Role of Power Electronics in Power Systems

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Power-Related Courses

- Energy, Environment and Society (3cr) - Freshman
  - Power Systems (3cr) Lab (1cr)
  - Power Electronics (3cr) Lab (1cr)
  - Senior Design Project (3cr)

- Electric Drives (3cr) Lab (1cr) - Junior/Senior

- Senior Design Project (3cr) - Senior

- Power Systems (3cr) - 1st Year Graduate
- Power Electronics (3cr)
- Electric Drives (3cr)

Advanced Graduate Courses
Role of Power Electronics in Power Systems

- Generation
- Delivery
- Efficient End-Use
Utilities Tomorrow versus Yesterday

Centralized utility of today

Distributed utility of tomorrow

Storage

EV
Power Electronics: An Enabling Technology
Continuing Evolution of Power Semiconductor Devices

(a) Siemens 5.2 kV Electrically triggered Thyristor 3500A_{eff}
(b) Toshiba 4.5kV GTO apr. 1500A_{eff}
(c) Siemens 7.5 kV Light triggered Thyristor 3500A_{eff}
(d) Fuji 4.5kV Press Pack IGBT apr. 800A_{eff}

Device current [A]

Device blocking voltage [V]

HVDC, Traction, Power Supply, Motor Drive, Automotive, Lighting, FACTS

Beyond Silicon: New Materials

<table>
<thead>
<tr>
<th>Key Parameter</th>
<th>Si</th>
<th>4H-SiC</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap</td>
<td>1.1</td>
<td>3</td>
<td>5.5</td>
</tr>
<tr>
<td>Breakdown field</td>
<td>0.3</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Max electron velocity</td>
<td>1.0</td>
<td>2</td>
<td>3 \times 10^7 cm/s</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>1.5</td>
<td>5</td>
<td>20 W/cmK</td>
</tr>
</tbody>
</table>

Silicon Carbide exceeds the fundamental limitations of Silicon by a factor 10-100 in improved device properties.
Controller ICs and Integrated Power Modules:
Potentially Lower Cost

Power Semiconductor Price

Copper and Steel Prices
- Copper prices have gone up five fold in three years

USD/A

1200 V
IGBTs
DOE Wind Research Consortium at UMN

Improving Reliability and Reducing the Nacelle Weight by 20%

- High-Frequency Transformer and Converter
- Light Cable at 34.5 kV
- 34.5 kV, 60-Hz Underground

Nanocrystalline High Frequency Transformers Are Over 150 Times Lighter And Significantly Smaller

- 150 kV, 60 Hz
- 20 Amp RMS
- 2 MVA Average
- DC test
- 470 MW Loss

- 145 kV, 60 Hz
- 20 Amp RMS
- 1.5 MVA Average (7) present use
- 20 MVA Loss
- 21.5% Loss at 2 MVA
GE 1.5 MW Turbine

<table>
<thead>
<tr>
<th>Operating Data</th>
<th>1,500 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Rated capacity:</td>
<td>4 m/s</td>
</tr>
<tr>
<td>• Cut-in wind speed:</td>
<td>25 m/s</td>
</tr>
<tr>
<td>• Cut-out wind speed at max. weight</td>
<td>13 m/s</td>
</tr>
<tr>
<td>• Rated wind speed:</td>
<td></td>
</tr>
<tr>
<td>• Wind Class - IEC:</td>
<td>11A</td>
</tr>
<tr>
<td>• Wind Class - D18t W2:</td>
<td>11/III</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rotor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Number of rotor blades:</td>
<td>3</td>
</tr>
<tr>
<td>• Rotor diameter:</td>
<td>12 m</td>
</tr>
<tr>
<td>• Swept area:</td>
<td>3904 m²</td>
</tr>
<tr>
<td>• Rotor speed (variable):</td>
<td>12.0 – 22.2 rpm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tower</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Hub heights - IEC:</td>
<td>64.7 m</td>
</tr>
<tr>
<td>• Hub heights - D18t:</td>
<td>64.7 m</td>
</tr>
</tbody>
</table>

| Power control              | Active blade pitch control |

Source: [www.gewindenergy.com](http://www.gewindenergy.com)
Power from the Wind

\[ P = \frac{1}{2} \rho A_r v_w^3 C_p(\lambda, \theta) \]

\( P \) is the mechanical power extracted from the wind, \( \rho \) is the air density in \( \text{kg/m}^3 \), \( A_r \) is the area swept by the rotor blades in \( \text{m}^2 \), \( v_w \) is the wind speed in \( \text{m/sec} \), and \( C_p \) is the power coefficient, which is a function of \( \lambda \) and \( \theta \). \( \lambda \) is the ratio of the rotor blade tip speed and the wind speed (\( v_{\text{tip}}/v_w \)), and \( \theta \) is the blade pitch angle in degrees. The relationship between blade tip speed and turbine rotor speed, \( \omega \), is a fixed constant, \( K_b \).
Role of Power Electronics in Wind
Solar: Photovoltaic

Source: ABB
Sodium Sulfur Battery Storage to Enable Further Integration of Wind (Xcel Energy)
High Voltage DC Transmission – HVDC (Current-Link)
HVDC (Voltage-Link)
Flexible AC Transmission Systems: FACTS

\[ E_1 \angle 0 \]

\[ E_2 \angle -\delta \]

\[ jX \]

\[ P = \frac{E_1 E_2}{X} \sin \delta \]

Control of X:

\[ (a) \]

Thyristor-Controlled Series Capacitor (TCSC)
Kayenta Substation, USA

\[ (b) \]
Voltage Control:

Unified Control:
Efficient End-Use

Adjustable Speed Drives

Lighting 19%
HVAC 16%
Motors 51%
IT 14%
Principle of Operation

conv1 + conv2

controller

utility Load
Step-Down (Buck) Converter

\[ d = \frac{T_{up}}{T_S} \]

\[ V_A = V_o = d V_{in} \]
Realizing a Bi-Positional Switch in A Step-Down Converter
Step-Up (Boost) Converter
Bi-Directional Power Flow

\[ V_1 \quad A \quad v_A \quad + \quad - \quad V_2 \]

\[ q = (1 - q) \]
Synthesizing Sinusoidal AC:
Average Representation of the Switching Power-Pole

\[ \bar{v}_{aN} = d_a V_d \]

\[ \bar{i}_{da} = d_a \bar{i}_a \]
Three-Phase Inverters

(a)

(b)
Interface for Wind Generator

\[ v_a(t) \quad i_a(t) \]

\[ + \quad - \]

\[ V_d \]

\[ A \quad B \quad C \quad n \]

\[ i_A(t) \quad e_A(t) \]

\[ + \quad - \]

\[ 0 \leq \omega t \leq 2\pi \]

\[ \frac{1}{2} V_d \]

\[ \bar{V}_{AN} \]

\[ \bar{V}_{An} \]
SV-PWM

\[ \vec{v}_s^a(t) = V_d (q_a e^{j0} + q_b e^{j2\pi/3} + q_c e^{j4\pi/3}) \]

**Basic Voltage Vectors**

\[ \vec{v}_s^a(000) = \vec{v}_0 = 0 \]
\[ \vec{v}_s^a(001) = \vec{v}_1 = V_d e^{j0} \]
\[ \vec{v}_s^a(010) = \vec{v}_2 = V_d e^{j2\pi/3} \]
\[ \vec{v}_s^a(011) = \vec{v}_3 = V_d e^{j\pi/3} \]
\[ \vec{v}_s^a(100) = \vec{v}_4 = V_d e^{j4\pi/3} \]
\[ \vec{v}_s^a(101) = \vec{v}_5 = V_d e^{j5\pi/3} \]
\[ \vec{v}_s^a(110) = \vec{v}_6 = V_d e^{j\pi} \]
\[ \vec{v}_s^a(111) = \vec{v}_7 = 0 \]
Only three carefully-designed courses

Complementary Courses:
- Analog/Digital Control
- DSPs, FPGAs
- Communication
- Programming Languages
- Policy Issues

- Students are Broadly Trained; They can work in any field of EE.
- Smart-Grid Ready!
Courses Developed
- Fundamentals-based; integrated
- Using commonality, in-depth coverage of more topics
- Supported by state-of-the-art laboratories

Power Electronics

Features:
- Switching Power-Pole as the Building-Block
- Includes dc-dc Converters and dc-ac Inverters
- Feedback control of Converters

Textbook
- Slides
- Solutions manual

Hardware Lab

Electric Drives

Teaching Machines as a subcomponent of Drive Systems

Applications:
- Harnessing of Wind Energy
- Electric and Hybrid-Electric Vehicles

Textbook
- Slides
- Solutions manual

DSP-Controlled Lab

Power Systems

Includes Topics such as
- Renewables/Storage
- HVDC, FACTS
- Voltage Stability

Textbook
- Slides
- Solutions manual

Software-based Lab:
- MATLAB/Simulink, PowerWorld, EMTDC
- Complete Lab on CD
- 18 Short Video Clips
NSF-Funded Research
An Innovative Instructional Strategy for Widespread Implementation of EES Curriculum, as a Model in STEM
(Co-PIs: Tamara Moore-UMN & Allison Kipple-NAU)

• Motivation:
  – To keep students actively engaged

• Procedure:
  – Pre-class: watch a 15-minute module and answer a brief online concept quiz – **5% of the Grade**
  – During-class: discuss and solve real-world, design-oriented, somewhat open-ended problems in small groups; Clickers – **15% of the Grade**
  – Post-class: online homework problems on individual basis; based on Moodle - **15% of the Grade**
Increasing Student Enrollments
CUSP™
(www.doeconsortium.ece.umn.edu/cusp)