Current Control System to PMSG in Overmodulation Region

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4th Power Electronics and Control Seminar, 2010
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Important features in wind energy conversion systems: wide range of speed operation, reduced torque pulsation and high efficiency.

To augment the range of speed operation and to maintain the generator voltage limited by DC link voltage, the operation of the PWM rectifier in the overmodulation region will become required.
Introduction

Review in the Overmodulation Control System

Simulation results

Conclusion

Exemplification

Objective
In this paper, a review of the space vector modulation in overmodulation region is presented and a control system with anti-windup action, and harmonics compensation is proposed to guarantee a good performance of wind energy conversion systems.
Space vector modulation

1. Linear mode: Full circular trajectory
2. Overmodulation mode I: Partially circular trajectory
3. Overmodulation mode II: Hexagonal trajectory
Overmodulation mode I
Overmodulation mode I

Modified vector

\[ \| u_{\text{mod}} \| = \frac{1}{\sqrt{3} \cos \left( \frac{\pi}{6} - \alpha_c \right)} \]

\[ u_{\text{mod}} = \frac{3}{2} [\sqrt{3} \ 1] \bullet u_{\text{mod}}^T \]
Overmodulation mode II
Overmodulation mode II
Overmodulation mode II

\[ v_\alpha, v_\beta \]

\[ v_0, v_1, v_2 \]

\[ u_{\alpha\beta}, u_{mod} \]

\[ \alpha_h \]
Overmodulation mode II

\[ v_\alpha, v_\beta, v_0, v^2, v_1, \alpha_h, u_{\alpha\beta}, u_{\text{mod}} \]
Overmodulation mode II
Overmodulation mode II

\[ v_\alpha \]

\[ v_\beta \]

\[ v_0 \]

\[ v_1 \]

\[ v_2 \]

\[ u_{\text{mod}} \]

\[ u_{\alpha\beta} \]

\[ \alpha_h \]
Overmodulation mode II
Overmodulation mode II

\[ v_\alpha \]
\[ v_\beta \]
\[ v_0 \]
\[ v_1 \]
\[ v_2 \]
\[ u_{\text{mod}} \]
\[ u_{\alpha \beta} \]
\[ \alpha_h \]
Overmodulation mode II

\[ v_\alpha \]

\[ v_\beta \]

\[ v_0 \]

\[ v_1 \]

\[ v_2 \]

\[ u_{\alpha\beta} \]

\[ u_{mod} \]

\[ \alpha_h \]
Overmodulation mode II

\[ v_0, v_1, v_2 \]

- Operation Modes
  - Description of the overmodulation mode I
  - Description of the overmodulation mode II

Results
Overmodulation mode II

Angular relationship

\[ \theta_m = \begin{cases} 
0, & 0 \leq \theta \leq \alpha_h \\
\frac{\theta - \alpha_h}{\frac{\pi}{6} - \alpha_h} \cdot \frac{\pi}{6}, & \alpha_h < \theta < \frac{\pi}{3} - \alpha_h \\
\frac{\pi}{3}, & \frac{\pi}{3} - \alpha_h \leq \theta \leq \frac{\pi}{3} 
\end{cases} \]
Fundamental magnitude versus modulation index

- **Linear mode**
- **Overmodulation mode I**
- **Overmodulation mode II**

The graph shows the fundamental magnitude ($V_f \over V_{cc}$) plotted against the modulation index ($m$). The key values are:

- $m = 0.906$
- $m = 0.952$
- $m = 1$
Voltage harmonics

- 5th harmonic
- 7th harmonic
- 11th harmonic
- 13th harmonic

Modulation index ($m$)

$\frac{V}{V_{cc}}$
PMSG Model

\[
\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \frac{\omega_e L_q}{L_d} \\ \frac{\omega_e L_q}{L_d} & -\frac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} \\ 0 \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{\psi_{pm}}{L_q} \end{bmatrix} \omega_e
\]

MIMO controller

\[
\frac{d}{dt} \begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} e_d \\ e_q \end{bmatrix} - k_w \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} u_{dL} - u_d \\ u_{qL} - u_q \end{bmatrix}
\]

\[
\begin{bmatrix} u_d \\ u_q \end{bmatrix} = k_i \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_d \\ x_q \end{bmatrix} + k_p \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} e_d \\ e_q \end{bmatrix}
\]
PI controller with anti-windup
Saturation function of the actuator

in Euclidean norm

\[
sat(u) = u_0 \frac{u}{\|u\|}
\]

in magnitude

\[
sat(u_i) = \text{sign}(u_i) \min(u_0, |u_i|)
\]
Estimation of the current harmonics
Implementation of the control system
## Parameters of the simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator resistance</td>
<td>$R_s$</td>
<td>0.64 Ω</td>
</tr>
<tr>
<td>Direct inductance</td>
<td>$L_d$</td>
<td>8.7 mH</td>
</tr>
<tr>
<td>Quadrature inductance</td>
<td>$L_q$</td>
<td>28.3 mH</td>
</tr>
<tr>
<td>PM flux</td>
<td>$\psi_{pm}$</td>
<td>0.108 Wb</td>
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<tr>
<td>Proportional gain</td>
<td>$k_p$</td>
<td>114.9</td>
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<tr>
<td>Integral gain</td>
<td>$k_i$</td>
<td>145426.8</td>
</tr>
<tr>
<td>Anti-windup gain</td>
<td>$k_w$</td>
<td>0.1375</td>
</tr>
</tbody>
</table>
Compensation of the current harmonics

- Proposed
- Convencional

Parameters of the simulation
Harmonics compensation
Comparing between the saturation functions
Current generator

in Euclidean norm

in magnitude
Review in the Overmodulation Control System

Simulation results

Comparing between the saturation functions

Parameters of the simulation

Voltage generator axis-\( d \)
in Euclidean norm

\[ \text{Voltage (normalized)} \]
\[ \omega_m \text{ (rpm)} \]

\[ u_d^\text{sat} \]
\[ u_d \]

in magnitude

\[ \text{Voltage (normalized)} \]
\[ \omega_m \text{ (rpm)} \]

\[ u_d^\text{sat} \]
\[ u_d \]
This paper presents a current control system in the overmodulation region, considering the saturation in Euclidean norm and in magnitude with anti-windup method.

A good agreement is obtained between the theoretical analysis and the simulations results that point out advantages in the use of magnitude saturation.

The proposed control system indicate that is is possible to control the currents in the overmodulation region as long as the current references are compute to hold the magnitude of the vector of control action smaller or equal that the fundamental of six-step.
Thanks for your attention!