Different Possibilities of Multiphase Drives Functioning in Constant Power Region

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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
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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

- Dahlander circuit
- Winding configuration
- Saliency ratio

Electronic pole commutation

rotor with PM

Stator with tooth concentrated winding

Number of phases > 3

PM
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

OUTLINE

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GENERALIZED VECTORIAL FORMALISM THEORY

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

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

Real n-phase machine

Fictitious Machines (diphase + homopolar)

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

Leads to

Fictitious machines

**I. Introduction**

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**Multiphase Decomposition Theory**

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Different Possibilities of Multiphase Drives functioning at Power Constant Region
3-phase PMSM

Real 3-phase machine

\[ C_\Sigma \]

Transformation (Concordia, Clarke, etc.)

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

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

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

\[ \Lambda_i \] Eigenvalues of inductance matrix

Fictitious Machines (1 diphase + 1 homopolar)

MM

\[ h = 1, 5, 7, 11, ... \]
\[ h \neq 3k \]

HM

\[ h = 3, 6, 9, ... \]
\[ h = 3k \]

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))
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5-phase PMSM

Real 5-phase machine

Torque

$C \sum$

Fictitious Machines (2 diphase + 1 homopolar)

MM

Main machine

$C \sum$

$h = 1, 9, 11, ...$

$h = 5k \pm 1$

SM

Second. machine

$h = 3, 7, ...$

$h = 5k \pm 2$

HM

Homo. Machine

$h = 5, 15, ...$

$h = 5k$

$h$: 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 ($\Lambda_0$)

5-phase PMSM

Real 5-phase machine

MM : 1st harmonic
SM : 3th harmonic

Fictitious Machines (2 diphase + 1 homopolar)

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

\[ \sum C \]

\[ h = 1, 9, 11, \ldots \]
\[ p \text{ pairs of poles} \]

\[ h = 3, 7, \ldots \]
\[ 3p \text{ pairs of poles} \]

\[ h = 5, 15, \ldots \]
\[ h=5k \]

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)**

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

Electronic pole changing with multiphase machines to extend the speed range

**Change number of pole pairs electronically**

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


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Different Possibilities of Multiphase Drives functioning at Power Constant Region
1. Pole Changing

**ISCAD : Intelligent Stator Cage Drive**

- 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

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

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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.

\[ \Omega = 500 \text{ [rpm]} \]

\[ \frac{E_3}{E_1} = 1.22 \]

Field map for \( J = 10 \text{A/mm}^2 \)

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

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1. Pole Changing

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

### Torque vs Speed

- **Secondary machine** (p=3)
- **Main Machine** (p=1)

### Power vs Speed

- **Power Iso-curve 7.7kW**
1. Pole Changing

**Maximum Torque Per Primary Machine (MTPPM)**

**Torque Vs Speed**

- **Main Machine (p=1)**
- **Second. Machine (p=3)**

**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 $\rightarrow$ \((N+1)/2\) configurations

<table>
<thead>
<tr>
<th>Number of phases</th>
<th>Possibilities of stator configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2: Wye and Delta</td>
</tr>
<tr>
<td>5</td>
<td>3: Wye, Pentagon and Pentacle</td>
</tr>
<tr>
<td>(\vdots)</td>
<td>(\vdots)</td>
</tr>
<tr>
<td>N</td>
<td>((N+1)/2)</td>
</tr>
</tbody>
</table>


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Different Possibilities of Multiphase Drives functioning at Power Constant Region
2. Different Stator Winding Connections

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

2. Different Stator Winding Connections

Objective

Electrical Gear Box (EGB)

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

5-phase open-end winding structure

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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

\[ \mathbf{V}_{abcde} = \mathbf{V}_{abcde-IINV1} - \mathbf{V}_{abcde-IINV2} + \mathbf{V}_{abcde-n_1n_2} \]

where

\[ \mathbf{V}_{abcde} = \begin{bmatrix} V_{aa'} & V_{bb'} & V_{cc'} & V_{dd'} & V_{ee'} \end{bmatrix}^T \]

\[ \mathbf{V}_{abcde-IINV1} = \begin{bmatrix} V_{an_1} & V_{bn_1} & V_{cn_1} & V_{dn_1} & V_{en_1} \end{bmatrix}^T \]

\[ \mathbf{V}_{abcde-IINV2} = \begin{bmatrix} V_{a'n_2} & V_{b'n_2} & V_{c'n_2} & V_{d'n_2} & V_{e'n_2} \end{bmatrix}^T \]

\[ \mathbf{V}_{abcde-n_1n_2} = \begin{bmatrix} V_{n_1n_2} & V_{n_1n_2} & V_{n_1n_2} & V_{n_1n_2} & V_{n_1n_2} \end{bmatrix}^T \]

Hypothesis: Sinusoidal and balanced phase voltages:

\[ \mathbf{V}_{abcde} = \mathbf{A} \cdot (\mathbf{V}_{abcde-IINV1} - \mathbf{V}_{abcde-IINV2}) \]

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

For phase a:

\[ \mathbf{v}_{ab} = \mathbf{A} \cdot \mathbf{v}_{ab} - \text{INV}1 - \mathbf{v}_{ab} - \text{INV}2 \]
2. Different Stator Winding Connections

**Wye-Connection**

\[ V_{INV-1} = V^* |\alpha \]  
\[ V_{INV-2} = 0 \]

**Pentagon Connection:**

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

**Pentacle Connection:**

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

**Bipolaire Connection:**

\[ V_{INV-1} = V^* |\alpha \]  
\[ V_{INV-2} = V^* \left|\alpha + \pi\right| \]
2. Different Stator Winding Connections

- Star
- Pentagon
- Pentacle
- Bipolar

**Graphs:**
- **Speed (p.u.)**
  - Speed vs time (s)
  - Reference vs response

- **Torque (p.u.)**
  - Torque vs time (s)

- **Voltage Magnitude**
  - Mod(V_{dq})
  - V_{max-star}, V_{max-pentagon}, V_{max-pentacle}, V_{max-bipolar}

- **Current**
  - Current vs time (s)

**Experimentation**
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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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II. Bi-harmonic machine Design: Stator

Tooth-Coil concentrated winding are used.

Advantages

➢ Shorter end-windings \(\rightarrow\) more useful copper \(\rightarrow\) more efficient machine.
➢ Higher filling factor: 20% more
➢ Simpler winding structure (easy manufacturing, maintenance, and recycling).

Winding topology: (slot/pole combinaison):

Bad choice of slot/pole combinaison \(\rightarrow\) MMF with a lot of MMF harmful harmonics and sub-harmonics and mechanical vibration \(\rightarrow\) Rotor eddy current losses can be induced especially at high frequencies \(\rightarrow\) Demagnetization of magnets is possible.

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).

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

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

\[ \frac{E_3}{E_1} = 0.46 \]
EXPERIMENTAL RESULTS

Fig. 1. Laboratory experimental test-bench

- 5-leg Inverter
- dSPACE1005
- DC supply
- 5-phase PMSM 1
- 5-phase PMSM 2

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**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: \( L_{3q} = 0.9 \, \text{mH} \)

\[
E_{\text{emf}-1} = \frac{E_1}{\Omega} = 0.32 \, \text{V.s.rad}^{-1}
\]

- Maximum torque: \( T_{\text{em-max}} = 20 \, \text{N.m} \)
- Maximum speed: \( \Omega_{\text{max}} = 2500 \, \text{rpm} \)
- Bus voltage: \( V_{\text{bus}} = 70 \, \text{V} \)
- Maximum phase current: \( I_{\text{max}} = 15 \, \text{A} \)
V.B.3. Caractéristiques couple /vitesse dans les espaces fictifs

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

Contrairement au défallaxage classique des machines triphasées, on agit sur la répartition de courant entre les machines fictives.
5-phase PMSM

Real 5-phase machine

\[ C \sum \]

5-phase machine

MM : 1st harmonic
SM : 3th harmonic

\[ \text{Torque can be created by injecting the 1st and the 3th harmonic of currents} \]

Fictitious Machines (2 diphase + 1 homopolar)

\[ h = 1, 9, 11, \ldots \]
\[ h = 3, 7, \ldots \]
\[ h = 5, 15, \ldots \]

MM : 1st harmonic
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Voltages \( V_{abcde} \)

Voltages in decoupled base

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2. Different Stator Winding Connections

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

\[ v_{abcde-INV1} = \begin{bmatrix} v_{an1} & v_{bn1} & v_{cn1} & v_{dn1} & v_{en1} \end{bmatrix}^T \]

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

For the 2nd Inverter:

- WYE: \[ v_{abcde-INV2} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T \] (1)
- PENTAGON: \[ v_{abcde-INV2} = \begin{bmatrix} v_{bn1} & v_{cn1} & v_{dn1} & v_{en1} & v_{an1} \end{bmatrix}^T \] (2)
- PENTACLE: \[ v_{abcde-INV2} = \begin{bmatrix} v_{cn1} & v_{dn1} & v_{en1} & v_{an1} & v_{bn1} \end{bmatrix}^T \] (3)
- BIPOLAR: \[ v_{abcde-INV2} = -\begin{bmatrix} v_{an1} & v_{bn1} & v_{cn1} & v_{dn1} & v_{en1} \end{bmatrix}^T \] (4)