High VOLT Interactive

Where power supply design meets collaboration

Isolated Bias Power Supply Architecture and Topology Trade-offs for HEV/EVs

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Acknowledgement: Peter Meaney, Billy Long, Xun Gong, Benjamin Lough

Texas Instruments

High VOLT Interactive

What will I get out of this session?

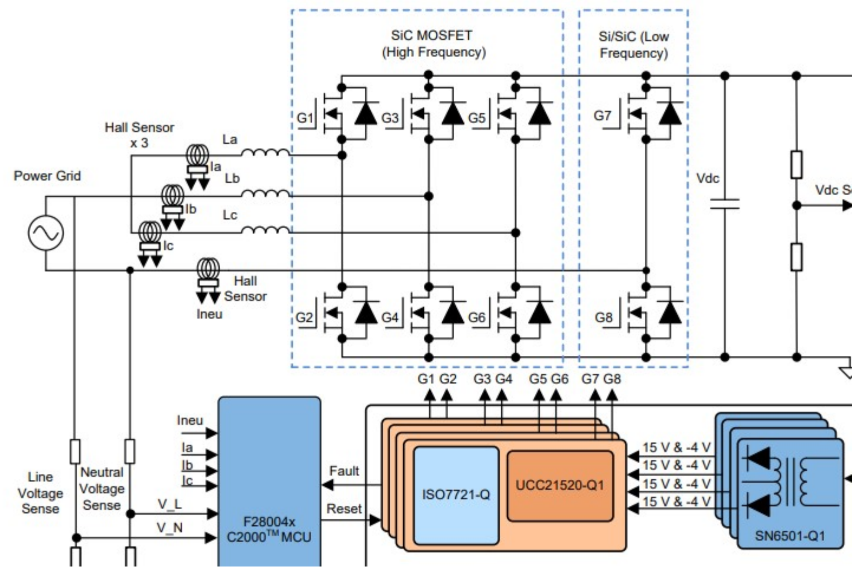
Purpose:

- ❑ **Review the isolated bias power supply architectures and topologies and discuss their trade-offs**

1. Isolated Bias Power Overview
2. Power Architecture
3. Topology Review
4. TI Solution Comparison

- Part numbers mentioned:
  - UCC21530-Q1
  - UCC2808A-1Q1
  - TPS40210-Q1
  - LM5180-Q1
  - SN6505B-Q1
  - LM5160-Q1
- Relevant applications:
  - On-board charger
  - DC/DC converter
  - Traction inverter

Isolated Bias Supply and Isolated Gate Driver Applications

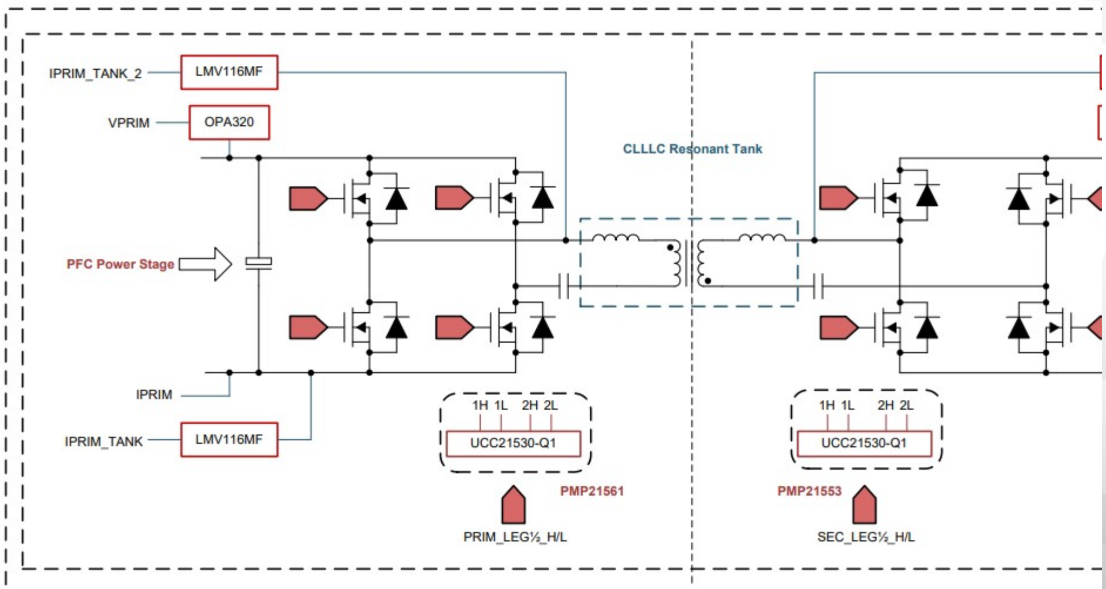


TIDA-01604 **98.6% Efficiency, 6.6-kW Totem-Pole PFC for OBC**

Isolated gate drivers and their bias supplies are required to drive high-side and low-side SiC FETs or IGBTs in the:

- On-board charger
  - **PFC stage**
  - Isolated DC/DC stage
- DC/DC Converter
- Traction inverter

Isolated Bias Supply and Isolated Gate Driver Applications

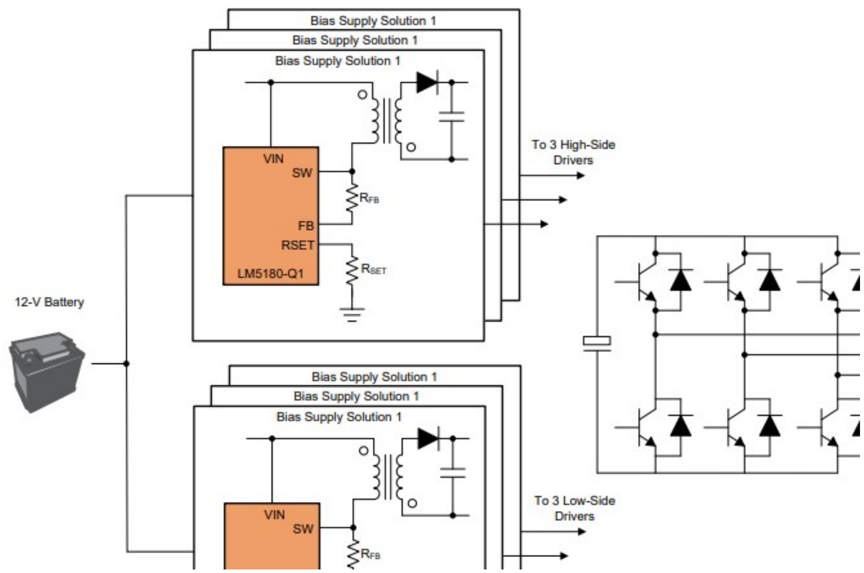


TIDM-02002 Bidirectional CLLLC Resonant Dual Active Bridge for OBC

Isolated gate drivers and their bias supplies are required to drive high-side and low-side SiC FETs or IGBTs in the:

- On-board charger
  - PFC stage
  - **Isolated DC/DC stage**
- DC/DC Converter
- Traction inverter

Isolated Bias Supply and Isolated Gate Driver Applications

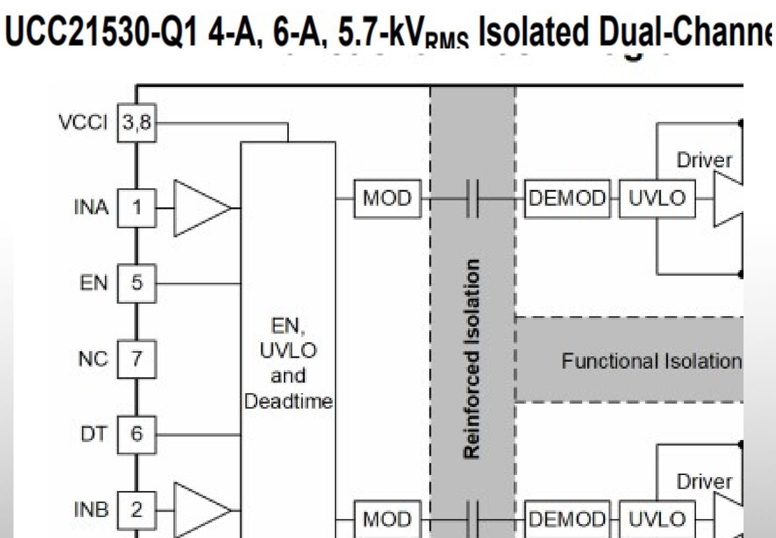


TIDA-020014 Traction Inverter Power Stage with 3 options for IGBT/SiC Bias Supply Solution

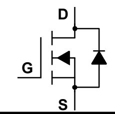
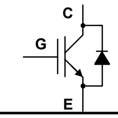
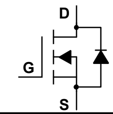
Isolated gate drivers and their bias supplies are required to drive high-side and low-side SiC FETs or IGBTs in the:

- On-board charger
  - PFC stage
  - Isolated DC/DC stage
- DC/DC Converter
- **Traction inverter**

Isolated Gate Driver and Power Device Overview



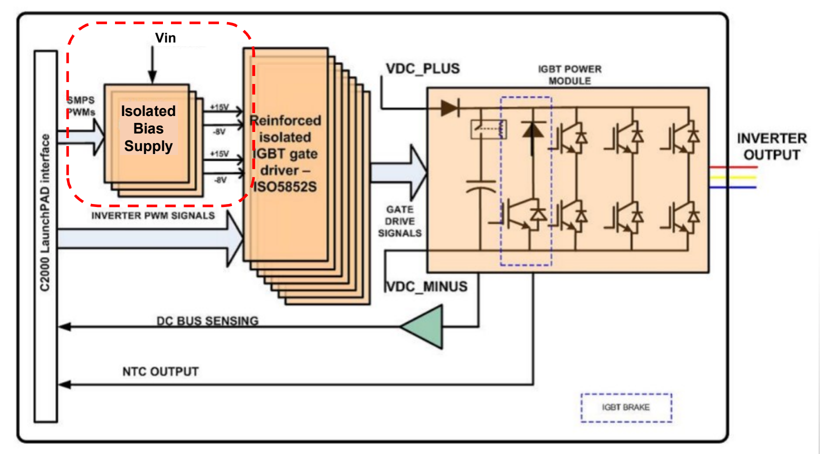
V_{GS}/V_{GE} = VDDA-VSSA, VDDB-VSSB

	Si MOSFETs	Si IGBTs	SiC MOSFETs
Circuit symbol			
Voltage rating	20 V-650 V	≥650 V	≥650 V
f_{sw}	Medium-high (>20 kHz)	Low-medium (5 kHz-20 kHz)	High (>50 kHz)
VDD	15 V	15 V	20 V
VSS	0 V	-10 V	-5 V
Optimal V_{GS}/V_{GE}	15V	25V	25 V
Typical applications	On-board charger, DC/DC Converter	HEV/EV traction inverters	On-board charger, DC/DC Converter, HEV/EV traction inverter
Power level	<3 kW	>3 kW	>5 kW

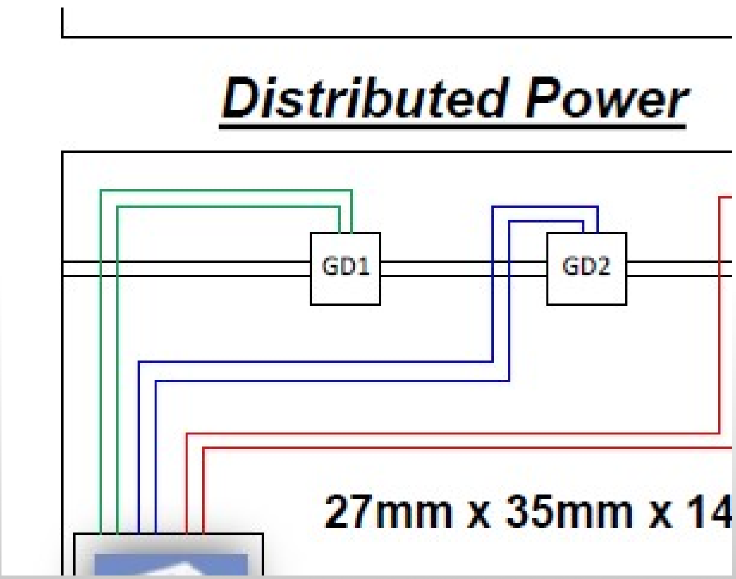
Power device ratings and applications

Isolated Bias Supply Requirements

- Tight output voltage regulation (+/- 5% for IGBT)
- Relatively high efficiency (Greater than 80%)
- Robust EMI/EMC performance
- Small solution size
- Protection features (OVP, OCP, short circuit protection, OTP)

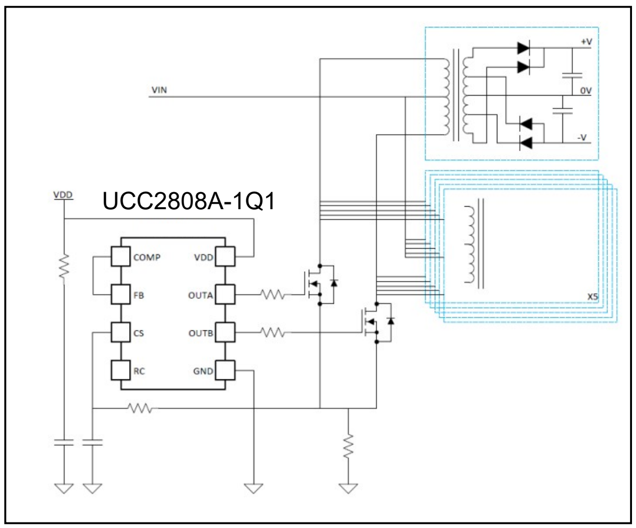


Centralized Power Architecture



- **One transformer is used to generate the bias voltages for all IGBT or SiC gate drivers**
- Advantages
  - ✓ Low component count
  - ✓ Low cost
  - ✓ Generic controllers and external FETs allows second sourcing
- Disadvantages
  - – Bulky transformer, harder to pass shock test.
  - – Common mode current can disturb functionality of low voltage circuits
  - – Complex PCB routing
  - – Lack of Redundancy

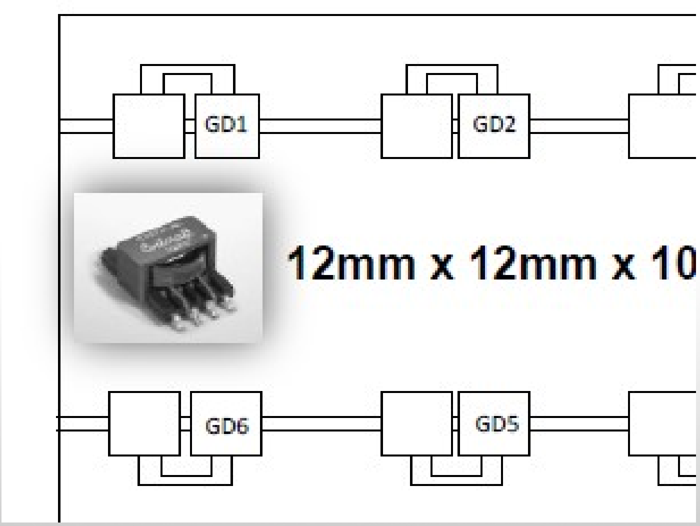
Semi-distributed Power Architecture



Semi-Distributed Power

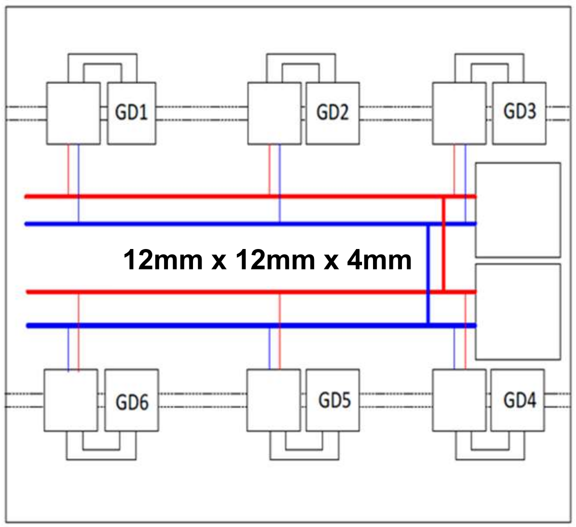
- **Multiple transformers are used to generate the bias voltages for IGBT or SiC gate drivers, but there is not an individual power stage for each gate driver**
- Advantages
  - ✓ Simpler transformer construction and PCB Layout
  - ✓ Better bias power quality
  - ✓ Distribution of weight for ease of passing shock
  - ✓ Generic controllers and external FETs allows second sourcing
- Disadvantages
  - – Higher component count than centralized
  - – Relatively high cost
  - – Lack of Redundancy

Distributed Power Architecture



- **Individual gate driver bias supply for each IGBT or SiC gate driver**
- Advantages
  - ✓ **Robustness against power supply failure**
  - ✓ Simpler transformer construction and PCB Layout
  - ✓ Better bias power quality
  - ✓ Distribution of weight for ease of passing shock
- Disadvantages
  - Higher component count
  - High cost

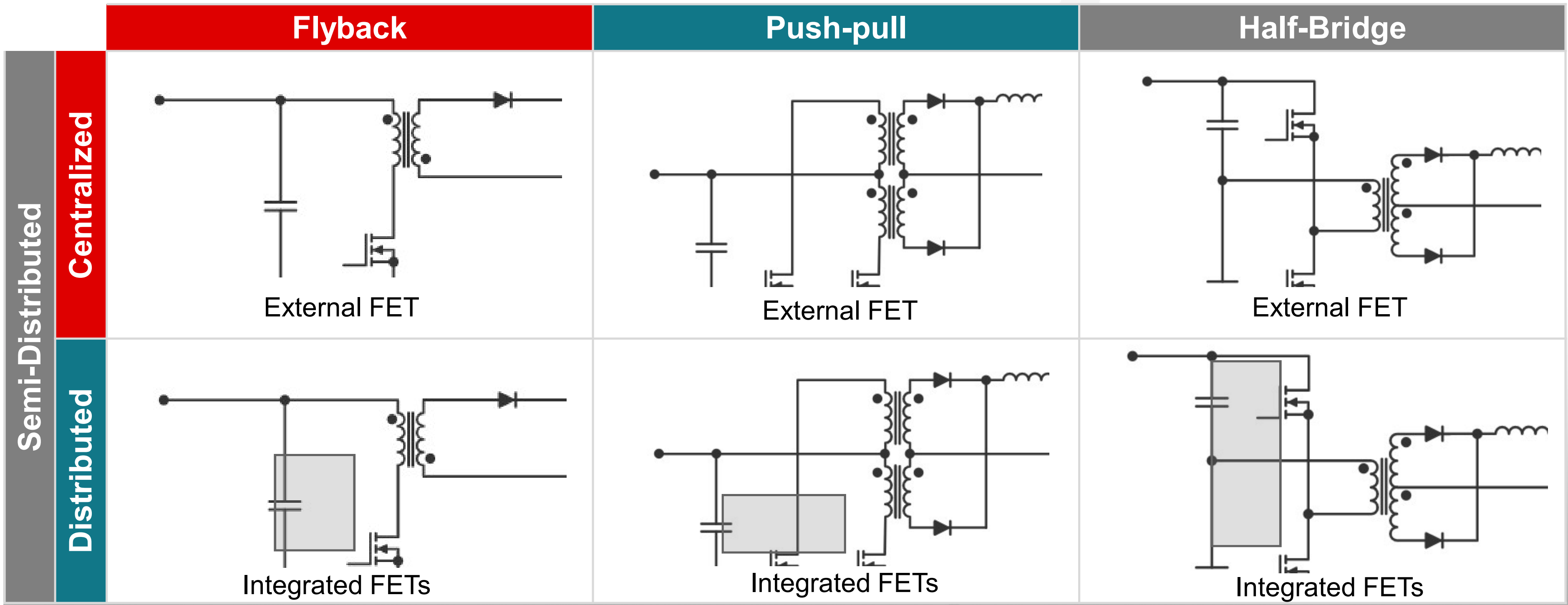
Two-Stage Distributed Power Architecture



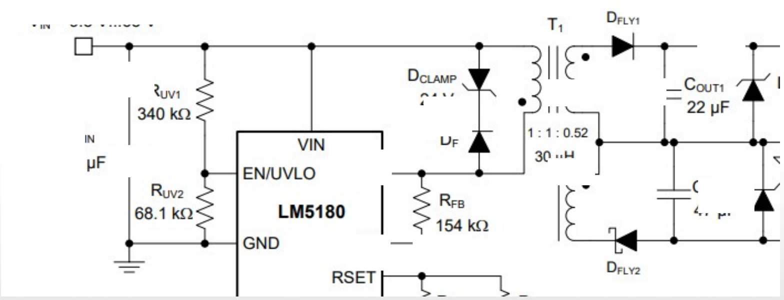
Two-stage Power Architecture

- **Individual gate driver bias supply for each IGBT or SiC gate driver with 2 pre-regulated rails for redundancy**
- Advantages
  - ✓ **Increased robustness against power supply failure**
  - ✓ Simpler transformer construction and PCB layout
  - ✓ Better bias power quality
  - ✓ Distribution of weight for ease of passing shock
- Disadvantages
  - – Highest component count
  - – High cost

Topology Overview

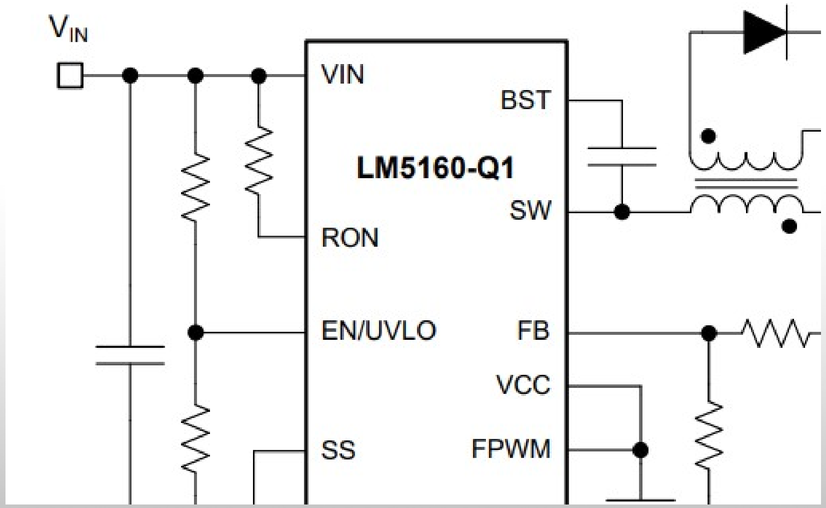


Flyback Topology



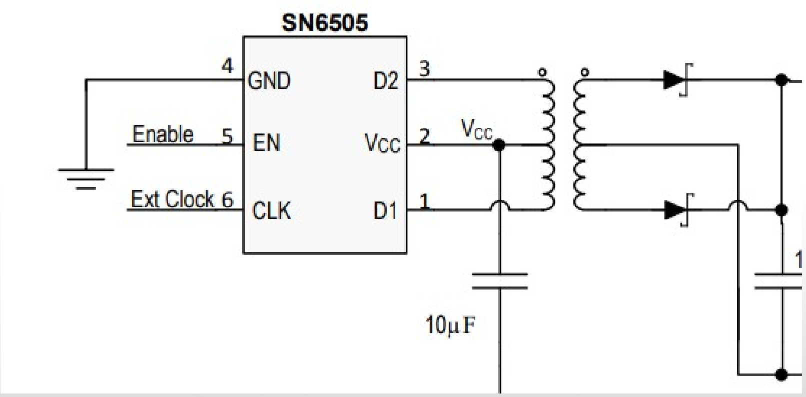
- Advantages
  - ✓ Operation directly off 12V battery for single stage solution
  - ✓ Regulated output (PSR)
  - ✓ Low component count
- Disadvantages
  - – Switching frequency limitation
  - – Prone to EMI issues due to switch node ringing and primary-secondary capacitance
  - – Requires a snubber to avoid overstress on power MOSFET

Fly-Buck Topology



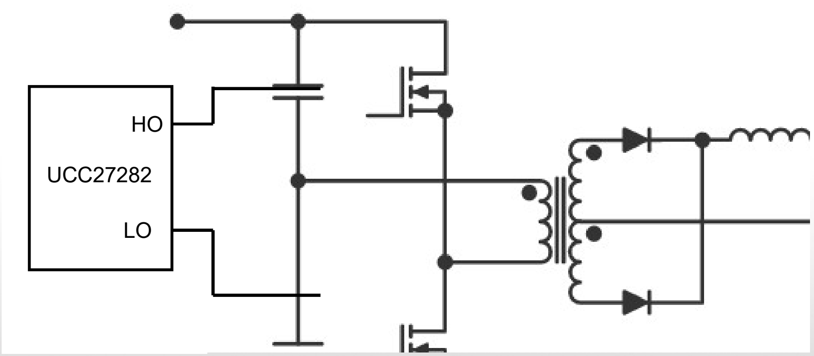
- Advantages
  - ✓ Operation directly off 12V battery for single stage solution
  - ✓ Regulated output without optocoupler
  - ✓ Low component count
- Disadvantages
  - – High leakage inductance can degrade load regulation
  - – Duty cycle limitation
  - – Magnetic design complexity

Push-pull Topology



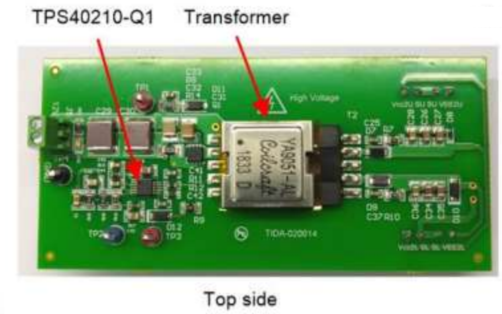
- Advantages
  - ✓ Design simplicity due to open loop configuration
  - ✓ More efficiently utilizes the transformer core's magnetizing current enables **smaller transformer** than flyback
  - ✓ Suitable for high frequency operation
  - ✓ Lower primary – secondary capacitance for **reduction in common mode noise** compared to flyback
- Disadvantages
  - – Two primary windings
  - – FETs see twice the input voltage
  - – Requires a pre-regulated rail
  - – Output regulation can be challenging

Half-bridge Topology

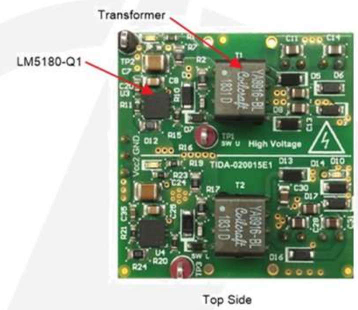


- Advantages
  - ✓ Design simplicity due to open loop configuration
  - ✓ More efficiently utilizes the transformer core's magnetizing current enables **smaller transformer** than flyback
  - ✓ Suitable for high frequency operation
  - ✓ Lower primary – secondary capacitance for **reduction in common mode noise** compared to flyback
- Disadvantages
  - Requires floating high side gate drive
  - Requires capacitor bridge
  - Requires a pre-regulated rail
  - Output regulation can be challenging

TI Solution Comparison – TIDA-020014 and PMP10654

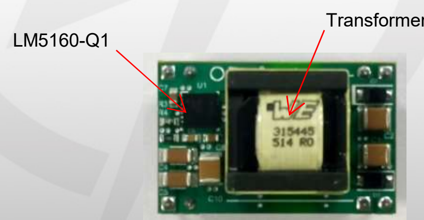


TPS40210-Q1 Flyback Controller



LM5180-Q1 Flyback Converter

Buck + SN6505B-Q1 Push-Pull

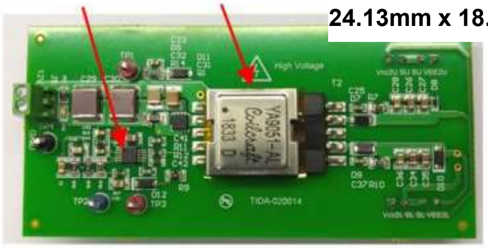


LM5160-Q1 Fly-Buck Converter

TPS40210-Q1 flyback controller solution

TPS40210-Q1 Transformer

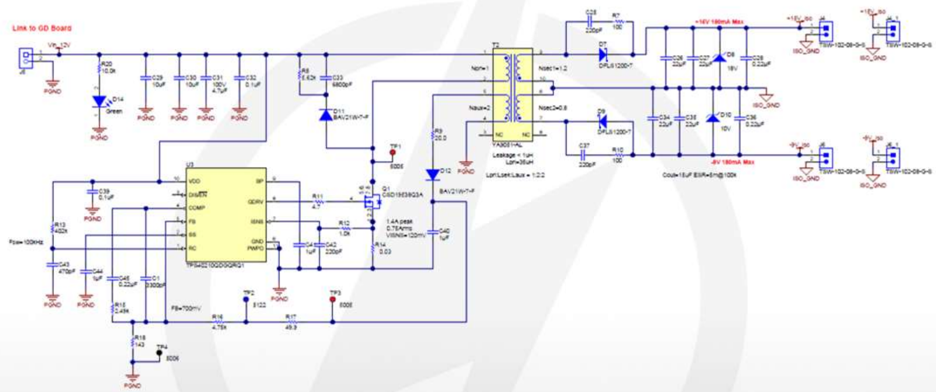
Transformer size: 24.13mm x 18.3mm x 10.1mm



Top side

Connectors to power stage

Bottom side



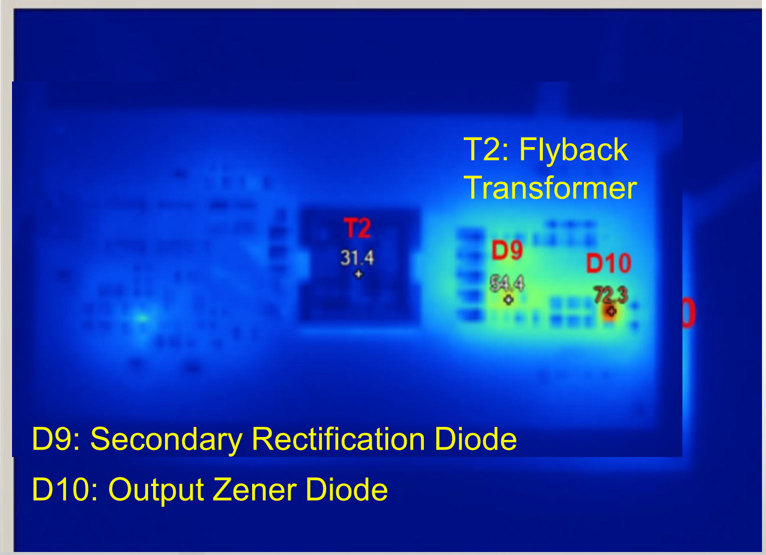
PARAMETER	SPECIFICATION
Input voltage (V_{IN})	5 V–42 V DC (52-V transient)
Output voltage (V_{OUT})	+15 V, –9 V
Output ripple	±3%
Maximum output current (I_{out_max})	180 mA
Switching frequency	100 kHz
Output power (P_{out_max})	4.32 W
Efficiency	> 81% peak, 80% at full load

TPS40210-Q1 Efficiency and Thermal performance

Measured Efficiency Under Input Voltages of 5V, 12V, and 18V

81.3% peak efficiency at 12Vin

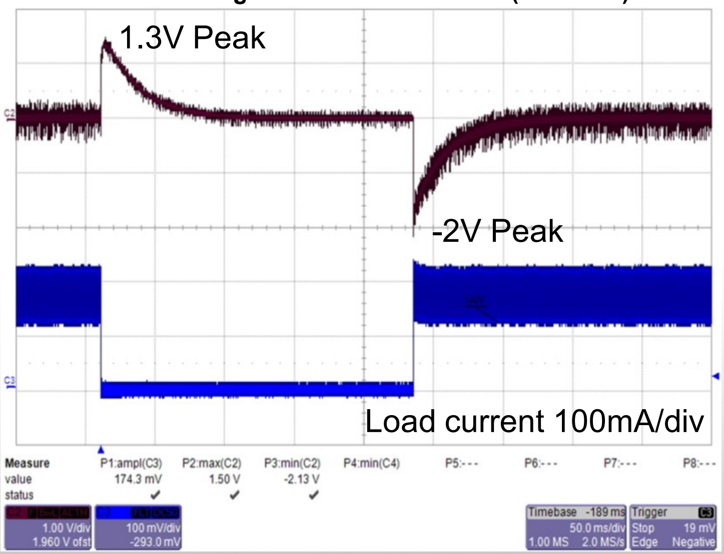
Thermal Image with Vin = 12V and Iout = 180mA



Secondary rectification diode: 54.4°C
Output zener diode: 72.3°C

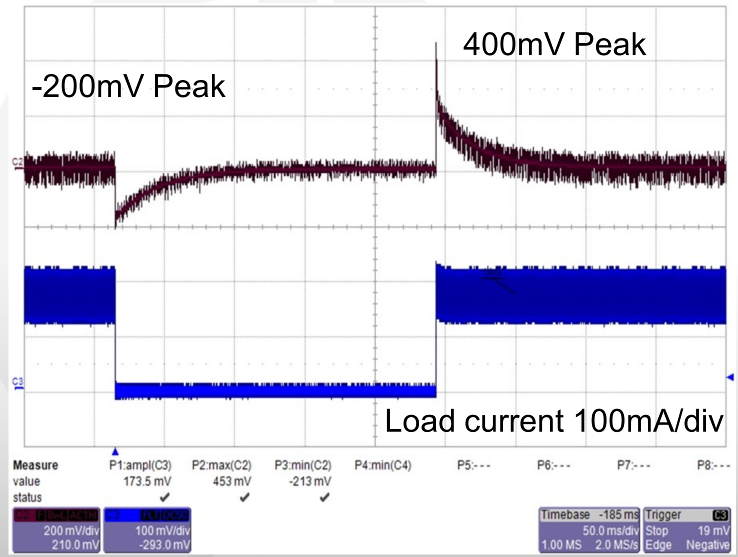
TPS40210-Q1 Load Transient Response

Load transient response of the +15V rail under Vin = 12V and Iout switching between 0 and 180mA (50ms/div)



1.3 V peak overshoot
2V peak undershoot

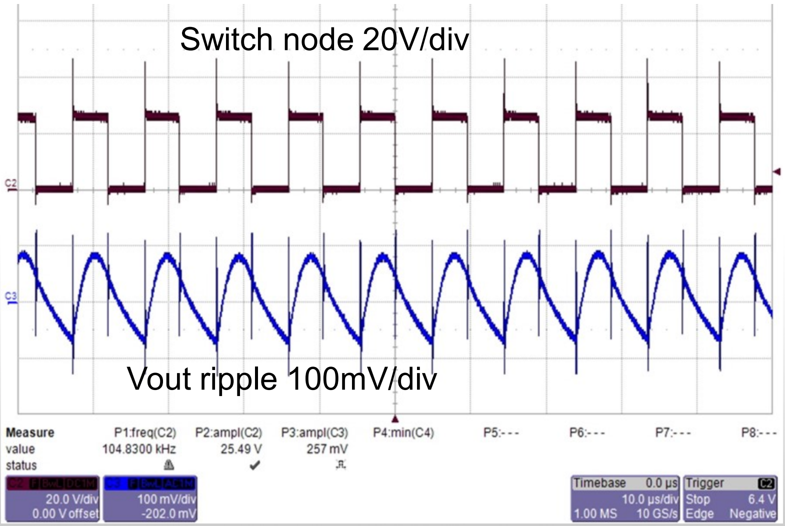
Load transient response of the -9V rail under Vin = 12V and Iout switching between 0 and 180mA (50ms/div)



200 mV undershoot
400 mV peak overshoot

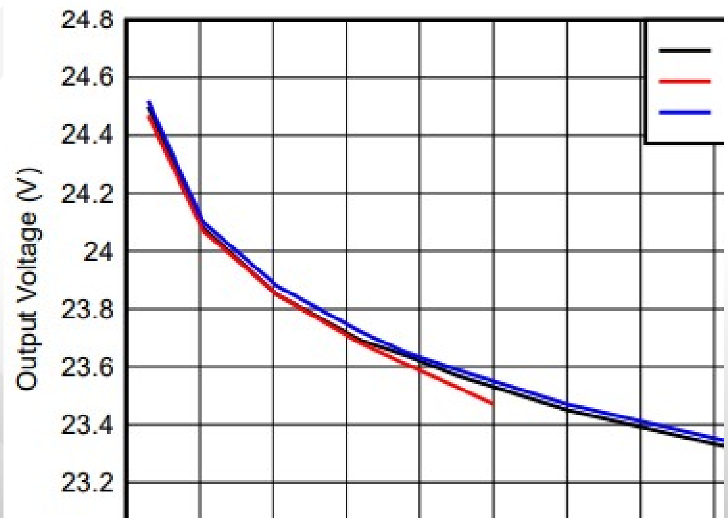
TPS40210-Q1 Output Voltage Ripple and Load Regulation

Switching node waveform and output voltage ripple of +15V rail with 12Vin and 180mA Iout (10µs/div)



180 mV peak to peak output voltage ripple

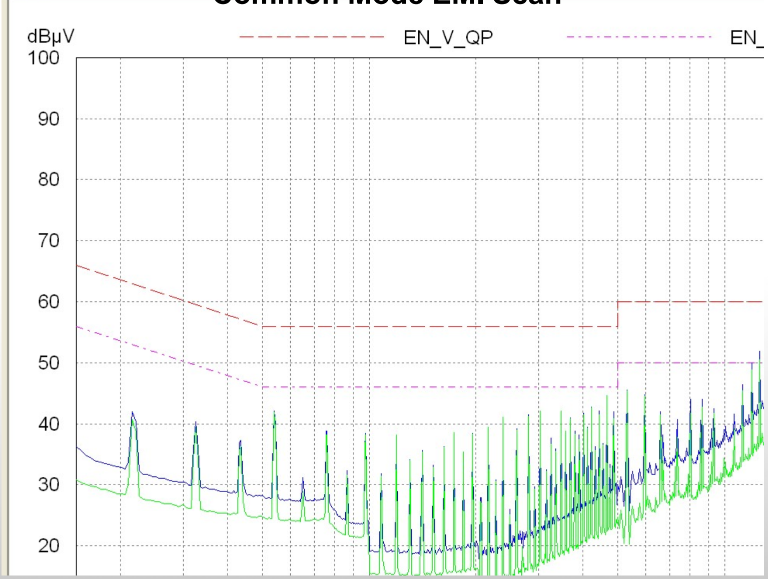
Load Regulation Under Input Voltages of 5V, 12V, and 18V



5.1% decrease in load regulation between 0 and 180mA load

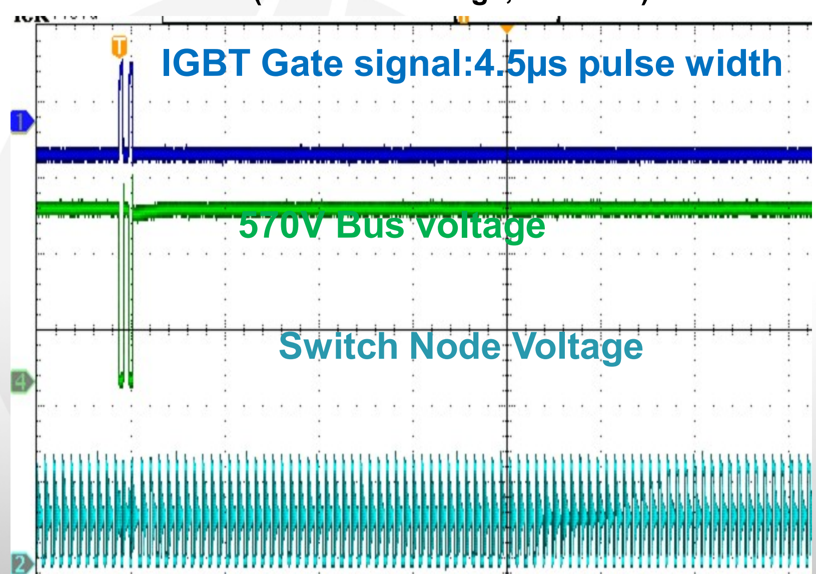
TPS40210-Q1 Common Mode EMI and CMTI

Common Mode EMI Scan



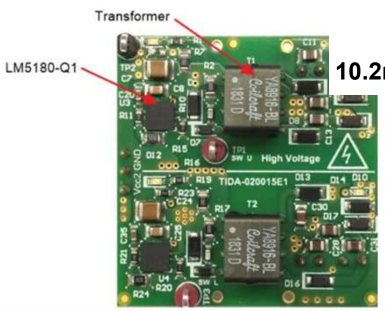
75 dBuV peak observed at around 22 MHz

CMTI (570V Bus voltage, 9.16V/ns)



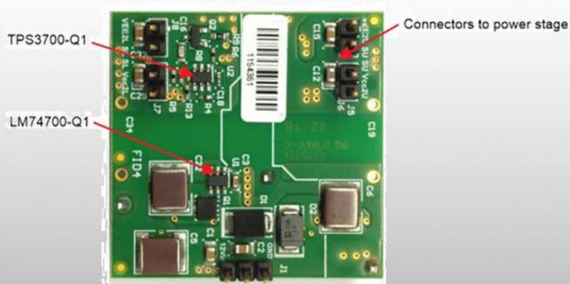
Supply operates smoothly without interruption to double pulse test

LM5180-Q1 flyback converter solution overview

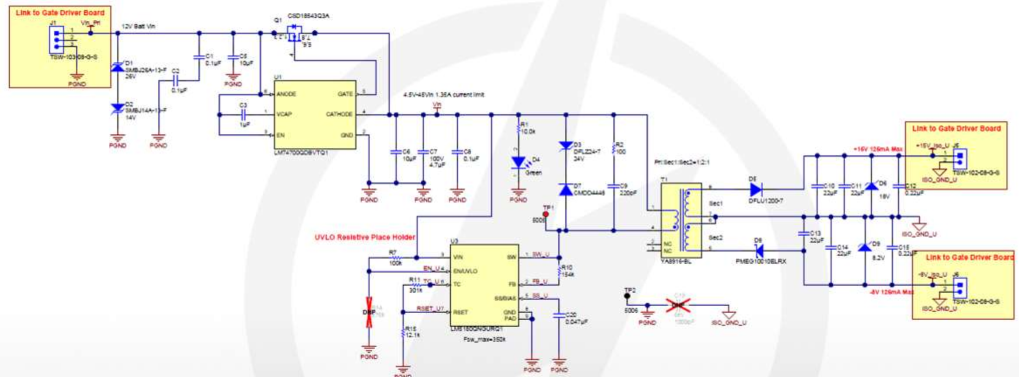


Top Side

Transformer size:
10.2mm x 9.3mm x 10.6mm



Bottom Side



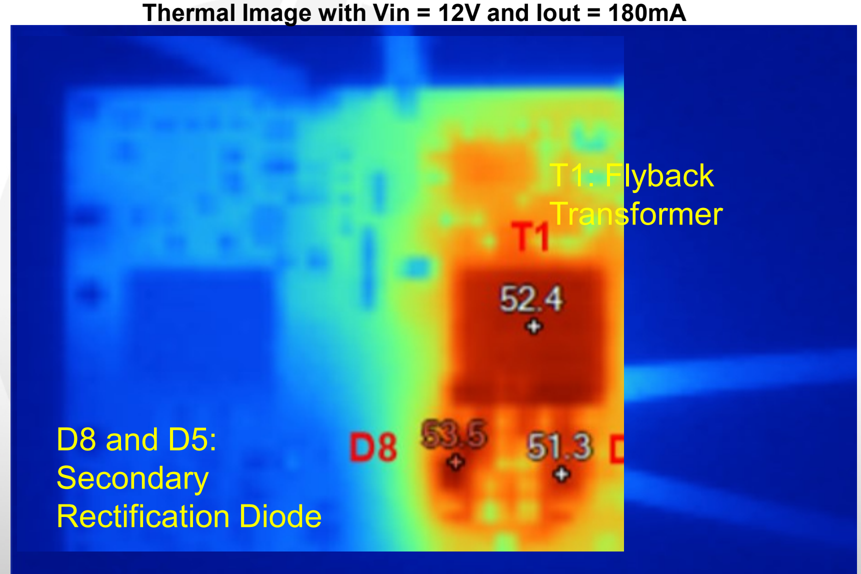
PARAMETER	SPECIFICATION
Input voltage (V_{in})	4.5 V–65 V DC (For flyback converter only, TVS limits the system input to 26 V DC)
Output voltage (V_{OUT})	15 V, -8 V
Output ripple	±3%
Maximum output current (I_{out_max})	180 mA
Switching frequency	< 350 kHz
Output power (P_{out_max})	4.14 W
Efficiency	86.2% peak at 12Vin

LM5180-Q1 Efficiency and Thermal Performance

Measured Efficiency Under Input Voltages of 5V, 12V, and 18V

86.2% peak efficiency at 12Vin

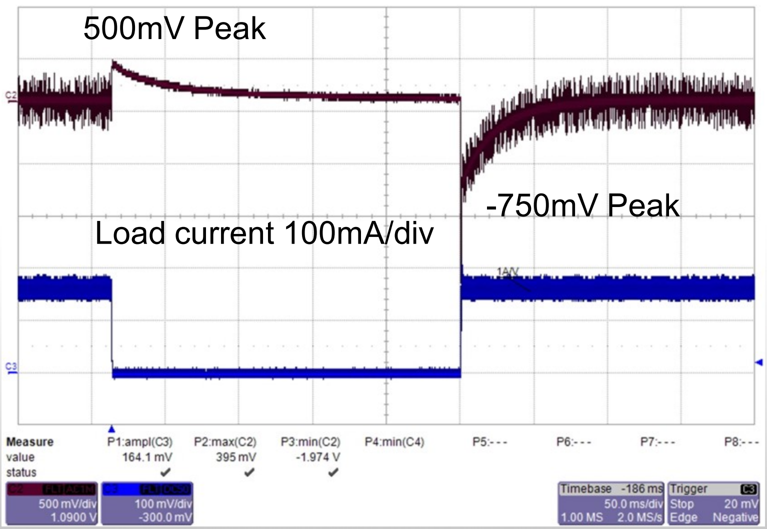
Thermal Image with Vin = 12V and Iout = 180mA



Flyback transformer: 52.4°C
Rectification Diodes: 53.5°C/51.3°C

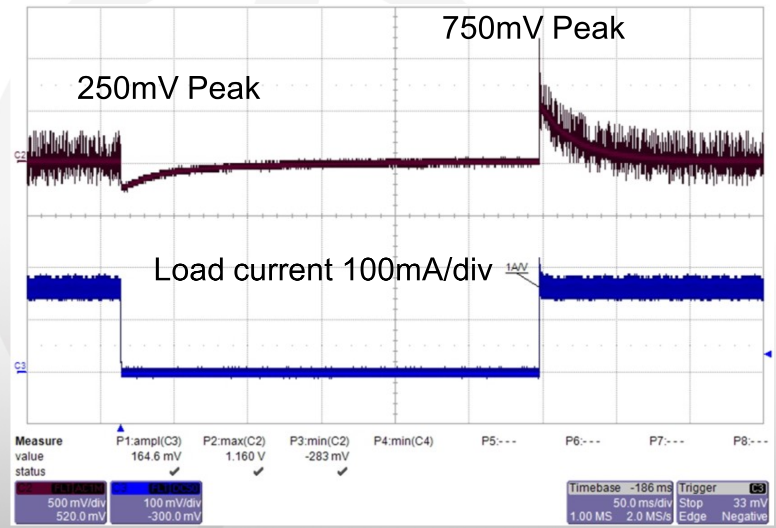
LM5180-Q1 Load Transient Response

Load transient response of the +15V rail under Vin = 12V and Iout switching between 0 and 180mA (50ms/div)



500 mV peak overshoot
750mV peak undershoot

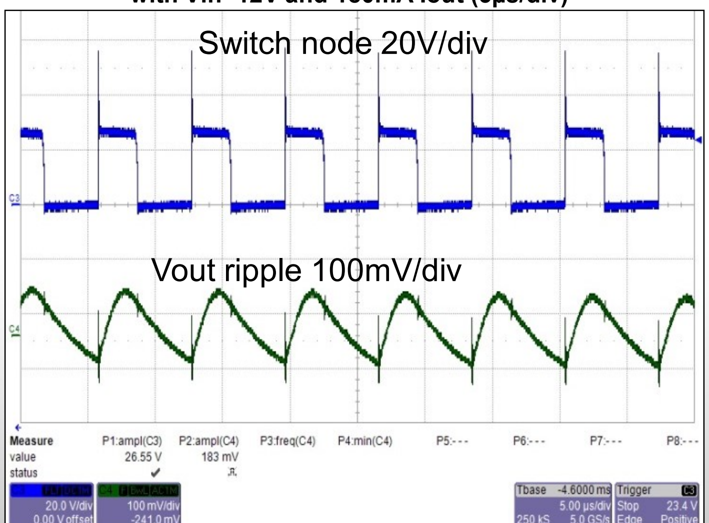
Load transient response of the -8V rail under Vin = 12V and Iout switching between 0 and 180mA (50ms/div)



250 mV peak undershoot
750mV peak overshoot

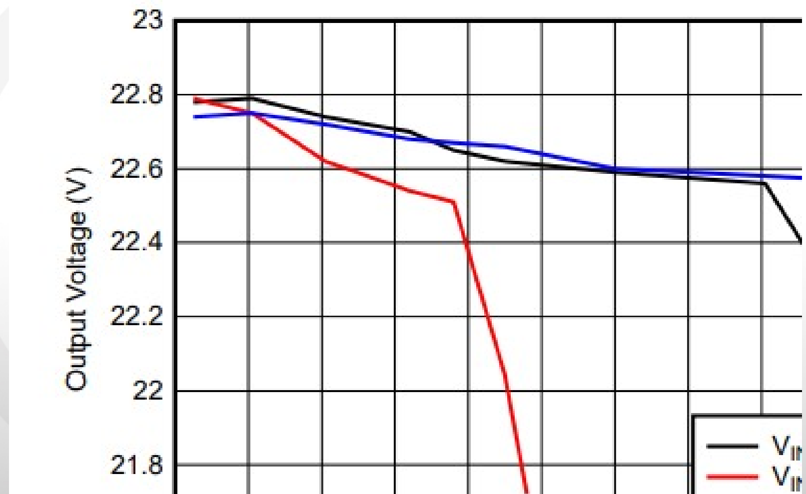
LM5180-Q1 Output Voltage Ripple and Load Regulation

Switching node waveform and output voltage ripple of +15V rail with Vin=12V and 180mA Iout (5µs/div)



150 mV peak to peak output voltage ripple

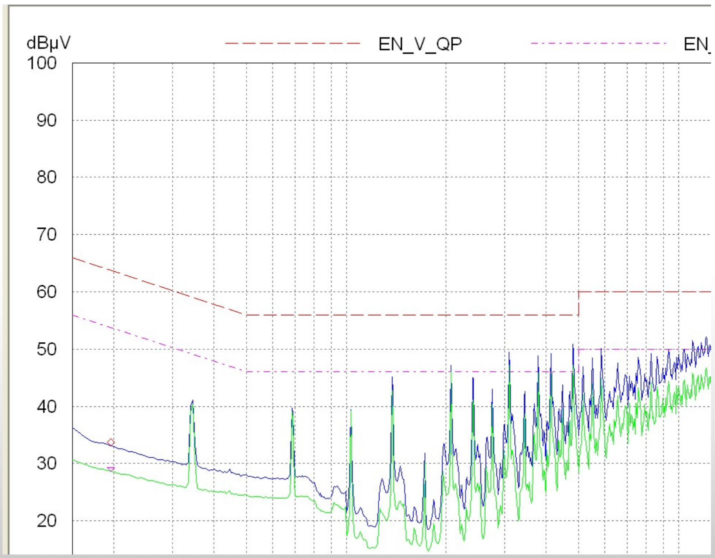
Load Regulation Under Input Voltages of 5V, 12V, and 18V



2.28% decrease in load regulation between 0 and 180mA load

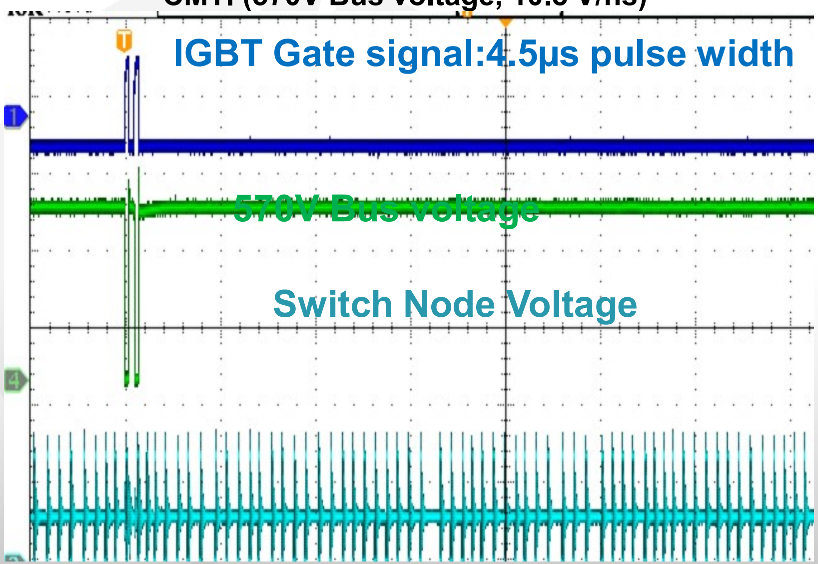
LM5180-Q1 Common Mode EMI Scan and CMTI

Common Mode EMI Scan



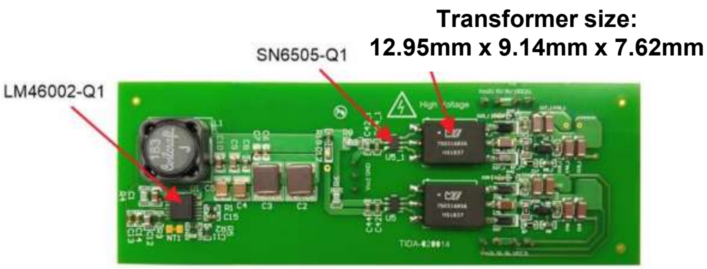
68 dBuV peak observed at 23 MHz

CMTI (570V Bus voltage, 10.8 V/ns)

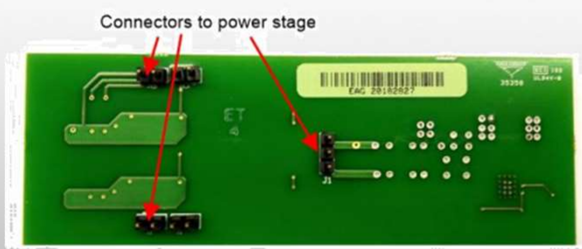


Supply operates smoothly without interruption to double pulse test

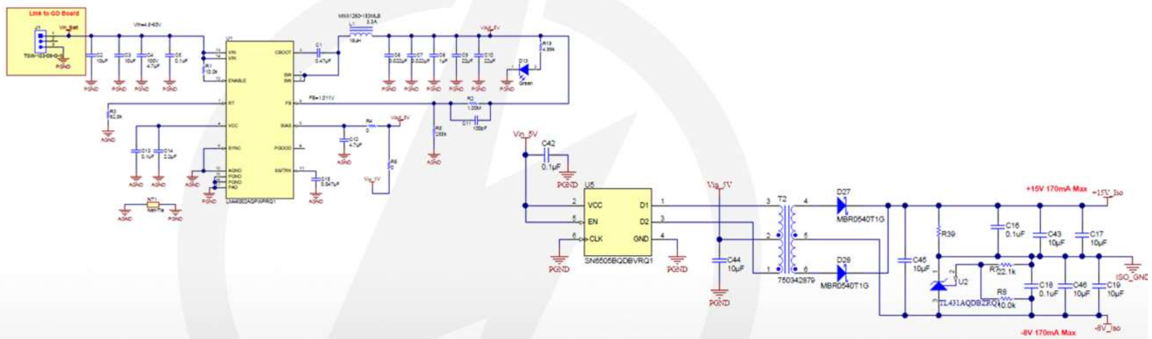
LM46002A-Q1 Buck + SN6505B-Q1 Push-pull Solution Overview



Top side



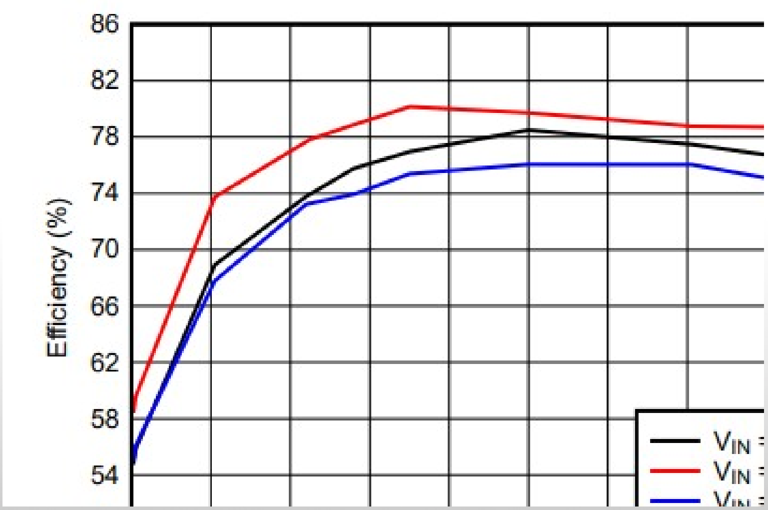
Bottom side



PARAMETER	SPECIFICATION
Input voltage (V_{in})	4.5V-60V (Buck stage) 5V +/- 5% (Push-pull stage)
Output voltage (V_{OUT})	+15 V, -8 V
Output ripple	+/- 3%
Maximum output current (I_{out_max})	180mA
Switching frequency	<450 kHz
Output power (P_{out_max})	4.14W
Efficiency	78.5% peak at 12Vin

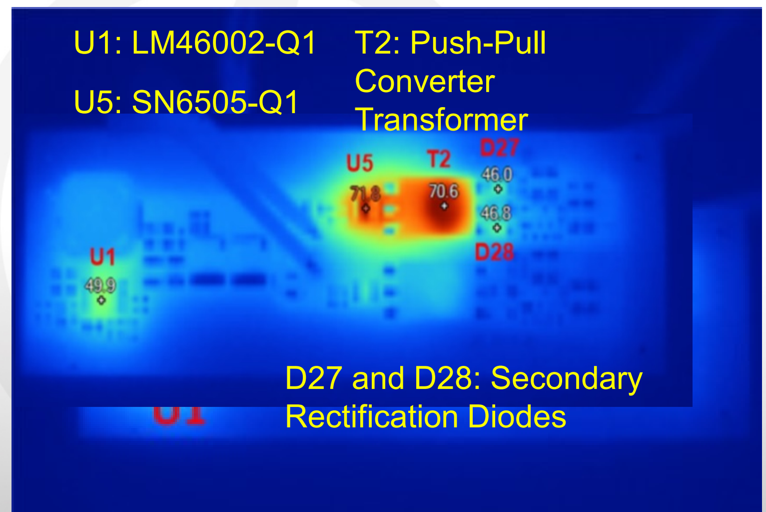
Buck + SN6505B-Q1 Efficiency and Thermal Performance

Measured Efficiency Under Input Voltages of 5V, 12V, and 18V



78.5% peak efficiency at 12Vin

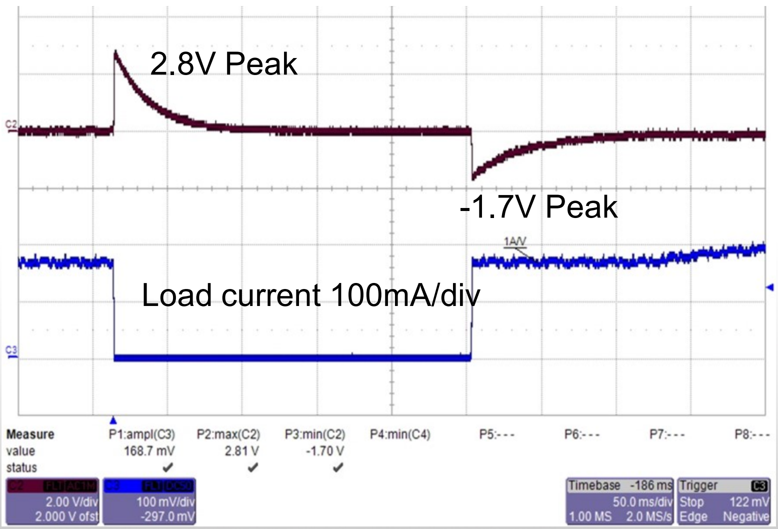
Thermal Image with Vin = 12V and Iout = 180mA



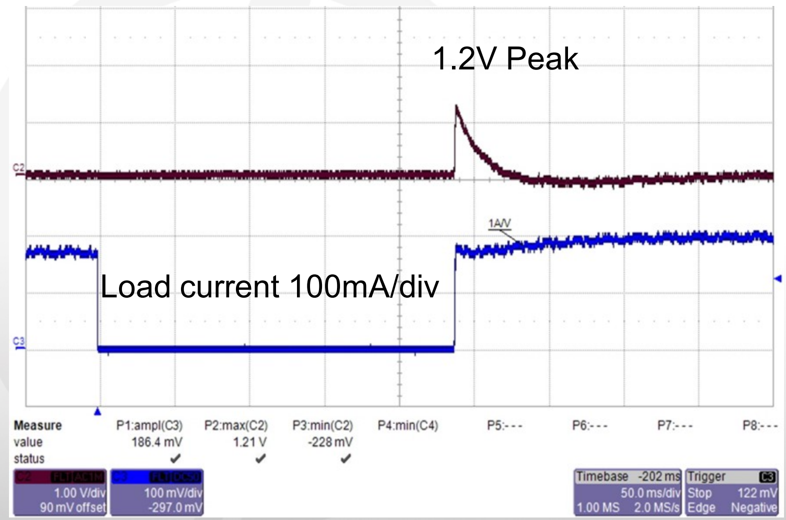
Push-pull transformer: 70.6°C
SN6505-Q1: 71.8°C

Buck + SN6505B-Q1 Load Transient Response

Load transient response of the +15V rail under Vin = 12V and Iout switching between 0 and 180mA (50ms/div)



Load transient response of the -8V rail under Vin = 12V and Iout switching between 0 and 180mA (50ms/div)

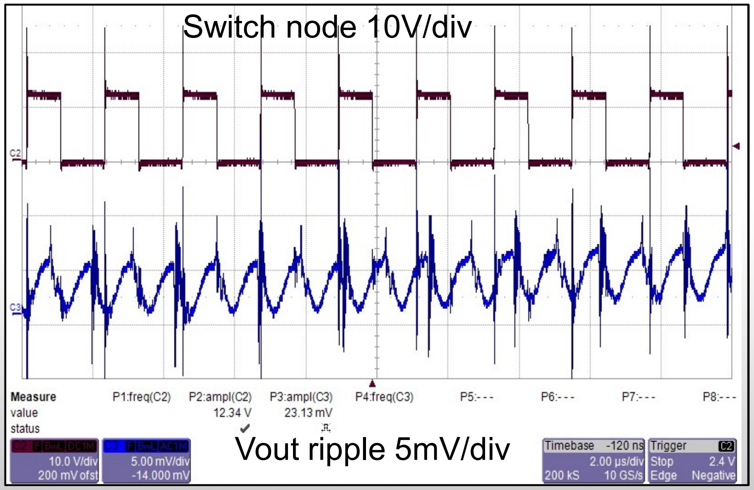


2.8V peak overshoot
1.7V peak undershoot

1.2 V peak overshoot

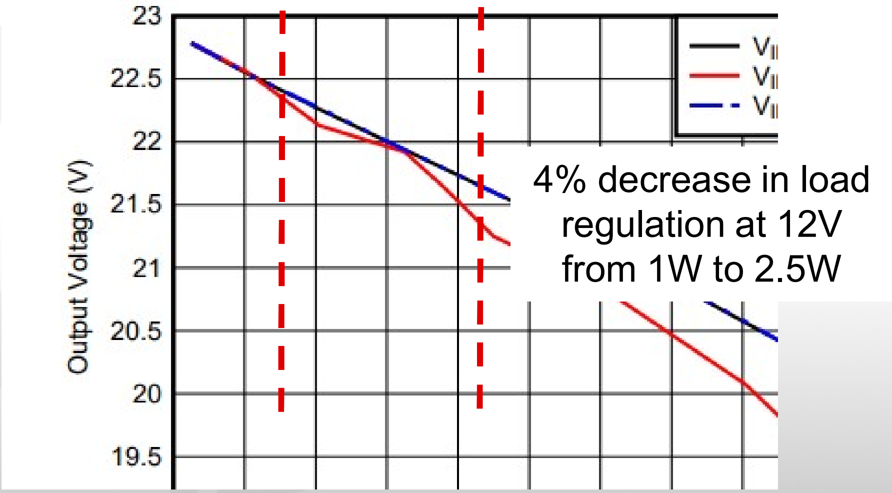
Buck + SN6505B-Q1 Output Voltage Ripple and Load Regulation

Switching node waveform and output voltage ripple of +15V rail with Vin=12V and 180mA Iout (2µs/div)



7 mV peak to peak output voltage ripple

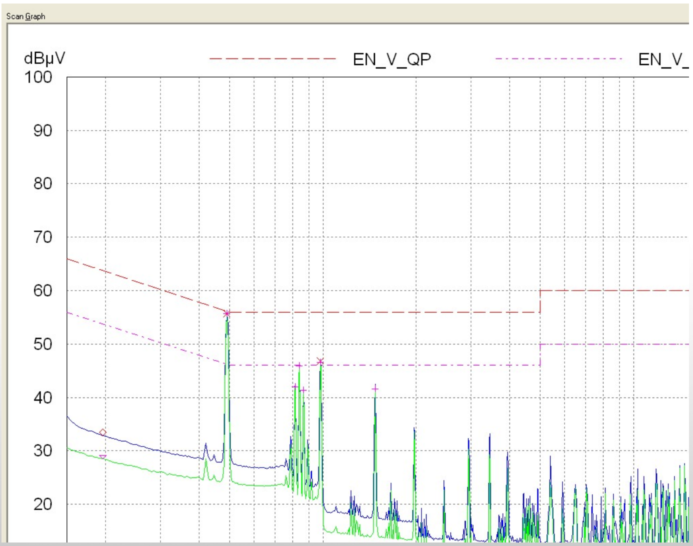
Load Regulation Under Input Voltages of 5V, 12V, and 18V



11.9% decrease in load regulation between 0 and 180mA load

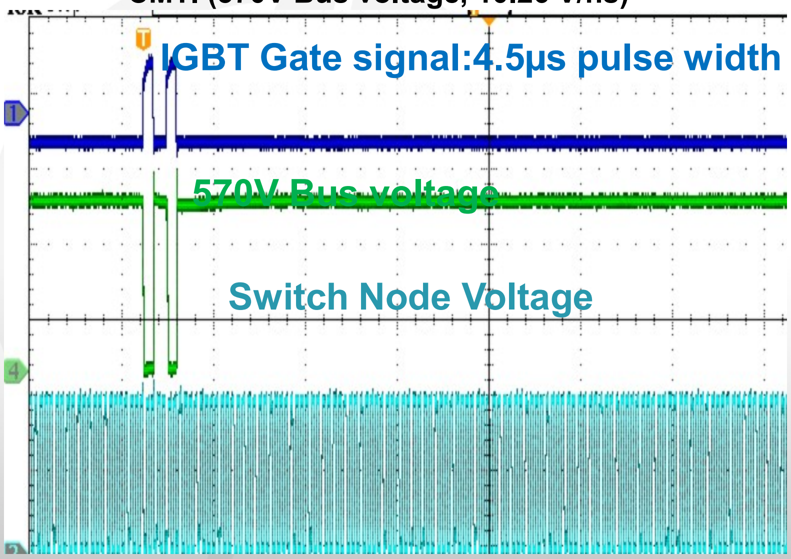
SN6505-Q1 Common Mode EMI Scan and CMTI

Common mode EMI scan



58 dBuV peak observed at 500 kHz

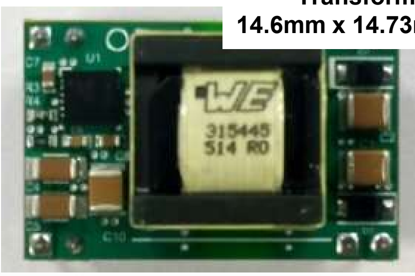
CMTI (570V Bus voltage, 10.26 V/ns)

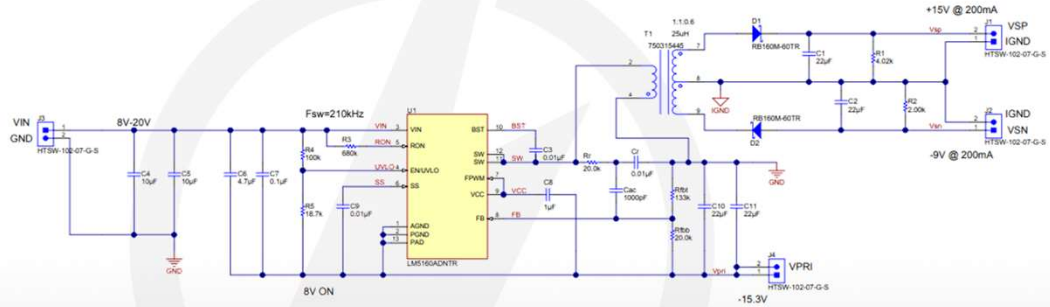


Supply operates smoothly without interruption to double pulse test

LM5160-Q1 Fly-buck converter solution

Transformer size:
14.6mm x 14.73mm x 8.5mm

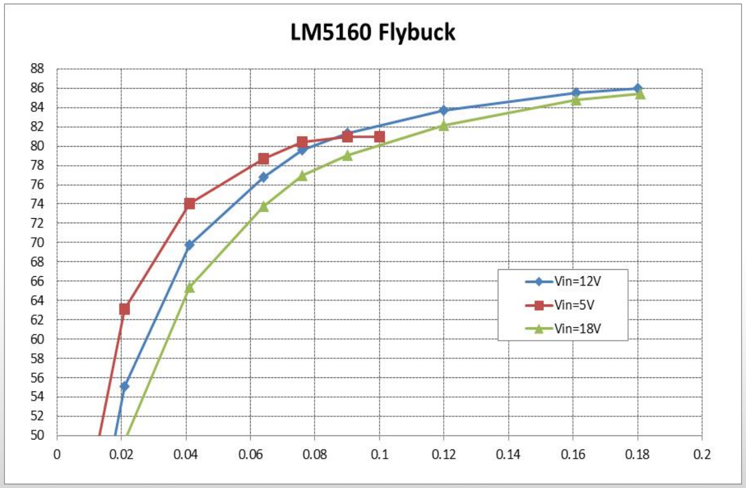




PARAMETER	SPECIFICATION
Input voltage (V_{in})	12V nominal, 8V – 20V
Output voltage (V_{OUT})	+15 V, -9 V
Output ripple	+/- 3%
Maximum output current (I_{out_max})	200mA
Switching frequency	210 kHz
Output power (P_{out_max})	4.8W
Efficiency	86% peak at 12Vin

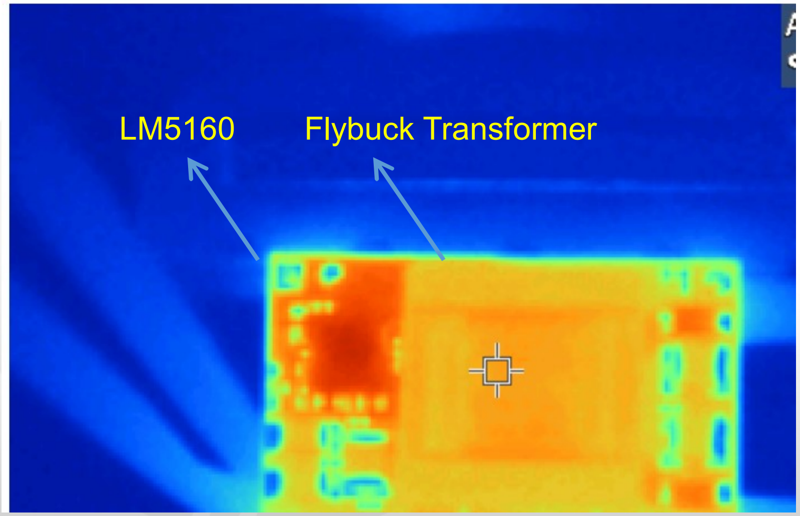
LM5160-Q1 Efficiency and Thermal

Measured Efficiency Under Input Voltages of 5V, 12V, and 18V



85.9% peak efficiency at 12Vin

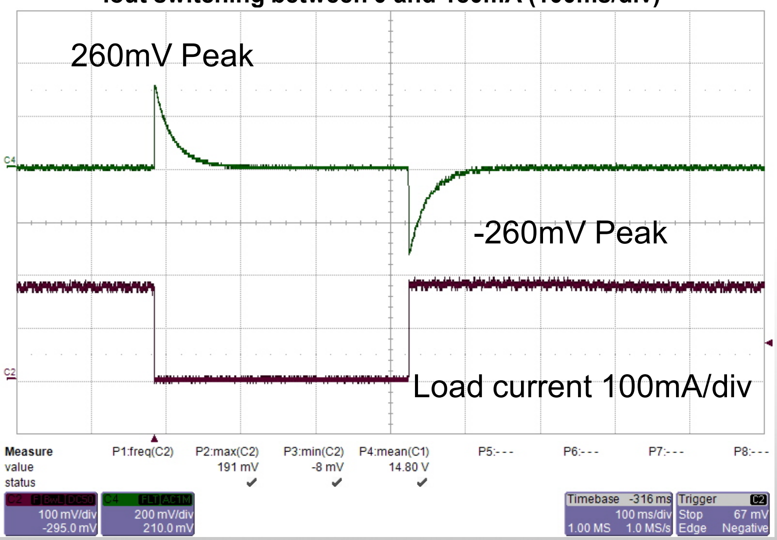
Thermal Image with Vin = 12V and Iout = 180mA



Flybuck transformer: 49°C
LM5160: 53°C

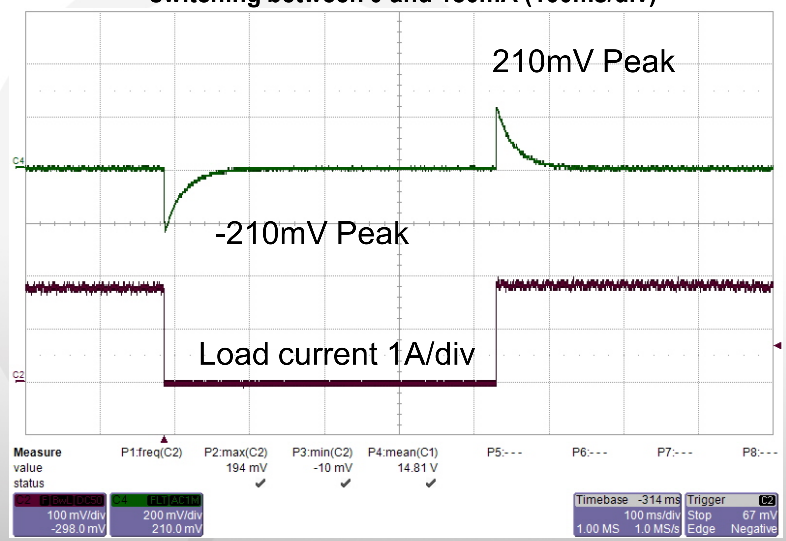
LM5160-Q1 Load Transient Response

Load transient response of the +15V rail under Vin = 12V and Iout switching between 0 and 180mA (100ms/div)



260 mV peak overshoot
260 mV peak undershoot

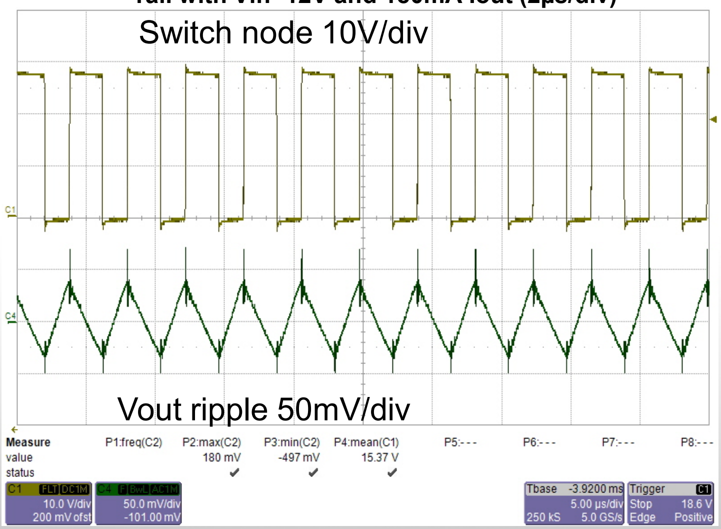
Load transient response of the -9V rail under Vin = 12V and Iout switching between 0 and 180mA (100ms/div)



210 mV peak undershoot
210 mV peak overshoot

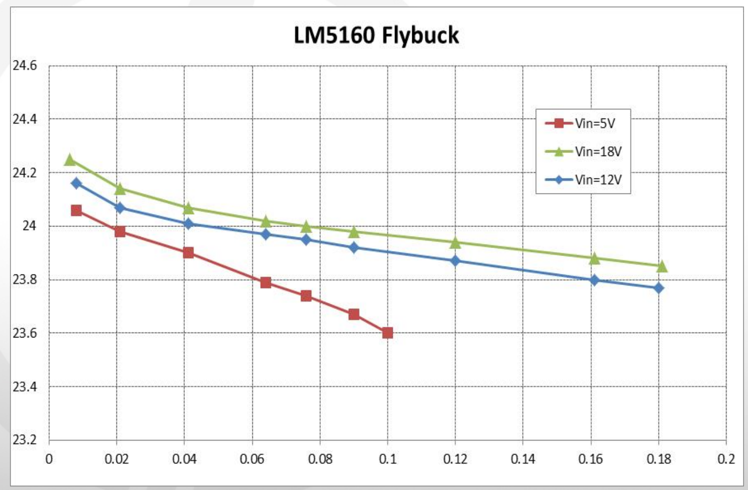
LM5160-Q1 Output Voltage and Load Regulation

Switching node waveform and output voltage ripple of +15V rail with Vin=12V and 180mA Iout (2μs/div)



50mV peak to peak output voltage ripple

Load Regulation Under Input Voltages of 5V, 12V, and 18V



1.6% decrease in load regulation between 0 and 180mA load

Comparison of TI solutions

Solution	Cpri_Sec (pF)	Tx_Vol (mm^3)	Isolation Voltage (kV_{RMS})	Sw Freq (kHz)	Common mode EMI Performance
TPS40210-Q1 Flyback Controller	31	4459	5000	110	75 dBuV peak at 20MHz
LM5180-Q1 Flyback Converter	24	1006	1500	340	68 dBuV peak at 28MHz
Buck with SN6505-Q1 push-pull transformer driver	8.7	947	3125	430	57 dBuV peak at 500kHz
LM5160-Q1 Flybuck Converter		1827	2500	210	

Comparison of TI solutions

Topology	Efficiency	Load Regulation	Load Transients	Solution Size (Dual)	Cost	Design Simplicity	Common mode EMI
LM5180-Q1 Flyback Converter	86.2% peak at 12Vin	2.28% decrease	3.3% Overshoot 5% Undershoot	37mm X38mm	High	Simple	
TPS40210-Q1 Flyback Controller	81.3% peak at 12Vin	5.1% decrease	8.6% Overshoot 13% Undershoot	160mm X64mm	Lowest	Simple	
Buck with SN6505-Q1 push-pull	78.5% peak at 12Vin	11.9% decrease	18.7% Overshoot 11.3% Undershoot	55mm x28mm	Low	Simple	
LM5160-Q1 Flybuck Converter	85.9% peak at 12Vin	1.6% decrease	1.7% Overshoot 1.7% Undershoot	42mm X38mm	High	Complex	

Summary

- **HEV/EV powertrain applications**
- Power architectures and their trade-offs
  - Centralized, Semi-Distributed, Distributed, and Two-stage Distributed
- Topology Comparison
  - Flyback, Fly-buck, Push-pull, and Half-Bridge
- TI solution comparison
  - TIDA-020014 and PMP10654

High VOLT Interactive

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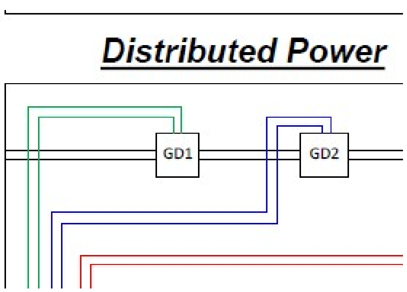
Power Architecture Summary

Centralized

Advantages
- ✓ Low component count
- ✓ Low cost
- ✓ Second sourcing

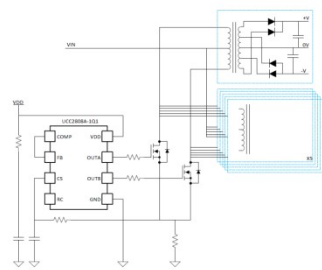
Disadvantages
- – Bulky transformer
- – Poor bias power quality
- – Complex PCB layout
- – Lack of redundancy



Semi-Distributed

Advantages
- ✓ Simpler transformer construction
- ✓ Simplified PCB Layout
- ✓ Better bias power quality
- ✓ Distribution of weight
- ✓ Second sourcing

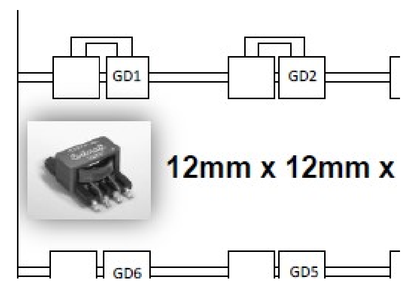
Disadvantages
- – Higher component count than centralized
- – Higher cost than centralized
- – Lack of redundancy



Distributed

Advantages
- ✓ Robustness against power supply failure
- ✓ Simpler transformer construction
- ✓ Simplified PCB Layout
- ✓ Better bias power quality
- ✓ Distribution of weight for ease of passing shock

Disadvantages
- – Highest component count
- – Highest cost



High VOLT Interactive

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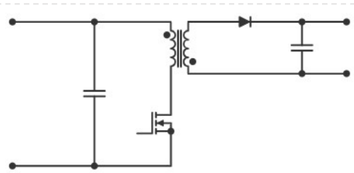
Topology Summary

Flyback

Advantages
- ✓ Operates directly off-battery
- ✓ Regulated output (PSR)
- ✓ Low Component count

Disadvantages
- Switching frequency limitation
- Prone to EMI issues
- Requires a snubber

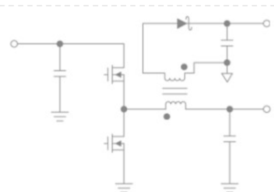


External FET: TPS40210-Q1, UCC2813-5-Q1, LM5155-Q1
Integrated FET: LM5180-Q1

Fly-buck

Advantages
- ✓ Operates directly off-battery
- ✓ Regulated output without opto
- ✓ Low Component count

Disadvantages
- High leakage inductance can degrade load regulation
- Duty cycle limitation
- Magnetic design complexity

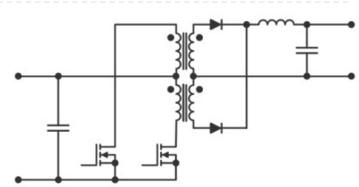


Integrated FET: LM5161-Q1, LM5160-Q1

Push-Pull

Advantages
- ✓ Design simplicity due to open loop configuration
- ✓ Suitable for high frequency
- ✓ Smaller magnetics
- ✓ Low primary-secondary capacitance

Disadvantages
- Requires a pre-regulated rail
- Output regulation can be challenging
- Two primary windings
- External FETs see twice the Vin

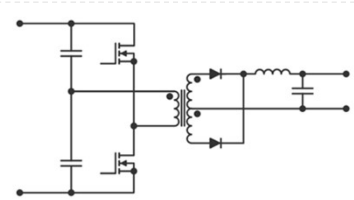


External FET: UCC2808A-1Q1/2Q1, LM25037-Q1
Integrated FET: SN6505B-Q1

Half-Bridge

Advantages
- ✓ Design simplicity due to open loop configuration
- ✓ Suitable for high frequency
- ✓ Smaller magnetics
- ✓ Low primary-secondary capacitance

Disadvantages
- Requires a pre-regulated rail
- Output regulation can be challenging
- Requires floating high side gate driver



External FET: TPS28225-Q1

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TEXAS INSTRUMENTS