Texas Instruments

HIGH VOLTAGE SEMINAR

BING LU

ELECTRIC VEHICLES

A SIMPLE, ROBUST AND LOW-EMI SOLUTION FOR INVERTER GATE-DRIVER BIAS SUPPLIES

Agenda

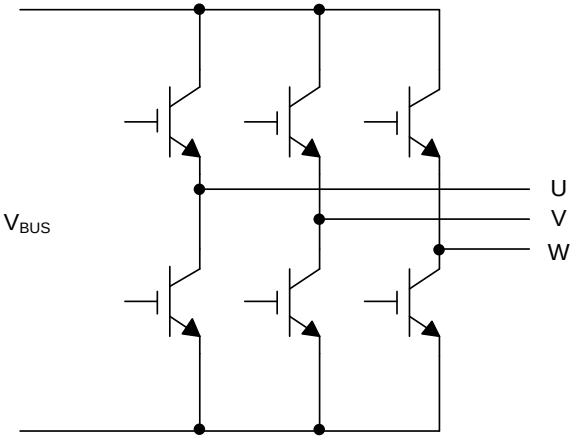
- Inverter and isolated gate driver bias supply architectures
- Different ways of creating isolated bias supply
  - Control method
  - Topology
  - Transformer
- LLC based open-loop isolated bias supply
  - Operation principles
  - Circuit variations
  - Voltage regulation
  - Multiple outputs
- Performance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

Inverters in different applications

Traction inverter

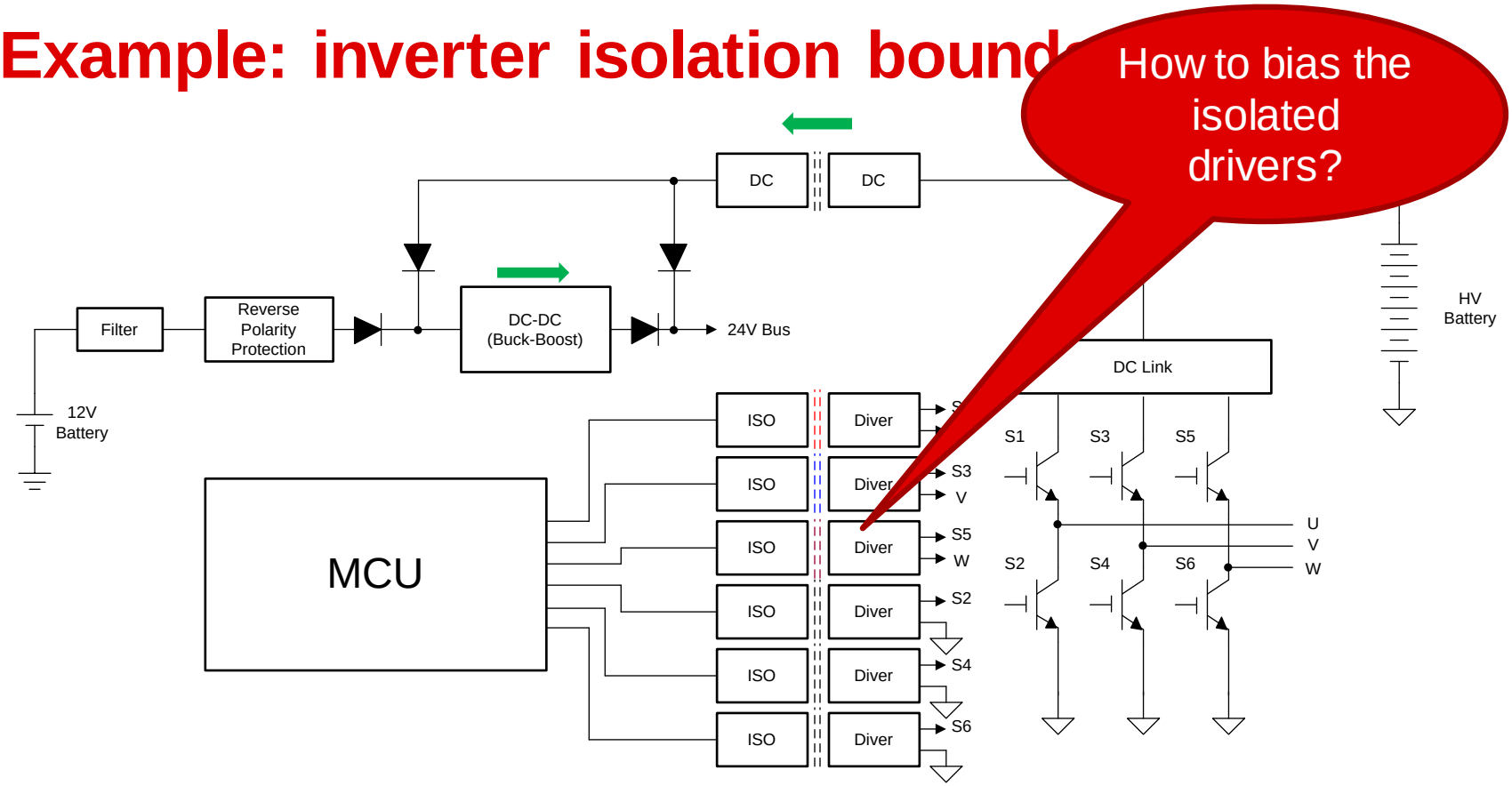
UPS

Motor drive



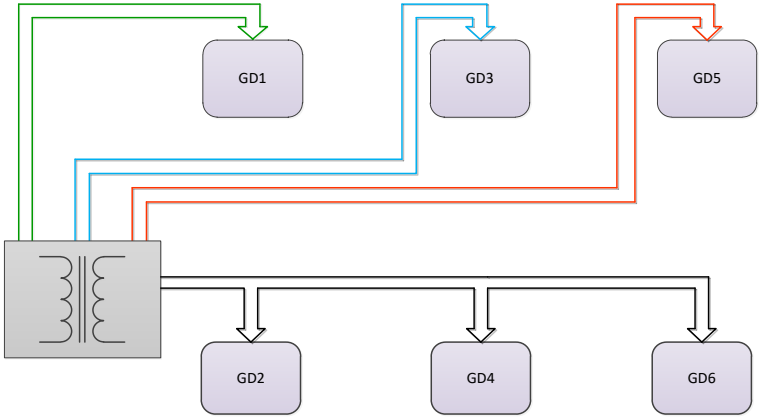
Onboard charger

Example: inverter isolation bound

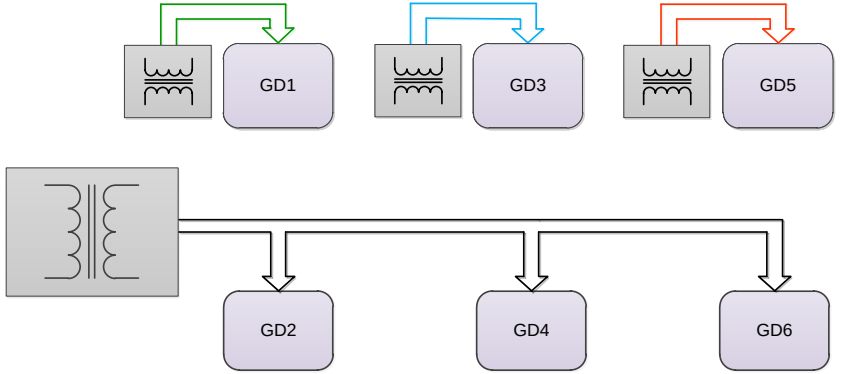


Different gate driver architectures

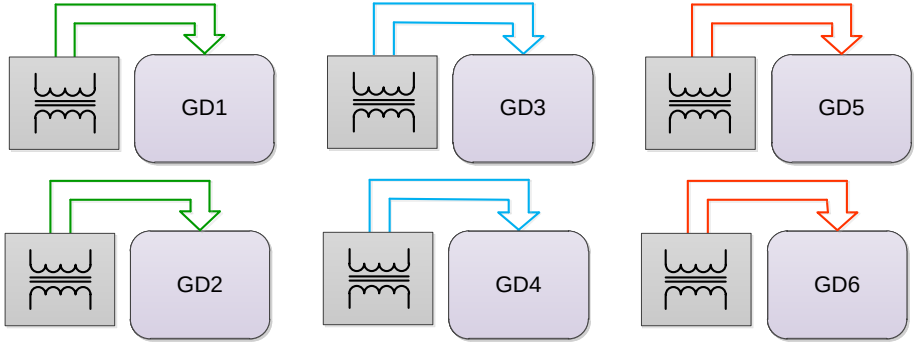
Centralized



Semi-Distributed

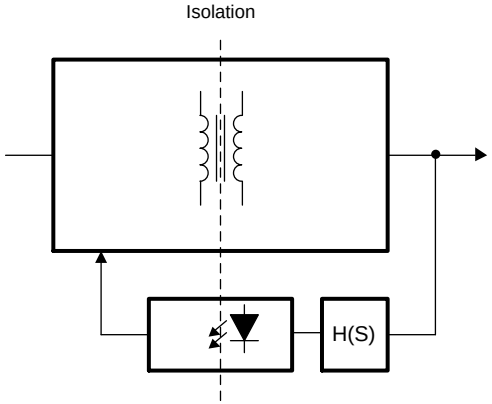


Distributed



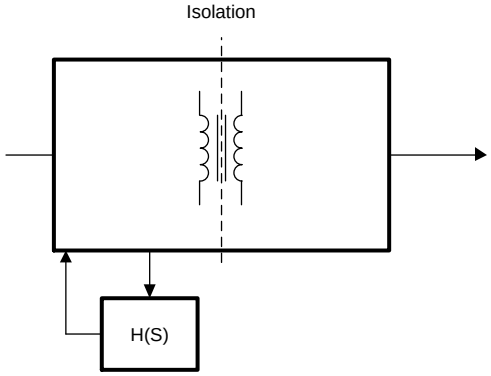
- Centralized system has lowest cost, but heavy and difficult to manage fault
- Distributed system distribute the weight and fault, but more expensive
- Semi-distributed is somewhere in the middle

Output voltage control



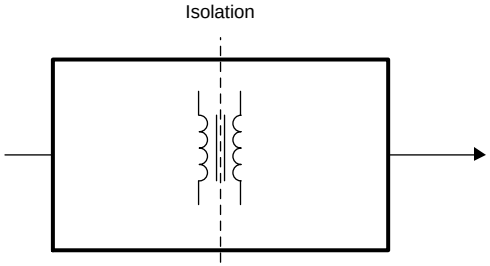
Close loop
Secondary side feedback

- Well regulated output
- No need pre-regulator
- More components
- Less reliable due to the opto coupler



Close loop
Primary side feedback

- Semi regulated output
  - Determined by cross regulation
- No need pre-regulator
- Noise sensitive due to the output voltage sampling method



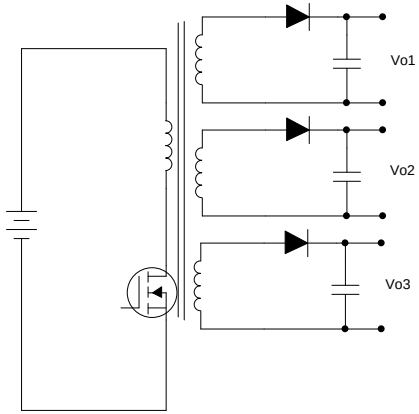
Open loop
No feedback

- No control loop, robust operation
- Less noise
  - Coupling only through the transformer
- Unregulated output, need pre-regulator

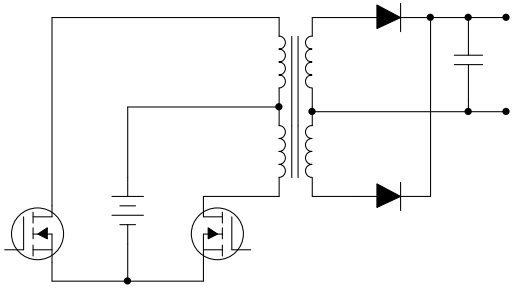
Open-loop control provides a robust solution

Topologies used for isolated bias supply

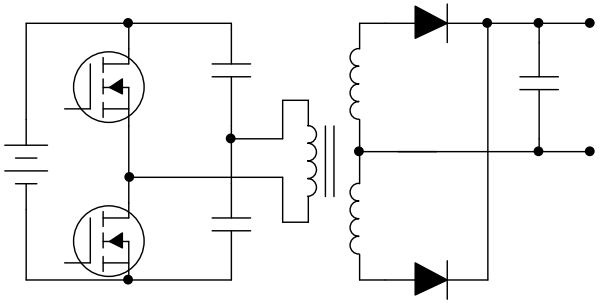
Flyback



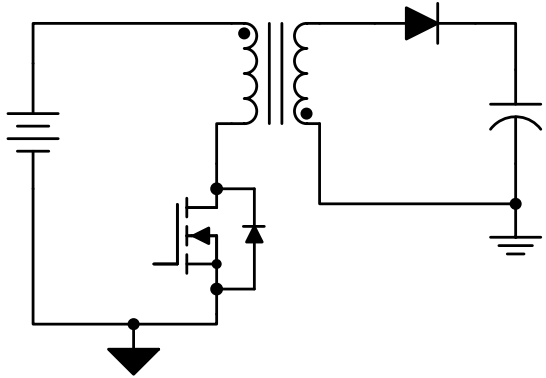
Push-pull

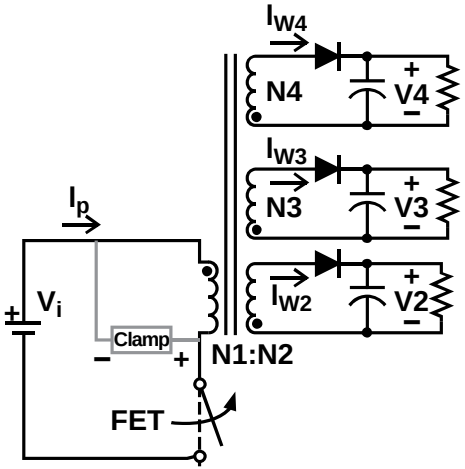


LLC

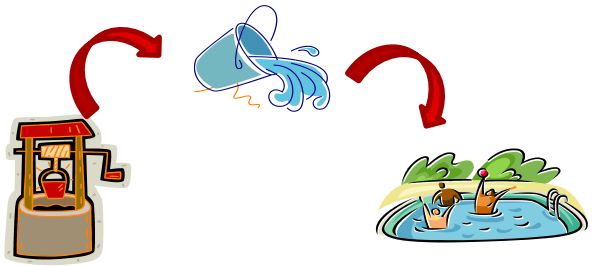


Flyback converter topology



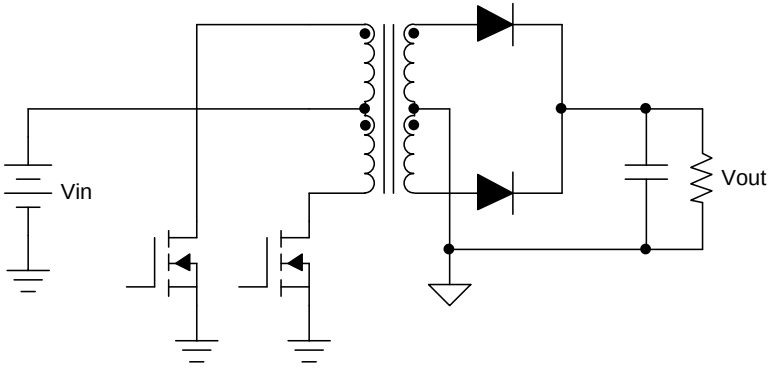


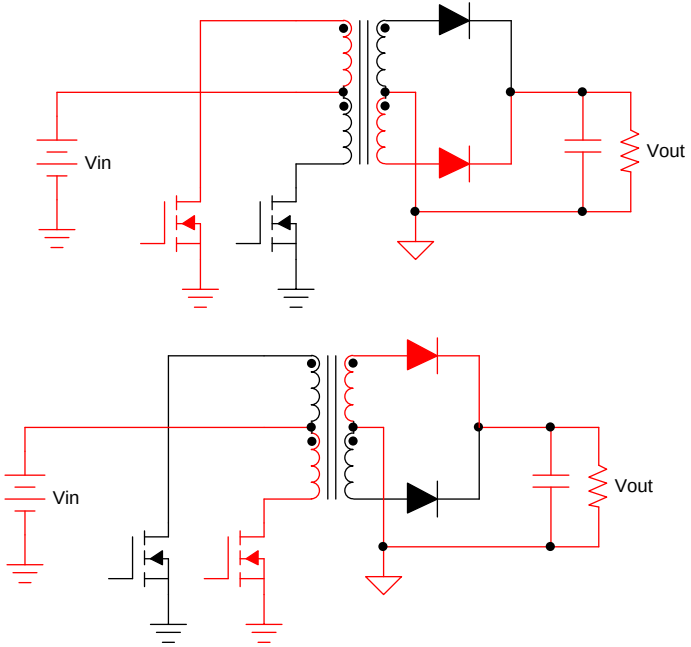
Basic Flyback Circuit



- Flyback can easily create multiple outputs
  - Voltage proportional to the turns ratio
  - Suitable for centralized architecture
- Can be controlled with opto feedback or primary side feedback
- Need well coupled transformer

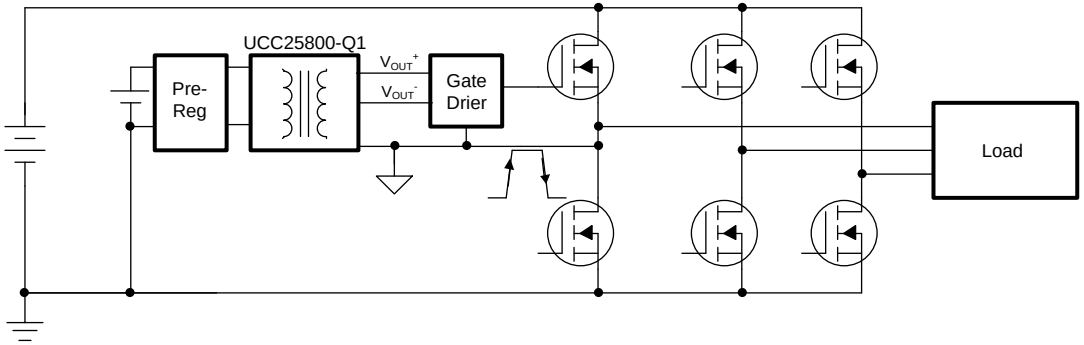
Push-pull topology



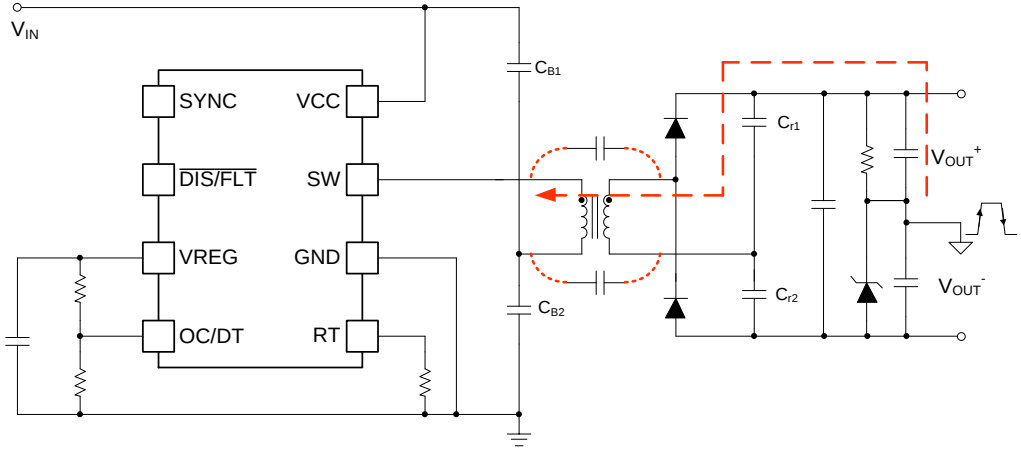


- With 50% duty cycle operation, in each half switching cycle, output is connected with input through the transformer
- Filter inductor is needed if the duty cycle is less than 50%
- Transformer needs to have low leakage inductance to avoid ringing and device over stress
- Good for distributed and semi-distributed architecture

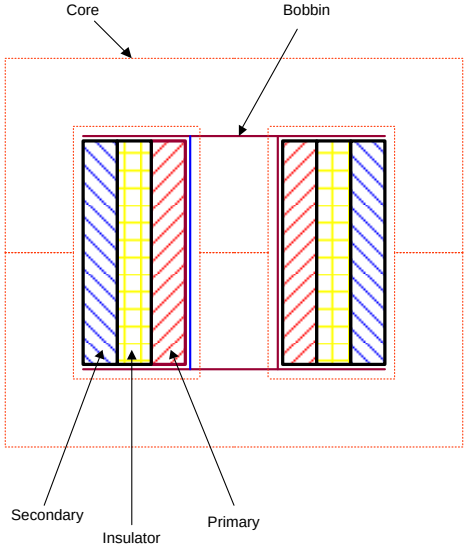
Transformer parameter impacts to system EMI

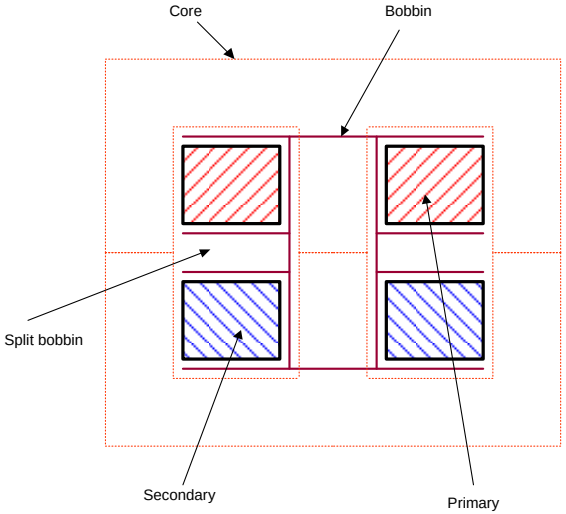


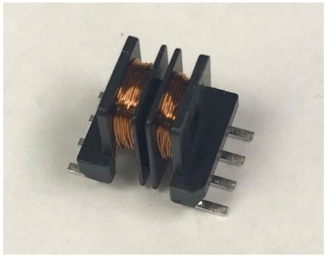
- High dv/dt couples through transformer parasitic capacitor to the primary side
- Higher EMI noise
- Extra loss
- More noise to the controller, CMTI issue
- It gets worse with SiC or GaN devices with higher dv/dt



Transformer structure: less parasitic capacitance







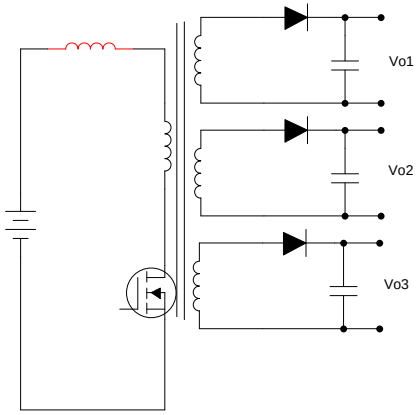
The capacitance can be reduced by increasing the insulator thickness
Less effective due to the large surface area

Split bobbin reduces the capacitance by reducing the surface area and increasing the distance
Much smaller capacitance can be achieve

Increasing the distance reduces the capacitance while increasing the leakage inductance

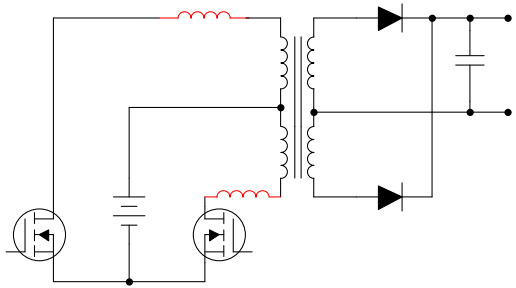
How topologies respond to leakage inductance

Flyback

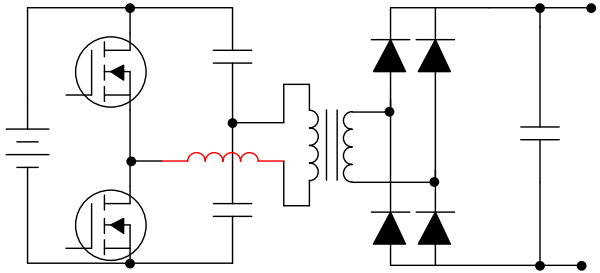


- Leakage energy can't be transferred to secondary side
- Leakage causes
  - More EMI noise due to ringing
  - More loss
  - More device stress
- **Leakage needs to be minimized**

Push-pull

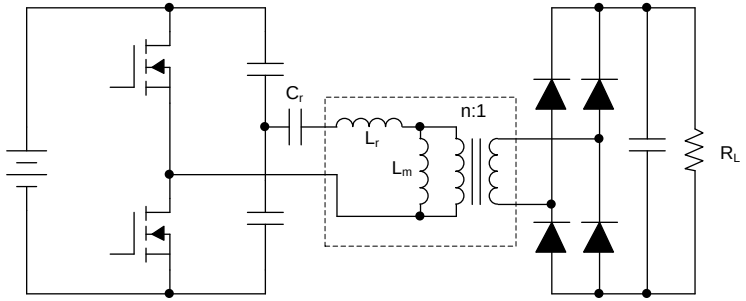


LLC



- Leakage is part of resonant circuit
- Leakage energy is fully recovered
- No extra ringing caused by the leakage
- **No limitations on the leakage inductance**

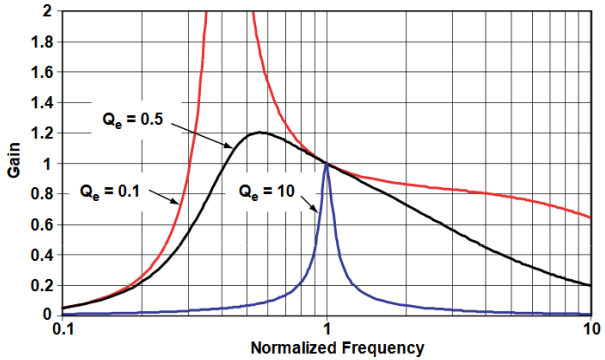
LLC converter

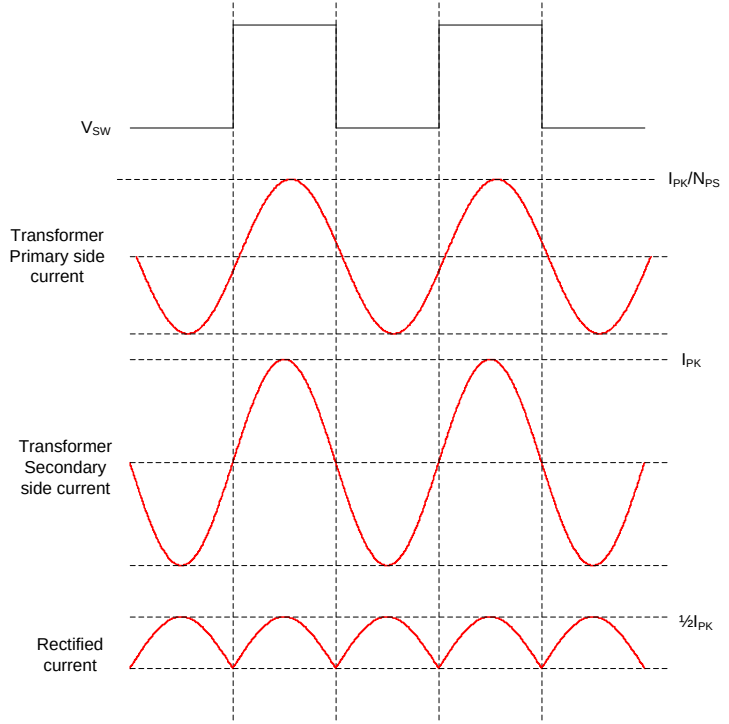


$$f_0 = \frac{1}{2\pi\sqrt{L_r C_r}}$$

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

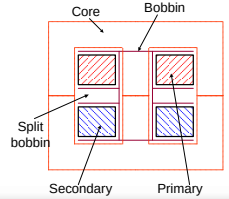
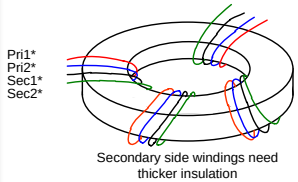
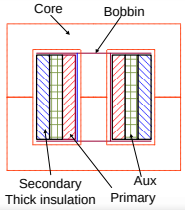
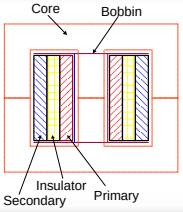
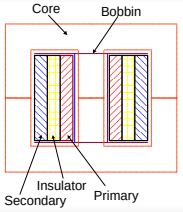
$$R_e = \frac{8n^2}{\pi^2} R_L$$





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

Transformers for isolated bias supply

	LLC Transformer	Push-Pull Transformer	Three-winding Flyback	Two-winding PSR Flyback	Half-Bridge
					
$C_{Pri-Sec}$	**<2pF**	~10 pF	~20 pF	~20 pF	~20 pF
CMTI	**>150V/ns**	Worse than LLC	Worse than LLC	Much worse than LLC	Much worse than LLC
Cost	**1X**	>1.15	>1.3X	>1.18X	>1.18X
EMI	**Best**	Good	Poor	Poor	Poor
Regulation	Good	Good	Better	**Best**	Good

LLC converter provides an order of amplitude capacitance reduction

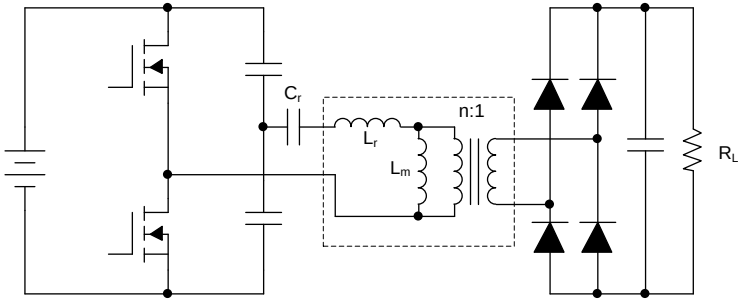
LLC converter variations

Transformer variations

Two-winding

Center-tap

Multi-output



Rectification Variations

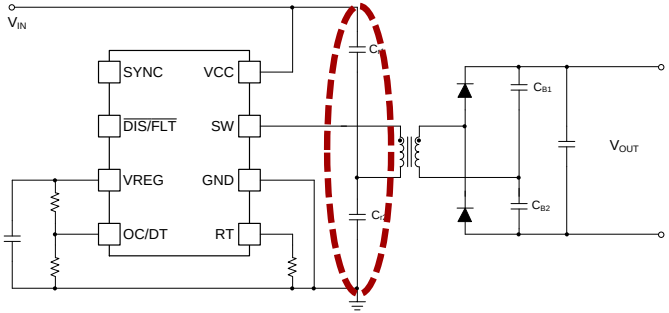
Full-wave

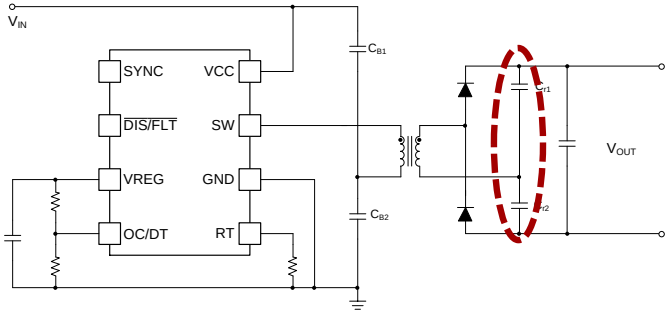
Center-tap

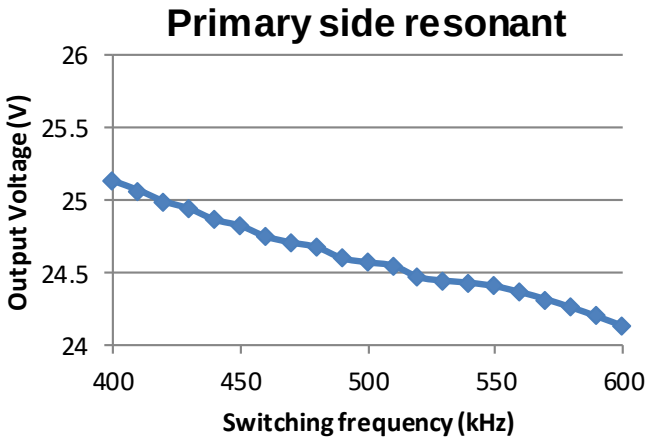
Voltage-doubler

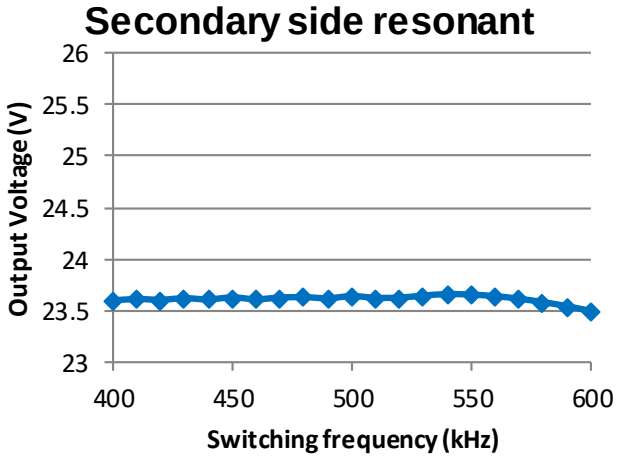
Voltage-doubler

Primary vs. Secondary side resonant



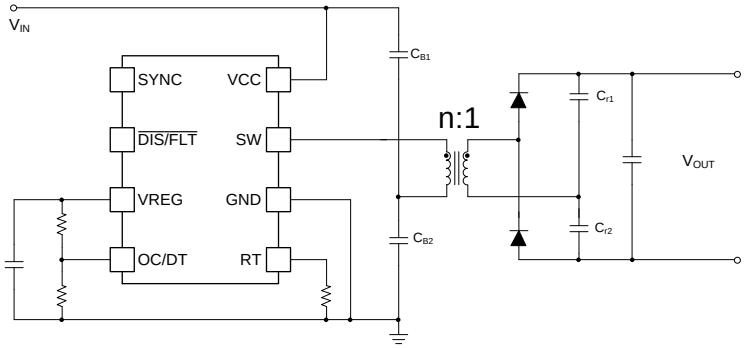


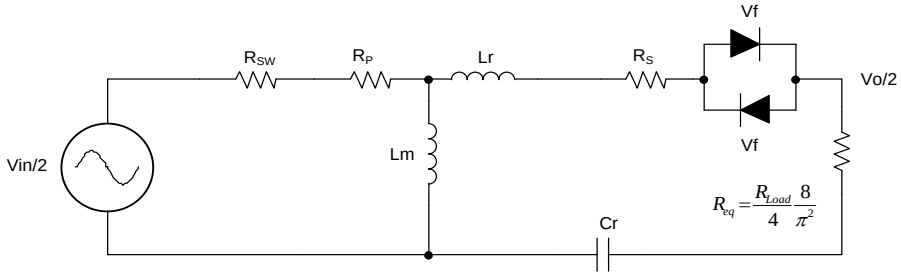




Secondary side resonant is less sensitive to switching frequency error

Open-loop LLC voltage regulation

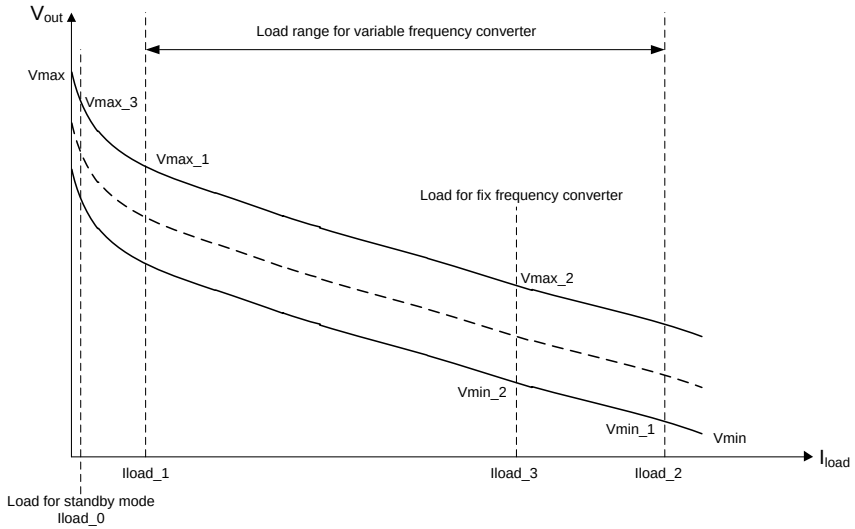




$$\frac{v_o}{v_{in}} \approx \frac{L_m}{L_m + L_{rp}} \frac{v_{in}}{n} - \frac{\pi^2}{2}\left(\frac{R_{SW}}{n^2} + \frac{R_P}{n^2} + R_S\right) \cdot I_O - 2v_f$$

- The voltage regulation is determined by transformer turns ratio and resistive loss, as well as the diode drop
- It is critical to keep the resistive loss low to get best load regulation

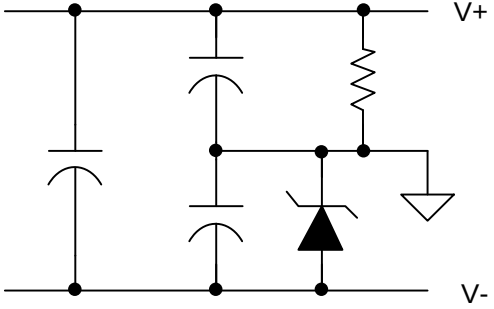
Illustration of voltage regulation



- For a fix switching frequency inverter, the gate driver load is fixed
  - The output voltage regulation can be very tight
- For a variable frequency inverter, the gate driver load varies
  - The output voltage varies more
- The standby mode load voltage tends to go up
  - It could be too high that need extra help from a Zener diode
  - It is mainly determined by the diode junction capacitor

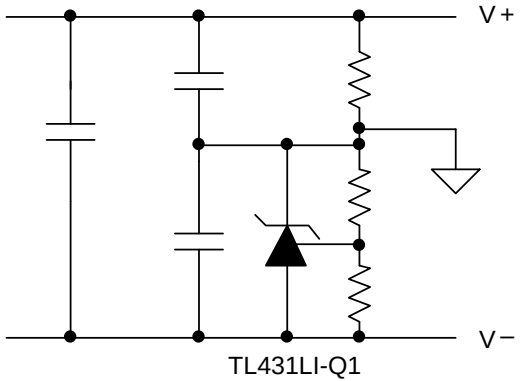
	Normal operation		Standby mode load	Vout		
	Min load	Max load		Min	Max	Standby max
Fixed Fre.	Iload_3	Iload_3	Iload_0	Vmin_2	Vmax_2	Vmax_3
Var. Fre.	Iload_1	Iload_2	Iload_0	Vmin_1	Vmax_1	Vmax3

Split single output voltage into dual outputs



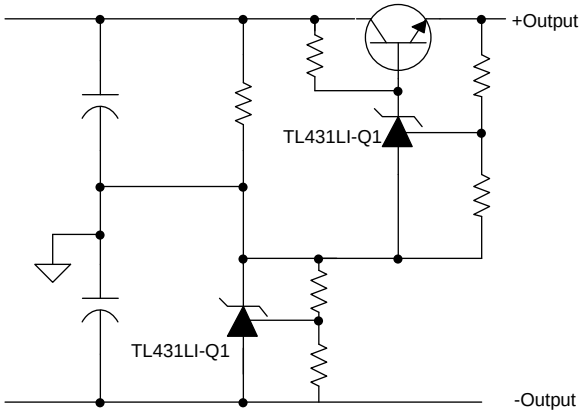
Zener split

- **Lowes cost**
- **Unregulated outputs**



Shunt Regulator

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



Shunt Regulator & Linear regulator

- **Highest cost**
- **Regulated output**

UCC25800-Q1

Sampling

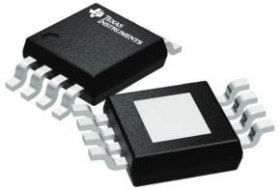
Low-cost LLC transformer driver with high performance

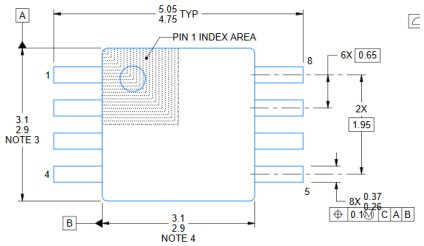
Features

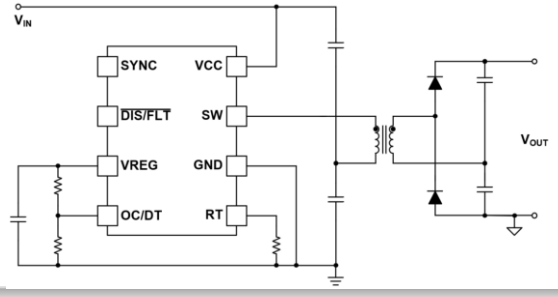
- Operation from 9 V to 34 V (40 V Abs Max)
- 6 W from 24-V input, Up to 10 W from 34-V input
- Integrated half-bridge MOSFETs
- Programmable fixed switching frequency up to 1.2 MHz
  - 1.2 MHz default, resistor settable 100 kHz – 1 MHz
  - Frequency accuracy +/-6% maximum over temperature
  - External SYNC function
- Drive multiple transformers with one UCC25800-Q1
- Automatic dead time adjustment with programmable maximum
- Integrated soft-start
- Disable pin with fault code output
- Two-level over current protection
  - Programmable via external resistor
  - UCC25800L is latched after over current
  - UCC25800R is retry after over current
- Over Temperature Protection
  - 160°C Junction
  - 10°C Hysteresis
- AEC Q100 Qualified

Benefits

- Low common mode noise due to minimal interwinding capacitance in transformer
- Simple design, highly integrated, no bootstrap capacitor
- High switching frequency for smaller size and more robustness







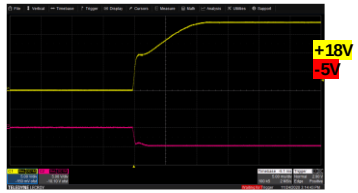
[*Disclaimer:* Specs, features & pinouts subject to change without prior notice.]

UCC25800-Q1 measurement data

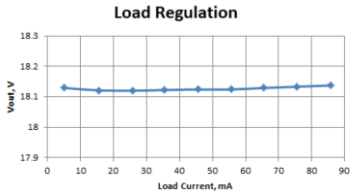
UCC25800 EVM with LM5156 Pre-Regulator

PARAMETER	SPECIFICATIONS
Input voltage range	6V – 26V
Output voltage and current	+18V / -5V
Switching frequency	2.2MHz and 500 kHz
Isolation	Yes, 2500 VAC (1 sec)
Topology	SEPIC + Open loop LLC transformer driver

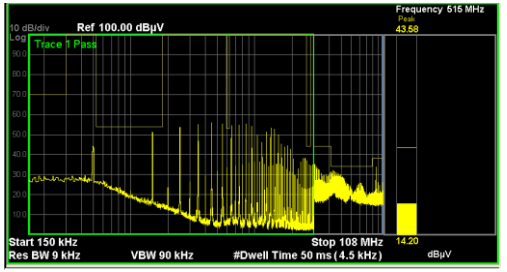
Predictable Startup of +/- rails



1% Load Regulation

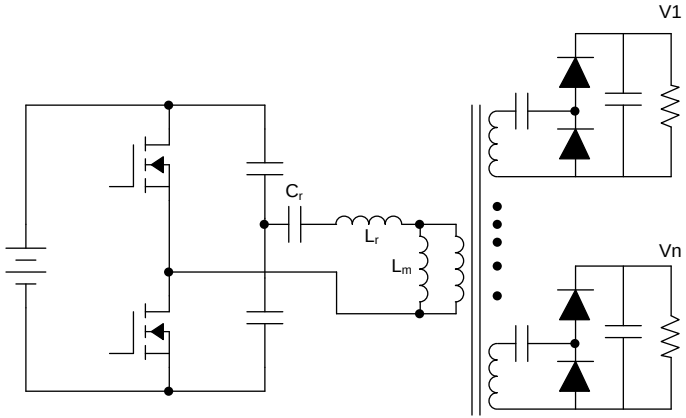


Surpasses CISPR 25 Class 5 EMI Standard

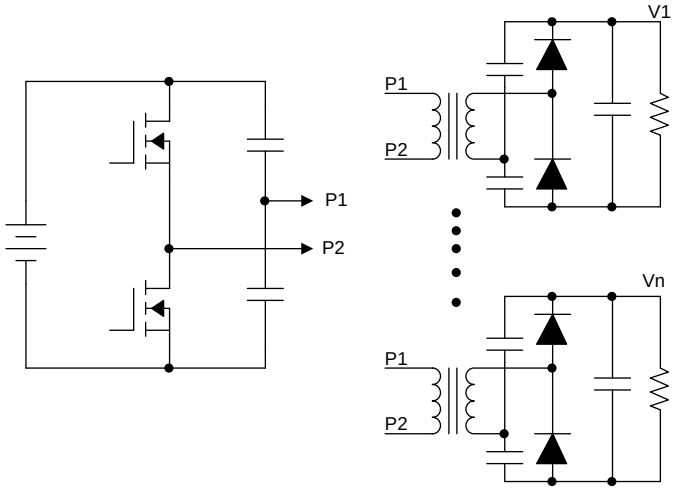


Pass - LLC Board Onlywith Filter

Multiple outputs

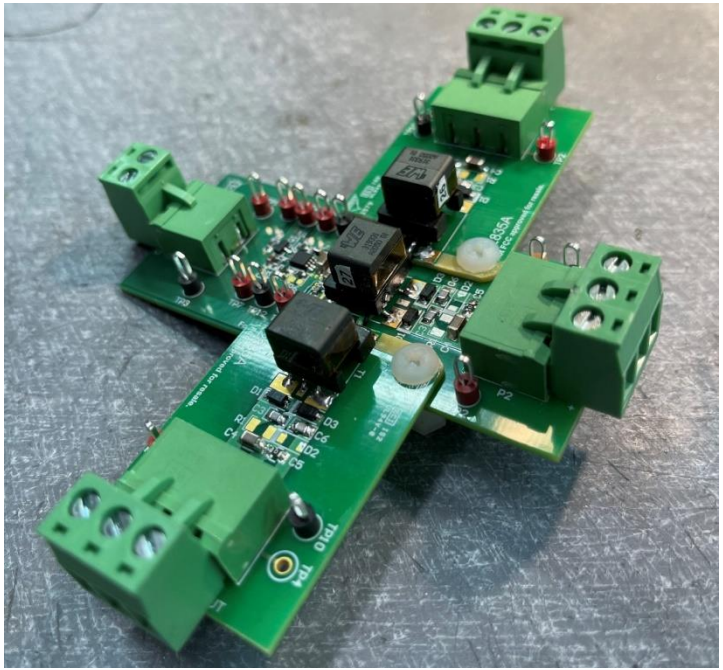


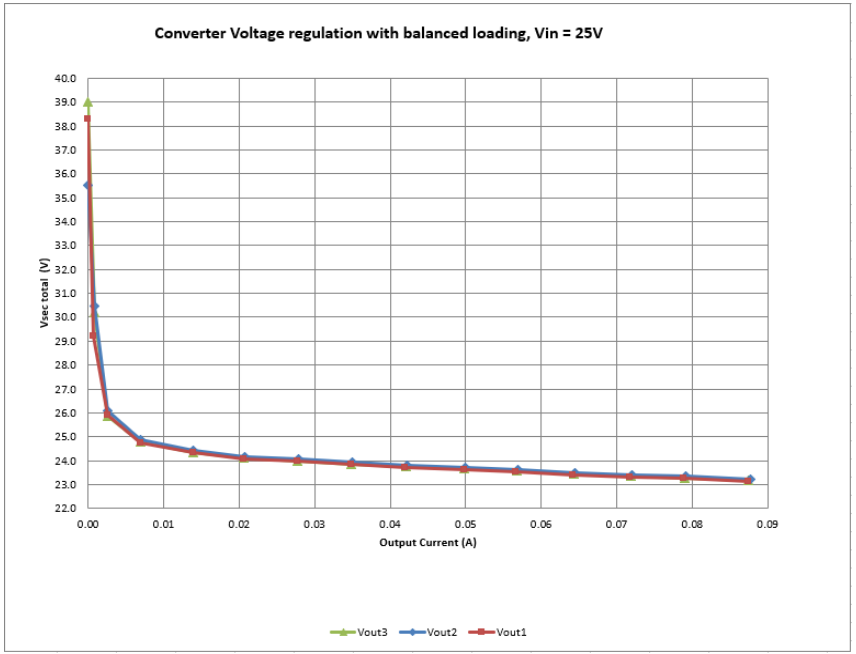
Driving one transformer with multiple secondary side windings



Driving multiple two winding transformers

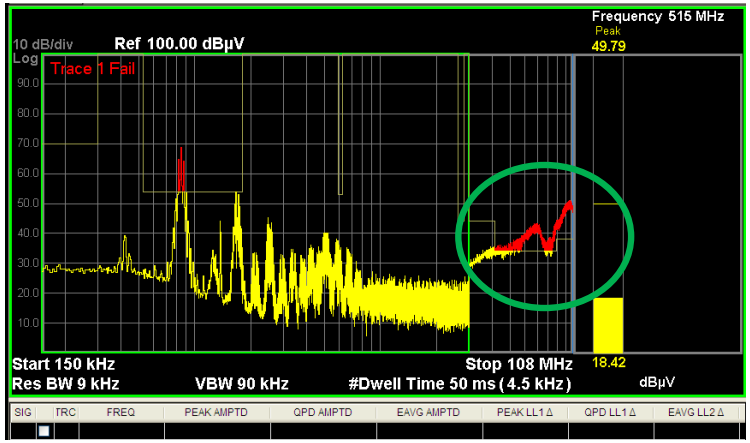
Example: driving multiple transformers



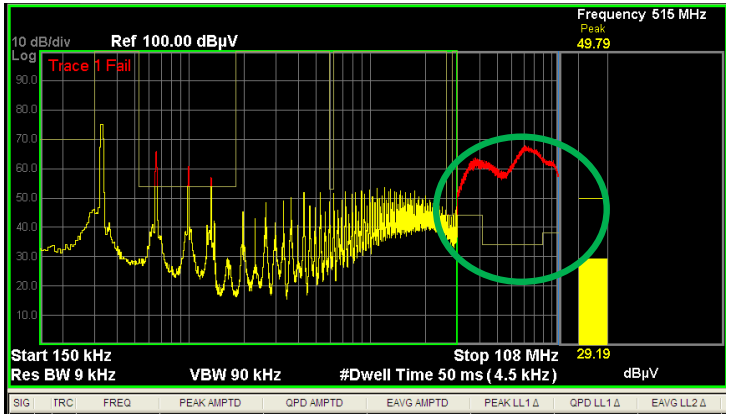


Single primary side power stage drives three transformers and secondary side circuits
Three matched output voltages are created

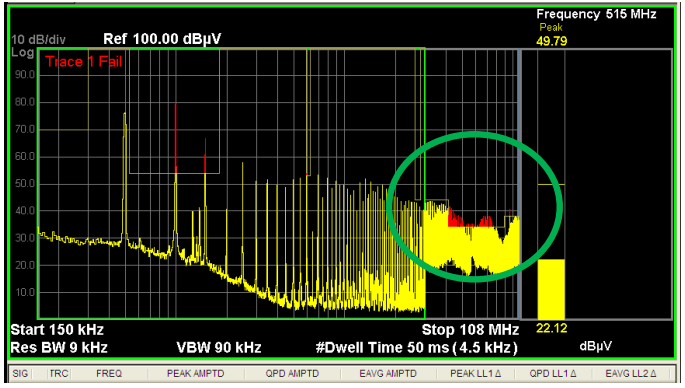
EMI noise performance comparison



5-V push-pull



24-V Flyback



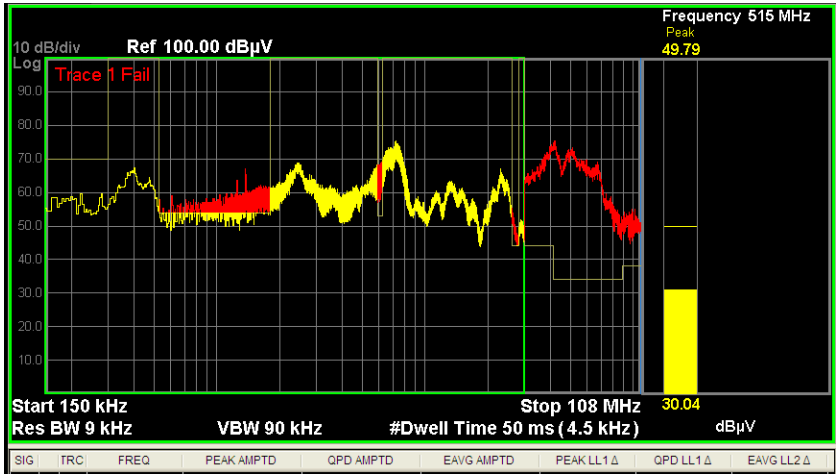
24-V LLC

LLC has much lower high frequency EMI noise

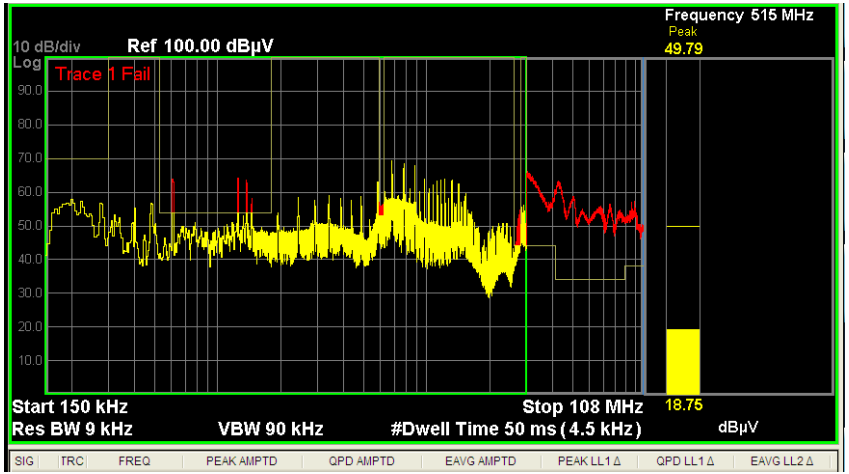
*No EMI filter added

EMI noise when connected with inverter

Flyback

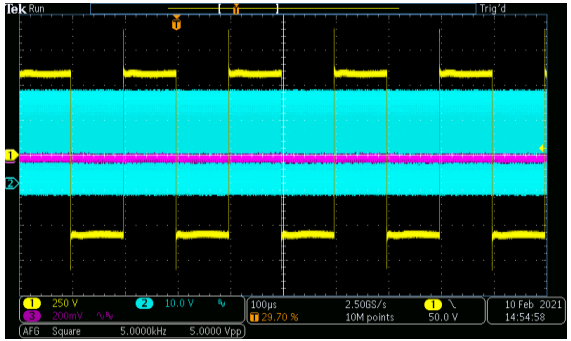


LLC

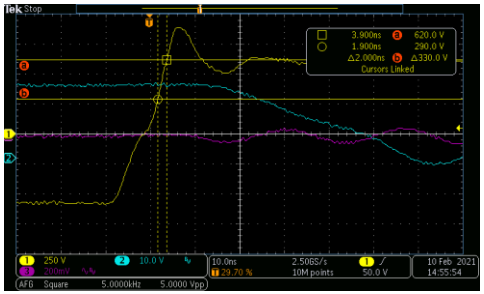


When connected with inverter and bias the isolated gate drivers, LLC solution provides a much lower EMI noise due to the less parasitic capacitance

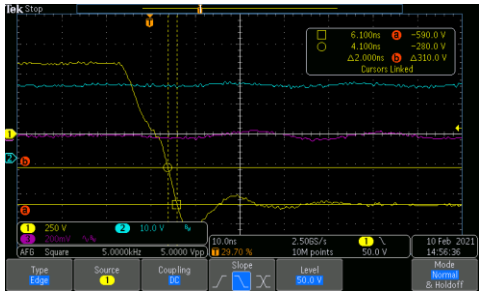
CMTI performance



165 V/ns

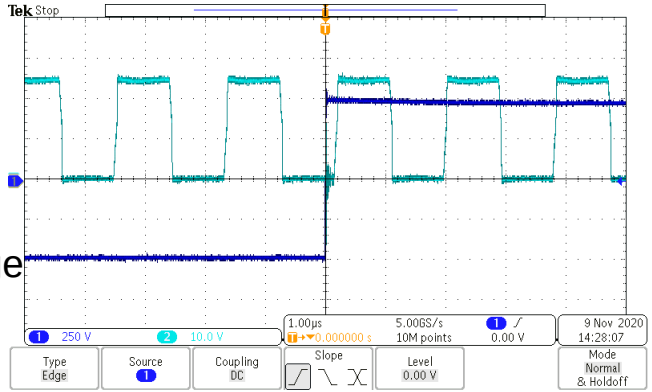


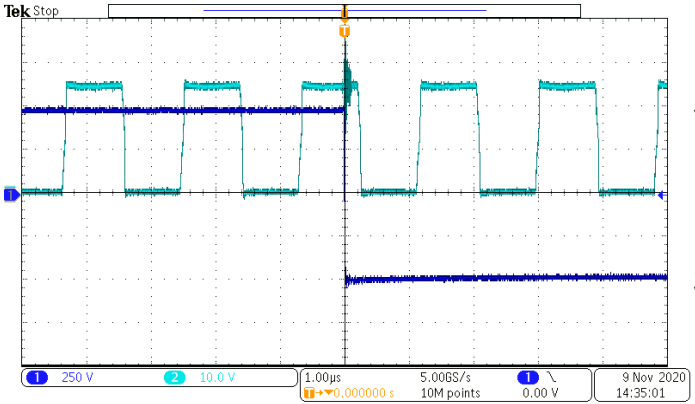
155 V/ns



Switch node

Strike voltage





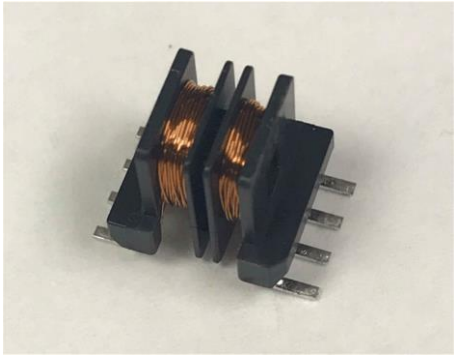
Switch node

Strike voltage

Operation is not affected by >150 V/ns CMTI

Transformer design considerations

- Transformer design is simple
  - Two windings
  - Turns ratio is roughly the voltage ratio between the input and output voltage (plus the diode drop)
  - Square voltage on primary side, setting up the volt-second rating
  - Lowest Rac possible
  - No airgap
- Once the transformer is made, measure the leakage inductance from secondary side
  - Short the primary side while measuring
- Match the leakage inductance with resonant capacitor



Part number (Wurth)	Turn ratio	Leakage inductance	Input / Output
750319331	1:1	1.4 uH	24 V/24 V
750319177	1.67:1	1.48 uH	15 V/24 V
750319177	1:1.67	0.53 uH	24 V/15 V

Summary

- Isolated bias supply is needed for biasing the isolated gate drivers in the inverters
  - Open loop control provides a robust solution, less noise sensitive
- LLC topology is able to utilize the transformer leakage inductance and minimize the transformer primary side 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

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