Texas Instruments

TI Live! POWER SUPPLY DESIGN SEMINAR

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ISOLATED GATE-DRIVER BIAS-SUPPLY DESIGN CONSIDERATIONS

TI POWER

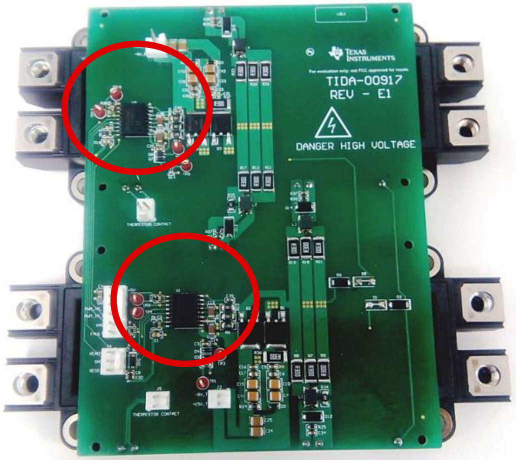
Agenda

- Inverter and isolated gate-driver bias-supply architectures.
- Different ways of creating an isolated bias supply:
  - Control method.
  - Topology.
  - Transformer.
- LLC-based open-loop isolated bias supply:
  - Operation principles.
  - Circuit variations.
  - Voltage regulation.
  - Multiple outputs.
  - Design procedure.
- Performance demonstration.

Isolated gate drivers in different applications

Traction inverter

Motor drive

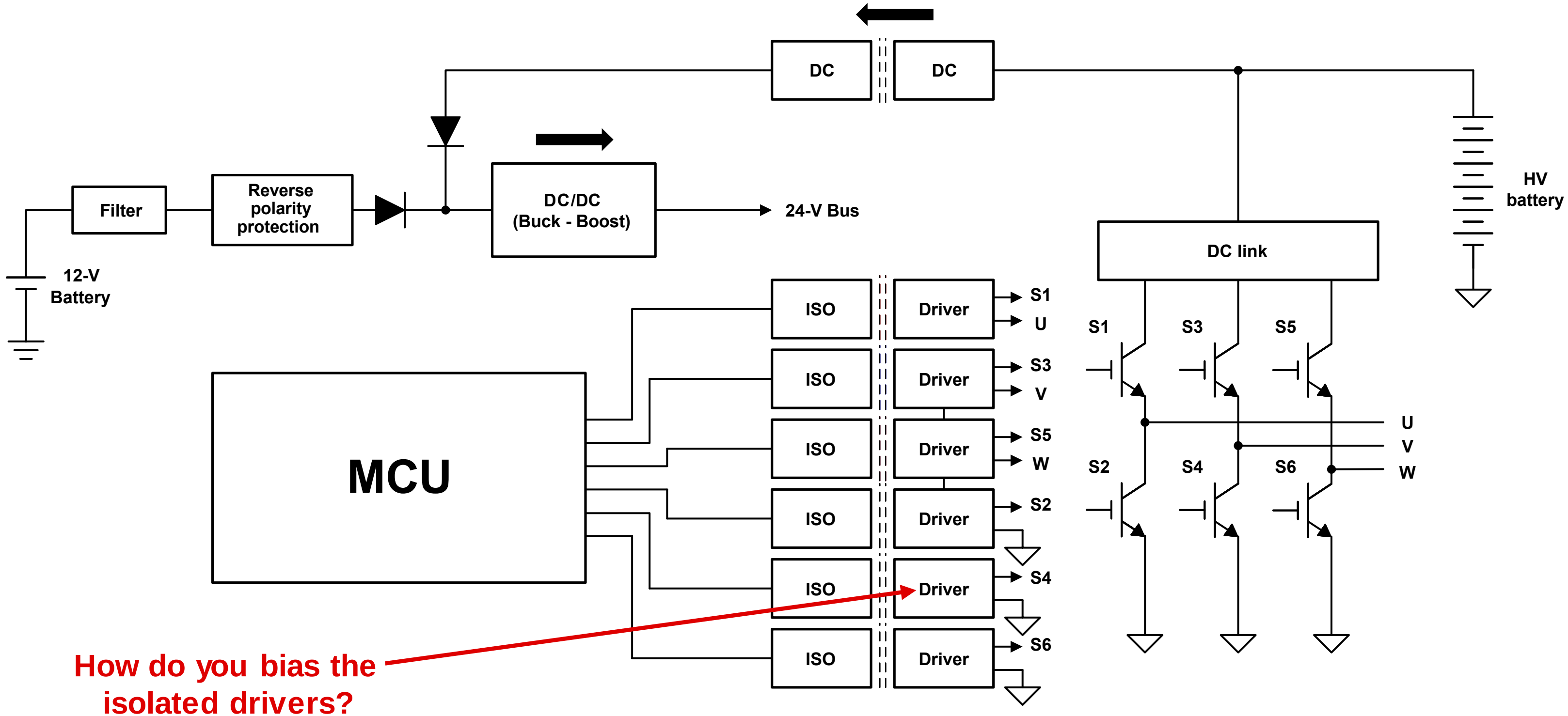


Inverter and
isolated gate drivers

UPS

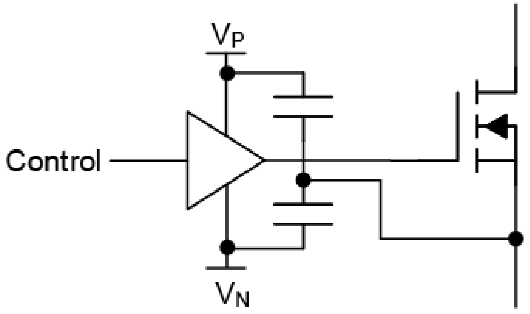
Onboard charger

Example: automotive traction inverter



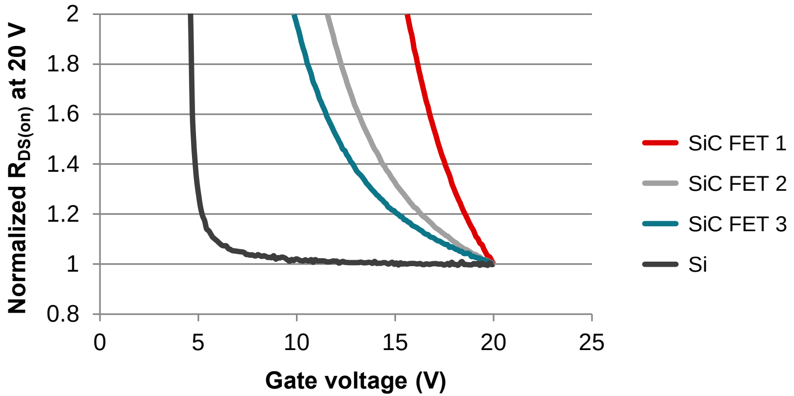
How do you bias the isolated drivers?

Gate-driver requirements



Gate-driver power

$$P_{DRV} = (V_P - V_N) \times Q_g \times f_{sw}$$
$$= V_{DRV} \times Q_g \times f_{sw}$$

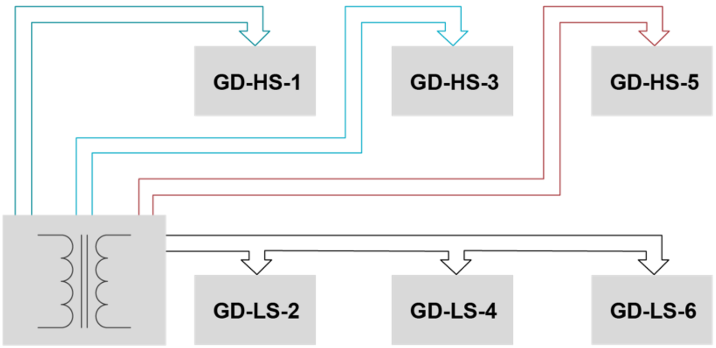


- $R_{DS(on)}$ is normalized with a 20-V gate-voltage value.
- SiC FET shows no $R_{DS(on)}$ saturation, lower $R_{DS(on)}$ with higher V_{GS}.

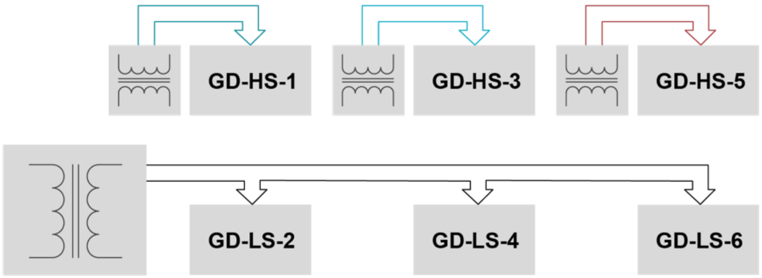
	Si MOSFET	SiC MOSFET	IGBT
Positive rail (V_P)	+12 V, +15 V	+18 V, +20 V (5%, 3%, 1%)	+15 V, +18 V
Negative rail (V_N)	0 V	–5 V, –4 V, –3 V	–8 V or 0 V

Different gate-driver architectures

Centralized



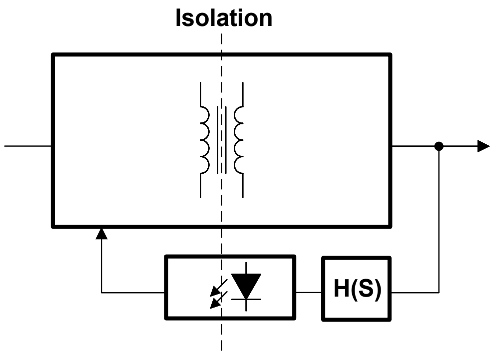
Semidistributed



Distributed

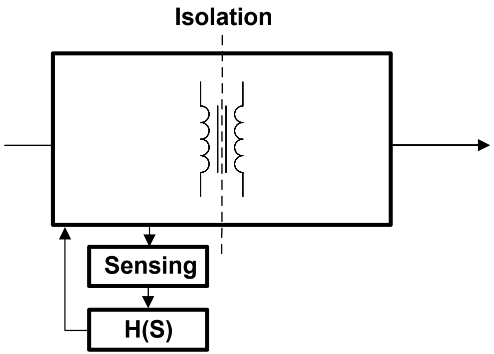
- A centralized system has the lowest cost, but is heavy and difficult to manage faults.
- A distributed system distributes the weight and fault, but is more expensive.
- A semidistributed system has the trade-off between cost and reliability.

Output voltage control



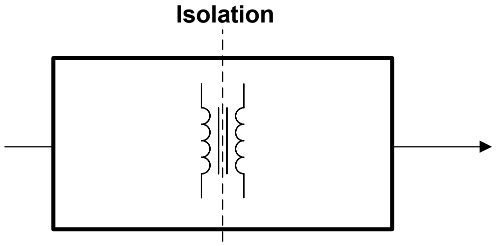
Closed loop
Secondary-side feedback

- Well-regulated output.
- Pre-regulator not necessary.
- More components.
- Less reliable because of the optocoupler.



Closed loop
Primary-side feedback

- Semiregulated output.
  - Sense auxiliary winding voltage.
- Pre-regulator not necessary.
- Noise sensitive given the output-voltage-sampling method.



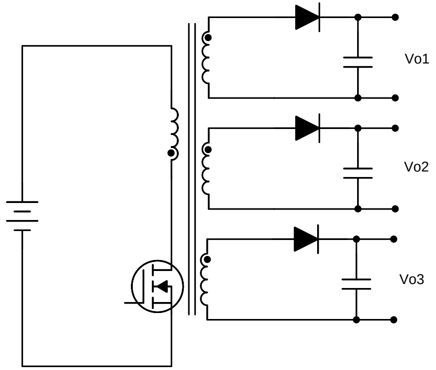
Open loop
No feedback

- No control loop, always-stable operation.
- Less noise sensitivity.
- Unregulated output, requires a pre-regulator.

Open-loop control provides a reliable solution.

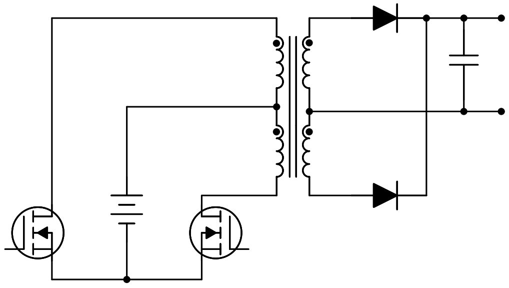
Topologies used for an isolated bias supply

Flyback



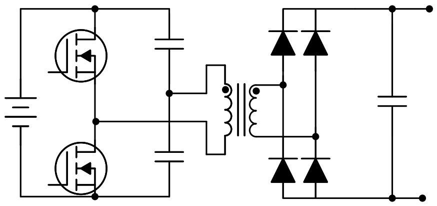
- The flyback can easily create multiple outputs:
  - Voltage proportional to the turns ratio.
  - Cross-regulation is less of an issue because of balanced loads.
  - Suitable for a centralized architecture.
- Can be controlled with opto- or primary-side feedback

Push-pull



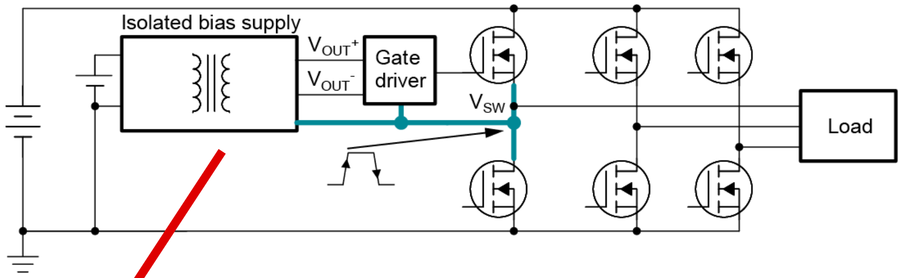
- With 50% duty-cycle open-loop operation, the output connects to the input through the transformer.
- A filter inductor is required if the duty cycle is less than 50% in order to regulate the output voltage for closed-loop operation.
- Good for distributed and semidistributed architectures.

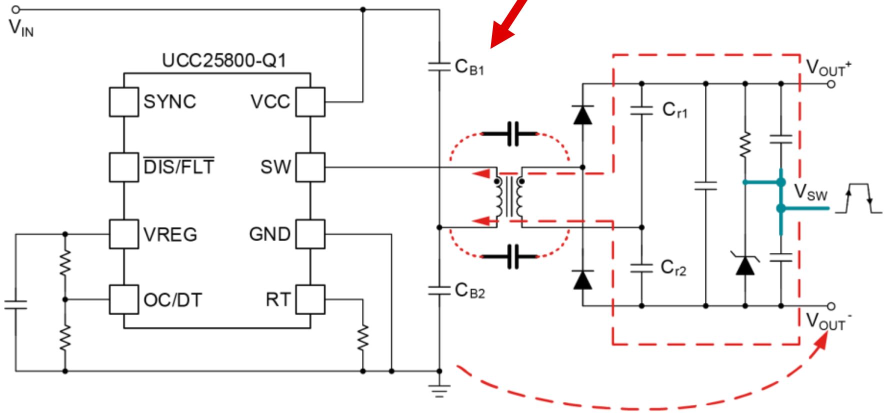
Half or full bridge



- 50% duty cycle operation; output connects to input through the transformer.
- Can be implemented with a gate-driver IC and a simple timer.
- Good for distributed and semidistributed architectures.

Transformer parameter impacts to system EMI

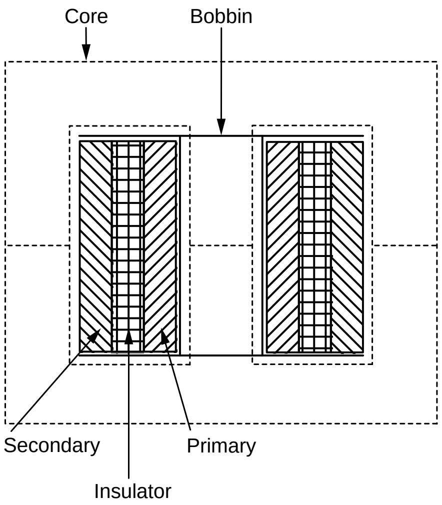




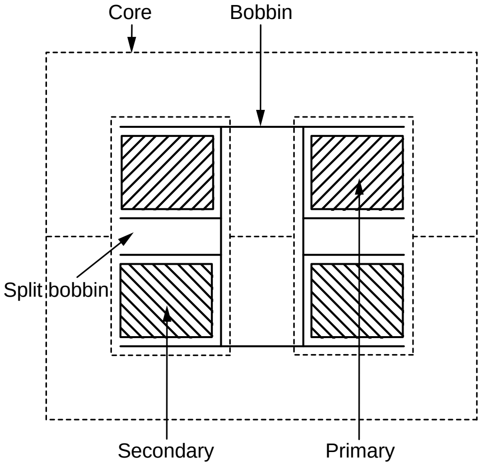
- High dv/dt couples through the transformer parasitic capacitor to the primary side.
- Higher EMI noise.
- Extra loss.
- More noise to the controller; a common-mode transient immunity (CMTI) issue.
- Noise gets worse with SiC or GaN devices with higher dv/dt.

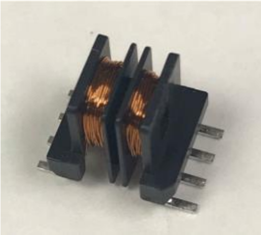
$$i = C\frac{dv}{dt} = 1\,pF \times \frac{100\,V}{ns} = 0.1\,A$$

Transformer structure: less parasitic capacitance



$$C = \frac{\epsilon A}{d}$$



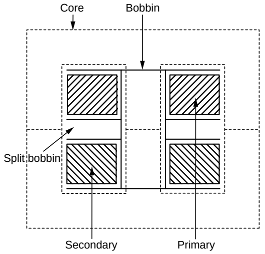
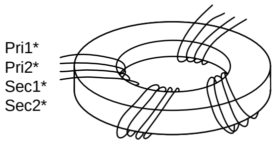
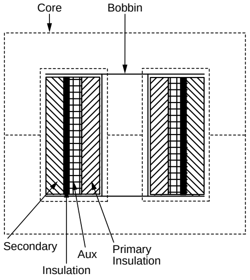
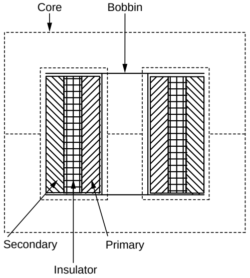
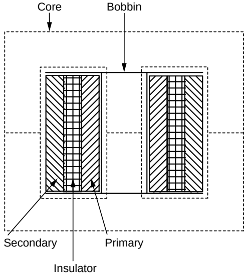


- Increasing the insulator thickness reduces the capacitance.
- Less effective given the large surface area.

- A split bobbin reduces the capacitance by reducing the surface area and increasing the distance.
- A much smaller capacitance is possible.

Increasing the distance reduces the capacitance while increasing the leakage inductance.

Transformers for an isolated bias supply

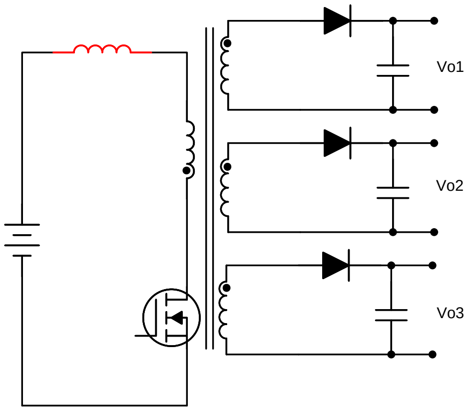
	Split-chamber transformer	Push-pull transformer	Three-winding flyback	Two-winding PSR flyback	Half bridge
		 Secondary side windings need thicker insulation			
$C_{Pri\text{-}Sec}$	**<2 pF**	≅10 pF	≅20 pF	≅20 pF	≅20 pF
CMTI	**>150 V/ns**	Worse	Worse	Much worse	Much worse
Cost comparison	**Baseline**	15% more expensive	30% more expensive	18% more expensive	18% more expensive
Leakage inductance	**High**	Very low	Low	Low	Low
Regulation	Good	Good	Better	**Best**	Good

6-W designs

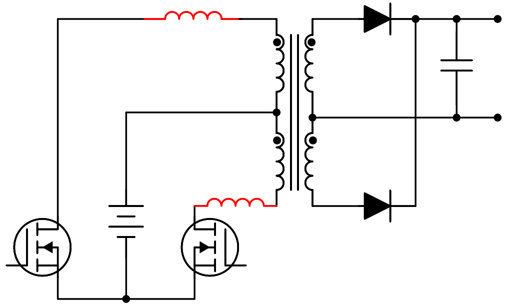
A split-chamber transformer provides an order-of-magnitude capacitance reduction.

How topologies respond to leakage inductance

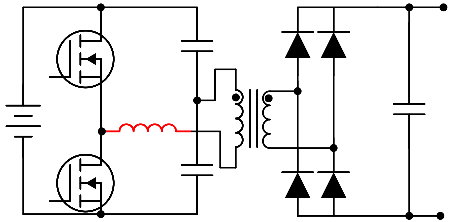
Flyback



Push-pull



Half bridge

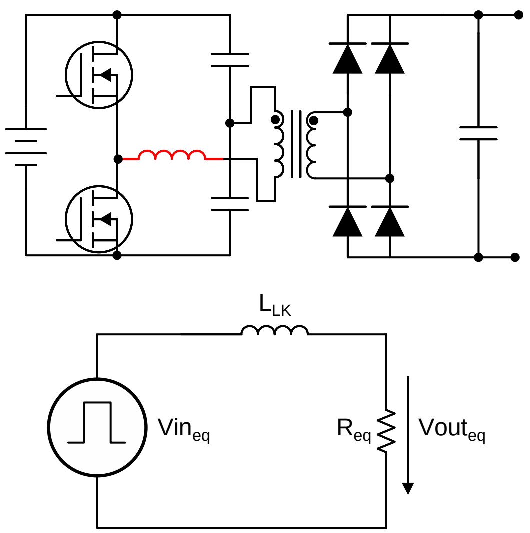


- Leakage energy can't be transferred to the secondary side.
- Leakage causes:
  - More EMI noise because of ringing.
  - More loss.
  - More device stress.
- Leakage needs minimizing.

- Leakage energy is fully recoverable.
- No extra ringing caused by leakage.
- Leakage still needs minimizing in order to obtain better voltage regulation.

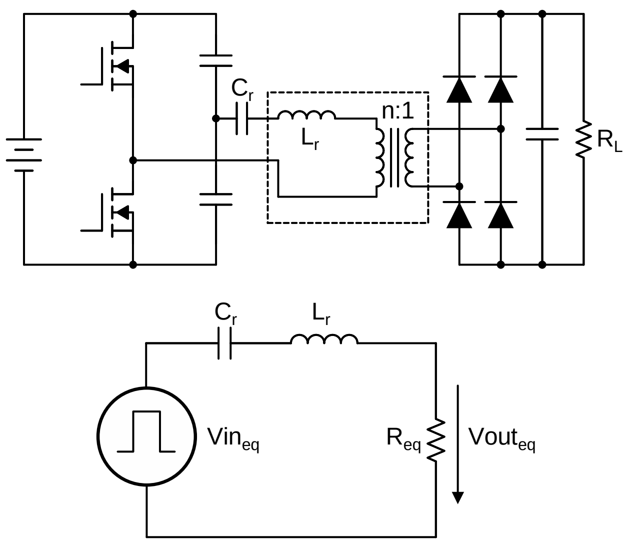
PWM converter vs. resonant converter

PWM converter



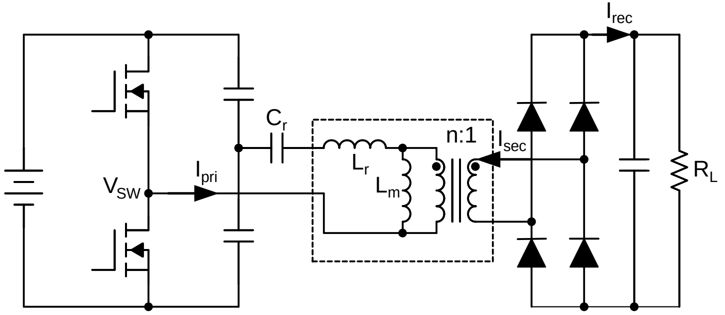
- Leakage inductance needs minimizing in order to reduce its voltage drop.

Resonant converter



- It is possible to **tune the resonant tank impedance to zero** without causing a voltage drop.

LLC converter

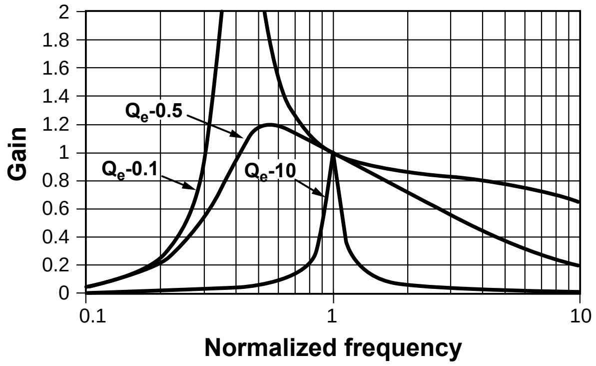


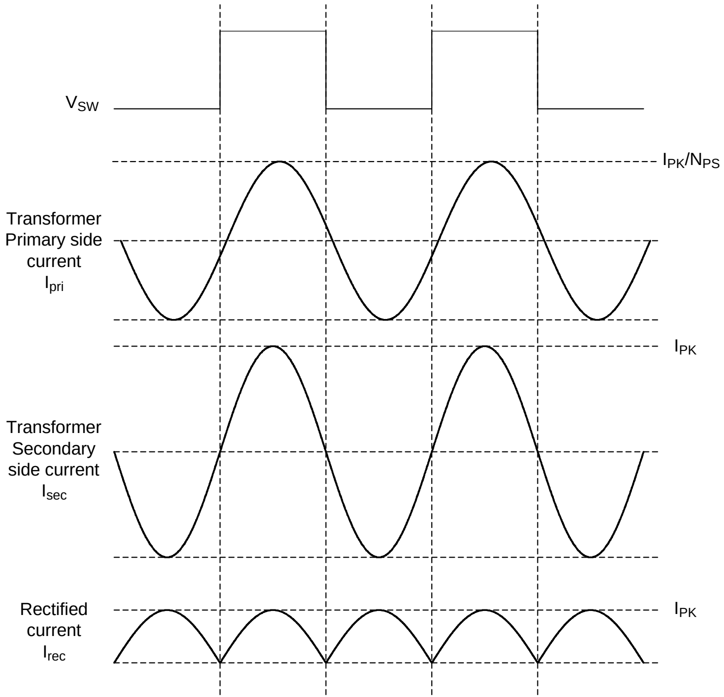
$$Gain = 2nV_O / V_{in}$$

$$f_0 = \frac{1}{2\pi\sqrt{L_r C_r}}$$

$$Q_e = \frac{\sqrt{L_r / C_r}}{R_e}$$

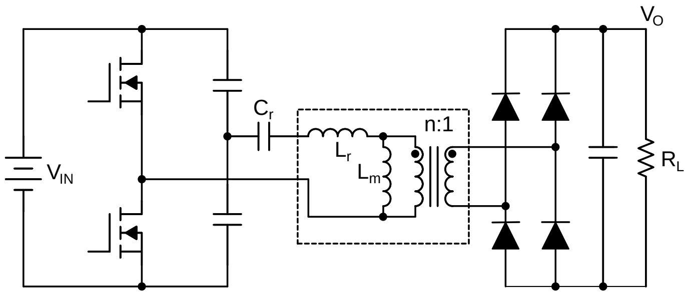
$$R_e = \frac{8n^2}{\pi^2} R_L$$





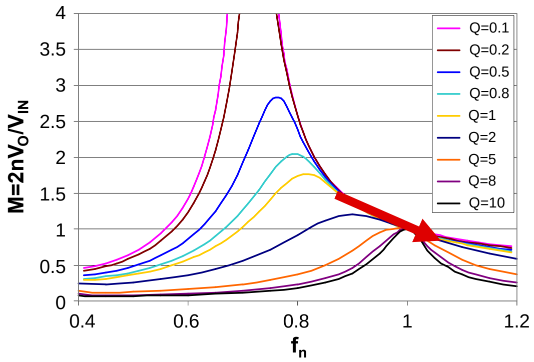
- At resonant frequency, the impedance of the resonant tank is equal to zero; the input and output are shorted through the transformer. Fixed frequency open-loop control is possible.
- You can use the leakage inductance of the transformer as the resonant inductor.

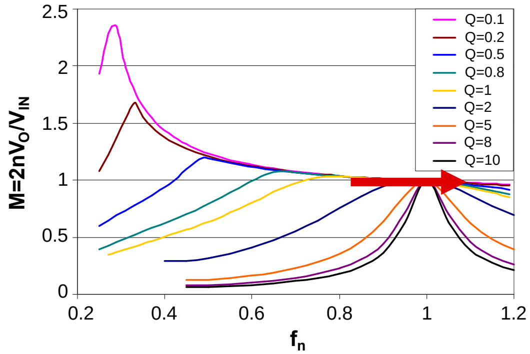
LLC gain curves with different leakage



$$L_n = \frac{L_m}{L_r} = \frac{1}{percentage\ leakage}$$

L_n=1

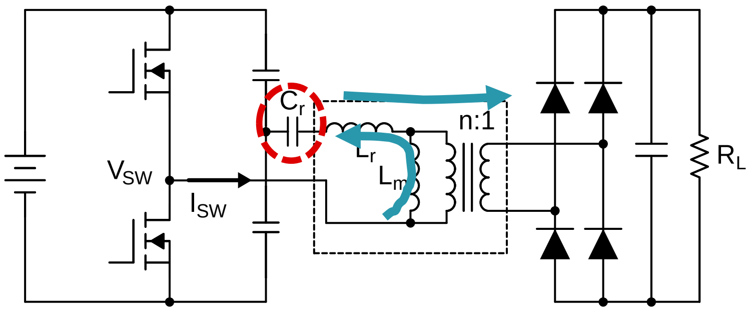




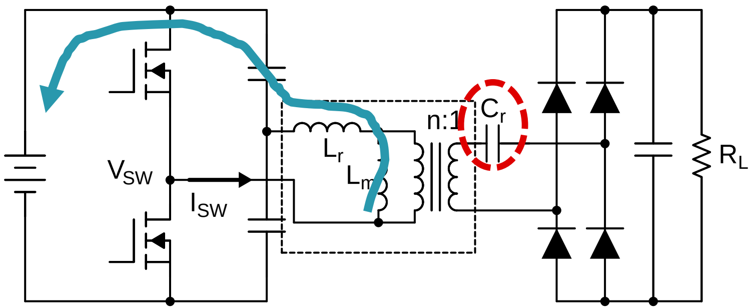
L_n=15

- When the magnetizing inductor is much larger than the resonant inductor, at around resonant frequency, the voltage gain curve is flat.
- The output voltage is less sensitive to the frequency error when L_n is larger.

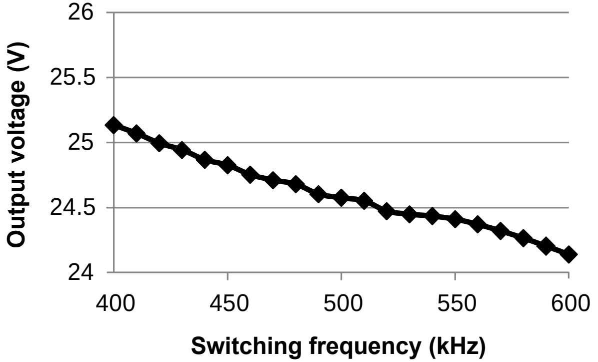
Primary- vs. secondary-side resonant

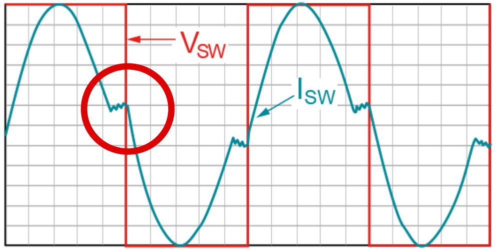


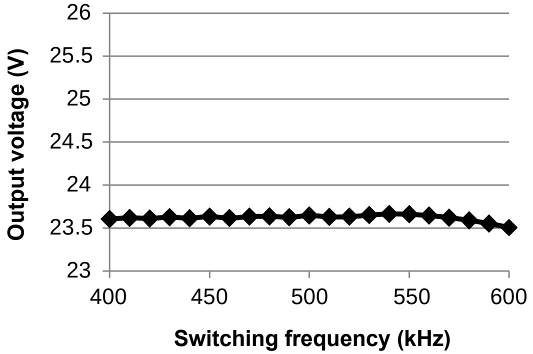
Primary-side resonant



Secondary-side resonant

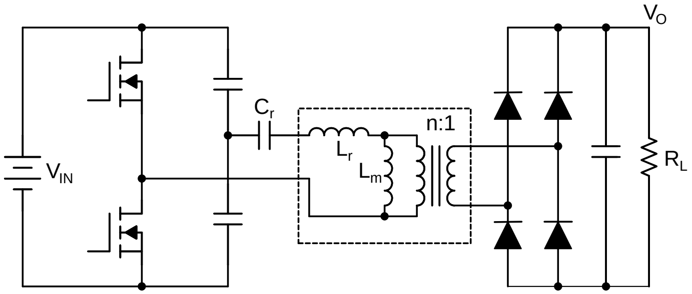






Secondary-side resonant is less sensitive to switching frequency errors.

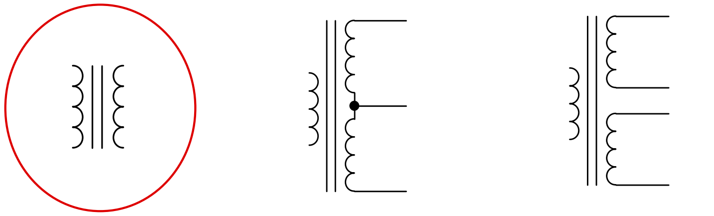
LLC converter variations



The filter capacitance needs to be much larger than the resonant capacitance.

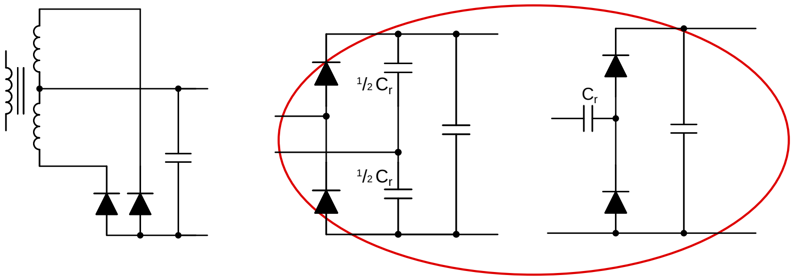
Transformer variations

Two windings | Center tap | Multioutput



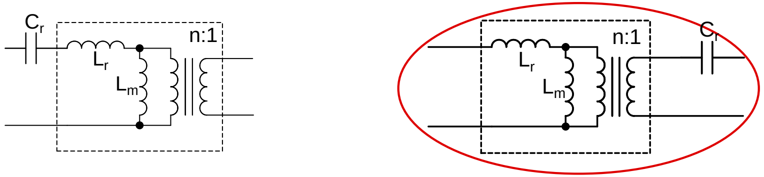
Rectification variations

Center tap | Voltage doubler

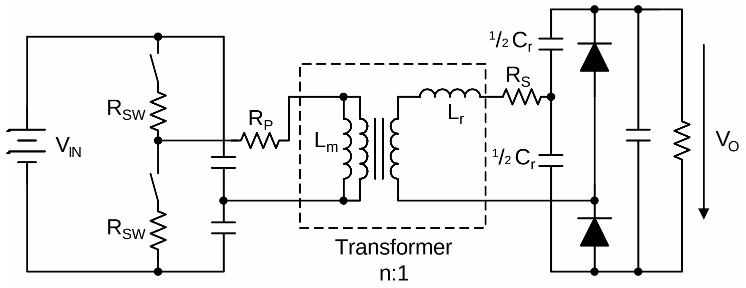


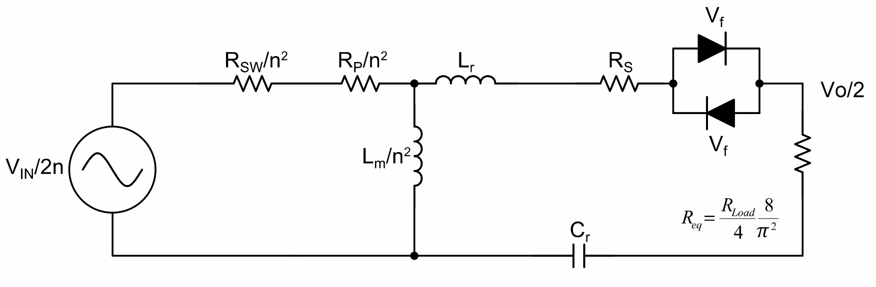
Resonant variations

Primary-side resonant | Secondary-side resonant



Open-loop LLC voltage regulation



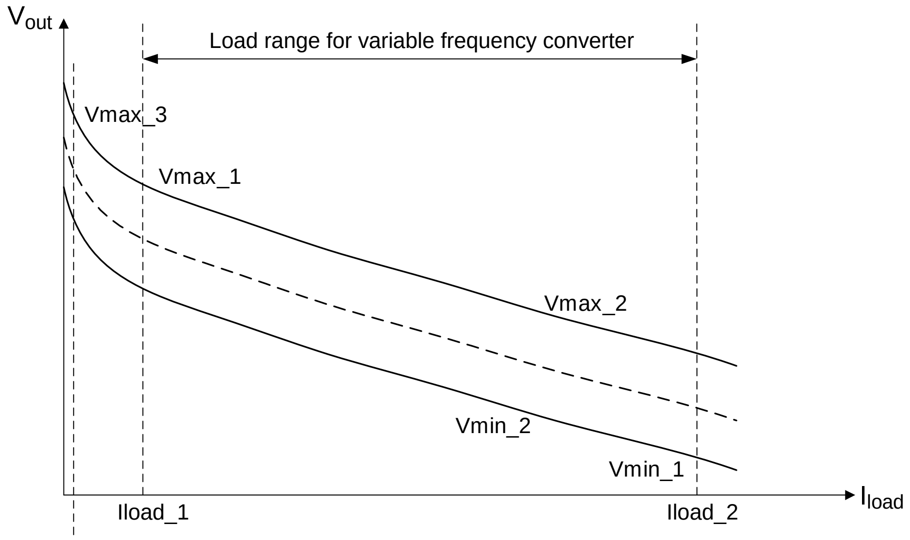


At resonant frequency

$$v_o \approx \underbrace{\frac{v_{in}}{n} - 2v_f}_{\text{DC voltage}} - \underbrace{\frac{\pi^2}{2}\left(\frac{R_{SW}}{n^2} + \frac{R_P}{n^2} + R_S\right)}_{\text{Internal resistance}} \times I_O = \frac{v_{in}}{n} - 2v_f - \frac{\pi^2}{2}\left(\frac{R_{SW}}{n^2} + R_{ac} + R_{ESR} + R_{Diode}\right) \times I_O$$

- The transformer turns ratio and resistive loss, as well as the diode drop, will determine the voltage regulation.
- Keeping the resistive loss low will result in the better load regulation.

Illustration of voltage regulation

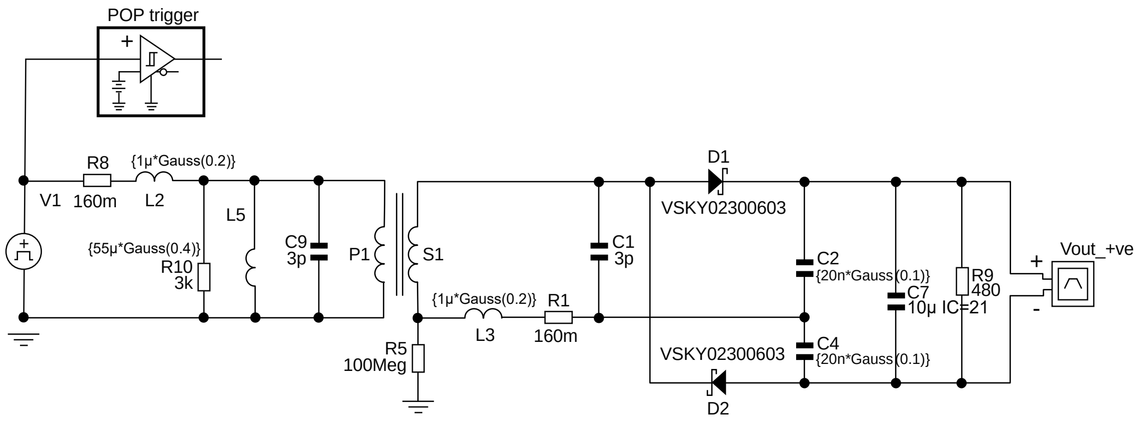


Gate-driver power

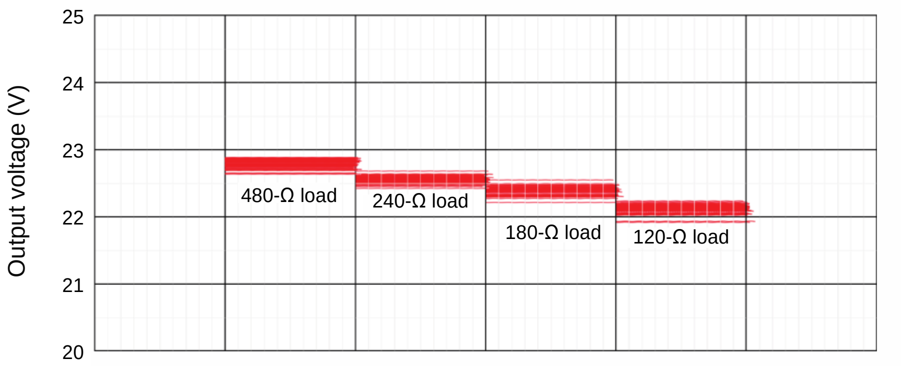
$$P_{DRV} = V_{DRV} \times Q_g \times f_{SW}$$

- The gate driver load for a fixed-switching-frequency inverter is fixed.
  - The output voltage regulation can be very tight.
- The standby-mode load voltage tends to rise.
  - Could be high enough to require an additional Zener diode clamp.
  - Mainly determined by the diode junction capacitor.
- For a variable-frequency inverter, the gate-driver load varies.
  - The output voltage varies more.

Output voltage sensitivity to tolerances



- Transformer turns ratio: 1:1.
- Leakage inductance distributed evenly on the primary and secondary sides.
  - Tolerance 20%.
- Magnetizing inductance tolerance 40%.
- Switching-frequency tolerance 6%.
- Resonant capacitance tolerance 10%.



- For each load condition, the output voltage varies ≅0.2 V out of 22 V, considering all tolerances.
- Load regulation dominates voltage regulation.

Open-loop LLC design flow

Switching frequency f_{SW}

Input voltage V_{IN}

Output voltage V_{OUT}

Volt-second rating

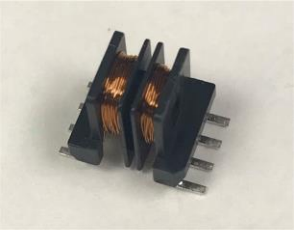
$$VS = \frac{V_{in}}{8 f_{SW}}$$

$$\frac{N_P}{N_S} = \frac{V_{in}}{V_{out} + V_{headroom}}$$

$$I_{rms_S} = \frac{\pi}{\sqrt{2}} I_{out}$$

$$I_{rms_P} = \frac{I_{rms_S}}{N_P / N_S}$$

Load current I_{OUT}



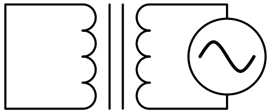
No air gap

Measure leakage L_K

$$L_m = \frac{t_d}{8 C_{SW} f_{SW}}$$

Primary side

N_P:N_S



f_{SW}

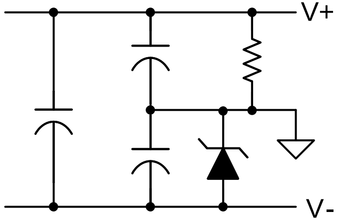
Secondary side

Calculate C_r

$$C_r = \frac{1}{4\pi^2 L_K f_r^2}$$

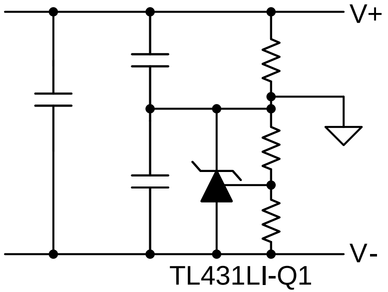
$$f_r = 1.1 f_{SW}$$

Splitting a single-output voltage into dual outputs



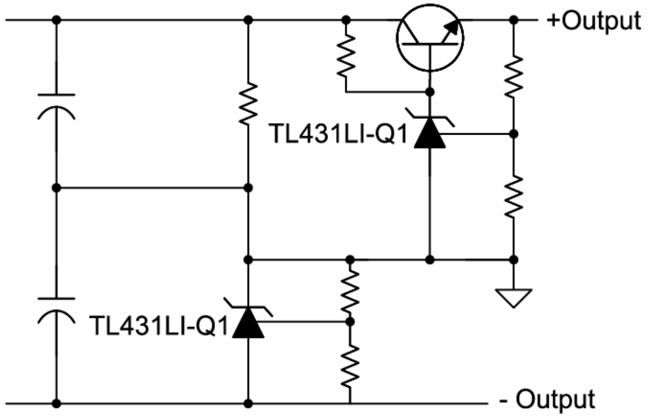
Zener split

- Lowest cost.
- Unregulated outputs.



Shunt regulator

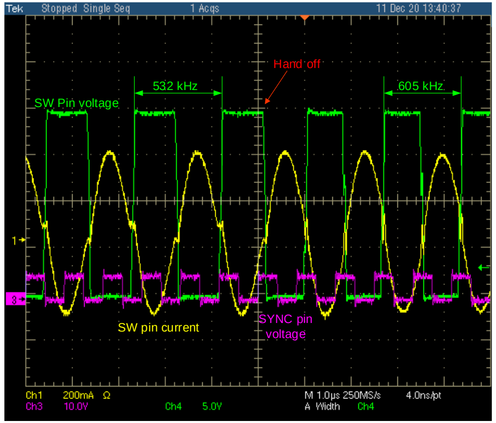
- Higher cost.
- Regulated negative output.
- Unregulated positive output.



Shunt regulator and linear regulator

- Highest cost.
- Less efficient.
- Regulated output.

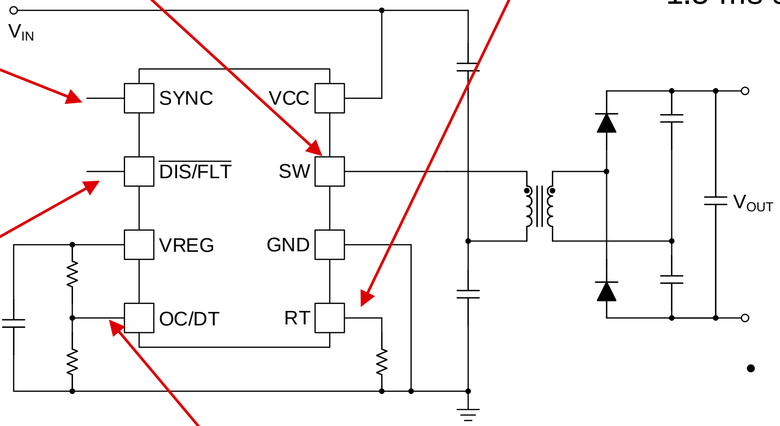
UCC25800-Q1 open-loop LLC transformer driver



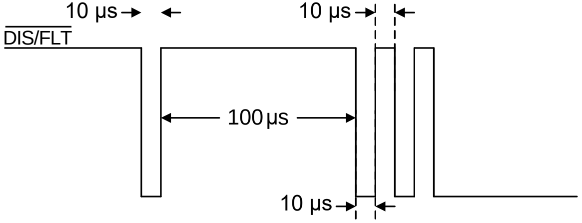
External sync

- Integrated half bridge.
- 1-A peak sinusoidal current.

- Programmable switching frequency:
  - 100 kHz to 1 MHz.
  - 1.2 MHz when left open.
  - 1.5-ms soft start.



Disable and fault report



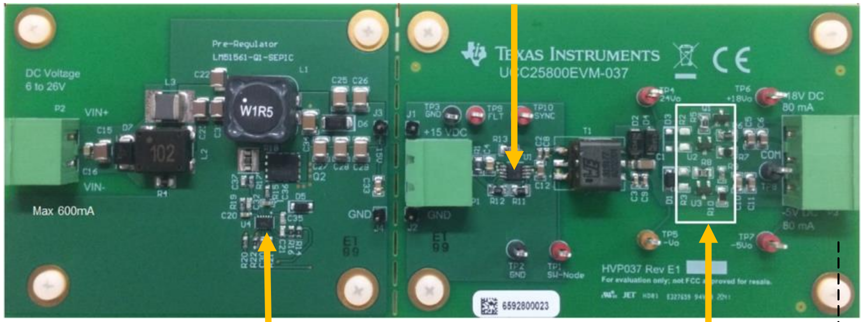
- Programmable overcurrent protection (overload and short-circuit protections).
- Programmable maximum dead time with automatic dead-time adjustment.

- Additional protections:
  - Input OVP.
  - Thermal shutdown.
  - Pin open-short.

Open-loop LLC isolated bias-supply measurement

UCC25800 EVM with LM5156 pre-regulator

UCC25800-Q1

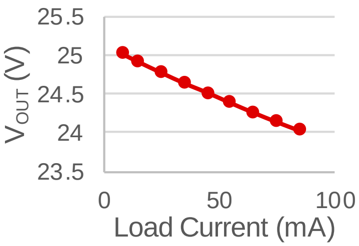


LM5156-Q1

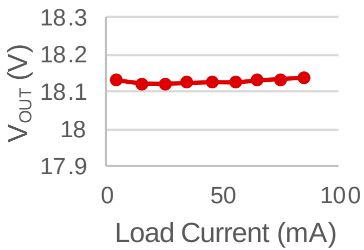
Optional components
for 1% load regulation

Parameter	Specifications
Input voltage range	6 V to 26 V
Output voltage and current	+18 V, –5 V, 0~85 mA
Switching frequency	2.2 MHz and 500 kHz
Isolation	Yes: 2,500 V_{AC} (1 s)
Topology	SEPIC + open-loop LLC transformer driver

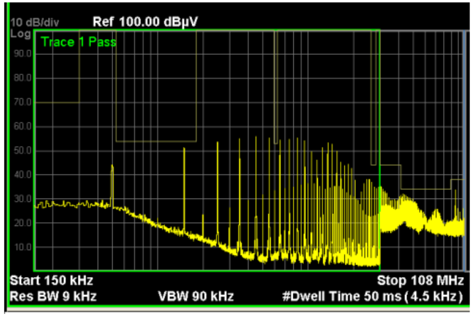
Load regulation



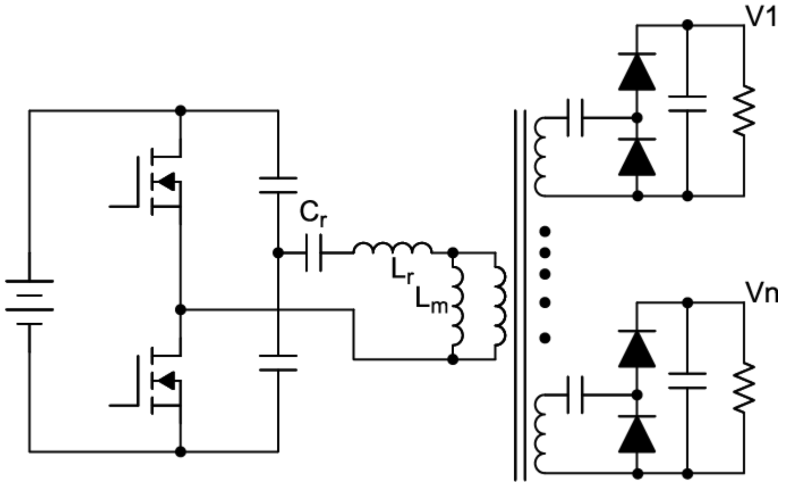
1% load regulation

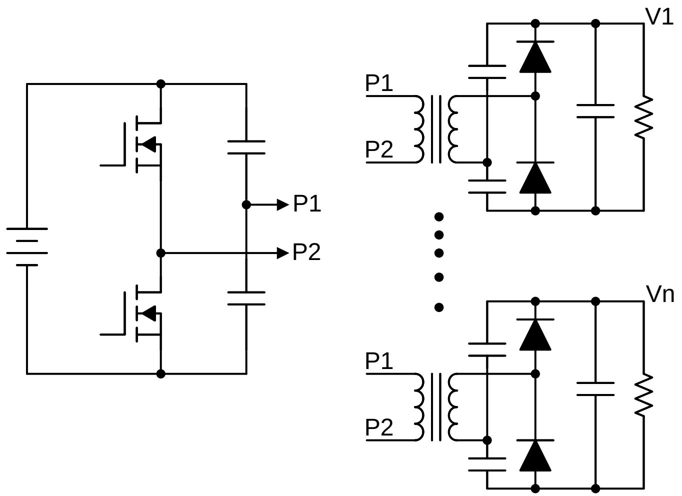


Surpasses CISPR 25 Class 5 EMI standard



Multiple outputs

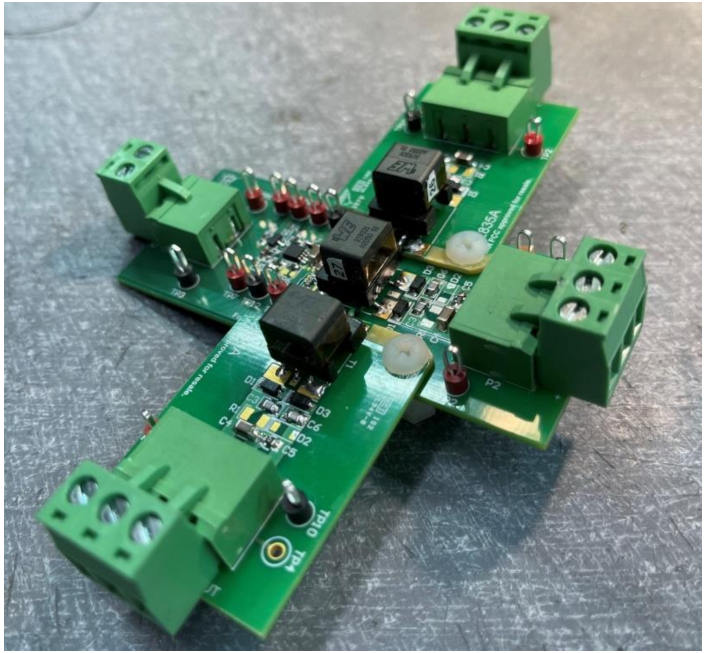




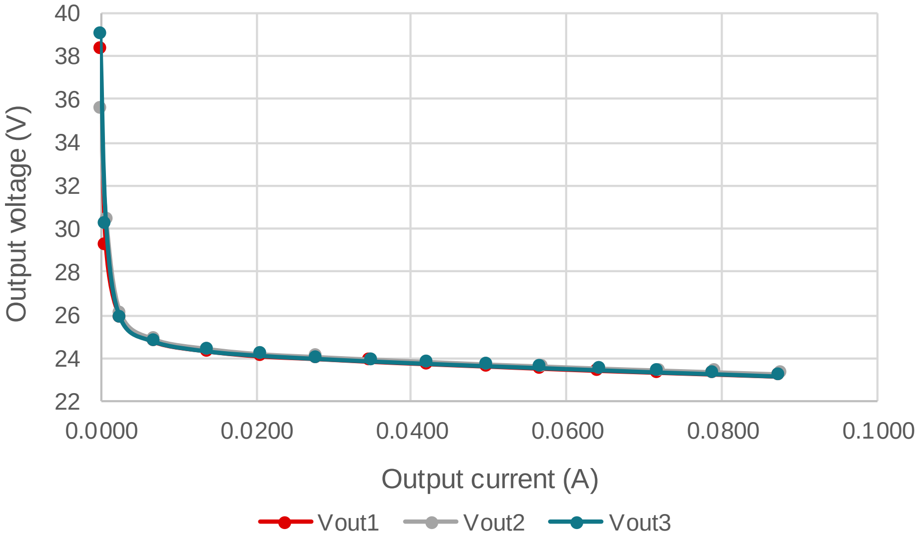
- Driving one transformer with multiple secondary-side windings.
- Uses primary-side resonant.
- Still has noise coupling among different outputs.

- Driving multiple two-winding transformers.
- Uses secondary-side resonant.
- Minimum noise coupling among different outputs.

Example: driving multiple transformers

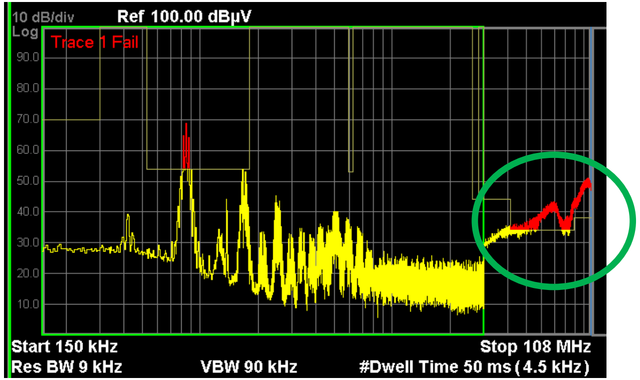


Converter voltage regulation with balanced loading, V_{IN} = 25 V

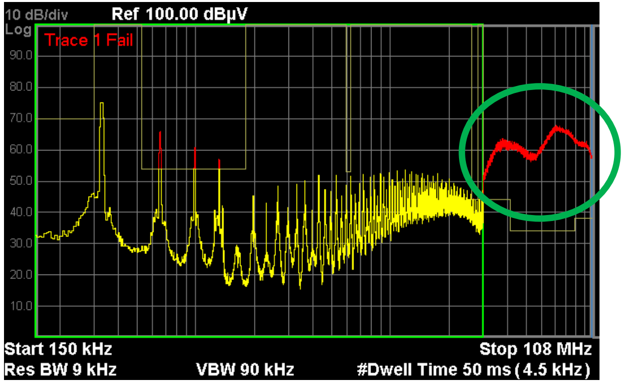


- Single primary-side power stage drives three transformers and secondary-side circuits.
- Creates three matched output voltages.

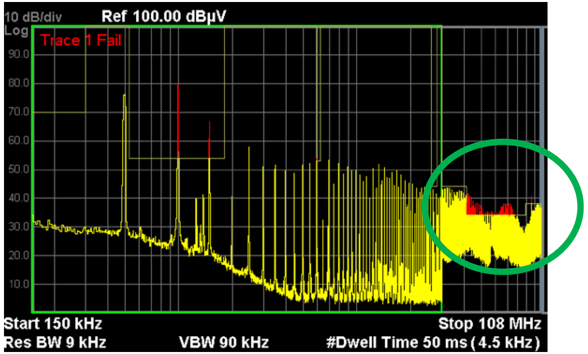
EMI noise performance comparison



5-V push-pull



24-V flyback

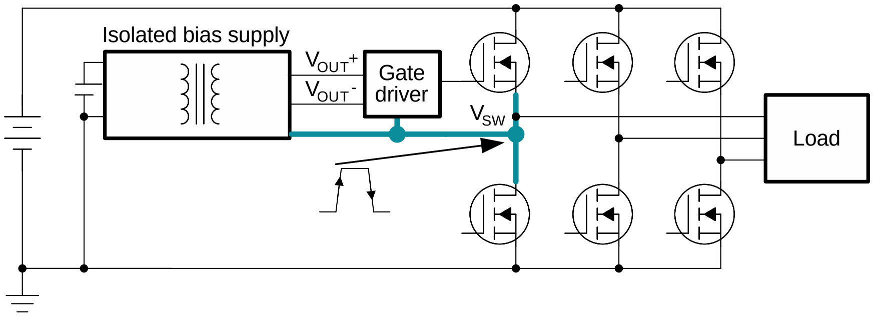


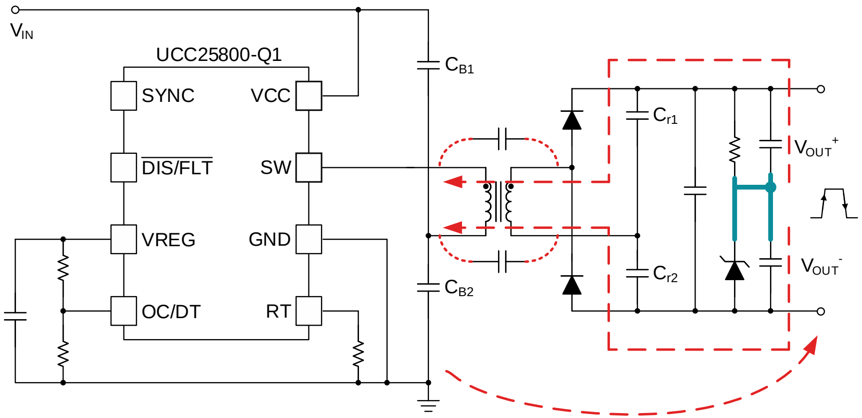
24-V LLC

The LLC has much lower high-frequency EMI noise.

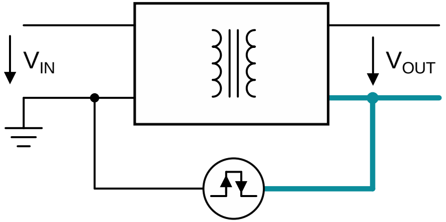
***No EMI filter added**

CMTI considerations



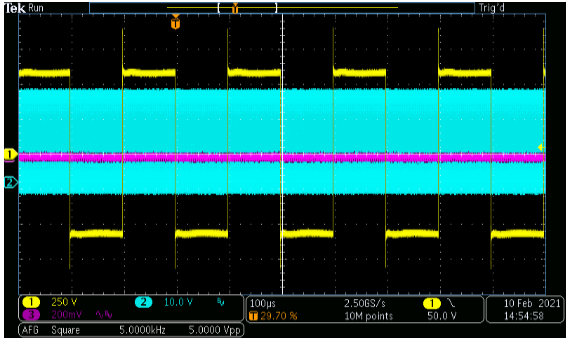


- dv/dt can reach >50 V/ns.
- Can be simulated by adding a pulse voltage between the bias-supply input and output ground.

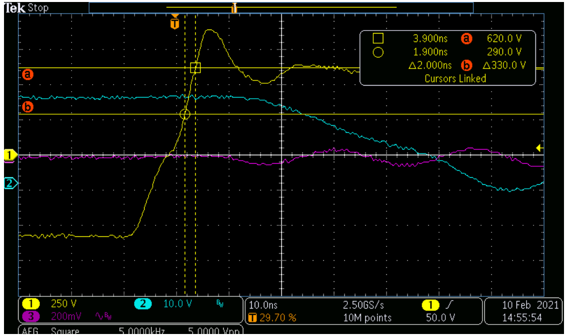


Strike voltage

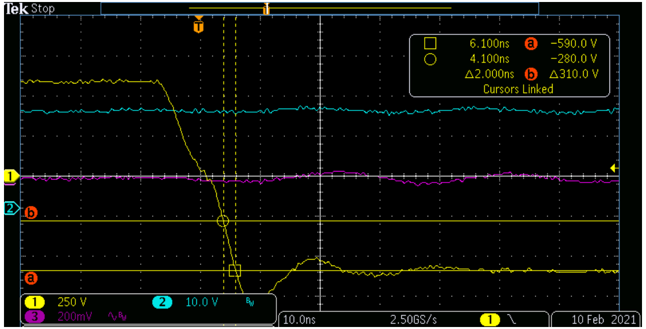
CMTI performance



165 V/ns

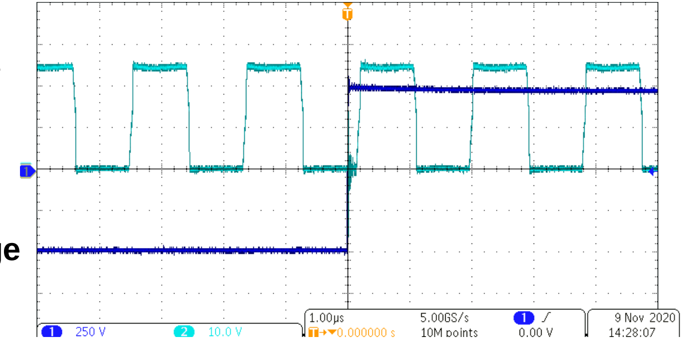


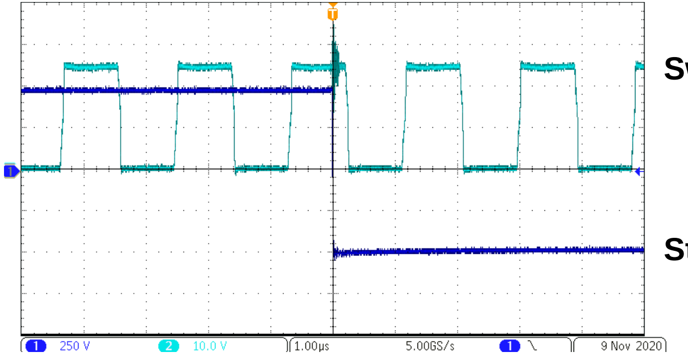
155 V/ns



Switch node

Strike voltage





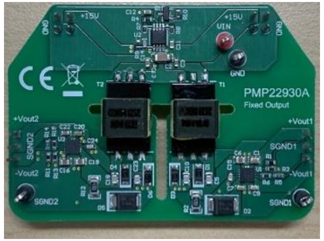
Switch node

Strike voltage

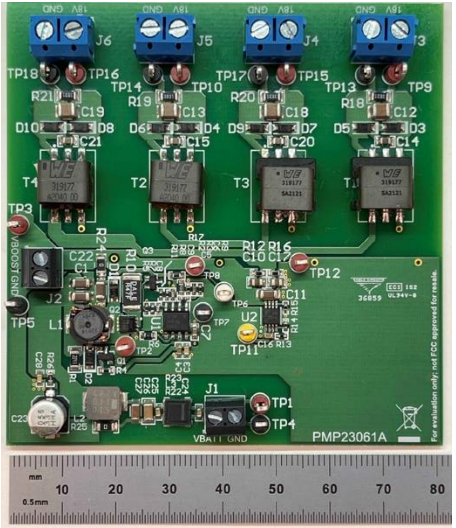
>150 V/ns CMTI does not affect operation.

Available reference designs

PMP22835
24-V in, 18-V and –5-V out, 6 W, 1-MHz switching frequency



PMP22930
15-V in, 15-V and –4-V out, 2.6 W, 600-kHz switching frequency



PMP23061
6-V to 28-V in, boost pre-regulator followed by an LLC, three 1-W 18-V outputs, one 3-W 18-V output, 500-kHz switching frequency

Summary

- An isolated bias supply is necessary for biasing isolated gate drivers in inverters.
  - Open-loop control provides a reliable solution and is less noise sensitive.
- The LLC topology is able to use the transformer with large leakage inductance and minimize the transformer's primary- to secondary-side parasitic capacitance.
  - Less EMI noise.
- The open-loop LLC converter provides a simple, robust solution:
  - Less EMI.
  - High CMTI.
  - Good voltage regulation.
  - Multiple output capability.