

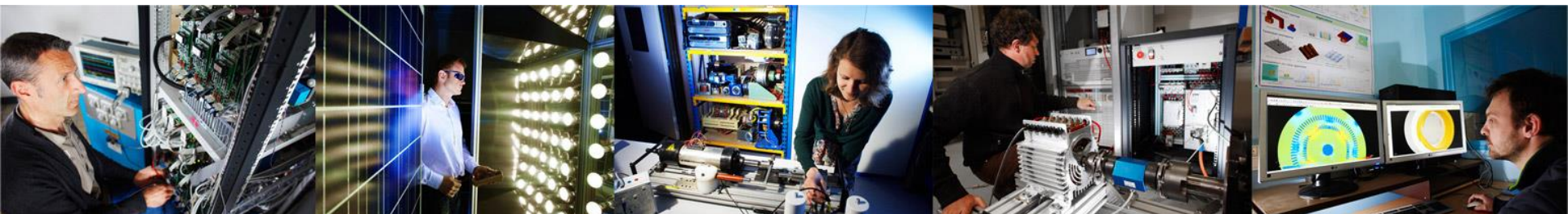
2018 IEEE 2nd International Electrical and Energy Conference (CIEEC)

# Different Possibilities of Multiphase Drives Functioning in Constant Power Region

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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

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

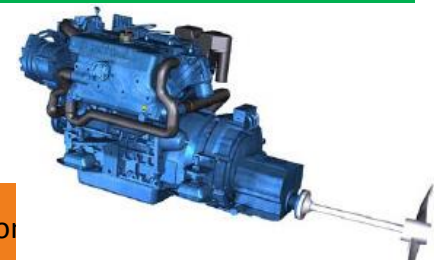
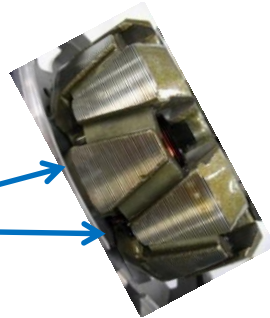
rotor with **PM**

Stator with tooth concentrated winding

Number of phases > 3

- Dahlander circuit
- Winding configuration
- Saliency ratio

Electronic pole commutation



# Introduction & Context

4

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

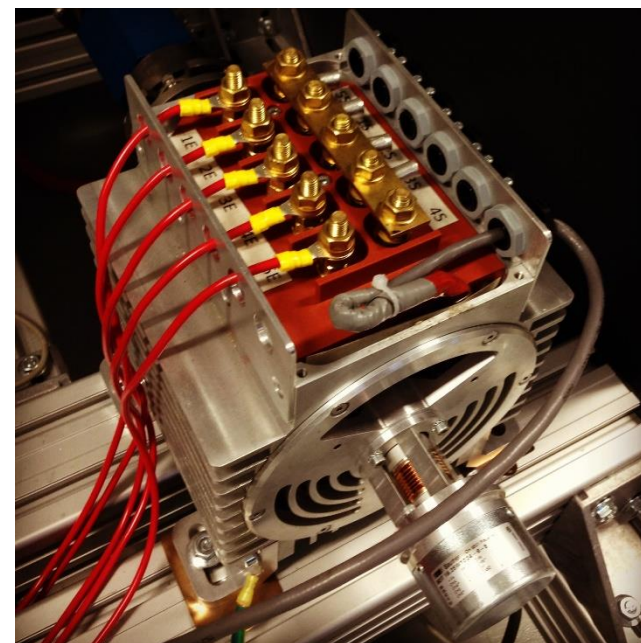
➤ **Acceptable current/phase** for low voltage high power (48V/15kW):

- ✓ **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

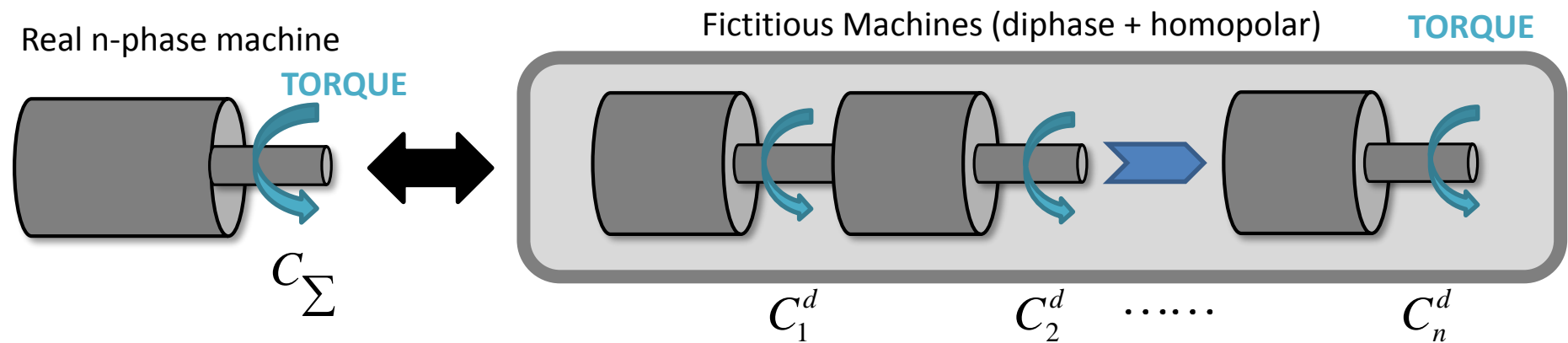
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# Multiphase Decomposition Theory

## GENERALIZED VECTORIAL FORMALISM THEORY

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

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



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



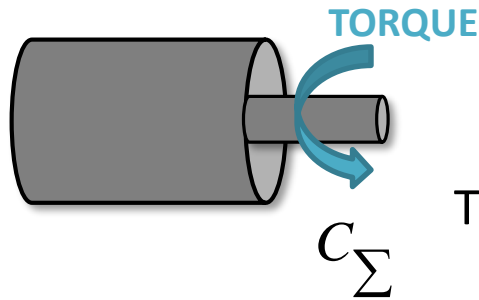
Fictitious machines

Leads to

# Multiphase Decomposition Theory

## 3-phase PMSM

Real 3-phase machine

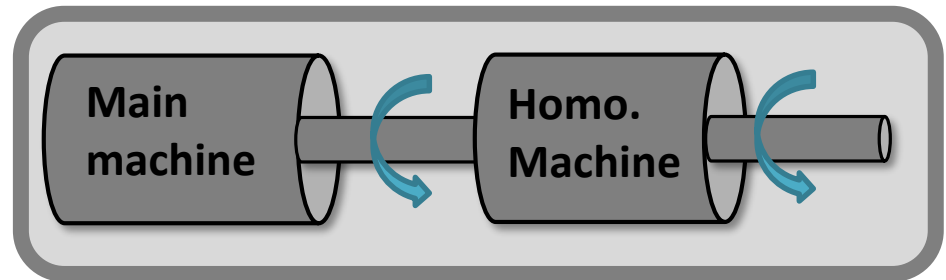


Transformation  
(Concordia,  
Clarke, etc.)

Fictitious Machines (1 diphase + 1 homopolar)

**MM**

**HM**



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

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

$h$  : odd harmonic rank

(even harmonics are ignored)

Main machine (MM) : diphase ( $\Lambda_1 = \Lambda_2$ )

Homo. Machine: monophasé ( $\Lambda_0$ )

$\Lambda_i$  Eigenvalues  
of inductance matrix

### 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))

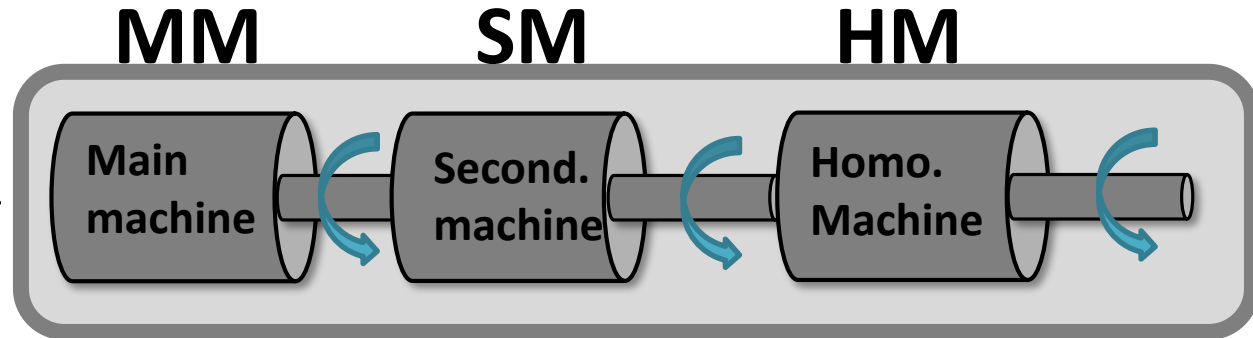
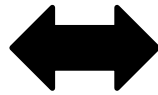
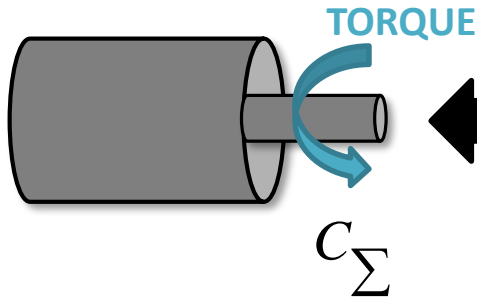


# Multiphase Decomposition Theory

## 5-phase PMSM

Fictitious Machines (2 diphase + 1 homopolar)

Real 5-phase machine



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

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

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

$h$  : harmonic rank of the back-EMF

+ : direct rotating vector

- : inverse rotating vector

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

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

**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  $\rightarrow$  **Interesting point**



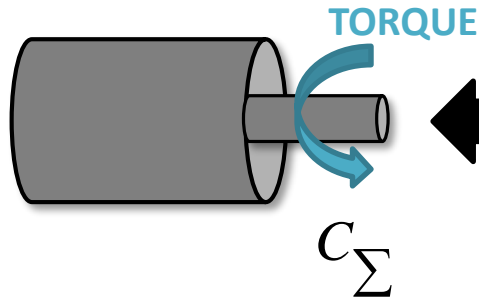
# Multiphase Decomposition Theory

## 5-phase PMSM

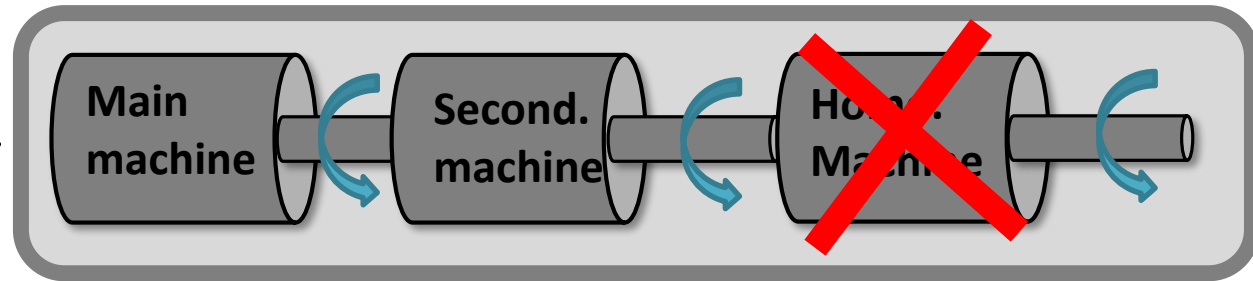
MM : 1st harmonic  
SM : 3th harmonic

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

Real 5-phase machine



Fictitious Machines (2 diphase + 1 homopolar)



$h = 1, 9, 11, \dots$

$p$  pairs of poles

$h = 3, 7, \dots$

$3p$  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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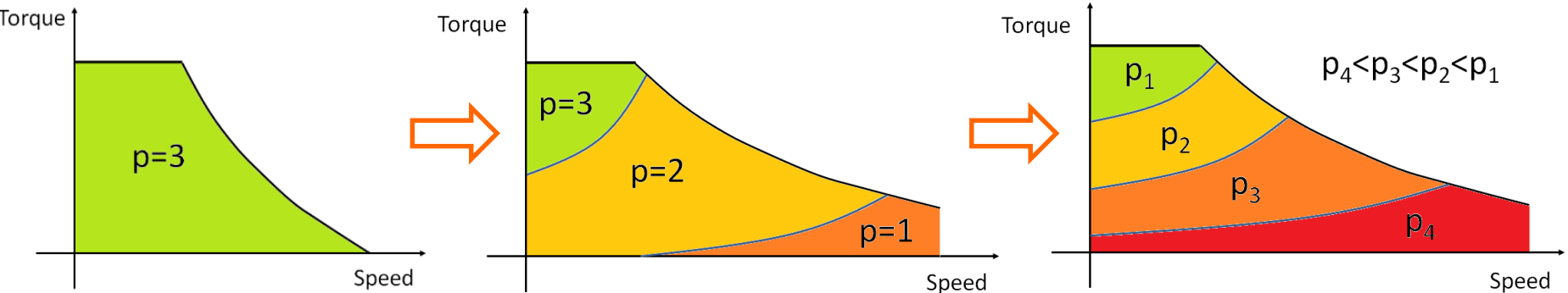
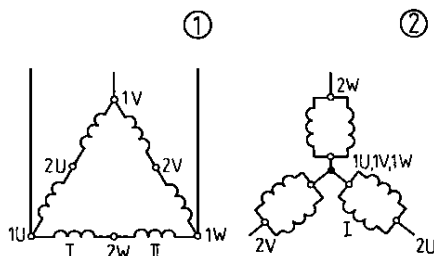
# 1. Pole Changing

**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*

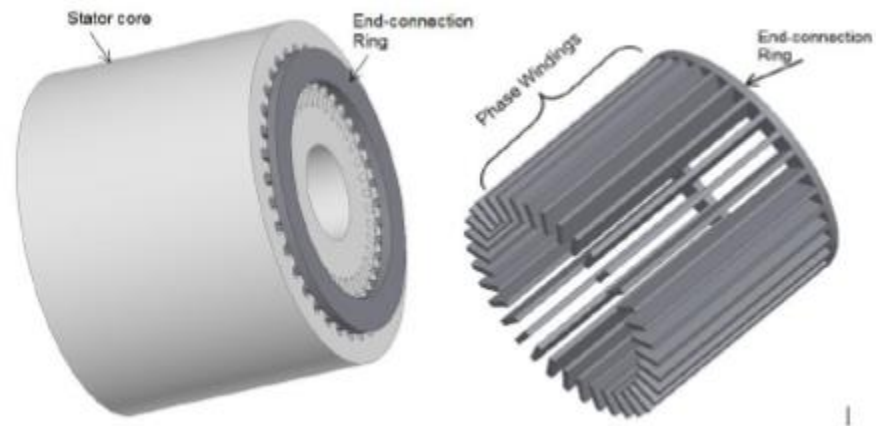
[1] G. Dajaku, F. Bachheibl, A. Patzak, and D. Gerling, "Intelligent stator cage winding for automotive traction electric machines," EVS28 International Electric Vehicle Symposium and Exhibition, Korea, 5/2015.

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

# 1. Pole Changing

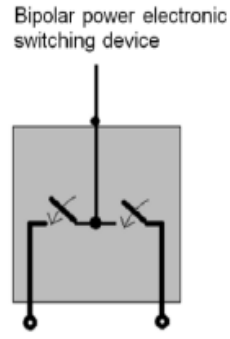
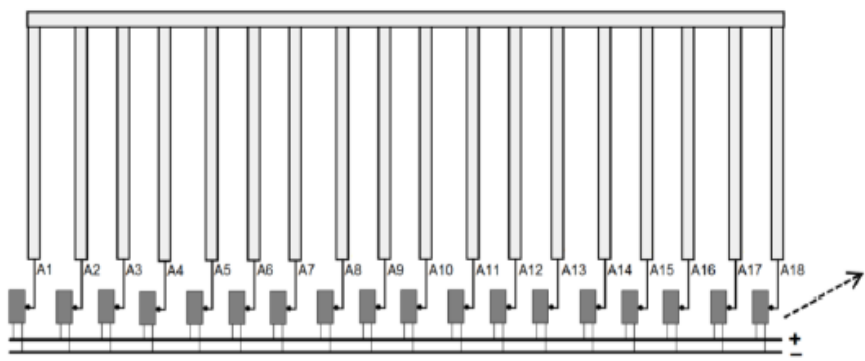
## ISCAD : Intelligent Stator Cage Drive

Stator cage winding

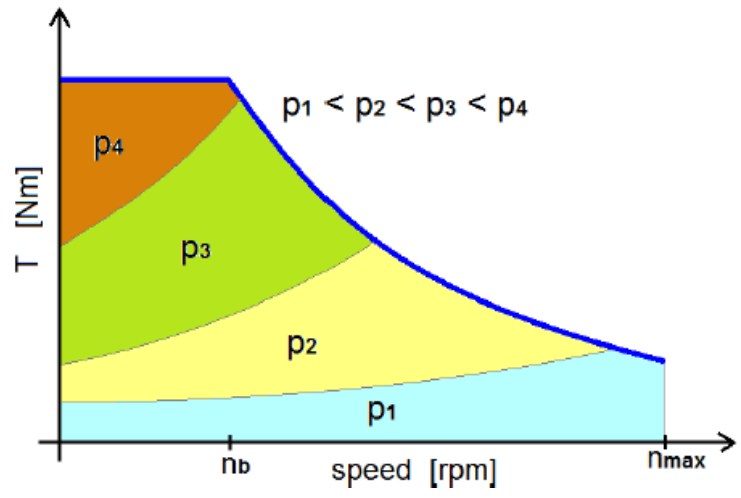


- Intelligent Stator → Each slot is one phase
- Modification (by controlling 60 legs) of Slot/pole according to operating points for maximizing the efficiency
- High fault-tolerant capability
- Double-polarity possibility to increase the performance

The m-phase stator winding supplied with multiphase inverter



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

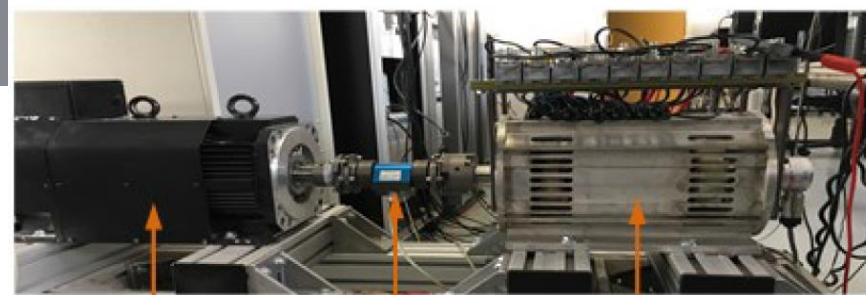
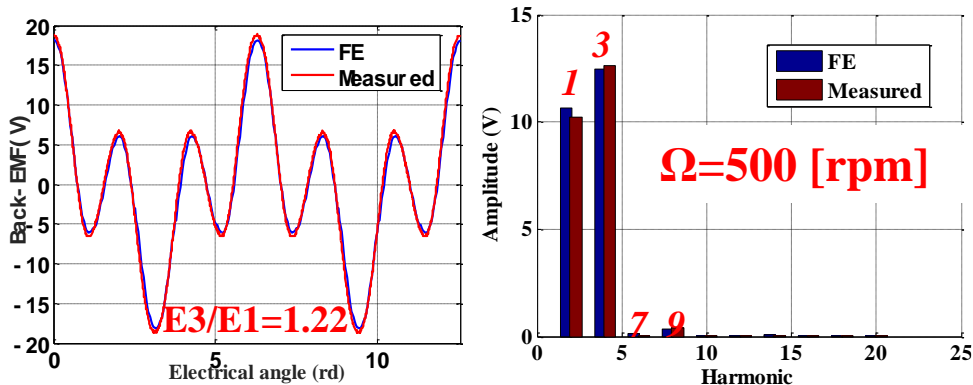


[1] G. Dajaku, F. Bachheibl, A. Patzak, and D. Gerling, "Intelligent stator cage winding for automotive traction electric machines," EVS28 International Electric Vehicle Symposium and Exhibition, Korea, 5/2015.

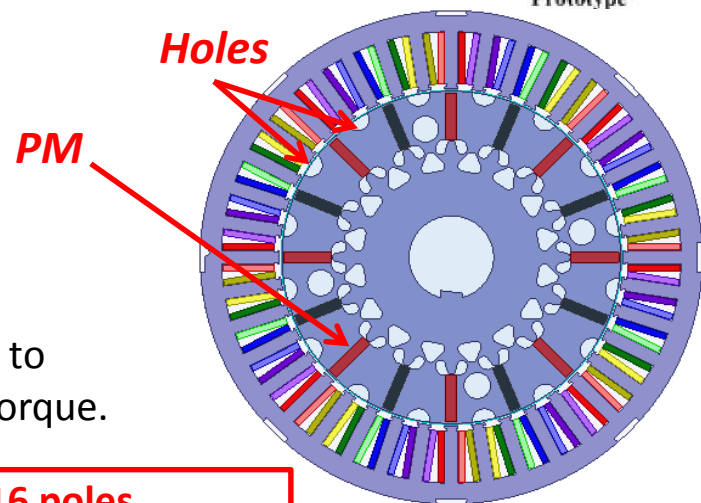
# 1. Pole Changing

## Structure with interior magnets

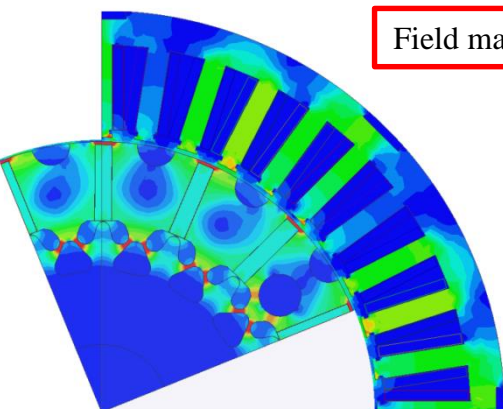
- Redistribution of flux between 1<sup>st</sup> & 3<sup>rd</sup> harmonic
- Introducing holes between poles



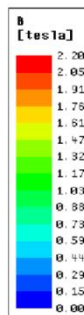
Load 3-Φ PMSM      Torque sensor      5-Φ bi-harmonic PMSM Prototype



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.



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



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

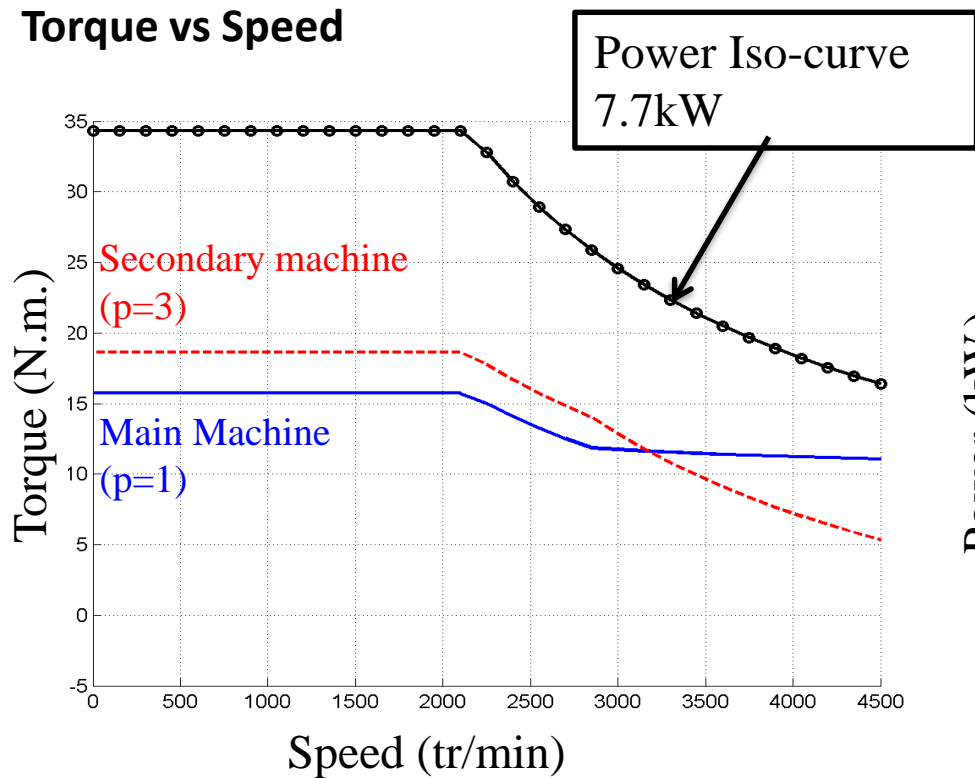
[3] H. Zahr, J. Gong, E. Semail and F. Scullier, "Comparison of Optimized Control Strategies of a High-Speed Traction Machine with Five Phases and Bi-harmonic Electromotive Force," *Energies* 2016, Vol. 9, No. 12, pp. 1-19.

[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

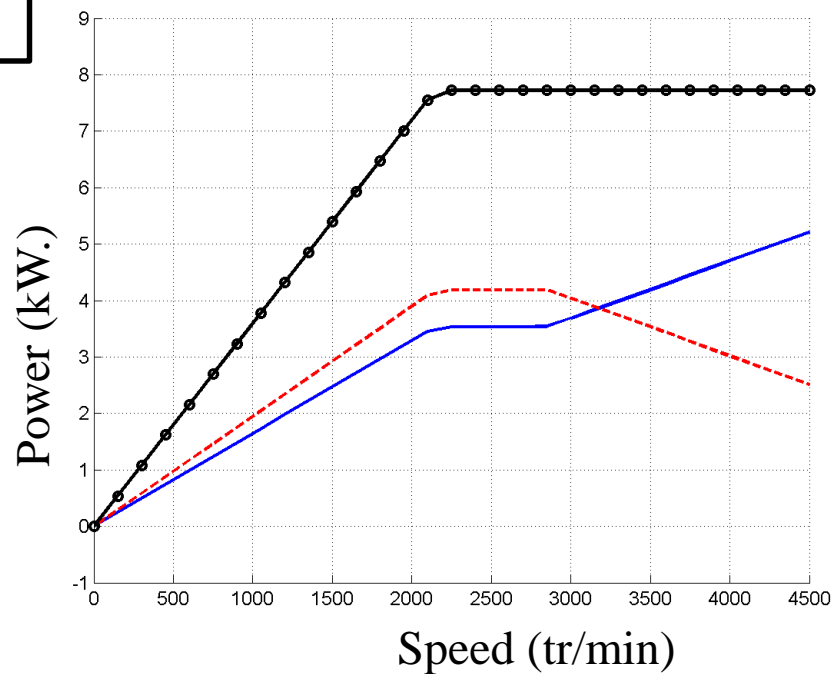
# 1. Pole Changing

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

**Torque vs Speed**



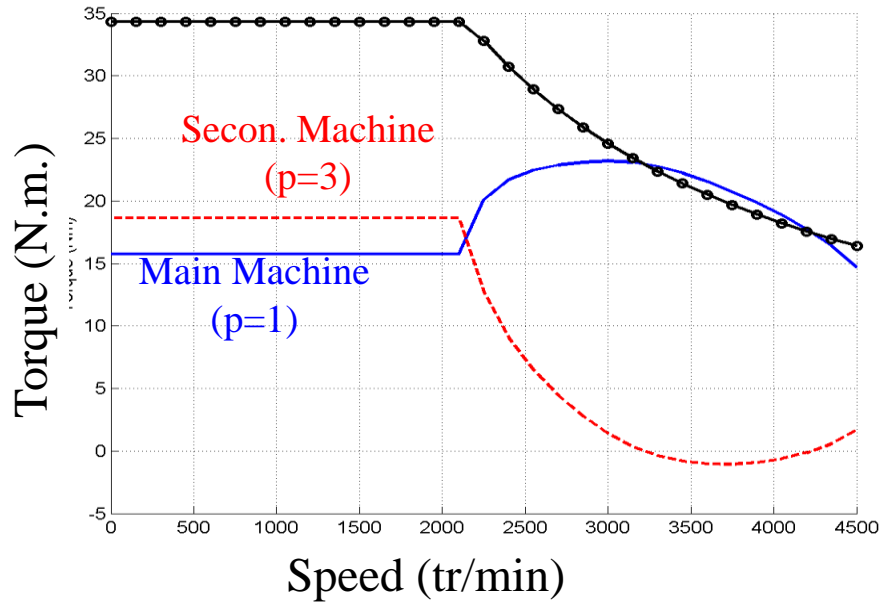
**Power vs Speed**



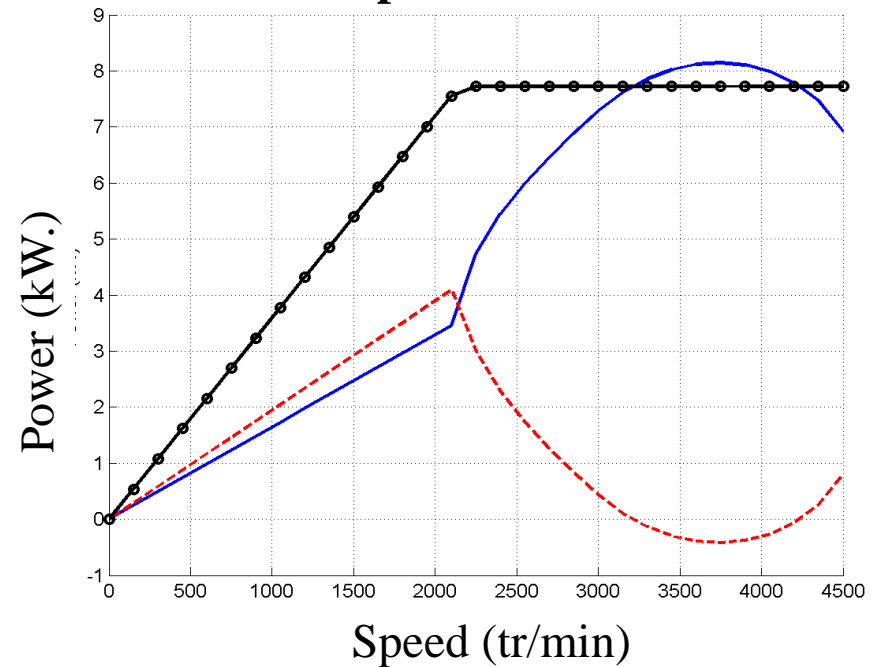
# 1. Pole Changing

## 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**

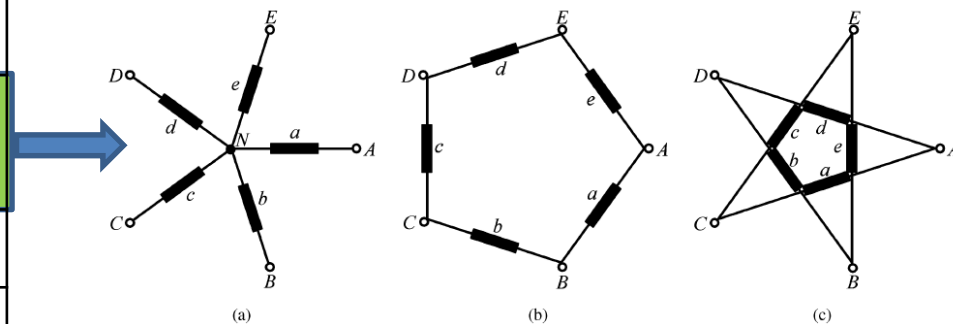
Functioning at **high speed** is very **different** with **three-phase** drives since there are **more degrees of freedom**



# 2. Different Stator Winding Connections

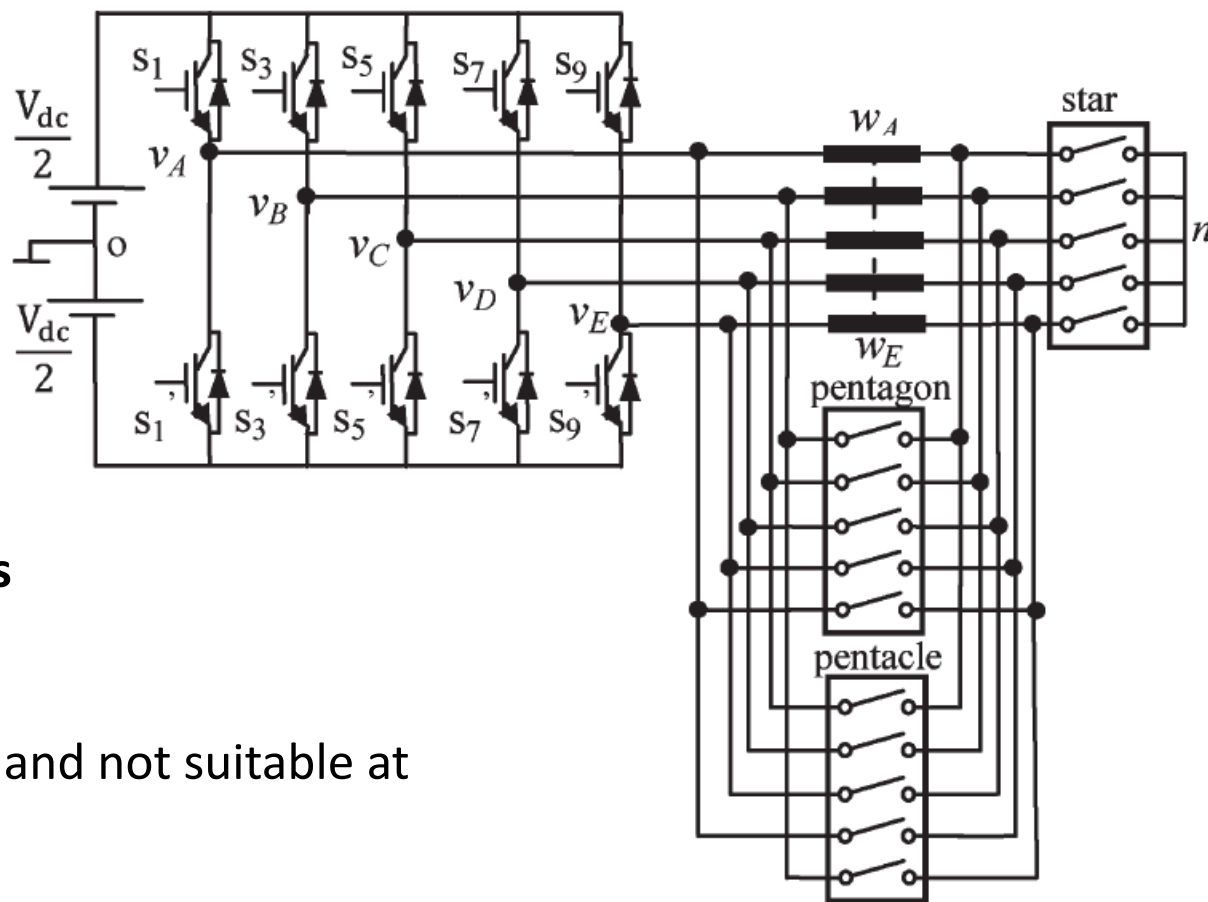
N-phase machine  $\longrightarrow$   $(N+1)/2$  configurations

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

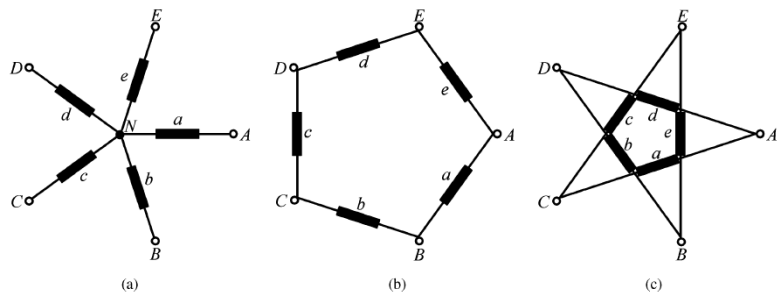


### Magnetic Contactors

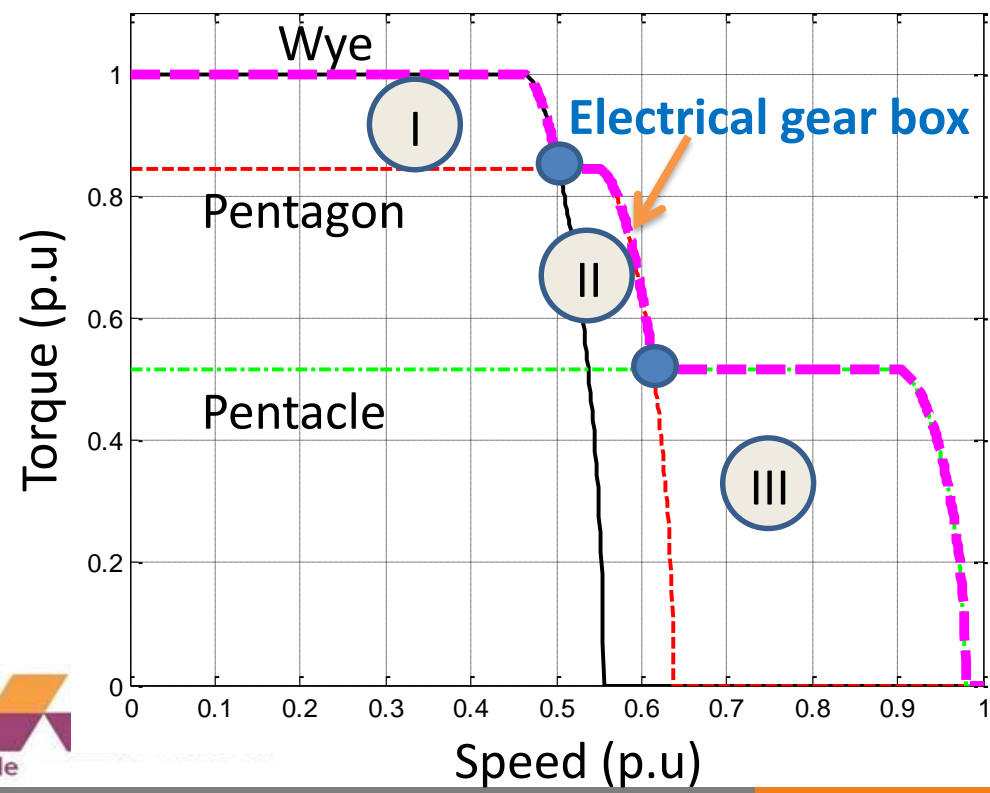
- Time delay
- Bulky
- “Hard” switching and not suitable at high speed

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



$|V_a| = V_m$      
  $|V_a| = 1,2 * V_m$      
  $|V_a| = 1,9 * V_m$



**Objective**

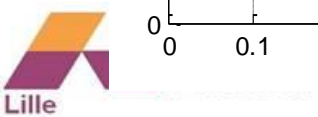


**Electrical Gear Box (EGB)**

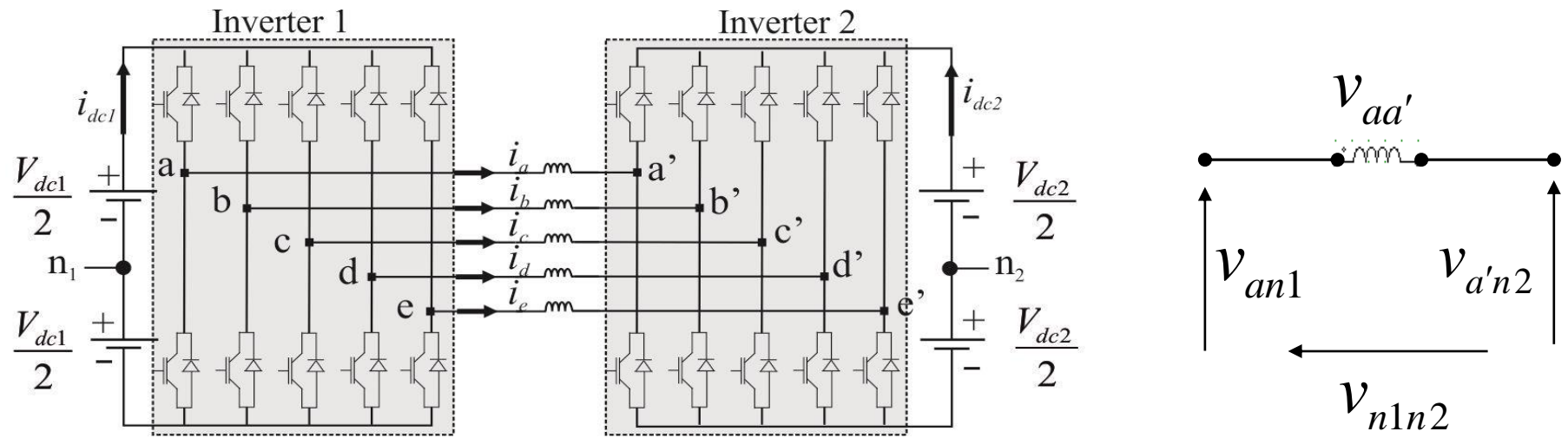
**How we can change these stator configurations by power electronics control ?**



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



# 2. Different Stator Winding Connections



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

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:

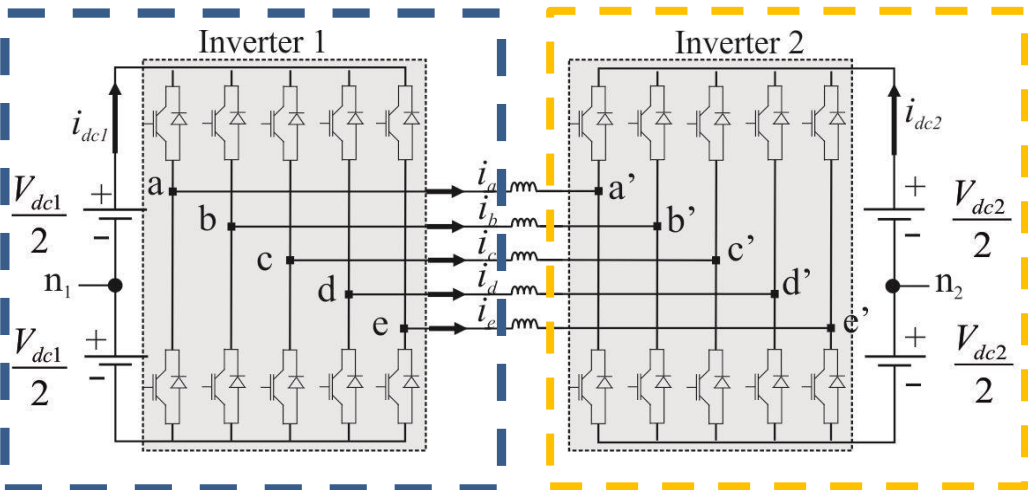
$$\mathbf{v}_{abcde} = \mathbf{A} \cdot \mathbf{v}_{abcde-INV1} - \mathbf{v}_{abcde-INV2}$$

where

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

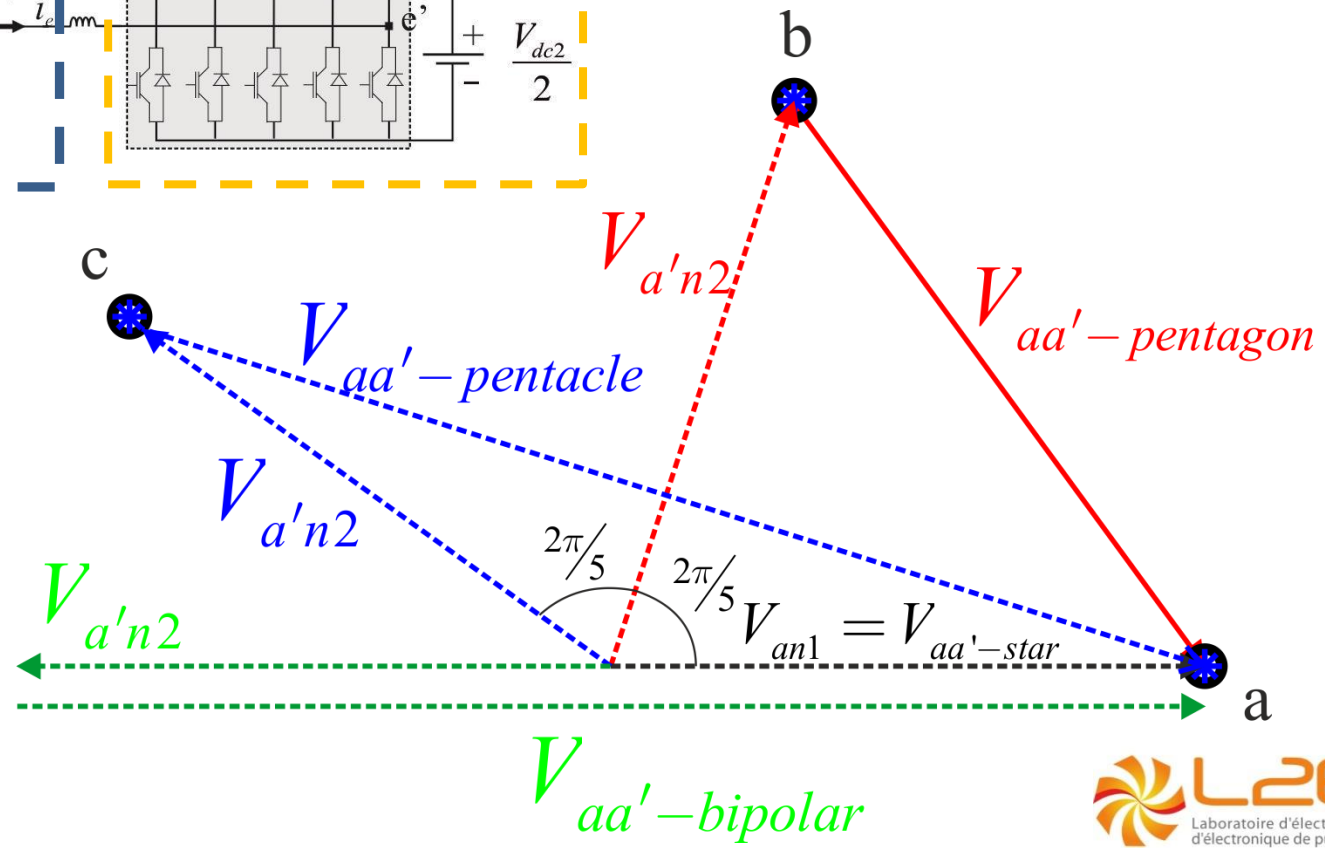


# 2. Different Stator Winding Connections



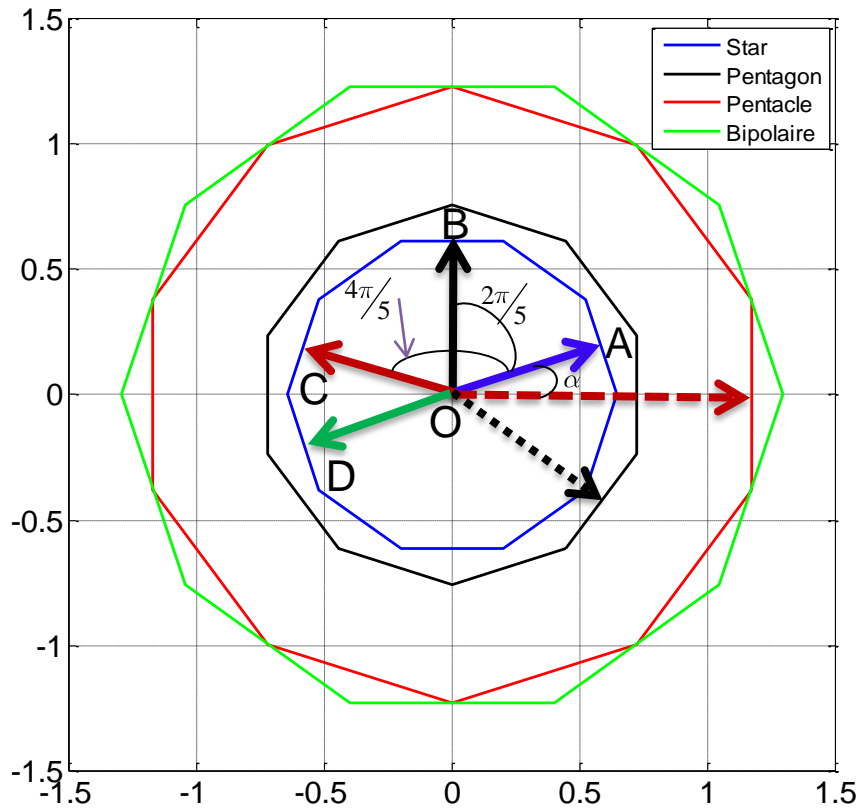
$$\mathbf{v}_{abcde} = \mathbf{A} \cdot \mathbf{v}_{abcde-INV1} - \mathbf{v}_{abcde-INV2}$$

For phase a:



## 2. Different Stator Winding Connections

$\alpha_1 - \beta_1$  frame of voltage



### Wye-Connection

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

### Pentagon Connection:

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

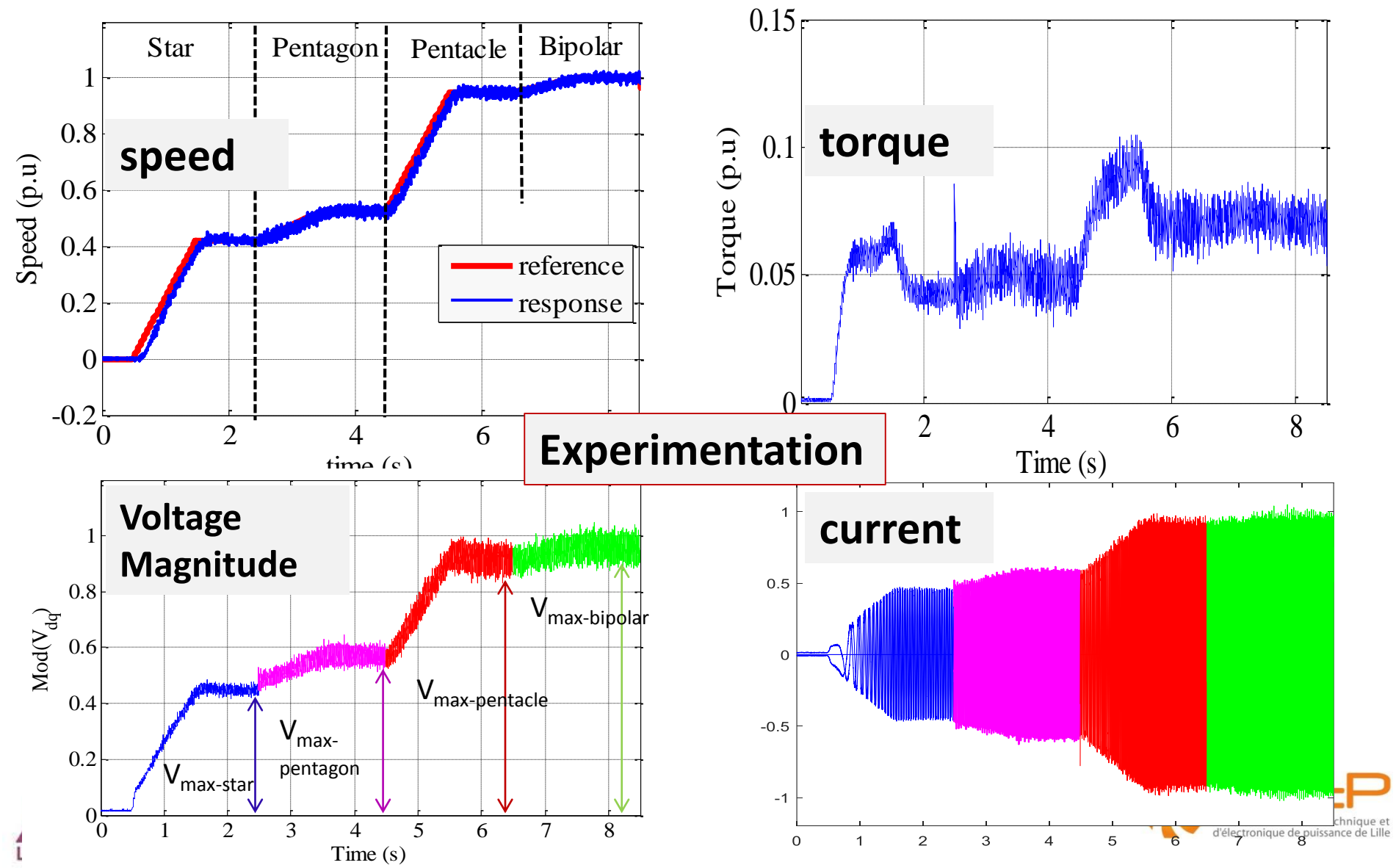
### Pentacle Connection:

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

### 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

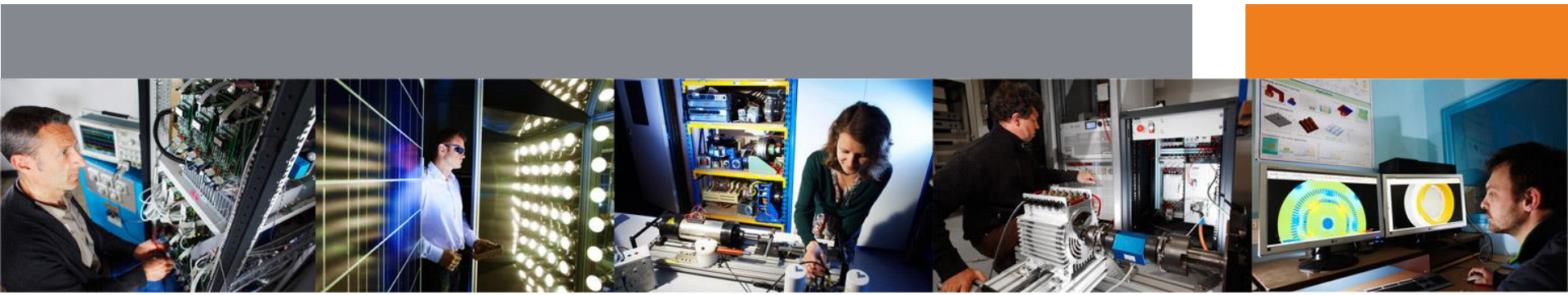
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- ✓ Properties of multiphase machines have been presented
- ✓ Different possibilities of multiphase drives for functioning at high speed
- ✓ Validation

## 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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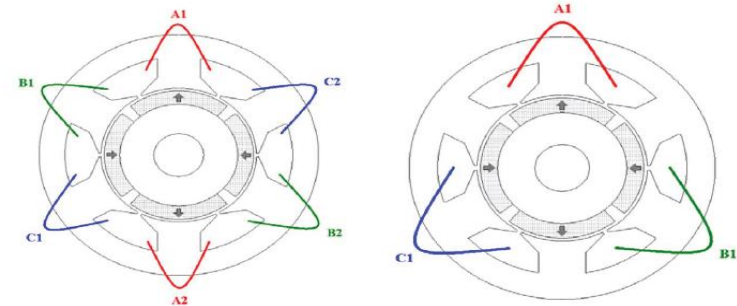


## II. Bi-harmonic machine Design: Stator

**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  
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.

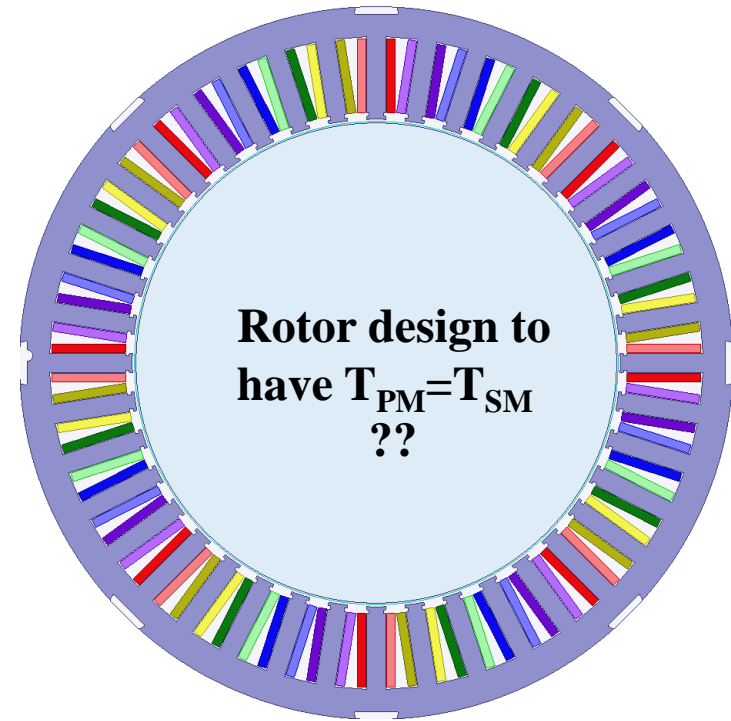
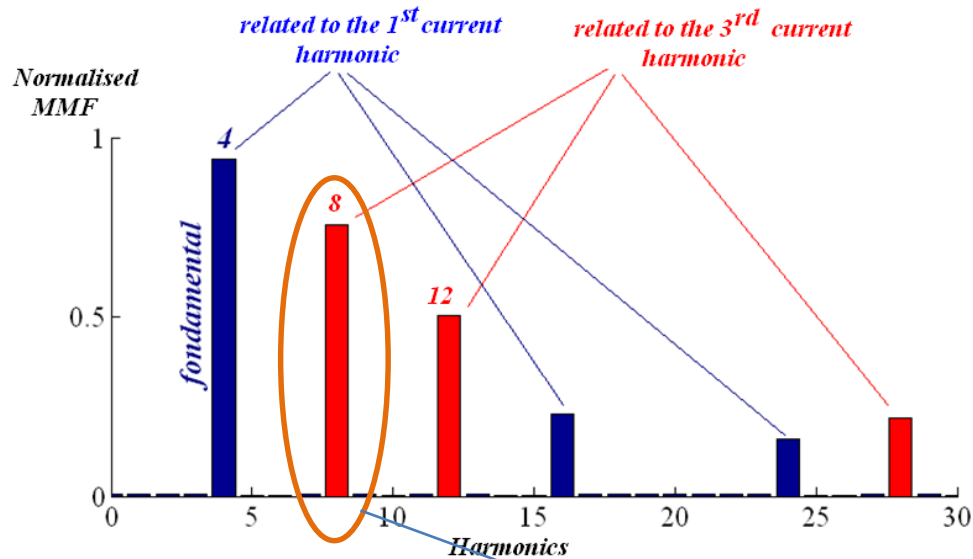


**3-Phase  
12 slots / 8  
poles 2010  
TOYOTA  
Prius  
Generator**

# II. Bi-harmonic machine Design: Stator

5-Phase combination: 40 slots / 16 poles (1/2 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.

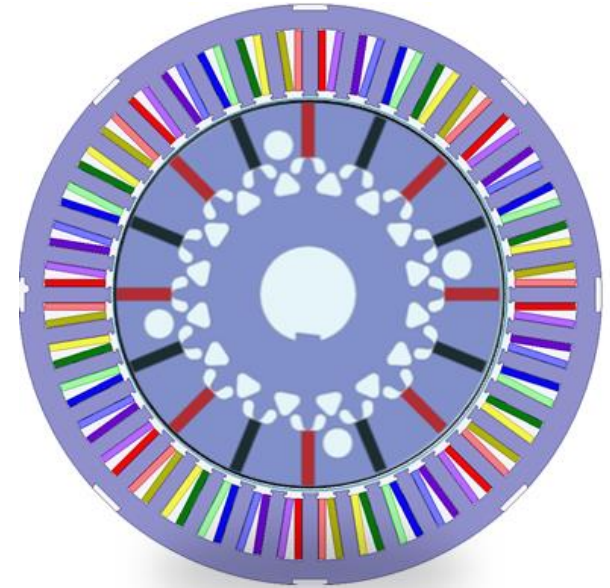


## II. Bi-harmonic machine Design: Rotor

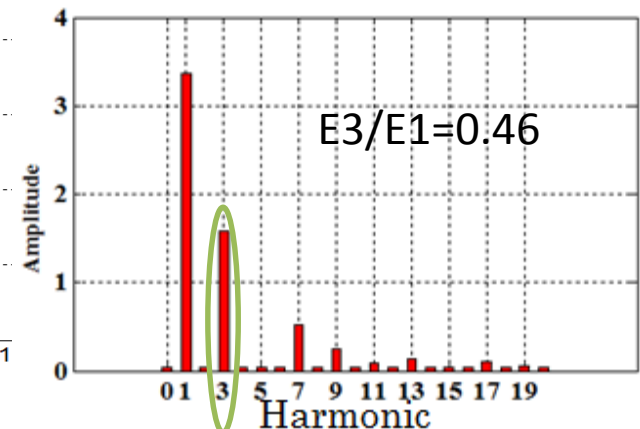
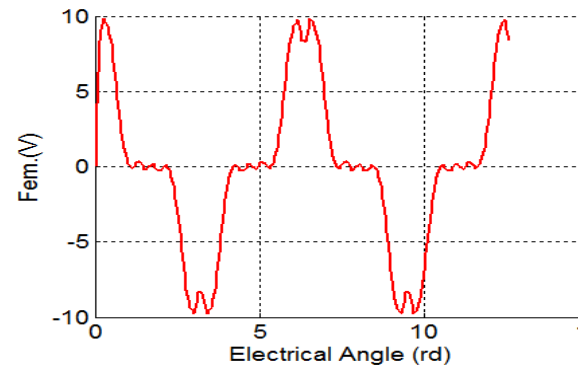
**Structure with interior magnets is used.**

### 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**

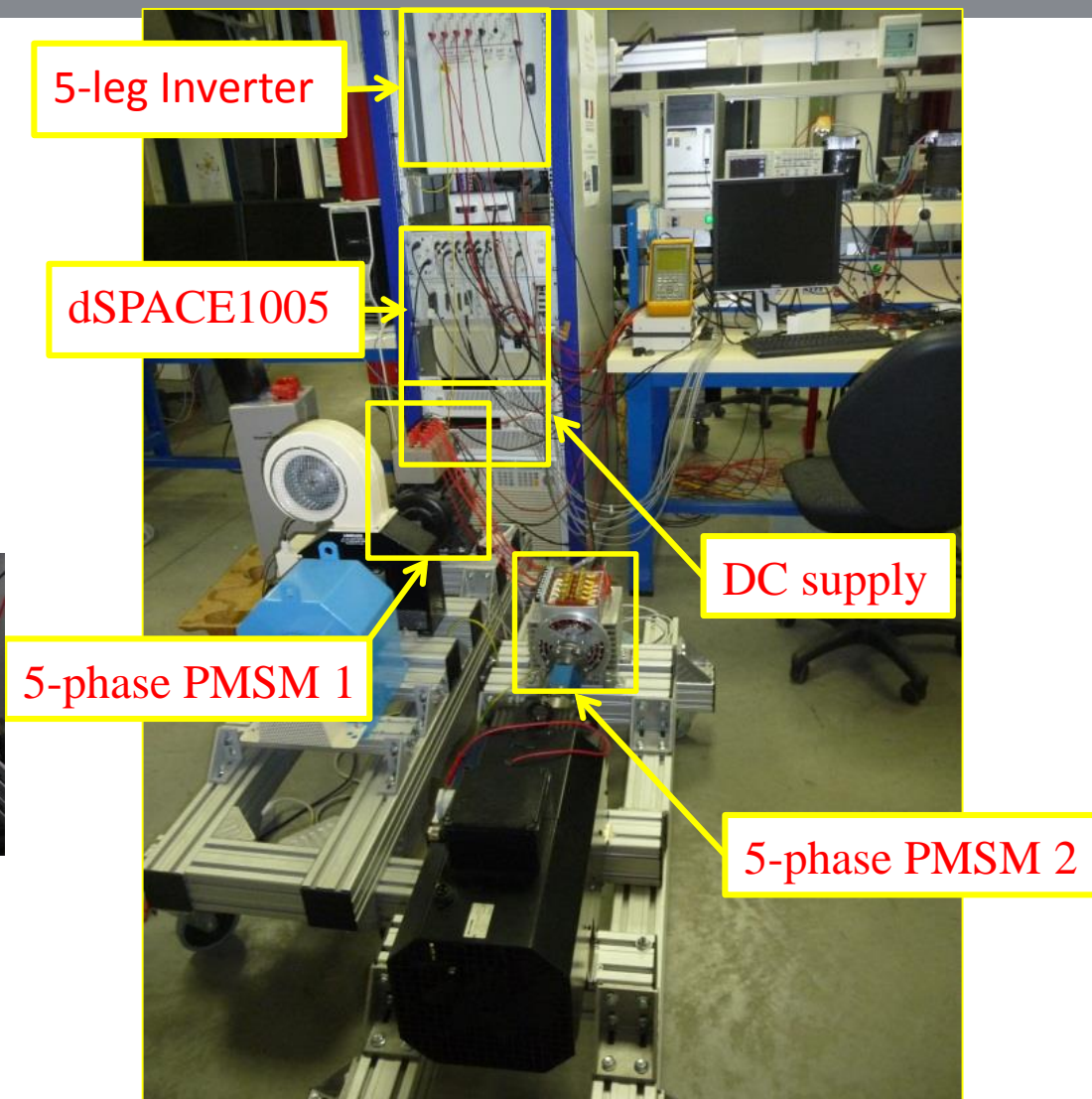


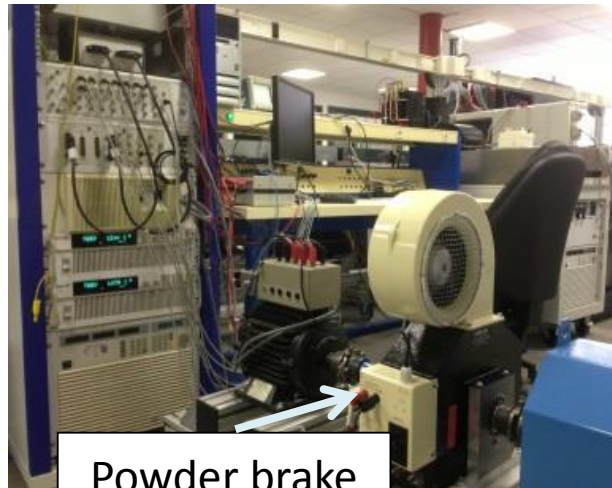
Fig. 1. Laboratory experimental test-bench



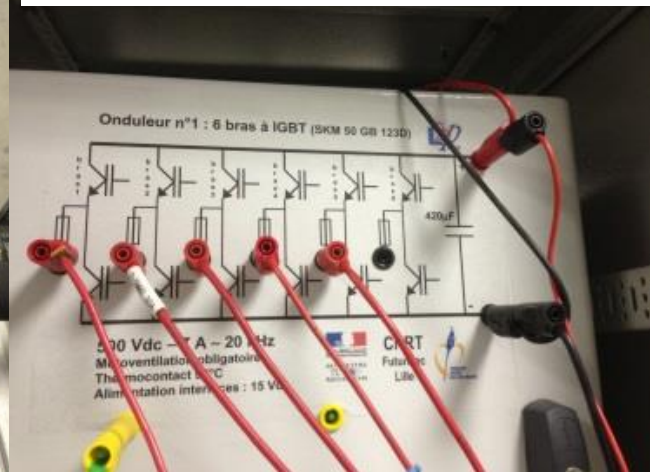
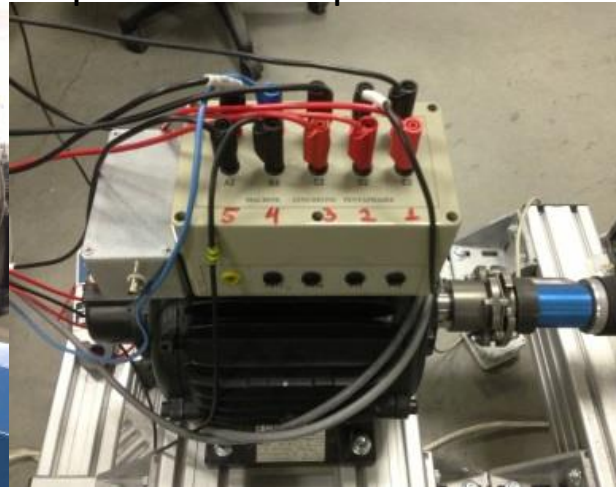
dSPACE and 2 DC sources

Open-end five-phase machine

Five-bridge inverter (one side)



Powder brake



Laboratory experimental platform setup

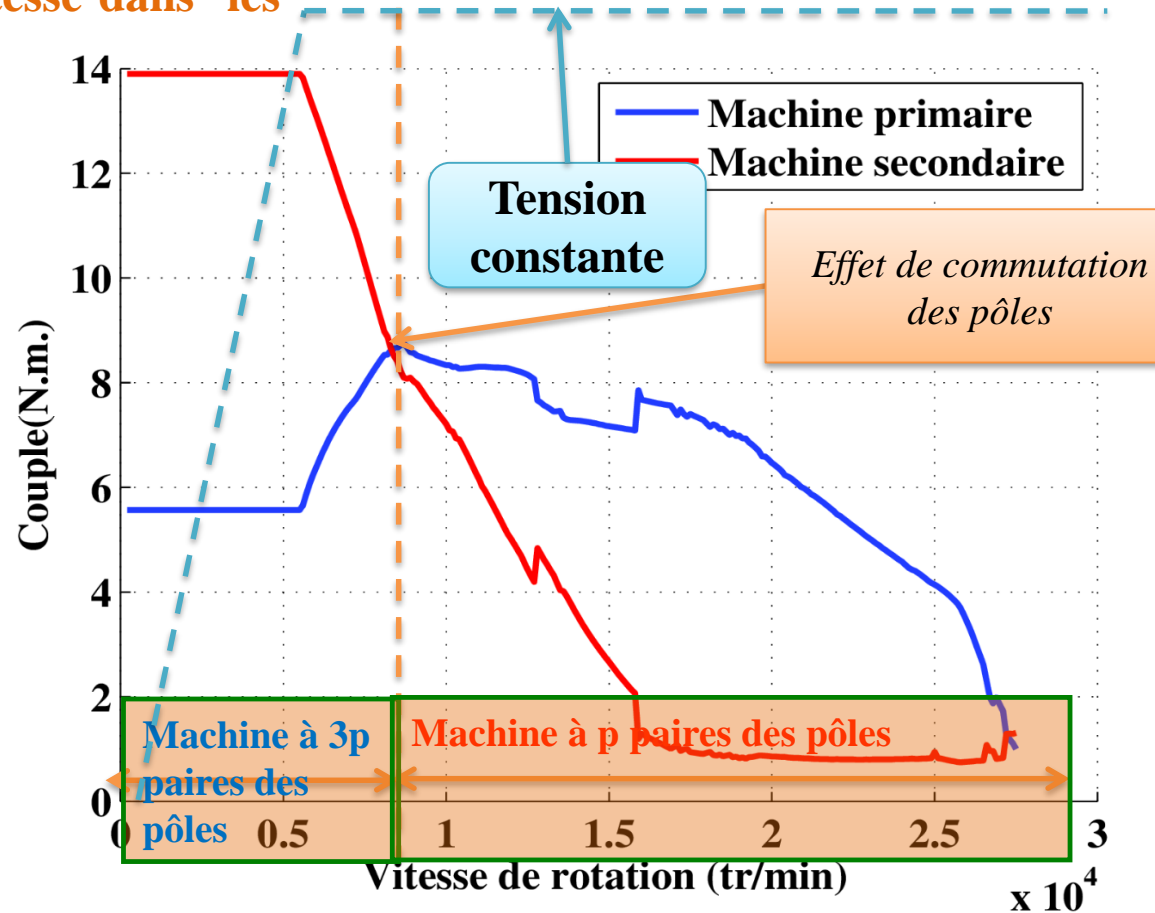
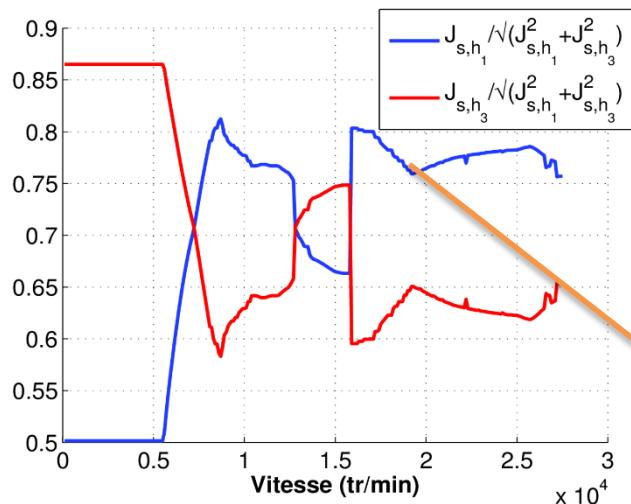
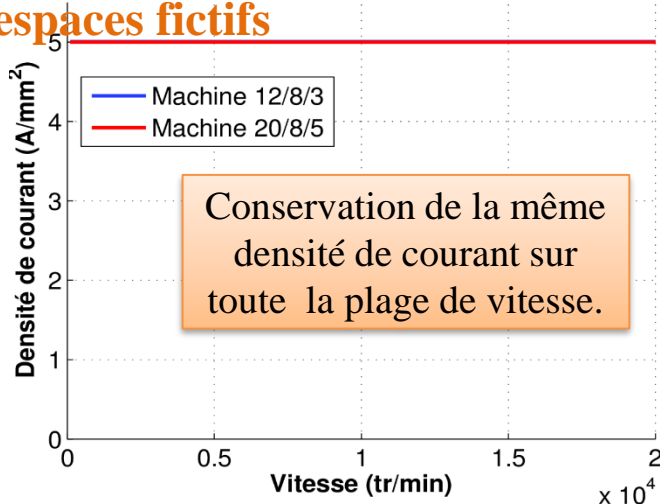
## 5-phase machine parameters

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.

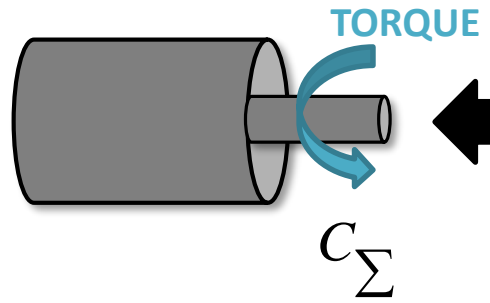
# Multiphase Decomposition Theory

## 5-phase PMSM

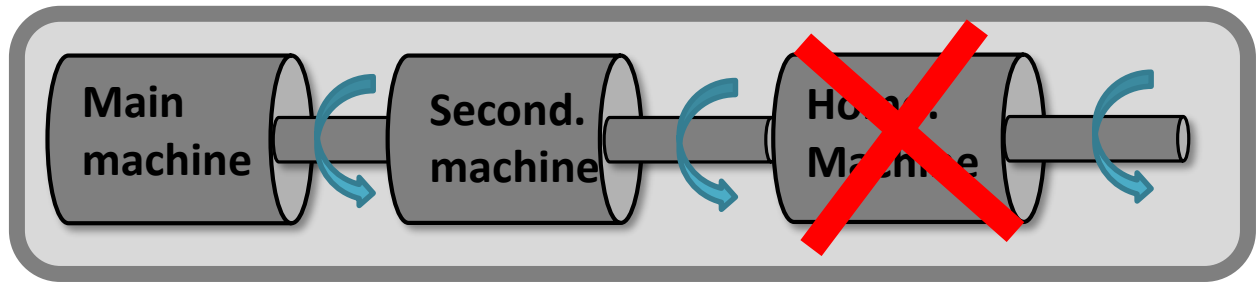
MM : 1st harmonic  
SM : 3th harmonic

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

Real 5-phase machine



Fictitious Machines (2 diphas + 1 homopolar)

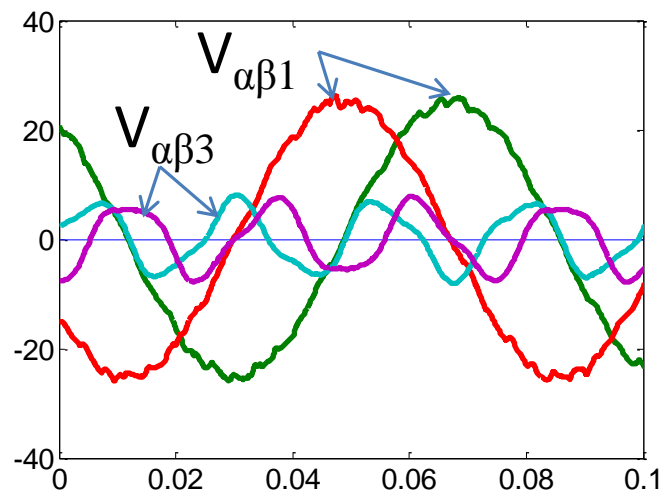
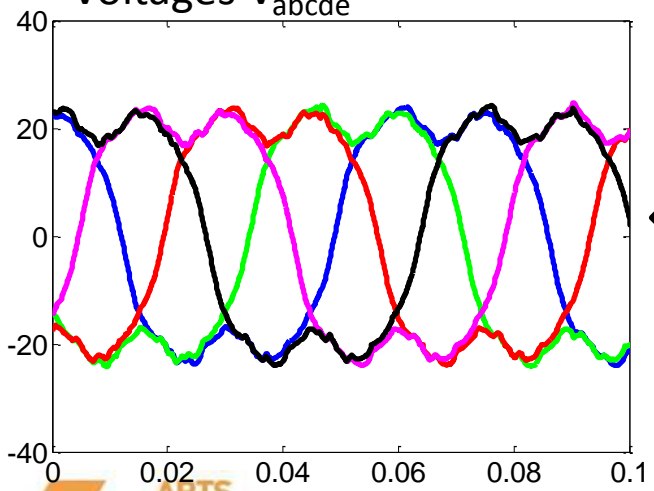


$h = \textcircled{1}, 9, 11, \dots$   
 $h = 5k \pm 1$

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

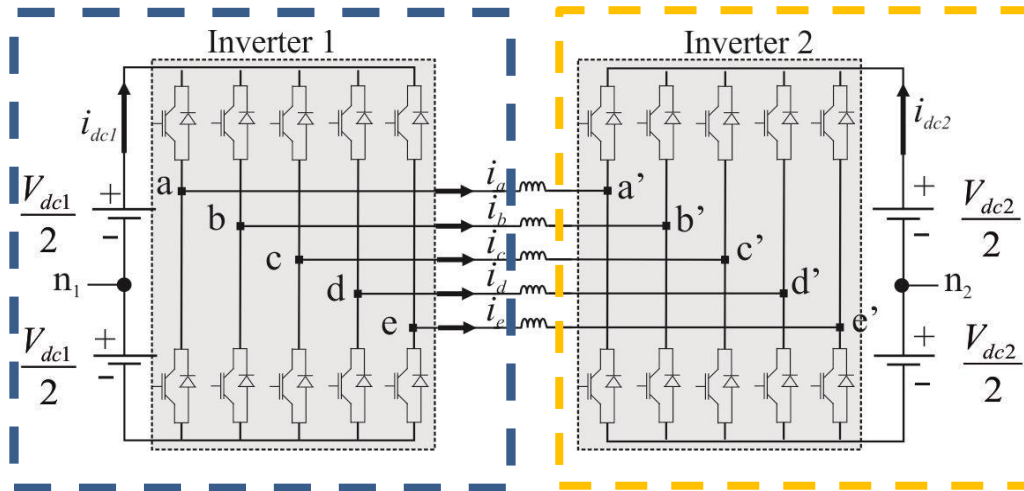
$h = 5, 15, \dots$   
 $h = 5k$

Voltages  $V_{abcde}$



Voltages in decoupled base

# 2. Different Stator Winding Connections



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  $\mathbf{v}_{abcde-INV2} = [0 \ 0 \ 0 \ 0 \ 0]^T$  (1)

PENTAGON  $\mathbf{v}_{abcde-INV2} = [v_{bn_1} \ v_{cn_1} \ v_{dn_1} \ v_{en_1} \ v_{an_1}]^T$  (2)

PENTACLE  $\mathbf{v}_{abcde-INV2} = [v_{cn_1} \ v_{dn_1} \ v_{en_1} \ v_{an_1} \ v_{bn_1}]^T$  (3)

BIPOLAR  $\mathbf{v}_{abcde-INV2} = -[v_{an_1} \ v_{bn_1} \ v_{cn_1} \ v_{dn_1} \ v_{en_1}]^T$  (4)

**SIMPLE**

