Introduction to Power Electronics in PV Systems

ECEN 2060

References:
- ECEN4797/5797 Intro to Power Electronics
ece.colorado.edu/~ecen5797
  http://ece.colorado.edu/~pwrelect/book/SecEd.html
**Example: Grid-Connected PV System**

One possible grid-connected PV system architecture

**DC input**
- \(V_{PV}, I_{PV}\)
- \(P_{PV} = V_{PV}I_{PV}\)

**Power electronics converter**
- Operate PV array at the maximum power point (MPP) under all conditions
- Generate AC output current in phase with the AC utility grid voltage
- Achieve power conversion efficiency close to 100%

\[
\eta_{converter} = \frac{P_{ac}}{P_{PV}} = \frac{V_{RMS}I_{RMS}}{V_{PV}I_{PV}}
\]

- Provide energy storage to balance the difference between \(P_{PV}\) and \(p_{ac}(t)\)

**Desirable features**
- Minimum weight, size, cost
- High reliability

**AC output**
\[
\begin{align*}
v_{ac}(t) &= \sqrt{2}V_{RMS} \sin(\omega t) \\
i_{ac}(t) &= \sqrt{2}I_{RMS} \sin(\omega t) \\
P_{ac} &= V_{RMS}I_{RMS}
\end{align*}
\]

\[
p_{ac}(t) = v_{ac}i_{ac} = V_{RMS}I_{RMS}(1 - \cos(2\omega t))
\]
Power electronics converter

One possible realization:

Class objectives: introduction to circuits and control of a DC-DC converter and a single-phase DC-AC inverter
Introduction to electronic power conversion

Four types of power electronics converters

- **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

- Control is invariably required
- In the PV system, for example:
  - Control input voltage of the DC-DC input voltage to operate PV at MPP
  - Control shape of the DC-AC output current to follow a sinusoidal reference
  - Control current amplitude to balance the input and output power
High efficiency is essential

\[ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} \]

\[ P_{\text{loss}} = P_{\text{in}} - P_{\text{out}} = P_{\text{out}} \left( \frac{1}{\eta} - 1 \right) \]

High efficiency leads to low power loss within converter
Small size and reliable operation is then feasible
Efficiency is a good measure of converter performance
Circuit components for efficient electronic power conversion?
Ideal switch

Power semiconductor devices (e.g. MOSFETs, diodes) operate as near-ideal power switches:

- When a power switch is ON, the voltage drop across it is relatively small
- When a power switch is OFF, the switch current is very close to zero

Switch closed:  $v(t) = 0$

Switch open:  $i(t) = 0$

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

Ideal switch consumes zero power

![Ideal switch diagram](image)
Capacitor

\[ i_C = C \frac{dv_C}{dt} \]

\[ P_C(t) = v_C(t)i_C(t) \]

For periodic \( v_C(t), i_C(t) \):

**No losses** (average capacitor power = 0)

\[
P_C = \frac{1}{T} \int_0^T p_C(t) dt = \frac{C}{T} \int_{v_C(0)}^{v_C(T)} v_C(t) dv_C = \frac{C}{2T} \left( v_C^2(T) - v_C^2(0) \right) = 0
\]

**Capacitor charge balance** (average capacitor current = 0)

\[
I_C = \frac{1}{T} \int_0^T i_C(t) dt = \frac{C}{T} \int_{v_C(0)}^{v_C(T)} dv_C = \frac{C}{T} \left( v_C(T) - v_C(0) \right) = 0
\]
Inductor

\[ v_L = L \frac{di_L}{dt} \]

\[ P_L(t) = v_L(t)i_L(t) \]

For periodic \( v_L(t), i_L(t) \):

**No losses** (average inductor power = 0)

\[
P_L = \frac{1}{T} \int_0^T P_L(t) \, dt = \frac{L}{T} \int_{i_L(0)}^{i_L(T)} i_L(t) \, di_L = \frac{L}{2T} \left( i_L^2(T) - i_L^2(0) \right) = 0
\]

**Inductor volt-second balance** (average inductor voltage = 0)

\[
V_L = \frac{1}{T} \int_0^T v_L(t) \, dt = \frac{L}{T} \int_{i_L(0)}^{i_L(T)} di_L = \frac{L}{T} \left( i_L(T) - i_L(0) \right) = 0
\]
Circuit components for efficient electronic power conversion

Power electronics converters are circuits consisting of semiconductor devices operated as (near-ideal) switches, capacitors and magnetic components (inductors, transformers)
Boost (step-up) DC-DC converter

Boost converter with ideal switch

\[ T_s = \text{switching period} \]

\[ f_s = 1/T_s = \text{switching frequency} \]

\[ D = \text{switch duty ratio (or duty cycle)}, \ 0 \leq D \leq 1 \]
Boost converter circuit

Boost converter with ideal switch

Realization using power MOSFET and diode

Power MOSFET and diode operate as near-ideal switches
## Power MOSFETs and diodes

### Characteristics of several commercial power MOSFETs

<table>
<thead>
<tr>
<th>Part number</th>
<th>Rated max voltage</th>
<th>Rated avg current</th>
<th>$R_{on}$</th>
<th>$Q_s$ (typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRFZ48</td>
<td>60V</td>
<td>50A</td>
<td>0.018Ω</td>
<td>110nC</td>
</tr>
<tr>
<td>IRF510</td>
<td>100V</td>
<td>5.6A</td>
<td>0.54Ω</td>
<td>83nC</td>
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<tr>
<td>IRF540</td>
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<td>28A</td>
<td>0.077Ω</td>
<td>72nC</td>
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<td>APT10M25BNR</td>
<td>100V</td>
<td>75A</td>
<td>0.025Ω</td>
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<td>10A</td>
<td>0.55Ω</td>
<td>63nC</td>
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<tr>
<td>MTM15N40E</td>
<td>400V</td>
<td>15A</td>
<td>0.3Ω</td>
<td>110nC</td>
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<tr>
<td>APT5025BN</td>
<td>500V</td>
<td>23A</td>
<td>0.25Ω</td>
<td>83nC</td>
</tr>
<tr>
<td>APT1001RBNR</td>
<td>1000V</td>
<td>11A</td>
<td>1.0Ω</td>
<td>150nC</td>
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</tbody>
</table>

Low on-resistance implies low conduction losses

### Fast switching enables high switching frequencies, e.g. 100’s of kHz to MHz

<table>
<thead>
<tr>
<th>Part number</th>
<th>Rated max voltage</th>
<th>Rated avg current</th>
<th>$V_f$ (typical)</th>
<th>$t_r$ (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ultra-fast recovery rectifiers</strong></td>
<td></td>
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<tr>
<td>MUR815</td>
<td>150V</td>
<td>8A</td>
<td>0.975V</td>
<td>35ns</td>
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<tr>
<td>MUR1560</td>
<td>600V</td>
<td>15A</td>
<td>1.2V</td>
<td>60ns</td>
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<td>RHU100120</td>
<td>1200V</td>
<td>100A</td>
<td>2.6V</td>
<td>60ns</td>
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<td><strong>Schottky rectifiers</strong></td>
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<td>MBR6030L</td>
<td>30V</td>
<td>60A</td>
<td>0.48V</td>
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<td>444CNOQ045</td>
<td>45V</td>
<td>440A</td>
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<tr>
<td>30CPQ150</td>
<td>150V</td>
<td>30A</td>
<td>1.19V</td>
<td></td>
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</tbody>
</table>

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Voltage, current and frequency ratings of power semiconductor devices

MOSFET: Metal Oxide Semiconductor Field Effect Transistor
IGBT: Insulated Gate Bipolar Transistor
SCR (or Thyristor): Silicon Controlled Rectifier
GTO: Gate Turn Off thyristor
Boost converter analysis

original converter

switch in position 1

switch in position 2
Inductor voltage and capacitor current

\[ v_L = V_g \]
\[ i_C = -\frac{v}{R} \]

Small ripple approximation:

\[ v_L = V_g \]
\[ i_C = -\frac{V}{R} \]
Inductor voltage and capacitor current

\[ v_L = V_g - v \]
\[ i_C = i_L - v / R \]

Small ripple approximation:

\[ v_L = V_g - V \]
\[ i_C = I - V / R \]
Inductor voltage and capacitor current waveforms

Periodic steady-state operation

- Inductor volt-second balance: average inductor voltage = 0
- Capacitor charge balance: average capacitor current = 0
Inductor volt-second balance

Net volt-seconds applied to inductor over one switching period:

$$\int_{0}^{T_s} v_L(t) \, dt = (V_g) \, DT_s + (V_g - V) \, D'T_s$$

Equate to zero and collect terms:

$$V_g \, (D + D') - V \, D' = 0$$

Solve for V:

$$V = \frac{V_g}{D'}$$

The voltage conversion ratio is therefore

$$M(D) = \frac{V}{V_g} = \frac{1}{D'} = \frac{1}{1 - D}$$
Boost DC voltage conversion ratio $M = \frac{V_{out}}{V_g}$

Boost DC-DC converter steps-up a DC input voltage by a ratio $M$ which is electronically adjustable by changing the switch duty ratio $D$. The relationship between $M$ and $D$ can be expressed as:

$$M(D) = \frac{1}{D'} = \frac{1}{1 - D}$$
Simulink model

Input voltage $V_g = 100$ V
Inductance $L = 200$ $\mu$H
Capacitance $C = 10$ $\mu$F
Load resistance $R = 100$ $\Omega$
Switch duty cycle $D = 0.5$
Output voltage $V_{out} = 200$ V
Input current $I_g = I_L = 4$ A
Power $P = 400$ W
Switching frequency $f_s = 100$ kHz
Switching period $T_s = 10$ $\mu$s
Averaged (DC) model

No losses:

\[ V_{out} = \frac{1}{1-D} V_g \quad I_g = \frac{1}{1-D} I_{out} \]

\[ V_g I_g = V_{out} I_{out} \]

Ideal boost DC-DC converter works as an ideal DC transformer with an electronically adjustable step-up ratio

\[ n = M(D) = \frac{1}{1-D} \]
Modeling of losses

• Losses in switched-mode power converters:
  ▪ **Conduction losses**, due to voltage drops across inductor winding resistance, and across power semiconductor switches when ON
    • Conduction losses depend strongly on the output power
  ▪ **Switching losses**, due to energy lost during ON/OFF transitions
    • Switching losses are not strongly dependent on output power; a portion of switching loss remains even at zero output power
    • Switching losses are proportional to the switching frequency
  ▪ **Other losses**, including:
    • Losses in magnetic cores
    • Power needed to operate control circuitry
Switching waveforms and switching losses

MOSFET turn-on transition

Drain voltage

Drain current

Switching power loss = Transition energy loss * Switching frequency

\[ p_t = V_t i_t \]
Switching waveforms and switching losses

MOSFET turn-off transition

Switching power loss = Transition energy loss * Switching frequency
Averaged (DC) model with losses

- Small $R_L$ models conduction losses due to inductor winding resistance and power switch resistances.
- Small $I_{sw}$ models switching and other load-independent losses.
- Efficiency with losses, when the load current $I_{out}$ is known:

$$\eta = \frac{1}{1 + \frac{R_L}{(1-D)^2} \frac{(I_{out} + I_{sw})^2}{V_{out}I_{out}} + \frac{I_{sw}}{I_{out}}}$$
Example: efficiency for various $R_L$

Assume:
- Resistive load $R = V_{out}/I_{out}$
- $I_{sw} = 0$

$$\eta = \frac{1}{1 + \frac{R_L}{(1 - D)^2} \frac{1}{R}}$$

Note that it is more difficult to achieve high efficiency if a large step-up ratio is required (i.e. if duty-ratio $D$ is close to 1)
• Switches in position 1 during $DT_s$, in position 2 during $(1-D)T_s$
• Switching frequency $f_s$ is much greater than the AC line frequency (60 Hz or 50 Hz)
• By controlling the switch duty ratio $D$, it is possible to generate a sinusoidal AC current $i_{ac}$ (+ small switching ripple) in phase with the AC line voltage, as long as the input DC voltage $V_{DC}$ is sufficiently high, i.e. as long as $V_{DC}$ is greater than the peak AC line voltage
\[ v_L = V_{DC} - v_{ac} \]

\[ i_L = i_{ac} \]

\[ i_{in} = i_L \]
\[ v_L = -V_{DC} - v_{ac} \]

\[ i_L = i_{ac} \]

\[ i_{in} = -i_L \]
Inductor volt-second balance

- Note that switching frequency $f_s \gg$ ac line frequency
- Over a switching period, $v_{ac}(t) \approx$ const.

\[ v_L = \begin{cases} 
+V_{DC} - v_{ac}, & 0 \leq t \leq DT_s \\
-V_{DC} - v_{ac}, & DT_s < t \leq T_s 
\end{cases} \]

\[ V_L = \frac{1}{T_s} \int_{0}^{T_s} v_L(t) dt = D(V_{DC} - v_{ac}) + (1 - D)(-V_{DC} - v_{ac}) = (2D - 1)V_{DC} - v_{ac} = 0 \]

\[ M(D) = \frac{v_{ac}}{V_{DC}} = 2D - 1 \]

\[ -1 \leq M(D) \leq 1 \]

$V_{DC}$ must be greater than the peak of $v_{ac}$
Control objectives:

- $i_{ac} = I_M \sin (\omega t)$, in phase with AC line voltage $v_{ac}(t)$
- Amplitude $I_M$ (or RMS value) adjustable to control power delivered to the AC line

\[
v_{ac}(t) = \sqrt{2}V_{\text{RMS}} \sin(\omega t)
\]
\[
i_{ac}(t) = \sqrt{2}I_{\text{RMS}} \sin(\omega t)
\]
\[
P_{ac}(t) = v_{ac}i_{ac} = V_{\text{RMS}}I_{\text{RMS}}(1 - \cos(2\omega t))
\]
\[
P_{ac} = V_{\text{RMS}}I_{\text{RMS}}
\]
A simple current controller

\[ i_{ref} = I_{Mref} \sin(\omega t) \]

- \( i_L < i_{ref} - \Delta i/2 \): position 1
- \( i_L > i_{ref} + \Delta i/2 \): position 2
- \( i_L \) is always within \( \Delta i/2 \) of \( i_{ref} \)

\(-\Delta i/2 \rightarrow \Delta i/2 \) current ripple

\(-\Delta i/2 \rightarrow i_{ref} - i_L \rightarrow \Delta i/2 \) switch control

position 1

position 2

comparator with hysteresis
Simulink model

**dcac_switching.mdl**

Waveforms $v_{ac}(t)$, $i_{ac}(t)$, $i_{in}(t)$, and switch control over one AC line period (1/60 s)

Input voltage

$$V_{DC} = 200 \text{ V}$$

Inductance $L = 2 \text{ mH}$

AC: $120\text{Vrms, 60Hz}$

$$I_{Mref} = 3\sqrt{2} = 4.2 \text{ A}$$

$$\Delta I_L = 1 \text{ A}$$

$P_{ac} = 360 \text{ W}$

With this simple controller, switching frequency is variable
Averaged DC-AC inverter model with losses

\[
\begin{align*}
+ & \quad I_{in} \quad 1 : 2D - 1 \quad R_L \quad i_{ac} \\
V_{DC} & \quad I_{sw} \quad \text{ideal transformer} \\
- & \quad v_{ac}
\end{align*}
\]

- Small \( R_L \) models inductor winding resistance and power switch resistances
- Small \( I_{sw} \) models switching and other losses
DC-AC inverter efficiency example

Simulink model

dcac_averaged.mdl

Input voltage $V_{DC} = 200$ V
AC: 120Vrms, 60Hz
$R_L = 0.8 \ \Omega$
$I_{sw} = 50 \ \text{mA}$
$P_{ac} = 0$ to 600 W

- Inverter efficiency of about 95% is typical
- At high power levels, conduction losses due to $R_L$ dominate
- At low power levels, efficiency drops due to switching and other fixed losses