HIGH VOLTAGE SEMINAR

BEN LOUGH

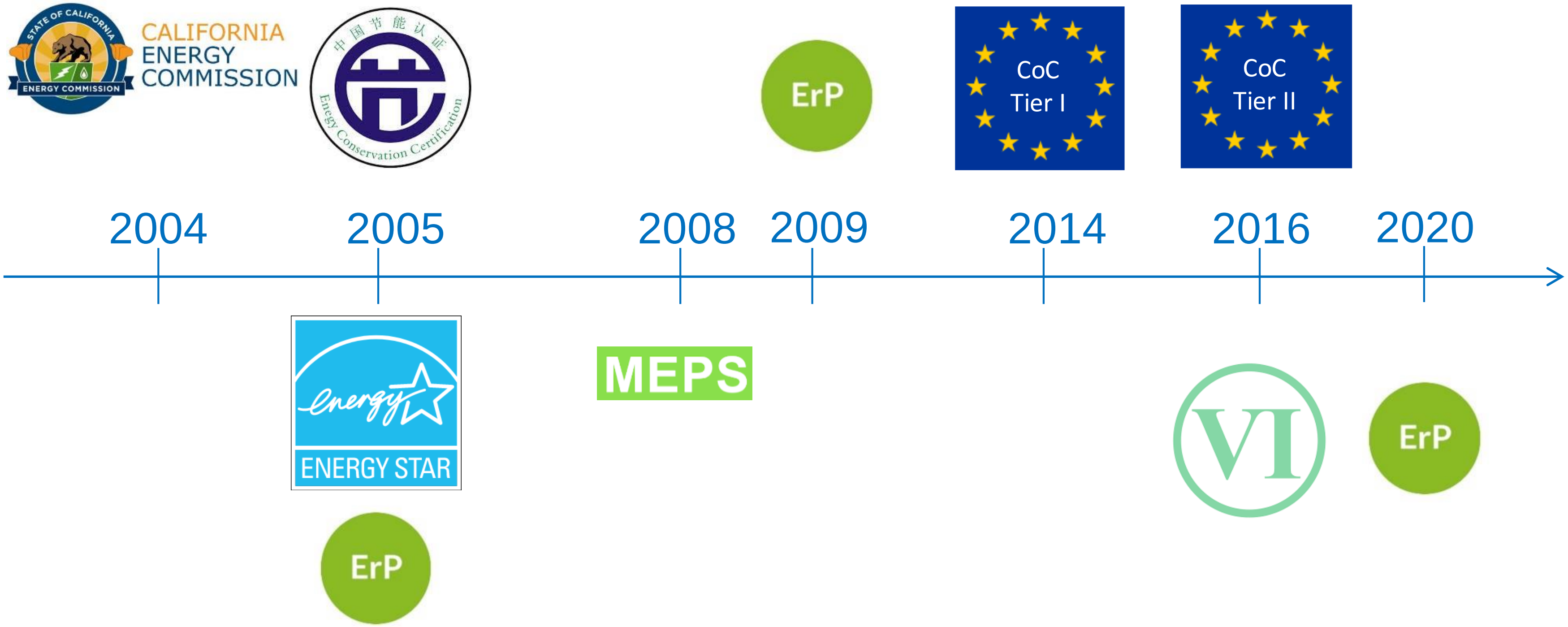
HIGH VOLTAGE CONTROLLERS

IMPLEMENTATION OF WIDE OUTPUT LLC IN POWER TOOL CHARGING AND LED LIGHTING APPLICATIONS

Agenda

- Efficiency targets and standards
- Battery charging and LED lighting application overview
- The LLC topology
- Practical implementation considerations

Efficiency standards: timeline



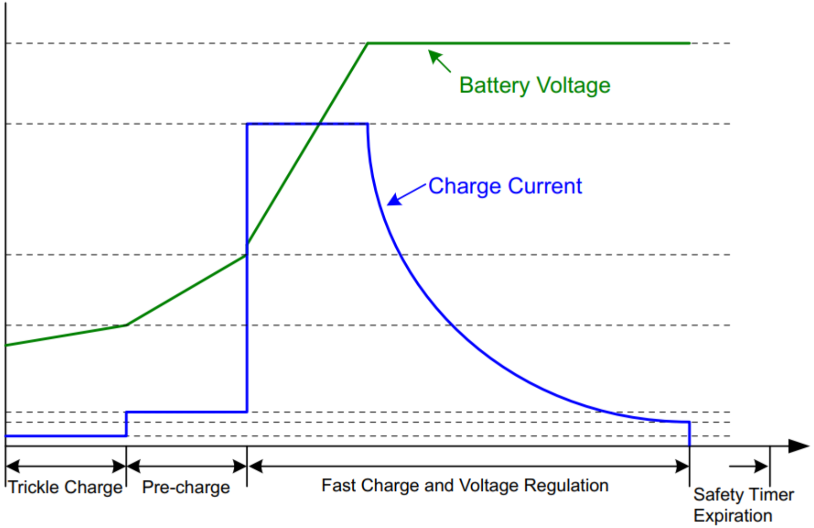
DOE Level VI and Ecodesign 2019/1782

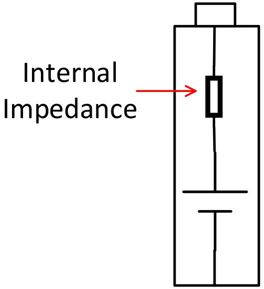
AC/DC low voltage external power supplies (excludes multi-output)		
Nameplat output power (pout)	Maximum input power at no load (in decimal)	Minimum average efficiency (active mode)
<1 W	$\leq 100\ mW$	$\geq 0.517 \times Pout + 0.087$
1 W to 49 W	$\leq 100\ mW$	$\geq 0.0834 \times ln(Pout) - 0.0014 \times Pout + 0.609$
49 W to 250 W	$\leq 210\ mW$	≥ 0.870
>250 W	$\leq 500\ mW$	≥ 0.875

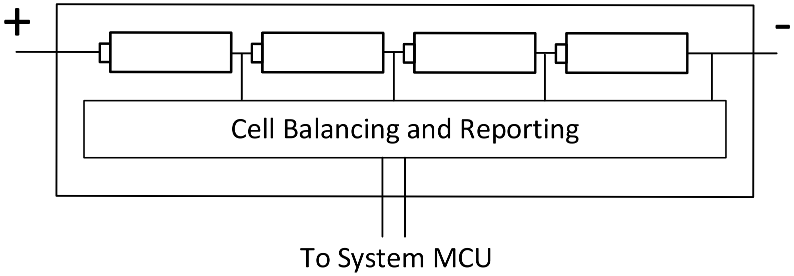
Key Differences			
	DOE Level VI	Ecodesign 2019/1782	CoC Tier II
Mandatory?	Yes	Yes	Voluntary
10% Load Requirement?	No	Reported but no requirement	Yes
Includes >250W Supplies?	Yes	No	No

Battery charging: overview

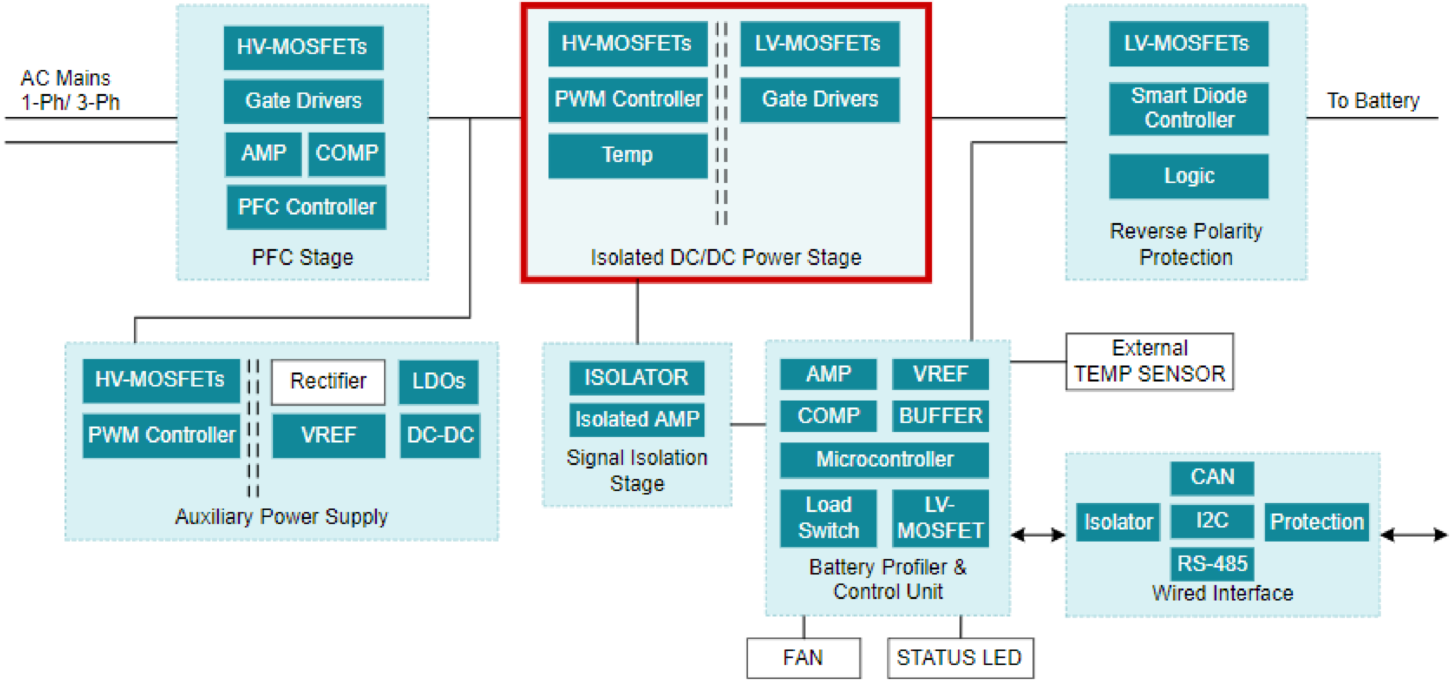
- Typical Output Voltage Range
  - 2.7 V to 4.4 V per cell for Li-ion chemistries
  - Cells stacked in series
  - Some chargers will support trickle charging for severely depleted batteries
- Battery charged at fixed current, then regulated at fixed voltage





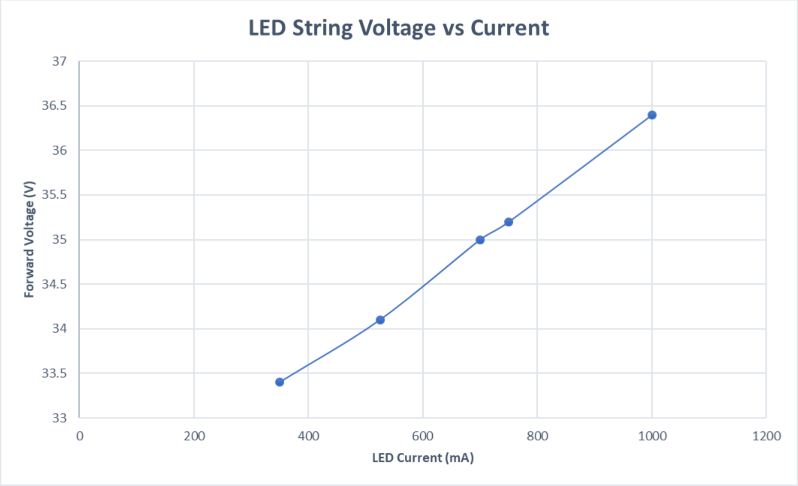


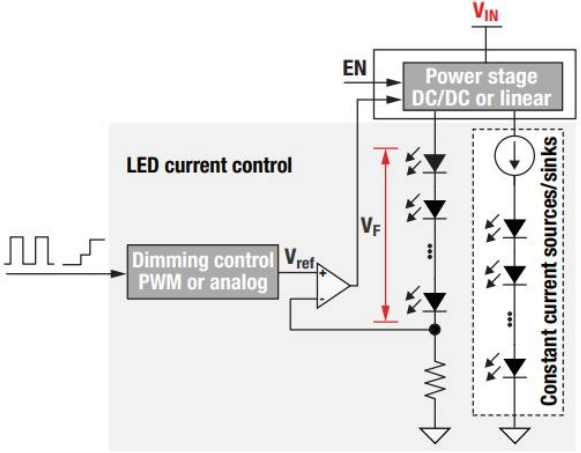
Battery charging: typical AC/DC charger



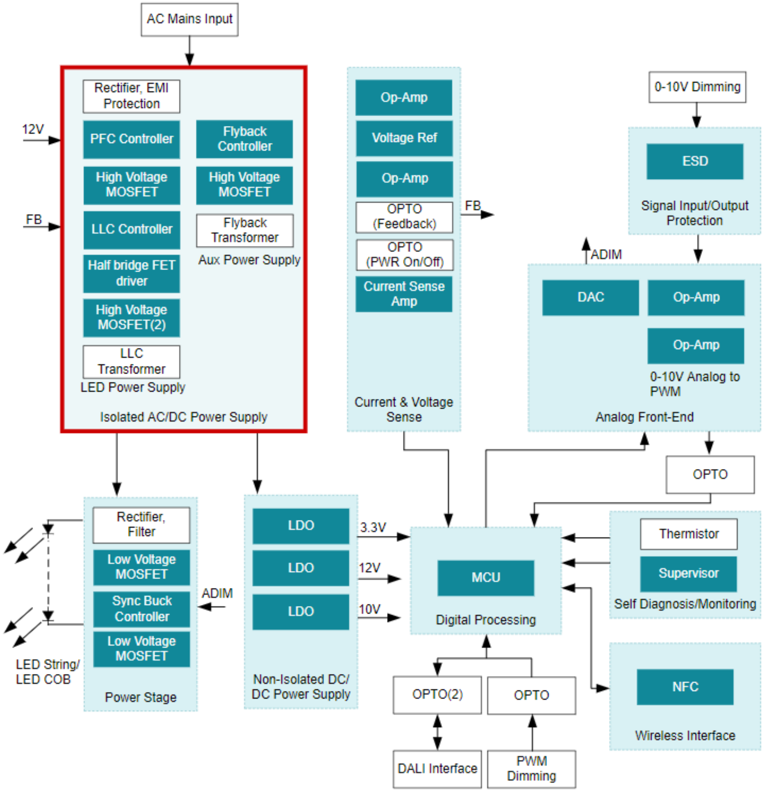
LED lighting

- Typical input of 120 Vac to 277 Vac, PFC bus voltage of ~450 V
- Brightness proportional to current
- Forward voltage increases as forward current increases
- Constant Current (CC)
  - Easy to achieve more consistent brightness by regulating LED current
- Constant Voltage (CV)
  - Required for some light engines with built in dimming



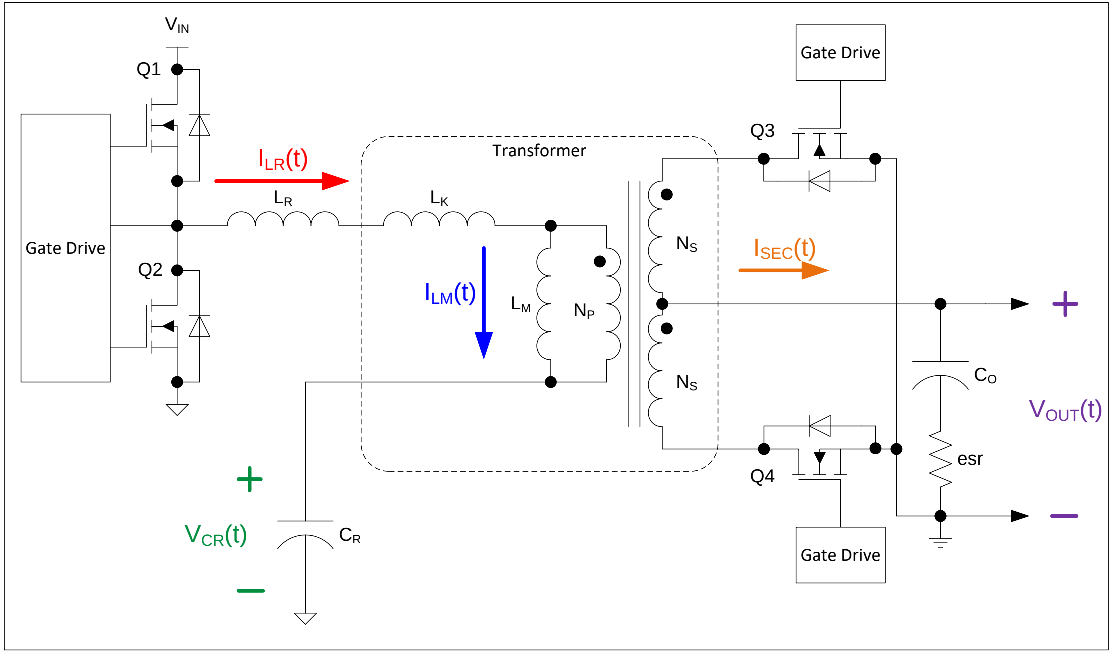


LED lighting: typical AC/DC LED driver



LLC converter: overview

- Why LLC?
  - Full zero voltage switching for primary switches (lower switching loss)
  - Zero current switching for secondary switches when at or below resonance
  - Sinusoidal power stage currents (lower DM currents from input)
  - Transformer leakage can be high (lower CM currents)



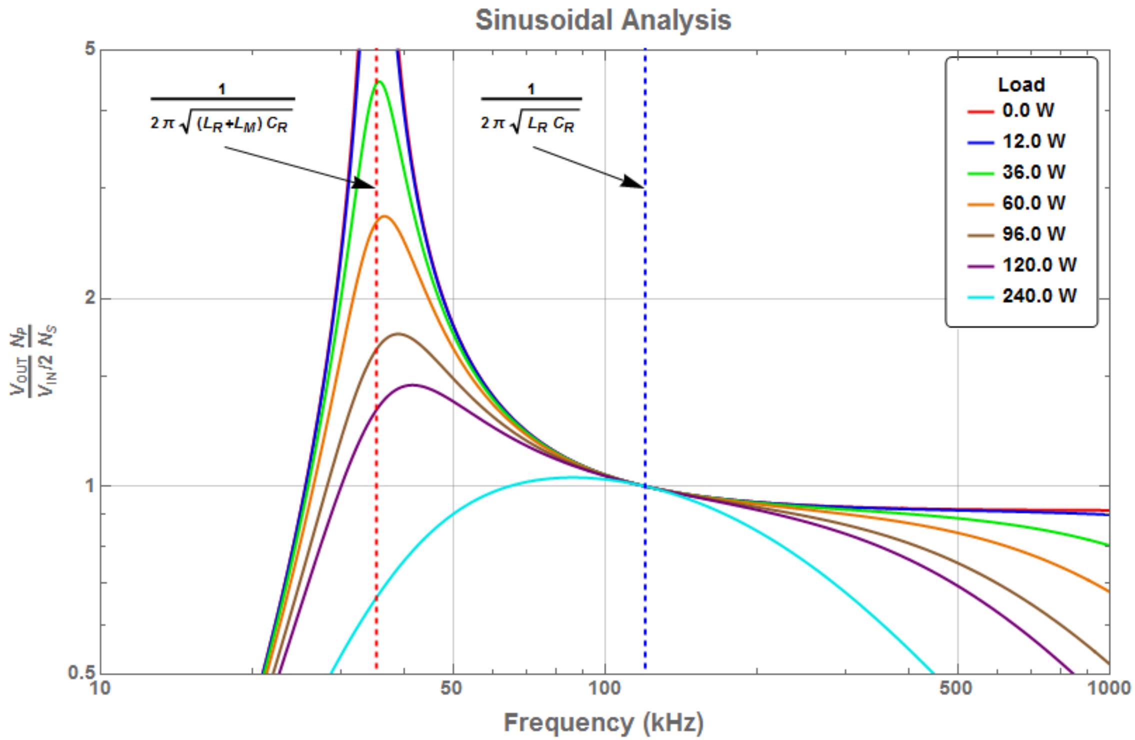
LLC converter: overview

- Fixed, 50% duty cycle
- Regulation achieved via modulating frequency

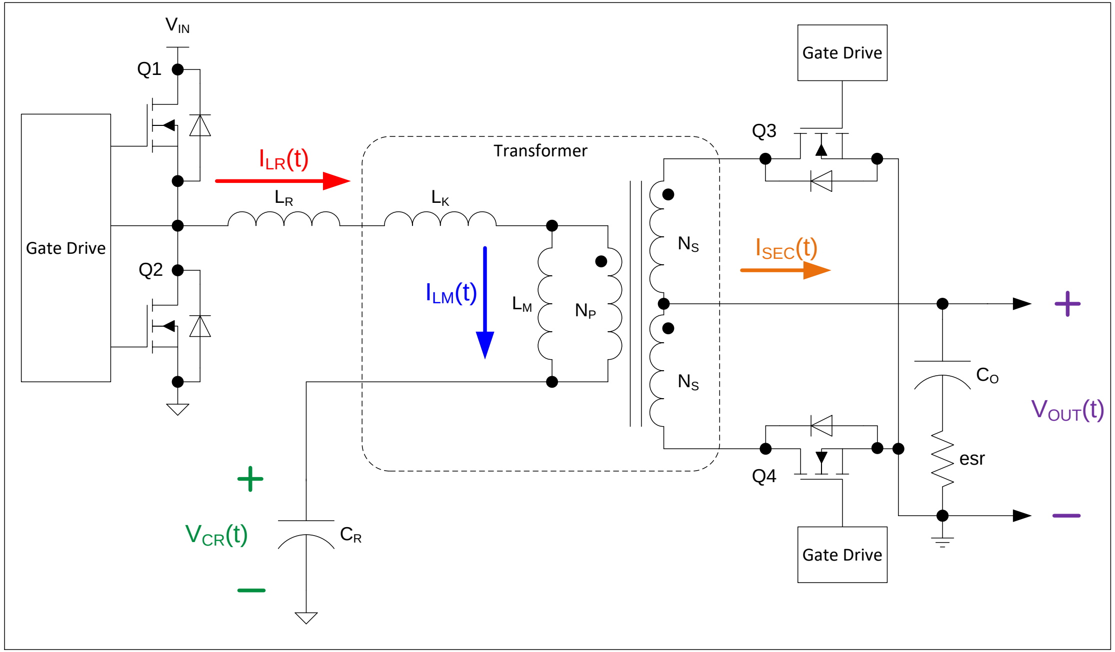
$$V_o = M_g \times \frac{1}{n} \times \frac{V_{in}}{2}.$$

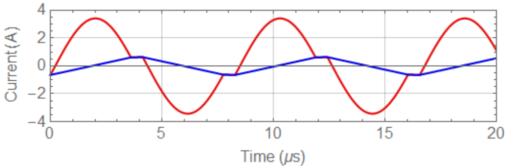
$$M_g = \frac{V_{oe}}{V_{ge}} = \left| \frac{jX_{L_m} \parallel R_e}{(jX_{L_m} \parallel R_e) + j(X_{L_r} - X_{C_r})} \right|$$

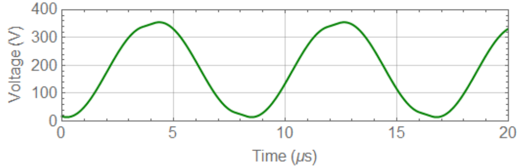
$$= \left| \frac{(j\omega L_m) \parallel R_e}{(j\omega L_m) \parallel R_e + j\omega L_r + \frac{1}{j\omega C_r}} \right|,$$

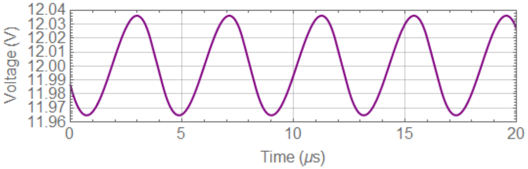


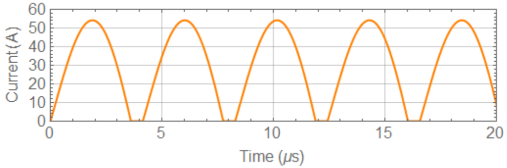
LLC converter: power stage waveforms




Tank Currents, V_{IN} = 370. V

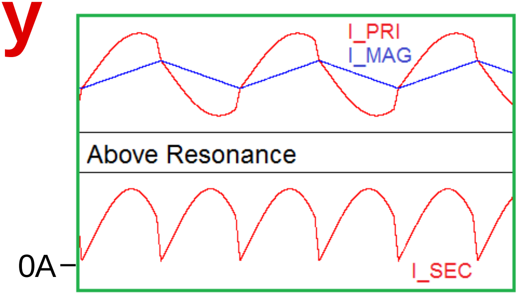

Resonant Capacitor Voltage


Output Capacitor Voltage

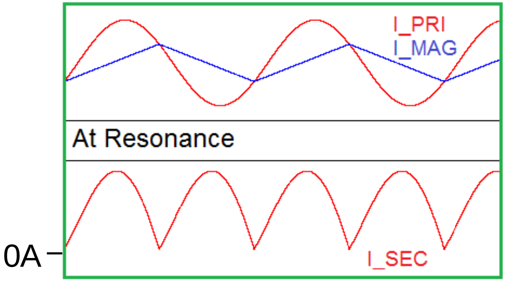

Rectified Secondary Current

LLC Converter: Operating Frequency

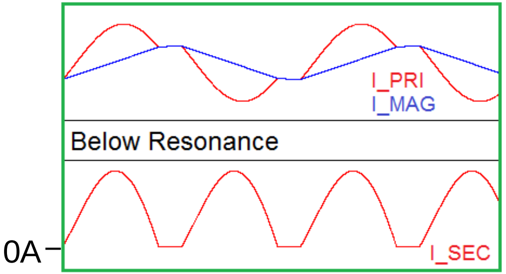
- Above resonance, ZVS achieved, CCM* on sec, rectifiers not soft switched. Lower RMS currents for given power



- At resonance, ZVS achieved, CCM on sec, rectifiers are soft switched (ZCS), optimum efficiency



- Below resonance, ZVS achieved, DCM on sec, rectifiers are soft switched (ZCS), RMS currents higher for given power

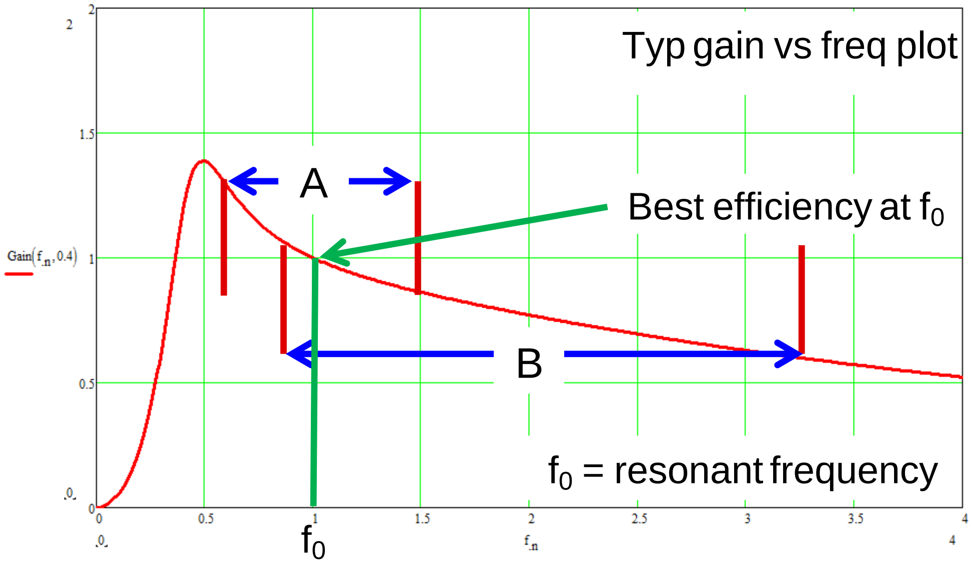


LLC converter: gain curve considerations

- Both A and B achieve the same gain range (vertical bars). Which is better?

- Noteworthy Characteristics of A
  - Narrow range of frequency operation: easier to optimize core losses
  - Requires smaller Lm: increased magnetizing currents

- Noteworthy Characteristics of B
  - Best efficiency at lowest frequency: less heat at highest output power
  - Reverse recovery in rectifiers
  - Need to make sure enough magnetizing current to maintain ZVS at highest frequency



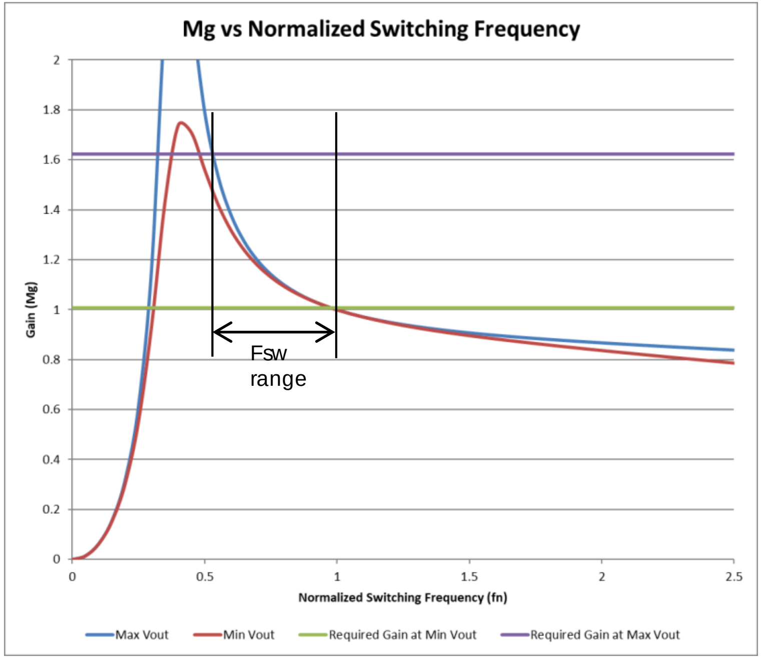
Typ gain vs freq plot

Best efficiency at f_0

f_0 = resonant frequency

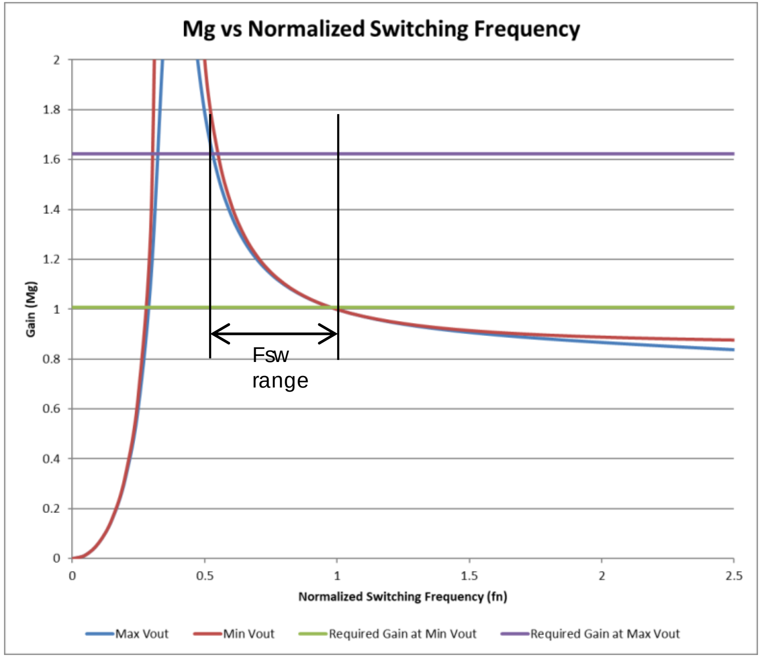
LLC converter: gain curve considerations

- Shown at right
  - Vout range of 13V to 21V
  - Charging current of 12A
  - Lm: 510uH
  - Lr: 85uH
  - Cr: 30nF
  - Turns ratio of 15:1
- For a battery charger where output current is fixed, Re increases with output voltage
  - $R_e = \frac{8 \times n^2}{\pi^2} \times \frac{V_{out}}{I_{out}}$
  - Re at 21V: 319 Ω
  - Re at 13V: 198 Ω



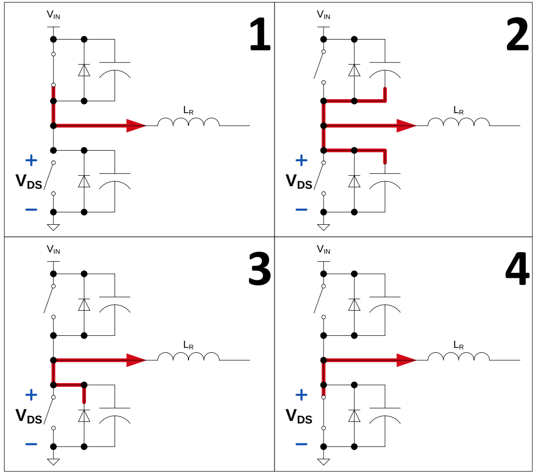
LLC converter: gain curve considerations

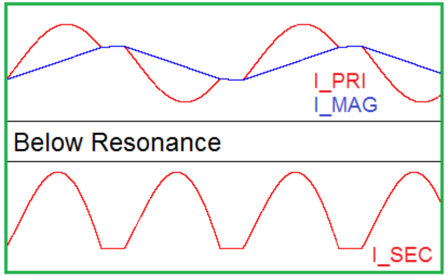
- Shown at right
  - Vout range of 13V to 21V
    - LED string current of 12A at 21V output
    - LED string current of 1A at 13V output
  - Lm: 510uH
  - Lr: 85uH
  - Cr: 30nF
  - Turns ratio of 15:1
- For a LED driver, light load expected at lower output voltage
  - $R_e = \frac{8 \times n^2}{\pi^2} \times \frac{V_{out}}{I_{out}}$
  - Re at 21V: 319 Ω
  - Re at 13V: 2370 Ω

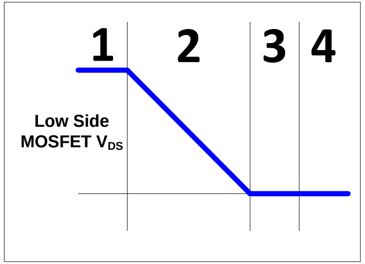


LLC converter: switching loss and dead time

- $t_{deadtime} = t_{d(off)} + t_{res}$
  - $t_{d(off)}$: delay time from falling edge of gate drive to MOSFET fully off
  - t_{res}: time needed for switch node to charge up to Vin or discharge down to gnd
    - $t_{res} = 2 \times C_{oss(tr)} \times \frac{V_{in}}{I_m}$
  - Optimal $t_{deadtime}$ changes with operating frequency
    - Excessive dead time gives longer body diode conduction
    - Insufficient dead time results in loss of ZVS and incurs turn on losses
    - Adaptive dead time convenient for wide Vout applications
- $P_{sw} \approx 0.5 \times I_m \times V_{in} \times t_{d(off)} \times fsw$
- $P_{drive} \approx Q_g \times V_{gate} \times fsw$

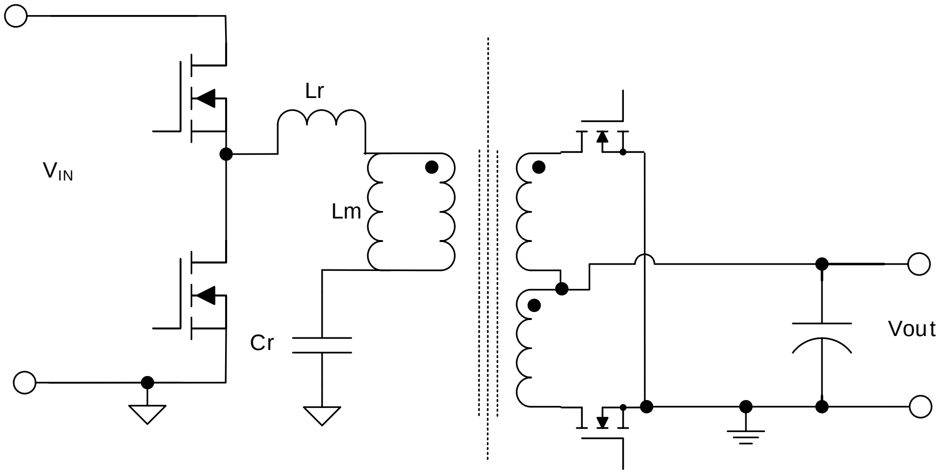






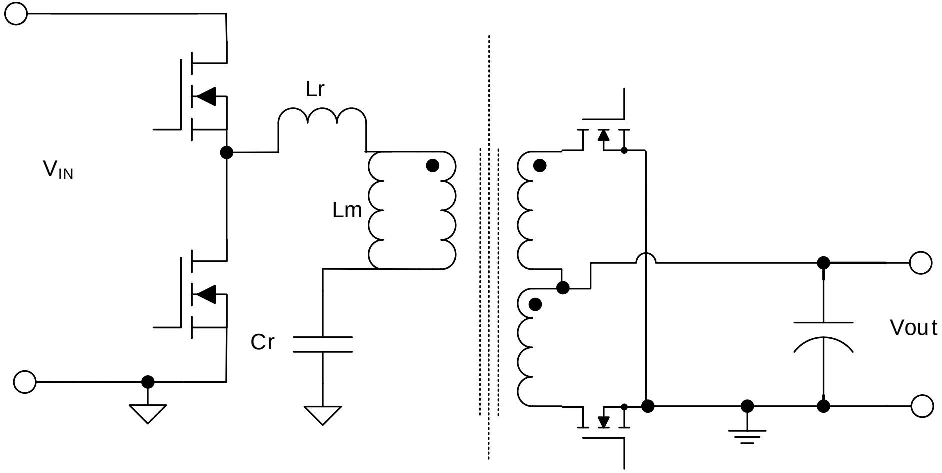
LLC converter: conduction loss

- Conduction loss
  - $I_{OE} = \frac{\pi}{2\sqrt{2}} \times \frac{I_{out}}{n}$
  - $I_m = \frac{2\sqrt{2}}{\pi} \times n \times \frac{V_{out}}{2\pi \times fsw \times Lm}$
  - $I_r = \sqrt{{I_m}^2 + {I_{OE}}^2}$
  - $P_{cond} = 0.5 \times {I_r}^2 \times R_{dson}$
- Total Loss
  - $P_{total} = P_{sw} + P_{drive} + P_{cond}$



LLC converter: rectifier losses

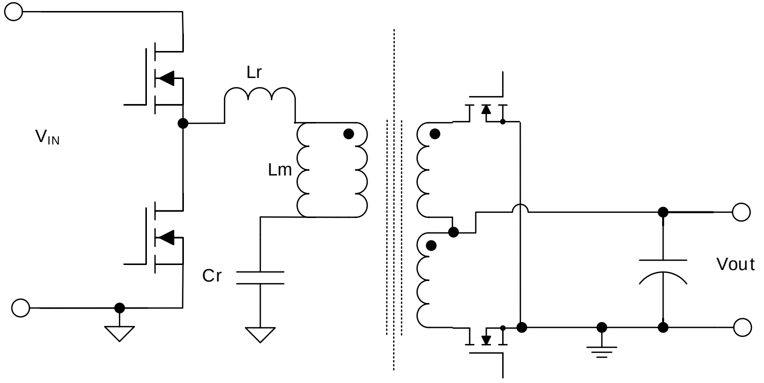
- Reverse Recovery Loss (above resonance only)
  - $P_{rr} \approx Q_{rr} \times fsw \times V_{ds}$
- Conduction Loss
  - $I_{OES} = n \times I_{OE}$
  - $P_{cond} \approx {I_{OES}}^2 \times Rdson$
- Switching Loss
  - $P_{sw} = 0.5 \times C_{oss(eq)} \times {V_{DS}}^2 \times fsw$
- Driver Loss
  - $P_{drive} \approx Q_g \times V_{gate} \times fsw$
- Total loss
  - $P_{total} = P_{rr} + P_{cond} + P_{sw} + P_{drive}$

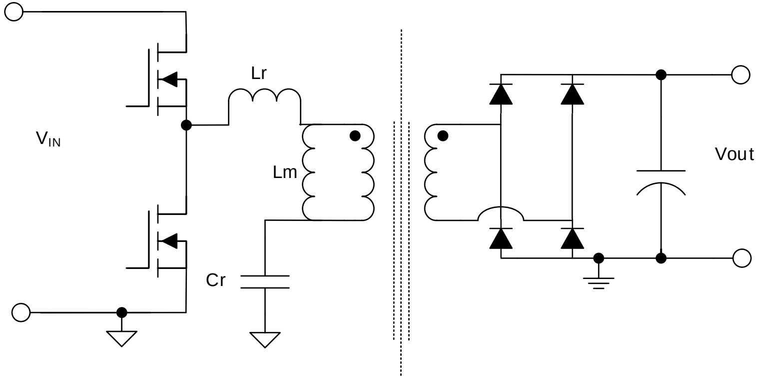


TEXAS INSTRUMENTS

LLC converter: center tap or full bridge?

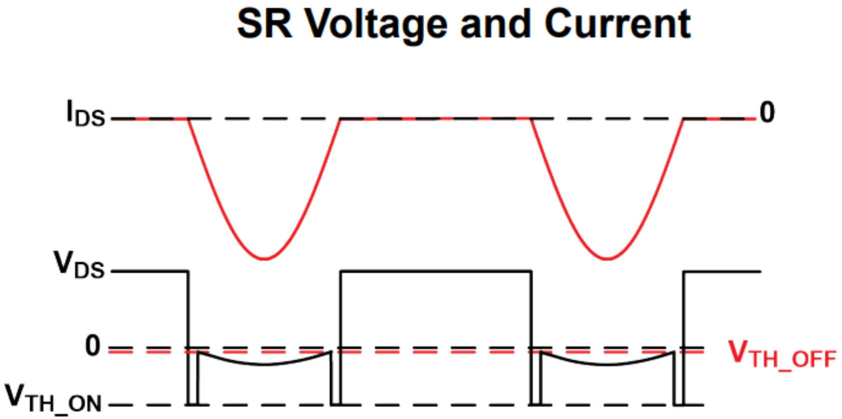
	Center Tap	Full Bridge
Rectifier Reverse Voltage Rating	>2x Vout	>Vout
Number of Rectifiers	2	4
Number of Secondary Windings	2 (needs tight matching)	1
Rectifier Conduction Losses		2x compared to center tap
R_{sec} for same winding area	2x compared to full bridge	
I_{rms} per winding	$\sqrt{0.5}$x compared to full bridge	
Transformer secondary copper loss	2x compared to full bridge	

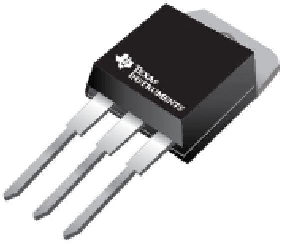


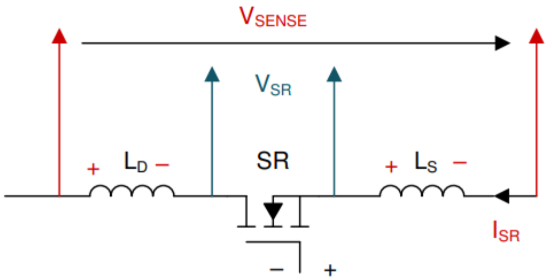


Synchronous rectifier considerations

- Majority of analog SR controllers for LLC are based on Vds sensing scheme
- Smaller Rdson reduces conduction loss when the MOSFET is on but can lead to earlier turn-off and longer body diode conduction time
- Some designs will include circuitry to shut off the SR at no load or use SR controllers that shut down at light load

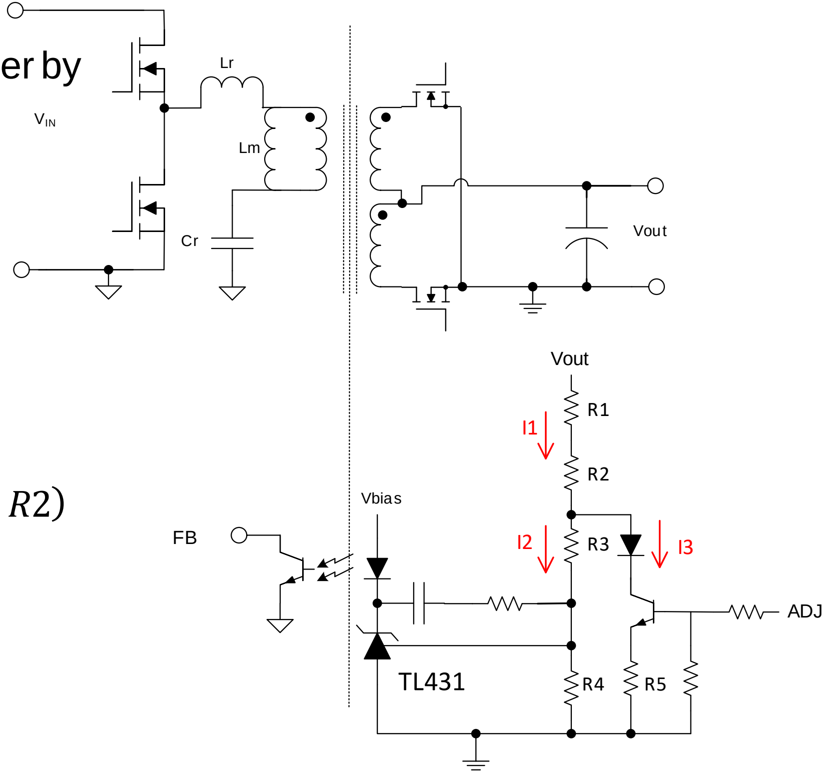

SR Voltage and Current





Practical implementation: CV LED driver

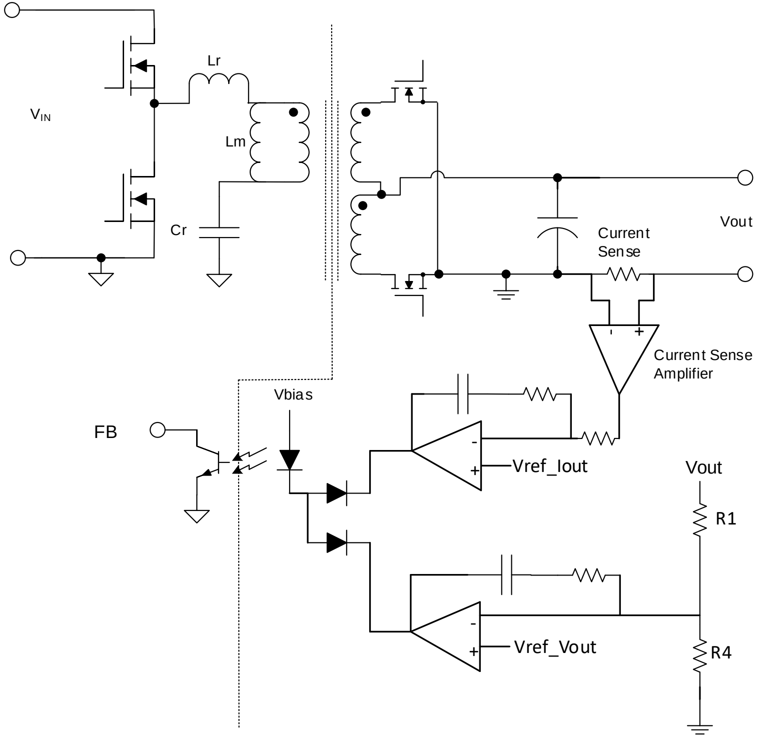
- Motivation: optimize efficiency of downstream converter by adjusting LLC output voltage
- BJT circuit sets current I_3
- $I_1 = I_2 + I_3$
- $V_{out} = 2.5V\left(\frac{(R1+R2)(R3+R4)}{R3R4} + \frac{R3+R4}{R4} - \frac{R1+R2}{R3}\right) + I_3(R1 + R2)$
- As ADJ voltage increases, Vout increases



Practical implementation: CC LED driver & battery charger

- Two control loops
  - One sets output current regulation
  - The other sets output voltage regulation
  - Diode OR'd together to opto-coupler
  - Loop with lowest error "wins" and controls the state of the LLC converter

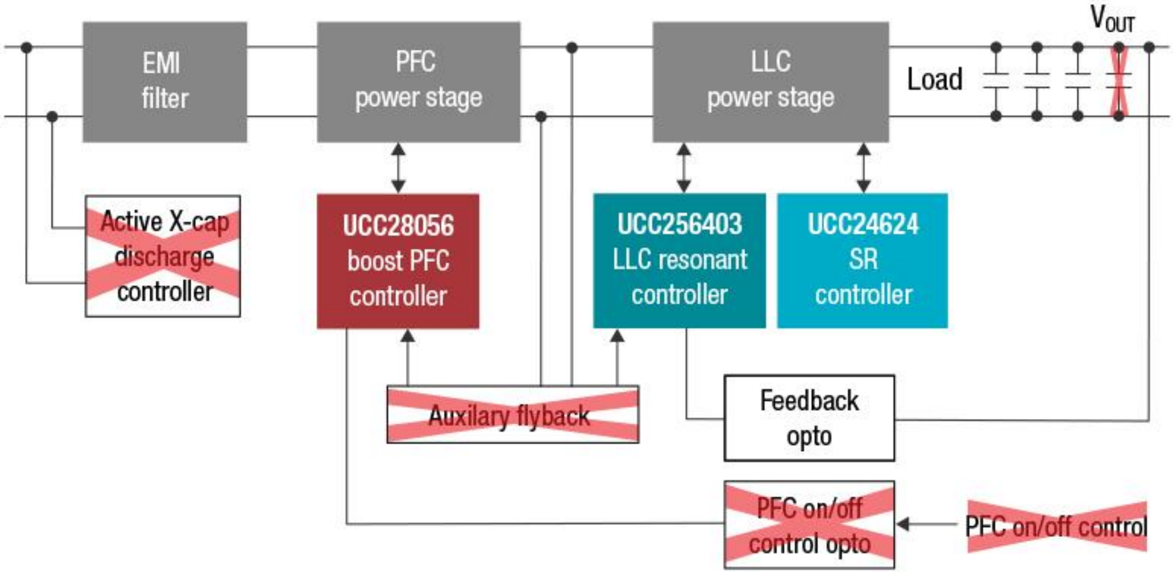
- References for the error amplifiers can be fixed (i.e. TL103W) or adjustable
  - Analog dimming or trickle charge accomplished by adjusting reference voltage of current control loop



Practical considerations: AUX or no AUX?

- Traditionally an AUX flyback is used to supply system power, PFC and LLC are shut down at standby to meet no load input power standards

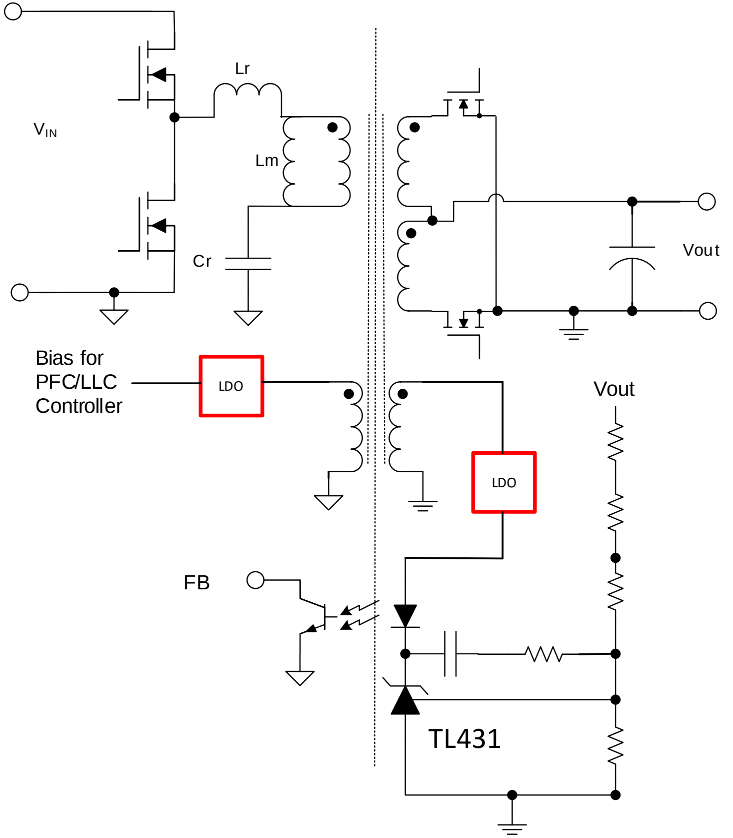
- Newer PFC+LLC+SR controllers contain advanced light load features that can enable removing AUX supply and on/off circuitry while still meeting regulation requirements



Practical considerations: AUX or no AUX?

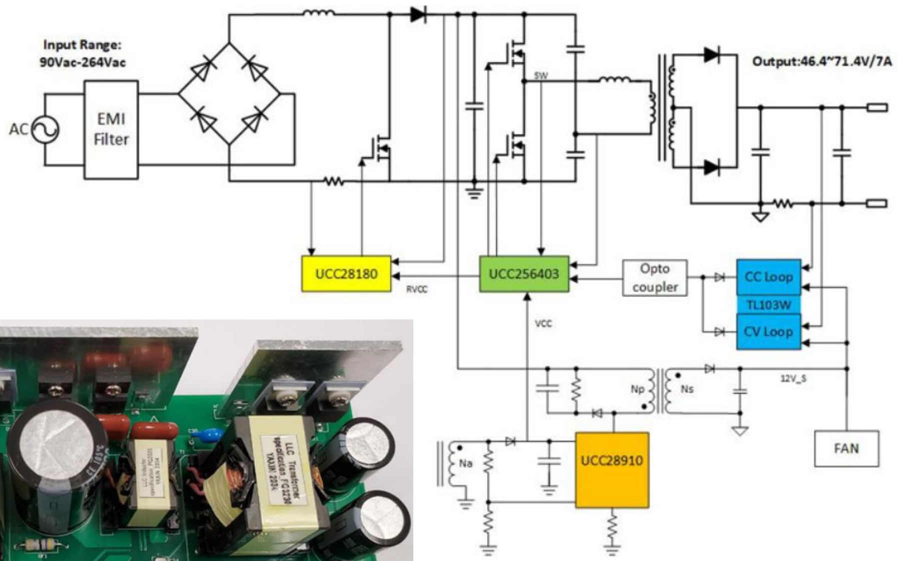
- If No AUX is pursued, bias for the primary/secondary side circuitry is typically done by adding AUX windings onto the LLC transformer

- Bias voltage will vary with the output voltage
  - AUX voltage may require post regulation to maintain safe voltage stresses depending on output voltage range



Reference design: 500W e-bike charger

- Universal AC input
- 46V to 71V output at 7A charging current
- Precharge mode for <46V output
- 94% peak efficiency
- Status indication and fan control



https://www.ti.com/tool/PMP40766

Additional resources

1. Design and Optimization of a High-Performance LLC Converter; B McDonald, J Freeman: slup306
2. Designing an LLC Resonant Half-Bridge Power Converter; H. Huang: slup263
3. LLC Design for UCC29950: J Leisten: (note: despite the title this covers LLC design in general) slua733
4. A current sharing, paralleled, synchronised HB-LLC, using a C2000 processor: tiduct9
5. LCC Converter Small Signal Modeling: McDonald.: Texas Instruments Power Supply Design Seminar, SEM2100, 2014. Note_1
6. Zero Voltage Switching Resonant Power Conversion: Andreycak:. Unitrode Power Supply Design Seminar 700, 1990.
7. Understanding Noise-Spreading Techniques and their Effects in Switch-Mode Power Applications, Rice et al. slup269
8. Survey of resonant converter topologies: slup376
9. Control and design challenges for synchronous rectifiers: slup378

Note_1: TI power supply design seminar archive at http://www.ti.com/ww/en/power-training/login.shtml?DCMP=pwr-psds-archive

Note_2: TI reference design library: https://www.ti.com/reference-designs/index.html

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