Control of a Seven-phase Axial Flux Machine in Fault Mode Operation

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Control of a 7-phase Machine in Fault Mode Operation

Outline

I> Introduction
II> 7-phase drive with special design for fault operation
III> Opening two phases: effect on the torque of the vector controlled 7-phase machine
IV> Improved vector control when only 5 phases are supplied
V> Conclusion
Reliability required for the drives of on-board systems such as automotive, aircraft, marine propulsion, offshore wind-generator.

Mean Time Between Failure (MTBF) ?

Electronic Power Devices are the most critical part of the drive.

Effect of a failure ?

Phases of the machine are opened.

Critical for wye-coupled 3-phase machines.
I. Introduction

Intrinsic reliability of multi-phase machines

Why seven phases?

- Using the third harmonic of emf for the torque
- Smooth torque in fault mode operation (two open phases)
- Reasonable number of connexions
I. Introduction

What happens when only 5 phases are supplied?

😊 Average Torque

BUT

😢 Torque Ripples

Challenges?

1> Reducing the torque ripples by control

2> Finding a friendly machine for fault operation
A machine specifically designed for fault operation

Special spectrum of electromotive force
II. The 7-phase drive

Axial flux PM machine, with two rotors

7-leg Voltage Source Inverter

DC drive motor
7-phase axial-flux PMSM

Torque transducer
Optical encoder

Back-ground with DC motor, seven-phase machine and torque transducer (MAGTROL TM211)
II. The 7-phase drive

Seven phases with toroidal winding

1 slot/pole/phase → No filtering effect

1 arc pole for the magnet repartition

6 poles

Rated Torque with 50°C in winding (Nm) | 65
---|---
Rated current at 65 Nm (A) | 5

Interesting for fault operation

Cancellation of the fifth harmonic
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II. The 7-phase drive

Synoptic of the 7-phase vector control

A generalization of 3-phase vector control in dq-reference frame
Effect of opening two phases on a vector controlled 7-phase machine
III. Vector controlled 7-phase machine: effect of a fault

Phases A and B are opened

7 measured currents in fault operation without change of control
III. Vector controlled 7-phase machine: effect of a fault

Interaction between the non-symmetrical system of currents and the symmetrical system of electromotive forces

Experimental torques in the seven-phase machine

In normal operation

In fault operation

Spectral analysis of torques
Improved control thanks to a Multi-machine concept
III. Improved vector control with 5-phase supplied

Tools to get the results?

* Vectorial formalism: important for high number of phases;
* Graphical Energetic Macroscopic Representation;

For a wye-coupled 3-phase PM machine

Equivalence of a 3-phase machine to a 2-phase machine (d-q components)
III. Improved vector control with 5-phase supplied

Equivalence of a 7-phase machine to a set of 3 2-phase machines
III. Improved vector control with 5-phase supplied

**Basic original idea**

Wye-coupled 7 phase machine

- **6 freedom degrees:**
  - control of the 3 2-phase machines

  *In case of 2 open phases*

- **4 freedom degrees:**
  - control of only 2 2-phase machines *which ones?*

  *Impossible to control the currents in one of the three machines*

  *No torque ripples in this machine if its EMF = 0*
III. Improved vector control with 5-phase supplied

<table>
<thead>
<tr>
<th>Fictitious 2-phase machines</th>
<th>Families of odd harmonics</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>1, 13, 15, 27, …,</td>
</tr>
<tr>
<td>M2</td>
<td>5, 9, 19, 23, …,</td>
</tr>
<tr>
<td>M3</td>
<td>3, 11, 17, 25, …,</td>
</tr>
</tbody>
</table>

Cancellation of the fifth harmonic
III. Improved vector control with 5-phase supplied

Opening of two phases

\[
\begin{align*}
    i_{M1\alpha} &= I_{M1} \sin(\omega t) \\
    i_{M1\beta} &= -I_{M1} \cos(\omega t) \\
    i_{M3\alpha} &= 0 \\
    i_{M3\beta} &= 0
\end{align*}
\]

Solution for M2 currents

\[
\begin{bmatrix}
    0 \\
    I_{M1} \sin(\omega t) \\
    -I_{M1} \cos(\omega t) \\
    0
\end{bmatrix} = \begin{bmatrix}
    i_A \\
    i_B \\
    i_C \\
    i_D \\
    i_E \\
    i_F \\
    i_G
\end{bmatrix}
\]

\[
\begin{align*}
    i_{M2\alpha} &= -I_{M1} \sin(\omega t) \\
    i_{M2\beta} &= 0.801938I_{M1} \cos(\omega t) - 0.867767I_{M1} \sin(\omega t)
\end{align*}
\]

Choice:
- Torque can be imposed by M1 and M3
- Physical mandatory currents of M2?

4+2 current references for the PI controllers
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III. Improved vector control with 5-phase supplied

By the cancellation of the emf fifth harmonic

No torque produced by the fictitious M2 machine even if supplied

Without changing modeling of the 7-phase machine

No torque ripples by change of M2 reference currents

Constant torque references for M1 and M3
IV. Conclusion

Vector control for a 7-phase machine
Smooth torque even with non-sinusoidal emf

Vector control with two open phases
Average torque but torque ripples

Modified Vector control with two open phases

A smooth torque can be obtained in this machine when one or two phases are opened thanks to:

• slight modification of the DESIGN of the machine
• slight modification of the control