Very high voltage AC-DC power:
From 3-phase to single phase offline bias supplies

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What will I get out of this session?

- **Purpose:**
  - Design Considerations for low power bias supplies from 3-phase inputs.
  - Configurations to meet the bulk cap and switch voltage rating.

- **Part numbers mentioned:**
  - UCC2872x, UCC2891x, UCC2870x, UCC2871x, UCC2888x, UCC28C4x, LM5021

- **Reference designs mentioned:**
  - PMP11236, PMP10937, PMP10834, PMP7769, PMP10415, TIDA-00628, PMP8678, TIDA-00173, PMP11302

- **Relevant End Equipment:**
  - E-Meters, Industrial Power Supplies
Agenda

• High voltage background
  • Why so high, what are the implications?
• Bias supplies and high voltages
  • Why are they needed, what topologies can be used?
• Bulk capacitor considerations
• Switch rating considerations
• Conclusions
Power distribution grid

- Power distribution at very high voltage – reduced currents & losses; lower cost & weight infrastructure
- Three-phase distribution – allows constant power transfer; lower rms currents
- High kV distribution voltage – down-converted at local distribution transformer.
  - Single phases tapped off for domestic use at ~120/240 V ac
  - High power loads supplied with 3-phase
Three phase supply voltages

- Three phase voltage is typically 400 V ac in Europe and 210-270 V ac in the US
- Voltage levels vary considerably by region, by configuration and by application
- Voltage ranges of 525-600 V ac or up to 690 V ac are sometimes encountered

Three phase loads

- Three-phase induction motors, industrial motor drives
- High power heating and welding equipment
- High power UPS for Data centers
- High voltage EV chargers
- E-meters – sometimes three-phase rated to withstand mistaken phase-phase wiring
Auxiliary bias supplies for three-phase input voltages

- Require bias power at low voltages to power controllers, gate drivers, CPUs etc.
- High input voltage => require physically larger and more expensive components
  - Since power is low, large & costly bias supply becomes unpalatable for customers

- Principal design requirements:
  - Robust and reliable
  - Low cost
  - Low EMI and low noise
  - Easy to design & develop.

- Secondary considerations:
  - Efficiency & thermal performance
  - Regulation & cross-regulation accuracy
  - Size
  - Fault response
High-voltage bias supplies topologies

- Most common approaches:
  - Non-isolated outputs: HV Buck or Flyback
  - Isolated outputs: Flyback

Most significant components for high-voltage — *bulk capacitors and the power switch.*
Low power, non-isolated integrated buck

- **UCC28880/1 – 700-V integrated switchers** [different $R_{ds(on)}$]
- Can be used in buck configuration up to $\sim450$ V ac input line
- E.g. **PMP11236** dual 24-V & 5-V outputs
- Can be deployed in high-side or low-side
- Can be used in non-isolated Flyback for higher power

### Table 1. Current Handling Capability for UCC28880 and UCC28881

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>MAXIMUM OUTPUT CURRENT for 85 ~ 265 VAC OPEN FRAME DESIGN</th>
<th>MAXIMUM OUTPUT POWER for 85 ~ 265 VAC OPEN FRAME DESIGN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NON-ISOLATED BUCK</td>
<td>FLYBACK</td>
</tr>
<tr>
<td>UCC28880</td>
<td>100 mA</td>
<td>3 W</td>
</tr>
<tr>
<td>UCC28881</td>
<td>225 mA</td>
<td>4.5 W</td>
</tr>
<tr>
<td>UCC28880</td>
<td>Discontinuous Conduction Mode (DCM)</td>
<td>150 mA</td>
</tr>
<tr>
<td></td>
<td>Continuous Conduction Mode (CCM)</td>
<td>225 mA</td>
</tr>
<tr>
<td>UCC28880</td>
<td>Discontinuous Conduction Mode (DCM)</td>
<td>70 mA</td>
</tr>
<tr>
<td></td>
<td>Continuous Conduction Mode (CCM)</td>
<td>100 mA</td>
</tr>
</tbody>
</table>

**Figure 16. Universal Input, 12-V, 226-mA Output High-Side Buck**
Low power, non-isolated buck with external FET

- External FET controlled by PWM IC for higher current & wider Vin/Vout range
- UCC287xx or UCC28C4x families can be used with external FET, e.g. **PMP10937**
- D2/C2 generates level-shifted FB signal – tradeoff no-load regulation vs burst freq
Low power isolated bias supply – Flyback

• For isolation, Flyback is near-universal choice
  • Only requires single magnetic for both isolation and voltage conversion

• Inherently better-suited to wide input range
  • Disadvantage – peak switch voltage is higher than the input voltage.

• For universal input range (90-264 V ac), 650-700V switch is typical

• For 440 V ac, switch rating > 1kV is required
  • Unless the bulk cap voltage is clamped or reduced in some way
Bulk capacitors

• Necessary for energy storage & filtering of 50-Hz AC voltage
• Aluminium electrolytics: high volumetric efficiency relative to other capacitor types
• Despite low cost vs other capacitor types, still quite expensive – big % of BOM cost
• Single-phase mains 240 V ac + 10% tolerance -> 373 V peak =>
  • Wide range of 400-V aluminum electrolytic caps available
  • At > 450-V aluminium electrolytics become expensive
  • Capacitance values required for 1-W to 100-W levels not generally available above 600 V
• How to cope with high bus voltage up to 1 kV? Several possible methods
Bulk capacitors for high bus voltage – connect in series

- Extra bulk caps connected in series to meet required voltage rating
- Most common approach
- Example here from PMP10236
- Here max AC input 440 V ac, peak equivalent to 622 V dc
- Two 400-V caps stacked in series to achieve required rating
Advantages
- Robust and reliable
- Simple implementation
- Re-use existing 400-V rated caps

Disadvantages
- More caps required to achieve required capacitance
  - Expensive, bulky
- Balancing resistors required to ensure that voltage divides equally across caps
  - Extra dissipation, PCB area and cost
  - Balancing current must be $>>$ cap leakage current
limit high bus voltage – add input clamp/regulator

- TVS diode sets clamp voltage
- BJT transistor drops the excess voltage
- Clips the voltage to the bulk cap
- BJT limited by base current and R2 value, causes line-dependent clamp
  - See appendix slide for more detail
- At higher power (> ~3 W), MOSFET may be required instead of BJT
- Disadvantage – high voltage MOSFETs are more expensive than high voltage BJTs.
Limit high bus voltage – add input clamp/regulator

• Advantages
  • Smaller solution size vs extra bulk capacitance
  • Lower cost solution, (BJT + R + TVS) vs bulk cap
  • Allows lower voltage-rating power switch
  • Effective for short-term line surges

• Disadvantage
  • Limited in power capability if using BJT; MOSFET solution adds cost
  • Can suffer high clamp dissipation if operated continuously at high line
High voltage power switch – single switch options

- Simplest solution – use a single high voltage Si FET
  - E.g. PMP7769 8-W Flyback
  - 860 V dc max Vin
  - LM5021-based fixed-frequency
  - 1.5-kV Si MOSFET STP3N150 6-ohm
- But SiC FETs getting cost competitive...
High voltage power switch – SiC switch options

• E.g. PMP10415 54-W Flyback

• Multi-output Flyback

• Based on UCC28700

• Uses 1.2-kV Silicon Carbide MOSFET
  • Rohm SCT2450KEC 0.45-ohm
High voltage power switch – BJT switch options

- Low cost option – high voltage BJTs
  - Less expensive than high voltage MOSFETs
- BJTs are current-controlled – more complex drive requirements compared to MOSFETs
- Excess base current => saturation & very slow turn off
- Proportional drive
  - Modulates base current, proportional to load
  - Light load – base not driven with excess current vs collector current, improves switching speed & efficiency

<table>
<thead>
<tr>
<th>Part</th>
<th>Manufacturer</th>
<th>Voltage Rating</th>
<th>$V_{CEO}$</th>
<th>$V_{CBO}$</th>
<th>$I_c$</th>
<th>Est High Vol Cost</th>
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<tr>
<td>STN2580</td>
<td>ST</td>
<td>400V</td>
<td>800V</td>
<td>1A</td>
<td>$0.05$</td>
<td></td>
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<tr>
<td>ST13003</td>
<td>ST and others</td>
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<td>700V</td>
<td>1.5A</td>
<td>$0.05$</td>
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<td>ST</td>
<td>500V</td>
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<td>1.5A</td>
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<td>ON/Fairchild</td>
<td>800V</td>
<td>1,100V</td>
<td>1.5A</td>
<td>$0.10$</td>
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<tr>
<td>KSC5027</td>
<td>ON/Fairchild</td>
<td>800V</td>
<td>1,100V</td>
<td>3A</td>
<td>$0.11-$0.12</td>
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<tr>
<td>FJI5603</td>
<td>ON/Fairchild</td>
<td>800V</td>
<td>1,600V</td>
<td>3A</td>
<td>$0.15$</td>
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</tbody>
</table>
High voltage power switch – BJT switch controllers options

- UCC28720 & UCC28722 designed for high voltage BJTs
  - Current source output rather than voltage source
  - Proportional drive, improves light load performance
  - Ideal for low power, high voltage applications
- High BJT blocking voltage may allow removal of snubber
  - E.g. TIDA-00628 BUJ302AX 1,050-V $V_{CESM}$
High voltage power switch – cascode arrangement

• Cascode two lower voltage devices in series
  • Achieves desired rating with LV devices
• Lower device driven by controller
• Upper device switched via the source/emitter
• For low power, integrated devices can be used as lower cascode switch, e.g. UCC28910/28911
  • Reduces the solution cost
• For higher power level, two external switches may be required.
High voltage power switch – cascode example

- E.g. [TIDA-00173](https://www.ti.com/TIDA-00173) 50-W Flyback
- 690 V ac, up to 1200 V dc
- ~300 V reflected
- Require Vds 1200 + 300 + spikes + margin = ~1.8-2 kV
- Cascode of two 950-V MOSFETs
- Efficiency > 88% @ full load, 400 V dc
High voltage power switch – non-isolated cascode example

- **PMP11302** – same cascode concept used for non-isolated 2.5-W buck design
- **UCC28881** (700-V max) cascaded with external MOSFET (650-V max)
- Increase voltage rating to ~1200 V (note three 400-V bulk caps in series)
Conclusions & key take-aways

- High voltage input adds considerable cost and component count to bias supplies
- Various methods to deal with voltage ratings for bulk capacitors and power switch
- Choosing the best configuration for your application bias supply can minimise cost & size overhead, whilst preserving required robustness.
- [TI Designs](https://www.ti.com) has many high voltage reference designs
  - May be suitable for your application, or give a starting point for your design.