An Efficiency-Focused Design of Direct-DC Loads in Buildings

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Motivation

• DC buildings are efficient
  – Up to 14% more efficient than AC
  – Most loads are internally DC
• Barriers to entry
  – Lack of DC loads on the market
  – Many 380 V DC demonstrations use loads that are not designed for 380 V
• This work explores how DC loads can be designed to leverage the benefits of DC distribution
Categories of Loads

- **DC-connected:** Internal DC stage of these loads can be connected or hardwired directly to the DC distribution.

- **DC-converted:** Requires a DC/DC converter in order to connect to the DC.

- **DC-indifferent:** Equivalent benefits with AC or DC input.

**Electric Loads**
- Lighting
  - Incandescent
  - Fluorescent
  - LED
- Electronics
  - Computer
  - Wireless Charger
- Heating Element
  - Water Heater
- Motor Loads
  - Fixed Speed Motor
  - Cheap Low Power Motor
  - HVAC Unit Compressor
  - Refrigerator
  - Water Heater

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**DC-indifferent:**
- DC-indifferent: Equivalent benefits with AC or DC input.

**Notes:**
- DC-connected
- DC-converted
- DC-indifferent
Motor Loads – BLDC Motors

- The most efficient motor loads use variable speed drive brushless DC (BLDC) motors
- AC BLDC motors have a rectifier, internal DC capacitors, and inverter
- The internal DC caps can connect directly to DC distribution, avoiding the rectification stage
Motor Loads – Bath Fan

- Internal DC bus: 12 V
- Modify for 48 V PoE input

1. Use a 48/12 V DC/DC converter: -4% consumption
2. Redesign inverter/motor for 48 V: potentially -14% consumption
Motor Loads – DC Bus Voltage

- No need for DC/DC converter if DC bus voltage equals DC distribution voltage
- BLDC motors can be redesigned for any DC bus voltage
  - Replace inverter if needed
  - High-voltage motors will use thinner wire and more turns on the stator coil
  - Winding area and loss is equivalent
Lighting – Today’s Integration Paradigm

• Most LED drivers are integrated into bulb, allows plug-and-play
  – Pros:
    • Plug-and-play compatibility
  – Cons:
    • High conversion ratio is inefficient
    • Components must tolerate high voltage: bulky and expensive

• The problems of integration are even worse at 380 V DC
• We propose (1) remote drivers, (2) series fixtures
Lighting – Why Remote Drivers?

- Reduces life-cycle cost by up to 58%
  - Separating the driver from the fixture doubles the fixture’s life span (40%)
  - Clever driver placement reduces maintenance costs for replacing light bulbs, especially in high bay (30%)

- Easy to add ancillary services
  - Wireless dimming
  - Battery backup

- Most remote drivers on the market wire fixtures in parallel

\[ V_{\text{FIX}} + \text{Fixture 1} - \]  \[ V_{\text{FIX}} + \text{Fixture N} - \]  \[ \text{Driver} = \text{Neutral} \to \text{Hot} \]
Lighting – Why Series Fixtures?

• Reduces life-cycle cost (10%-20%)
  – One driver powers many fixtures
• Improves efficiency (>98%)
  – Can stack fixtures such that $N \cdot V_{\text{FIX}}$ is close to 380 V
  – In prototype, adding extra bulbs increased efficiency from 94% to 98%
Conclusion

• Design DC loads to avoid unnecessary conversion stages
• Motor loads can be easily redesigned with any DC bus voltage
• Zone lighting at 380 V can benefit from series remote drivers
Thank you!
Project Goals

• Categorize loads based on how they benefit from DC
• Modify several AC loads for DC input and demonstrate reduced consumption
• Determine how to optimally design various classes of loads for DC input
Motor Loads - Sizing the DC Capacitors

- Reasons for DC capacitors
  - Filter PWM ripple (20-100 kHz)
  - Provide a buffer for transients in load current
  - Filter 120 Hz AC ripple from the DC bus
- DC loads do not need to filter 120 Hz AC ripple
- DC loads allow for smaller DC capacitors for both motor loads and lighting

![Model to analyze AC and PWM ripple](image)

![Model to analyze load transients](image)

<table>
<thead>
<tr>
<th>C (uF)</th>
<th>AC Ripple (V)</th>
<th>PWM Ripple (V)</th>
<th>Transient Ripple (V)</th>
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Lighting – Low Voltage

- Many task lamps or PoE fixtures have their own integrated LED drivers
  - Two conversion stages: power distribution module (PDM) and LED driver
- Allowing the PDM to act as an LED driver reduces conversion stages
- USB task lamp
  - USB charging station acts as LED driver
  - Uses Qualcomm quick charge to control current
Bypass Circuit