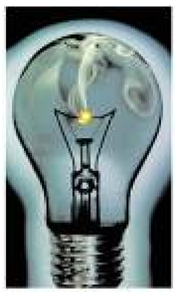
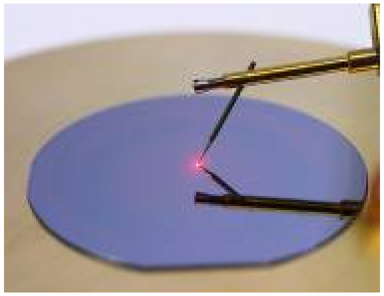
ON Semiconductor®

Driving High Brightness LEDs in the General Lighting Market







Outline

- Overview of LEDs and Solid State Lighting
- System Perspective and Driver Requirements
- Example Applications
  - Powering LEDs from an offline supply
  - Low voltage ac and dc applications
  - Portable applications
- Conclusions

Solid state lighting evolution

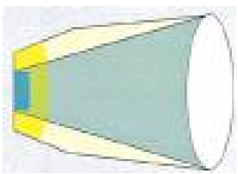
- New lighting technologies based on LEDs offer a great potential to create new and exciting products and reduce global energy impact of lighting
- International Energy Agency estimates for 2005 are that 1900 Mt of $C0_2$ were emitted globally for lighting (equivalent to 70% of light passenger car emissions)
- Example products benefiting from this technology today:
  - Exit signs, traffic control, signage, small LCD backlighting and torch-lights



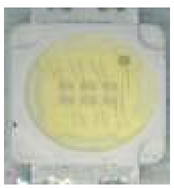

- High brightness LEDs technology has advanced both in light output/package (lumens) and conversion efficiency
- Unlike traditional lighting, LEDs are inherently low voltage devices and require current drive for optimum performance due to steep I/V slope

LED overview

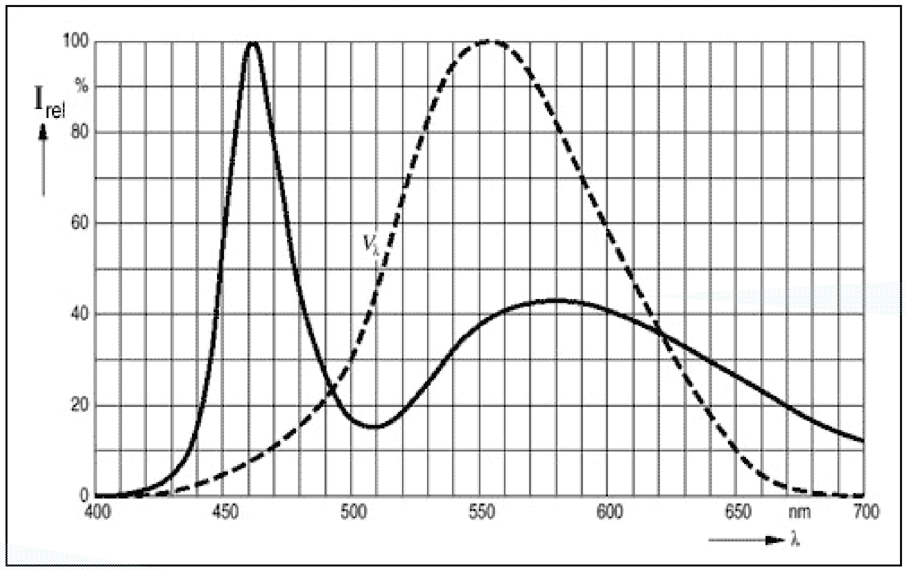
- The most common “white LED” is a blue emitting LED coated with a phosphor which then emits yellow light when excited.



CREE
XP-E



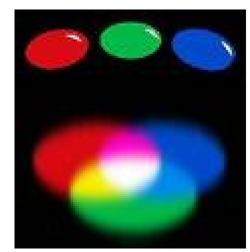
Nichia
NS6W083



Spectrum of a “white” LED – blue with yellow phosphor

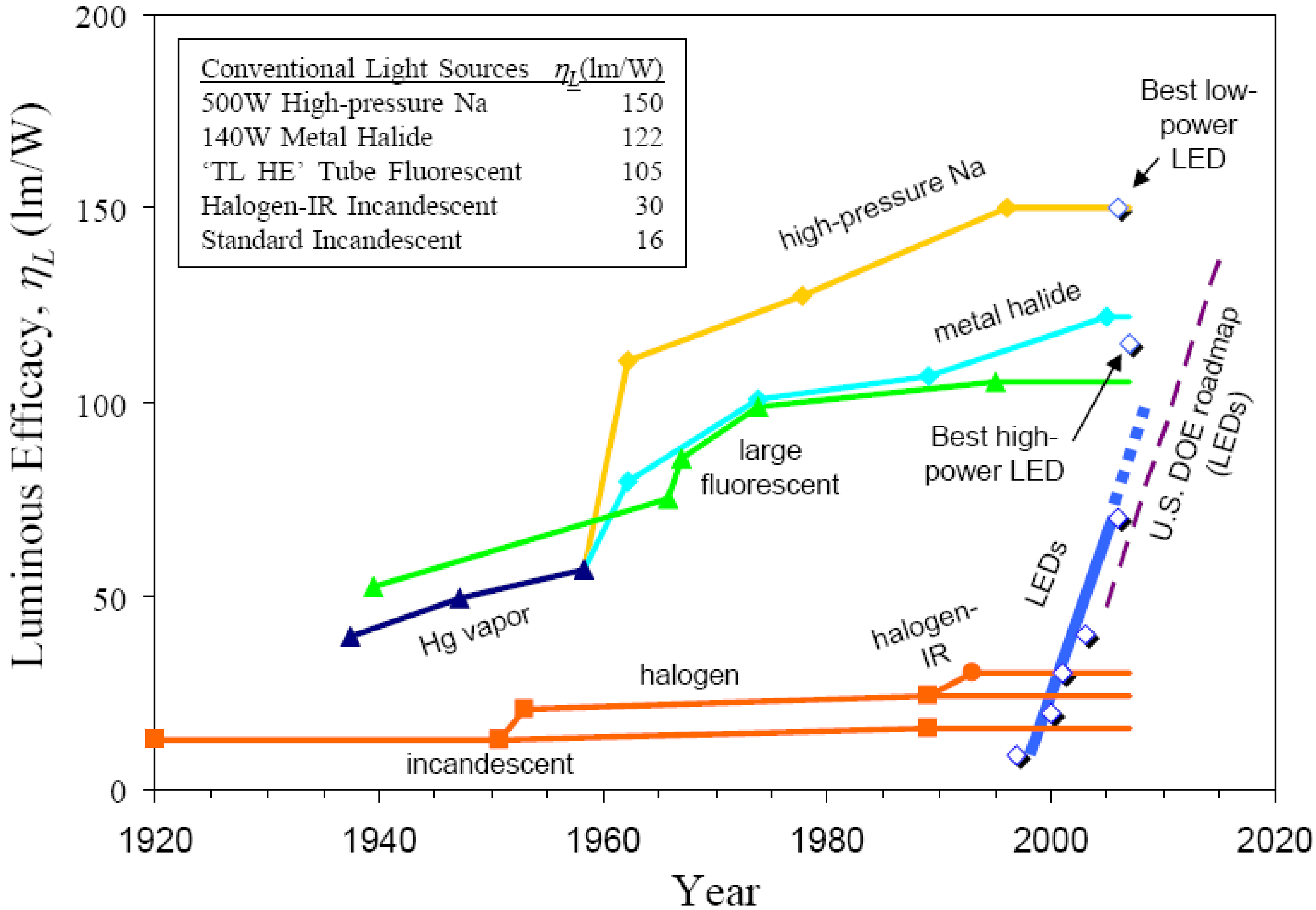
Blue .... 470 nm
Green .... 510 nm
Yellow ....570 nm
Red ....650 nm

Relative sensitivity of the human eye to different colors



- A white light can also be generated by modulating (mixing) the light from 3 colors - Red, Green, and Blue LEDs

High Brightness High Power LED Performance



Solid state lighting requires a system solution

- "Edison was the 38th inventor of a filament based lamp. Edison was the 1st to deliver the entire lighting system." - Roland Haitz

- **The LED Source:** compact effective light source available in a broad range of colors and output power

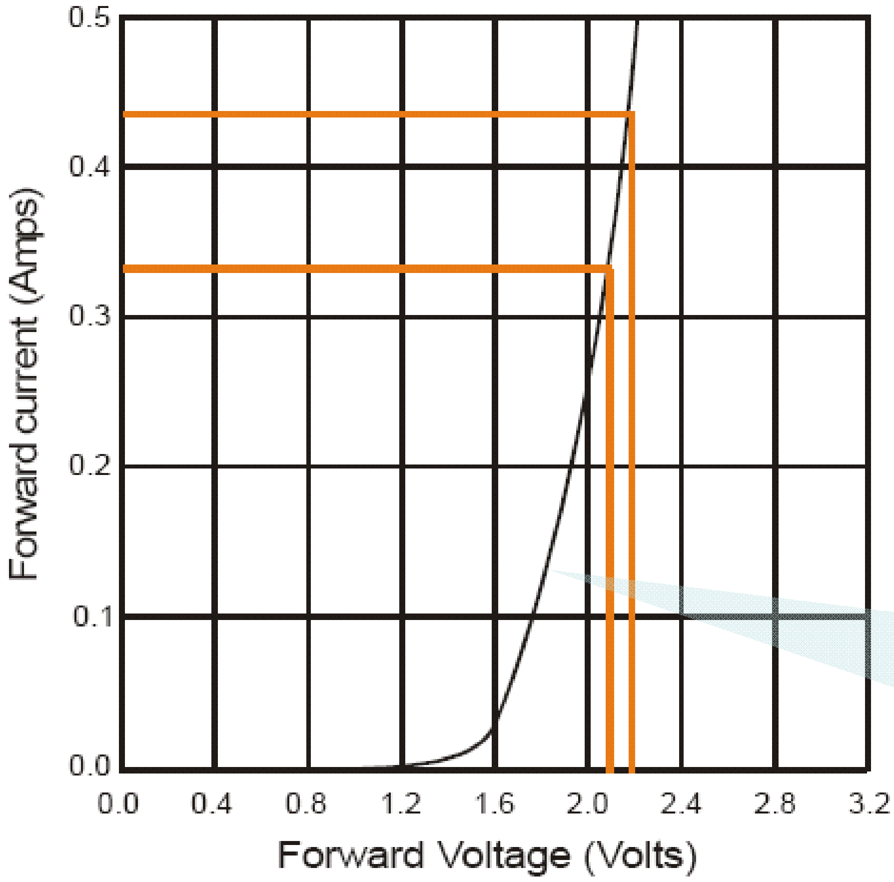
- **Power Conversion:** Efficient conversion– ac wall plug, battery, solar cell - to safe, low voltage dc

- **Control & Drive:** Electronics to regulate and control the LED

- **Thermal Management :** To achieve long operating lifetime, control of the junction temperature is critical, heat-sinking needs to be analyzed

- **Optics:** Focusing the light to were it needs to be requires lenses or light guides

Challenges of Driving LEDs



- LEDs are non-linear
  - Forward voltage varies with current & temperature
  - Forward voltage varies from part to part
  - “Color point” shifts with current and temperature
  - LEDs have to be operated within their specifications for reliable operation

Example of Iout as a function of Vf for an Amber OSRAM Golden Dragon®

100 mV difference in Forward voltage results in an approximately 100mA change in Current

Effectively a **5% change in voltage** results in a **40% change in current!**

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Relating LED behaviors

- Increasing the junction temperature, lowers the LED V_f

- Increasing the LED drive current, increases the forward voltage.

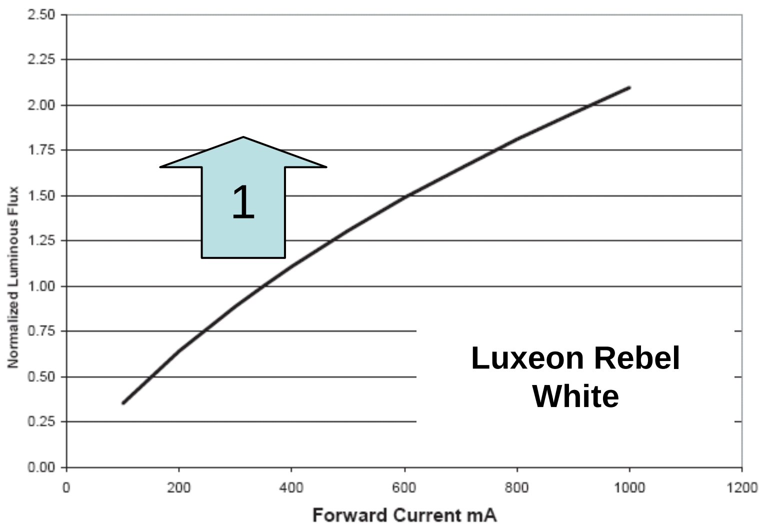
The nominal forward voltage at 350mA (Cree XLAMP™ XR-E) is 3.3 V with a maximum of 3.9 V, the typical forward voltage increasing to 3.5 V at 700mA

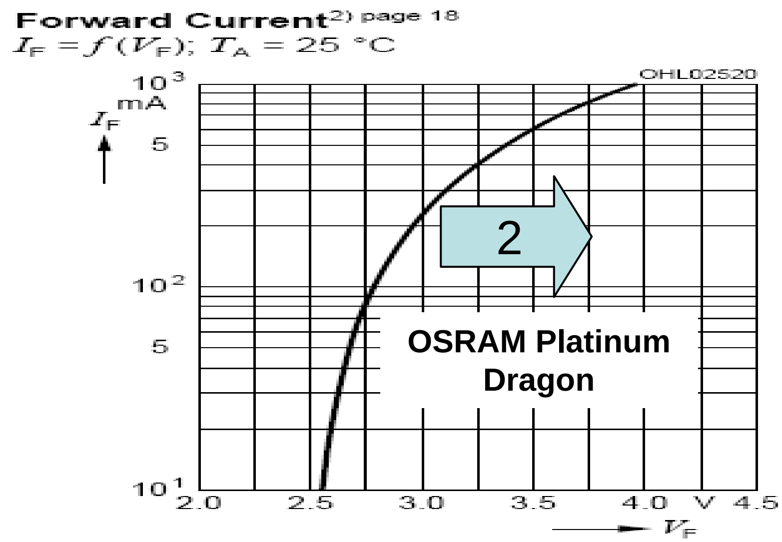
- For a white Luxeon Rebel™, doubling the current from 350 to 700mA increases light output by approximately 1.8-2x, this assumes the junction temperature is fixed at 25 C

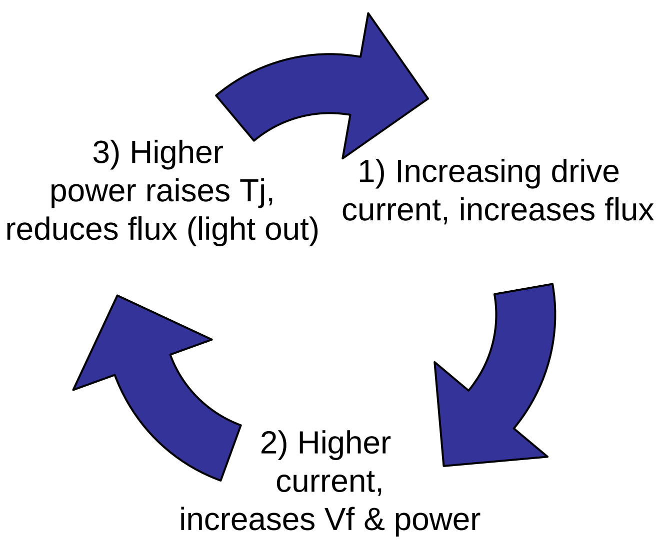
- As the junction temperature increases, the light output is reduced

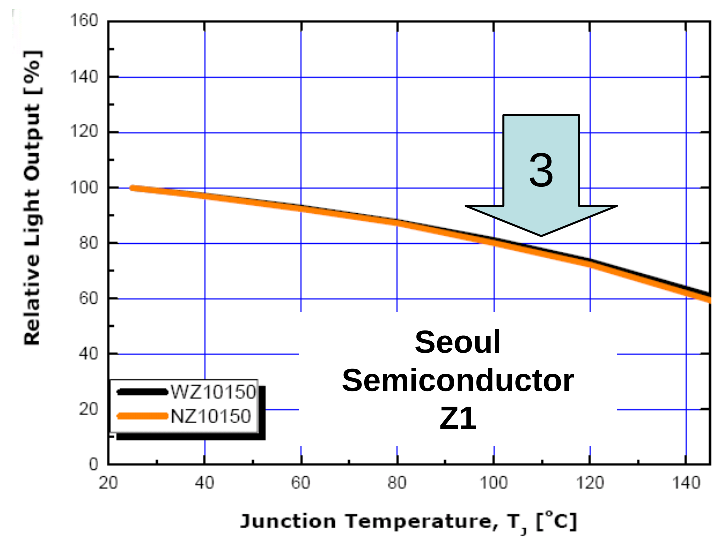
- Forward voltage has a negative temperature coefficient of approximately -2.5 to -5 mV/C. A white OSRAM Platinum Dragon™ has a typical -4.5mV/C temperature coefficient

Operating Relationship



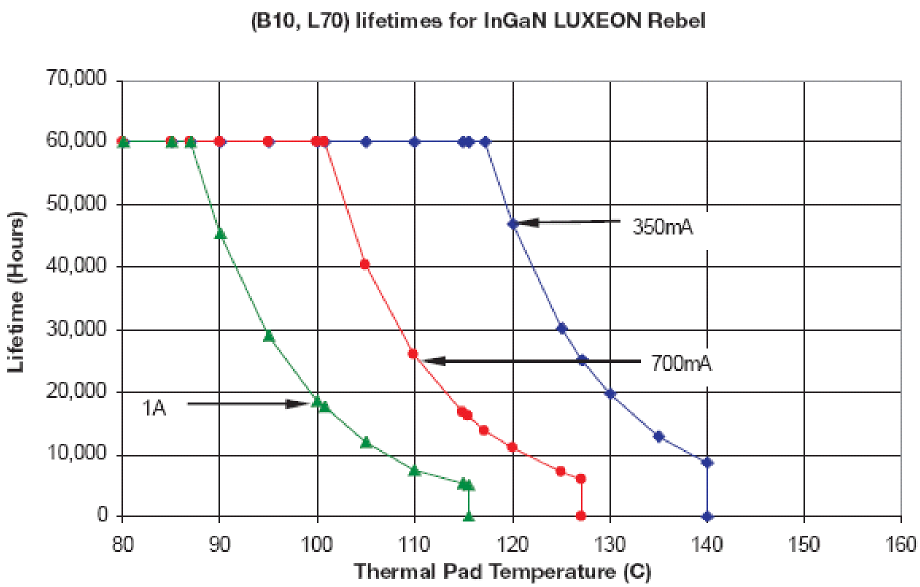




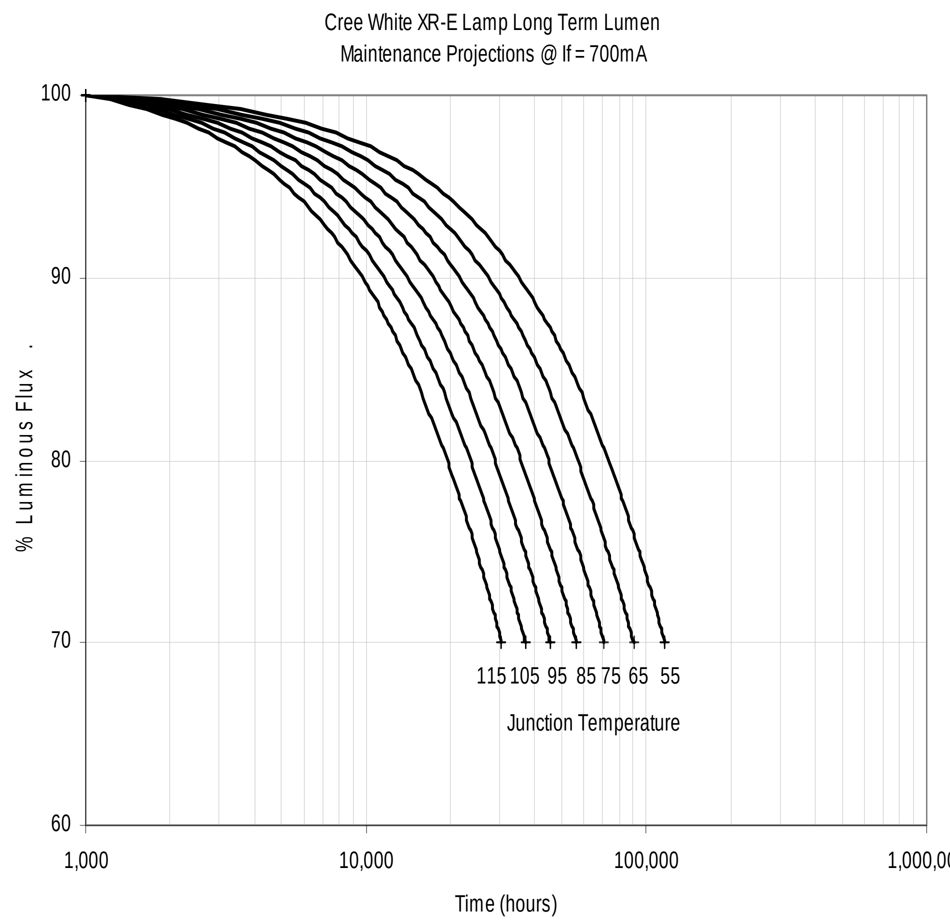


Thermal Management is Key

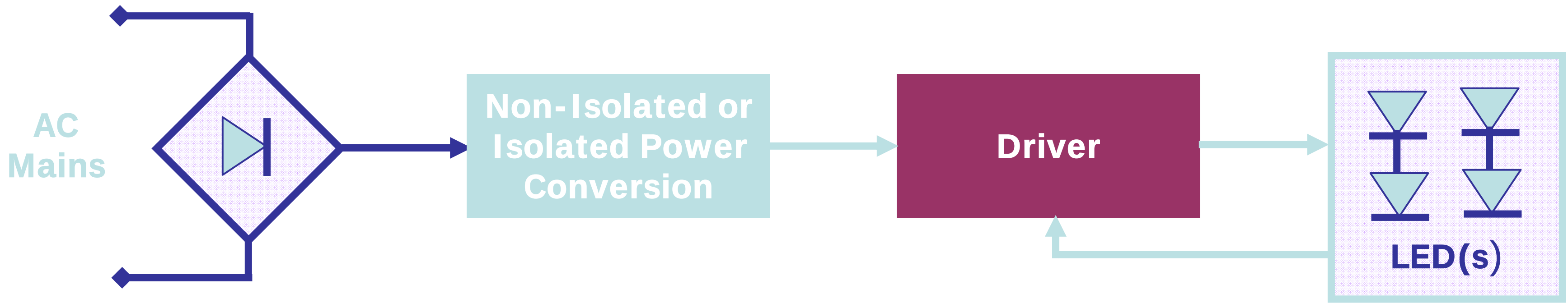
- LED failure criteria (L70) is when light output drops to 70% of initial value



Philips Lumileds defines this level when 10% of the population drops below 70% (B10,L70)



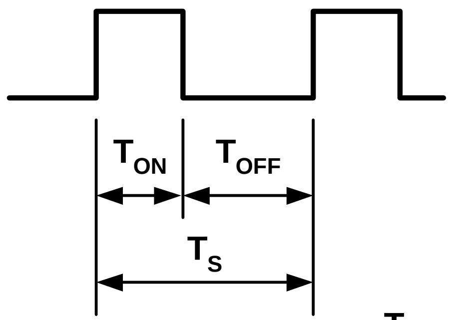
LED Driver Basics



- The primary function of a driver is to limit the current regardless of input condition and forward voltage variation across a range of operating conditions
- The end product needs dictate the performance objectives:
  - Parametric requirements, efficiency, current tolerance
  - Cost, form factor, size
  - Safety, industry and user expectations
- Driver "constant" current is not required to be a DC level as human vision filters out current ripple if the switching frequency > 100-150 Hz

Key LED driver circuit requirements

- Constant current regulation
  - Linear current source or sink
  - Switching regulator topologies
- If dimming of the LED is needed, provisions for pulse width modulation techniques are required
- Adequate power handling
- Robust for fault conditions
- Simplicity of implementation



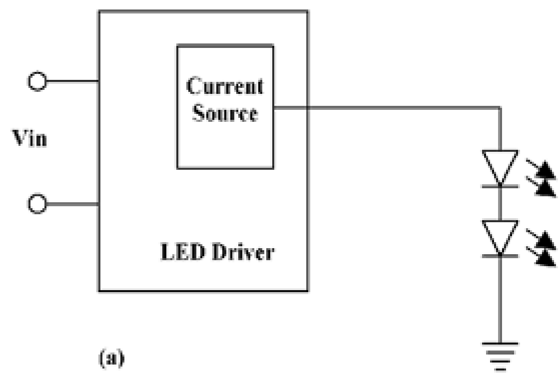
$$\text{Duty Cycle} = \text{Duty Ratio} = D = \frac{T_{ON}}{T_{ON} + T_{OFF}} = \frac{T_{ON}}{T_S}$$

Typical PWM frequency for LED dimming is 1 – 3 kHz

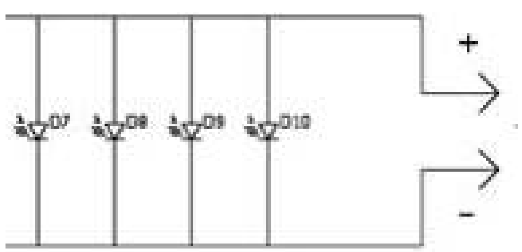
Color does not shift since LED is always “ON” at optimum current

LED Configurations

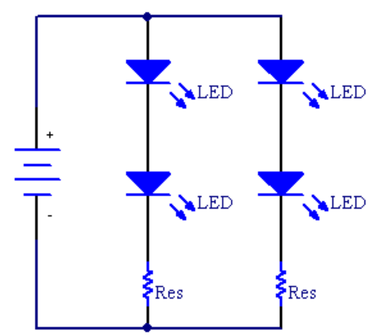
- Driving single strings of LEDs is preferred as it provides ideal current matching independent of forward voltage variation, Vout "floats"



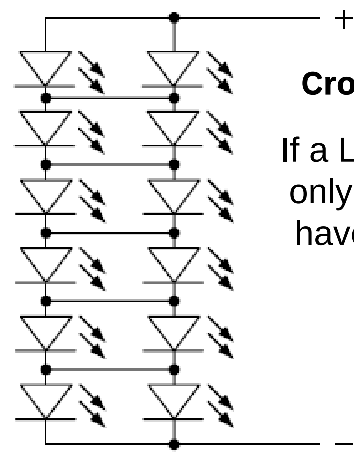
- Users do configure LEDs in Parallel/Series combinations
  - Requires "matched" LED forward voltages
  - If an LED fails open, the other LEDs may be overdriven
- Cross connecting and multiple parallel techniques try to mitigate the risk of a fault and force both LEDs to have the same voltage
- The same voltage across two LEDs does not guarantee the same current through the LEDs



Parallel (matched LEDs)



Parallel with balancer resistor



Cross connect

If a LED fails open, only 1 LED will be have 2x the drive current

Offline applications

- Lighting ballasts
- Fluorescent Lamp Replacement
- Traffic signals
- LED light bulbs
- Street and parking lighting
- Architectural lighting
- Obstruction lights
- Signage

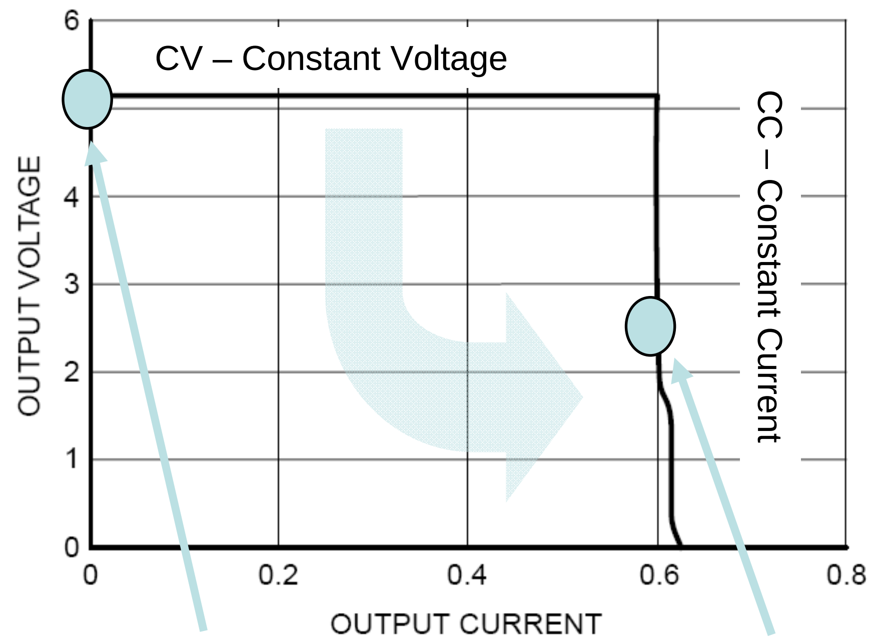
- Applications may or may not require galvanic isolation for safety

… fortunately offline LED drivers have similarities with battery chargers/adapters

Moving to the purely "constant current" realm based on proven ac mains solutions

AND8042/D

Implementing Constant Current Constant Voltage AC Adapter by NCP1200



Output is voltage clamped at No Load

Output can be designed to have tight current limited

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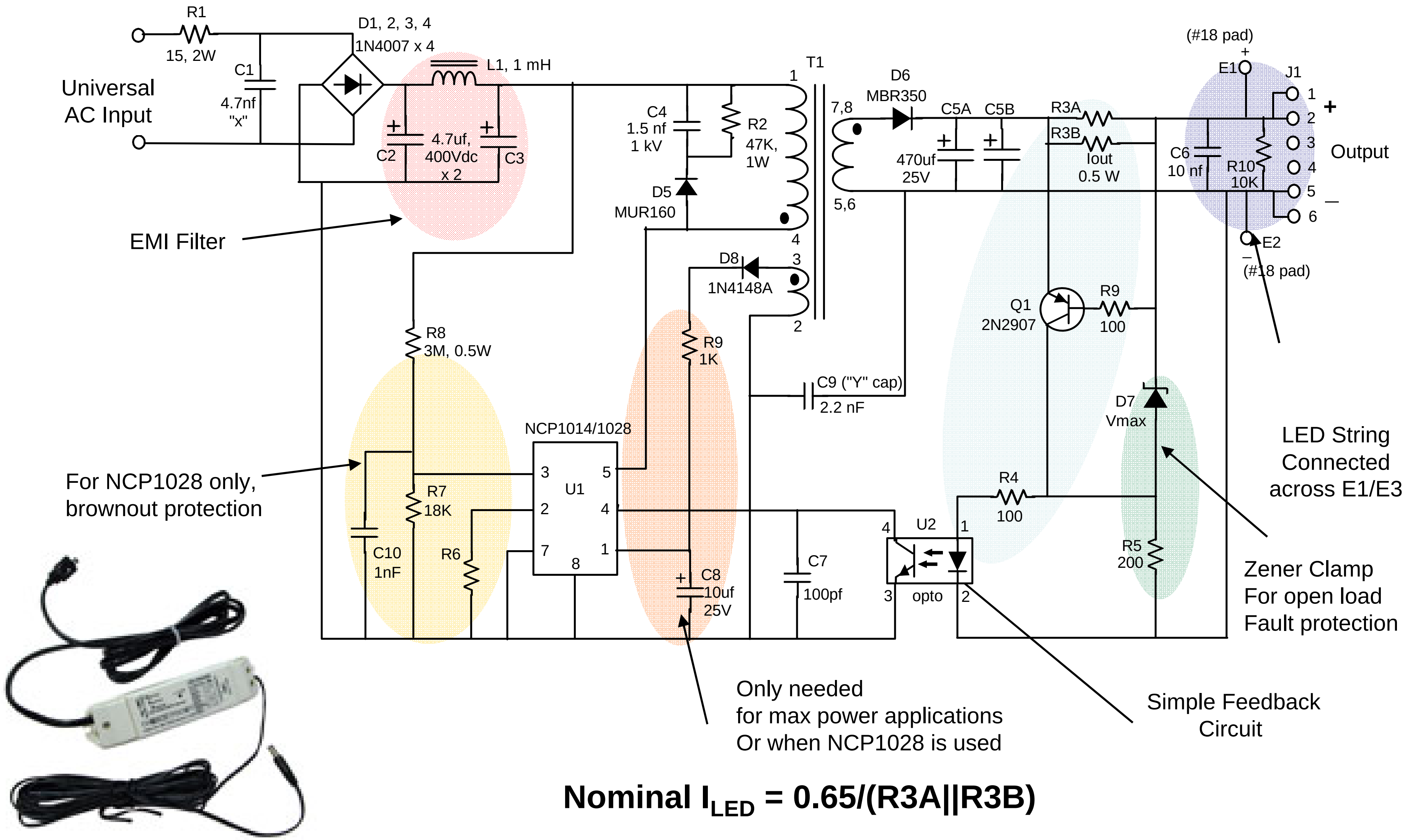
NCP1014/28 offline Gen2 LED driver



Nominal I_{LED} = 0.65/(R3A||R3B)

NCP1014/28 LED driver Gen2 demo board

ON Semiconductor offers the NCP1014 an offline PWM switcher with integrated high voltage MOSFET capable of providing up to 8 W when powered from a universal ac main.

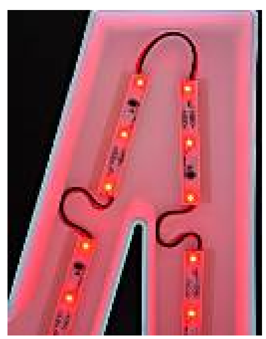
The NCP1014 LED driver board is a fully isolated ac-dc converter optimized for constant current applications.

350 mA / 22 Vdc transformer design as well as 700 mA / 17 Vdc configuration (NCP1014/NCP1028)

Note with an alternate transformer for 230 Vac ac main, the converter is capable of delivering up to 19 W (NCP1014) or 25 W (NCP1028)

Applications

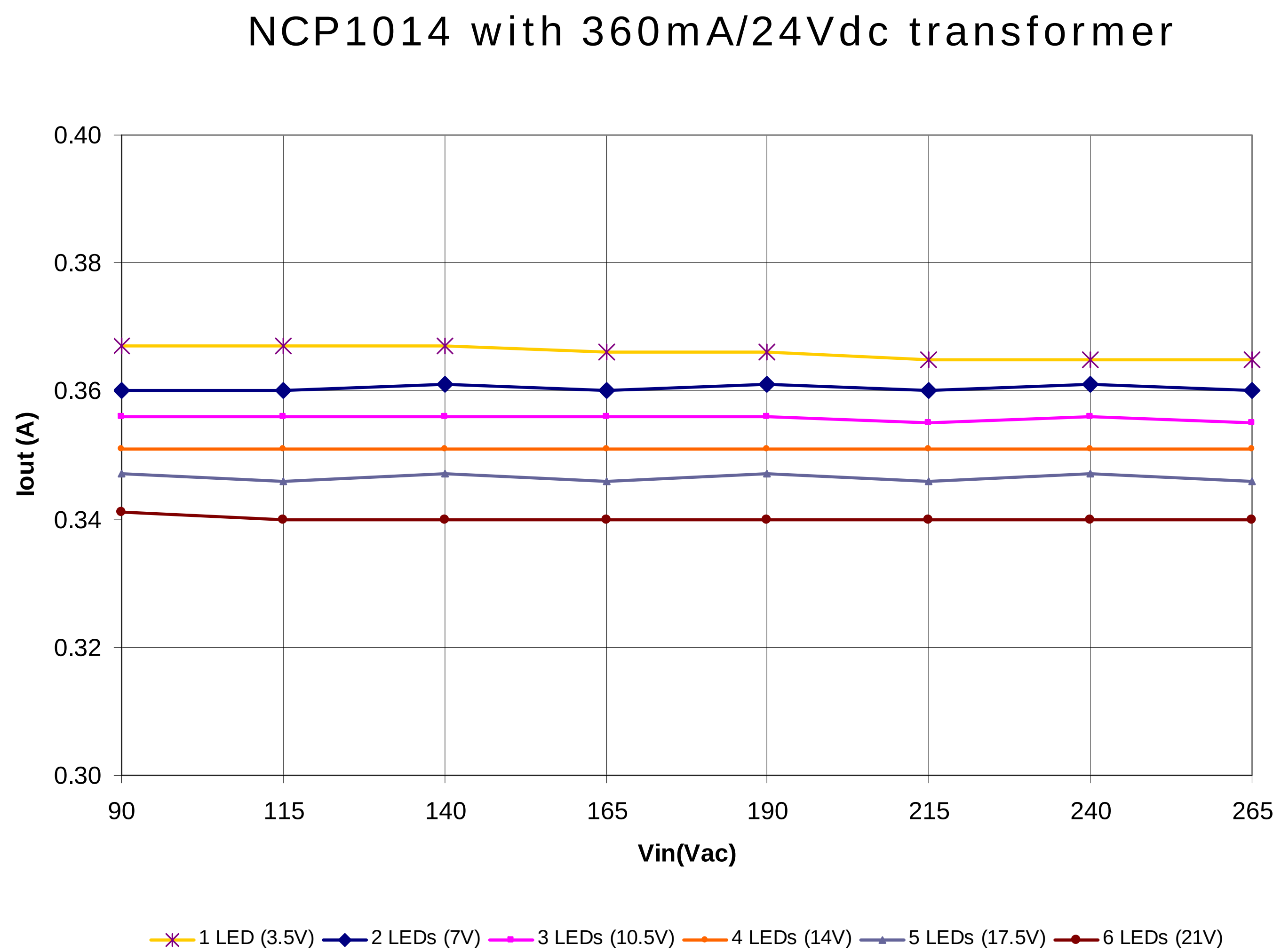
- ❑ LED ballasts
- ❑ Architectural lighting
- ❑ Display lighting
- ❑ Signage and channel lighting
- ❑ Task lighting



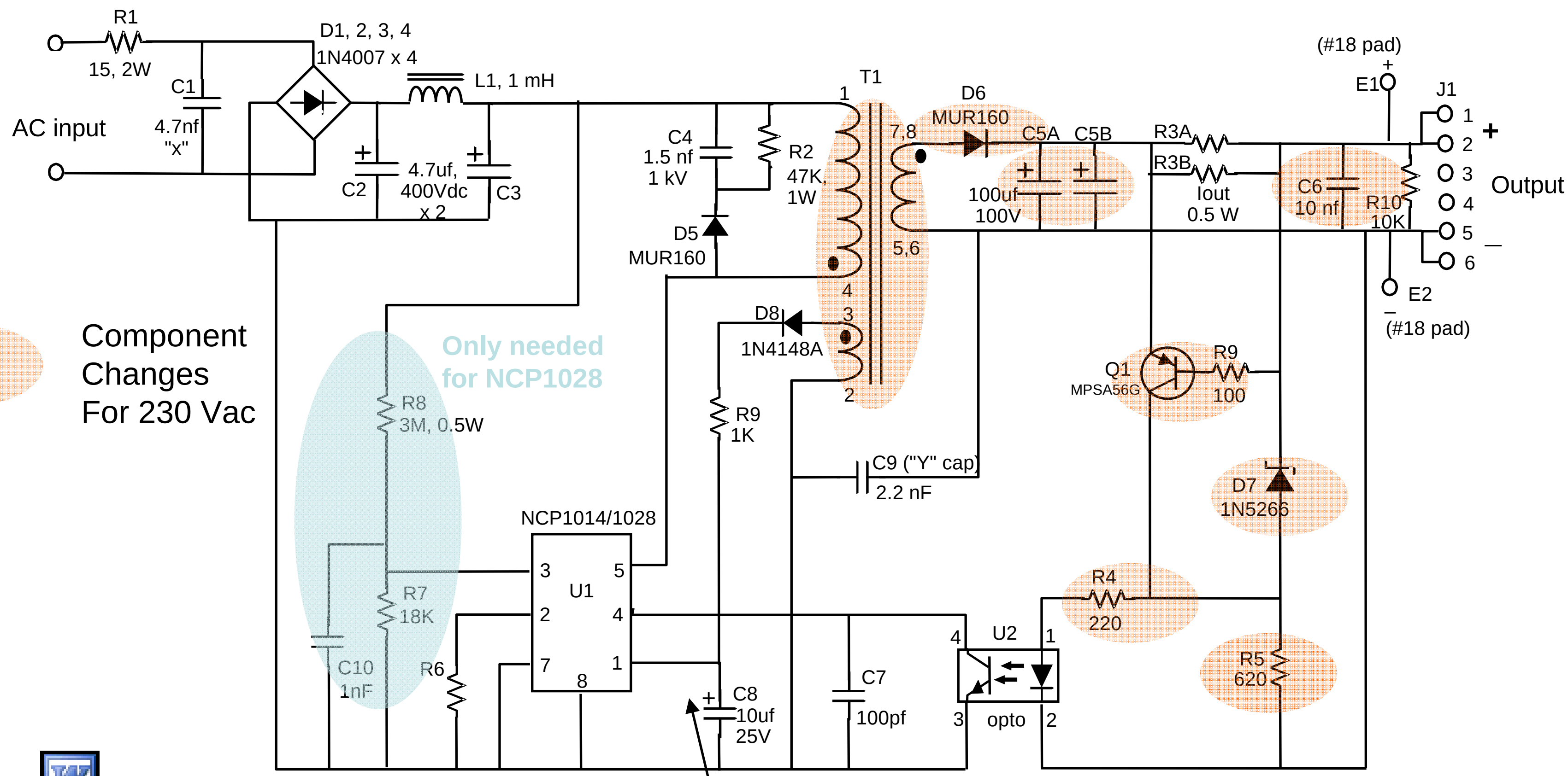
Key Features

- ❑ Input voltage range from **90 to 265 Vac**
- ❑ Continuous output power **up to 8 W**
- ❑ Output **Open Circuit voltage clamping**
- ❑ Frequency jittering for **reduced EMI signature**
- ❑ Built in **thermal shutdown** protection

Current Regulation Across Line (1-5 LEDs)



200 - 265 Vac version of NCP1014 (15W+)



Component Changes For 230 Vac

20W 65V Transformer

Only needed for max power applications Or when NCP1028 is used

Nominal I_{LED} = 0.65/(R3A||R3B)

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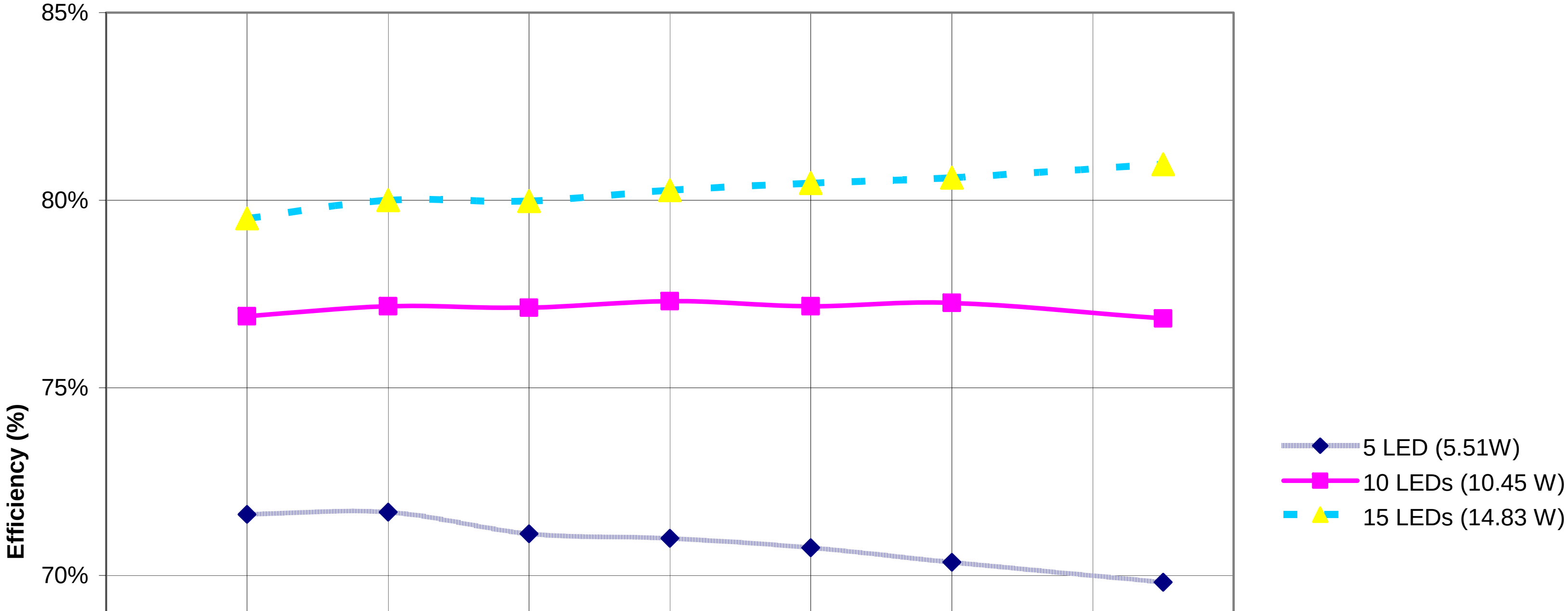
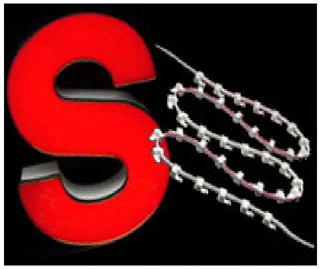
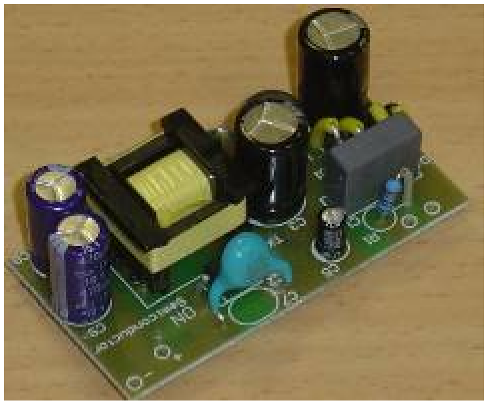
230 Vac NCP1014 20 W/360 mA Efficiency





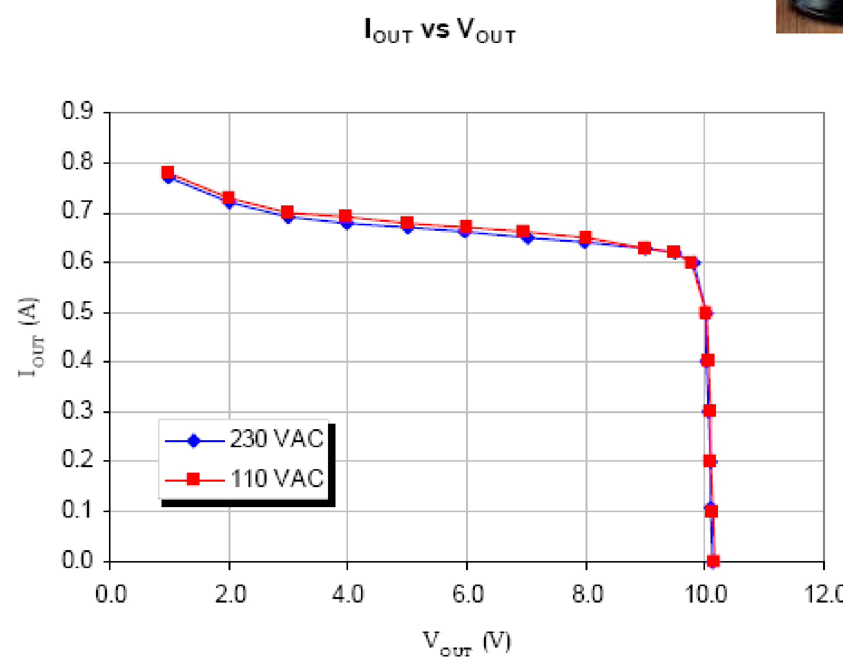
NCP1013 Offline LED Driver
Small Form Factor Reference Design



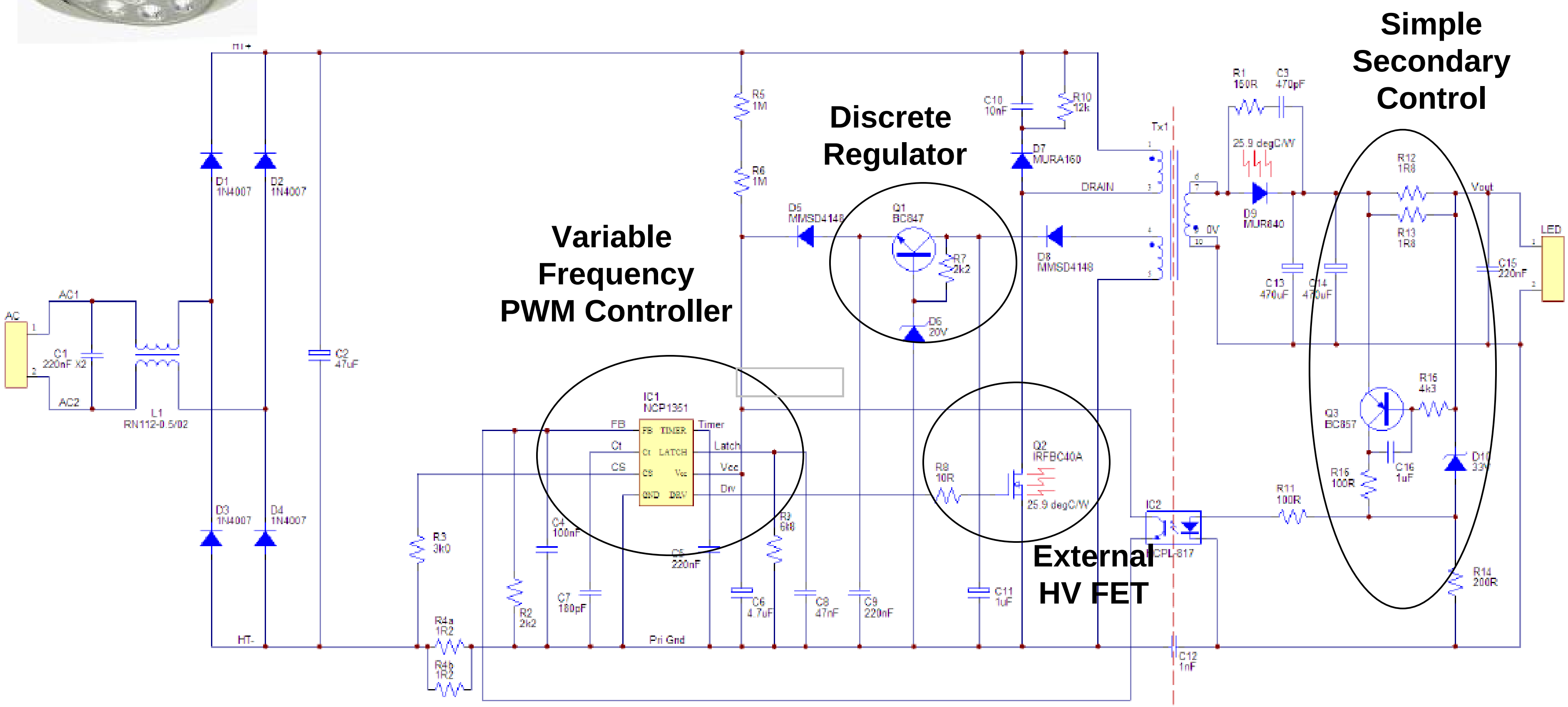
- Compact design for up to 5W – 350, 700mA or 1A with simple resistor change (R3/4)
- Open LED clamp at 10V, short circuit protected
- Direct HV operation, no auxiliary winding
- Universal Input (90-265 Vac)

DN6027 NCP1013
Design Note

- Schematic
- Bill of Material
- Transformer Design
- Theory of Operation
- Typical Performance

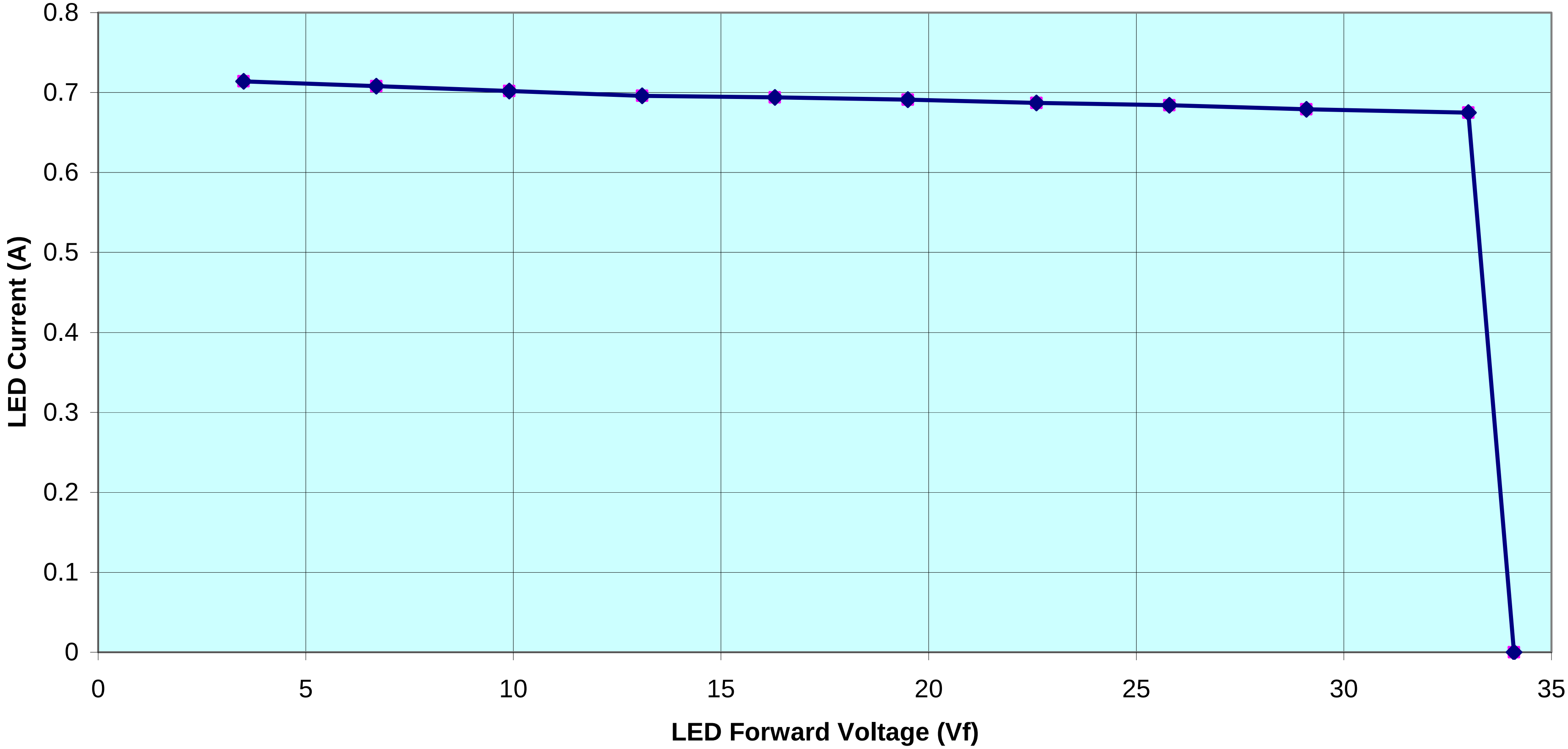


For Higher Power >15W Universal NCP1351 Controllers



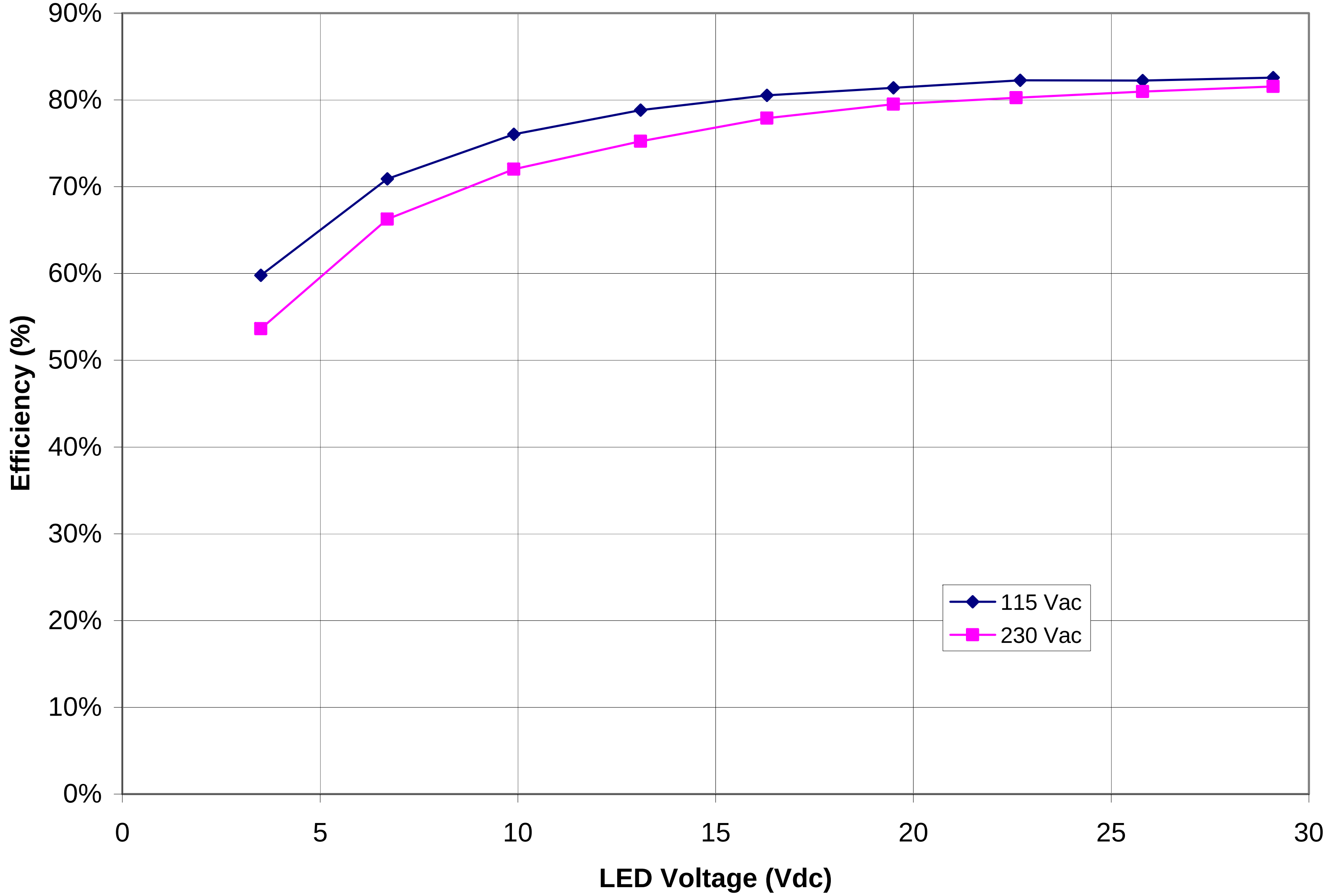
- Example based on NCP1351 20W Universal input (DN06040)
- Can support 350mA to 1A, design set for 700mA, 33Vdc

NCP1351LED Performance
Current Regulation across V_f and V_{in}



Vin = 115 / 230 Vac

NCP1351LED Performance Efficiency across V_f and Line



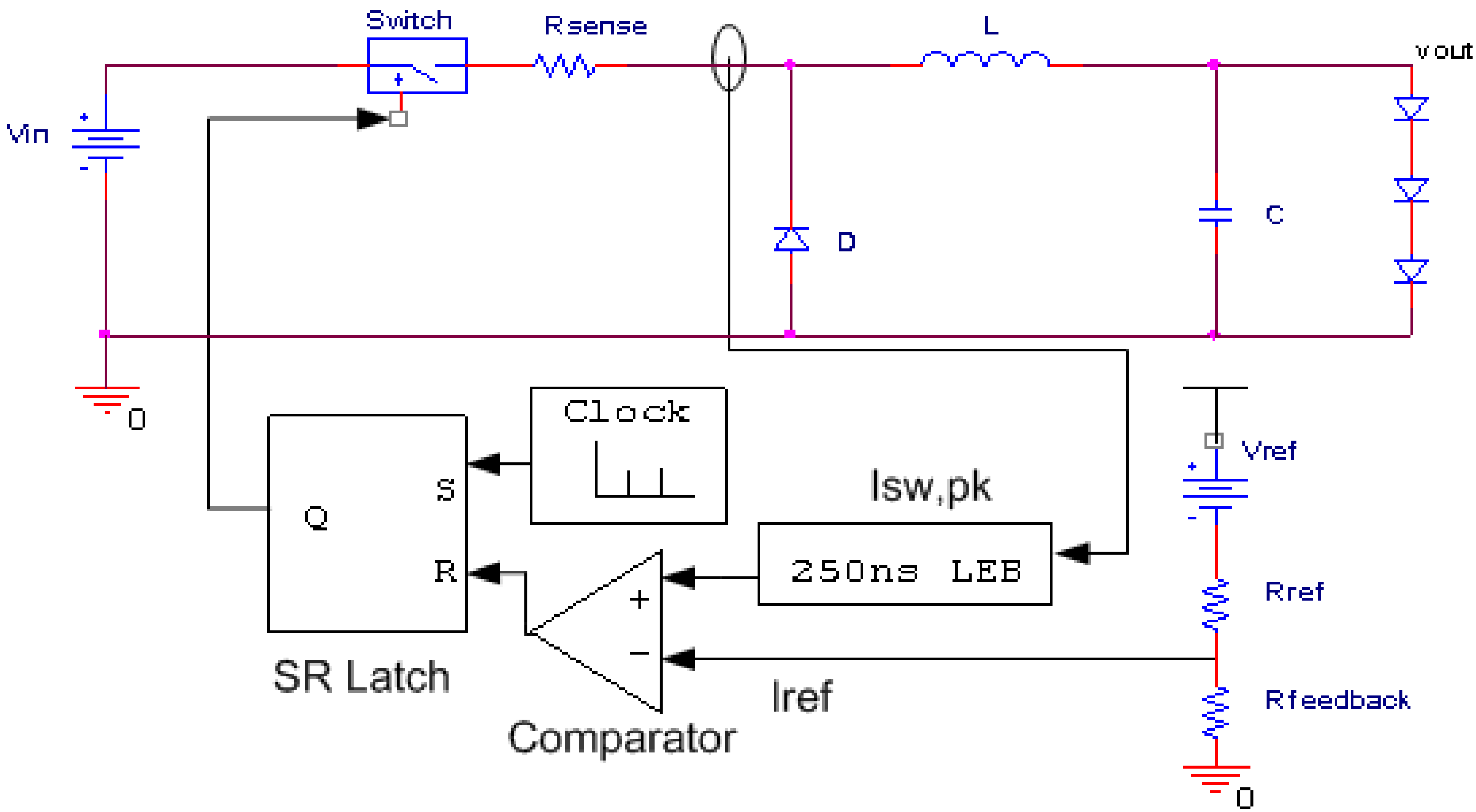
Non-isolated offline Buck Circuits

- Peak Current Controlled Topology operating in Deep Continuous Conduction

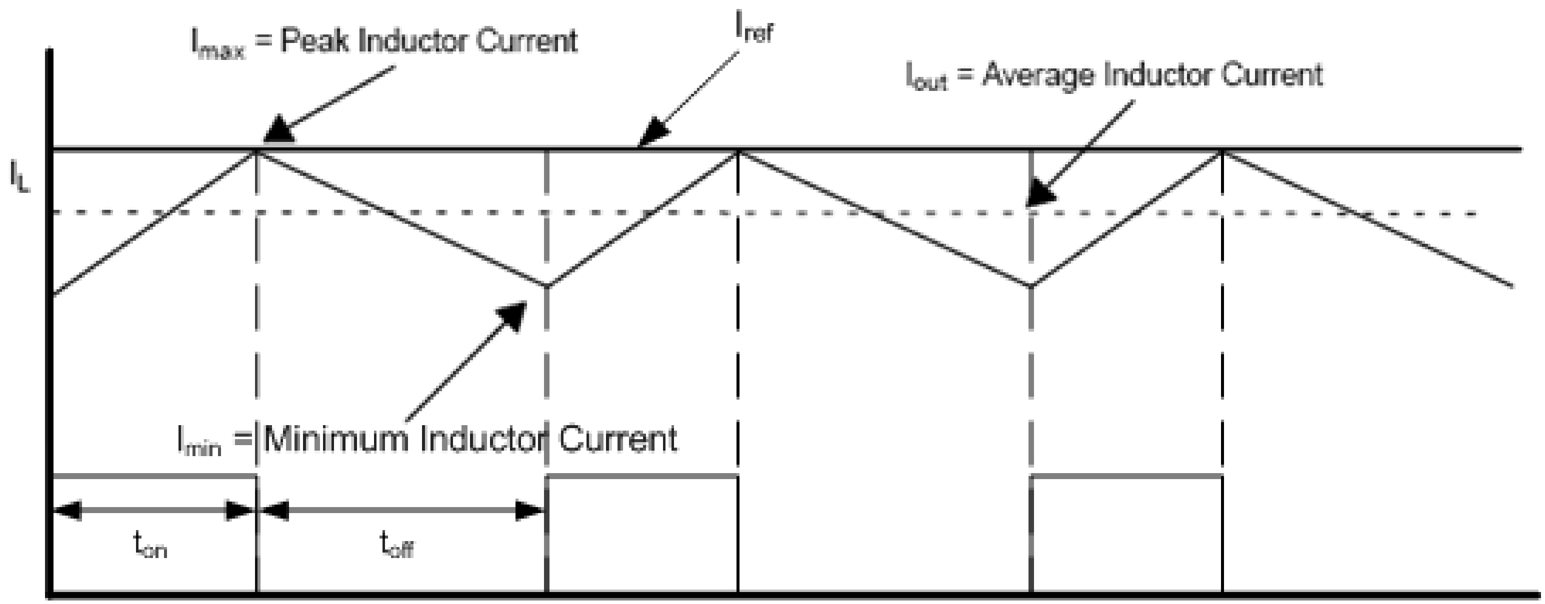
- Why:
  - Option to eliminate need for large electrolytic output capacitor
  - Simple control scheme with “good” current regulation
  - Can take advantage of the ON Semiconductor DSS capability to power driver directly from the line

- Circuit should be optimized for the number of LEDs

PCC Buck Theory

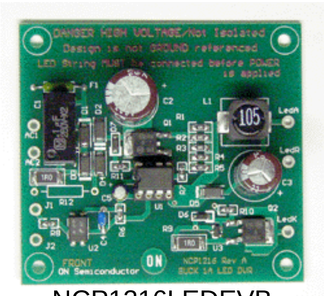


Regulate Peak – Control Valley



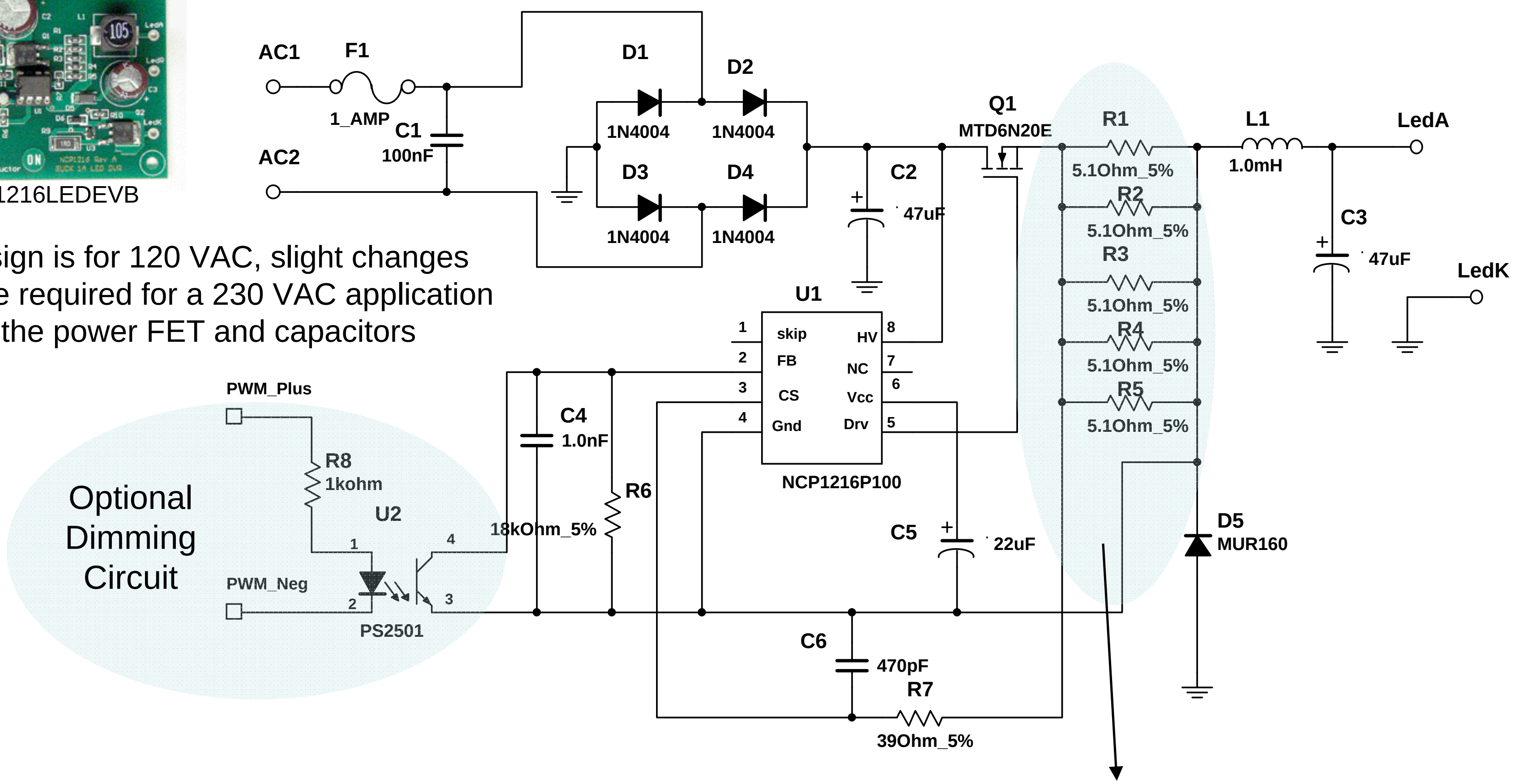
- CCM Operation
- L = (VIN,MAX – VOUT) * (VOUT / VIN,MAX) * (1/fs) *(1/ (%Ripple * Iout))
- Must Respect Minimum Duty cycle

Offline Non-Isolated buck LED driver



NCP1216LEDEVB

This design is for 120 VAC, slight changes would be required for a 230 VAC application such as the power FET and capacitors

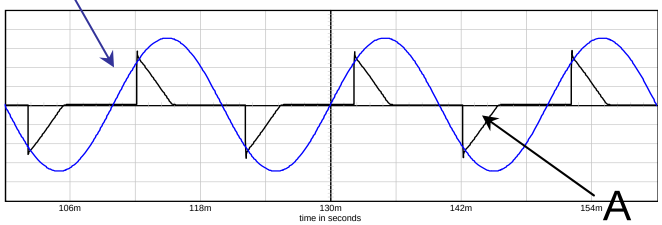


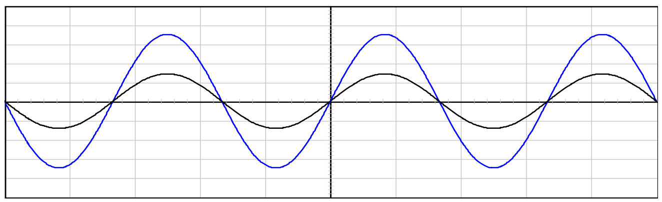
Since this is a **non-isolated** AC to DC design, high voltages are present. This is a floating design and the IC and LEDs are not reference to earth ground. The LEDs **MUST** be connected to the board before powering the device

Peak Current feedback when 1V is across the sense resistor, parallel of for cost savings

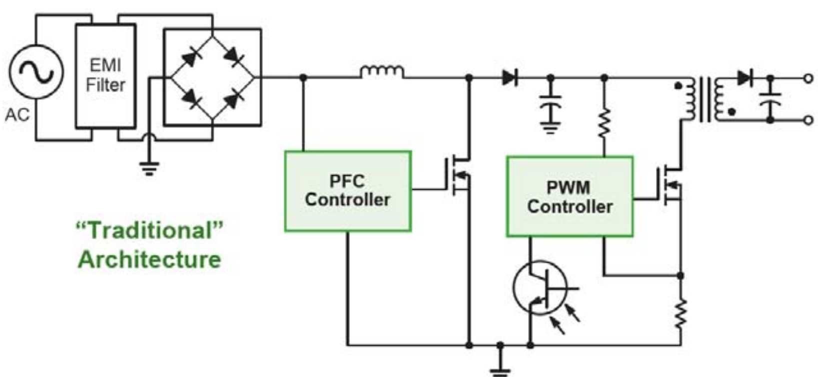
PFC regulation

V Without PFC ☹

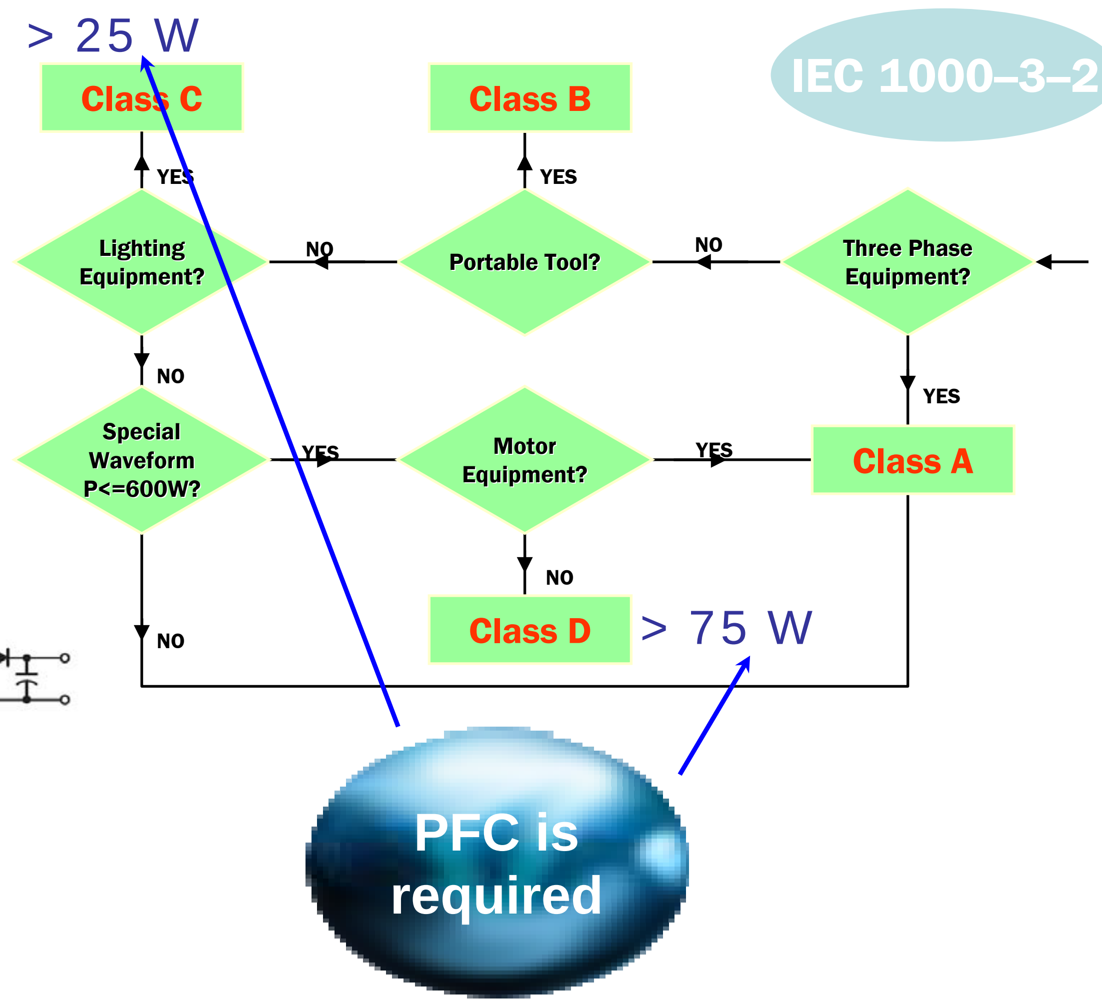




With PFC ☺



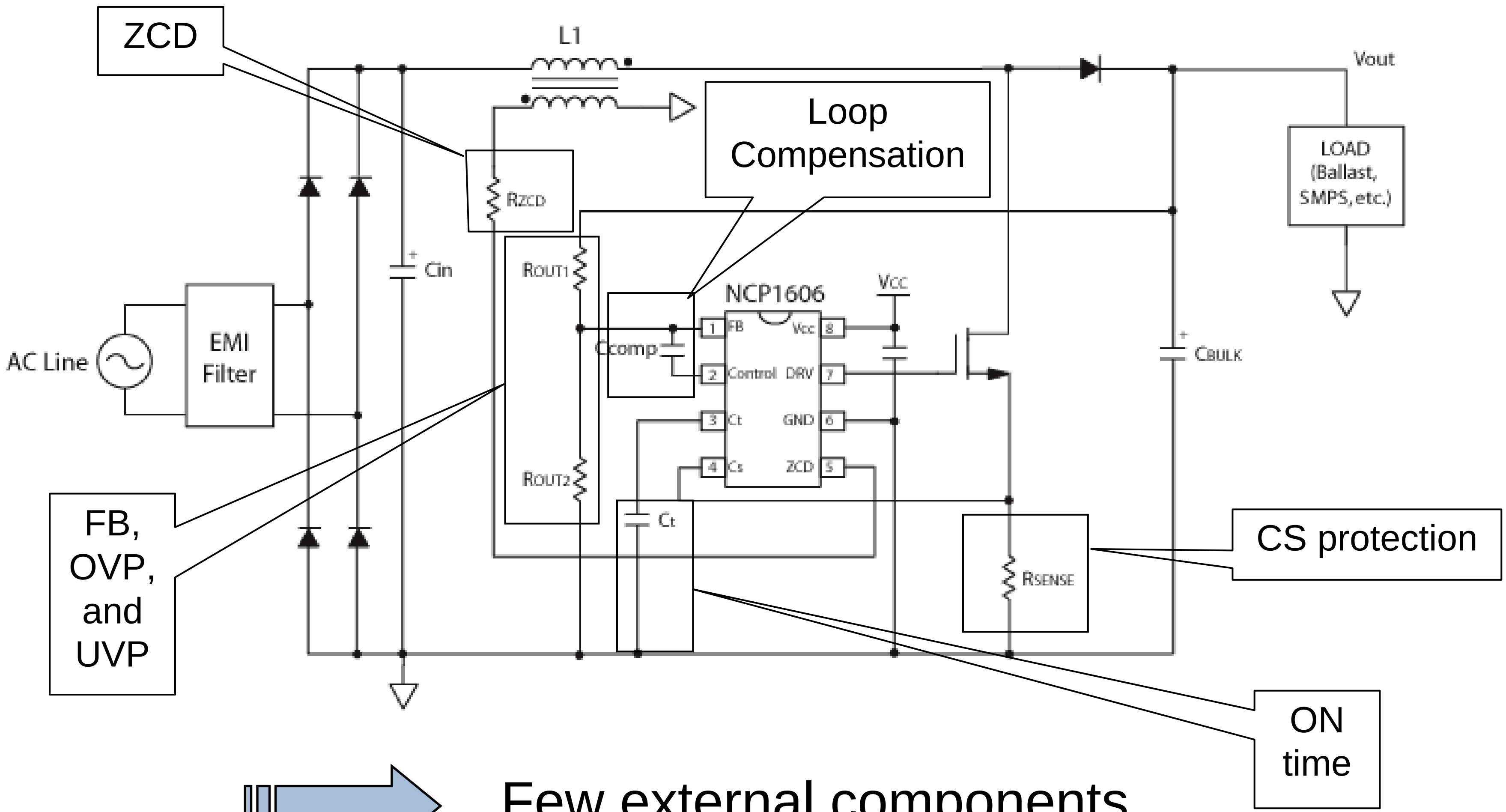
"Traditional" Architecture



Does the driver need good PF?

- US DOE ENERGYSTAR™ includes mandatory PFC for Solid State Lighting regardless of the power level. This is a voluntary standard and applies to a limited set of applications
  - >0.7 for residential applications
  - >0.9 for commercial applications
- While not absolutely mandated in the US for lighting, it may be required based on the application:
  - Utilities drive major commercial uses to have high PF at the facility level
  - Moreover when utilities owns/service the streetlight it is in their interest to have good power factor, typically > 0.95+
- IEC (EU) requirements dictate THD performance for Lighting (over 25 W)

Typical PFC Boost Circuit

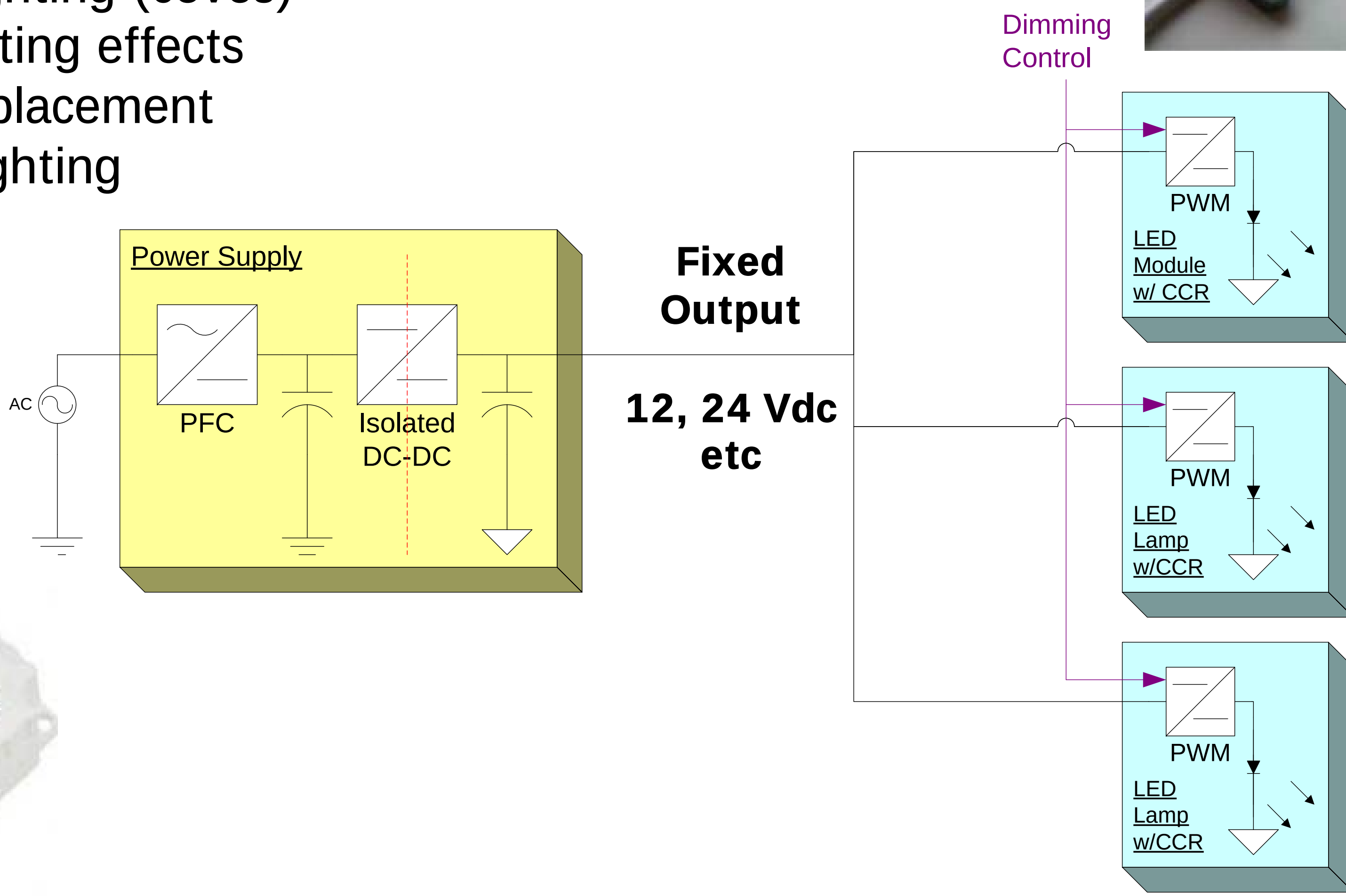


Few external components

Distributed DC Architecture

Typical Applications:

- linear lighting (coves)
- backlighting effects
- neon replacement
- street lighting



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Large Area Lighting

- Two stage architecture is quite common with products on the market now
  - fixed voltage offline supply to generate 24, 36, or 48V (UL Class 2)
  - Constant current driver embedded in LED strip
  - Multiple strips per Light
- Two separate stages compromises overall efficiency but supports modularity / simplicity in certification
  - Ex: 87%/90% (AC/DC) * 85%/90% (DC-DC) = 74-81% overall, HID Ballasts are 90+% efficient
- As LEDs continue to improve, we would expect this to migrate to a more optimal, higher efficiency approach
- Multiple options depending on requirements
  - PFC plus non-isolated Buck
  - PFC plus isolated Flyback or HB-LLC
  - NCP1651/NCP1652 Single Stage

Wide Input DC-DC LED Applications

- Landscape Lighting
- Interior Low Voltage Track Lighting
- Solar Powered Lighting
- Transportation
- Emergency Vehicles
- Display Backlighting
- Marine Applications
- Portable Projectors
- Low Voltage Halogen Replacement
- Automotive Applications

12 VAC
5W LED

Solar
Powered
Tempe, AZ

12 V Lead Acid
Boat
Light

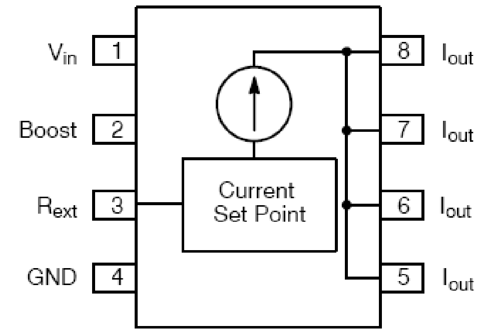
Common Power Sources

Power Source	Use/Application	Voltage & Regulation
Offline AC Regulated Adapter	Low to medium volume applications, reduces safety requirements	Common voltages of 5, 12, 24 VDC, regulation to +/- 10%
(Sealed) Lead Acid Battery	Automotive or Solar Powered, marine	Loose regulation, 8-13+ VDC, plus for automotive, load dump considerations
12 VDC and 12 VAC	Common in interior, track lighting & outdoor landscaping applications	Loose if magnetic ballast, tight to +/-5% if electronic ballast, minimum load may be required, cable losses

Linear LED Drivers

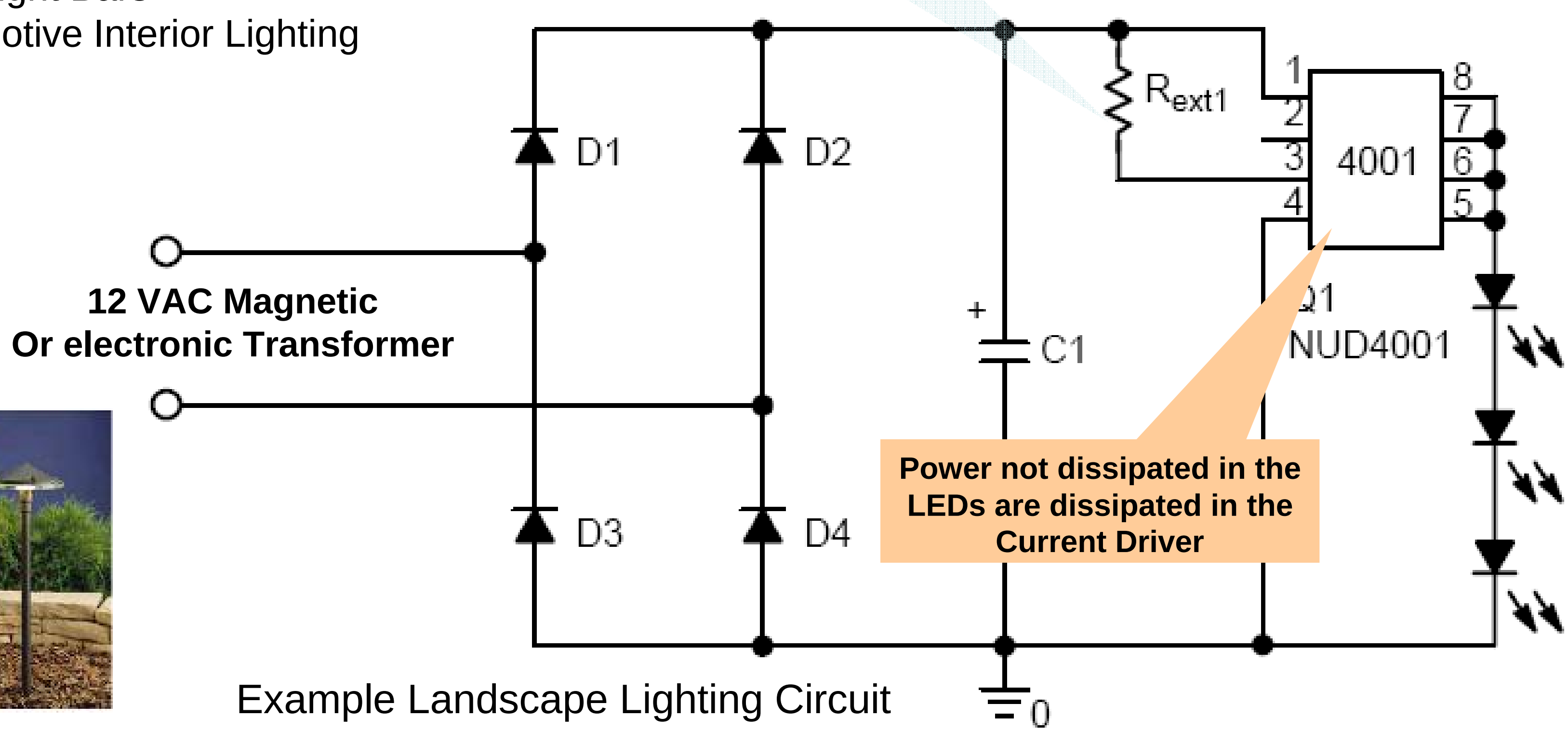
Applications

•NUD4001 up to 500mA, 6 to 40 Vdc
•NUD4011 up to 70mA, 48 to 200 Vdc



- Low Voltage Track Lighting
- Landscape Lighting
- Path Lighting
- Step Lighting
- LED Light Bars
- Automotive Interior Lighting

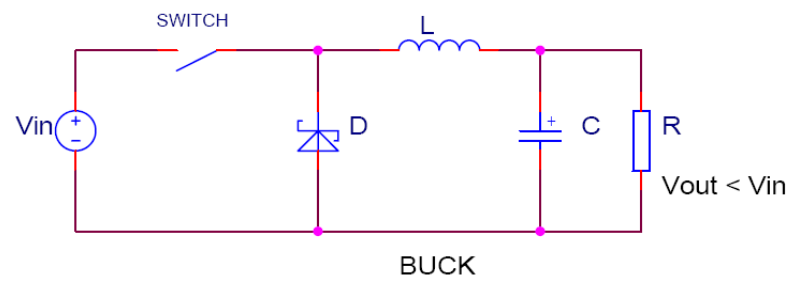
Resistor Sets LED Current

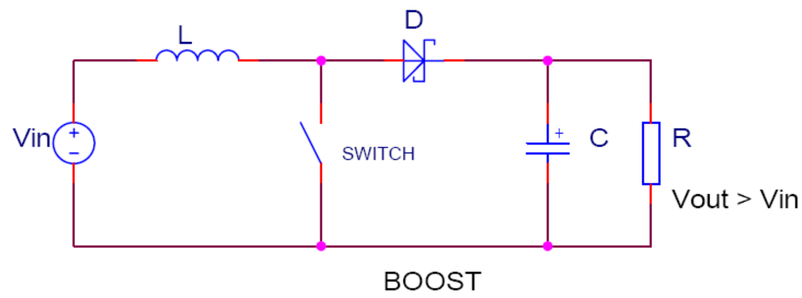


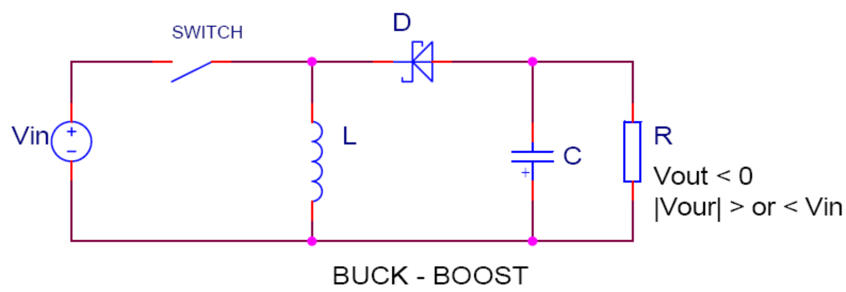
Example Landscape Lighting Circuit

Switching regulator topologies for LEDs

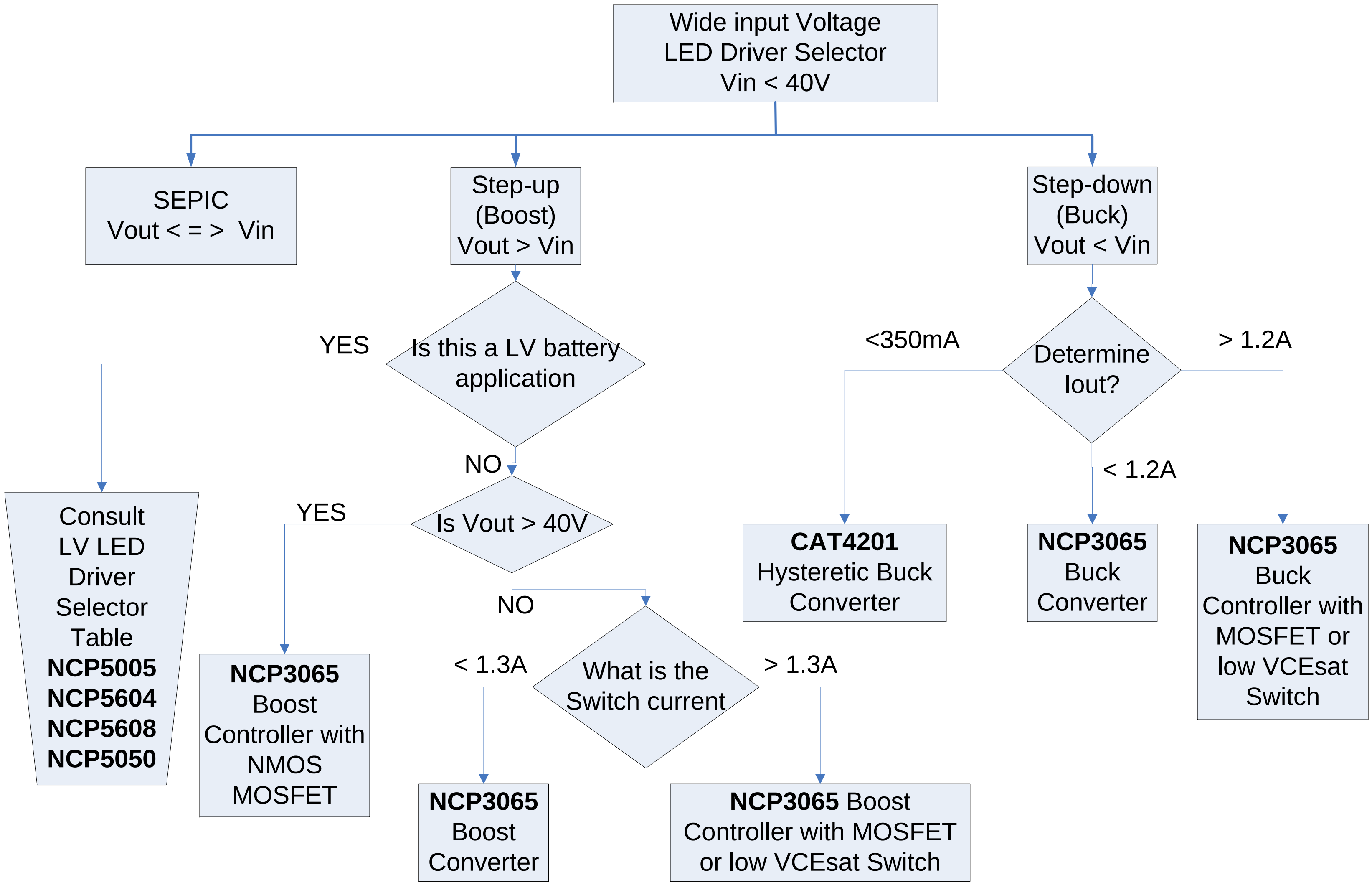
- Buck (Step Down) –when minimum Vin is always greater than the maximum voltage of the LED string under all operating conditions
  - Driving a single 1W LED from a 12V supply
- Boost (Step-Up) - when maximum Vin is always less than the minimum voltage of the LED string under all operating conditions
  - Driving 6 LEDs in series from a 5V supply
- Buck-Boost or SEPIC – Input and output voltages overlap
  - Driving 4 LEDs from a 12 V car battery



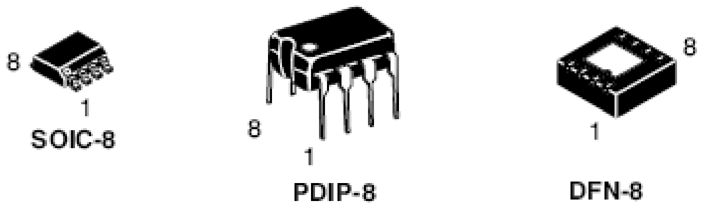


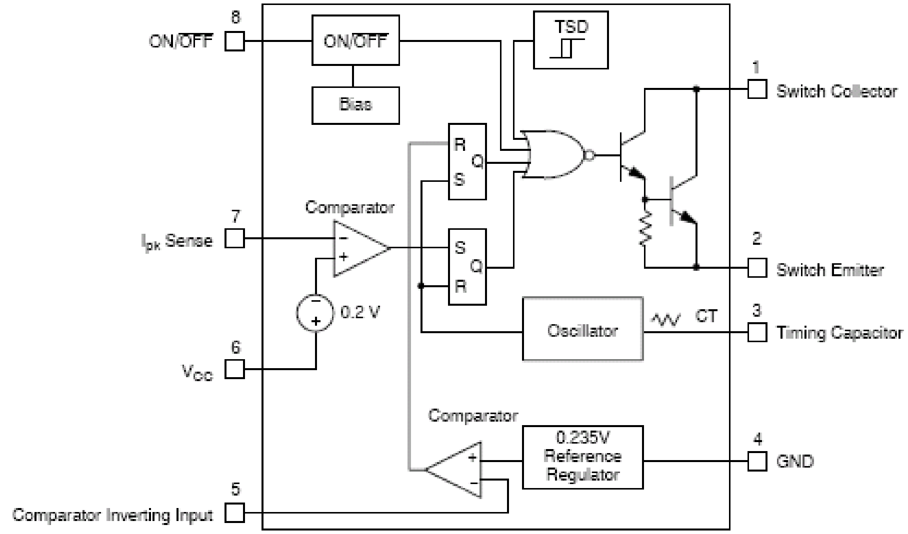


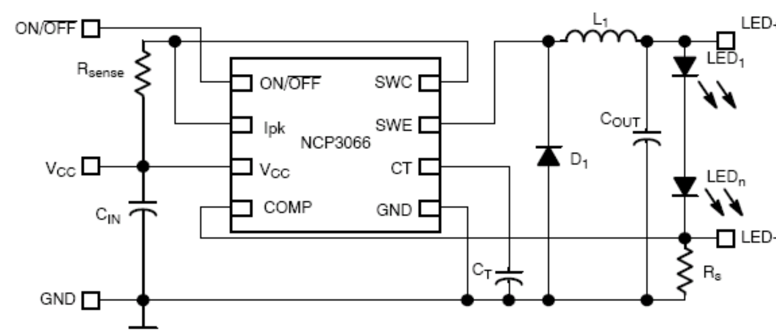
LED Driver DC-DC Decision Tree



NCP3065/6 Multi-mode LED Driver

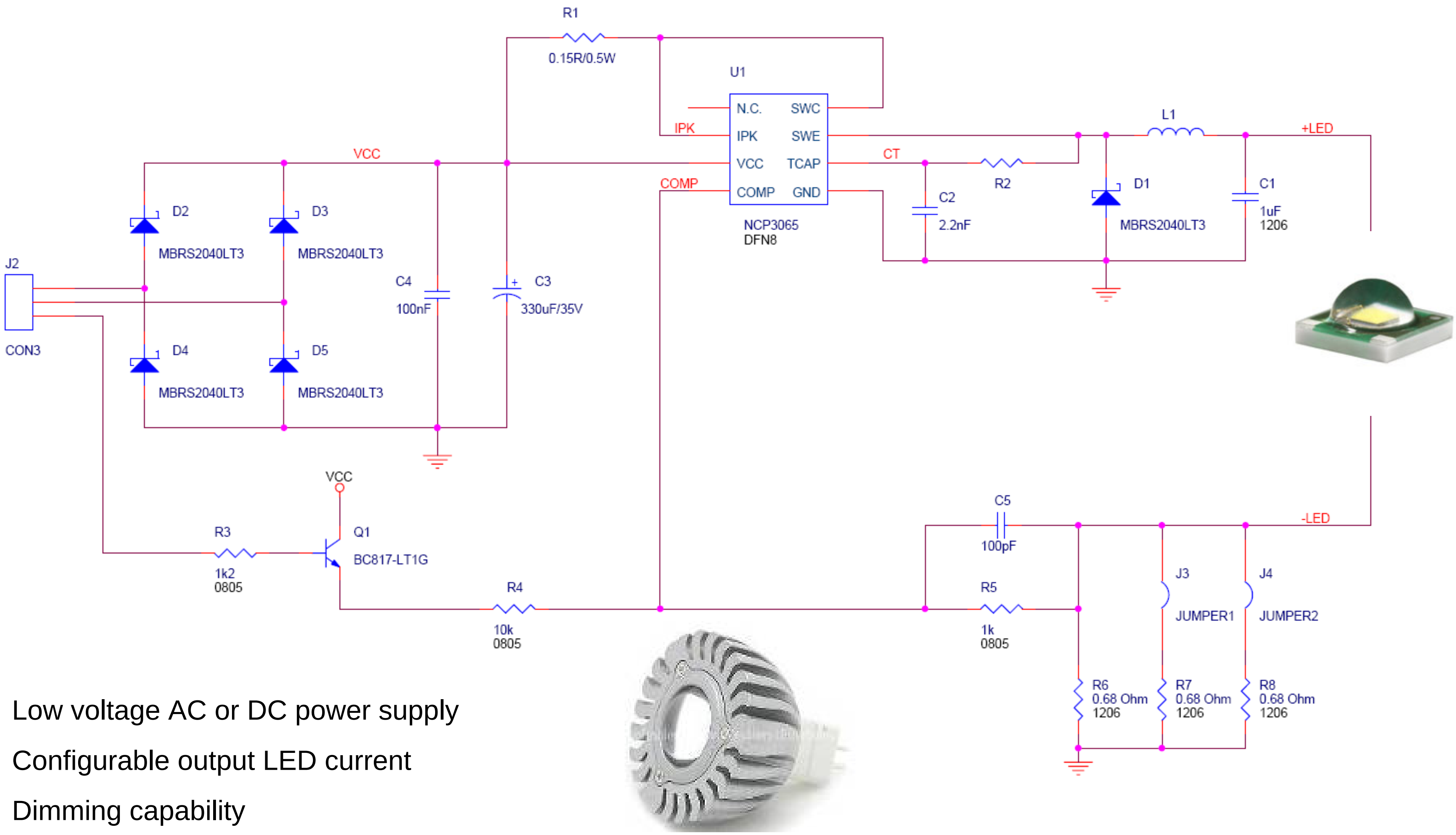






- Integrated 1.5 A Switch
- Buck, Boost and Inverter/SEPIC Topologies
- Input Voltage Range from 3.0 V to 40 V
- Low Feedback Voltage of 235 mV
- Cycle-by-Cycle Current Limit capable
- No Control Loop Compensation Required
- Frequency of Operation Adjustable up to 250 kHz
- Operation With All Ceramic Output Capacitors
- Analog and Digital PWM Dimming Capability
- Internal Thermal Shutdown with Hysteresis
- NCP3065 does not have an enable pin

Constant Current Buck Regulator for LED



Low voltage AC or DC power supply

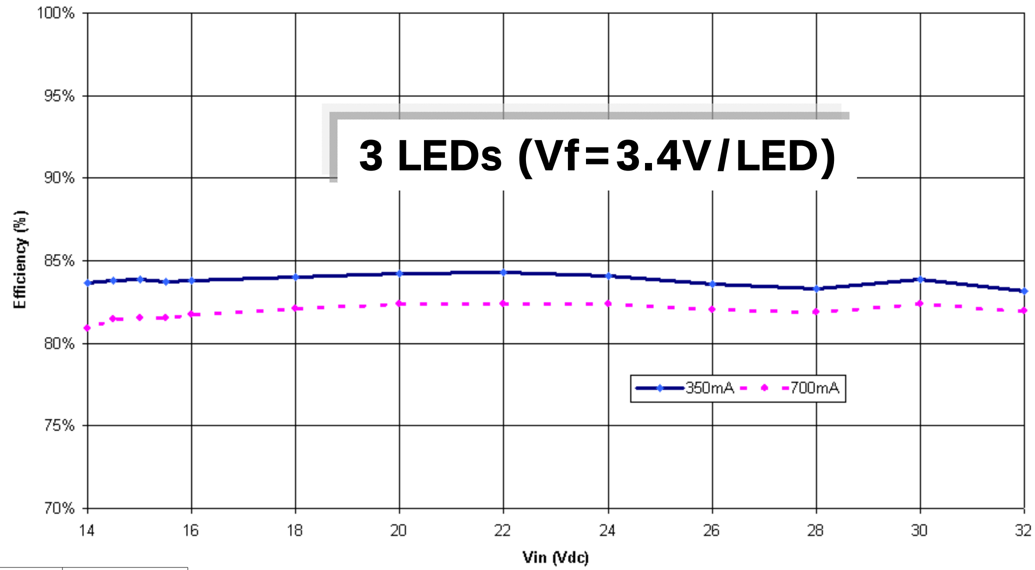
Configurable output LED current

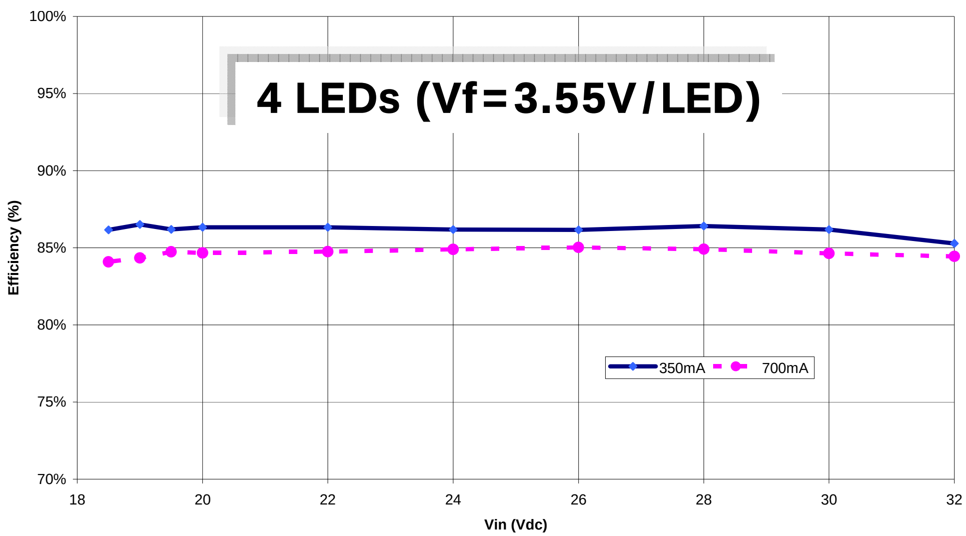
Dimming capability

NCP3065/6 Buck Performance

- **Efficiency Performance**

  - **350 mA and 700 mA**
  - **3 LEDs – 14 to 32V input**
  - **4 LEDs - 18 to 40V input**





Ideal for 24 V DC Supplies

85%+ for 4 LEDs
82%+ for 3 LEDs

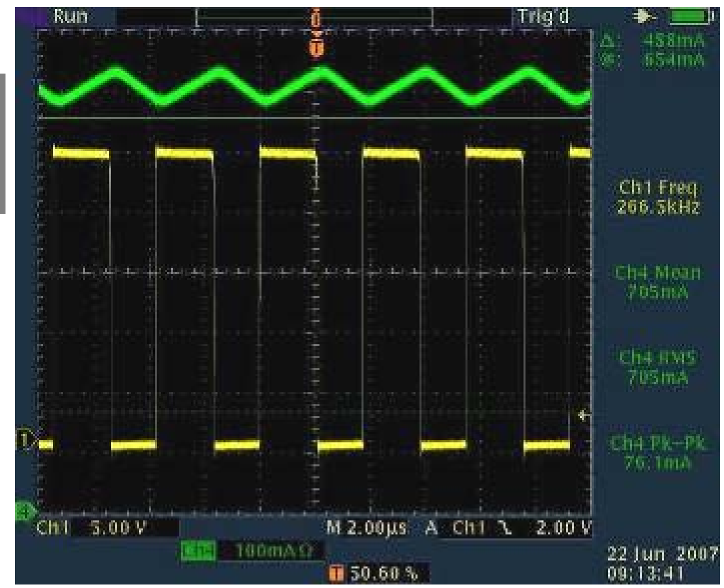
Output current ripple
with/out output cap

The human eye has a relatively low bandwidth and cannot distinguish light variation caused by the LED ripple current. For buck applications if we keep the ripple low, the output capacitor can be eliminated - a good guideline is the keep the ripple to less than +/- 15% of the nominal current (must always stay below maximum rating of LED)

With output capacitor L = 47uH, C = 100uF

LED Current in Green

Without output capacitor L = 220uH



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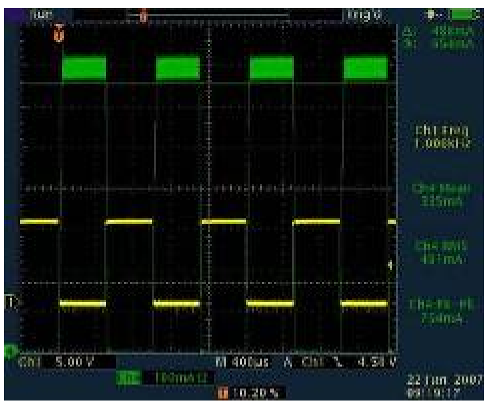
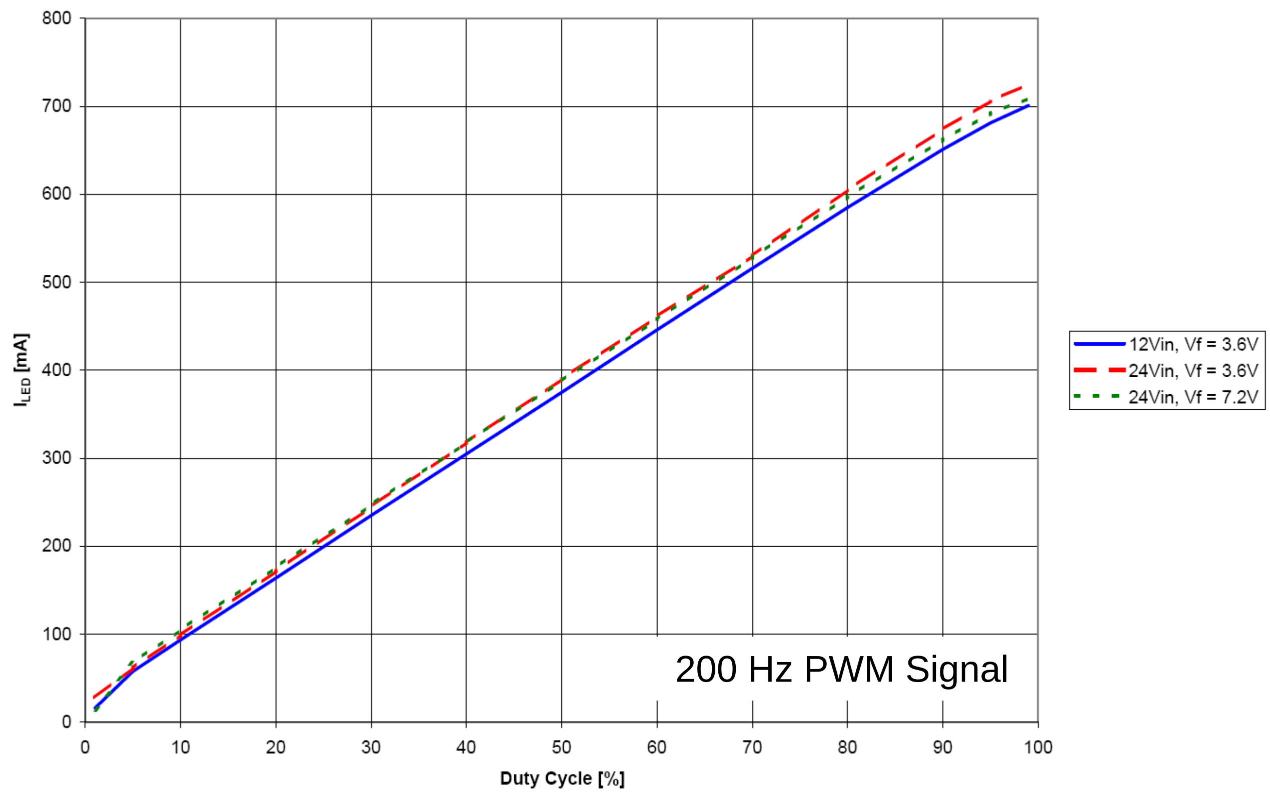
Dimming Capability

- Example using a NCP3065 in a buck configuration
- Good Linearity across wide dimming range

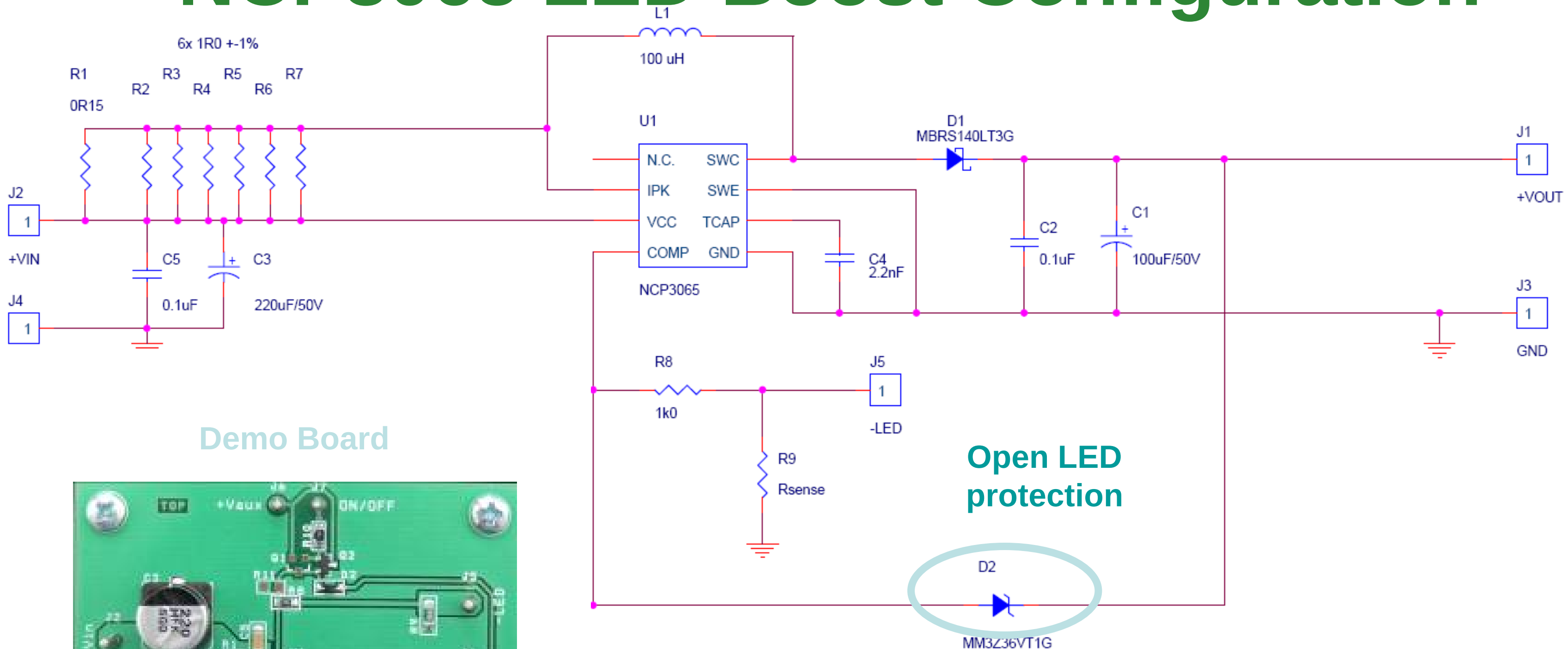
Dimming frequency 200 Hz



Dimming frequency 1kHz



NCP3065 LED Boost Configuration

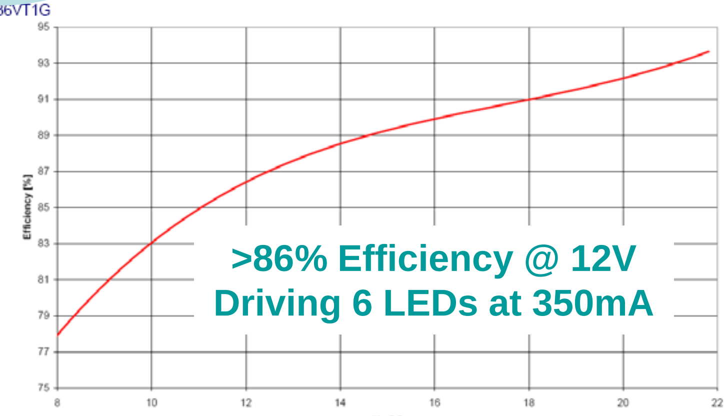


Open LED protection

Demo Board

AND8289

AND8289 discusses boost LED Driver Circuits

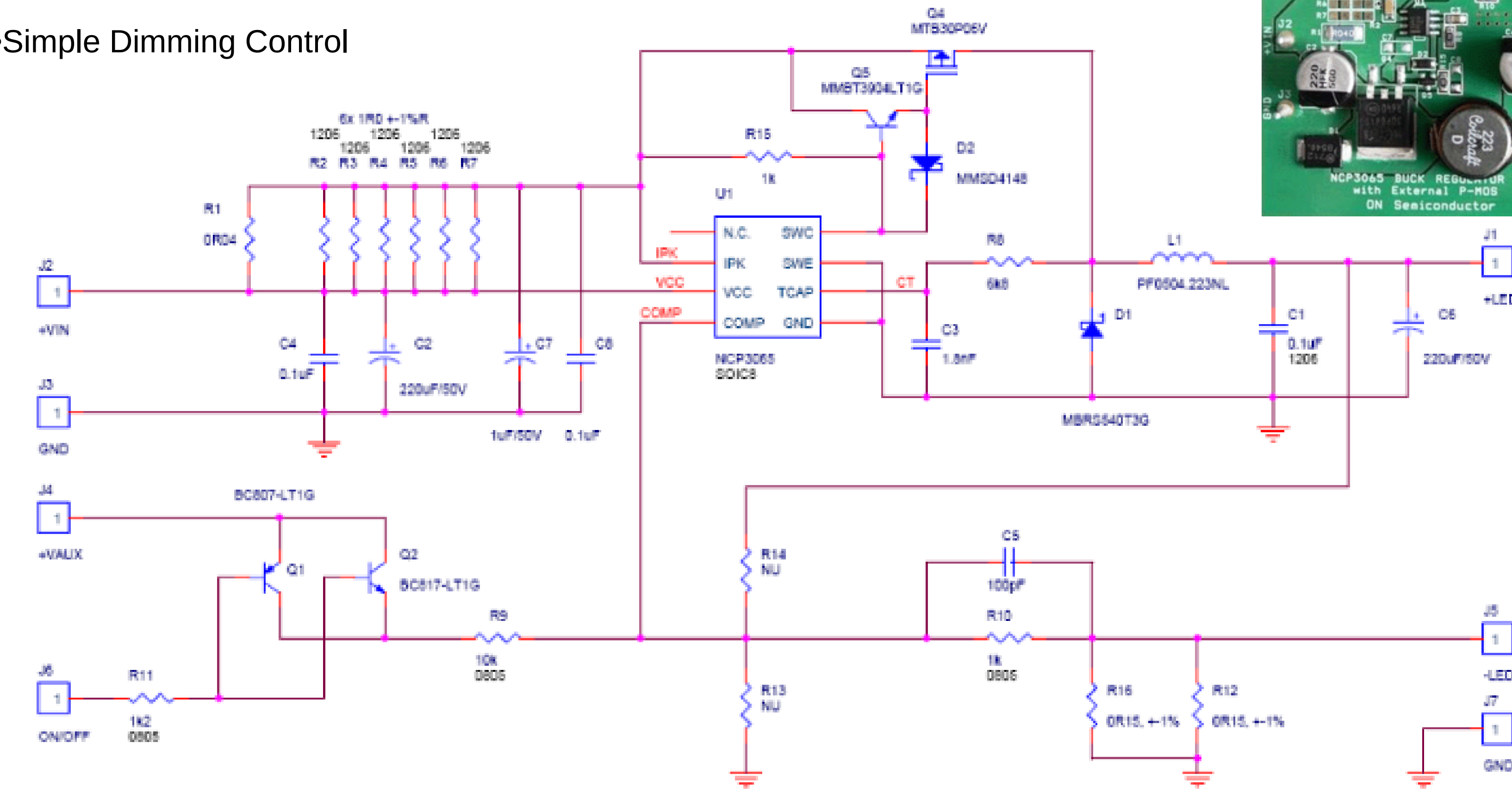


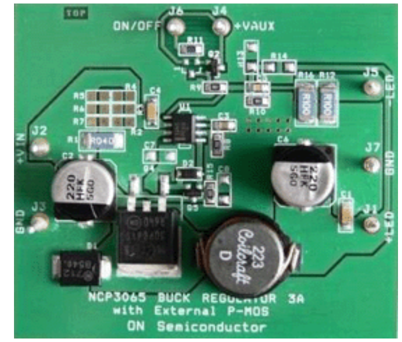
>86% Efficiency @ 12V Driving 6 LEDs at 350mA

Figure 21: Efficiency vs. Input Voltage at I_{OUT} = 350mA, V_{OUT} = 22V
(6xLED with V_F=3.6V), T_A = 25°C

NCP3065 in PFET Buck Controller Configuration

- •Supports inputs to 40 VDC
- •Controller allows LED currents >3A
- •Simple Dimming Control





Buck LED Driver

CAT4201 Applications

- General Lighting
  - Light bulb replacement
  - Gaming lights
  - Decorative lighting
  - Pool and spa lighting
  - Desk lamps and task lighting
- Transportation
  - Automotive (incl. RV) illumination lighting
    - Turn signal, brake, interior lights
  - Aircraft
    - Interior lighting
  - Marine lighting (boats)
  - Bicycle lights
- Signage
  - Roadway signage

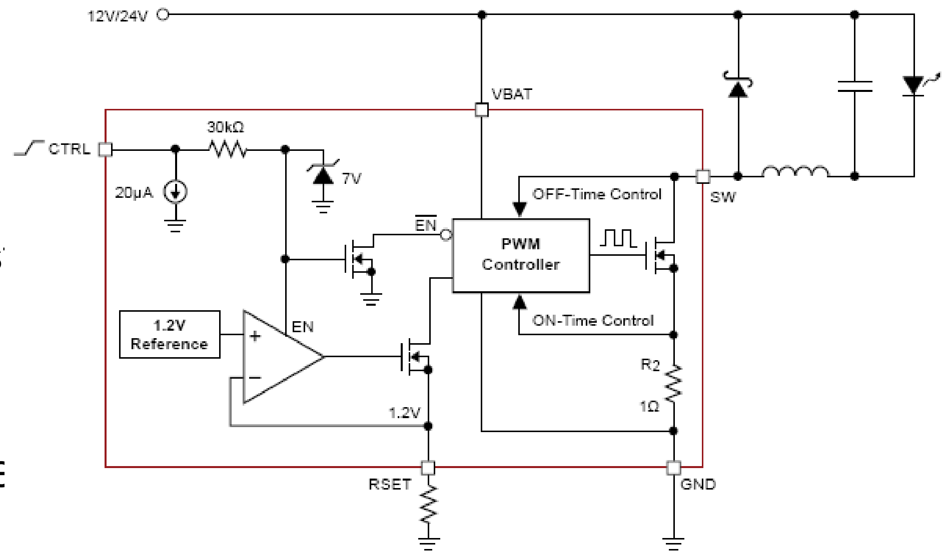
Part Number	V_{IN} [V]	LEDs	Total I_{OUT} (max) [mA]	Dimming Interface	R_{SET} Control
CAT4201	7 - 24	7	350	PWM	Yes

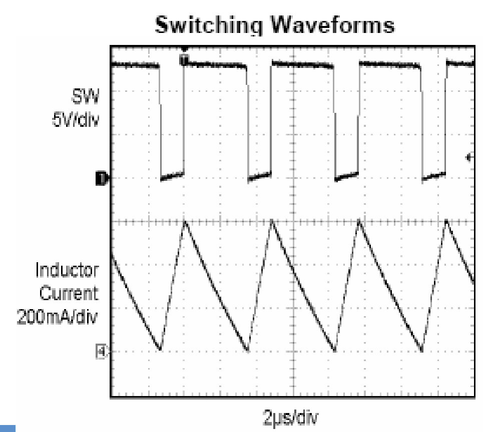
Buck LED Driver
CAT4201

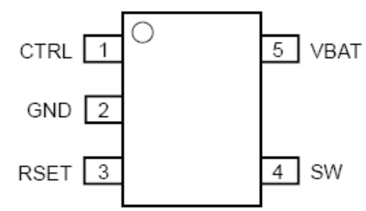
- Functionality
  - LED drive current up to 350mA
  - 12V and 24V system compatible
  - Handles transients up to 40V
  - Enable Pin
  - Power efficiency up to 94 percent
  - Drives up to 7 LEDs in series (24V sys
- Fully Protected
  - Current limit and thermal protection
  - Open LED Protection
- Patented switching control architecture
  - Reduces system complexity
  - Critical Conduction Operation
  - Improves efficiency

- Packaging
  - 5-lead thin SOT-23-5 (1mm height)

Simplified Block Diagram



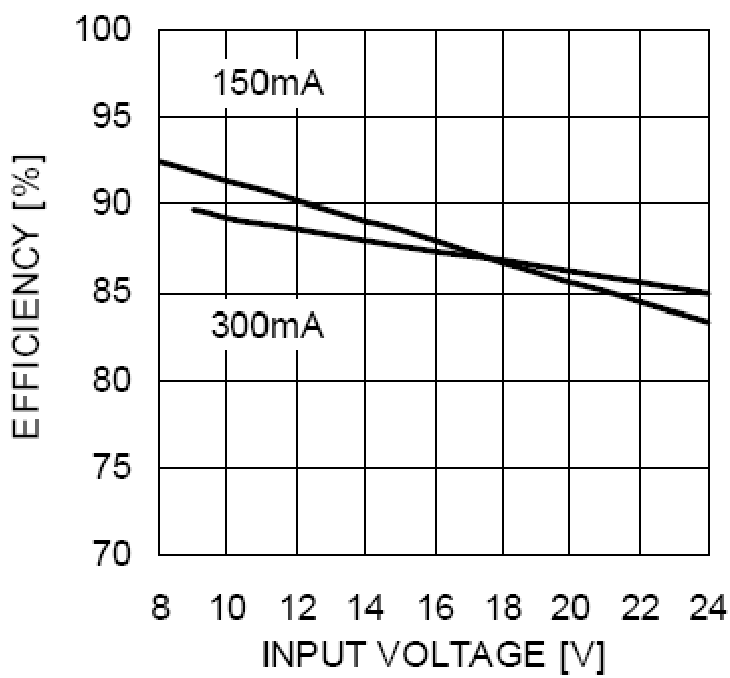




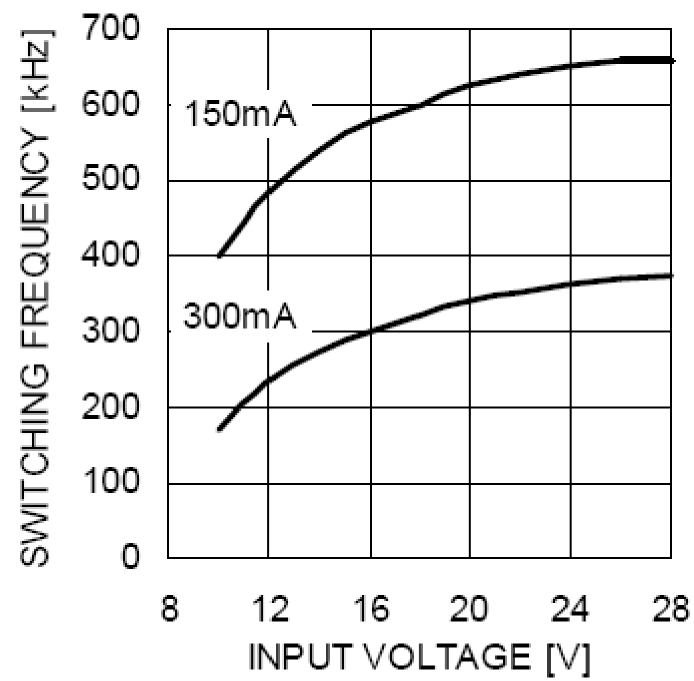
(Top View)

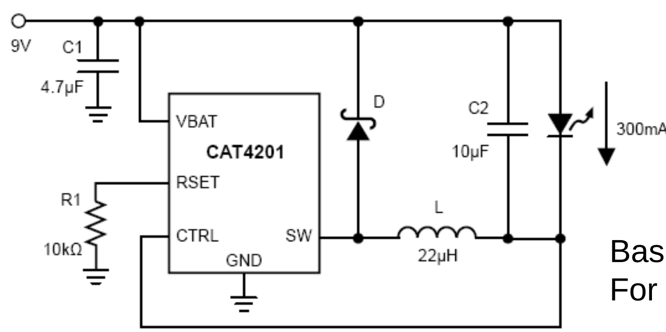
CAT4201 Parametric Performance

Efficiency vs. Input Voltage (2 LEDs)



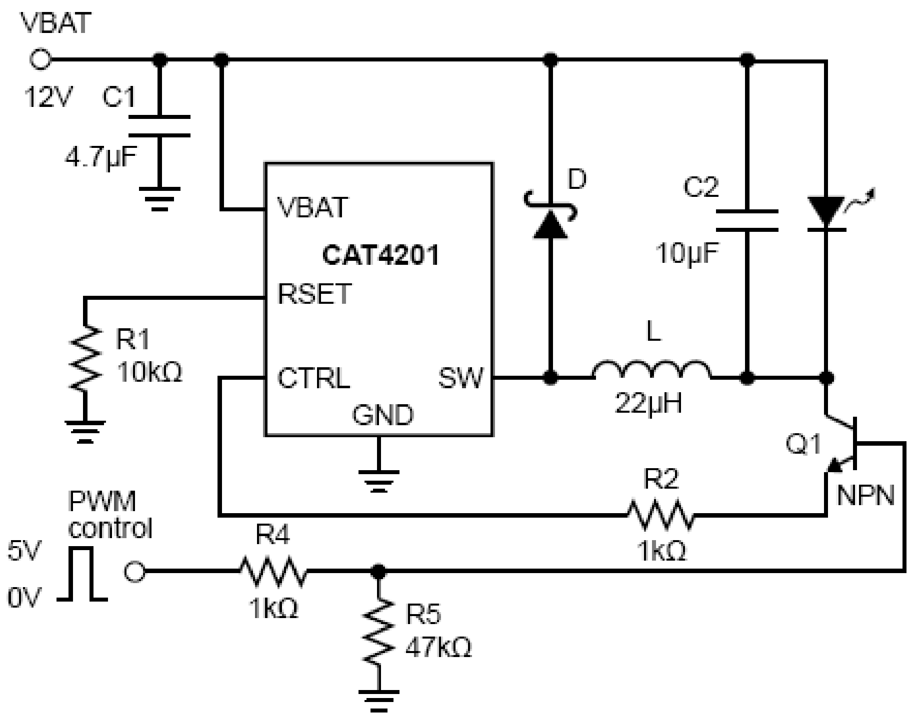
Switching Frequency vs. Input Voltage (2 LEDs)

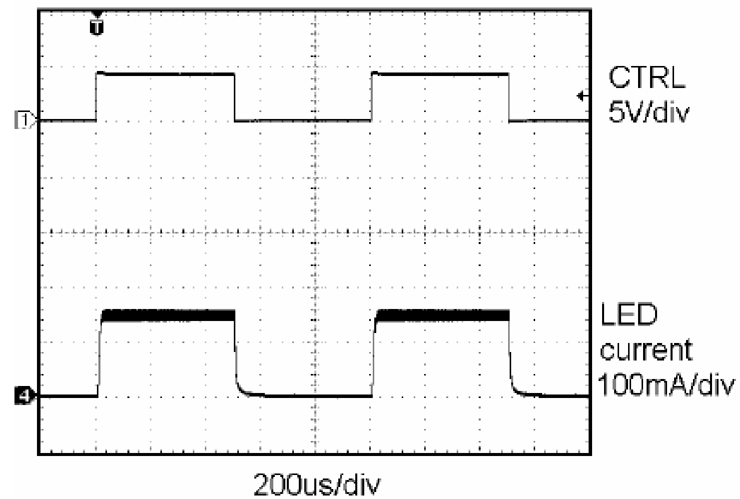


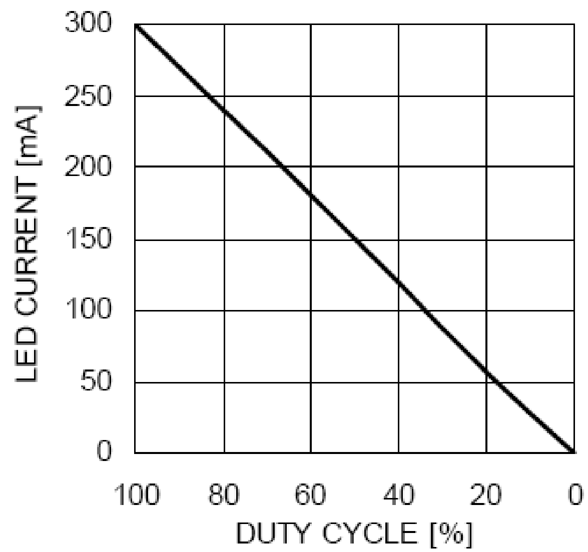


Basic schematic
For test data

CAT4201 Dimming Operation

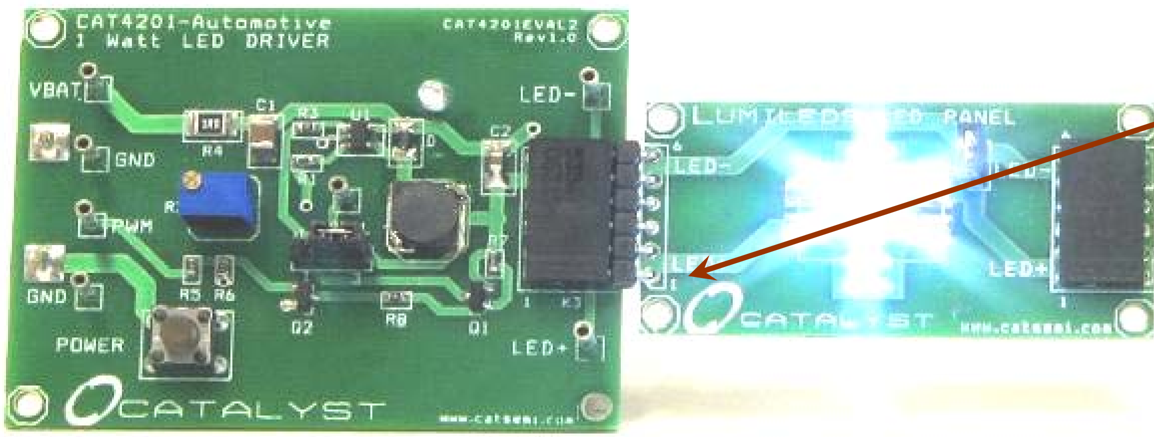






- Example circuit for PWM dimming
- PWM range from 100 Hz to 2 kHz

CAT4201 : Evaluation Kit



Cascadable
LED Panels (1Watt)
‘Daisy-Chain’

Figure 1. CAT4201EVAL2 with LED Module

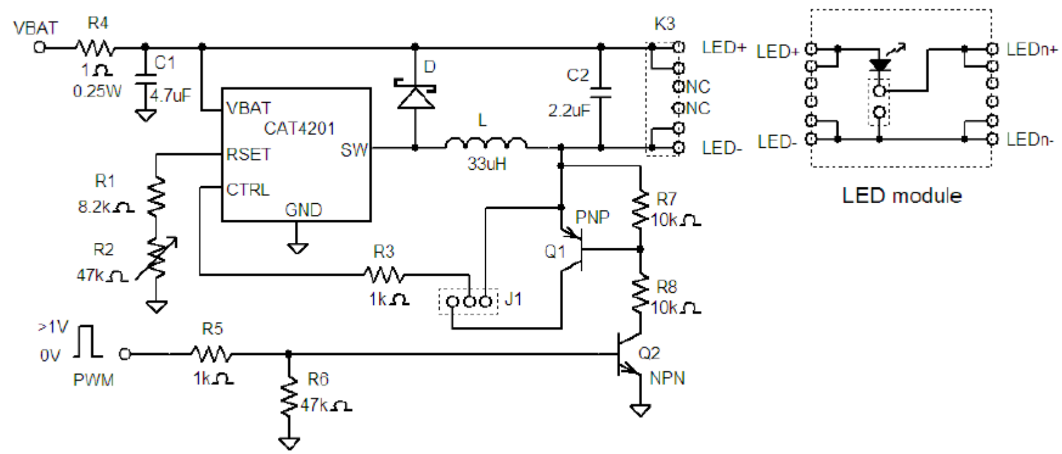
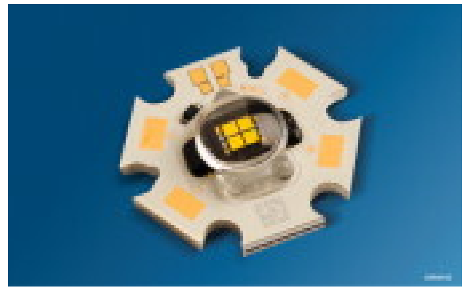


Figure 2. CAT4201EVAL2 Schematic

Driving Clusters of LEDs

- Start with a "Generic" LED specification
  - V_f range 2.9 – 3.8V @ 25 C/350mA
  - Negative TC of – 3mV/ C
  - Assume no V_f binning
- LED is rated at up to 140 C, lets limit junction temperature to 125 C (max), to calculate V_f shift
- Consider a cluster of 3 LEDs @700mA or 4 LEDs@ 350mA
- Tolerance of a 12 Vac/12 Vdc low voltage system
  - 12 Vdc – 10% = 10.8 Vdc
  - 12 Vdc + 10% = 13.2 Vdc
  - 12 Vac no loss = 17.0 Vdc
- For 3 and 4 LED cases, it is common to have Vin overlap Vout

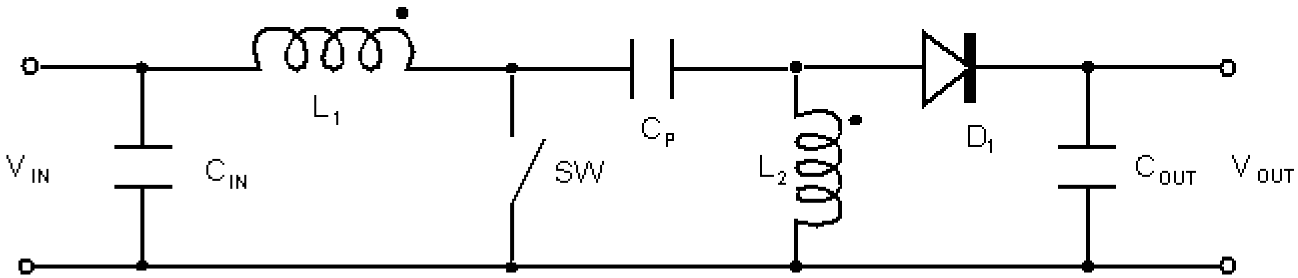


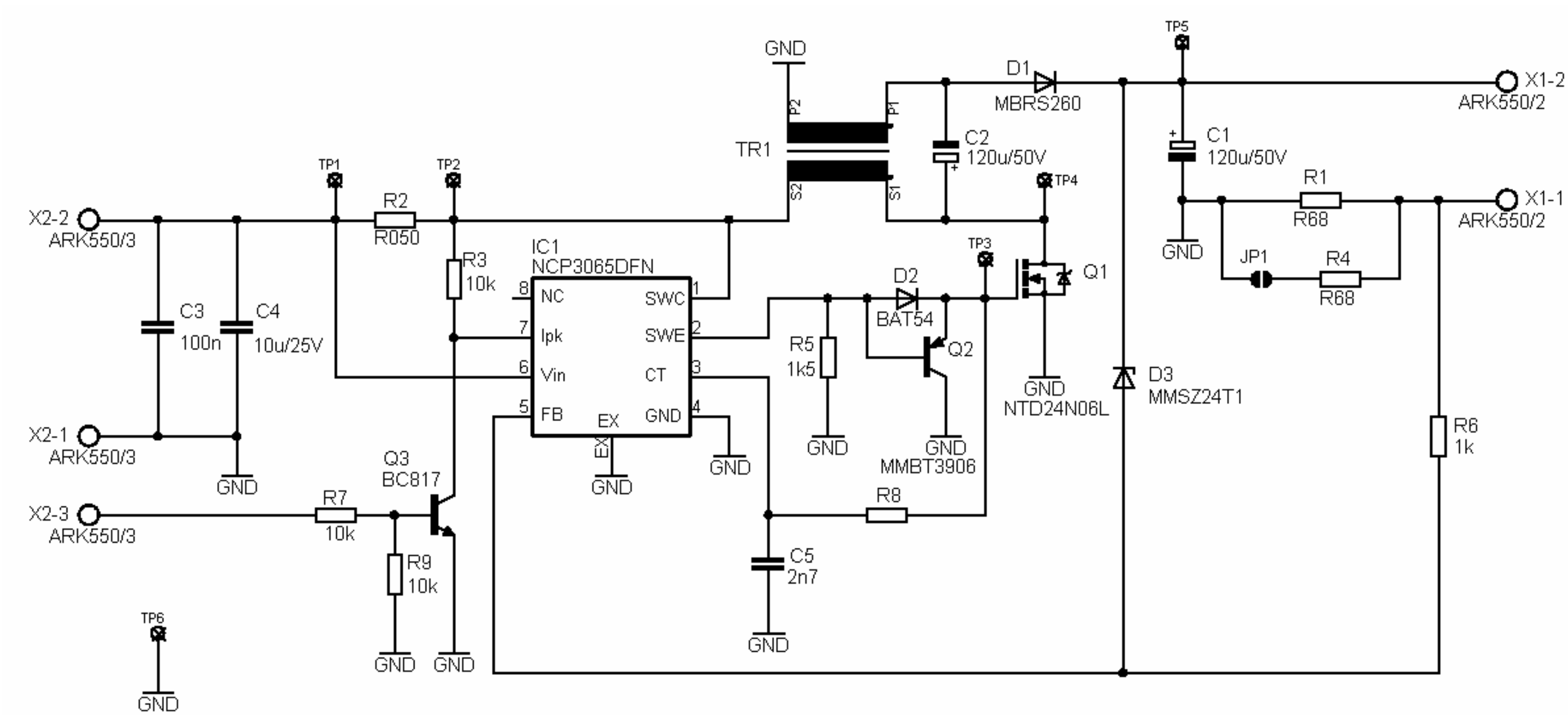
Journee Lighting

Cluster 3	Vf vs Current Tj=25 C		Vf vs Current Tj=125C	
	350 mA	700 mA	350 mA	700 mA
min	8.7	9.6	7.8	8.7
typ	10.2	10.8	9.3	9.9
max	11.4	12.3	10.5	11.4

Cluster 4	Vf vs Current Tj=25 C		Vf vs Current Tj=125C	
	350 mA	700 mA	350 mA	700 mA
min	11.6	12.8	10.4	11.6
typ	13.6	14.4	12.4	13.2
max	15.2	16.4	14.0	15.2

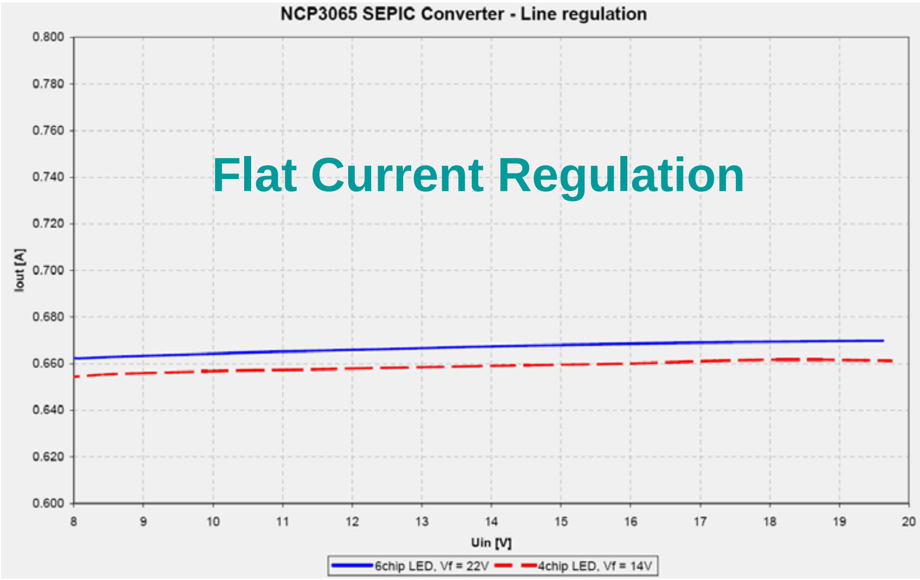
NCP3065 SEPIC Schematic

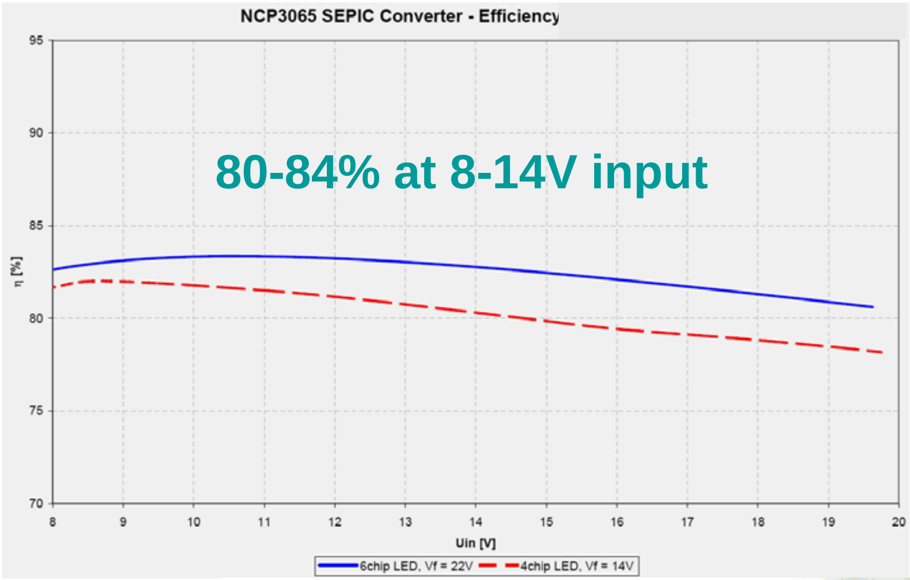


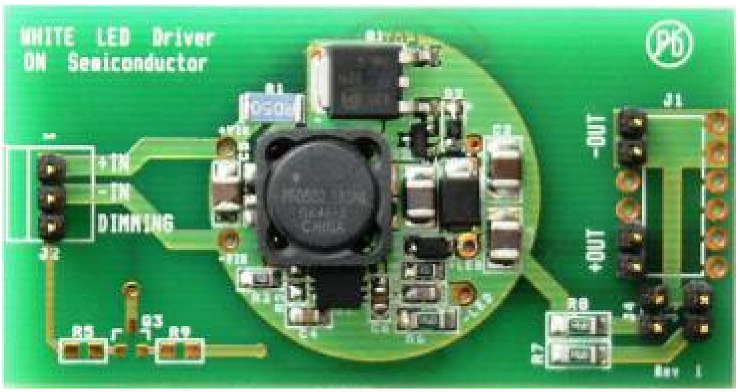


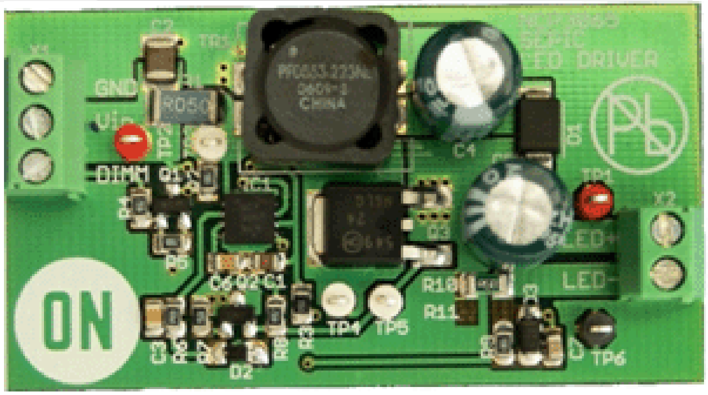
NCP3065 SEPIC Demo Boards

Used when Vin and Vout Overlap



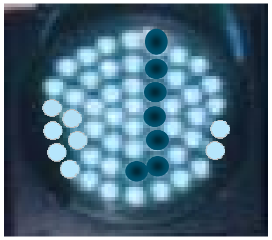






50,000 hour LED life is great but . . .

Occasionally there can be failures



Caused by. . .

- ✓LED infant mortality
- ✓Assembly Partial Defects
- ✓Transients

Some Application Are. . .

- ✓ Mission Critical
- ✓ Safety Dependent
- ✓ Difficult Access

NUD4700 LED Shunt Protection

•**Protects operation in the event of an open LED fault**

•**Supports >1A with proper heat sinking**

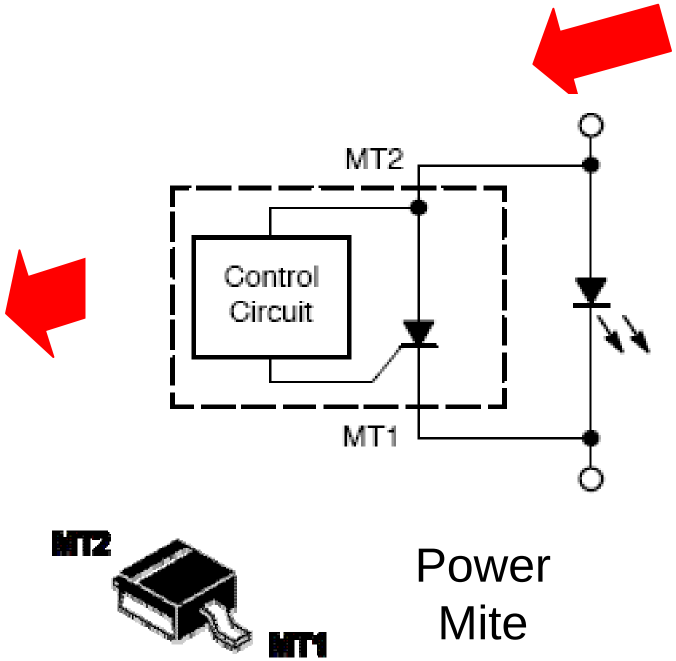
•**Space saving small packaging**

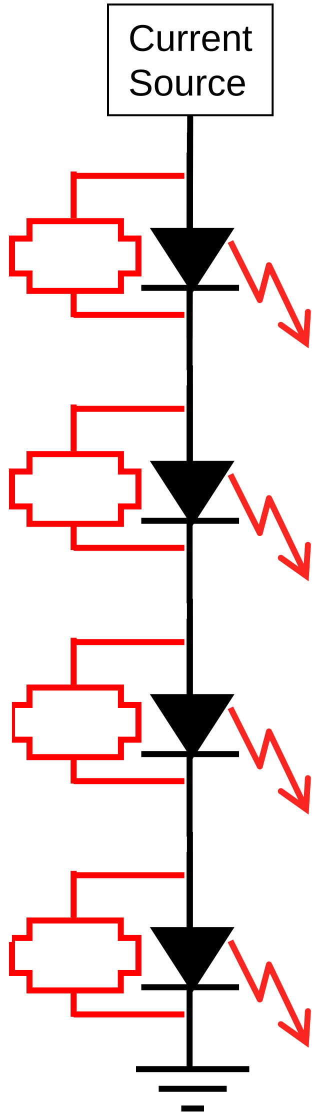
<u>If LED operating then</u> . . .

- ➢ Approx 100uA leakage

<u>If LED open then</u> . . .

- ➢ Shunt path activates
- ➢ Approx 1.0 volt drop



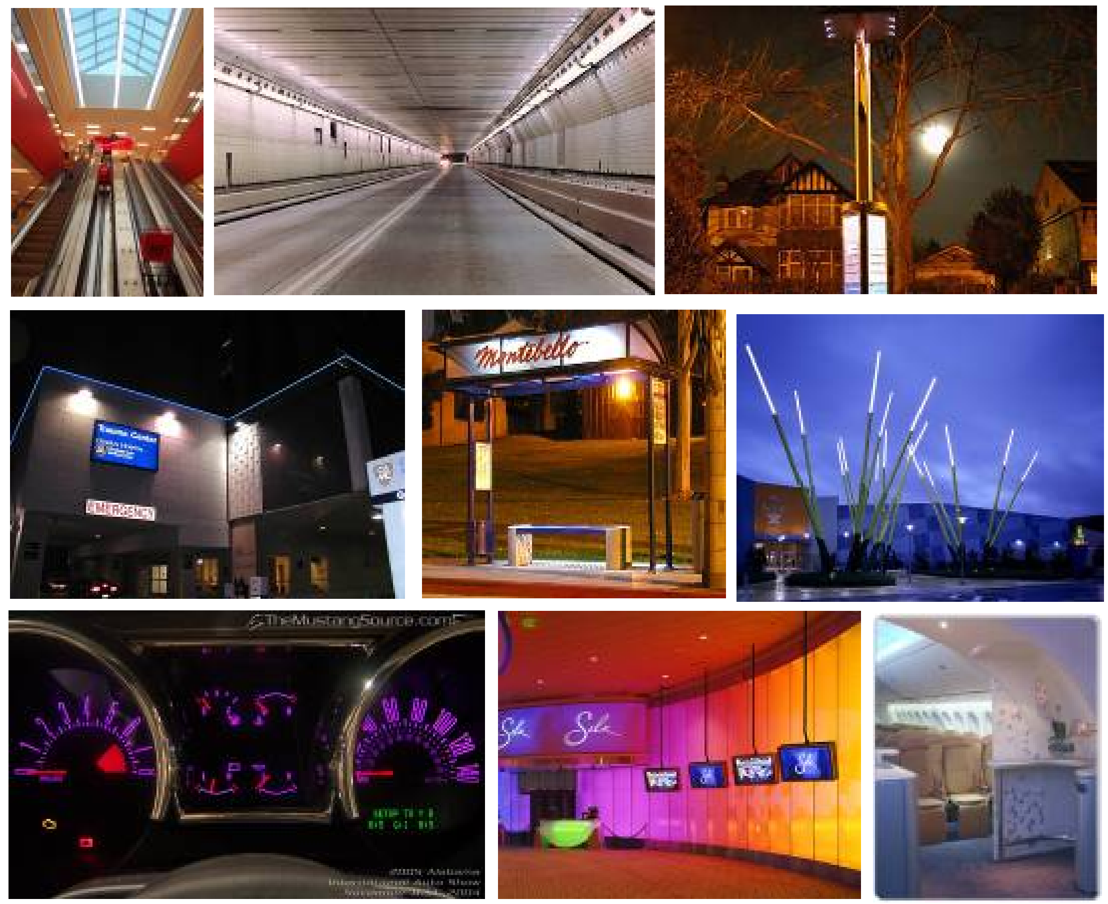


More than just energy savings

Examples of solid state lighting in use today

Architectural, High Availability, Accent, Solar Powered, Task, Backlighting

- Difficulty of maintenance
- Cost of "downtime"
- Safety
- Extending use
- Branding and advertising
- Product design
- Art/Architecture
- Personalization
- Entertainment
- Remote "solar powered"
- New functionality



Conclusion

- Solid State Lighting is evolving rapidly with the emergence of cost effective ultra high bright power LEDs
- Constant current drive architecture is key to driving LEDs due to the steep V/I transfer curve
- A wide variety of power solutions is required depending on the power source and LED configuration
- To achieve a robust product requires a system oriented approach taking into account electrical, thermal and optical considerations

Visit the LED Website

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