Cost-Effective Hundred-Year Life for Single-Phase Inverters and Rectifiers in Solar and LED Lighting Applications through Port-Based Ripple Management Port

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SmartSpark Energy Systems
Key Point

- Single-phase energy conversion requires storage.
Key Points

- Power electronics life needs to match application life.
- Energy storage requirements in single-phase grid-connected applications lead to large (electrolytic) capacitors and limit life.
- Successful designs that minimize energy storage and deliver extreme life at temperature are presented here.
Single-Phase Conversion

• In single-phase power, voltage and current are sinusoidal.

• Instantaneous power:
  \[ p(t) = V_0 I_0 \cos(2\omega t + \phi) \]

• Desired output: constant energy flow.

• The difference: storage
Application Push

• LED lighting: 100,000 operating hours, increasing quickly.

• Photovoltaic conversion: 30 to 40 year operation.

• Both benefit from integrated power electronics.

www.philipslumileds.com
Reliability Limitations

• System reliability is limited by a few relatively failure-prone components:
  – Fans
  – Electrolytic capacitors
  – Optocouplers

• Other problems areas:
  – Batteries
  – Connectors

• Also quality control and manufacturing

• Usually storage is addressed with large electrolytic capacitors.

• Must store the area under a half cycle of $p(t)$.

• Amplitude: same as $<P>$.

LED flicker without energy storage
Traditional Single-Phase Cases

• Motors:
  – Rotor acts as flywheel to store the energy mechanically.

• Lamps
  – Incandescent: thermal time constants
  – Fluorescent: yes, it flickers (some impact from phosphors and ballasts)
Power Supplies

• Energy is stored in electrolytic capacitors.
Operating Life and Reliability

- Operating life and failure rates not the same.
- Modern electrolytic capacitors have low failure rates, but also limited operating life.
- Example:
  - 5000 hrs operating life at 105°C
  - Pre-wearout failure rate: 20 ppb/yr
- Expected life at 85°C: 20000 hrs.
- Reliability dominated by life expectancy.

www.capacitorlab.com/visible-failures
Energy Requirements

- Integrate the time plot.
- Required energy storage for double-frequency power:
  \[ W_{\text{min}} = \frac{P}{2\pi f} \]
- No topology or tricks can reduce this.
Dc bus configuration

- Capacitors: voltage nearly constant, *but* energy variation requires voltage variation.
- Capacitor current: double frequency.
Dc bus configuration

• The energy storage on the dc bus is

\[ W = \frac{P}{4\pi f V \Delta V} \]

• Ratio of actual energy to required energy is

\[ \frac{W_{dc}}{W_{\text{min}}} = \frac{V_{dc}}{2 \Delta V} \]

• 1% bus ripple means 50x energy storage, 10% means 5x, etc.

• Dual analysis holds for inductive storage
## Dc Bus Configuration

2% ripple, 100 W application

<table>
<thead>
<tr>
<th>Dc bus voltage</th>
<th>Capacitance required</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 V</td>
<td>23000 uF</td>
</tr>
<tr>
<td>48 V</td>
<td>5760 uF</td>
</tr>
<tr>
<td>100 V</td>
<td>1330 uF</td>
</tr>
<tr>
<td>380 V</td>
<td>92 uF</td>
</tr>
<tr>
<td>600 V</td>
<td>37 uF</td>
</tr>
</tbody>
</table>
Active Filtering

- Known active filter configurations can reduce capacitance by decoupling voltage variation: inject compensation current\(^1\).
- In this case: double frequency filter current.

Power Flows?

- Obvious: capacitor voltage and current are linked.
  - Notice that $i_C(t) = k \cos(2\omega t)$ is *not consistent* with desired power
  - V-I product at $4\omega t$.

- Avoid this and truly *minimize* energy storage and capacitance requirements.

- Need instantaneous power match – deliver double-frequency power directly.
Achieving the Minimum

• Solution: Let $i_C(t) = I_0 \cos(\omega t + \theta)$

$$P(t) = \frac{I_0^2}{\omega C} \sin(\omega t + \theta) \cos(\omega t + \theta)$$

• Matches if $\theta = -\frac{\pi}{4}$, $P_0 = \frac{I_0^2}{2\omega C}$

• Peak voltage: $V_c^2 = \frac{P_0}{\pi fC}$

Patents pending
## Minimum Storage

### 0% ripple, 100 W application

<table>
<thead>
<tr>
<th>Peak voltage</th>
<th>Capacitance required</th>
<th>Before (2% ripple)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 V</td>
<td>921 uF</td>
<td>23000 uF</td>
</tr>
<tr>
<td>48 V</td>
<td>230 uF</td>
<td>5760 uF</td>
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<tr>
<td>100 V</td>
<td>53 uF</td>
<td>1330 uF</td>
</tr>
<tr>
<td>380 V</td>
<td>3.7 uF</td>
<td>92 uF</td>
</tr>
<tr>
<td>600 V</td>
<td>1.5 uF</td>
<td>37 uF</td>
</tr>
</tbody>
</table>
Film Capacitors

- The higher voltage levels are an ideal match to film capacitors.
- The best film capacitors have high reliability with no special wear-out mechanisms: failure rates are typically two orders of magnitude better than for electrolytic capacitors.
- Designs that completely eliminate electrolytic capacitors have much higher reliability.
Sample Topology

• Ac link with active filter port.
Other Reliability Enhancements

- Thyristors for grid connection
  - Thoroughly proven in grid-connected configurations
  - About an order of magnitude lower failure rates than IGBTs and MOSFETs
  - Supports simple gate drives
- Careful attention to parts count.
- Parts fully qualified at 85°C.
- As shown: bidirectional at dc port.
Typical Traces

Low-cost implementation, 100 W inverter.
Reliability and Life Results

• MIL-217F understood to be extremely conservative.
  – Suitable basis for comparison
• Power electronics packaged with application.
  – Design peak: 85°C.
• Recent MIL-217 analysis of actual hardware for PV: 2 million hour MTBF.

Photovoltaic ac module
SmartSpark Energy Systems, Inc.
Reliability and Life Results

• Expected result: likely to exceed 500 year MTBF or more in actual service.

• Operating life now limited by MTBF, not by additional wear-out mechanisms.

• Result is 100x compared to electrolytics.

• The result: grid-connected inverters and rectifiers with true hundred-year operating life for single-phase applications.
Conclusion

• Single-phase conversion requires substantial energy storage.
• The minimum capacitance and energy to eliminate double-frequency power ripple has been established.
• Cost-effective single-phase converters with at least 100 year expected operating life have been demonstrated in hardware.