YSP Power Electronics Overview

Prof. Daniel Costinett
June 10, 2014
Voltage Levels

- 1V
- 10V
- 100V
- 10kV
- 1MV

Devices:
- Battery
- Hard drive
- Car battery
- Outlet
- Power lines
- Computer chip
- Laptop
- Tesla car
- Lamp
The War of the Currents

**DC**
+ Low-loss transmission
+ Asynchronous
+ Used by electronics, batteries, PV
+ 2-wire transmission
○ Can kill an elephant
- Difficult to control power flow
- Requires power electronics for voltage conversion

**AC**
+ Simple control of power flow
+ Zero-crossings
+ Easy to step convert voltage
+ Used by motors, generators, heaters
○ Can kill an elephant
- Increased losses in transmission
- Requires synchronization
- 3-wire transmission
Introduction to Power Conversion

- **Dc-dc conversion**: Change and control voltage magnitude
- **Ac-dc rectification**: Possibly control dc voltage, ac current
- **Dc-ac inversion**: Produce sinusoid of controllable magnitude and frequency
- **Ac-ac cycloconversion**: Change and control voltage magnitude and frequency
Example Server Power Distribution

- 16kVac 3Φ
- 400Vac 3Φ
- 380Vdc
- 48Vdc
- 12Vdc
A goal of current converter technology is to construct converters of small size and weight, which process substantial power at high efficiency.
US Energy Usage

Estimated U.S. Energy Use in 2013: ~97.4 Quads

Source: LLNL 2014. Data is based on DOE/EIA-0035(2014-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant “heat rate.” The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527
Power Loss in an Ideal Switch

Switch closed: \( v(t) = 0 \)

Switch open: \( i(t) = 0 \)

In either event: \( p(t) = v(t) \cdot i(t) = 0 \)

Ideal switch consumes zero power
Buck Converter: Basic SMPS Operation

DC component of $v_s(t)$ = average value:

$$V_s = \frac{1}{T_s} \int_0^{T_s} v_s(t) \, dt = DV_g$$
Buck Converter: Basic SMPS Operation

\[ V_s = \frac{1}{T_s} \int_{0}^{T_s} v_s(t) \, dt = DV_g \]
Implementation of Power Electronics

[Diagram of power electronics system with labeled components: SPDT Switch, Low-Pass Filter, Switching converter, Power input, Load, Sensor gain, Error signal, Reference input, Voltage source, Current sensor, and Time variables.]
Interfacing AC

![Diagram of an AC circuit with a Low-Pass Filter]

- $V_g$
- $v_s(t)$
- $L$
- $C$
- $i(t)$
- Low-Pass Filter
- $V_{ao}$

Graph showing:
- $f_s$
- $V_{dc}$
- $v(t)$

![Graph with time and voltage values]

- Time values: 0, 0.002, 0.004, 0.006, 0.008, 0.01, 0.012, 0.014, 0.016, 0.018
- Voltage values: $V_{dc}$, $\frac{V_{dc}}{2}$, $0$, $-\frac{V_{dc}}{2}$
Control System for Voltage Regulation
Switch Implementation

Realization of switch requires consideration of:
- Magnitude and polarity of current and voltage
- Frequency of switching actions
- Operating temperature
- Cost
- Control circuitry
SMPS Topologies
Power Electronics Overview

- Solid-state physics
- Circuit theory
- Systems and control theory
- Signal processing
- Electronics
- Electromagnetics
- Power systems
- Electric machines
- Simulation and computing
Design of Power Electronics


• To meet the demands of future applications, power electronics need to be designed with multi-objective tradeoffs and multi-function operation in mind
• Two example applications in EVs:
  • Drivetrain DC-DC converter
  • Battery management system
Applications of Power Electronics
Grid Applications of Power Electronics

- Wind
- Photovoltaic
- STATCOM
- HVDC

AC SST

Energy Storage
$63.5B Industry 2009 with 25% AAGR last 5 years
Airborne Wind Turbines

Kolar, J.W.; et al. "Conceptualization and multi-objective optimization of the electric system of an Airborne Wind Turbine,"
Solar Photovoltaic
Earth Orbiting Spacecraft
Future EVs
EV Power and Drive System

Diagram showing a power and drive system for an electric vehicle, including components such as battery charger, inverters, ac machines, and control systems.
Example: 2010 Prius

Power electronics (2 inverters and a boost DC-DC)
## Conventional Vs. Electric Vehicle

<table>
<thead>
<tr>
<th></th>
<th>Tank + Internal Combustion Engine</th>
<th>Electric Vehicle (EV) Battery + Inverter + AC machine</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Regenerative braking</strong></td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Tank-to-wheel efficiency</strong></td>
<td>≈ 20% 1.2 kWh/mile, 28 mpg</td>
<td>≈ 85% 0.17 kWh/mile, 200 mpg equiv.</td>
</tr>
<tr>
<td><strong>Energy storage</strong></td>
<td>Gasoline energy content 12.3 kWh/kg, 36.4 kWh/gallon</td>
<td>LiF 0.1 kWh/kg, 0.8 kWh/gallon</td>
</tr>
<tr>
<td><strong>Refueling</strong></td>
<td>5 gallons/minute 11 MW, 140 miles/minute</td>
<td>Level I (120Vac): 1.5 kW, &lt;8 miles/hour Level II (240Vac): 6 kW, &lt;32 miles/hour Level III (DC): 100 kW, &lt;9 miles/minute</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>12 ¢/mile [$3.50/gallon]</td>
<td>2 ¢/mile [$0.12/kWh]</td>
</tr>
<tr>
<td><strong>C (tailpipe, total)</strong></td>
<td>≈ (0 [current U.S. electricity mix])</td>
<td></td>
</tr>
</tbody>
</table>

(Prius-sized vehicle example)
A Vision: Renewable Sources + Battery Electric Vehicles

- Zero GHG emissions, no petroleum
- High efficiencies are feasible: 80% grid-to-wheel
- Challenges
  - Battery technology: cost, cycle life, power and energy density
  - Efficient, reliably and cost-effective drivetrain components
  - Need for charging infrastructure
  - Limited charging power, long charge-up times
Future Applications: Hyperloop

Figure 1. Energy cost per passenger for a journey between Los Angeles and San Francisco for various modes of transport.
Proposed Power Conversion Architecture

Figure 22. Linear accelerator concept for capsule acceleration and deceleration between 300 and 760 mph (480 and 1,220 kph).
Power management in mobile electronics

Battery example: single-cell Lithium-Ion
Power distribution: $V_{bat} = 2.7-4.5$ V

- **Major power consumers**: baseband digital, display, multiple radio channels
- **Power supply demands**: small footprint area & integration, high efficiency over wide range of loads, power management interface
IPhone 5 Internal Circuitry

- RFPA, LNA
- Power Mgmt IC
- Power Semiconductors, Inductors
Lighting Technologies

Conventional Technologies

Solid State Lighting

Light Emitting Diodes

Year of invention
1879
1904
1938
1959
1961
1981
1995

Light source efficiency in Lumen/Watt
50
100
150

1990
2000
2010
2020

1990
2000
2005
2006
2008
2010
HID Lighting Ballast
Energy Harvesting

**Goal** – Enable long life, low maintenance, wireless operation and miniaturization where not possible before

**Application** – medical & military devices, structural & industrial monitoring, ubiquitous remote devices; Power range: 1 µW – 1 mW
Implantable Biomedical Sensor

- RF energy harvesting used as an enabling technology for long lifetime, low power, high data throughput implantable devices

<table>
<thead>
<tr>
<th>$P_{out}$ (µW)</th>
<th>$\eta_{boost}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16</td>
<td>18.05</td>
</tr>
<tr>
<td>0.52</td>
<td>35.13</td>
</tr>
<tr>
<td>1.29</td>
<td>47.36</td>
</tr>
<tr>
<td>2.57</td>
<td>53.58</td>
</tr>
<tr>
<td>8.81</td>
<td>65.16</td>
</tr>
<tr>
<td>23.86</td>
<td>71.14</td>
</tr>
<tr>
<td>60.66</td>
<td>75.70</td>
</tr>
<tr>
<td>123.6</td>
<td>79.06</td>
</tr>
</tbody>
</table>

System is powered entirely from commercial 2.4 GHz WiFi Adapter
Power Electronics Applications

- RF Energy Harvesting
- Laptop Power Supply
- Drivetrain Power Electronics
- Future EVs