmatrix} v_{an_1} & v_{bn_1} & v_{cn_1} & v_{dn_1} & v_{en_1} \end{bmatrix}^T \quad (4)$

SIMPLE