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**2018 IEEE 2nd International Electrical and Energy Conference (CIEEC)**

# **Different Possibilities of Multiphase Drives Functioning in Constant Power Region**

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Arts et Métiers ParisTech

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



- 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

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Hybrid and Full electric automotive applications

Electrical machines requirements

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

Fault tolerance capability or low voltage (48V)

Wide speed range

rotor with **PM**

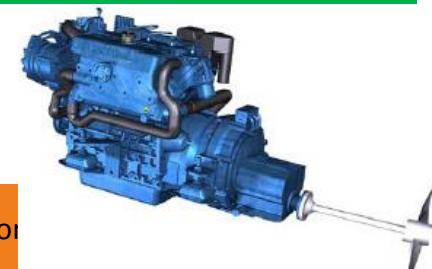
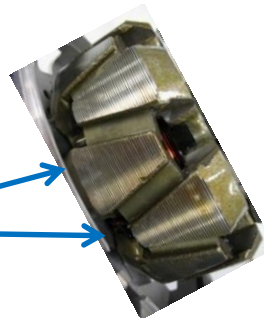
Stator with tooth concentrated winding

Number of phases  $> 3$

- Dahlander circuit
- Winding configuration
- Saliency ratio

Electronic pole commutation

PM



# Introduction & Context

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

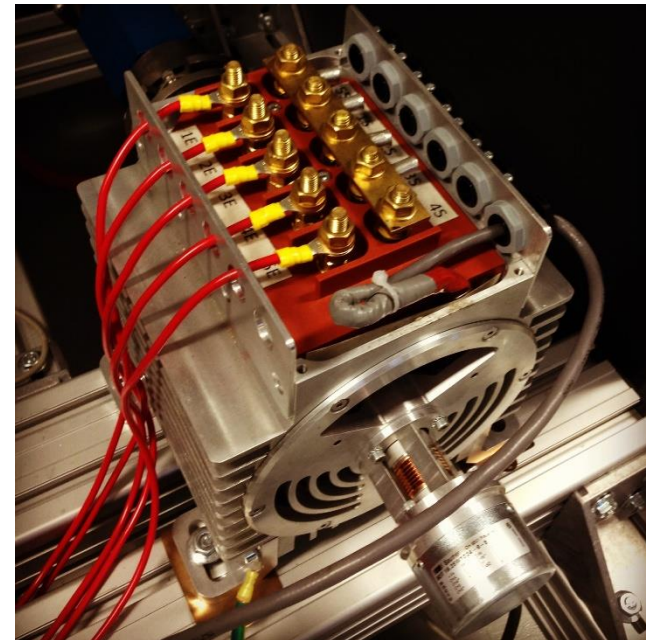
➤ **Acceptable current/phase** for low voltage high power (48V/15kW):

- ✓ **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

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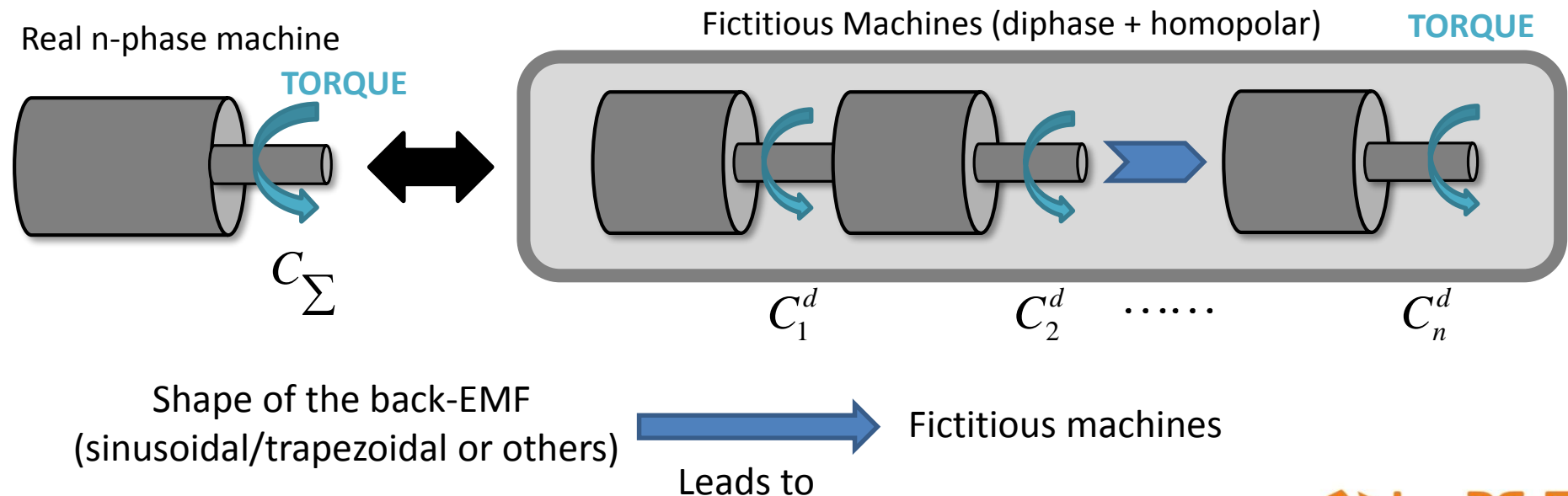
# Multiphase Decomposition Theory

6

## GENERALIZED VECTORIAL FORMALISM THEORY

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

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

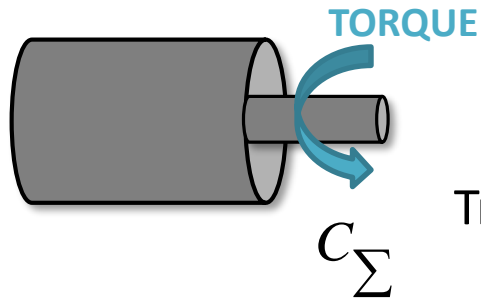


# Multiphase Decomposition Theory

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## 3-phase PMSM

Real 3-phase machine



Transformation  
(Concordia,  
Clarke, etc.)

$h$  : odd harmonic rank  
(even harmonics are ignored)

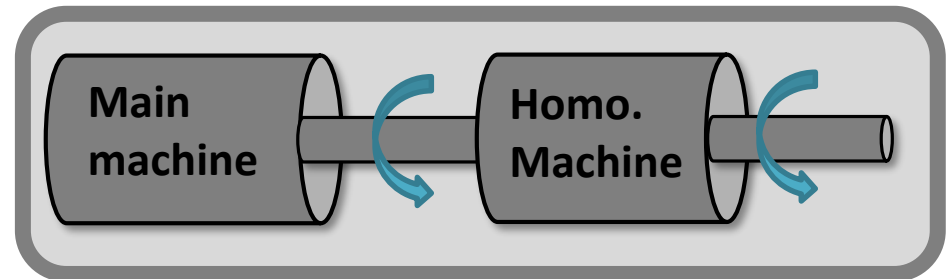
**Main machine (MM) :** diphasé ( $\Lambda_1 = \Lambda_2$ )  
**Homo. Machine:** monophasé ( $\Lambda_0$ )

$\Lambda_i$  Eigenvalues  
of inductance matrix

Fictitious Machines (1 diphasé + 1 homopolar)

**MM**

**HM**



$h = 1, 5, 7, 11, \dots$   
 $h \neq 3k$

$h = 3, 6, 9, \dots$   
 $h = 3k$

### Notes

- Wye connection: current of homopolar machine  $i_0 = 0$   $C_0 = 0$
- All **harmonics**, different from  $3 \cdot k$ , are **regrouped** in the **main machine** and **INTERACT** between them (currents (time) and back-EMFs (space))

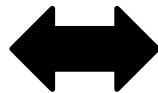
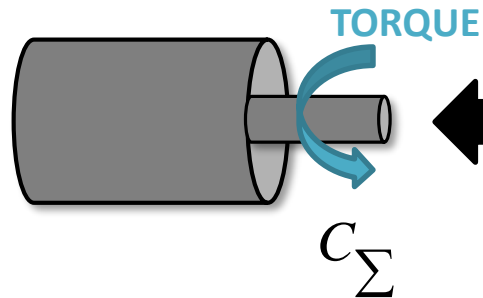
# Multiphase Decomposition Theory

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## 5-phase PMSM

Fictitious Machines (2 diphas + 1 homopolar)

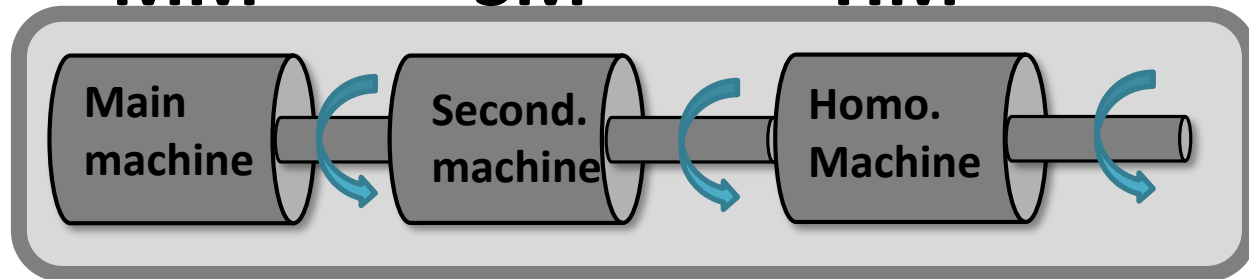
Real 5-phase machine



**MM**

**SM**

**HM**



$h = 1, 9, 11, \dots$   
 $h = 5k \pm 1$

$h = 3, 7, \dots$   
 $h = 5k \pm 2$

$h = 5, 15, \dots$   
 $h = 5k$

$h$  : harmonic rank of the back-EMF

+ : direct rotating vector

- : inverse rotating vector

**Main machine (MM) : diphas ( $\Lambda_1 = \Lambda_2$ )**

**Second. Machine (SM): diphas ( $\Lambda_3 = \Lambda_4$ )**

**Homo. Machine: monophase ( $\Lambda_0$ )**

### Notes

- Wye connection: current of homopolar machine

$$i_0 = 0 \quad C_0 = 0$$

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

# Multiphase Decomposition Theory

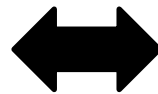
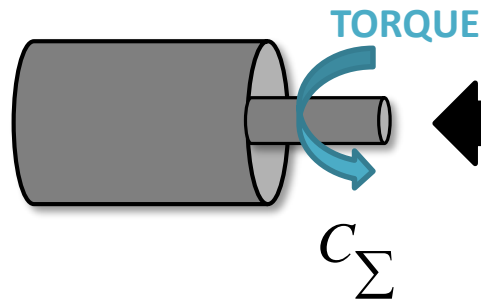
9

## 5-phase PMSM

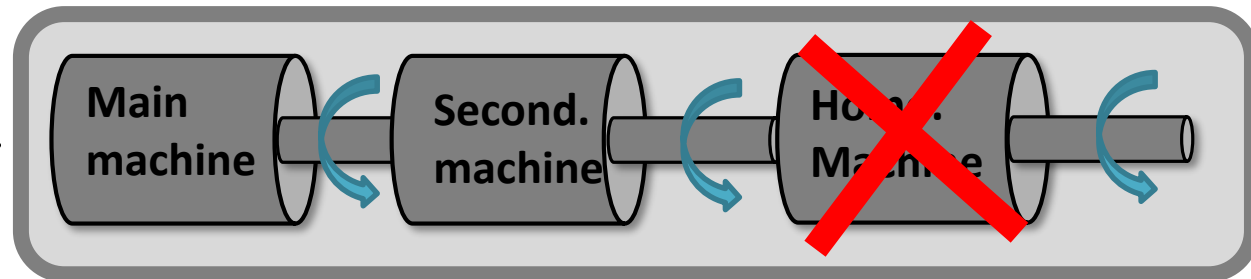
MM : 1st harmonic  
SM : 3th harmonic

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

Real 5-phase machine



Fictitious Machines (2 diphas + 1 homopolar)



$h = \textcircled{1}, 9, 11, \dots$

$p$  pairs of poles

$h = \textcircled{3}, 7, \dots$

$3p$  pairs of poles

$h = 5, 15, \dots$   
 $h = 5k$

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

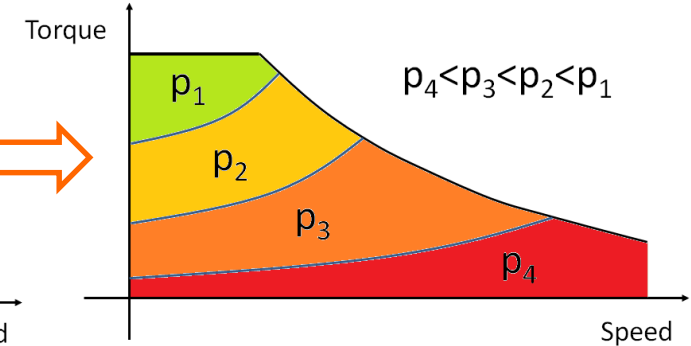
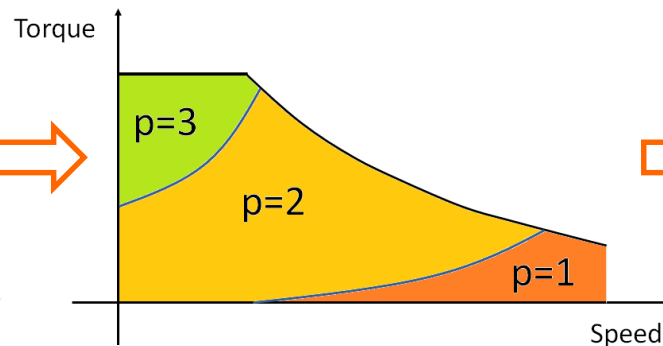
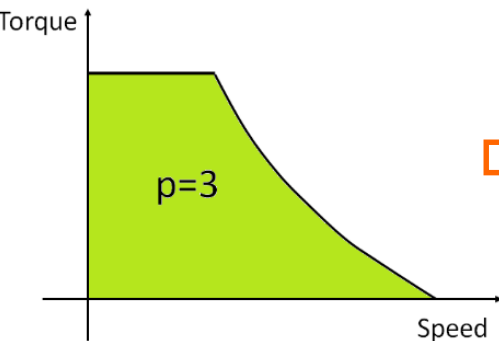
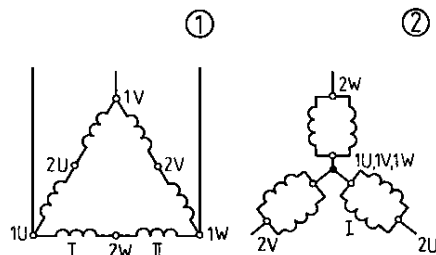
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# 1. Pole Changing

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**Mechanical** commutations of windings (Dahlander)

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



*Electronic pole changing with multiphase machines to extend the speed range*

Multiphase machine

Change number of pole pairs **electronically**

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

[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.

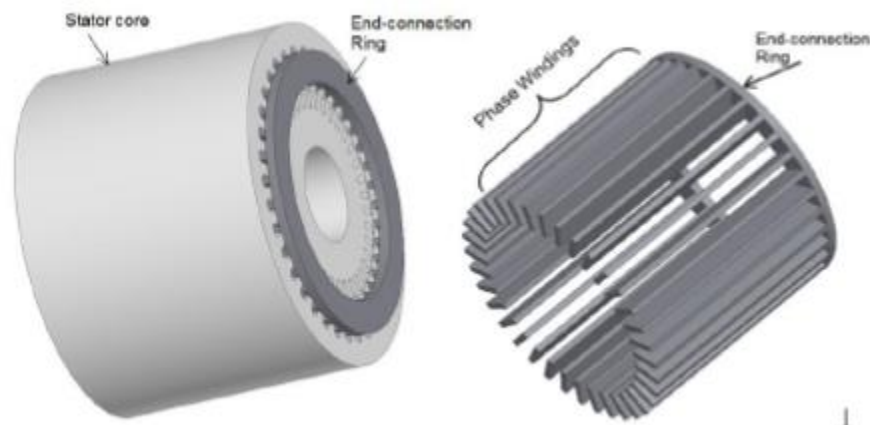
[2] J. Gong, H. Zahr, E. Semail, M. Trabelsi, B. Aslan, and F. Scuiller, "Design Considerations of Five-Phase Machine with Double  $p/3p$  Polarity," IEEE Transactions on Energy Conversion, pp. 1-1, 2018.

# 1. Pole Changing

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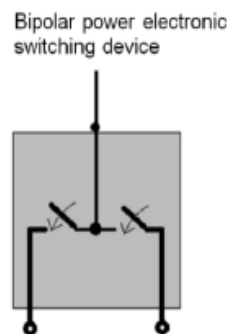
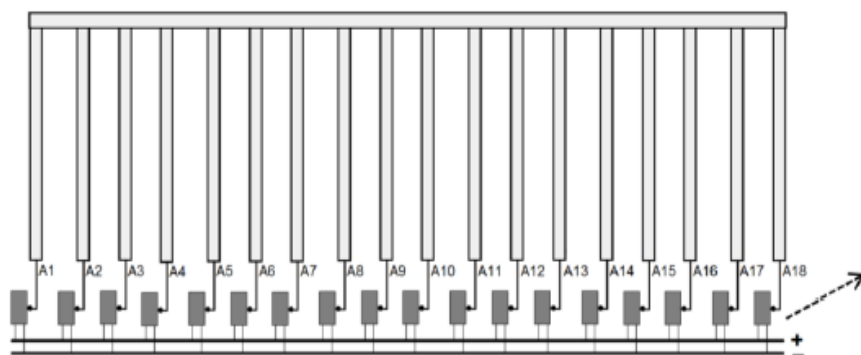
## ISCAD : Intelligent Stator Cage Drive

### Stator cage winding

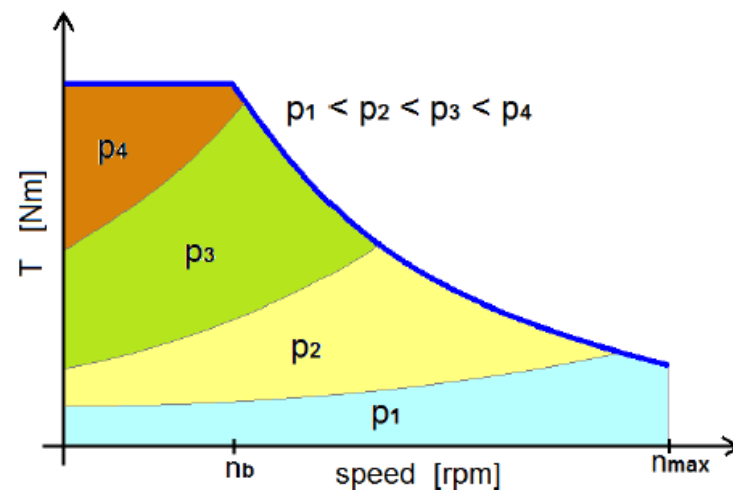


- Intelligent Stator → Each slot is one phase
- Modification (by controlling 60 legs) of Slot/pole according to operating points for maximizing the efficiency
- High fault-tolerant capability
- Double-polarity possibility to increase the performance

### The m-phase stator winding supplied with multiphase inverter



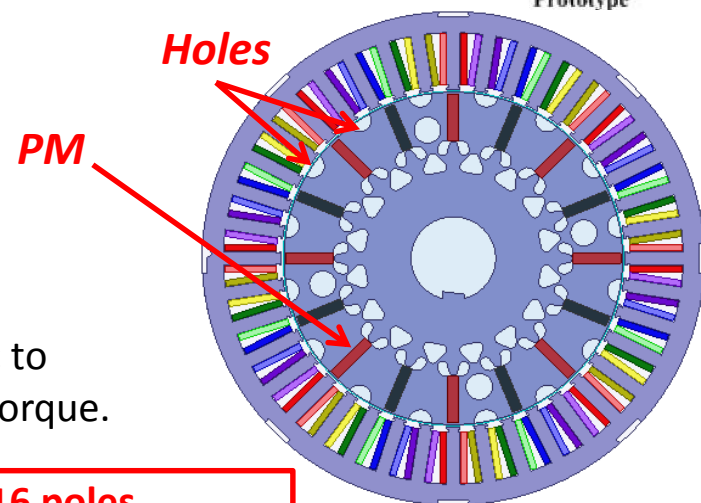
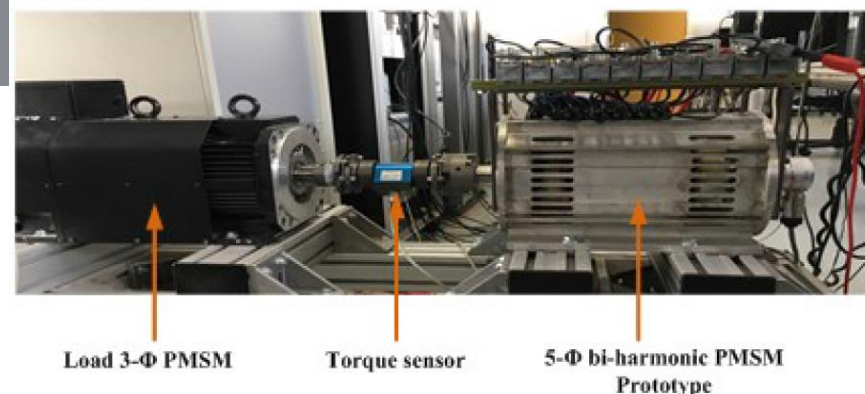
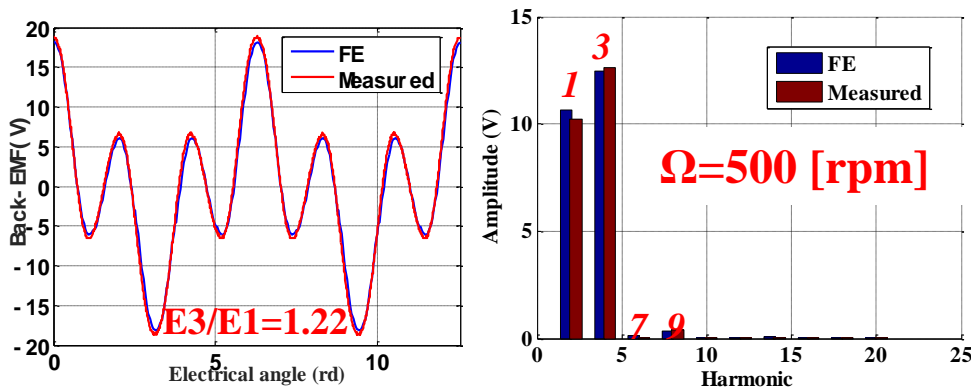
**60 stator slots/ 73 rotor slots  
(Induction machine)**



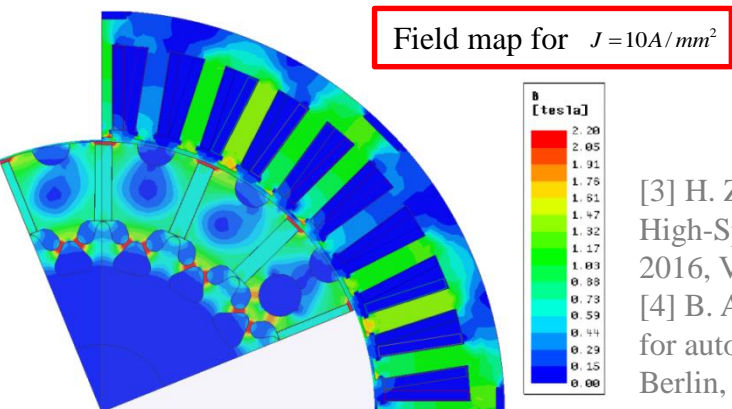
# 1. Pole Changing

## Structure with interior magnets

- Redistribution of flux between 1<sup>st</sup> & 3<sup>rd</sup> harmonic
- Introducing holes between poles



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



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

[3] H. Zahr, J. Gong, E. Semail and F. Scullier, "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.

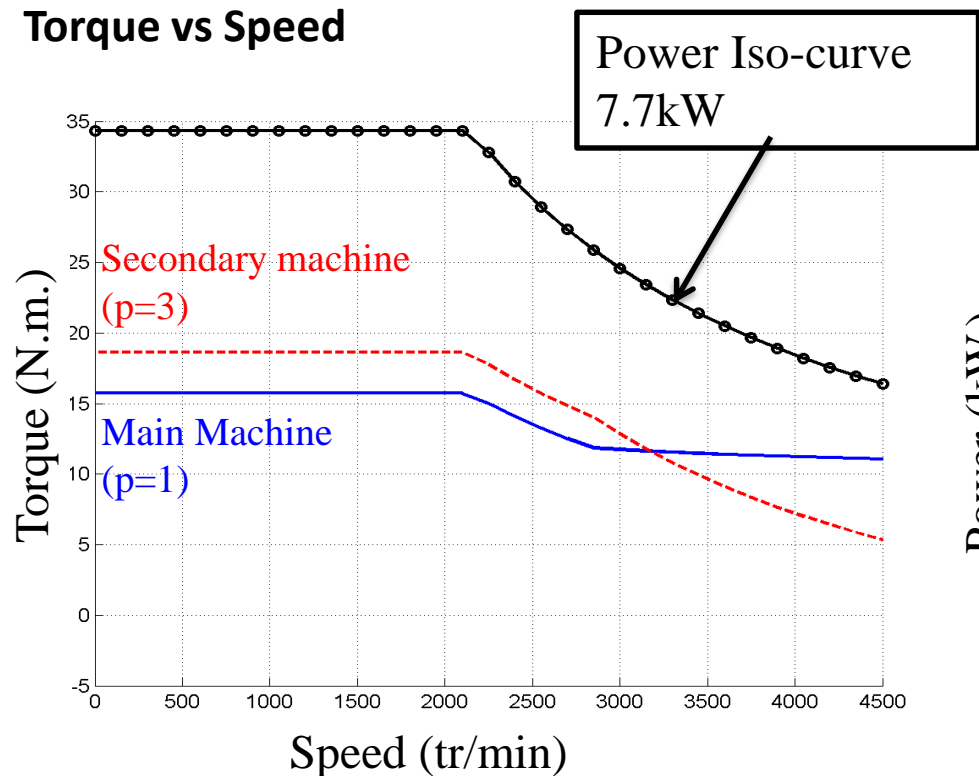
[4] B. Aslan and E. Semail, "New 5-phase concentrated winding machine with bi-harmonic rotor for automotive application," *2014 International Conference on Electrical Machines (ICEM)*, Berlin, 2014, pp. 2114-2119

# 1. Pole Changing

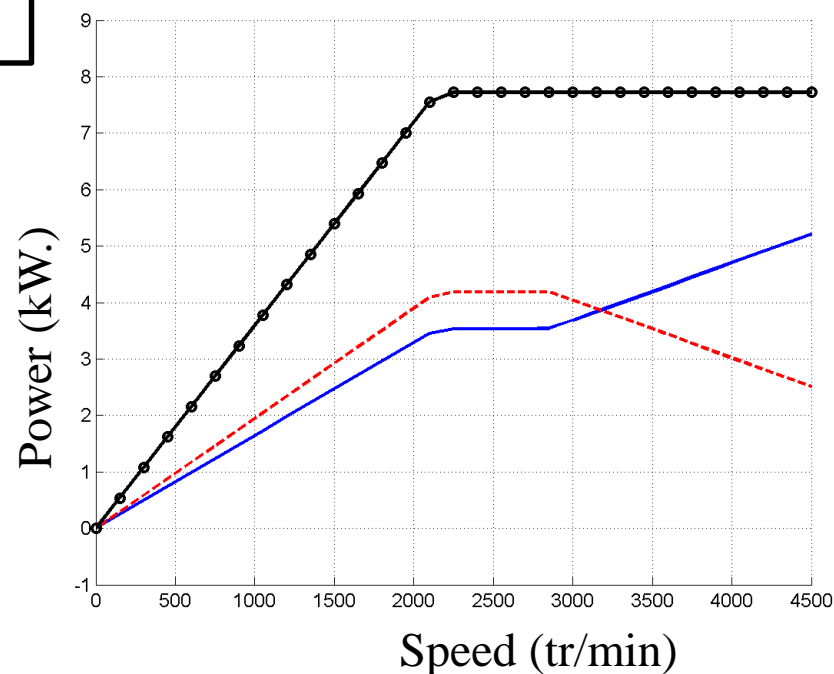
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## MTPA strategy and **Constraint** on **Voltage** at High Speed

**Torque vs Speed**



**Power vs Speed**

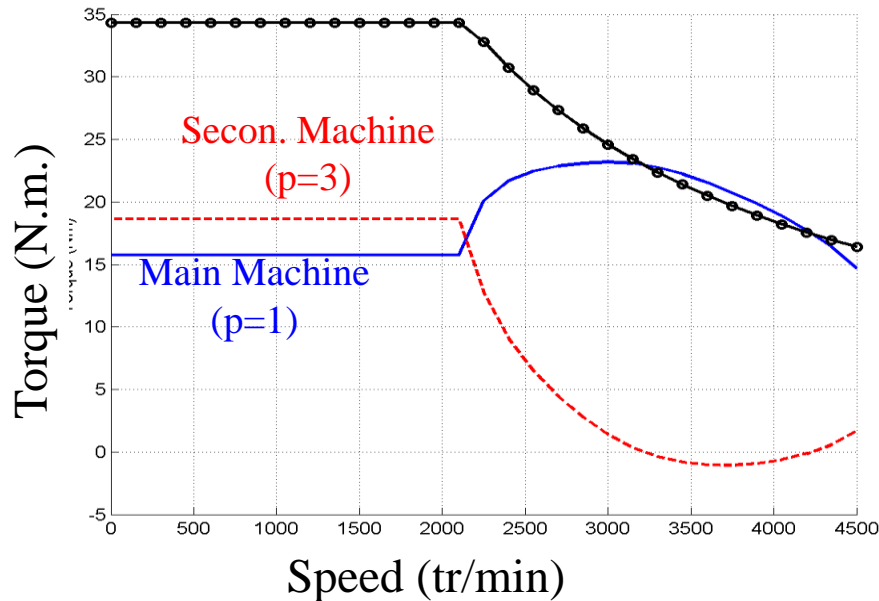


# 1. Pole Changing

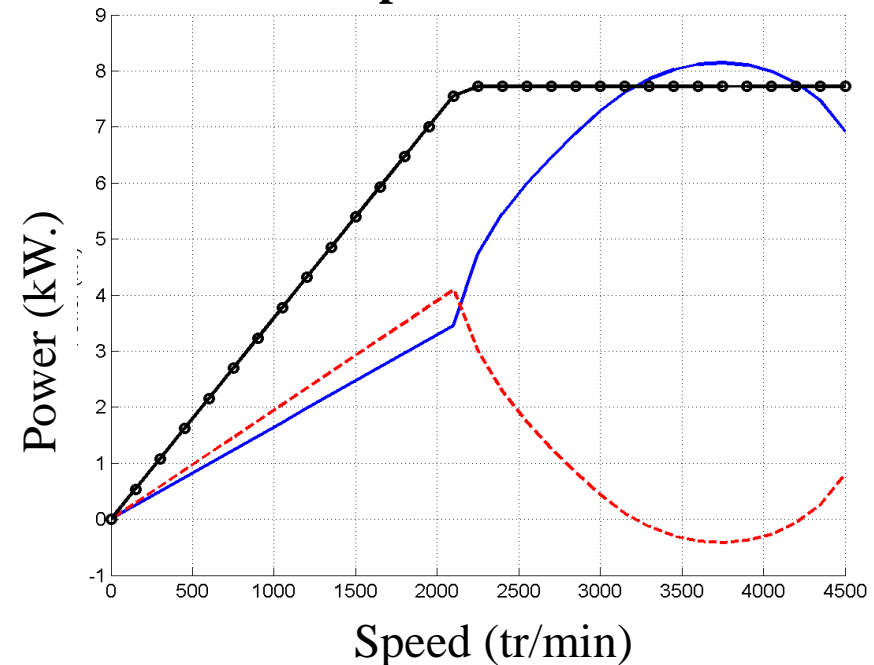
15

## 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**

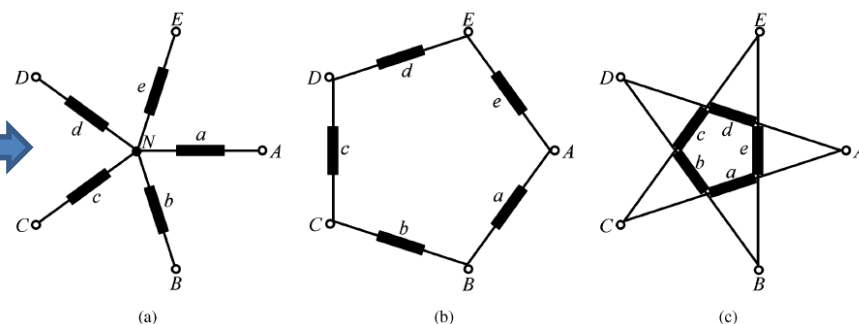
Functioning at **high speed** is very **different** with **three-phase** drives since there are **more degrees of freedom**

## 2. Different Stator Winding Connections

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N-phase machine  $\longrightarrow$   $(N+1)/2$  configurations

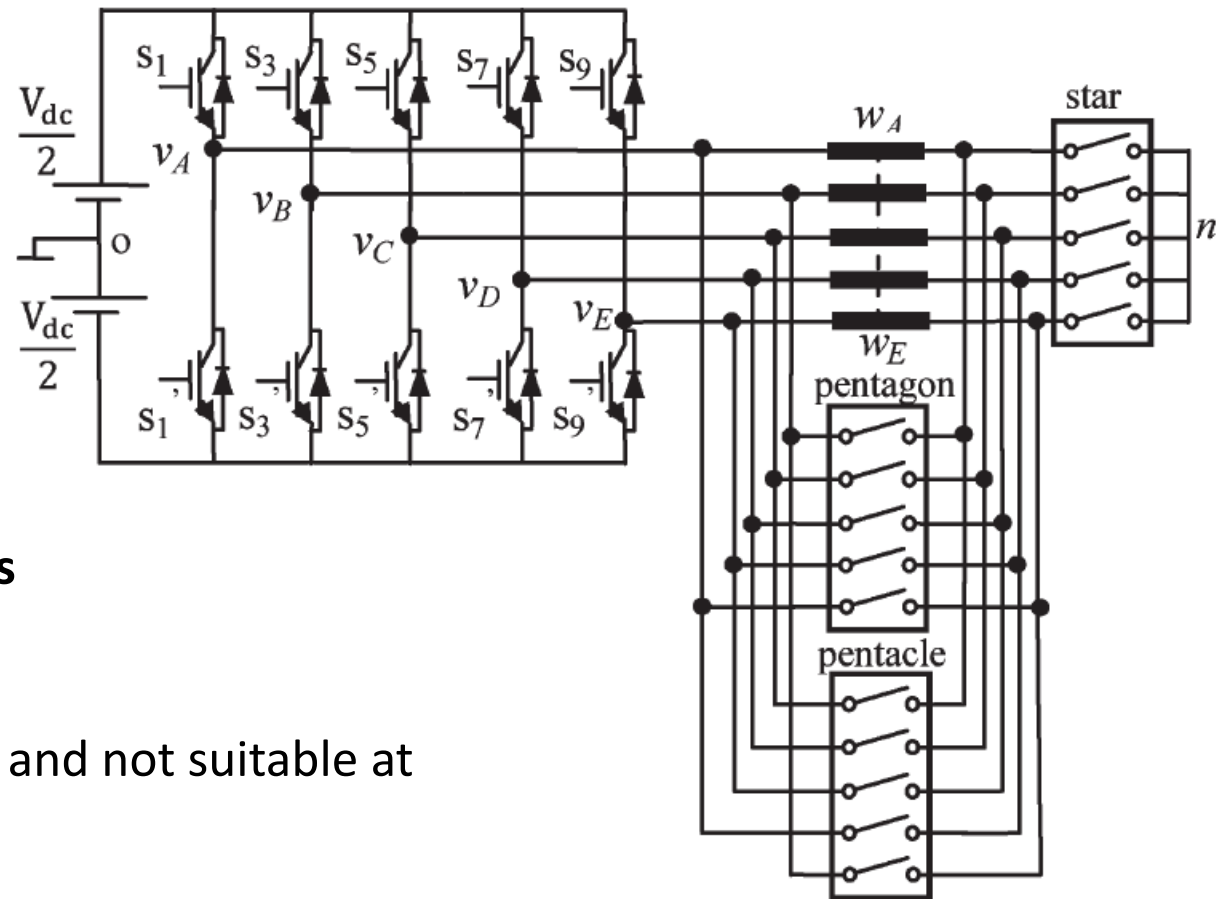
Number of phases	Possibilities of stator configuration
3	2 : Wye and Delta
5	3: Wye, Pentagon and Pentacle
:	:
N	$(N+1)/2$



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

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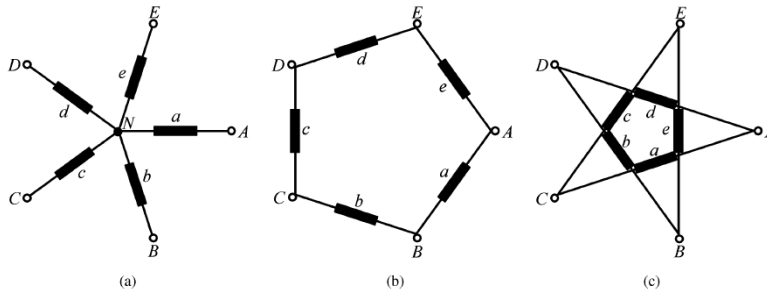
### Magnetic Contactors

- 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

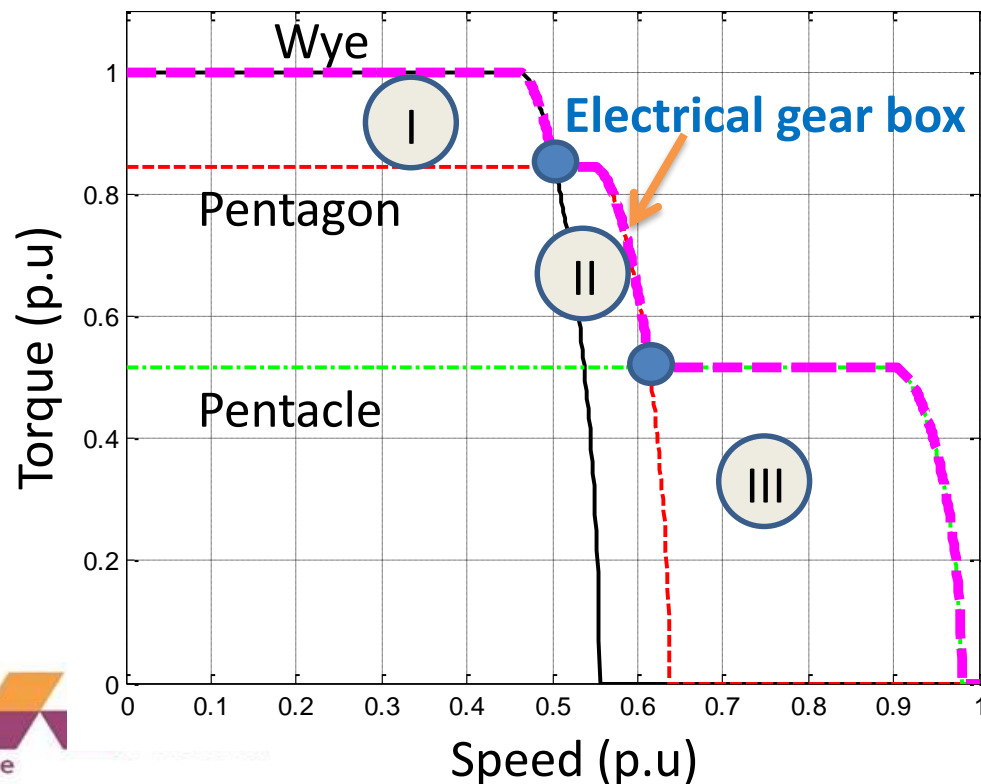
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$$|V_a| = V_m$$

$$|V_a| = 1,2 * V_m$$

$$|V_a| = 1,9 * V_m$$



**Objective**



**Electrical Gear Box (EGB)**

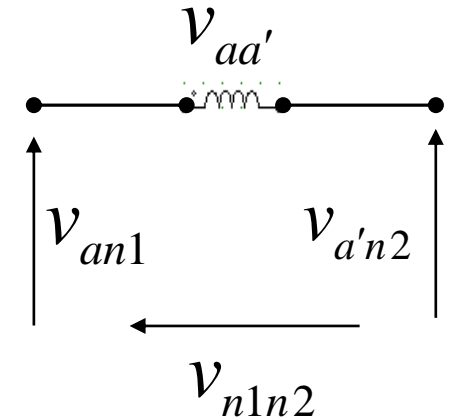
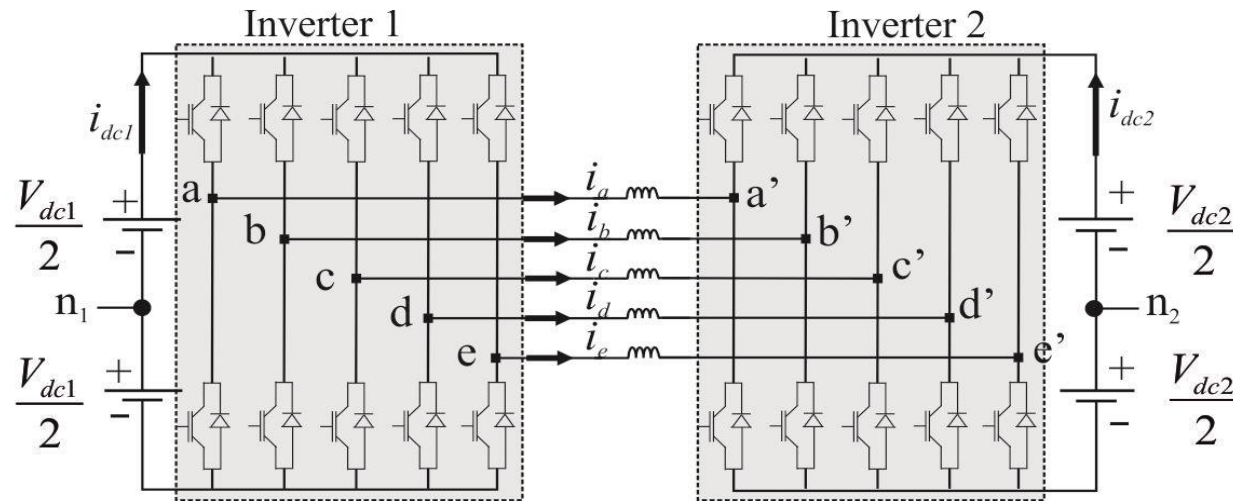
**How we can change these stator configurations by power electronics control ?**



**5-phase open-end winding structure**

## 2. Different Stator Winding Connections

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

where

$$\mathbf{v}_{abcde} = \begin{bmatrix} v_{aa'} & v_{bb'} & v_{cc'} & v_{dd'} & v_{ee'} \end{bmatrix}^T$$

$$\mathbf{v}_{abcde-INV1} = \begin{bmatrix} v_{an_1} & v_{bn_1} & v_{cn_1} & v_{dn_1} & v_{en_1} \end{bmatrix}^T$$

$$\mathbf{v}_{abcde-INV2} = \begin{bmatrix} v_{a'n_2} & v_{b'n_2} & v_{c'n_2} & v_{d'n_2} & v_{e'n_2} \end{bmatrix}^T$$

$$\mathbf{v}_{abcde-n_1n_2} = \begin{bmatrix} v_{n_1n_2} & v_{n_1n_2} & v_{n_1n_2} & v_{n_1n_2} & v_{n_1n_2} \end{bmatrix}^T$$

Hypothesis : Sinusoidal and balanced phase voltages:

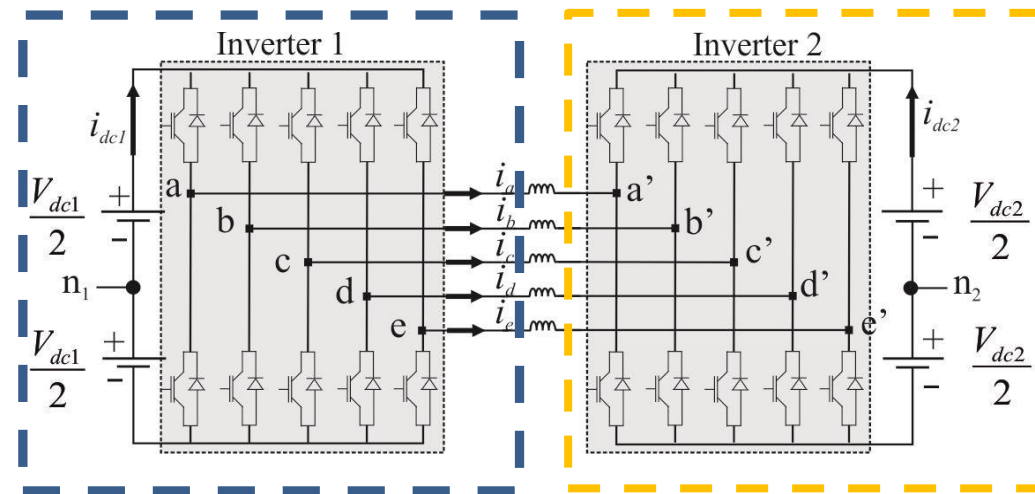
$$\mathbf{v}_{abcde} = \mathbf{A} \cdot \mathbf{v}_{abcde-INV1} - \mathbf{v}_{abcde-INV2}$$

where

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

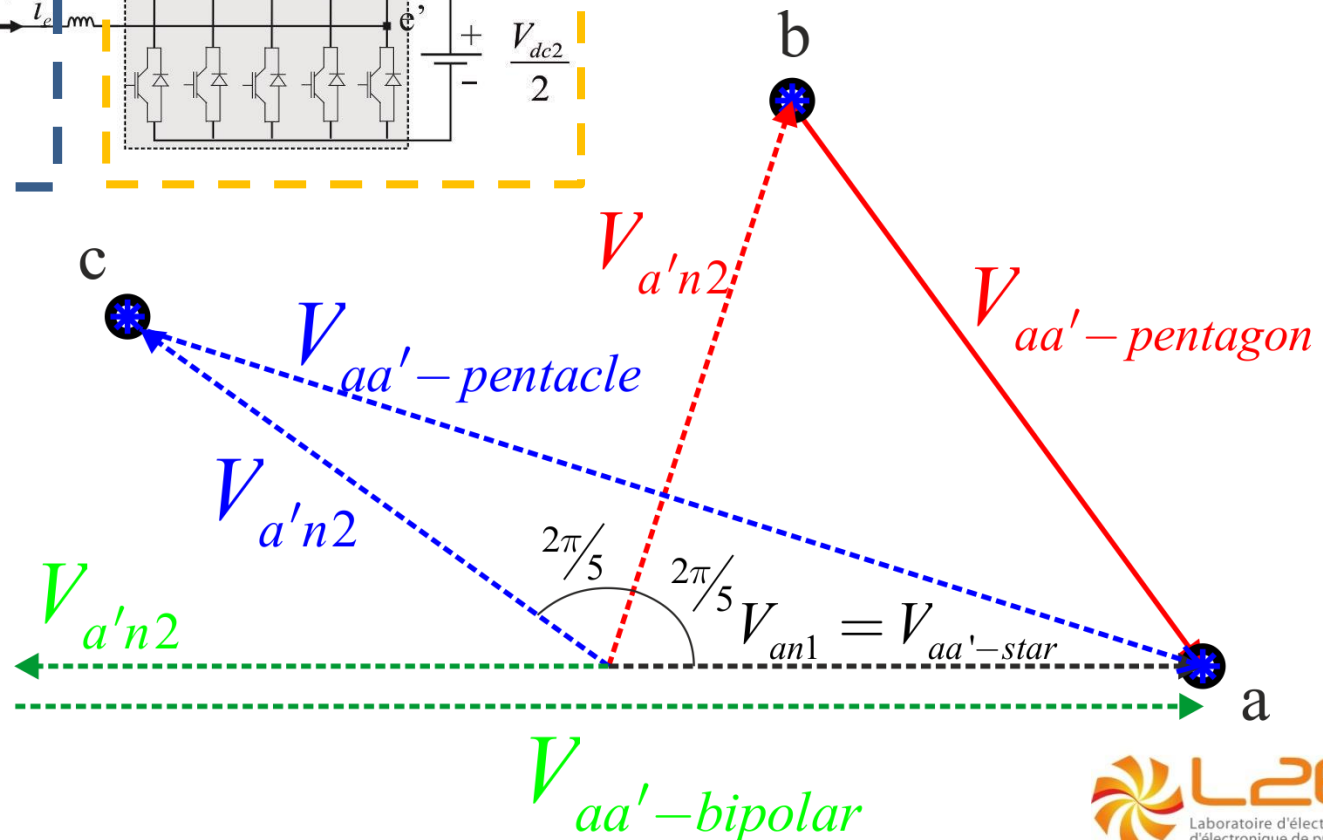
## 2. Different Stator Winding Connections

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

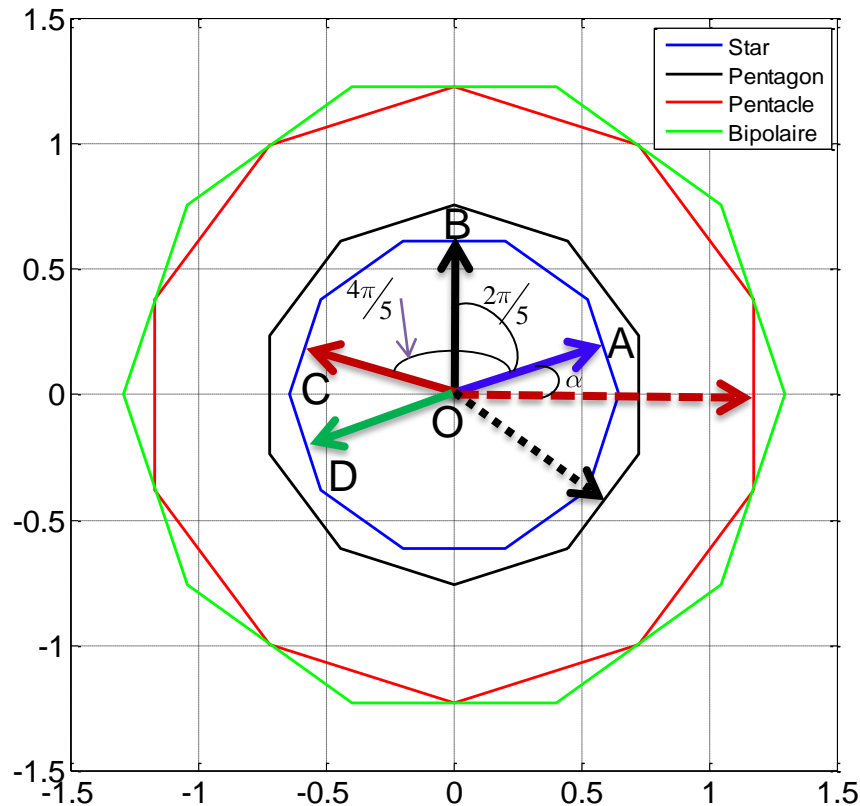
**For phase a:**



## 2. Different Stator Winding Connections

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$\alpha_1 - \beta_1$  frame of voltage



### Wye-Connection

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

### Pentagon Connection:

$$V_{INV-1} = V^* \underline{\alpha} \quad V_{INV-2} = V^* \left[ \alpha + \frac{2\pi}{5} \right]$$

### Pentacle Connection:

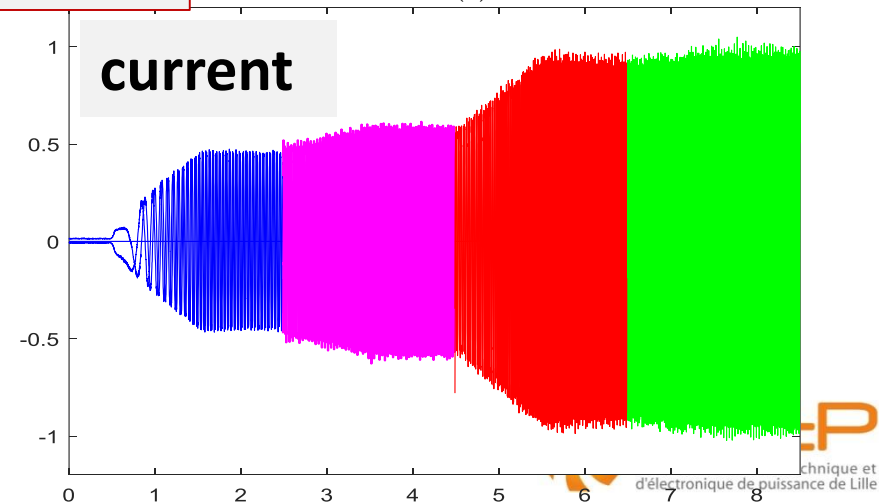
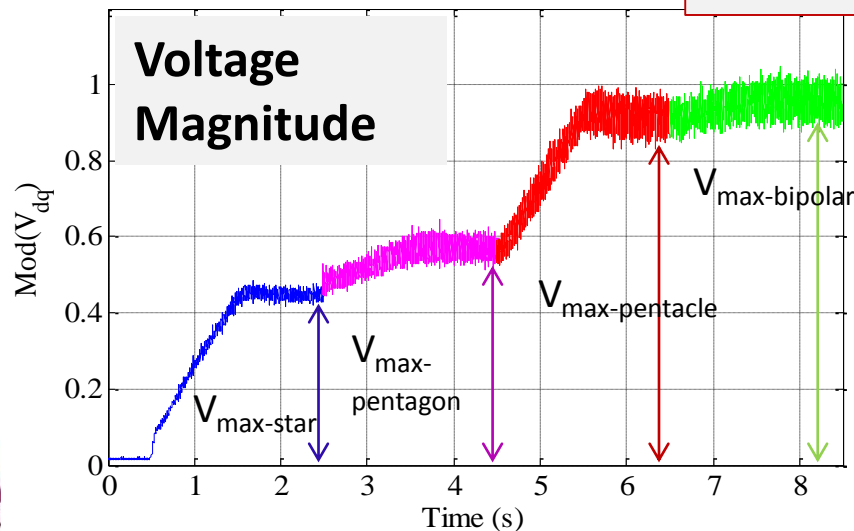
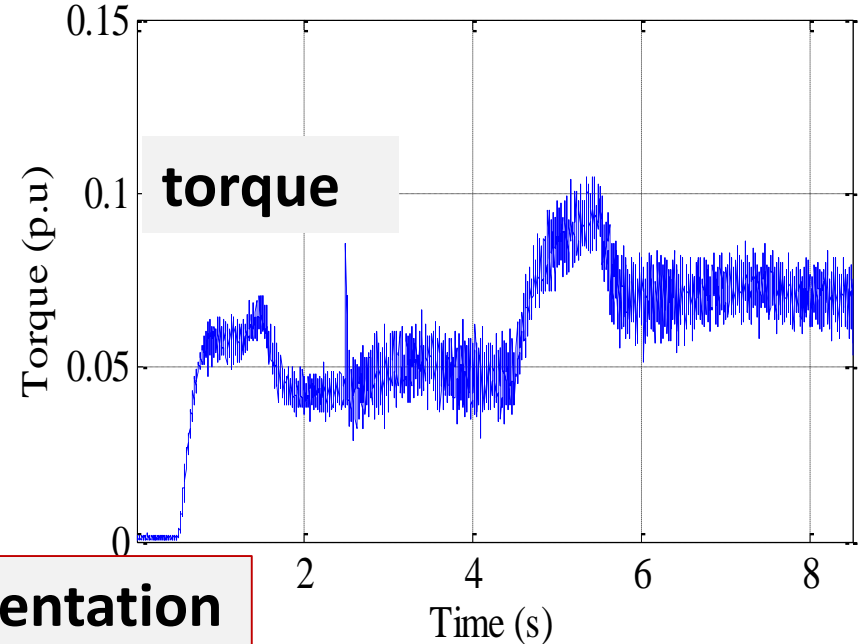
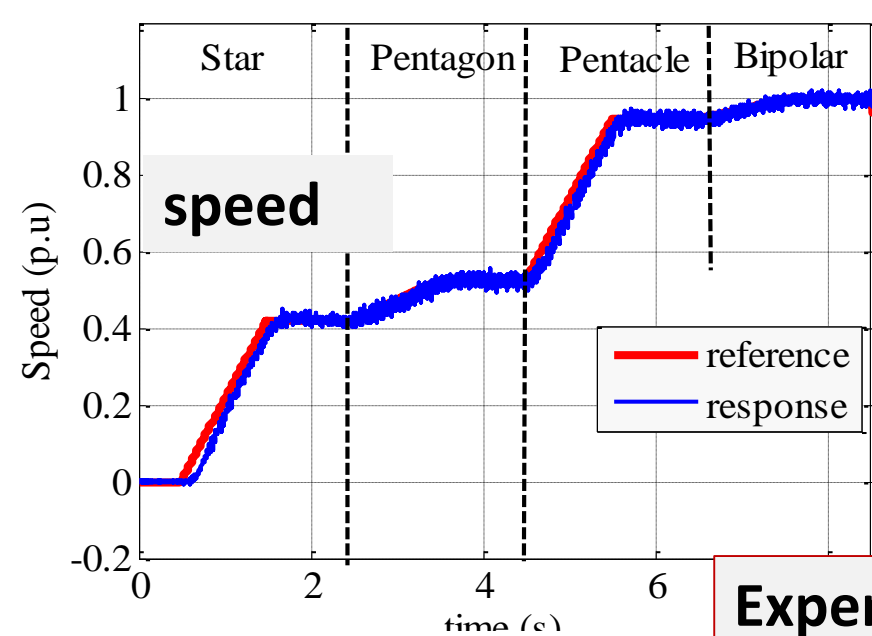
$$V_{INV-1} = V^* \underline{\alpha} \quad V_{INV-2} = V^* \left[ \alpha + \frac{4\pi}{5} \right]$$

### Bipolaire Connection :

$$V_{INV-1} = V^* \underline{\alpha} \quad V_{INV-2} = V^* \left[ \alpha + \pi \right]$$

## 2. Different Stator Winding Connections

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# Conclusion

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- ✓ 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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[Ngacky.NGUYEN@ensam.eu](mailto:Ngacky.NGUYEN@ensam.eu)

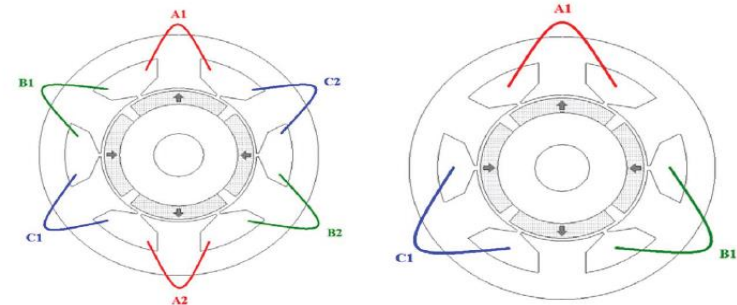


## II. Bi-harmonic machine Design: Stator

**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  $S_{pp} = 0,5$  slot per pole and per phase.: Low MMF harmonic content, Less undesired 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 especially at high frequencies → Demagnetization of magnets is possible.

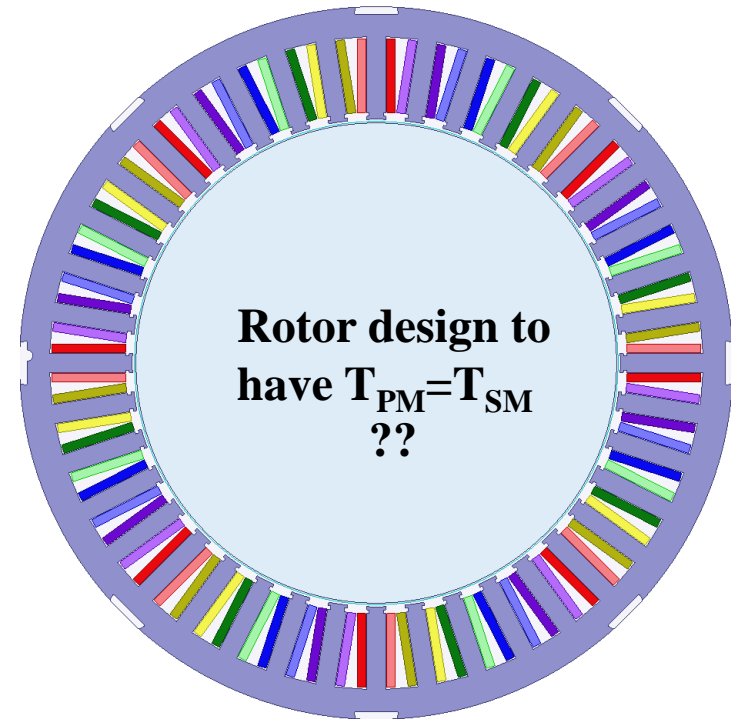
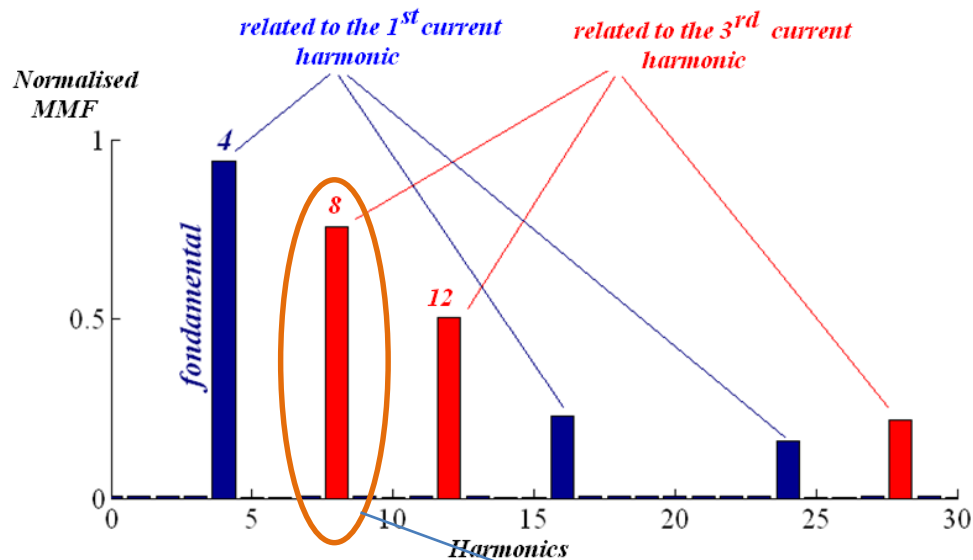


**3-Phase  
12 slots / 8  
poles 2010  
TOYOTA  
Prius  
Generator**

# 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 1<sup>st</sup> harmonic)



- Weak 1<sup>st</sup> harmonic winding factor  $(\xi_w)_1 = 0.588$

- High 3<sup>rd</sup> harmonic winding factor  $(\xi_w)_3 = 0.95$

**Possible Weak points:**

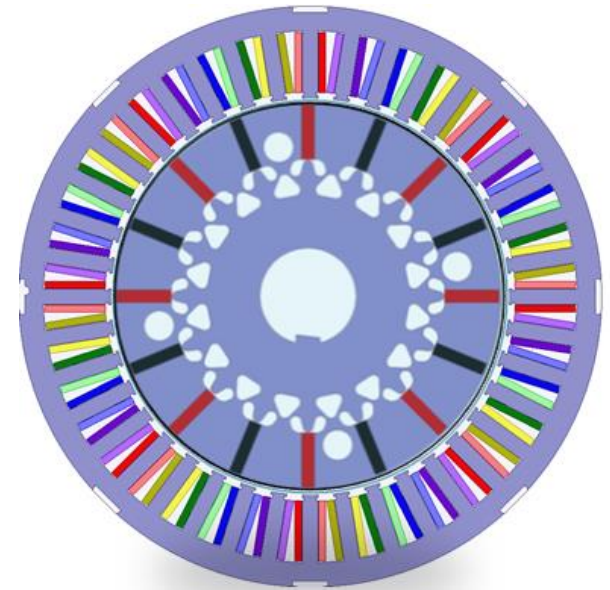
- small winding factor of first harmonic.
- one subharmonic (8) when supplied with 3 harmonic.

## II. Bi-harmonic machine Design: Rotor

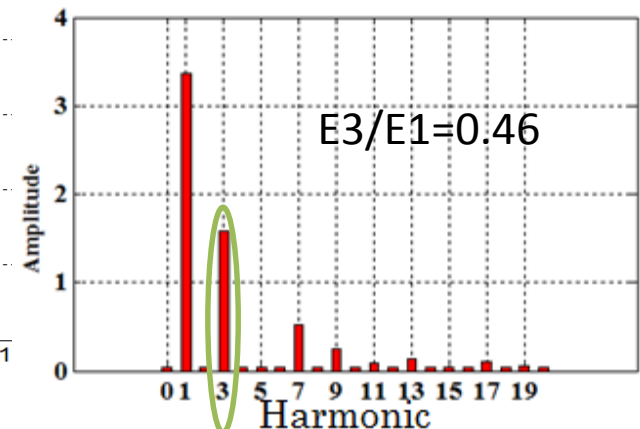
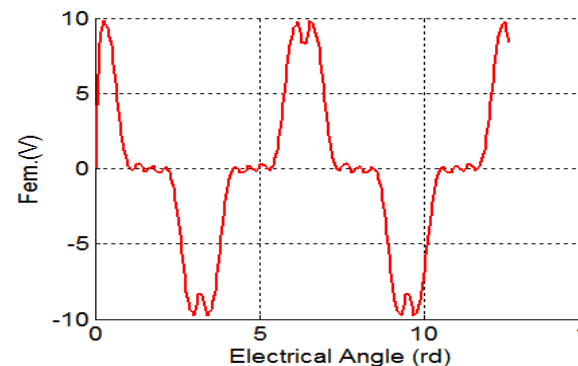
**Structure with interior magnets is used.**

### 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

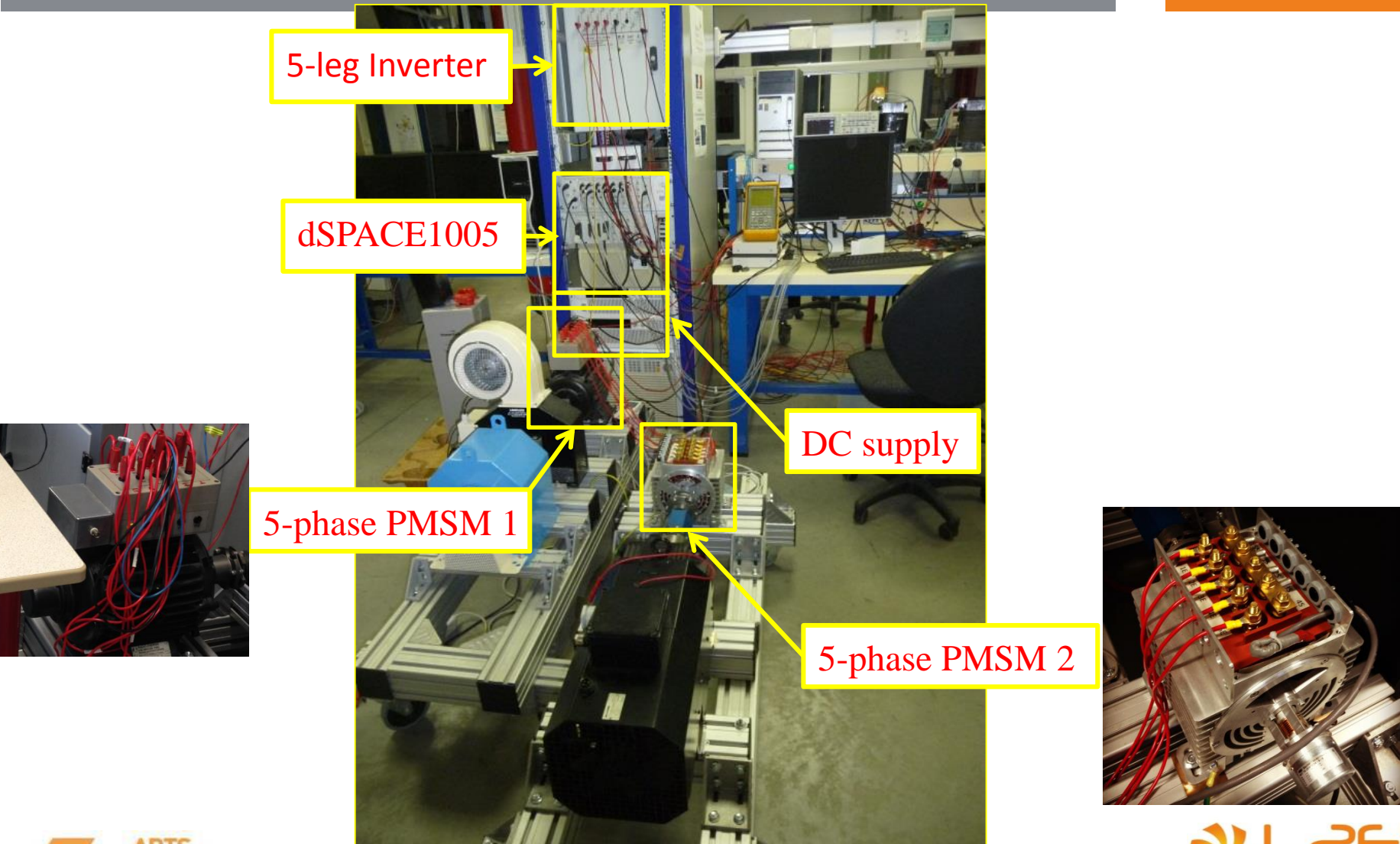
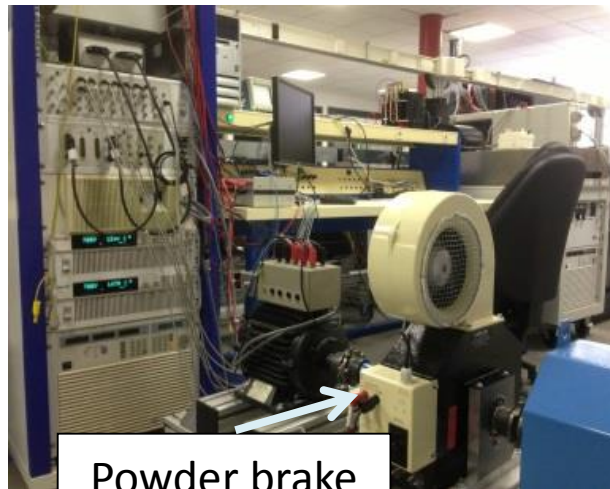


Fig. 1. Laboratory experimental test-bench

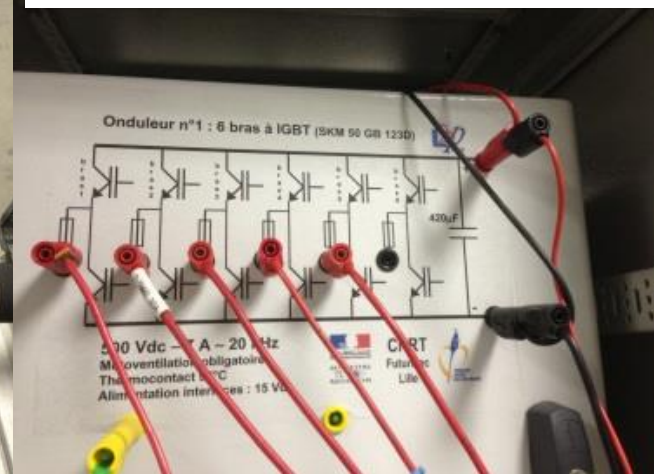
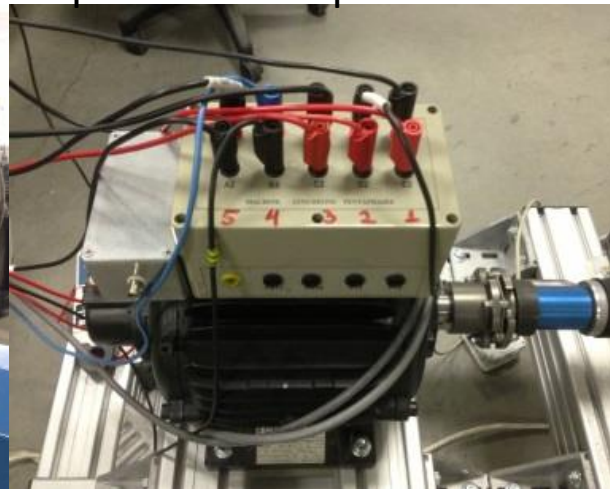
dSPACE and 2 DC sources

Open-end five-phase machine

Five-bridge inverter (one side)



Powder brake



Laboratory experimental platform setup

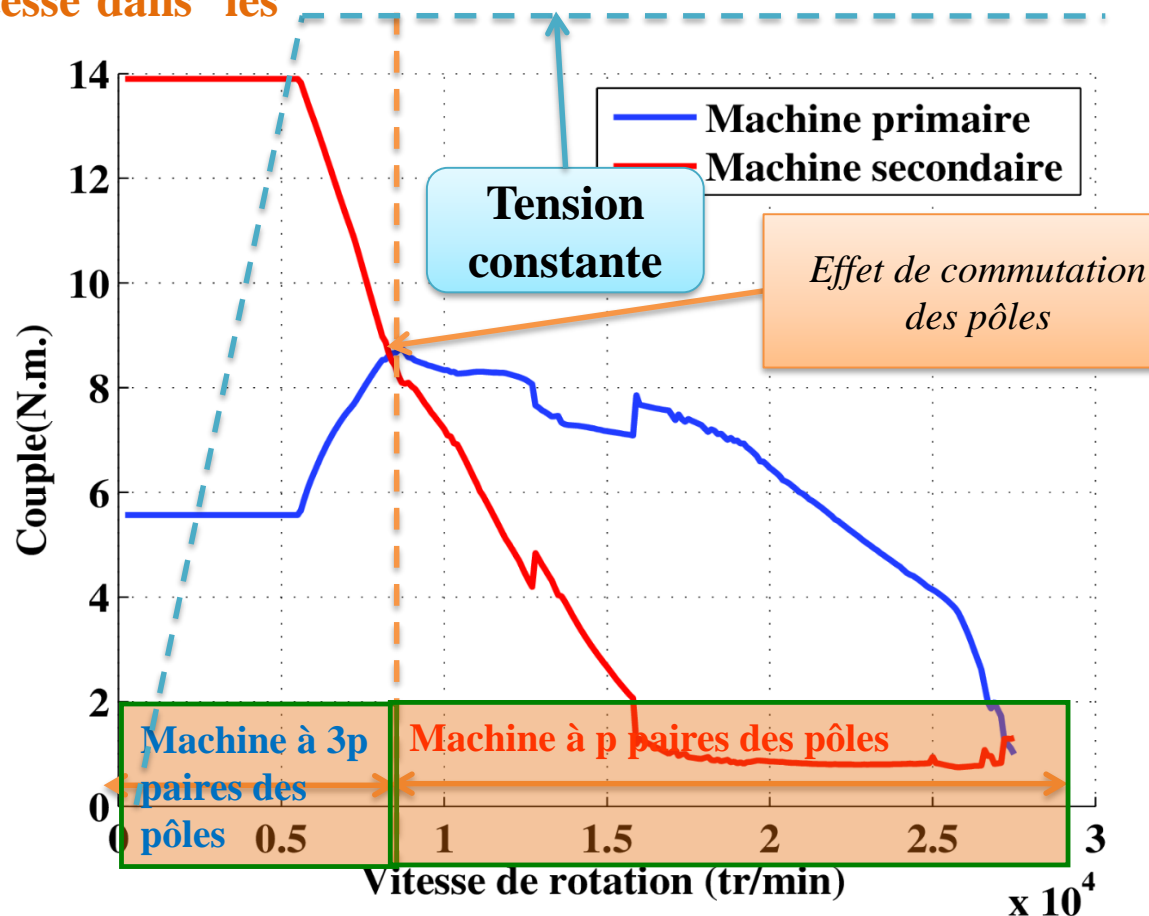
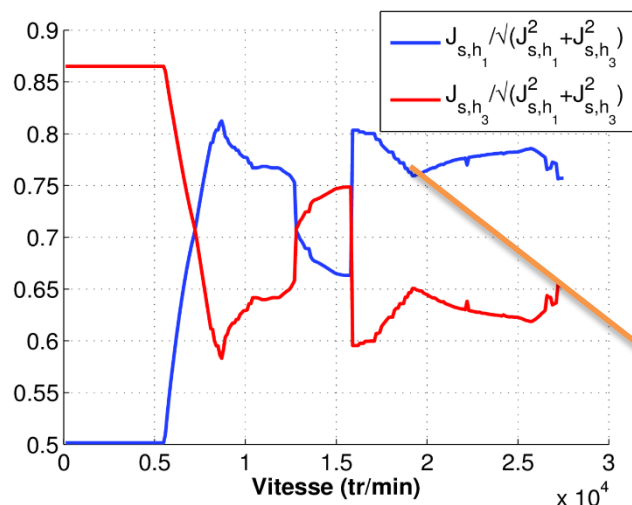
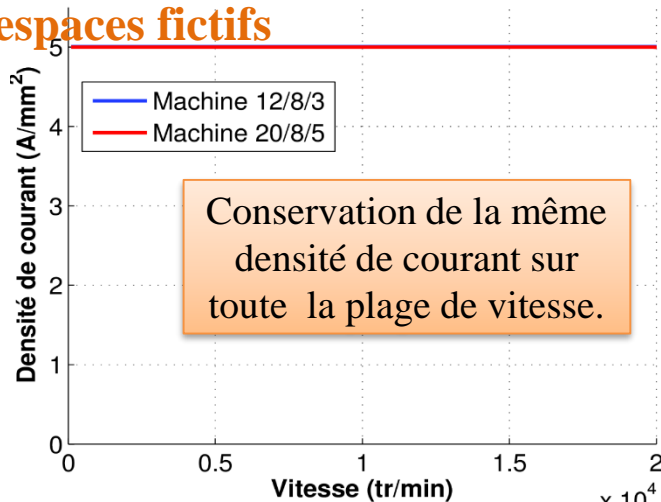
## 5-phase machine parameters

Phase resistance:  $R=2.24 \Omega$ Inductance :  $L_{1d}=3.2 \text{ mH}$ Inductance  $L_{1q}=3.2 \text{ mH}$ Inductance  $L_{3d}=0.9 \text{ mH}$ Inductance  $L_{3q}=0.9 \text{ mH}$ 

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

Maximum torque  $T_{em-max} = 20 \text{ N.m}$ Maximum speed  $\Omega_{max} = 2500 \text{ rpm}$ Bus voltage  $V_{bus}=70 \text{ V}$ Maximum phase current  $I_{max}=15 \text{ A}$

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



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

# Multiphase Decomposition Theory

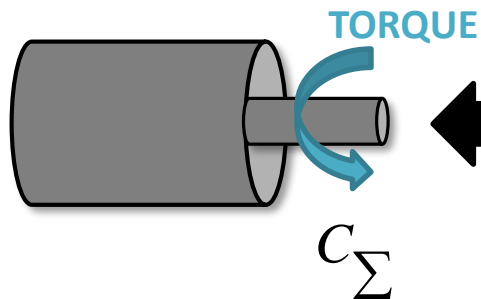
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## 5-phase PMSM

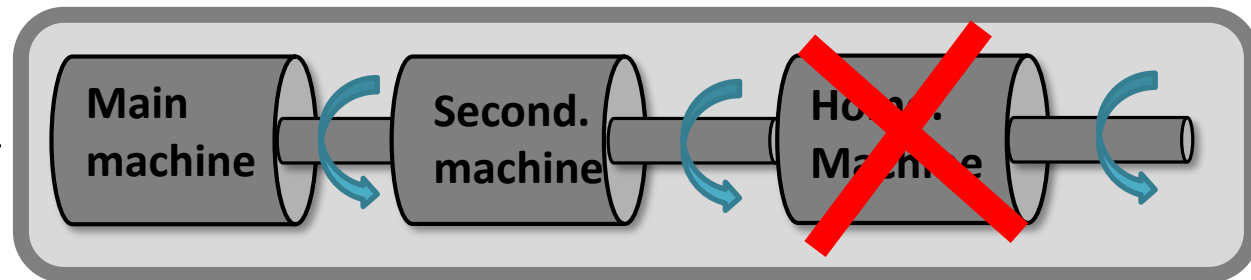
MM : 1st harmonic  
SM : 3th harmonic

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

Real 5-phase machine



Fictitious Machines (2 diphas + 1 homopolar)

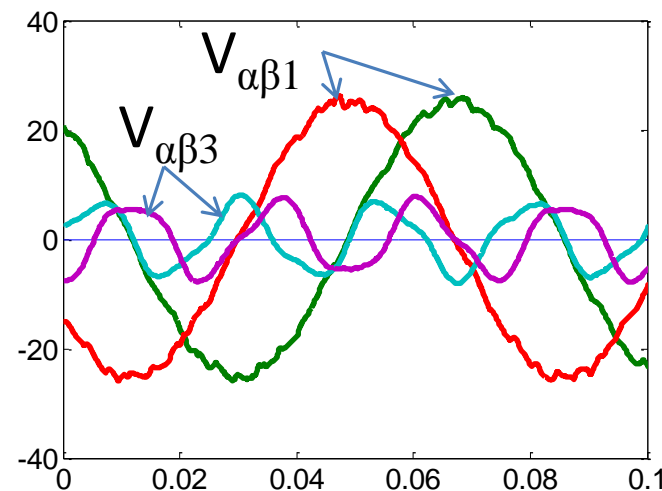
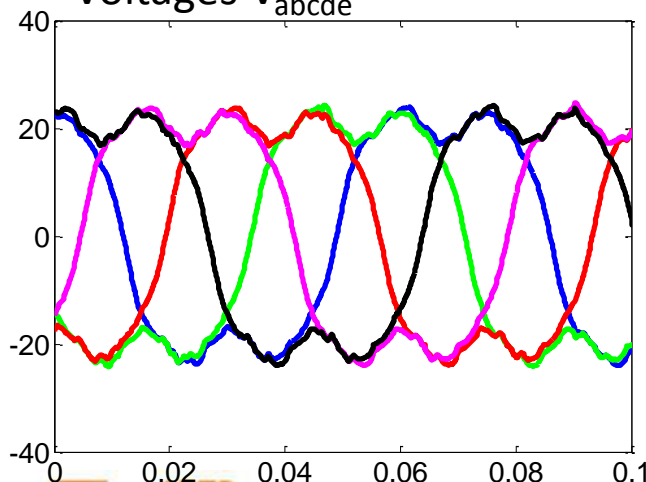


$h = \textcircled{1}, 9, 11, \dots$   
 $h = 5k \pm 1$

$h = \textcircled{3}, 7, \dots$   
 $h = 5k \pm 2$

$h = 5, 15, \dots$   
 $h = 5k$

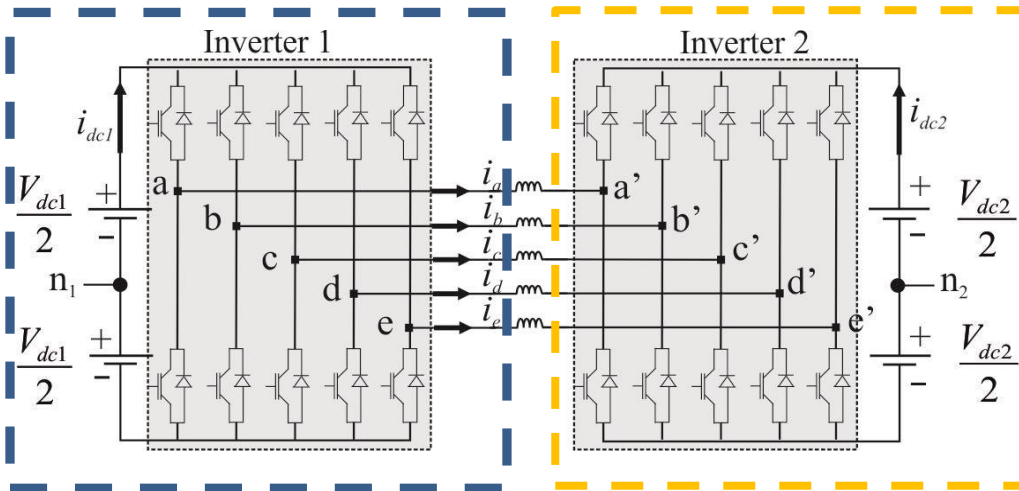
Voltages  $V_{abcde}$



Voltages in decoupled base

## 2. Different Stator Winding Connections

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For all configurations,  
the **1<sup>st</sup> Inverter** is  
controlled as :

$$\mathbf{v}_{abcde-INV1} = \begin{bmatrix} v_{an_1} & v_{bn_1} & v_{cn_1} & v_{dn_1} & v_{en_1} \end{bmatrix}^T$$

$$= V \begin{bmatrix} \sin \theta & \dots & \sin \left( \theta - \frac{8\pi}{5} \right) \end{bmatrix}^T$$

For **the 2<sup>nd</sup> Inverter**:

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

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

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

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

**SIMPLE**