Power Electronics

Power is precious, if you need to use it efficiently, you need Power Electronics

- Dr. Z V Lakaparampil -
Power Electronics Technology

Multi-disciplinary nature

Optimally Convert, Control & Condition electric power to suit load requirements

Technology for Renewable Energy

Full Spectrum Simulator

Real time controller

PQ & UPS Technology

400Hz Inverter

Share of electrical energy controlled through Power electronics, 40% in 2010 to 80% in 2030
## Technology Elements

<table>
<thead>
<tr>
<th>Power</th>
<th>Control</th>
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<tbody>
<tr>
<td><strong>Switches</strong></td>
<td><strong>Analog Controller</strong></td>
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<tr>
<td><strong>Topology</strong></td>
<td><strong>Digital Controller (H/W &amp; S/W)</strong></td>
</tr>
<tr>
<td><strong>Filter</strong></td>
<td></td>
</tr>
<tr>
<td>DC filter, AC filter</td>
<td>Microprocessor based</td>
</tr>
<tr>
<td><strong>Sensor</strong></td>
<td>DSP based</td>
</tr>
<tr>
<td>Voltage, Current, Speed, Position</td>
<td>FPGA based</td>
</tr>
<tr>
<td><strong>Protection</strong></td>
<td>Hybrid</td>
</tr>
<tr>
<td>External disturbances load &amp; source</td>
<td>Communication</td>
</tr>
<tr>
<td></td>
<td><strong>GUI</strong></td>
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### Design Support

- Offline simulation
- Real time simulation with HiL feature
- EMI/EMC standards
Technology elements: Switches

Power devices, Power circuits & Digital controllers

Power device - Thyristor

Power device – IGBT (MOSFET low power)
Future: Technology Trends
Smaller size, Light weight, Reliable

**Future:**
- Packaging / interconnection technology
- High power density system integration
- Use of low loss new devices – SiC, GaN etc
- Simulation to platform

**Key Factors:**
- System reliability will dominate PE development
- Efficiency improvements with power management and energy recovery
- Storage

**Applications:**
High voltage circuits
## Technology elements: Topology

### Power devices, Power circuits & Digital controllers

<table>
<thead>
<tr>
<th>Power circuits - Chopper</th>
<th>Power circuits – Inverter</th>
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<tr>
<td><strong>DC-DC conversion</strong></td>
<td><strong>DC-AC conversion</strong></td>
</tr>
<tr>
<td><strong>Fixed voltage/ current from a varying source</strong></td>
<td><strong>AC-AC conversion</strong></td>
</tr>
<tr>
<td><strong>Magnitude change increase/ decrease</strong></td>
<td><strong>Output fixed frequency AC</strong></td>
</tr>
<tr>
<td>Stored energy element</td>
<td><strong>Output variable frequency AC</strong></td>
</tr>
<tr>
<td>➤ <strong>Inductively stored</strong></td>
<td>➤ Output single phase</td>
</tr>
<tr>
<td>Buck, Boost, Buck-Boost</td>
<td>Output three phase</td>
</tr>
<tr>
<td>➤ <strong>Capacitive stored</strong></td>
<td>DC side isolation</td>
</tr>
<tr>
<td>CUK</td>
<td>AC side isolation</td>
</tr>
<tr>
<td></td>
<td><strong>Multilevel inverter</strong></td>
</tr>
</tbody>
</table>

### Input Output coupling

<table>
<thead>
<tr>
<th>Isolated</th>
<th>Stored energy element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly-back, Forward, Push-Pull, Half &amp; Full Bridge</td>
<td>➤ <strong>Capacitive stored</strong> Voltage source inverter (Majority applications)</td>
</tr>
<tr>
<td><strong>Non Isolated</strong></td>
<td>➤ <strong>Inductively stored</strong> Current source inverter (High power applications)</td>
</tr>
</tbody>
</table>
DC-DC buck converter

\[
\frac{V_i - V_o}{L} t_{on} - \frac{V_o}{L} t_{off} = 0
\]

\[(V_i - V_o) DT - V_o (1 - D) T = 0\]

\[\Rightarrow V_o - DV_i = 0\]

\[\Rightarrow D = \frac{V_o}{V_i}\]

In discontinuous mode

\[(V_i - V_o) DT - V_o \delta T = 0\]

\[\delta = \frac{V_i - V_o}{V_o D}\]
DC-DC boost converter

\[ \Delta I_{LOn} = \frac{1}{L} \int_{0}^{DT} V_i \, dt = \frac{DT}{L} V_i \]

\[ \Delta I_{LOff} = \int_{DT}^{T} \frac{(V_i - V_o) \, dt}{L} = \frac{(V_i - V_o) (1 - D) T}{L} \]

\[ \Delta I_{LOn} + \Delta I_{LOff} = \frac{V_i DT}{L} + \frac{(V_i - V_o) (1 - D) T}{L} = 0 \]

\[ \frac{V_o}{V_i} = \frac{1}{1 - D} \]
DC-AC Conversion single phase

State 1 and State 2

State 3 and State 4

<table>
<thead>
<tr>
<th>State</th>
<th>Switches Closed</th>
<th>Vo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S1 &amp; S2</td>
<td>+ Vdc</td>
</tr>
<tr>
<td>2</td>
<td>S3 &amp; S4</td>
<td>-Vdc</td>
</tr>
<tr>
<td>3</td>
<td>S1 &amp; S3</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>S2 &amp; S4</td>
<td>0</td>
</tr>
</tbody>
</table>
DC-AC Conversion three phase

SVM Inverter

Three phase VSI configuration

1. DC voltage ideal
2. Zero impedance between two switches in an arm
3. No shoot through
4. Low loss device
5. High frequency switching capability
**DC-AC Conversion three phase inverter**

<table>
<thead>
<tr>
<th></th>
<th>Leg A</th>
<th>Leg B</th>
<th>Leg C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>$S_4$</td>
<td>$V_{AO}$</td>
<td>$S_3$</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>$+V_{DC}/2$</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>$-V_{DC}/2$</td>
<td>0</td>
</tr>
</tbody>
</table>
Inverter Switching states

- Eight possible switching combination for a three phase inverter.
- Six non zero vectors shape the axis of hexagonal.
- Angle between adjacent two non zero vector is 60°.
Space Vector Modulation (SVM)

\[ \vec{V}_{ref} = V_{ref} \cdot e^{i\theta} \]
\[ \omega = 2\pi f \]

\[ |V_{ref}| = \sqrt{(V_{\alpha}^2 + V_{\beta}^2)} \]
\[ \theta = \tan^{-1}\left(\frac{V_{\beta}}{V_{\alpha}}\right) \]

\[ V_n = V_{DC} \cdot e^{j(n-1)\pi/3}, \quad n = 1, 2, \ldots, 6 \]

Maximum Radii: The average variation of the voltage space vector will move along a circle with uniform velocity.

**Max. line to line voltage**

\[ V_{\alpha\max} = V_{DC} \cos(30) \]

\[ = \frac{2}{\sqrt{3}} m_{\max} V_{DC} = V_{DC} \]
Space Vector Modulation (SVM)

Sector-I

Sector-II

Sector-III

Sector-IV

Sector-V

Sector-VI
Block diagram for SVM pulse generation

The waveform contain 3rd order harmonics
Cancel out for three phase

Inverter phasor angular position in fundamental cycle
Clark transformation

Transforms 3 phase currents or voltages into 2 orthogonal vectors in fixed frame.

\[ I_a + I_b + I_c = 0 \]

\[ I_{s\alpha} = \frac{3}{2} I_a \]

\[ I_{s\beta} = \frac{\sqrt{3}}{2} (I_b - I_c) \]
Rotating reference frame

Stator current space vector

Vector diagram in stationary and rotating reference frame
Transforms 2 orthogonal vectors in fixed frame to 2 orthogonal vectors on a rotating frame.

\[ I_{sd} = I_{sa} \cos \theta + I_{sb} \sin \theta \]
\[ I_{sq} = -I_{sa} \sin \theta + I_{sb} \cos \theta \]
Direct and inverse transformation

Direct:
\[ I_{sd} = I_{sa} \cos \theta + I_{s\beta} \sin \theta \]
\[ I_{sq} = -I_{sa} \sin \theta + I_{s\beta} \cos \theta \]

Inverse:
\[ V_{sa} = V_{sd} \cos \theta - V_{sq} \sin \theta \]
\[ V_{s\beta} = V_{sd} \sin \theta + V_{sq} \cos \theta \]
Field Oriented Control Transformations

- 3-phase to 2-phase
- Stationary to Rotating
- Rotating to Stationary
- SVM

<table>
<thead>
<tr>
<th>3 φ system</th>
<th>2 φ system</th>
<th>DC</th>
<th>3 φ system</th>
</tr>
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<tbody>
<tr>
<td>Stationary Reference Frame</td>
<td>Rotating Reference Frame</td>
<td>Stationary Reference Frame</td>
<td></td>
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</table>
Real time controller architecture

- Sensors
- Analog Interface
- User Interface
- Digital Logic
- Development System
- JTAG Interface
- Clock
- Reset
- Fault Interlock
- Gate Signal Generation
- FPGA
- Analog output (Debug)
- Serial Interface
- Network
- Brain
- Muscle Power
Equipment architecture

Converter Module

Real-time Controller

Muscle Power

Brain

Equipment

Load
Classical Control

- Speed Control
- Torque Control
- DC Motor

DC drive

AC Drive - Scalar Control

- Frequency Reference
- V/f Ratio
- PWM Modulator
- AC Motor

Modern Control

- Speed Control
- Torque Control
- Vector Control
- PWM Modulator
- AC Motor

AC Drive - Vector Control (Field Oriented Control)

- Speed Control
- Torque and Flux Control
- Optimal pattern
- AC Motor

AC Drive - Direct Torque Control

- Speed Feedback
Thank you