LEDs for General Illumination – A Disruptive Technology

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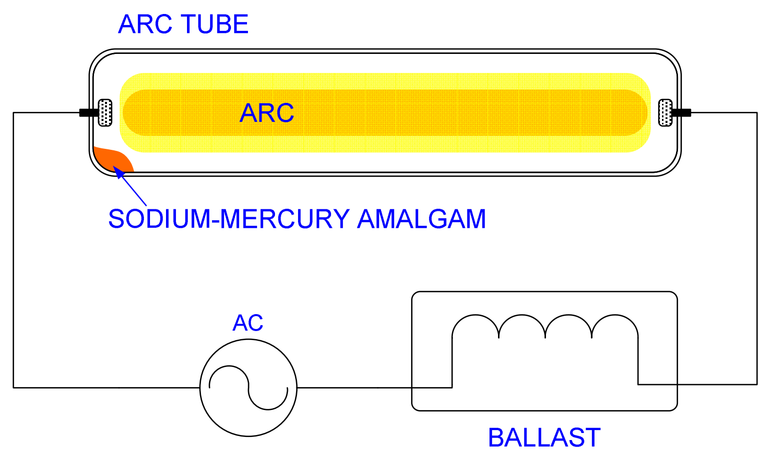
General Purpose Lighting – Where We are Today

- Commercial/Industrial
  - Factory Lighting
  - Street Lamps
  - Types
    - Mercury Vapor
    - Sodium (High/Low Pressure)
    - Other High Intensity Discharge (HID)
    - Fluorescent

Courtesy Wikipedia

High Pressure Sodium Lamp



General Purpose Lighting Today

- Residential
  - Incandescent
    - Tungsten, Halogen
  - Compact Fluorescent
  - Fluorescent

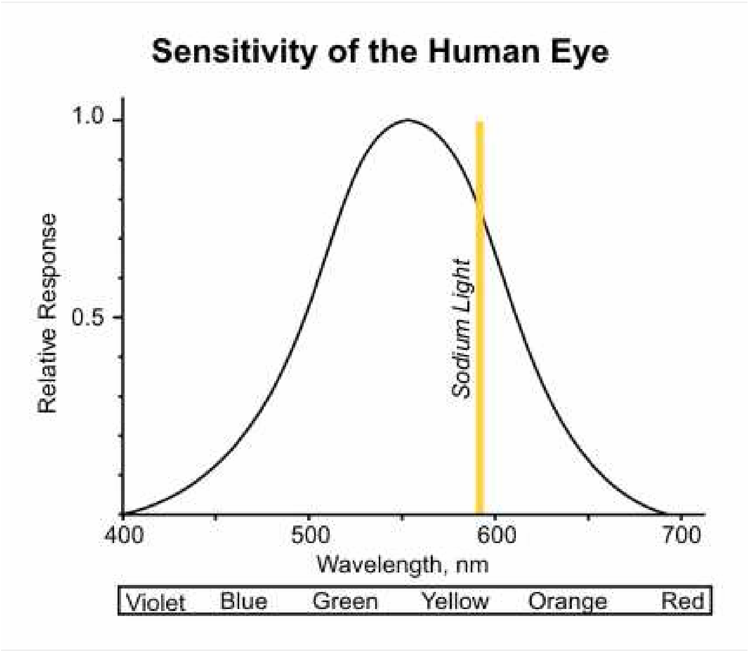
Photos courtesy OSRAM SYLVANIA

General Purpose Lighting Today

- Terminology and Performance
  - Efficiency/Efficacy
    - Cost of operation
    - Efficacy – Measure of output useful for illumination determined by the sensitivity of the human eye
    - Incandescent – 2.6% luminous efficacy, 100W tungsten [1]
    - Mercury Vapor - < 6% (coated) [8]
    - Compact FL – < 8.8 % luminous efficacy, 5-24W [1]
    - Fluorescent – < 15.2% luminous efficacy [1]
    - HP Sodium – 22% [1]
    - LP Sodium – 27% [1]

General Purpose Lighting Today

- Characteristics
  - Color
    - Chromacity/Color temperature
    - How close is output to natural sunlight at noon?



Human Eye Sensitivity and Low Pressure Sodium Spectrum[5]

General Purpose Lighting Today

- Characteristics (cont'd)
  - Warm-up
    - How long before intensity/color is steady state?
      - Mercury Vapor
      - Sodium
        - » LPS/SOX low pressure (600nm)
        - » HPS/SON
      - Compact Fluorescent/Fluorescent
  - Reliability/Life Expectancy/Disposal
    - Service/Maintenance costs
    - Mercury Vapor – 24,000 hours (50% output @ 5 years)
    - LPS/SOX Sodium - 18,000 hours
    - Incandescent - 1000 hours
    - Disposal (toxic/reactive)

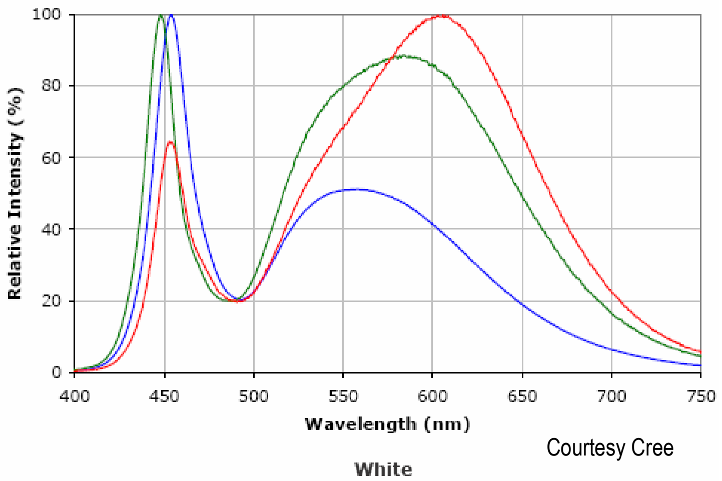
Power Requirements

- Conventional Lighting
  - AC Power
    - Off-line AC mains (120/240/415 VAC, etc.)
    - Low voltage AC systems (12 VAC)
      - Architectural lighting
    - Resistive (incandescent), or
    - Ballasted
      - Starter
      - Limits current
      - Improves Power Factor

White LEDs

- Characteristics
  - Efficiency/Efficacy
    - Up to 22%[4]
    - Single proto-type LED 1000 lumens (60W tungsten = 850 lm)[6]
  - Color
    - Similar to Fluorescent (NUV/UV emitter plus phosphor)
      - Cool, Neutral, Warm
      - Color can be further adjusted by interspersing colored LEDs
  - Warm-up
    - None
  - Reliability/Life Expectancy
    - Catastrophic failure rare
    - Reduction of intensity
    - Color shift
    - 50,000 hour life expectancy

Courtesy Cree



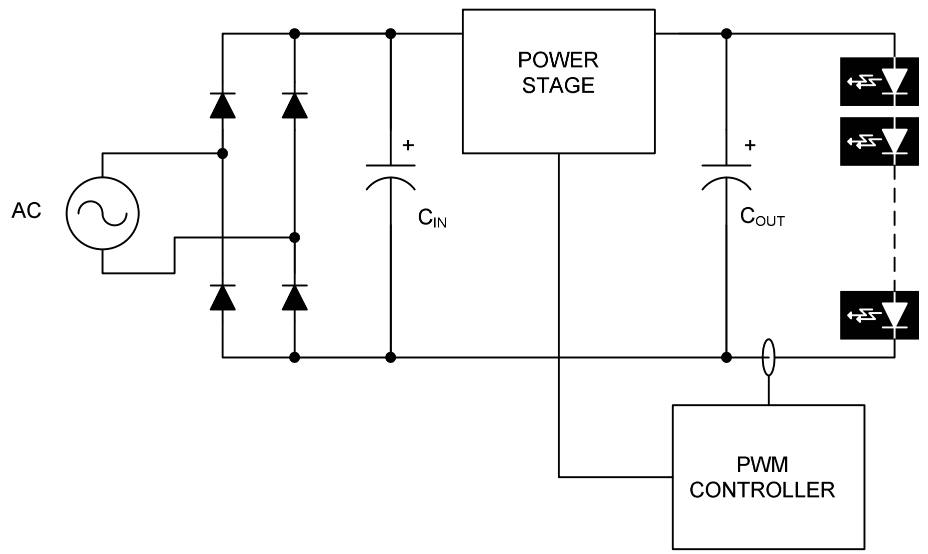
Courtesy Cree

White LEDs

- Characteristics
  - Cost
    - A quickly moving target
    - Still several times the cost of equivalent fluorescent
    - Adopted in high maintenance cost locations

Power Requirements

- LEDs
  - Low voltage DC
  - 3.5 V @ 350 – 1000 mA (typ.)
  - Up to 107 lumens (production)
  - Requires a current source, not a voltage source

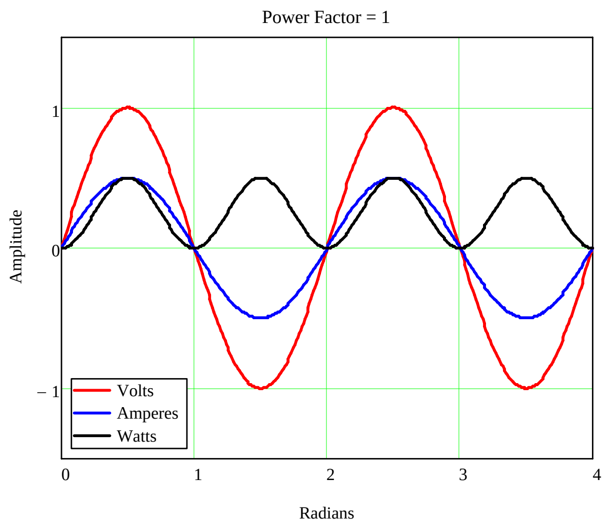


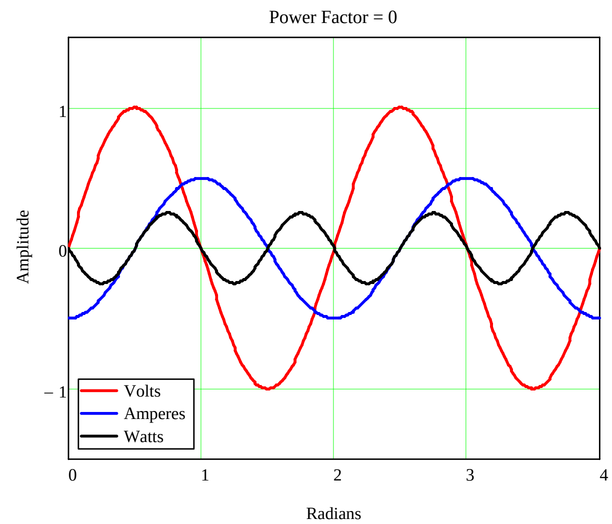
LED Driver Block Diagram

Power Quality

– Power Factor – A Quick Review

- PF=Real Power/Apparent Power = Watts/(Vrms x Arms)
- Dimensionless ratio ranging from 0 to 1
- If V and A are not in phase, or if system is non-linear (rectified input), then PF will be reduced
  - – Real Power + Reactive Power/Harmonics





THE NUMBER ONE SOURCE FOR HIGH PERFORMANCE ANALOG

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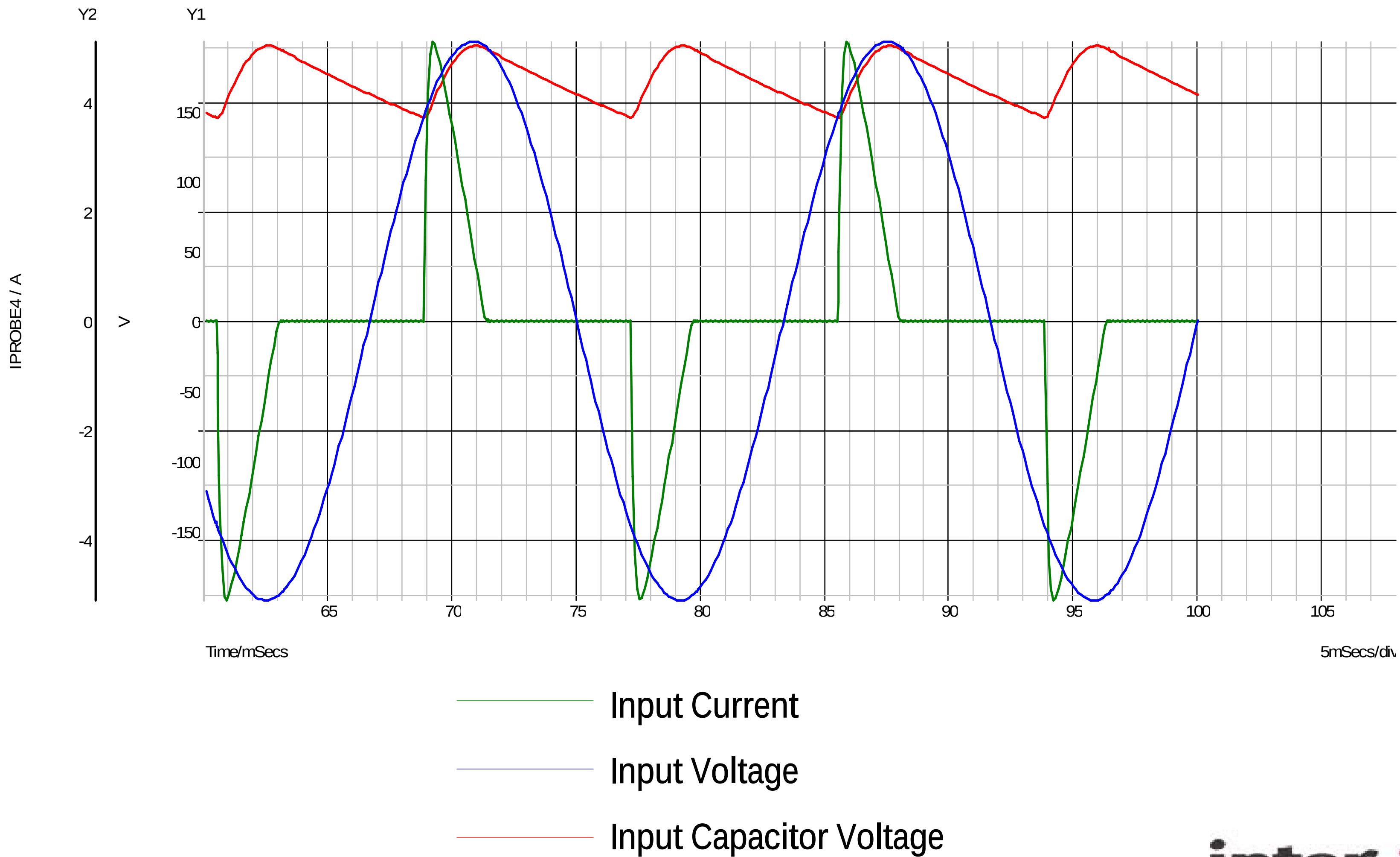
Power Supply w/o PFC

– Power Factor in an Uncorrected AC Input P/S

- PF = 0.55 to 0.65



Power Factor Facts

- Power Factor/Harmonic Content
  - Why is this important?
    - Only Real Power is capable of doing work
  - Low PF requires higher currents to deliver equal power
    - Low PF means higher generation and transmission costs
  - Non-PFC power converters reduce any energy efficiency gains by 1-PF
  - Cause higher currents in neutral branch (3ϕ)

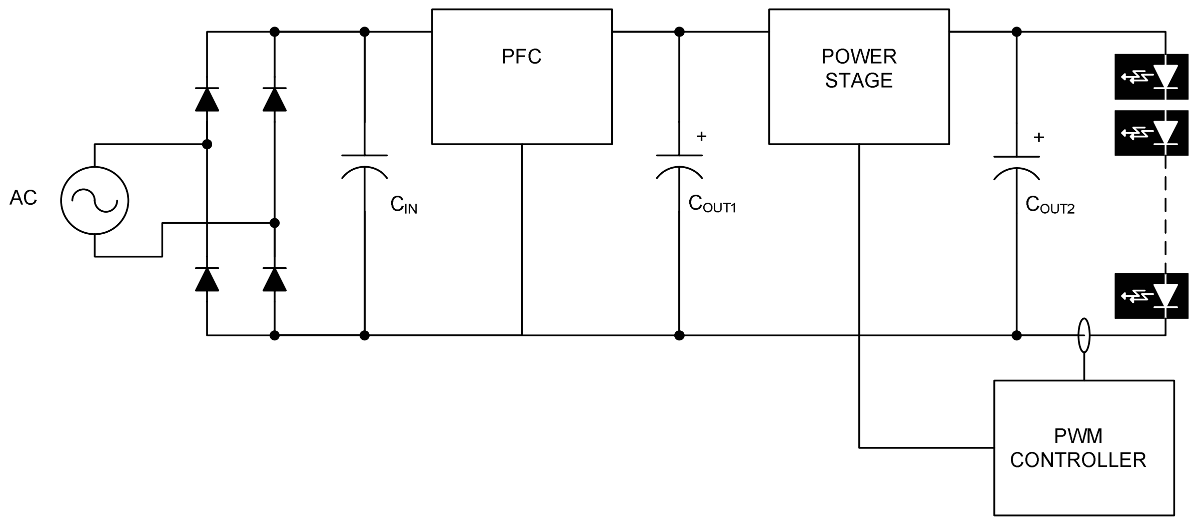
- Is PFC Actually Required?
  - Europe specifies harmonic content limits (IEC61000-3-2 A,C, D)
    - Class C applies to lighting >25W
    - Class D applies to lighting <25W (mA/W)
    - Class A/D applies to all converters
  - Most are anticipating regulatory requirements

Power Factor Facts

- What is the Energy Impact?
  - LED vs. CFL vs. Incandescent
  - PFC vs. non-PFC
  - ~110 Million US households (US Census)
  - A typical US household has 50-100 light bulb sockets[7]
  - Do the math…
- What is the cost of adding PFC?
  - Essentially free

Adding PFC

- Power Factor Correction (PFC)
  - How is PFC provided?
  - Could use 2-stage approach, but…..

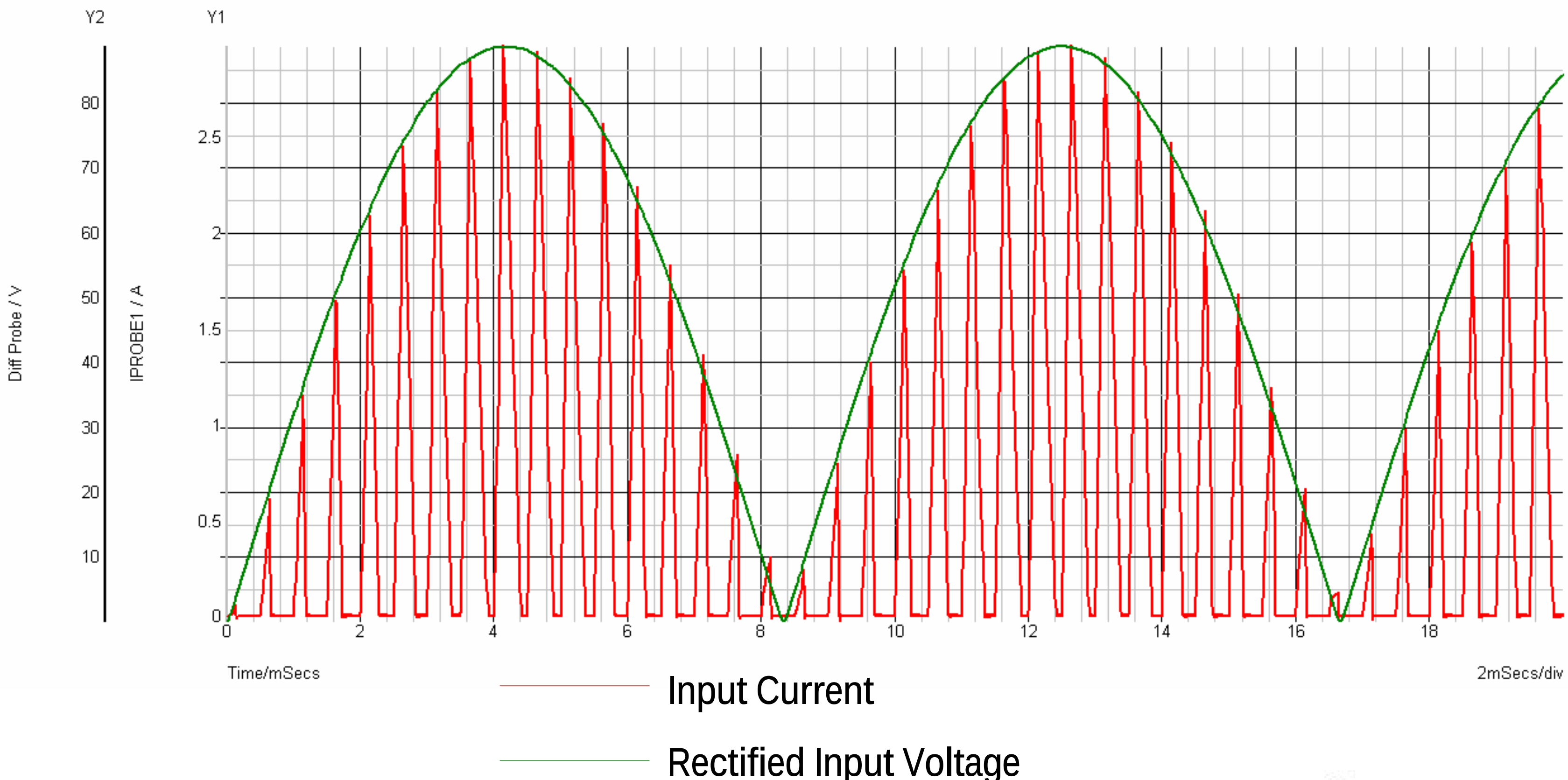


Adding PFC

- Power Factor Correction (PFC)
  - …..2-stage PFC is costly (not free) and unnecessary
  - To get high PF, the load reflected to the AC line needs to appear resistive
    - $I = V/R$ or $I \propto \kappa V$
    - For an inductor, $\Delta I = \Delta T * V/L$
      - where $\Delta T = T_{ON}$ is the time V is applied across L
  - If T_{ON} is a constant
    - then $\Delta I \propto \kappa V$
  - If operating in DCM (or CrCM), then $\Delta I = I_{PEAK}$, and we have $I_{PEAK} \propto \kappa V$
    - If I_{PEAK} is averaged, then $I \propto \kappa V$
    - has same form as a resistance
  - Can do this in a single stage converter with
    - Constant On-time control
    - DCM or CrCM operation
    - Differential EMI filter

Adding PFC

- Single- stage PFC
  - Constant On-Time
  - DCM (fixed frequency)/CRCM (variable frequency) operation

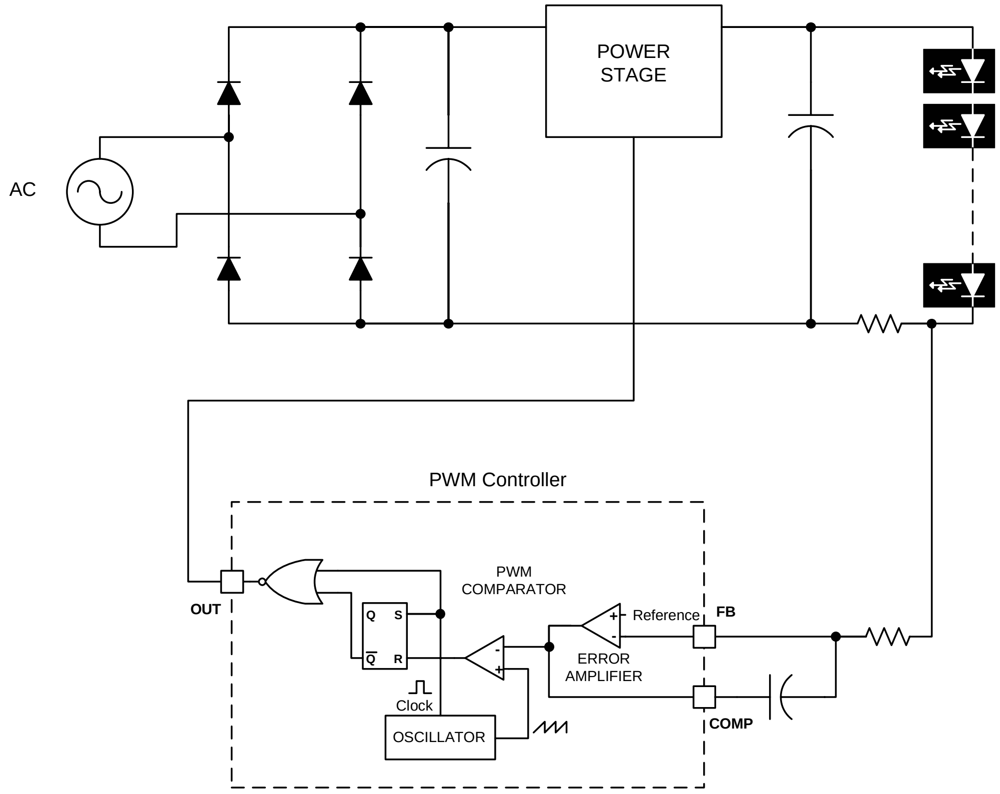


Adding PFC

- Single-stage PFC to output
  - Existing Voltage-Mode PWM controllers are constant frequency
    - Support DCM operation
  - Many PFC controllers are available
    - Support CrCM operation
  - How do you get Constant On-Time control?
    - T_{ON} must be essentially constant over an AC half-cycle
    - Very low BW control loop
      - < 100 Hz
  - Applicable to virtually any hard-switched PWM topology
    - Boost
    - Flyback
    - SEPIC
    - CUK
    - Forward
    - Buck-Boost
    - Buck
    - Bridge (half and full)

Adding PFC

- Single-stage PFC to output (cont'd)
  - Control loop monitors output current
  - Simple Type 1 integrator



Selecting the Topology

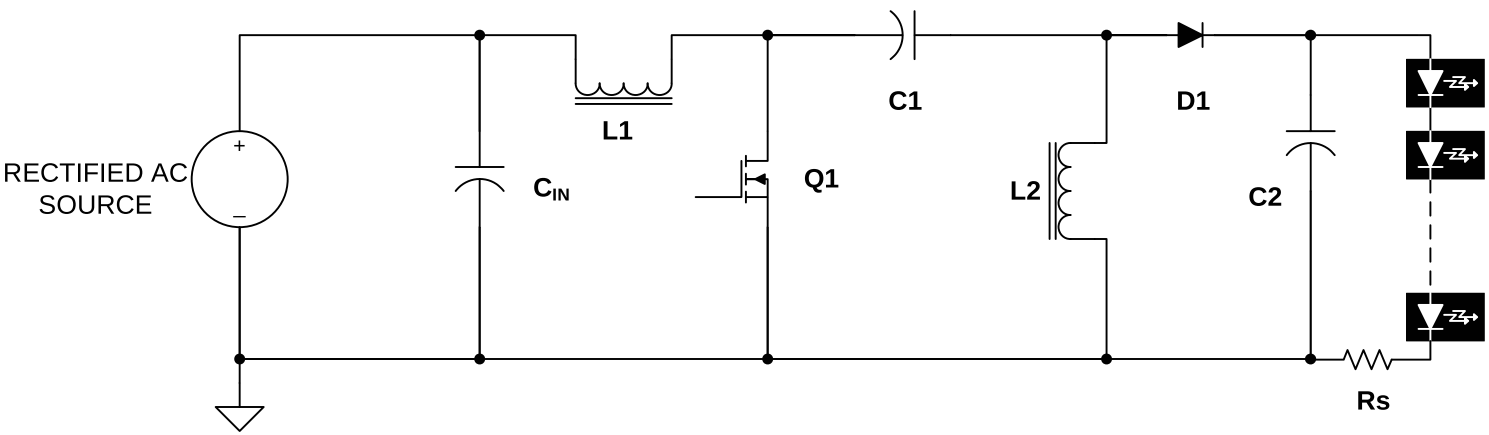
- What topology to choose?
  - Is input to output isolation required?
    - Existing lighting does not require it – should LED lighting?
    - But some customers are asking for it
      - Industrial applications
      - Modular applications
  - Input to output voltage differential
    - Large differential between V_{IN} and V_{OUT} means narrow duty cycle
      - Typical when operating from AC to small LED string
      - Choose transformer based topology if duty cycle is too small
        - » However, input and output can have a common ground

Design Example

- Requirements
  - V_{IN} = 120/240 VAC (90-275VAC)
    - $V_{IN(min, avg)}$ = 81 V
    - $V_{IN(max, avg)}$ = 250 V
  - 21 LED series string
    - V_{OUT} = 21 x 3.5 = 73.5V
    - I_{LED} = 350 mA
  - Switching frequency < 140 kHz (FCC, CISPR)
    - Use 100 kHz
  - Want to choose cheapest voltage step-down topology
    - Any of the transformer-based topologies
    - Buck
    - Buck-Boost
    - CUK
    - SEPIC

Design Example

- The SEPIC converter



- Steady State Operation
  - Average inductor (L1, L2) voltage must be zero
  - $\therefore$ V_{C1} must be V_{IN}
  - Average capacitor (C1) current must be zero
  - $\therefore$ I_{OUT} must be $I_{L2(avg)}$

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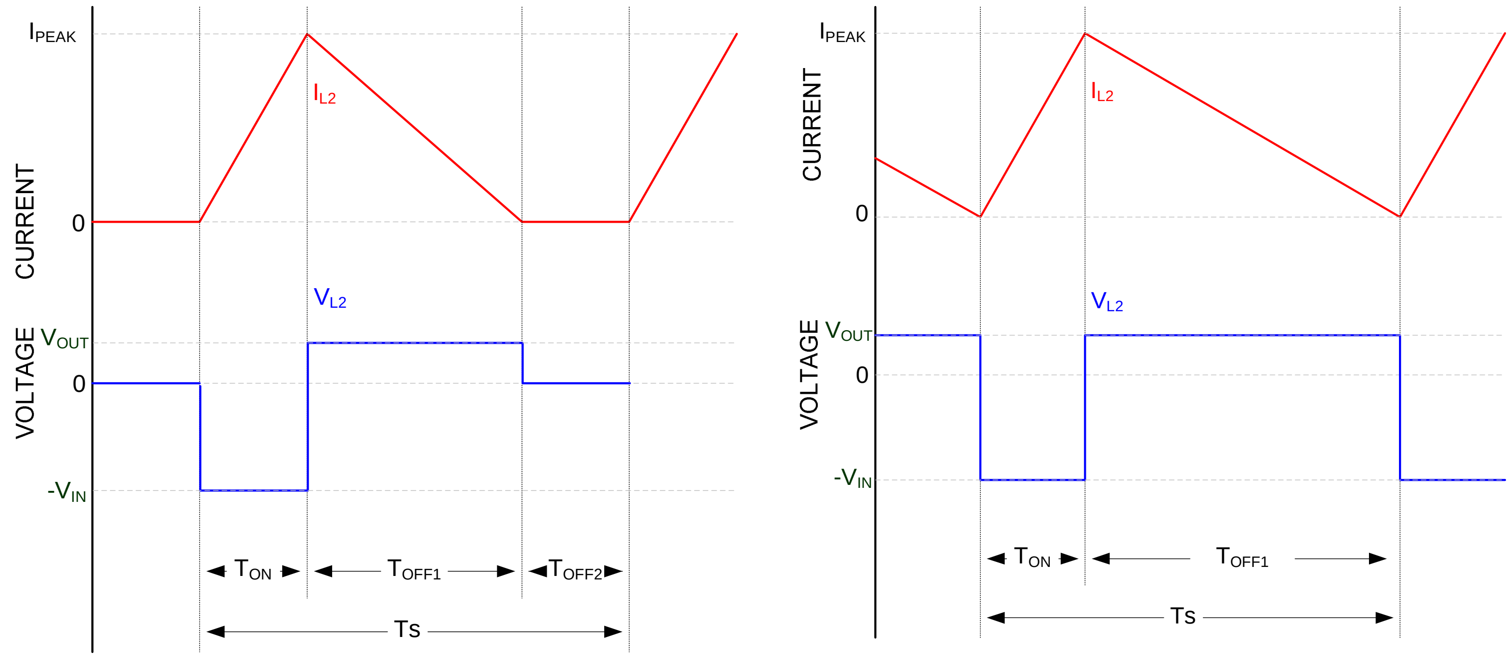
Time Interval Review



DCM Timing

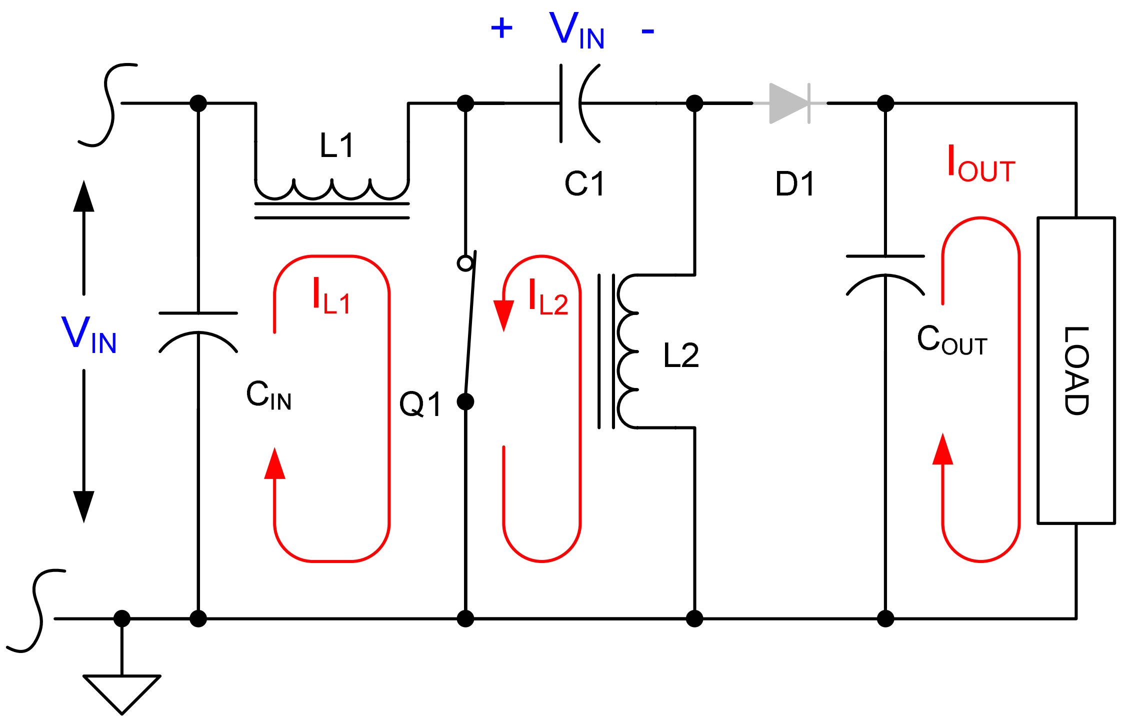
(Fixed Frequency)

CrCM Timing

(Variable Frequency)

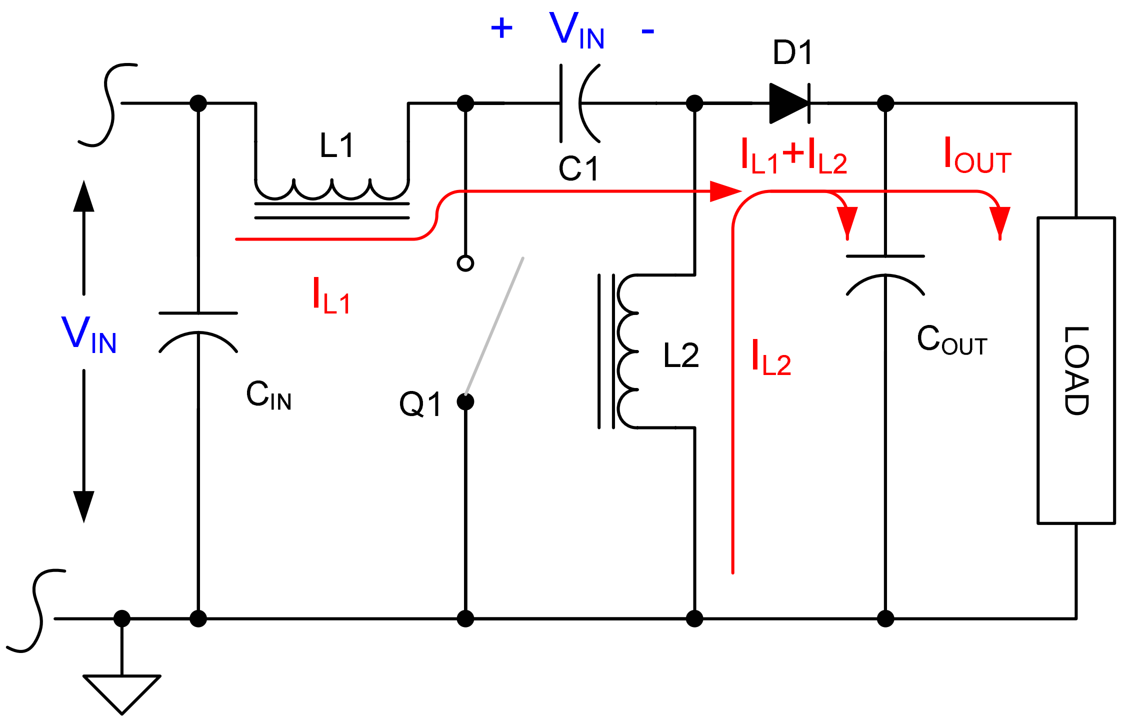
Design Example - SEPIC

- The SEPIC converter -T_{ON}



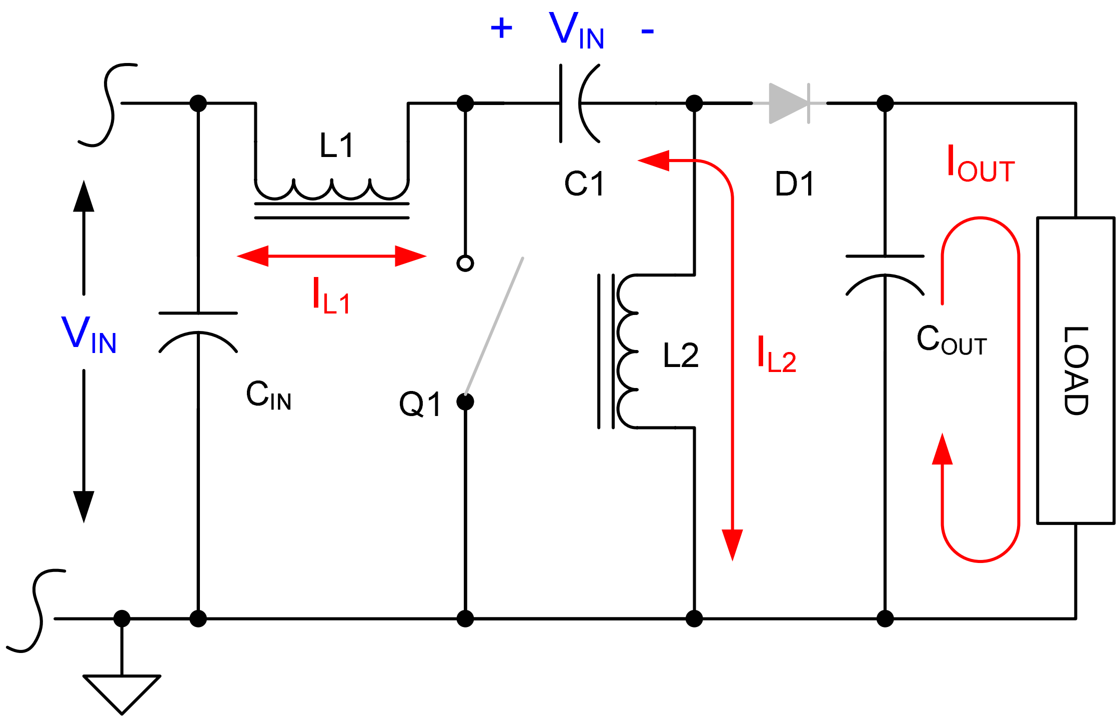
Design Example - SEPIC

- The SEPIC converter $-T_{OFF1}$



Design Example - SEPIC

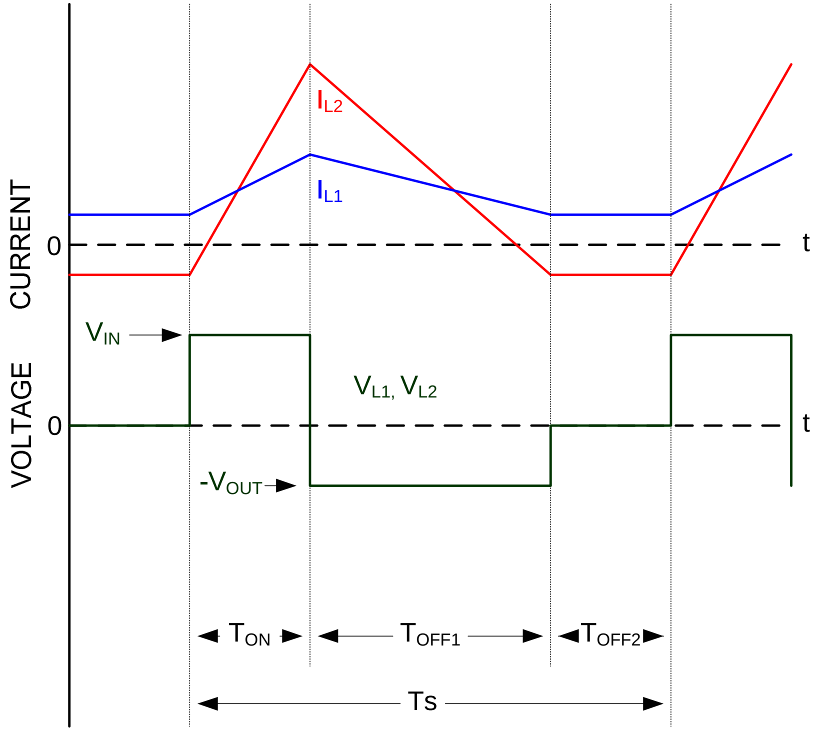
- The SEPIC converter –T_{OFF2}



Design Example - SEPIC

- The SEPIC converter $-T_{OFF2}$
  - I_{Lx} not zero during T_{OFF2} due to charge balancing in coupling capacitor C1
  - Want to keep I_{C1} positive
    - Or it charges CIN and distorts input current
    - L1 >> L2

$$I_{C1(DC)} = \frac{L_1 I_{OUT}}{L_1 + L_2}\left(\frac{V_{IN} V_{OUT}}{\overline{V}_{IN}^{2}} - \frac{L_2}{L_1}\right)$$



Design Example - SEPIC

- Operation (cont'd)
  - For DCM operation
    - Worst case is at maximum duty cycle (min $V_{IN(PEAK)}$)

$$\frac{L_1 L_2}{L_1 + L_2} \le \frac{\left(\frac{\overline{V}_{IN}}{V_{IN} + V_{OUT}}\right)^2 T_S V_{OUT}}{2 I_{OUT}}$$

Ts = Switching Period

V_{IN} = Minimum Vrms peak voltage

$\overline{V}_{IN}$ = Minimum V_{IN} Vrms average

  - L1 selection has conflicting requirements
    - Large L1 reduces peak currents
    - Large L1 increases distortion at AC zero-voltage crossing which compromises PF

Design Example - SEPIC

- Operation (cont'd)
  - $V_{OUT}/V_{IN} \neq D/(1-D)$ due to DCM operation

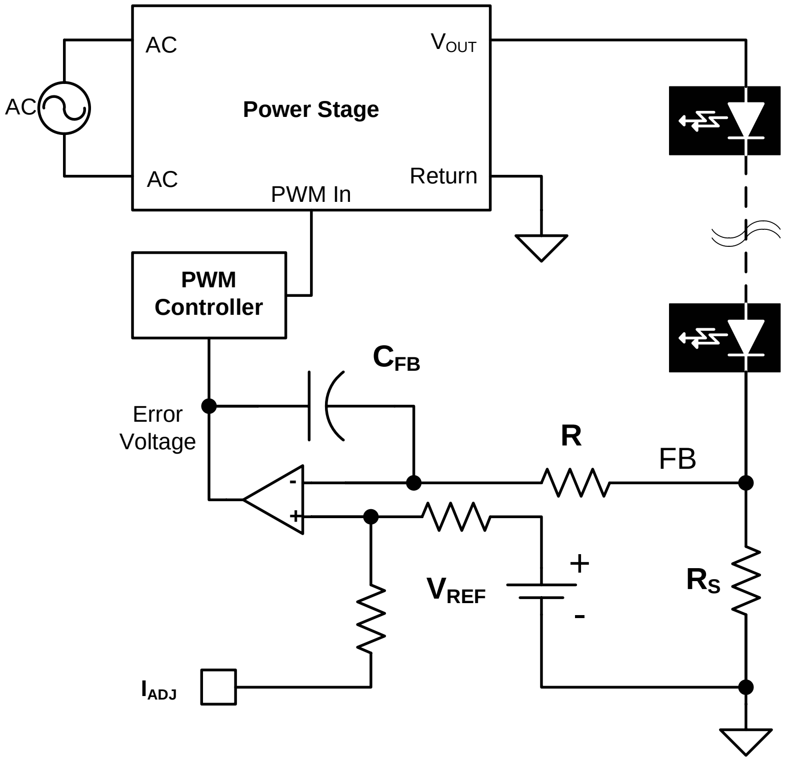
$$T_{OFF1} = \sqrt{\frac{2T_S I_{OUT}}{\left(\frac{1}{L_1}+\frac{1}{L_2}\right)V_{OUT}}}$$

$$T_{ON} = \frac{V_{OUT}}{V_{IN}} T_{OFF1}$$

$$T_{OFF2} = T_S - T_{ON} - T_{OFF1}$$

Design Example - SEPIC

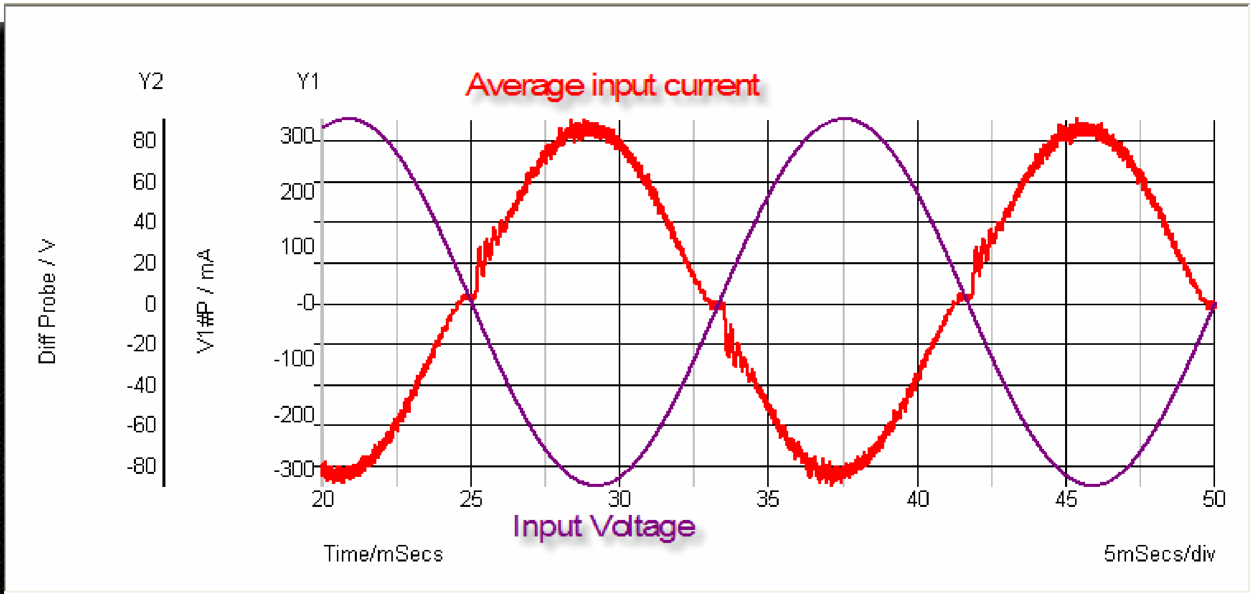
- Control Loop BW
  - $f_C = 1/2\pi RC_{FB}$ = 40 Hz
  - C_{FB} = 0.1 µF
  - R = 40.2 kΩ
  - Valid for all topologies



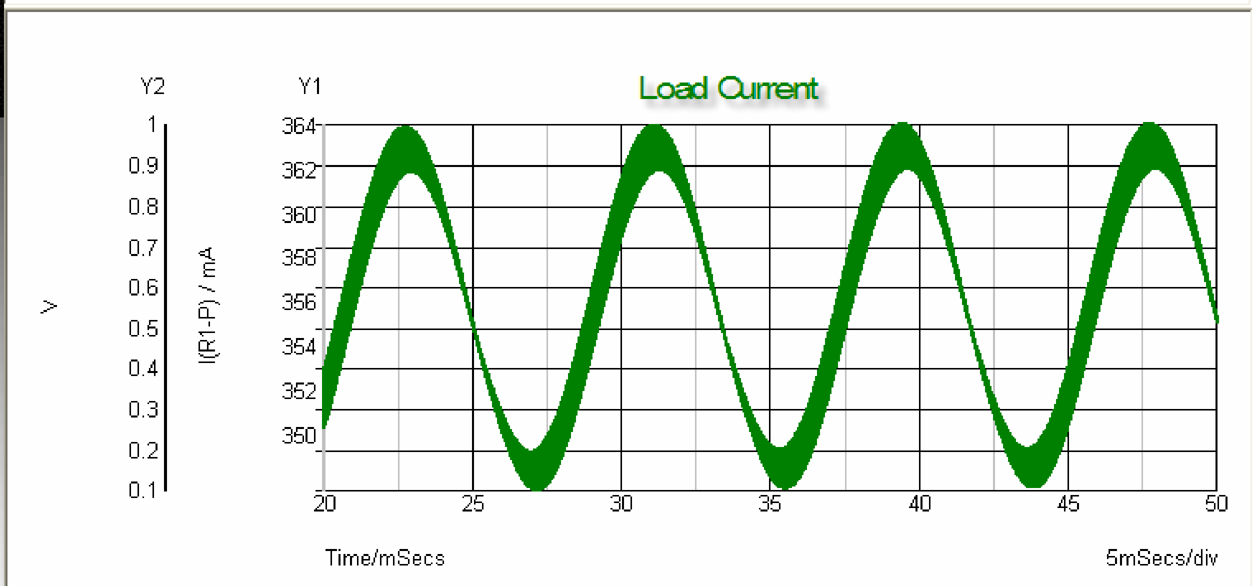
Design Example - SEPIC

- Choose L1 = 820 μF
- Choose L2 = 82 μF
- What PWM controller to use?
  - Voltage mode
  - Cheap
  - ISL6745

Design Example – SEPIC (simulation)

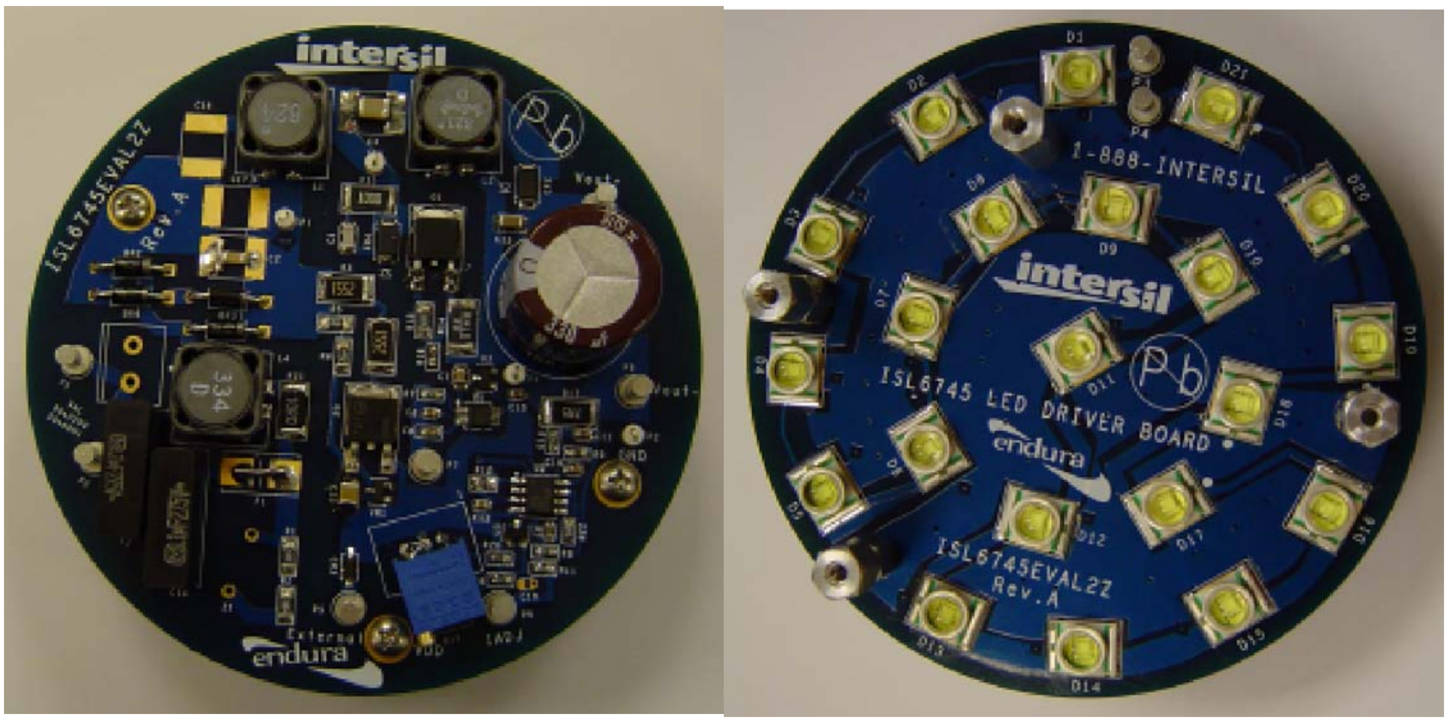


Typical input waveforms (Voltage waveform intentionally shifted 180º for clarity)

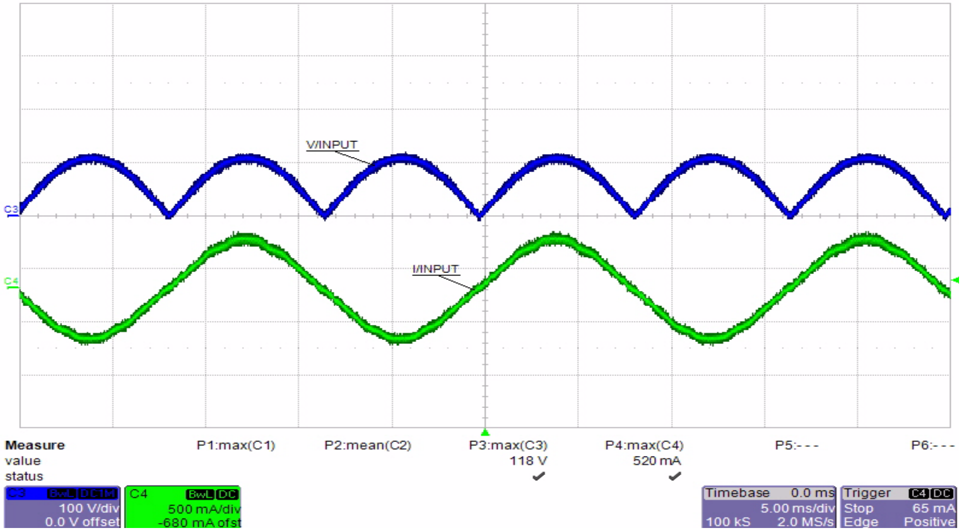


Typical output waveforms AC+DC current, AC amplitude dependent on size of output capacitor

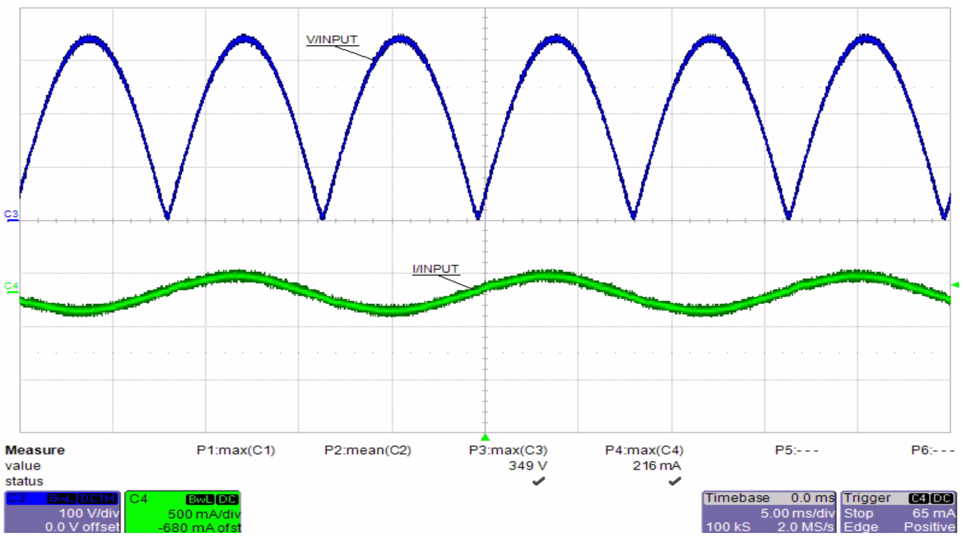
Design Example – SEPIC (experimental)



Design Example – SEPIC (experimental)

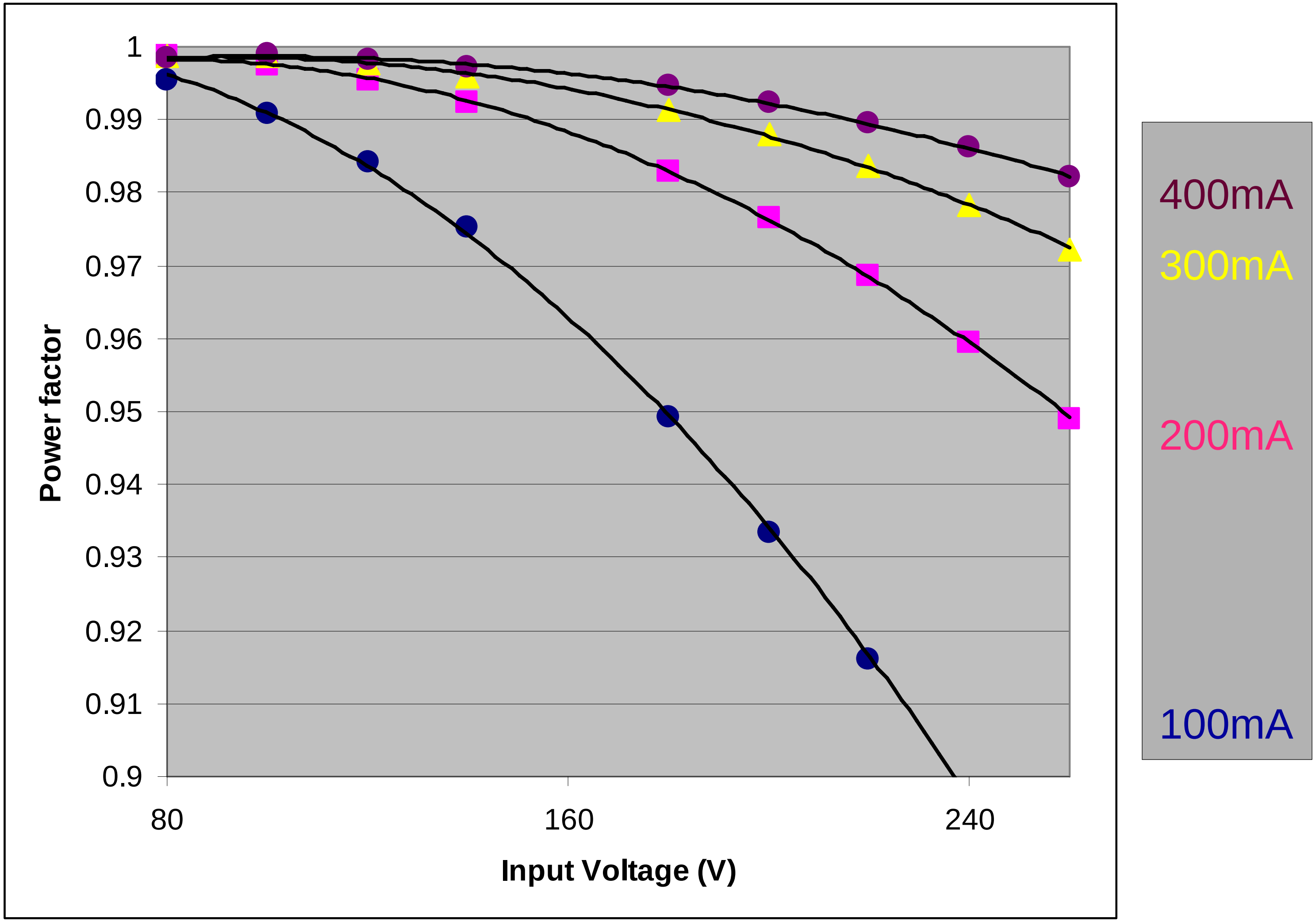


Input waveforms:
V_{IN} = 80VAC
Rectified Vin (blue)
100V/div
Input current (green)
500mA/div



Input waveforms:
V_{IN} = 240VAC
Rectified Vin (blue)
100V/div
Input current (green)
500mA/div

Design Example – SEPIC (experimental)



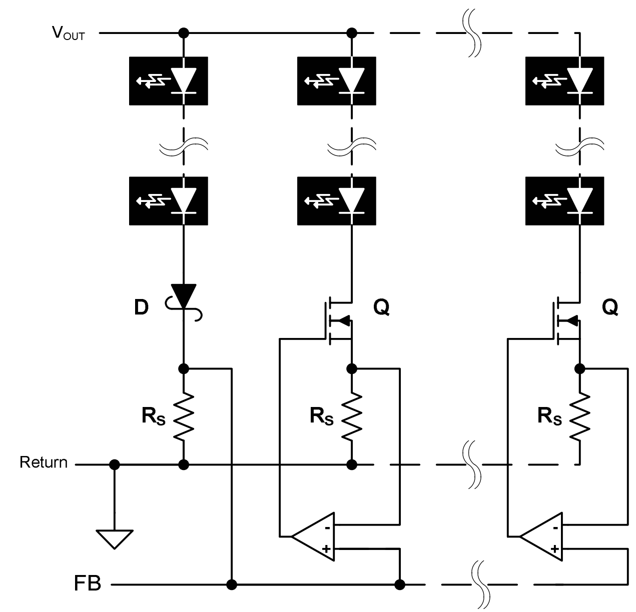
PF vs. Load and V_{IN}

Dimming LEDs

- Intensity dependent on current
- Color rendition also dependent on current
- Can use PWM techniques to turn LEDs on and off to modulate intensity rather than current modulation
  - But low end applications will likely modulate current only
- Strong industry desire to have LED fixtures compatible with incandescent wall dimmers
  - Constant output with varying AC amplitude
  - Variable output proportional to AC conduction angle

Multiple LED Strings

- Industrial/Commercial applications can require multiple LED strings
  - Increased output
  - Fault tolerance
- How to control the current through each string?



Product Example

- 6” Can Light Replacement
  - LLF (division of CREE) Model LR6
  - 650 Lumens (~75W reflector flood)
  - 12W
  - Dimmable
  - PFC
  - Color corrected $120 - $144 (as of May 1, 2008)

Courtesy Cree

Conclusions

- White LEDs will become a significant, if not the dominant, light source for general illumination
- LED lighting products can be designed using readily available components
- Operating LED fixtures can have minimum impact on power quality

References

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