# PLC Analog Output and Transmitter Introduction: 4-20mA Iout/0-10V Vout

# PLC 類比輸出和傳送器介紹：4-20mA Iout / 0-10V Vout

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TEXAS INSTRUMENTS

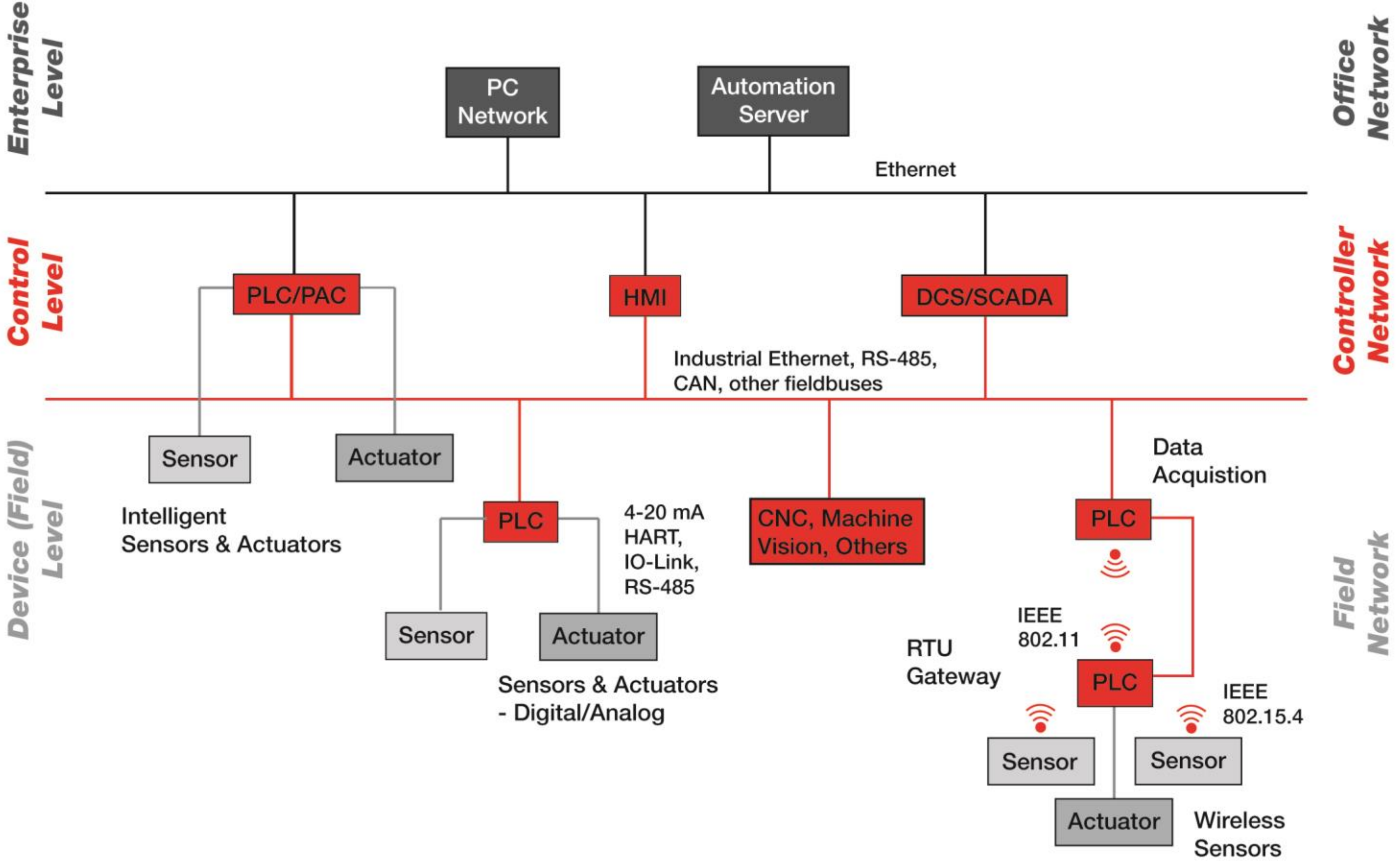
# Agenda

- Overview
  - Where/how are analog outputs used in industrial automation?
  - What are the standard configurations for analog outputs?
- Designing 3-wire Transmitters
  - Theory of Operation
  - Design Examples
- Designing 2-wire Transmitters
  - Theory of Operation
  - Design Examples
- Designing Protection Solutions
  - How does a device get damaged?
  - How do customers test for industrial transient immunity?
  - How do I stop these transients from damaging my design?

# Overview

## *Where are analog outputs used in Industrial Automation? What do they look like?*

# Industrial Automation Overview



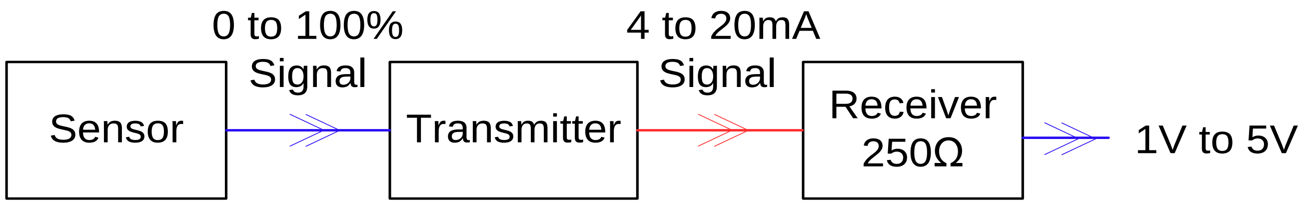
# How are Analog Outputs used in Industrial Automation?

- Programmable Logic Controllers
  - Analog output modules that control something placed in the field
    - Communication, valve position, position of linear actuator, etc.
  - Analog output module is powered by PLC back-plane
    - Primarily 3-wire systems

- Field Elements
  - Analog outputs paired with sensors, placed remotely in the field
  - Comprise a majority of the market for industrial analog outputs
  - Most often 2-wire, or loop-powered, 4-20mA sensor transmitters
  - Some transmitter current requirements are greater than 4mA
    - Use 3-wire configuration

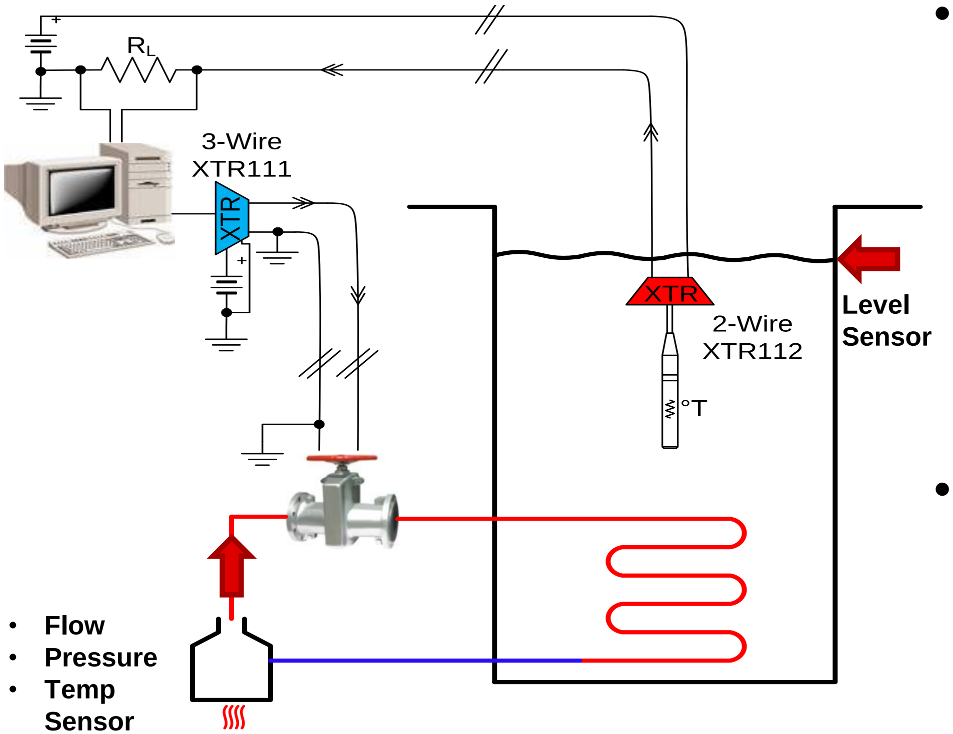
- Is isolation required? Why? Is isolation provided by the receiver or the transmitter?
  - There are isolated variants of 2-wire and 3-wire analog outputs
  - Power isolation, at least, is implied in all 4-wire analog outputs

# 4-20mA Overview




- 4mA represents 0% input level
  - Allows up to 4mA to power external input circuitry
  - 4mA zero level allows under-scale settings and fault detection
- 20mA represents 100% input level
  - Provides sufficient current to power electromechanical devices
  - Over-scale can also be used to detect fault conditions

# Example of AO application

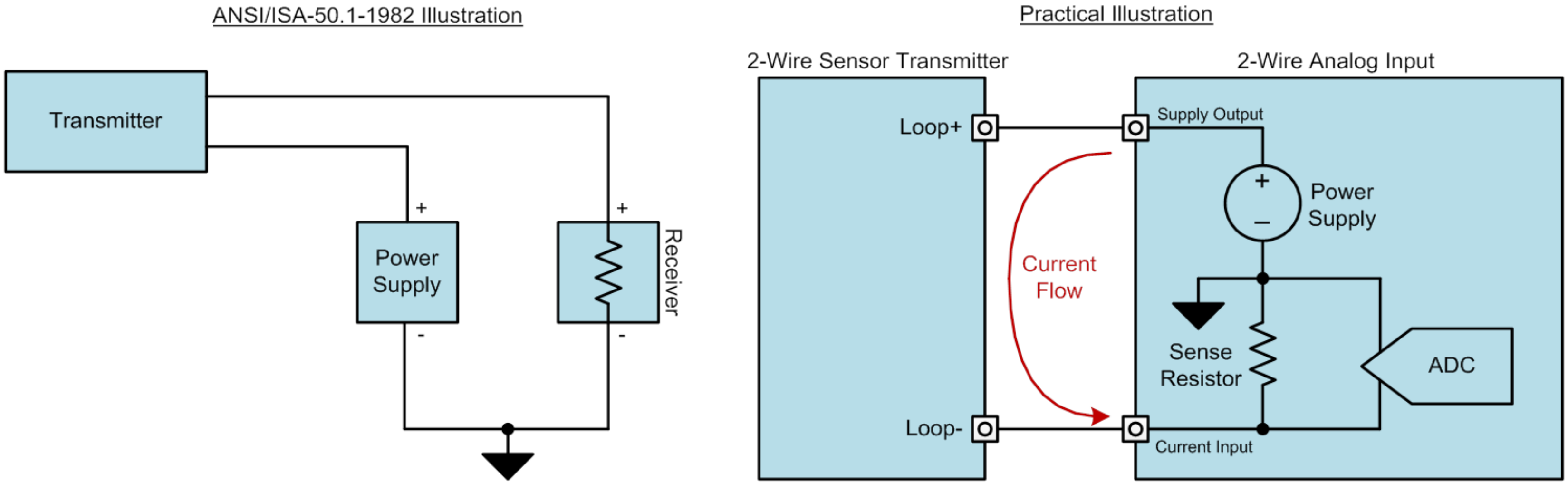



- Flow
- Pressure
- Temp
Sensor

- 2-Wire Transmitter
  - Submersible temperature sensor
  - Remote location prevents local power supply
  - Sends data back to control station

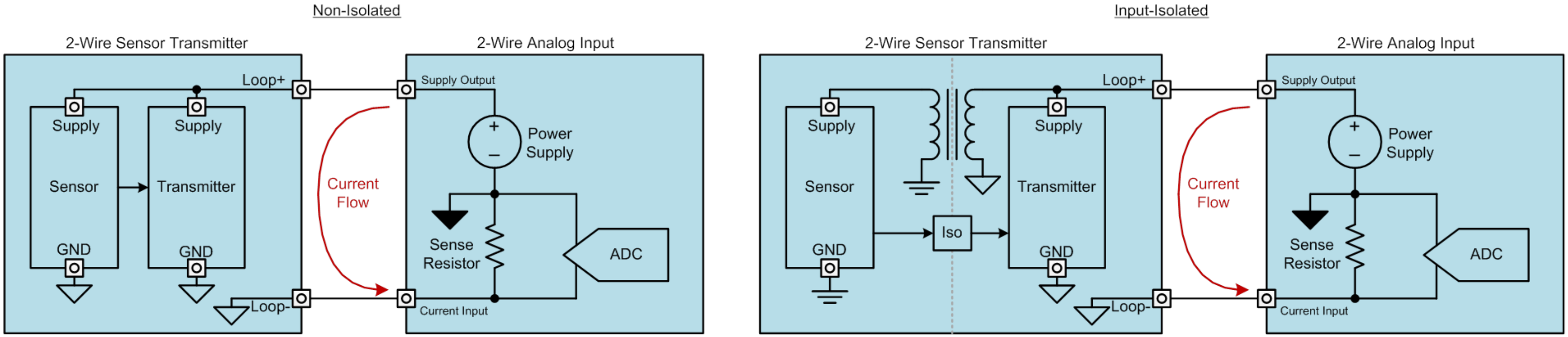
- 3-Wire Transmitter
  - Sends control signal to element at remote location
  - Local power supply is available

# 2-wire Configuration



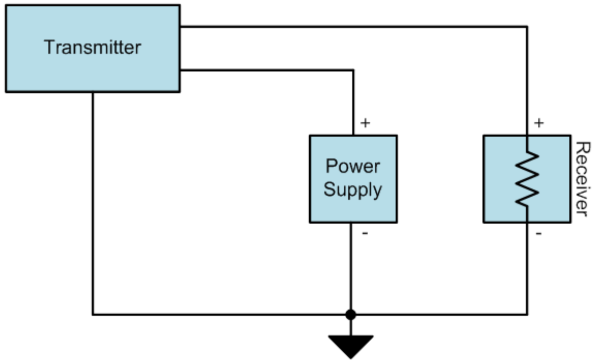

- Supply, transmitter, and receiver are in series – power & signal are in the same loop
- Transmitter communicates with receiver through return current (4-20mA)
- Transmitter must be powered on ≤4mA of supply current
- Long cable lengths between supply and transmitter, transmitter and receiver, and large sense resistors can reduce voltage available for transmitter

# 2-wire Isolation



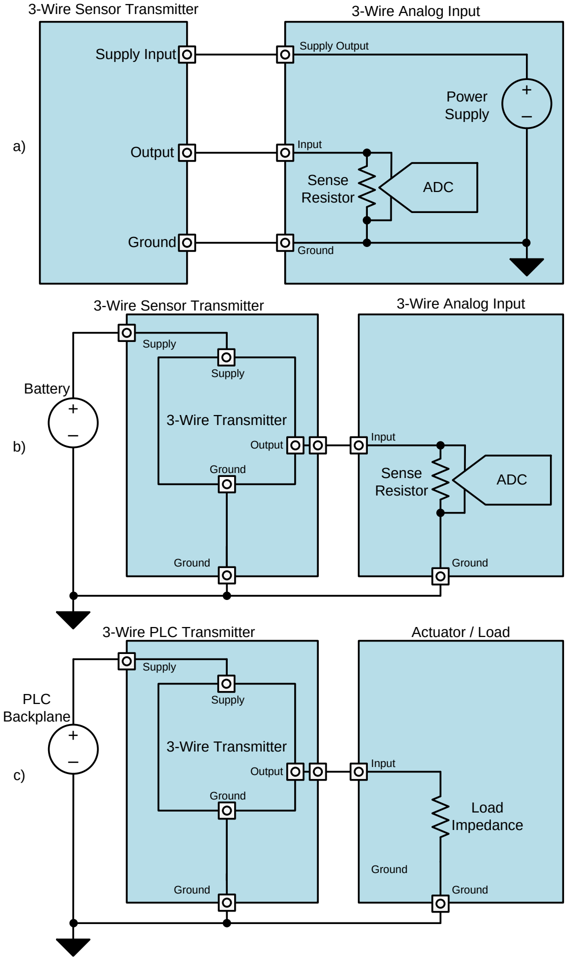
# 3-wire Configuration

ANSI/ISA-50.1-1982 Illustration



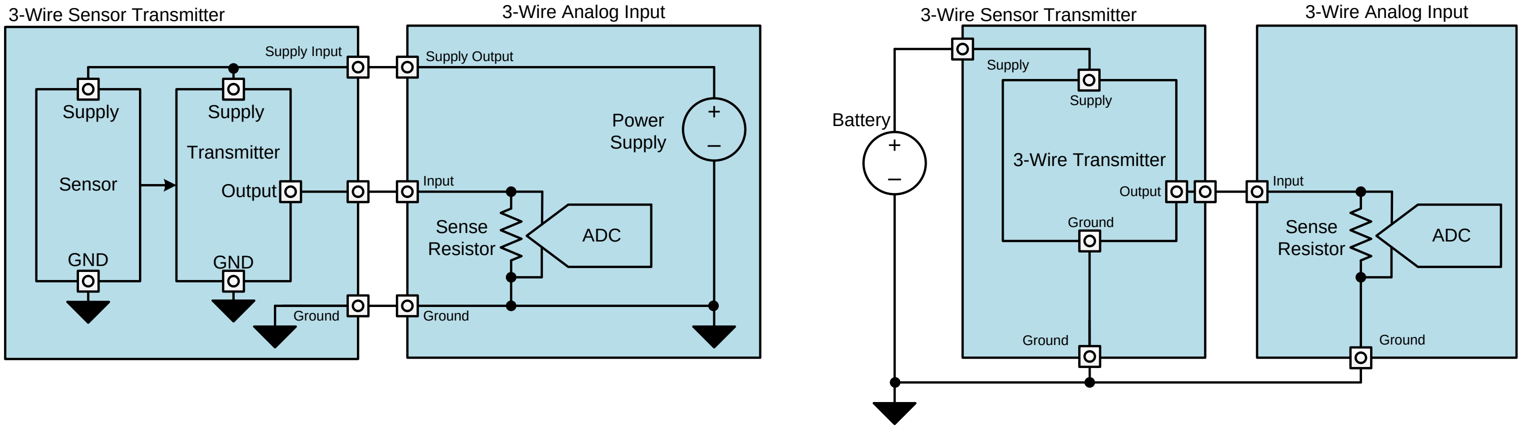

- Transmitter has separate loops for power and for analog output
  - Output current can reach 0mA
- Grouping of power supply, transmitter, and receiver may vary
  a) >4mA supply current available for transmitter
  b) Similar to a) but with local supply to remove cable impedance voltage drop
  c) Typical implementation for PLC transmitter, battery from b) replaced by PLC backplane

Practical Illustrations

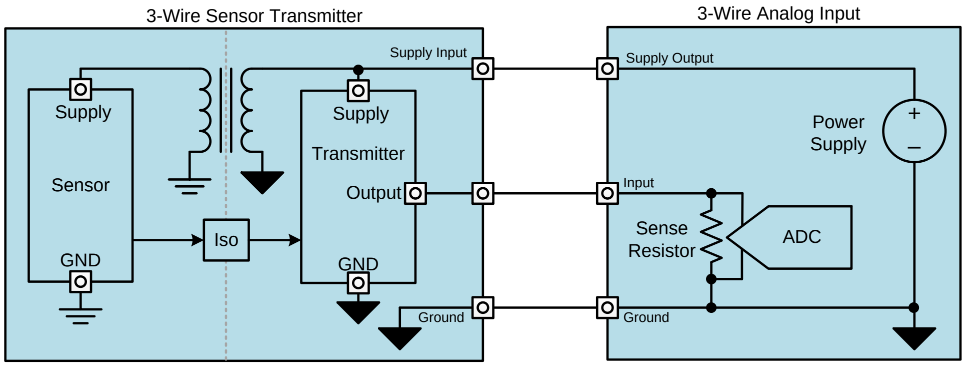


# 3-wire Isolation

Non-Isolated

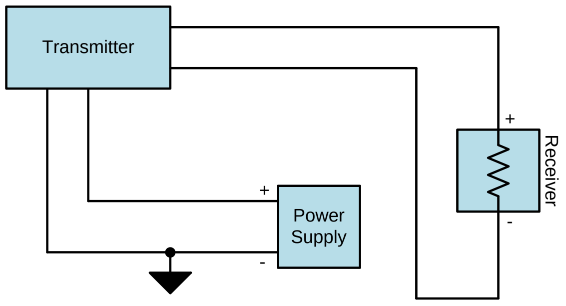



Input-Isolated

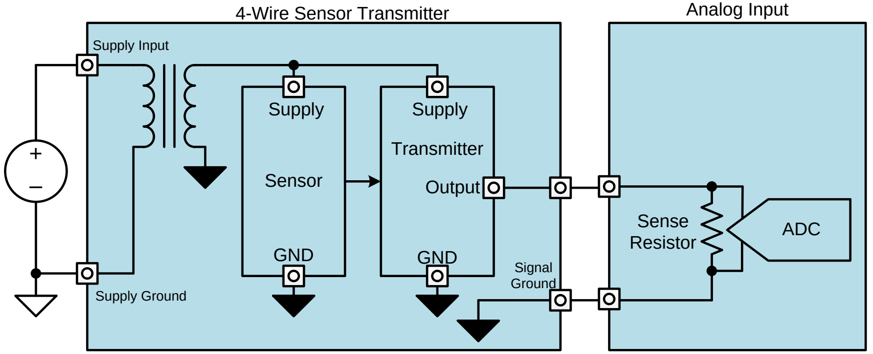


# 4-wire Configuration & Isolation

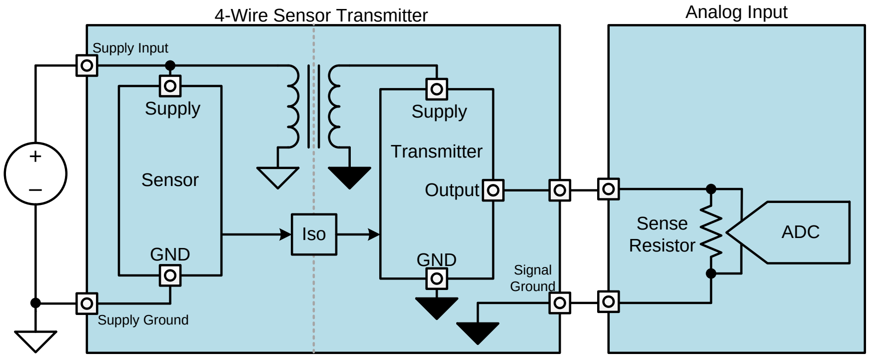
ANSI/ISA-50.1-1982 Illustration



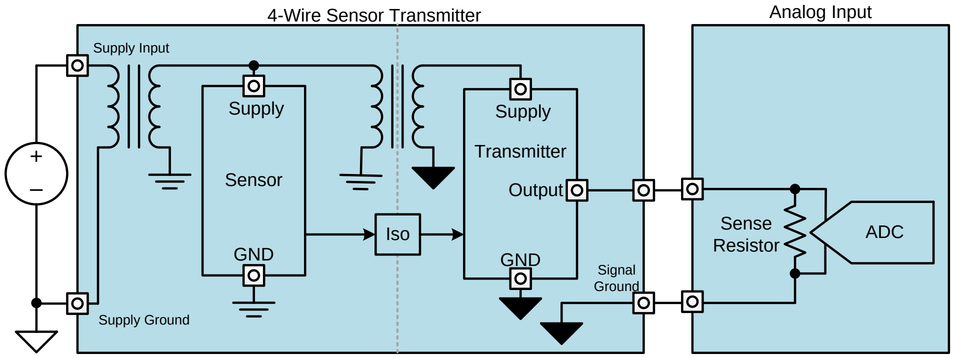

Power-Isolated




Output-Isolated



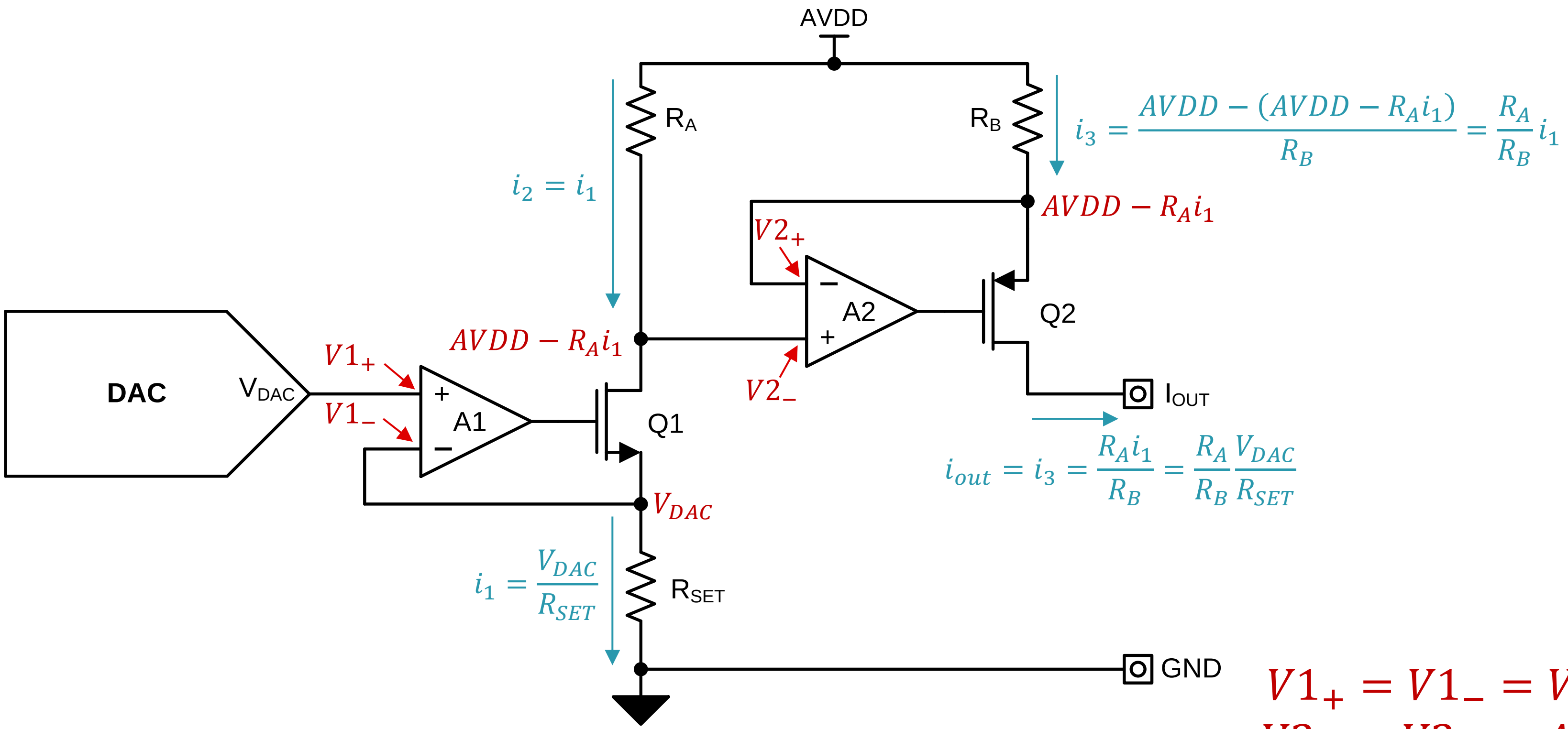

Fully-Isolated



# Designing 3-wire Transmitters

## *Theory of Operation & Design Examples*

# Current Output: Theory of Operation

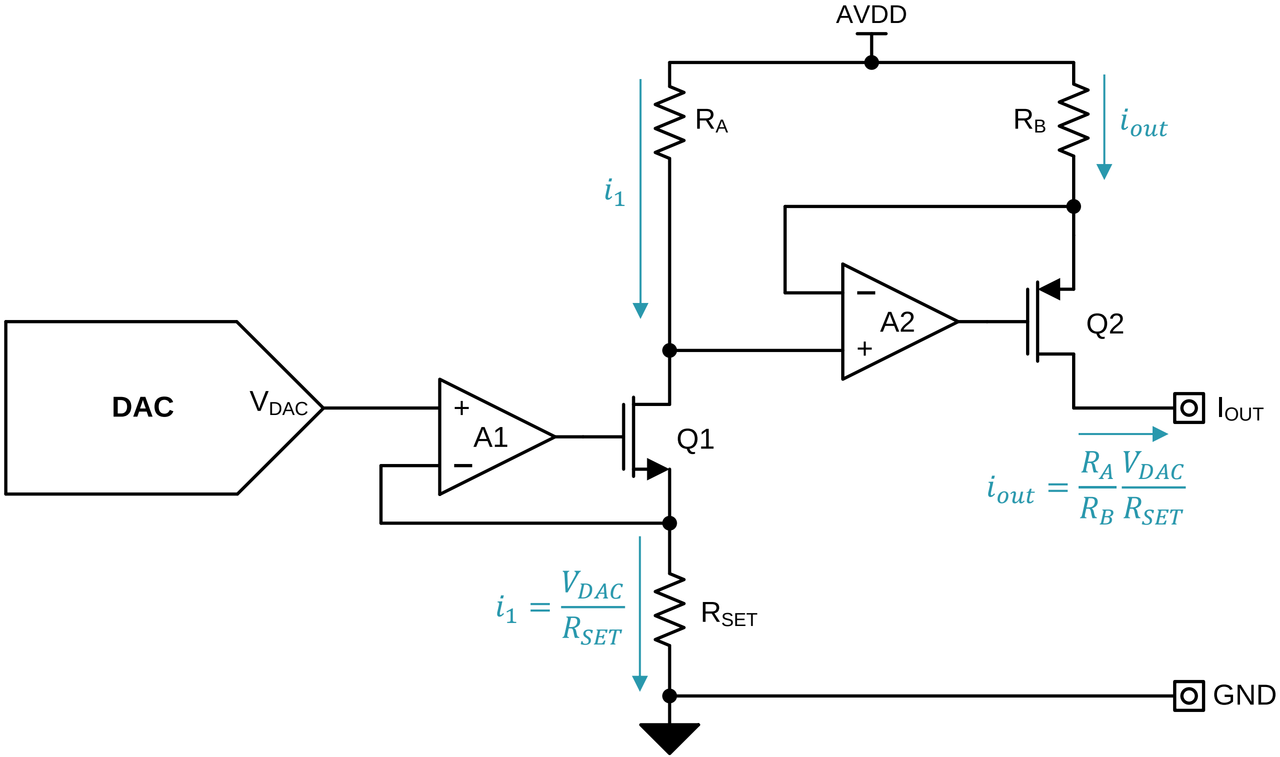



$$V1_+ = V1_- = V_{DAC}$$
$$V2_+ = V2_- = AVDD - R_A i_1$$



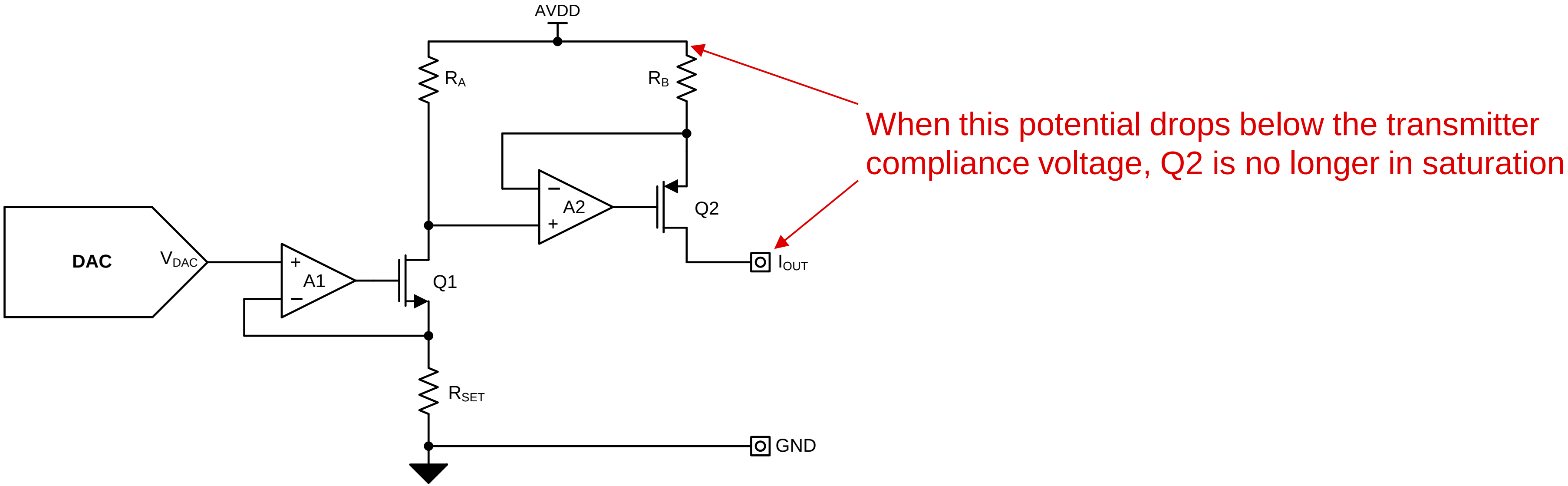
Texas Instruments

# Current Output: Considerations



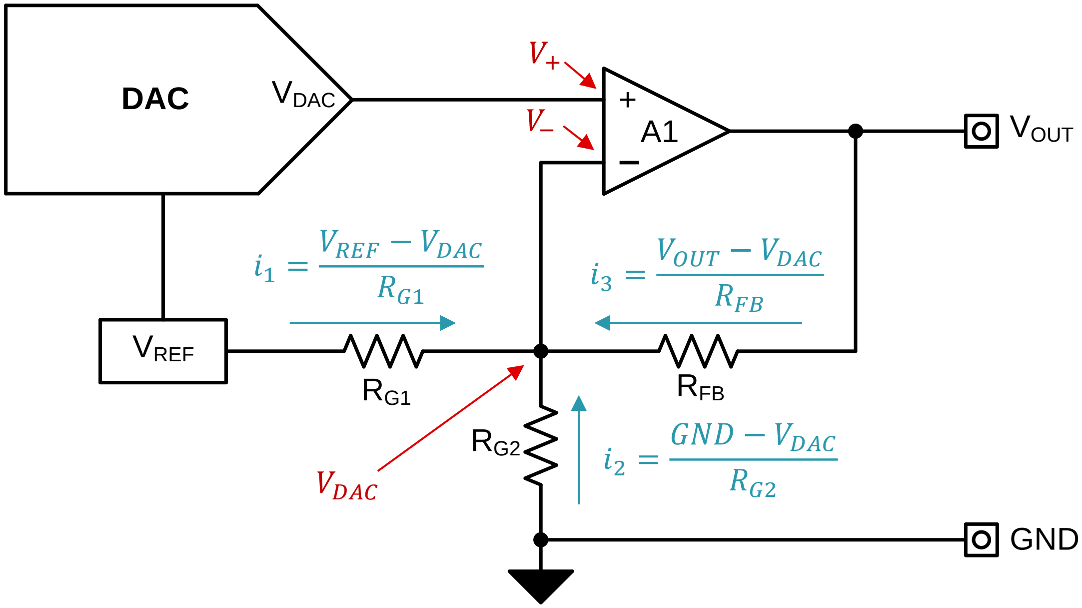

- $i_1$ current is wasted power
  - All of this current goes straight to ground
- Large $i_1$ current creates heating / drift of Q1 & $R_{SET}$
- Ratio of $R_A$:$R_B$ sets current gain from first stage to output stage
- At full-scale output & low impedance load, Q2 power / heat dissipation rises
  - In layout, keep away from other sensitive components

# Current Output: Compliance Voltage




- Compliance voltage is the point at which the voltage potential at the point of load is too high for the voltage to current converter to maintain linear operation
- To accommodate for compliance voltage:
  - Understand the maximum current output
  - Understand the maximum load impedance
  - Ensure that AVDD > MaxCurrent*MaxLoad + Compliance Voltage

# Voltage Output: Theory of Operation



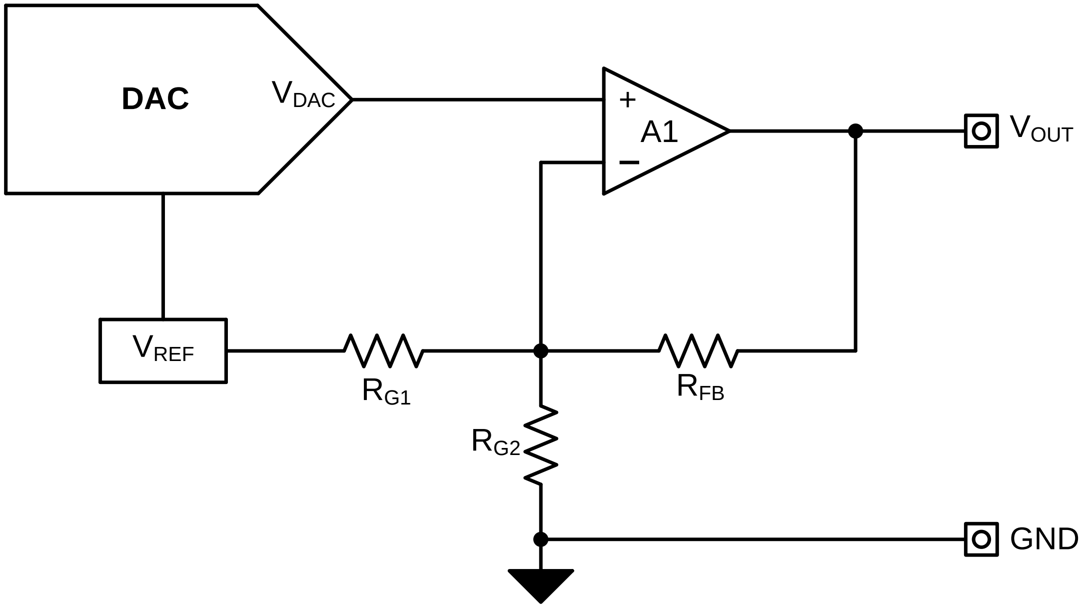

$$\frac{-V_{DAC}}{R_{G2}} + \frac{V_{REF} - V_{DAC}}{R_{G1}} + \frac{V_{OUT} - V_{DAC}}{R_{FB}} = 0$$

$$\frac{-V_{DAC}}{R_{G2}} + \frac{V_{REF}}{R_{G1}} - \frac{V_{DAC}}{R_{G1}} + \frac{V_{OUT}}{R_{FB}} - \frac{V_{DAC}}{R_{FB}} = 0$$

$$\frac{V_{OUT}}{R_{FB}} = \frac{V_{DAC}}{R_{FB}} + \frac{V_{DAC}}{R_{G1}} + \frac{V_{DAC}}{R_{FB}} - \frac{V_{REF}}{R_{G1}}$$

$$V_{OUT} = \left(1 + \frac{R_{FB}}{R_{G1}} + \frac{R_{FB}}{R_{G2}}\right) V_{DAC} - \frac{R_{FB}}{R_{G1}} V_{REF}$$

# Voltage Output: Consideration




- Select offset gain to set negative full-scale end point

$$V_{NegativeFS} = -\frac{R_{FB}}{R_{G1}} V_{REF}$$

- Modify full-scale range gain

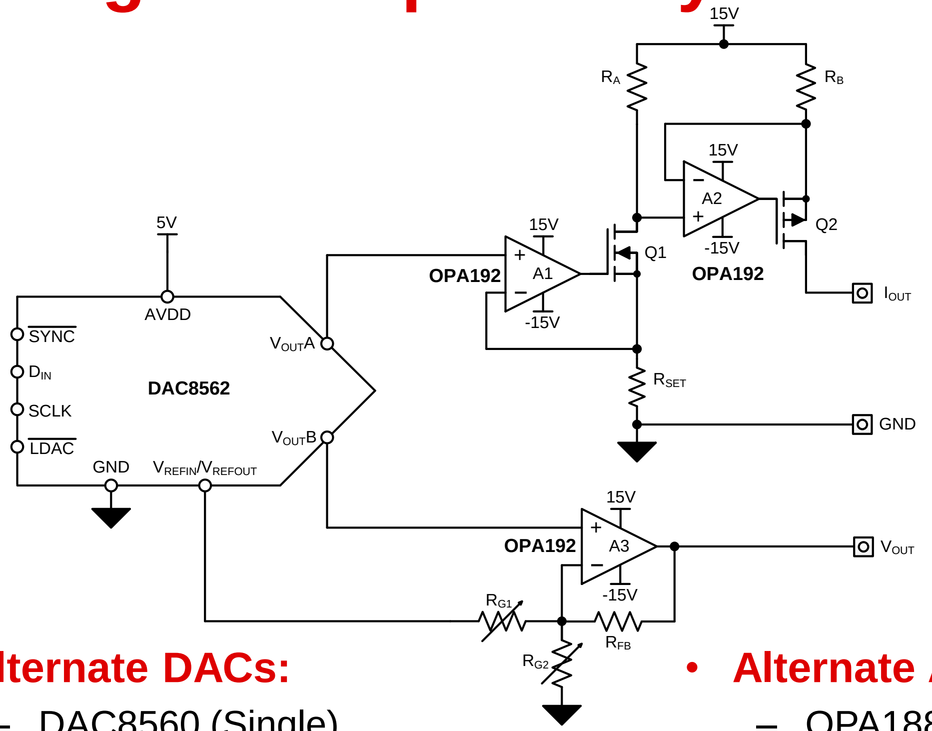
$$V_{FSR} = \left(1 + \frac{R_{FB}}{R_{G1}} + \frac{R_{FB}}{R_{G2}}\right) V_{DAC}$$

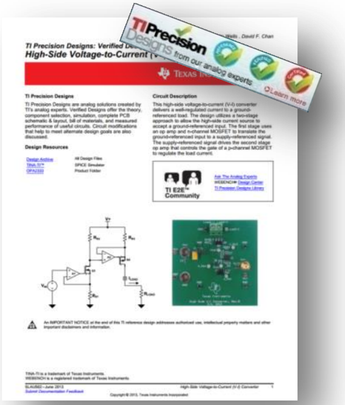
- Check full-scale output

$$V_{Positive\ FS} = V_{FSR} - V_{NegativeFS}$$

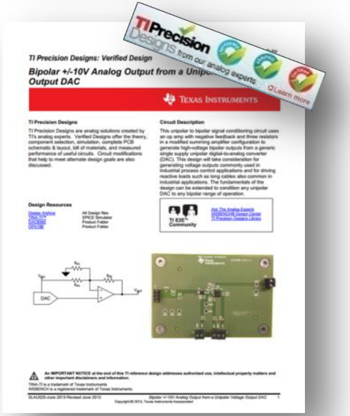
$$V_{OUT} = \left(1 + \frac{R_{FB}}{R_{G1}} + \frac{R_{FB}}{R_{G2}}\right) V_{DAC} - \frac{R_{FB}}{R_{G1}} V_{REF}$$

# Design Example: Fully Discrete



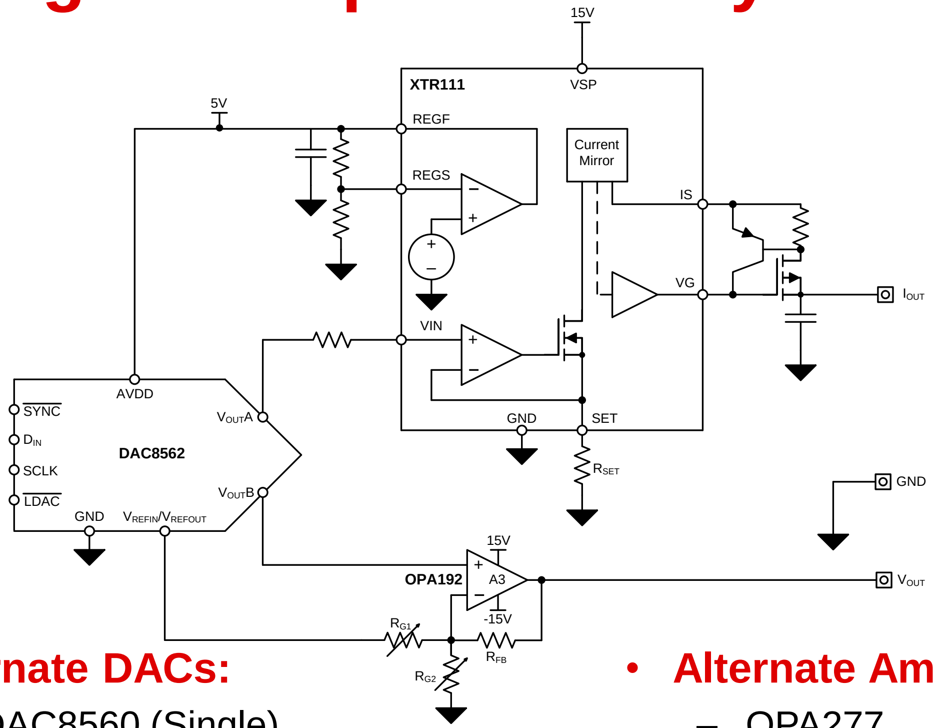
**TIPD102**



**TIPD125**

- **Alternate DACs:**
  - DAC8560 (Single)
  - DAC8564/8 (Quad/Octal)
  - DAC8811/2 (Improved Single/Dual)
- **Alternate Amplifiers:**
  - OPA188
  - OPA277
  - OPA170/OPA172

# Design Example: Partially Discrete




- Alternate XTRs:
  - XTR110 (Internal $R_{SET}$)
  - XTR300 (Source/Sink)

[TIPD in Test]

- **Alternate DACs:**
  - DAC8560 (Single)
  - DAC8564/8 (Quad/Octal)
  - DAC8811/2 (Improved Single/Dual)
- **Alternate Amplifiers:**
  - OPA277
  - OPA170/OPA172
  - OPA188

# DAC8760/7760

## 16-/12-bit DACs with Voltage and 4-20mA Current Outputs

RELEASED

## Features

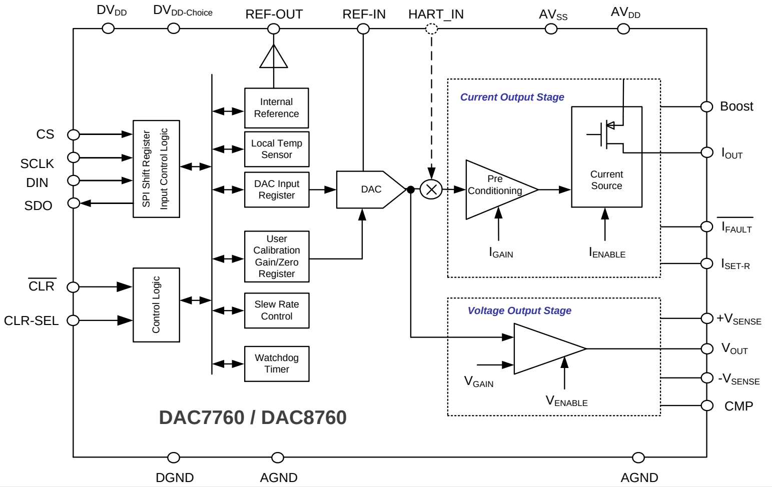
- DAC with Current & Voltage Outputs
- Selectable Ranges
  - Current: 0-20mA; 4-20mA; 0-24mA
  - Voltage: 0-5V; 0-10V; +/-5V; +/-10V (10% over-range)
- TUE: 0.1% FSR max
- Internal Reference (10ppm/$^0$C max)
- Wide Temp Range: -40°C to +125°C
- Fault Detect: Open-Circuit of I-Out, thermal alarm, compliance voltage
- HART Interface
- Reliability: Short-Circuit limit, CRC, Watchdog timer
- Pin compatible to competition: 40-QFN / 24-QSSOP

## Applications

- PLC I/O modules
- Sensor Transmitters
- Industrial Automation
- Building Automation

## Benefits

- Integrates 3 different components on board to help save board space, cost and reduce design time
- Higher accuracy than competition
- Allows easy upgrade from existing solutions
- Key benefits over competition:
  - Only part with features to improve system reliability
  - Reliable operation in extended industrial temp range



# DAC8750/7750

## 16-/12-bit DACs with 4-20mA Current Outputs

RELEASED

## Features

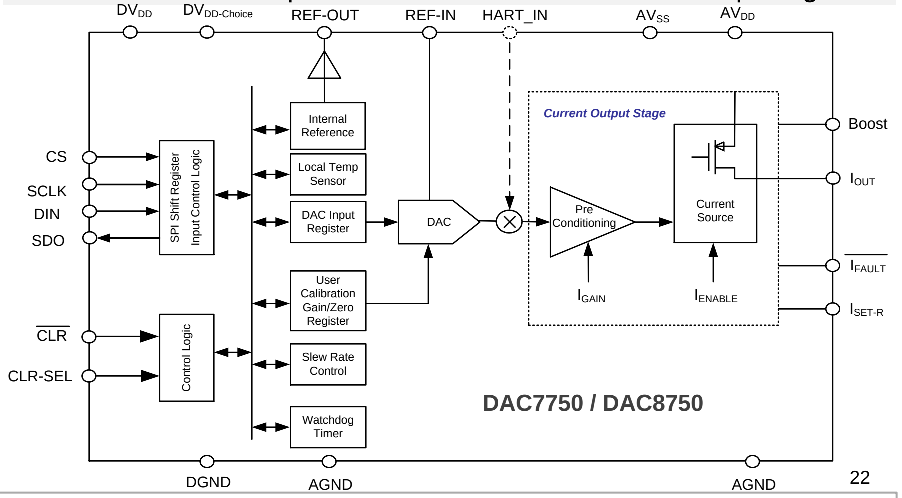
- DAC with Current Outputs
- Selectable Ranges
  - Current: 0-20mA; 4-20mA; 0-24mA
- TUE: 0.1% FSR max
- Internal Reference (10ppm/$^0$C max)
- Wide Temp Range: -40°C to +125°C
- Fault Detect: Open-Circuit of I-Out, thermal alarm, compliance voltage
- HART Interface
- Reliability: Short-Circuit limit, CRC, Watchdog timer
- Pin compatible to competition: 40-QFN / 24-QSSOP

## Benefits

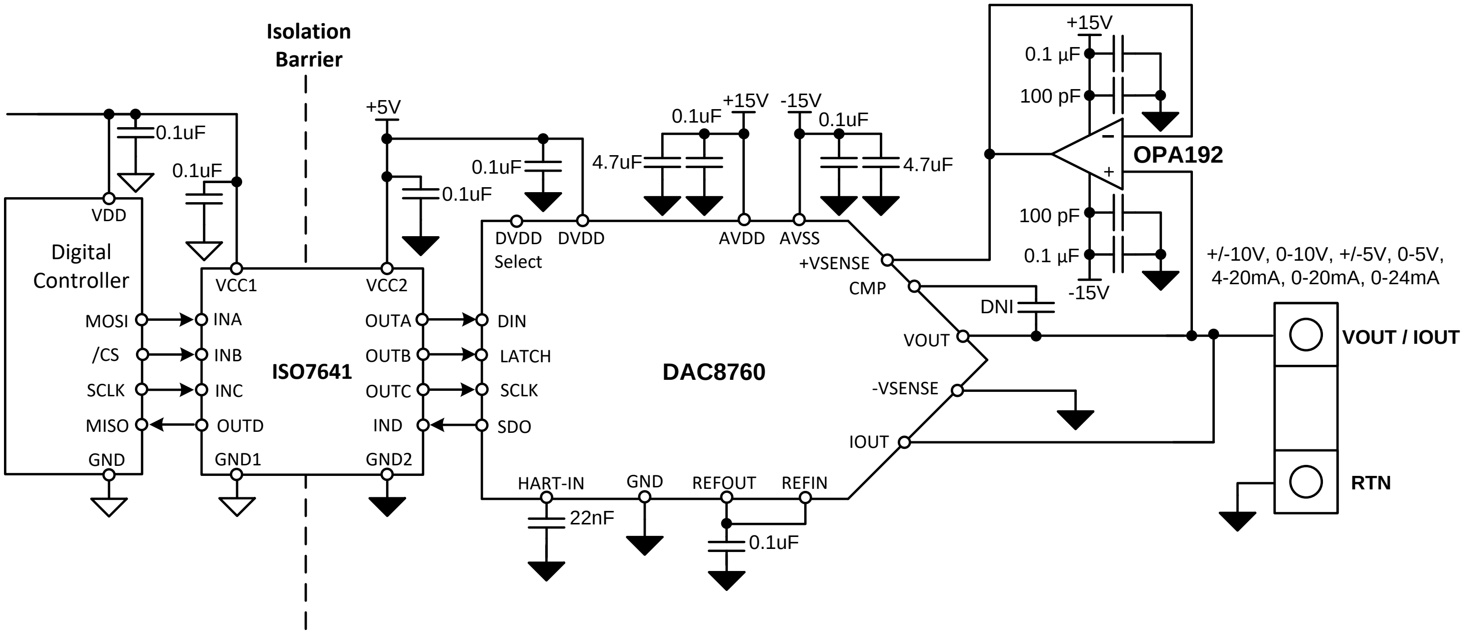
- Integrates 3 different components on board to help save board space, cost and reduce design time
- Higher accuracy than competition
- Allows easy upgrade from existing solutions
- Key benefits over competition:
  - Only part with features to improve system reliability
  - Reliable operation in extended industrial temp range

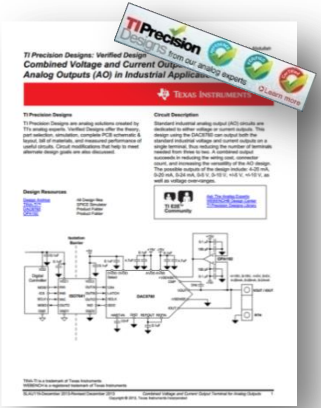
## Applications

- PLC I/O modules
- Sensor Transmitters
- Industrial Automation
- Building Automation



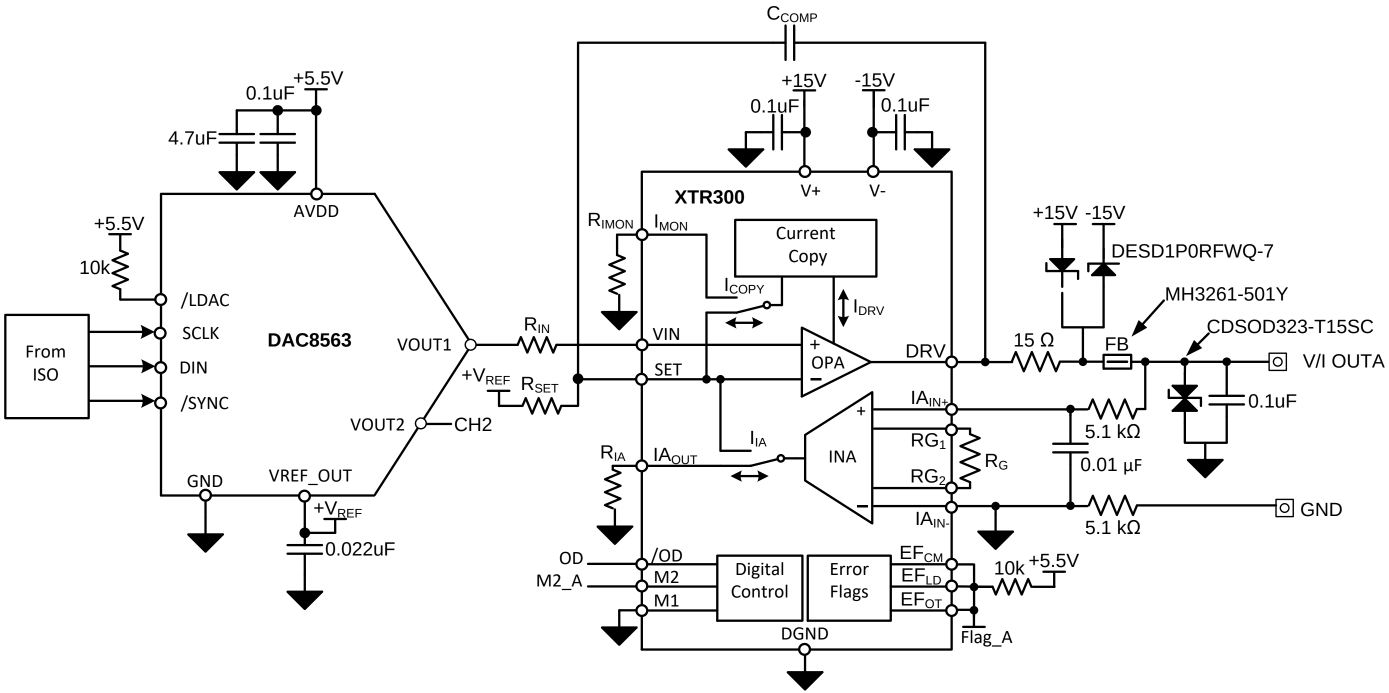
# Design Example: Single Channel Universal Analog Output

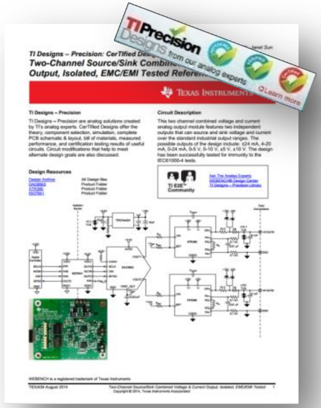


**TIPD119**

# Design Example: Dual Channel Universal Analog Output w/Bipolar Current Outputs

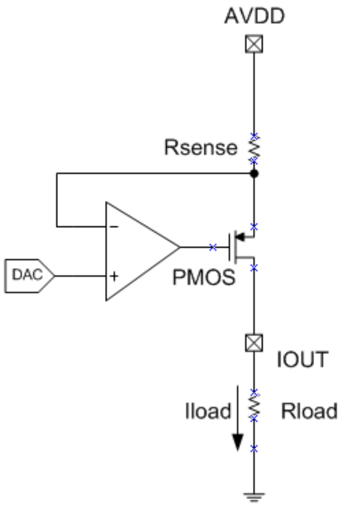


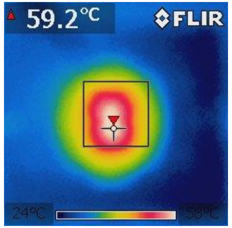
**TIPD155**

# Power Dissipation for PLC AO Modules

## Analog Current Output Circuit
**(No Power Management)**



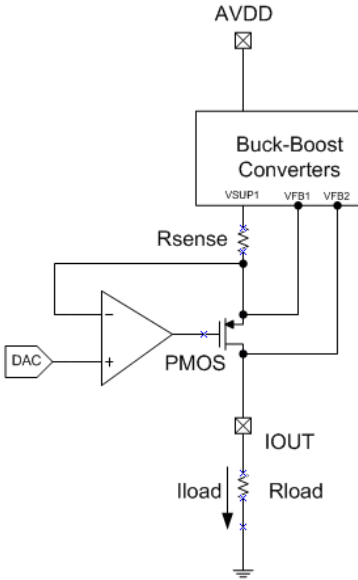

AVDD = 24V
Rload = 1Ω
IOUT = 24mA



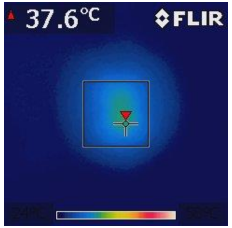

**High Power dissipation**

| | Rload | Chip |
|---|---|---|
| Power Dissipation | 0.6mW | 576mW |

## Analog Current Output Circuit
**(Adaptive Power Management)**




AVDD = 24V
Rload = 1Ω
IOUT = 24mA
70% Efficiency



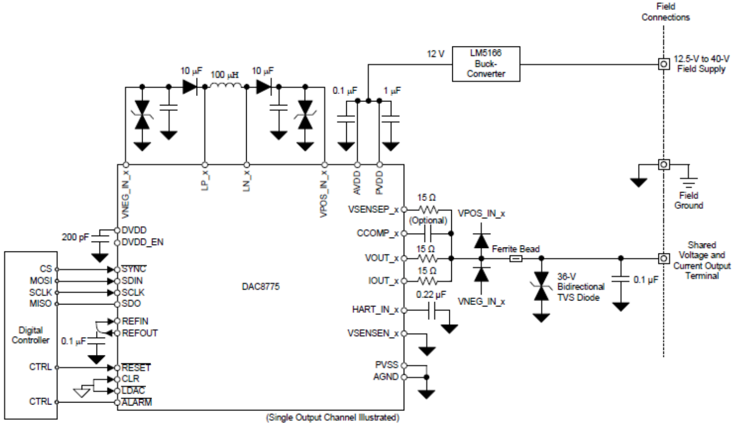

**Low Power dissipation**

| | Rload | Chip |
|---|---|---|
| Power Dissipation | 0.6mW | 185mW |

# DAC8775 TI Precision Designs

## TIPD215

- Less than 1W Quad Channel Analog Output Module with Adaptive power management
- DAC8775 with LM5166
- 13-65V Supply Input <1W total power dissipation

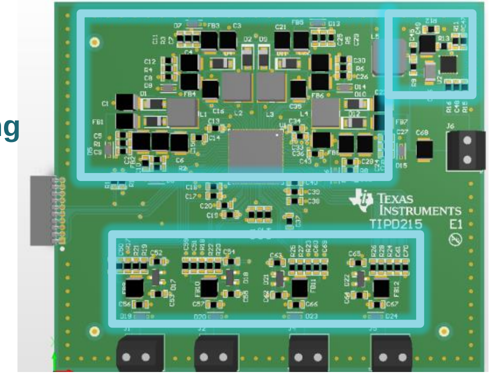



## TIPD216

- Quad Channel Industrial Voltage and Current output Driver- EMC/EMI tested
- 4x Channel, Shared V+I Output Terminal
  - IEC61000-4 ESD, EFT, Surge, CI, and RI tested protection circuitry
  - CE / FCC Radiated Emission testing
- DAC8775 Buck-Boost Converter Adaptive Power Management

**68x58 mm Solution Size**

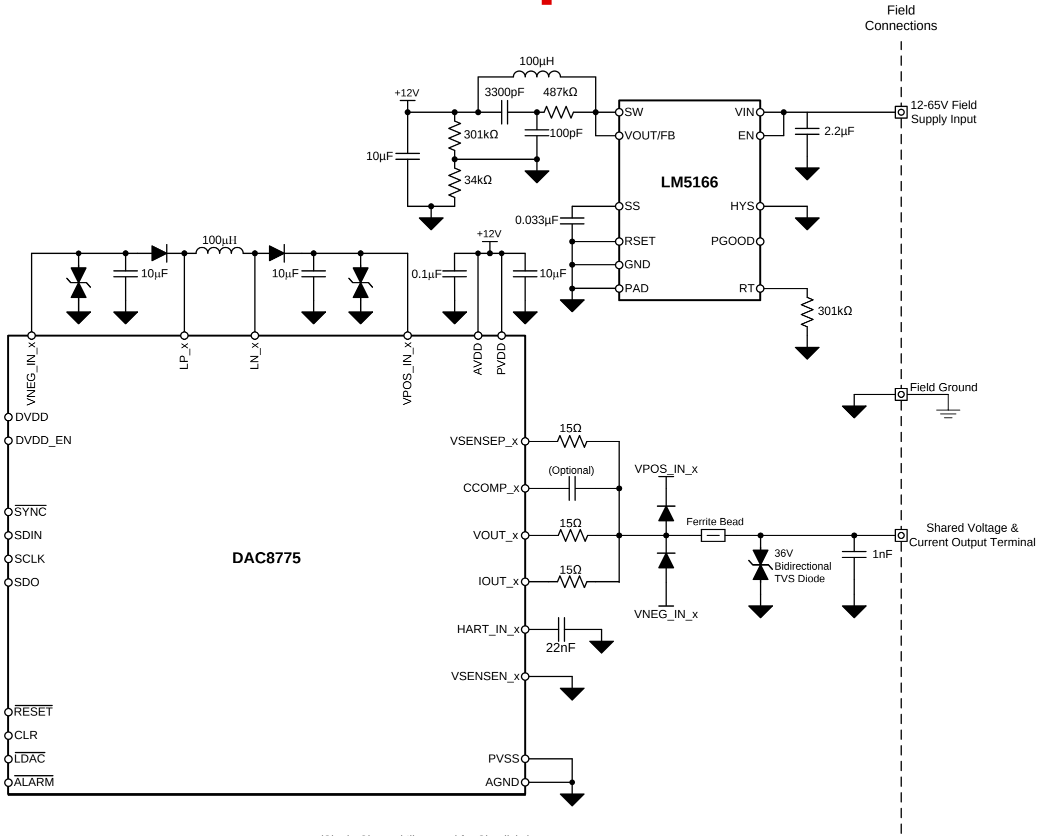
**DC/DC External Components & optional filtering**



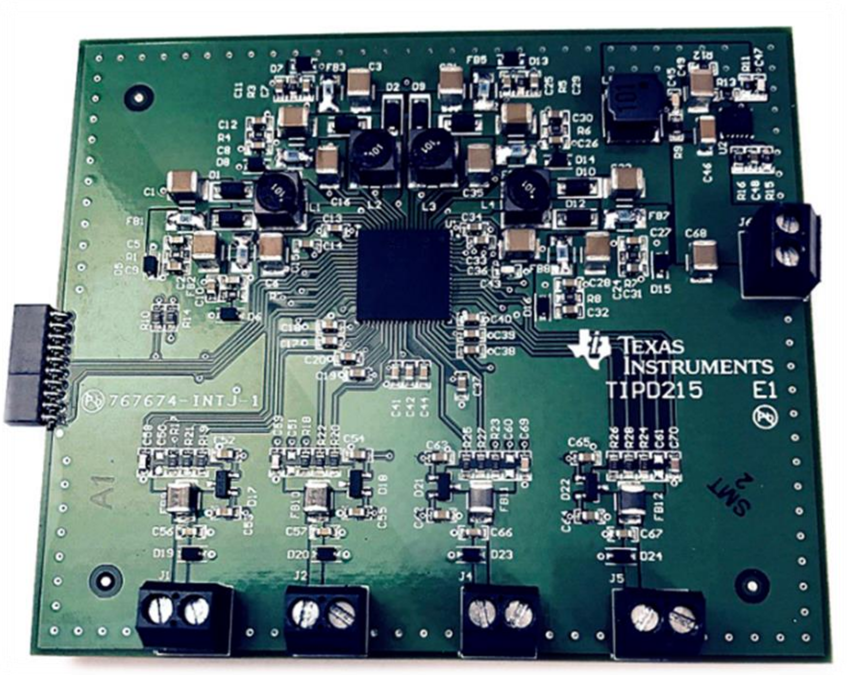

**Optional External buck converter**

**IEC61000-4 Protection Block**

# Generic Example Circuit




(Single Channel Illustrated for Simplicity)



# DAC8775

## Quad-Channel 16-bit DACs with Voltage/Current Outputs & Adaptive Power

RELEASED

## Features

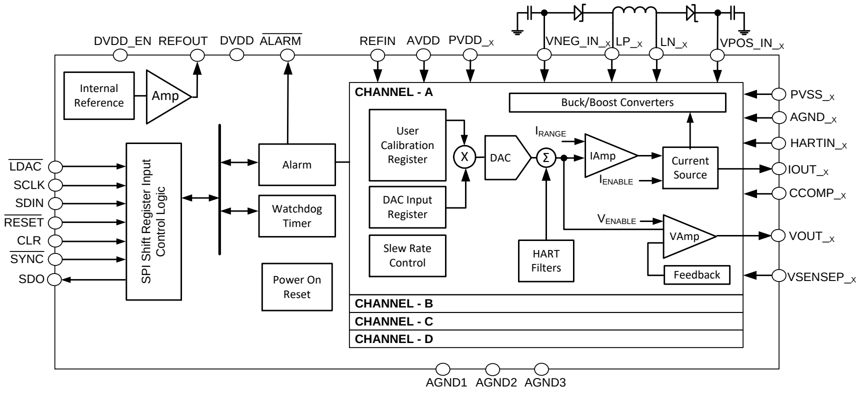
- Integrated DAC and selectable voltage/current ranges
  - Iout: 0-20mA; 4-20mA; 3.5-23.5mA; 0-24mA ; ±24mA
  - Vout: 0-5V; 0-10V; +/-5V; +/-10V (20% over-range)
  - TUE: 0.1% FSR max; 5V reference: 10 ppm/°C max
- Adaptive Power Management
  - Single supply pin for full chip (12-36V)
  - Single Inductor buck-boost converter generates
    - Current out supply: 4-32V
    - Voltage out supply: +/-15V
    - Auto learn mode
- Integrated LDO for digital supply: 5V
- Enhanced Reliability: Open-Circuit of I-Out, thermal alarm, compliance voltage, Watchdog timer
- Enhanced safety features
- Wide Temp Range: -40°C to +125°C
- Package QFN-72 (10x10 mm)

## Applications

- PLC I/O modules
- Sensor Transmitters
- Industrial Automation
- Building Automation

## Benefits

- Reduce thermal stress and module size
- Simple power supply scheme
- Overall solution compared to others
  - Saves cost with only one supply pin
  - Lower power dissipation
  - Rated over extended industrial temperature range



# DAC8771

## Single-Channel 16-bit DACs with Voltage/Current Outputs & Adaptive Power

RELEASED

## Features

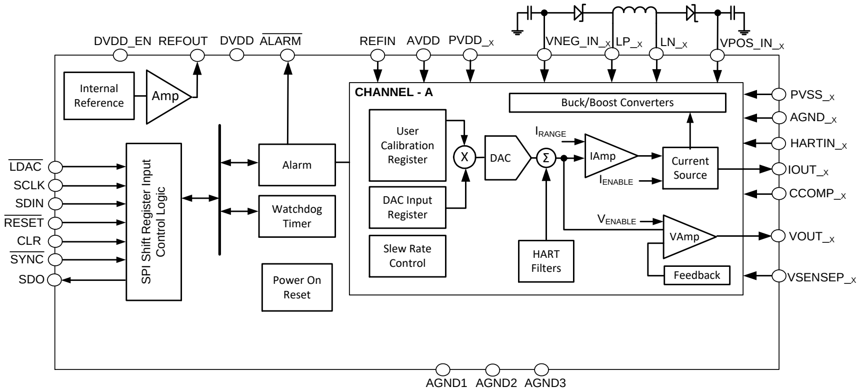
- Integrated DAC and selectable voltage/current ranges
  - Iout: 0-20mA; 4-20mA; 3.5-23.5mA; 0-24mA ; ±24mA
  - Vout: 0-5V; 0-10V; +/-5V; +/-10V (20% over-range)
  - TUE: 0.1% FSR max; 5V reference: 10 ppm/°C max
- Adaptive Power Management
  - Single supply pin for full chip (12-36V)
  - Single Inductor buck-boost converter generates
    - Current out supply: 4-32V
    - Voltage out supply: +/-15V
    - Auto learn mode
- Integrated LDO for digital supply: 5V
- Enhanced Reliability: Open-Circuit of I-Out, thermal alarm, compliance voltage, Watchdog timer
- Enhanced safety features
- Wide Temp Range: -40°C to +125°C
- Package QFN-48 (7x7 mm)

## Applications

- PLC I/O modules
- Sensor Transmitters
- Industrial Automation
- Building Automation

## Benefits

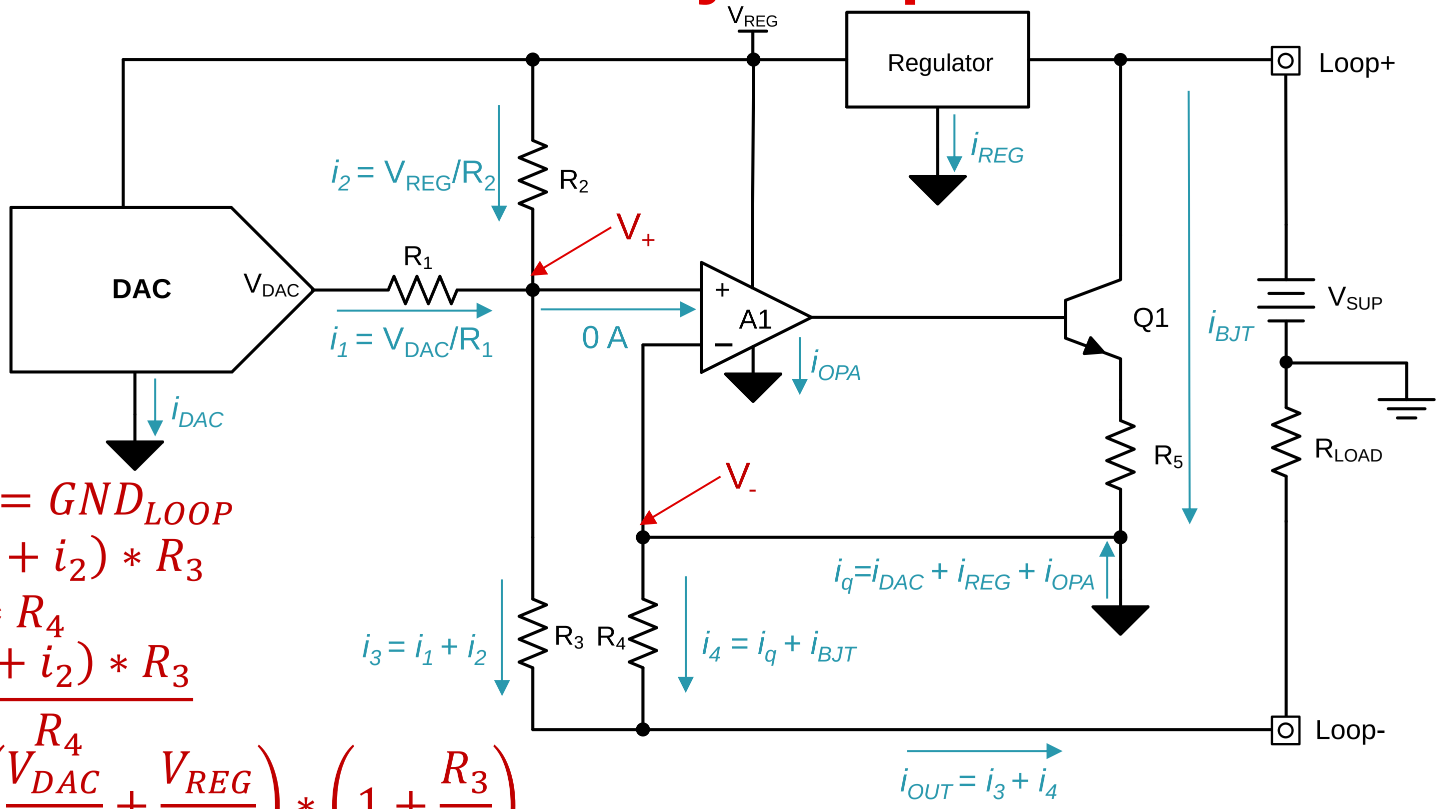
- Reduce thermal stress and module size
- Simple power supply scheme
- Overall solution compared to others
  - Saves cost with only one supply pin
  - Lower power dissipation
  - Rated over extended industrial temperature range



# Designing 2-wire Transmitters

## *Theory of Operation & Design Examples*

# 2-Wire Transmitter: Theory of Operation




$$V_+ = V_- = GND_{LOOP}$$

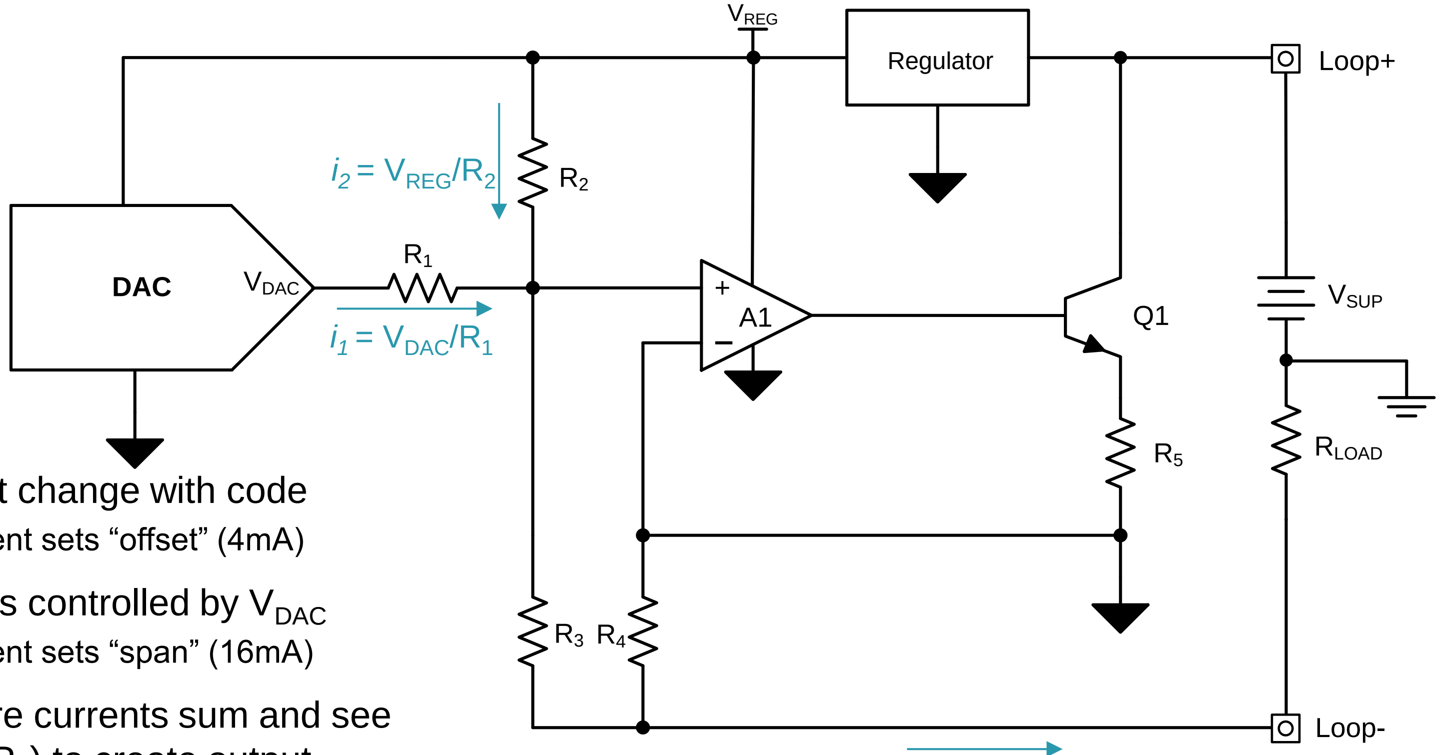
$$V_+ = (i_1 + i_2) * R_3$$

$$V_- = i_4 * R_4$$

$$i_4 = \frac{(i_1 + i_2) * R_3}{R_4}$$

$$i_{OUT} = \left(\frac{V_{DAC}}{R_1} + \frac{V_{REG}}{R_2}\right) * \left(1 + \frac{R_3}{R_4}\right)$$

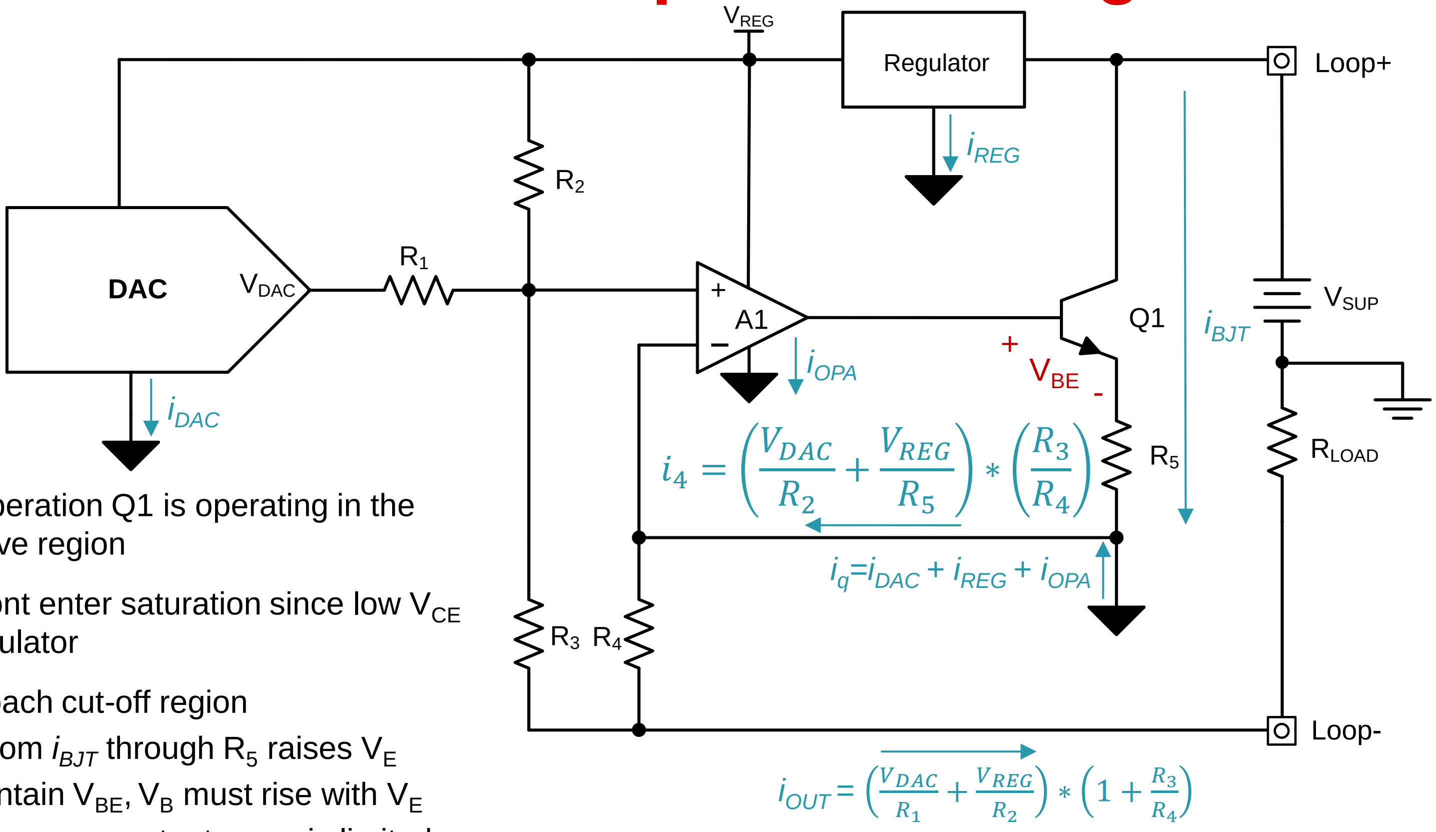
# 2-Wire Transmitter: Considerations




$$i_{OUT} = \left(\frac{V_{DAC}}{R_1} + \frac{V_{REG}}{R_2}\right) * \left(1 + \frac{R_3}{R_4}\right)$$

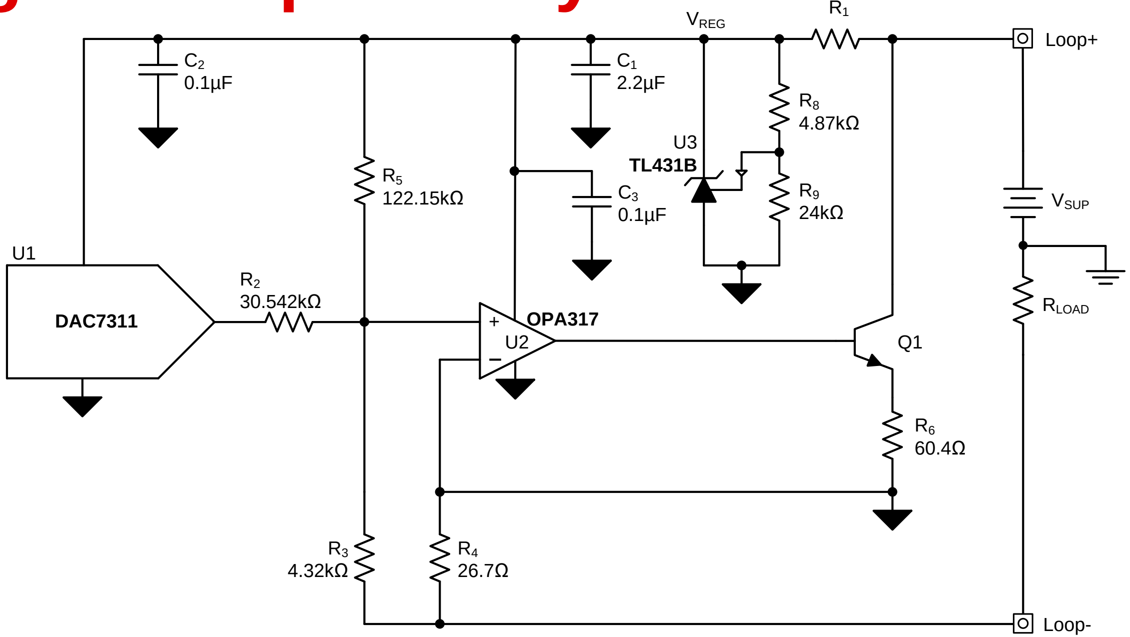
- $i_2$ does not change with code
  - $i_2$ current sets "offset" (4mA)
- $i_1$ current is controlled by $V_{DAC}$
  - $i_1$ current sets "span" (16mA)
- $i_1$ and $i_2$ are currents sum and see G=1+($R_3$/$R_4$) to create output
  - High gain means output current primarily flows from loop through BJT

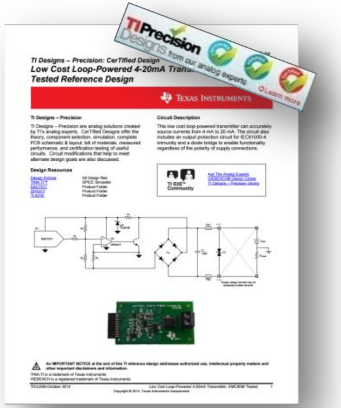
# 2-Wire Transmitter: Compliance Voltage




- In normal operation Q1 is operating in the forward-active region
- Probably wont enter saturation since low $V_{CE}$ turns off regulator
- Could approach cut-off region
  - Drop from $i_{BJT}$ through $R_5$ raises $V_E$
  - To maintain $V_{BE}$, $V_B$ must rise with $V_E$
  - $V_B$, the op amp output, span is limited

# Design Example: Fully Discrete

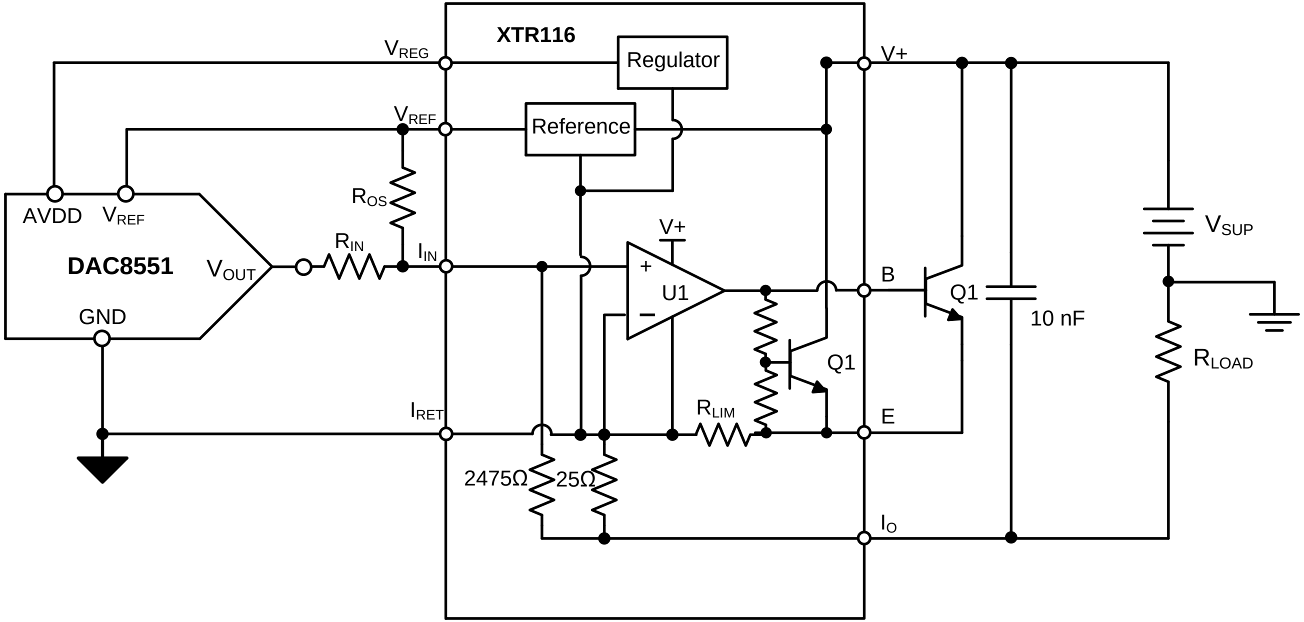


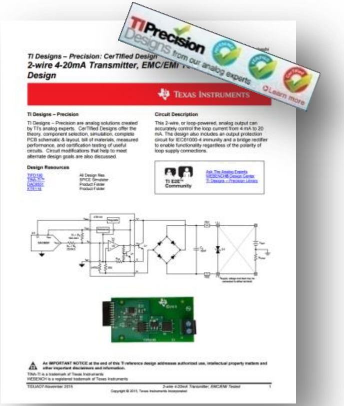



TIPD158

- **Alternate DACs:**
  - DAC5311, DAC6311, DAC7311, DAC8311, DAC8411
  - DAC8550/DAC8551 (16-bit, Buffered Output)
  - DAC8830 (16-bit, Very High Accuracy)
- **Alternate Amplifiers:**
  - OPA316
  - OPA170
  - OPA333

# Design Example: Partially Discrete



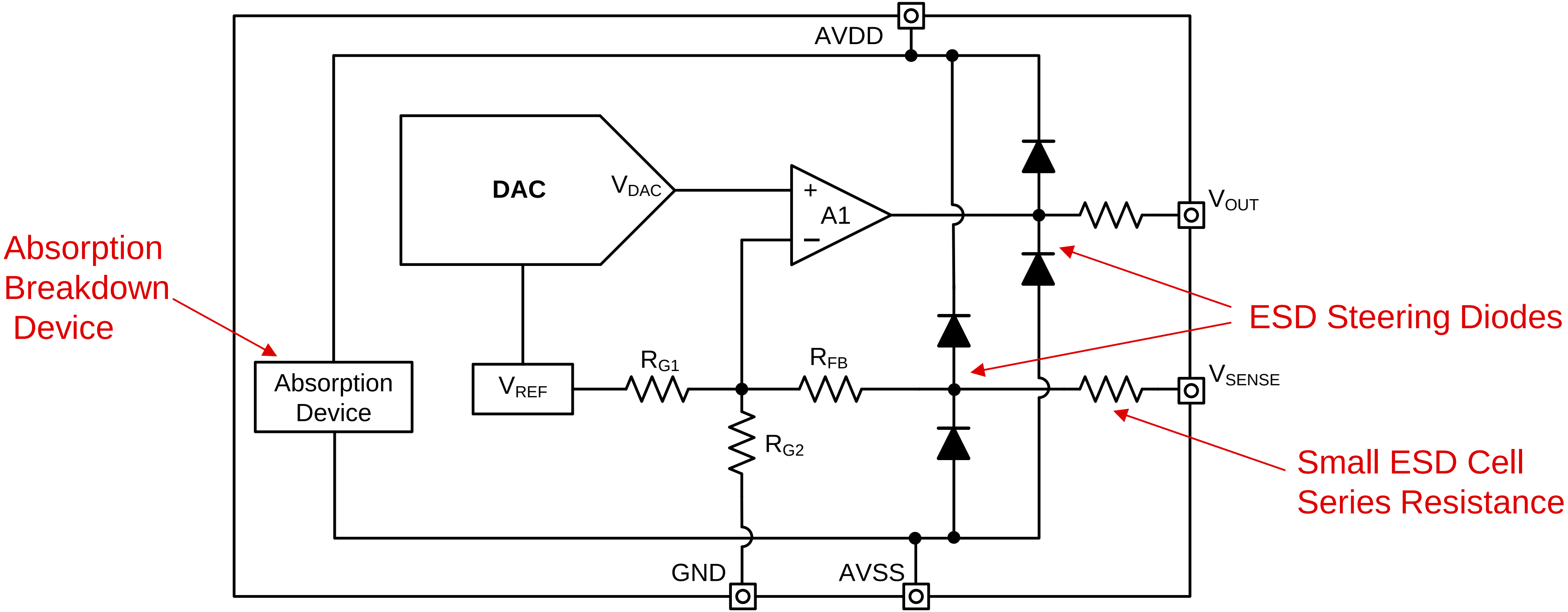
[TIPD190](#)

- **Alternate DACs:**
  - DAC5311, DAC6311, DAC7311, DAC8311, DAC8411
  - DAC8550/DAC8551 (16-bit, Buffered Output)
  - DAC8830 (16-bit, Very High Accuracy)
- **Alternate XTRs:**
  - XTR115
  - XTR117

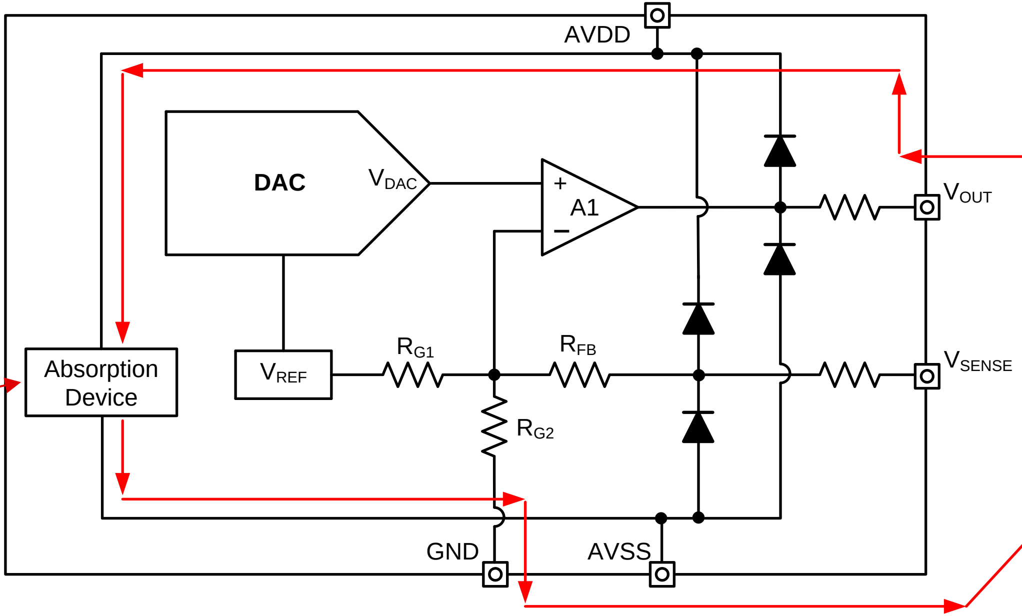
# Designing Protection Solutions

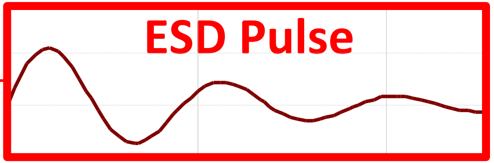
## *How do parts get damaged? How is this tested? How do we prevent designs from damage?*

# ESD Protection Inside an IC



# ESD Protection Circuit with ESD Pulse Applied

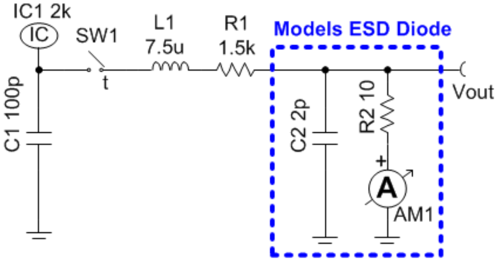


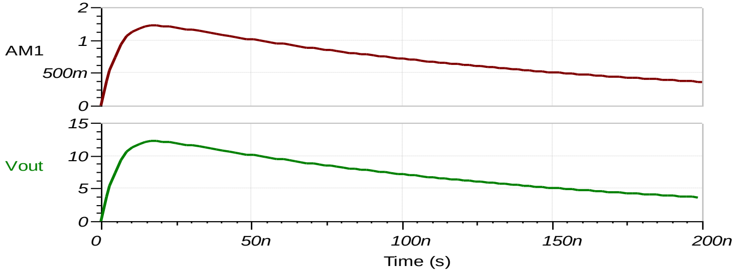




ESD diodes direct ESD pulse to absorption device

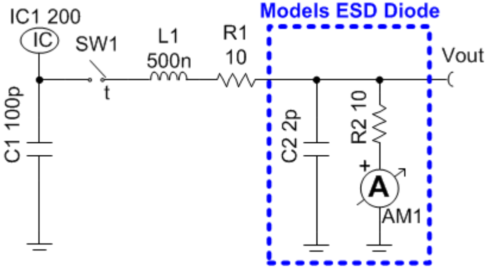
# Types of ESD Simulator Pulses

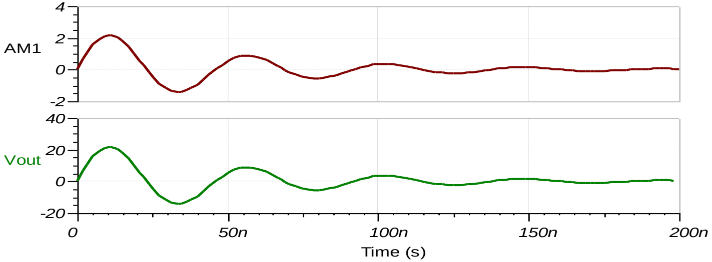
## Human Body Model (HBM)



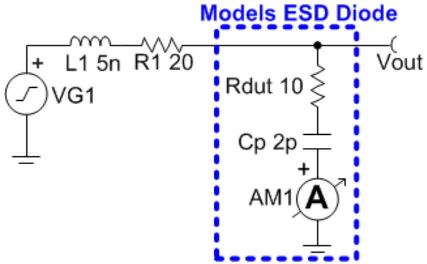



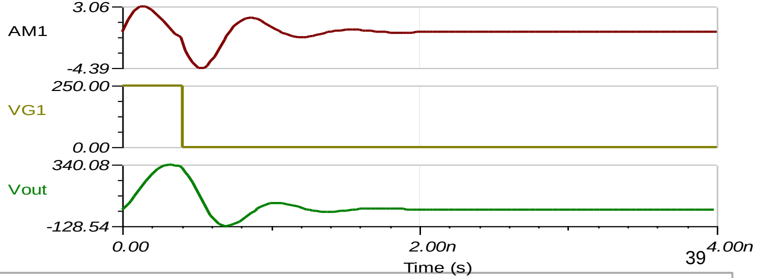

## Machine Model (MM)




## Charged Device Model (CDM)



# Electrostatic Discharge vs. Electrical Overstress

## ESD

- Short duration event (1-100ns)
- High voltage (kV)
- Fast edges
- Low Energy
- Both “in-circuit” and “out-of-circuit”

## EOS

- Can be a short or longer duration event
  - Nanoseconds to Milliseconds or more
  - Can be continuous
- High or Lower voltage
  - May be kVs or only a few volts beyond absolute maximum ratings
- High Energy
- “In-circuit” event only

# IEC61000-4 Test Suite

- IEC61000-4 contains 35 different immunity test standards
- Most commonly applied immunity tests:
  - Electrostatic Discharges
    - **IEC61000-4-2: Electrostatic Discharge Immunity**
  - HF Conducted Disturbances
    - **IEC61000-4-4: Electrically Fast Transient Immunity**
    - **IEC61000-4-5: Surge Immunity**
    - **IEC61000-4-6: Conducted Immunity Tests**
  - HF Radiated Disturbances
    - **IEC61000-4-3: Radiated Immunity**
    - IEC61000-4-9: Pulse Magnetic Field Tests
  - LF Radiated Disturbances
    - IEC61000-4-8: Power Frequency Magnetic Field Immunity

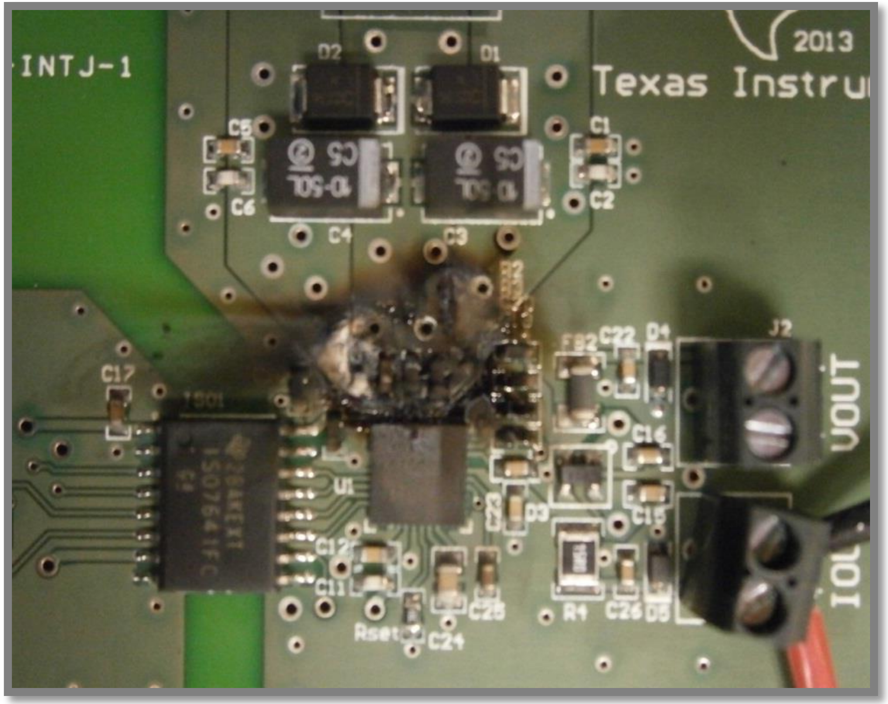
# IEC61000-4 Classifications

- Two Components for each test
  I. Threat Level
  II. Class

Classification of results for IEC61000-4 Immunity

| Grade | Description |
|---|---|
| **Class A** | Normal performance within an error band specified by the manufacturer. |
| **Class B** | Temporary loss of function or degradation of performance which ceases after the disturbance is removed. The equipment under test recovers its normal performance without operator interference. |
| **Class C** | Temporary loss of function or degradation of performance, correction of performance requires operator intervention. |
| **Class D** | Loss of function or degradation of performance which is not recoverable, permanent damage to hardware or software, or loss of data. |

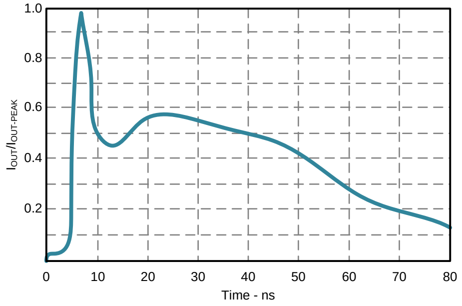
# Example of Class D Results



# IEC61000-4 Test

- IEC61000-4-2: Electrostatic Discharge Immunity (2kV to 15kV)
  - Simulates the electrostatic discharge of an operator directly onto an electrical component

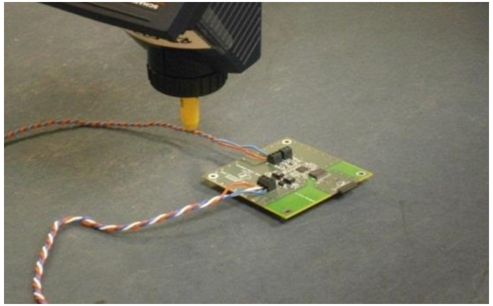
ESD Test Pulse



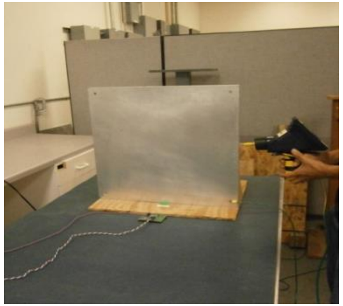

- This is system level immunity
- This ***is not*** JEDEC HBM/CDM/MM device level immunity!!
- Read article for more information:

Understanding and Comparing the differences in ESD Testing – T. Kugelstadt & D. Byrd on EDN, Oct 6, 2011

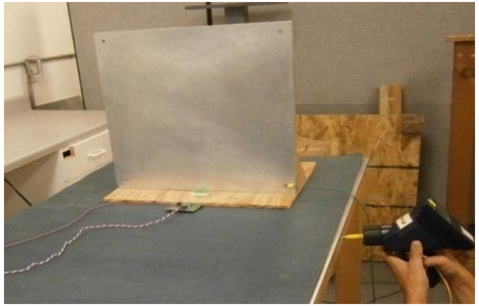
Air Discharge



Vertical Coupling



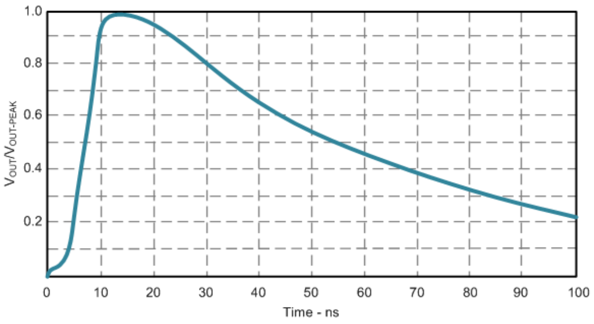
Horizontal Coupling



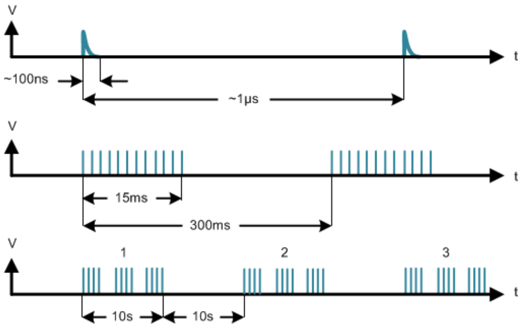
# IEC61000-4 Testing

- IEC61000-4-4: Electrically Fast Transient Immunity (0.5kV to 4kV)
  - Simulates every day switching transients common in industrial applications

### EFT Test Pulse




### EFT Pulse Train

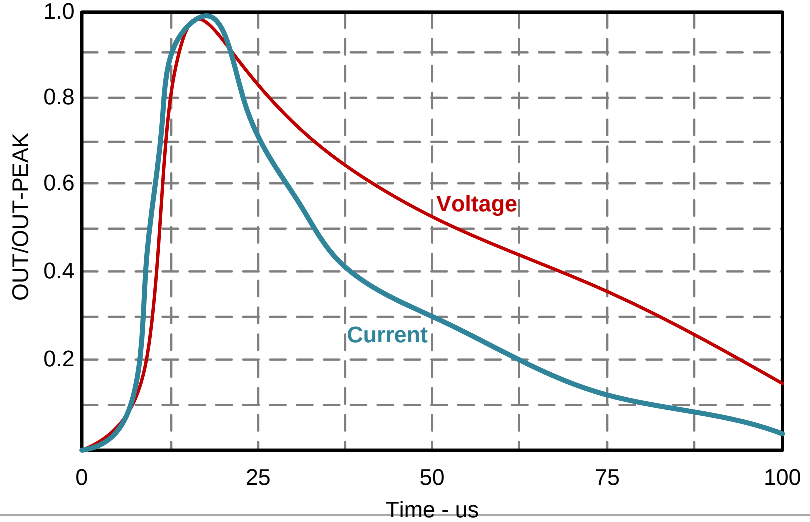



### EFT Test Setup

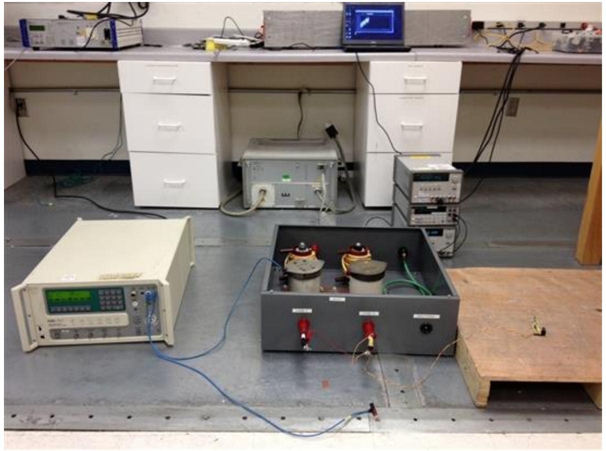
# IEC61000-4 Testing

- IEC61000-4-5: Surge Immunity (0.5kV to 4kV)
  - Simulates very severe transients such as lightning strikes
- Output impedance for Surge Immunity tests varies
  - Energy content of test pulse could be very large, protection solution will vary

Surge Test Pulse




EFT Test Setup



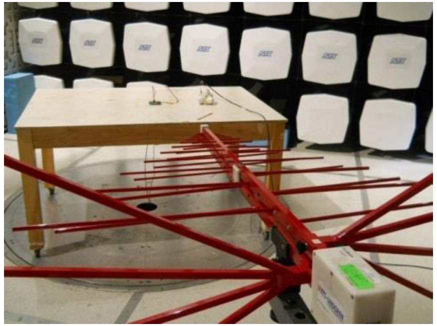


Texas Instruments

# IEC61000-4 Testing

- IEC61000-4-3: Radiated Immunity (1V/m to 30V/m)
  - Simulates exposure to high frequency radiated emissions in the range of 80MHz to 1GHz
- IEC61000-4-6: Conducted Immunity (3V/m to 10V/m)
  - Simulates exposure to radio frequency emissions in the range of 150kHz to 80MHz

RI Horizontal Setup



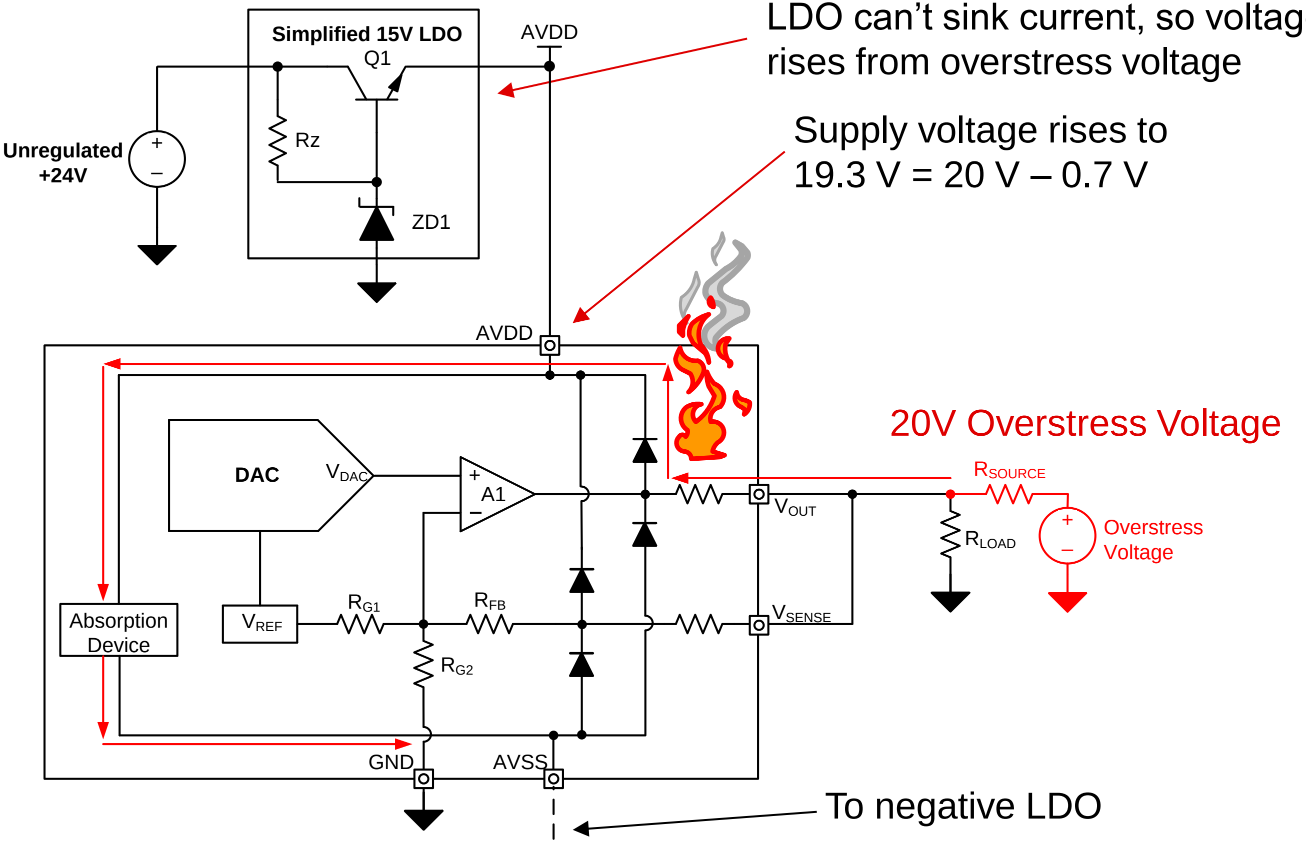
RI Vertical Setup

CI Test Setup

# Continuous Electrical Overstress on Output

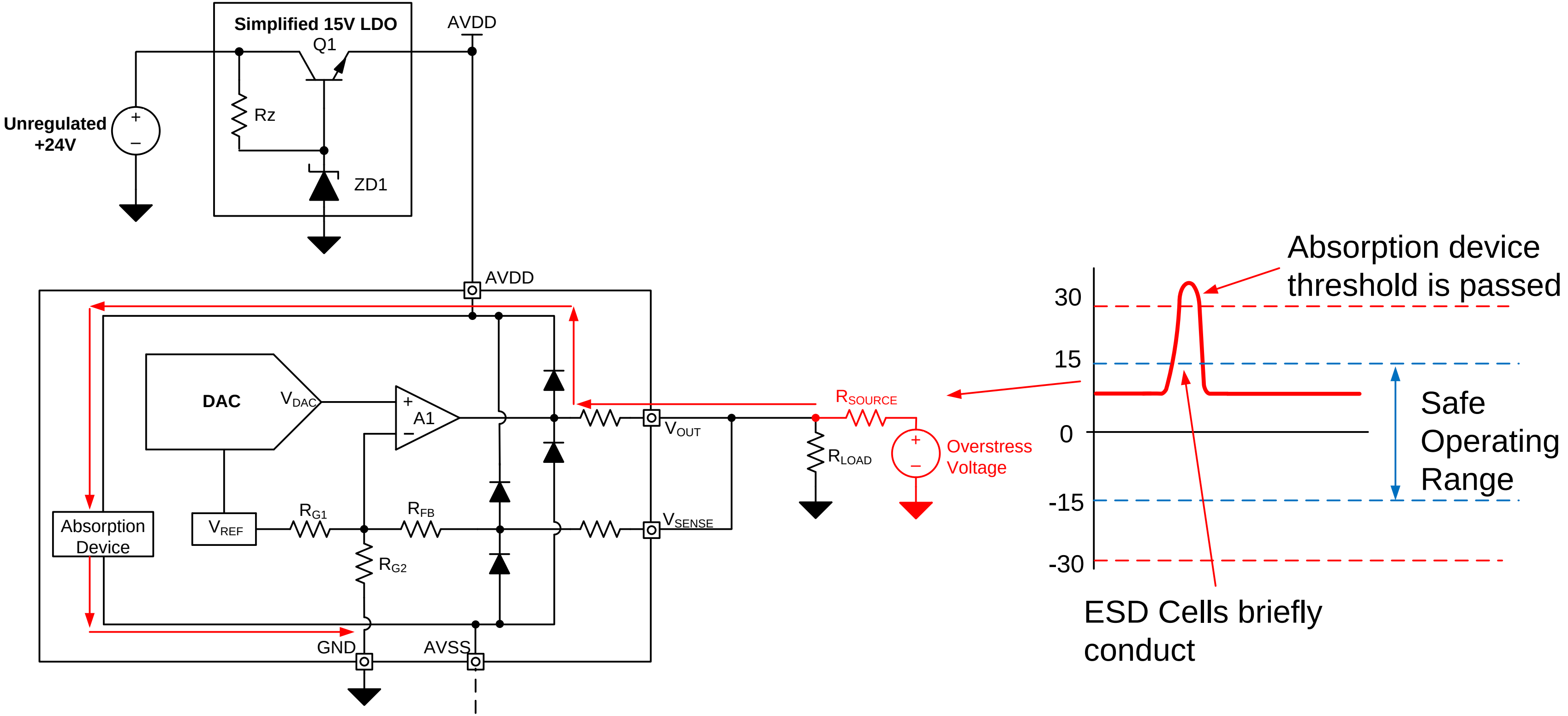
LDO can't sink current, so voltage rises from overstress voltage

Supply voltage rises to 19.3 V = 20 V – 0.7 V

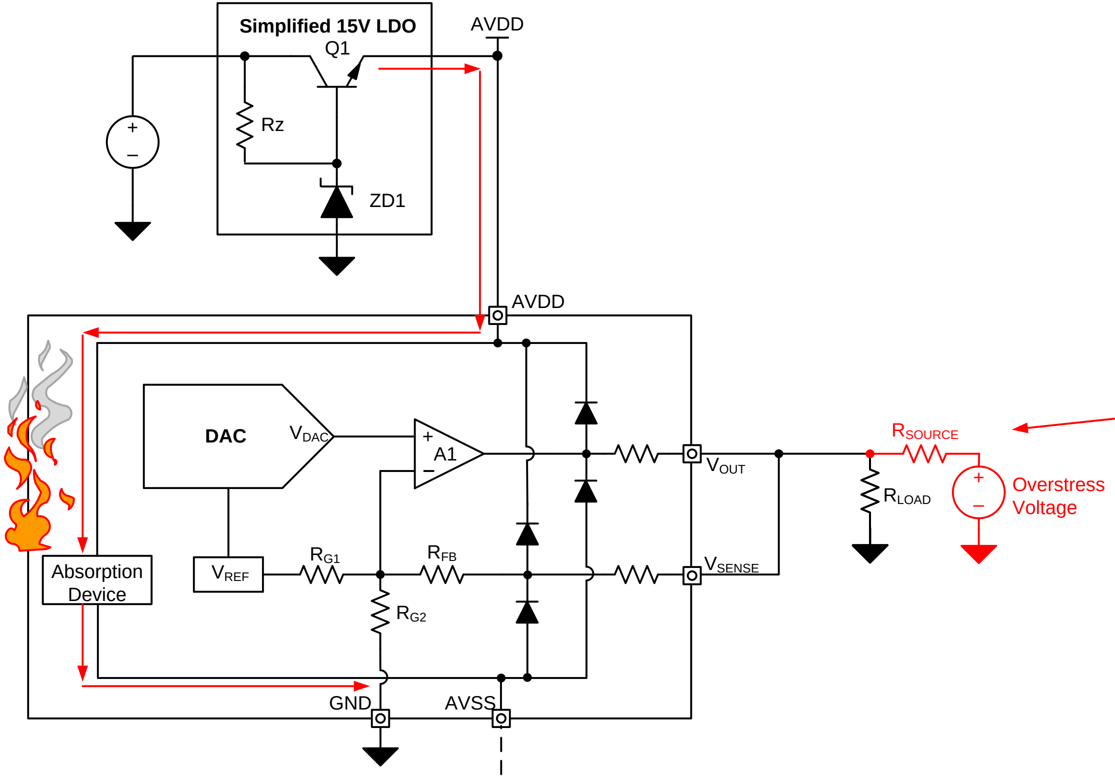


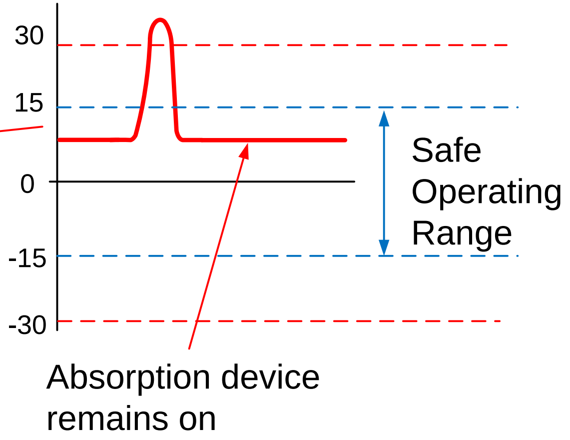

To negative LDO

# Fast Electrical Overstress on Output

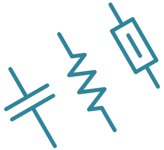


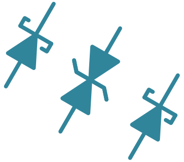
# Fast Electrical Overstress on Output



# EMC/EMI Tested Analog Output





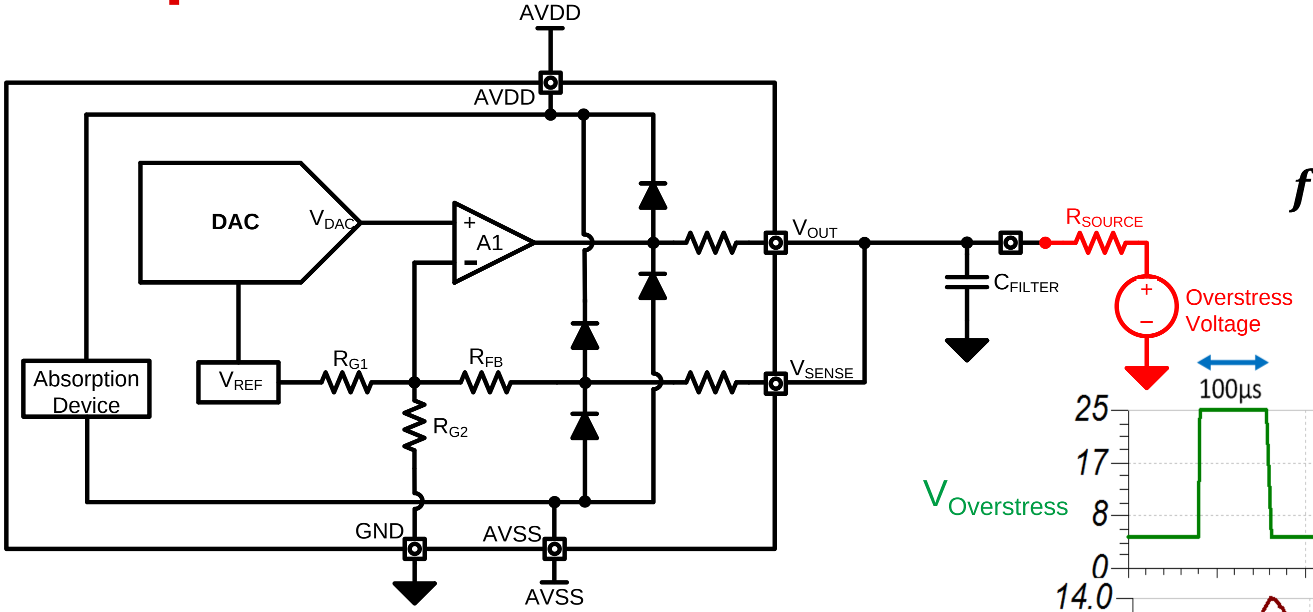
## Attenuation

- This method uses passives (resistors, capacitors, ferrite beads) to *attenuate* sudden voltage changes and limit current
- Level of protection depends on ability to anticipate input signal magnitude, frequency and shape
- IR drops skew DC accuracy
- Excessive capacitance limits bandwidth

## Diversion

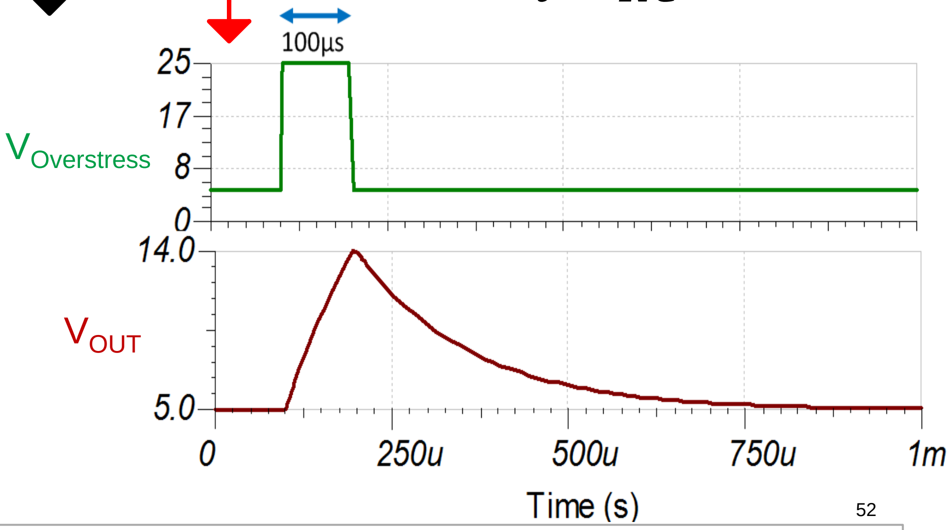
- This method uses voltage clamps (TVS diodes, Schottky diodes)
- These devices *clamp* the input voltage and divert the energy away from the IC
- *Does not limit current*
- Parasitic capacitance, current leakage and response time can complicate design

# Simple RC Filter Can Reduce Transients




$$f_c = \frac{1}{2\pi C_{Filter} R_{Source}}$$

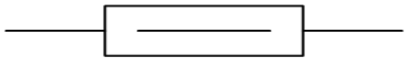
$$\tau = RC$$




**Note:** After one time constant, the filter output will be ~63% of maximum

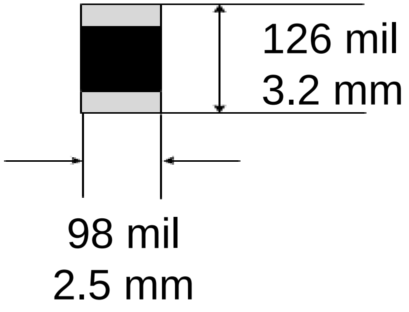
# Ferrite Bead/Ferrite Chip

## Schematic Symbol

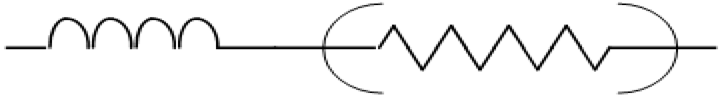


**42 mΩ** at DC
**600 Ω** at 600 MHz
**3 A** rated current

## 1210 Package (3225 Metric)



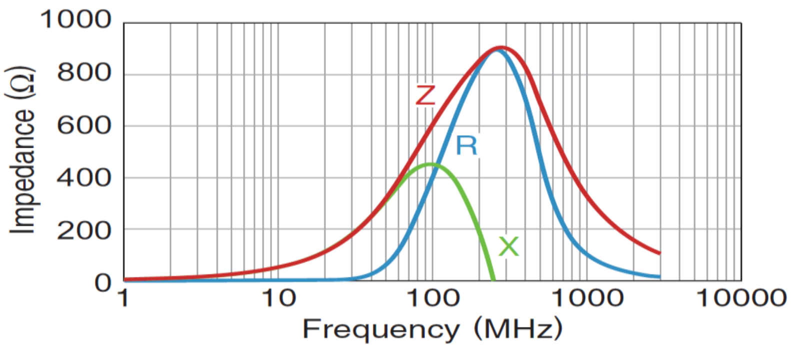

## Model



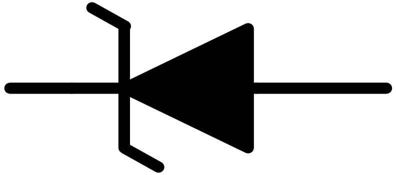
Inductance

Frequency-variable resistance

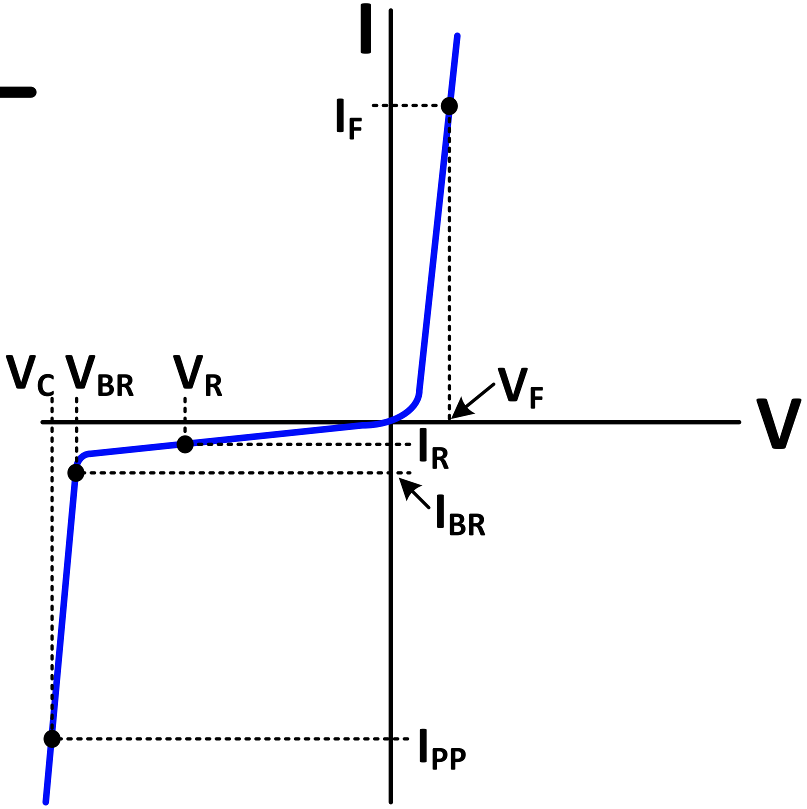
## Characteristic



# Unidirectional Transient Voltage Suppressor (TVS) Diode



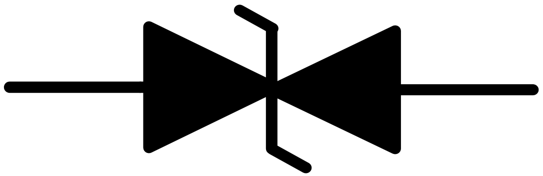
| Symbol | Parameter |
|---|---|
| $V_{BR}$ | Breakdown voltage |
| $V_R$ | Stand-off voltage |
| $V_C$ | Clamping voltage |
| $V_F$ | Forward voltage drop |
| $I_{BR}$ | Breakdown Current @ $V_{BR}$ |
| $I_R$ | Reverse Leakage @ $V_R$ |
| $I_F$ | Forward Current @ $V_F$ |
| $I_{PP}$ | Peak Pulse current @ $V_C$ |



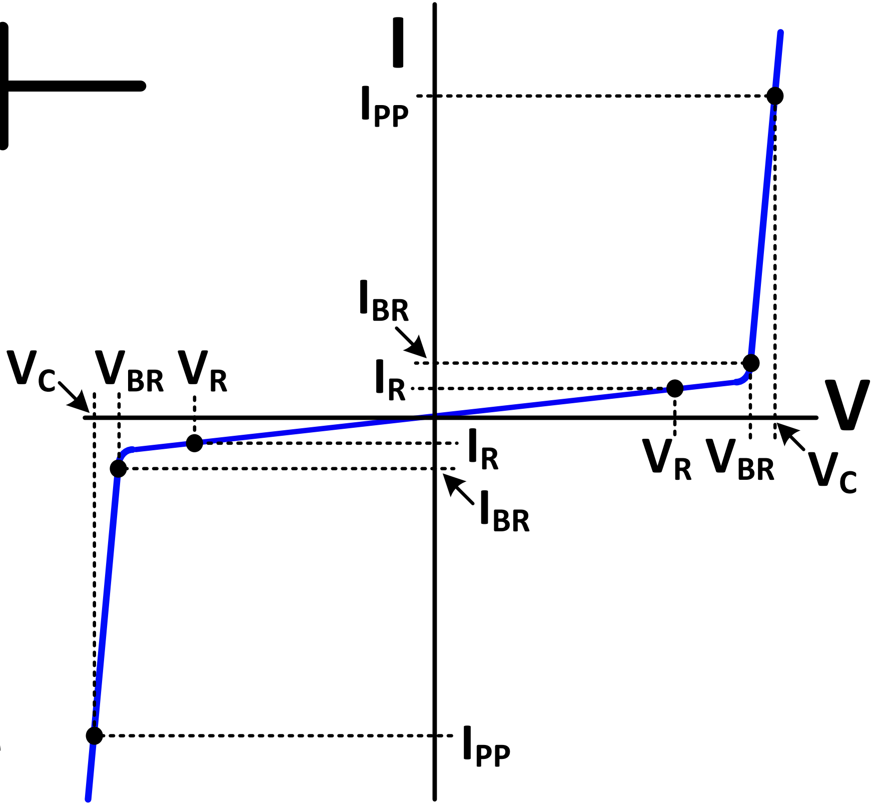

Set $\mathbf{V_R}$ = maximum operating supply voltage

**Note:** leakage current $I_R$ is specified at $V_R$

# Bidirectional Transient Voltage Suppressor (TVS) Diode



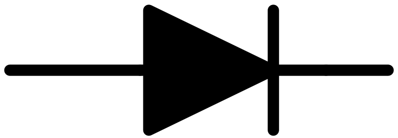
| Symbol | Parameter |
|---|---|
| $V_{BR}$ | Breakdown voltage |
| $V_R$ | Stand-off voltage |
| $V_C$ | Clamping voltage |
| $V_F$ | Forward voltage drop |
| $I_{BR}$ | Breakdown Current @ $V_{BR}$ |
| $I_R$ | Reverse Leakage @ $V_R$ |



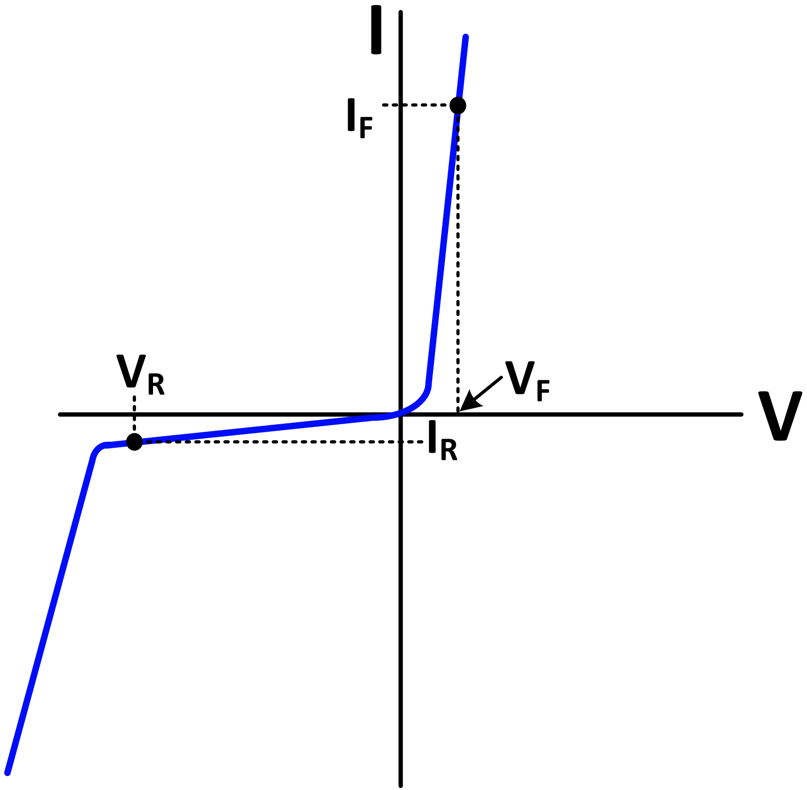

Set $\mathbf{V_R}$ = maximum operating supply voltage

**Note:** leakage current $I_R$ is specified at $V_R$

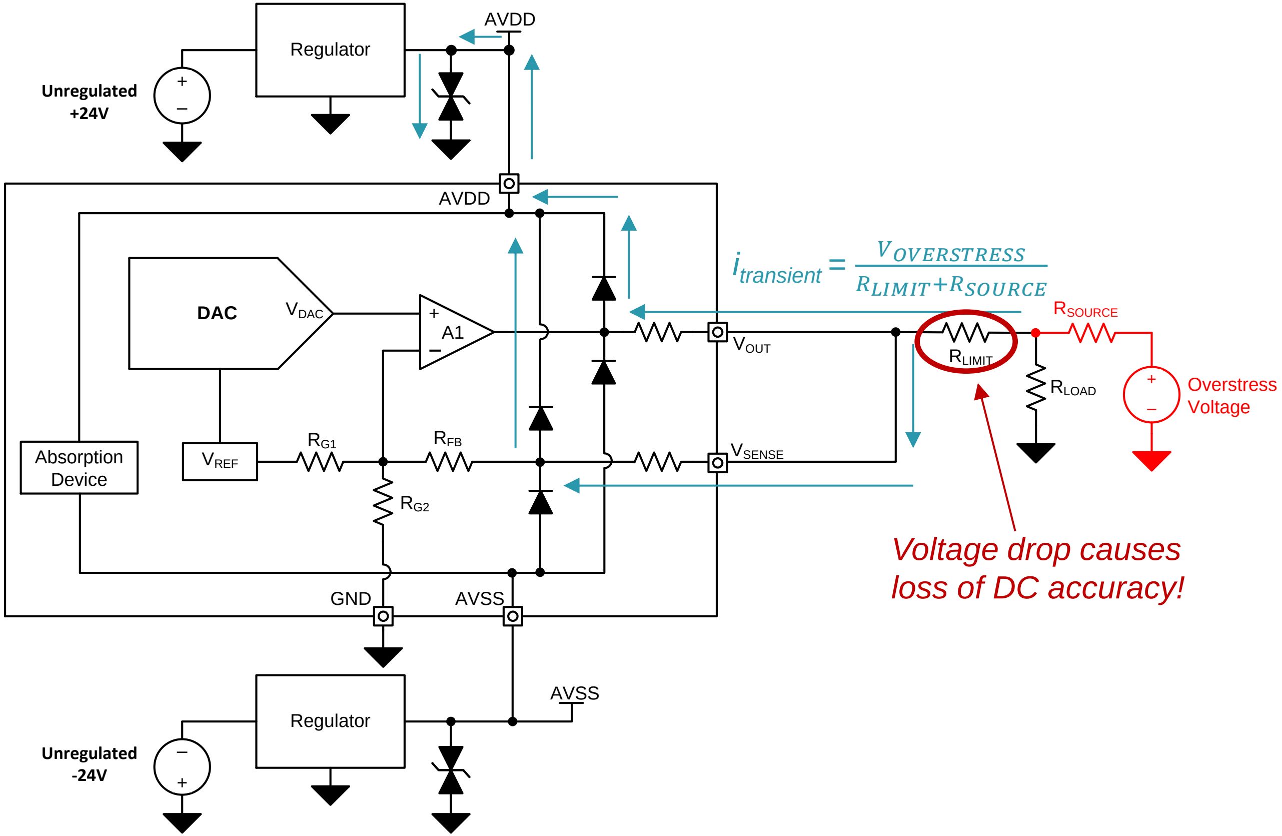
# Low Forward Voltage Diodes (may be Schottky)



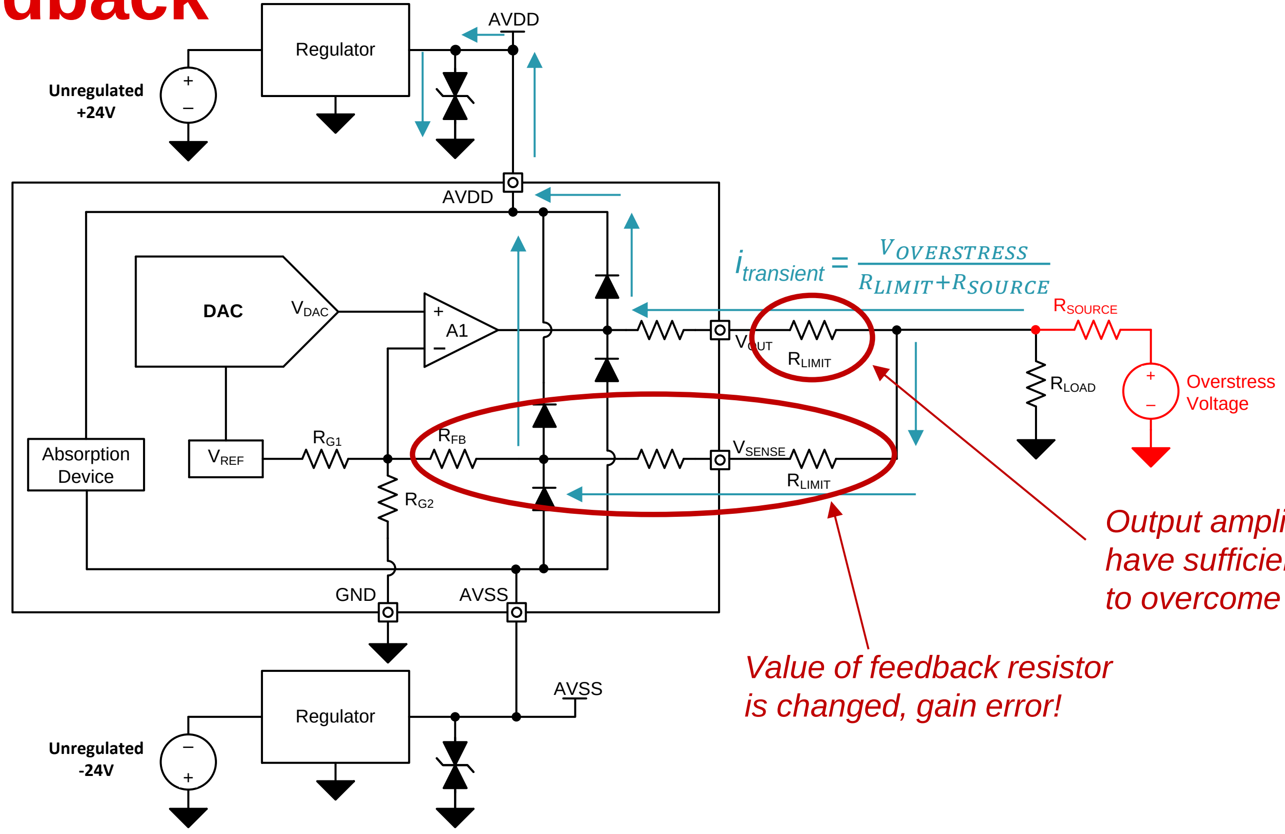
| Symbol | Parameter |
|---|---|
| $V_R$ | Max reverse voltage |
| $V_F$ | Forward voltage drop |
| $I_R$ | Reverse Leakage @ $V_R$ |
| $I_F$ | Forward Current @ $V_F$ |
| $I_{PP}$ | Peak Pulse current @ $V_C$ |



# TVS Diodes on Supplies, Pass Element



# TVS Diodes on Supplies, Pass Elements inside Feedback

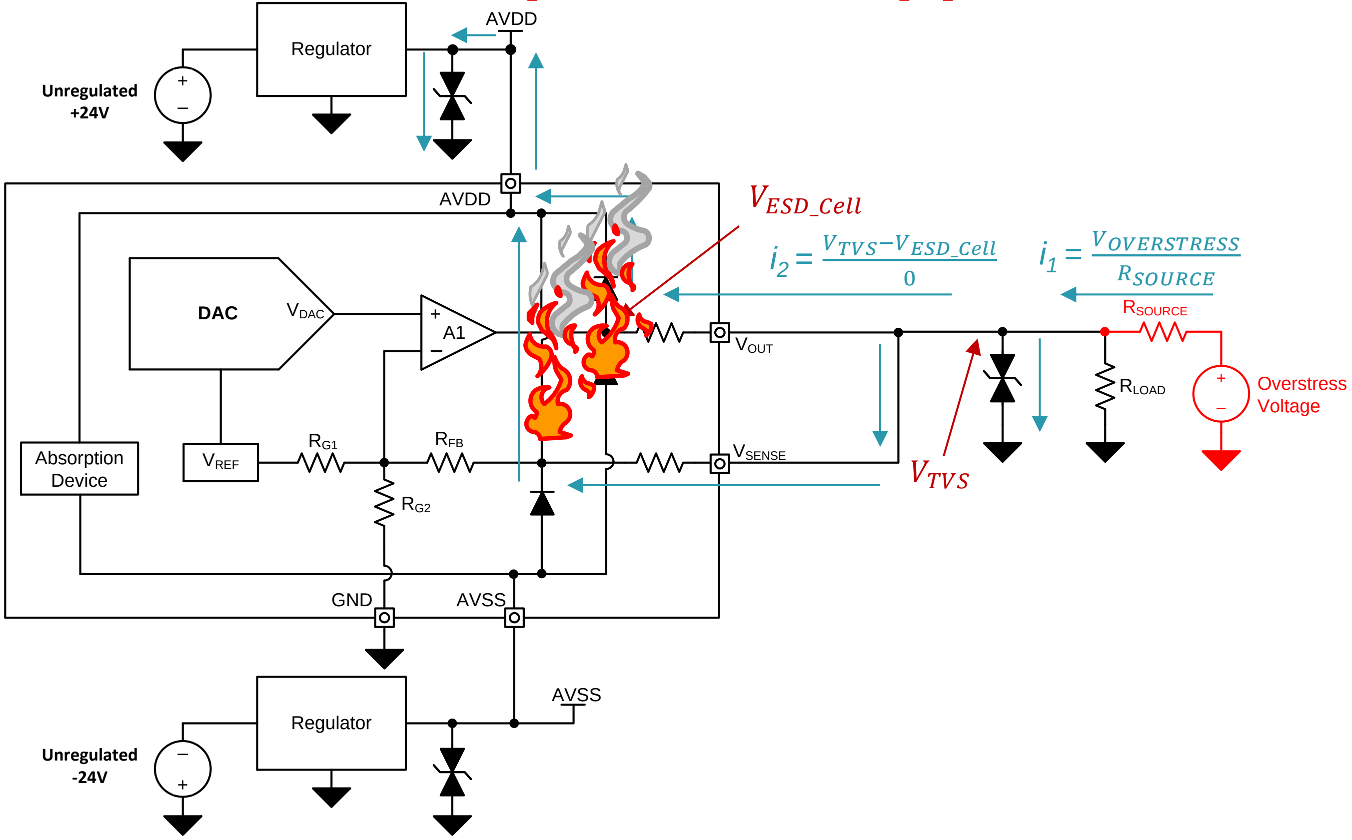



$$i_{transient} = \frac{V_{OVERSTRESS}}{R_{LIMIT} + R_{SOURCE}}$$

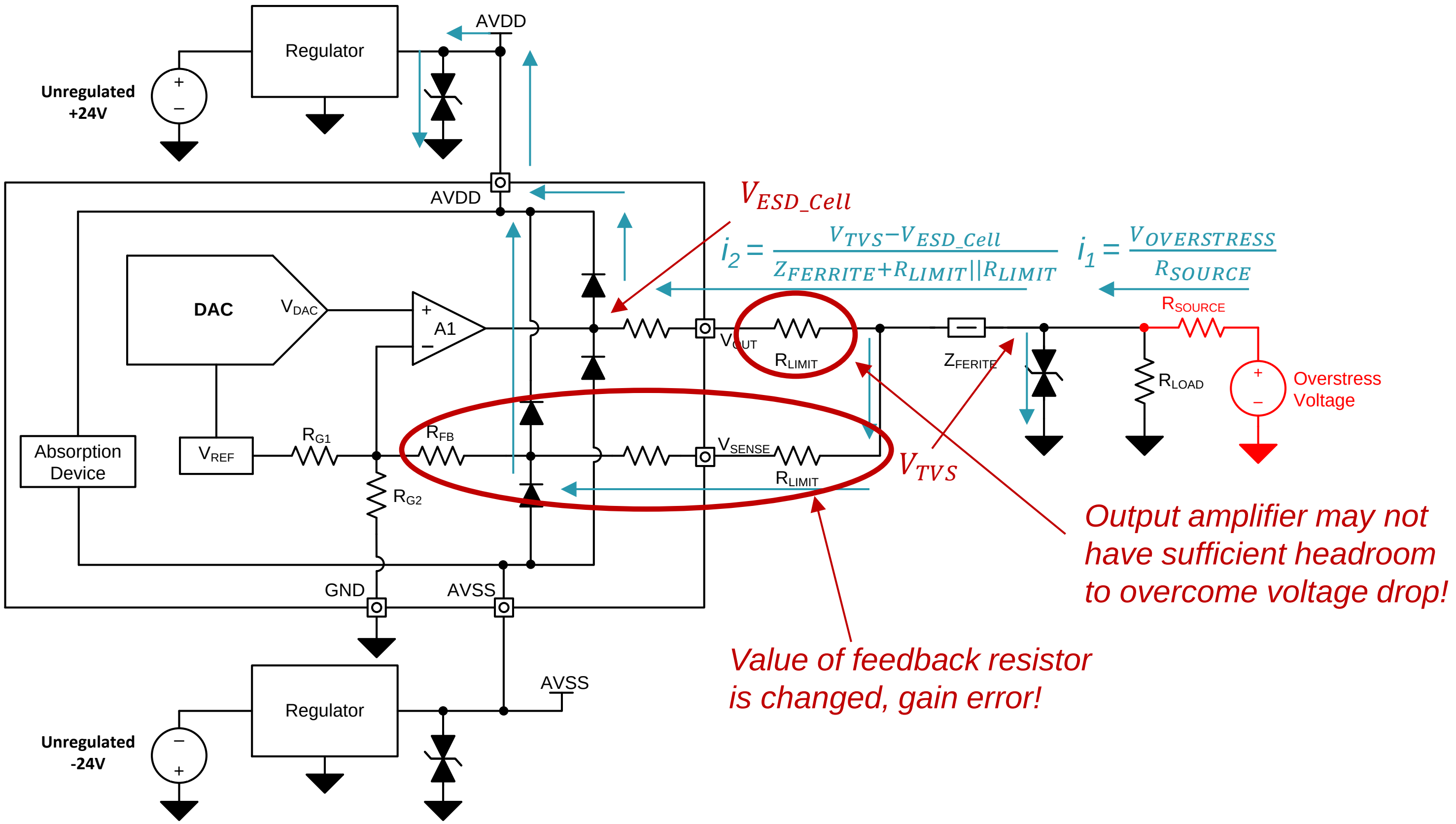
*Output amplifier may not have sufficient headroom to overcome voltage drop!*

*Value of feedback resistor is changed, gain error!*

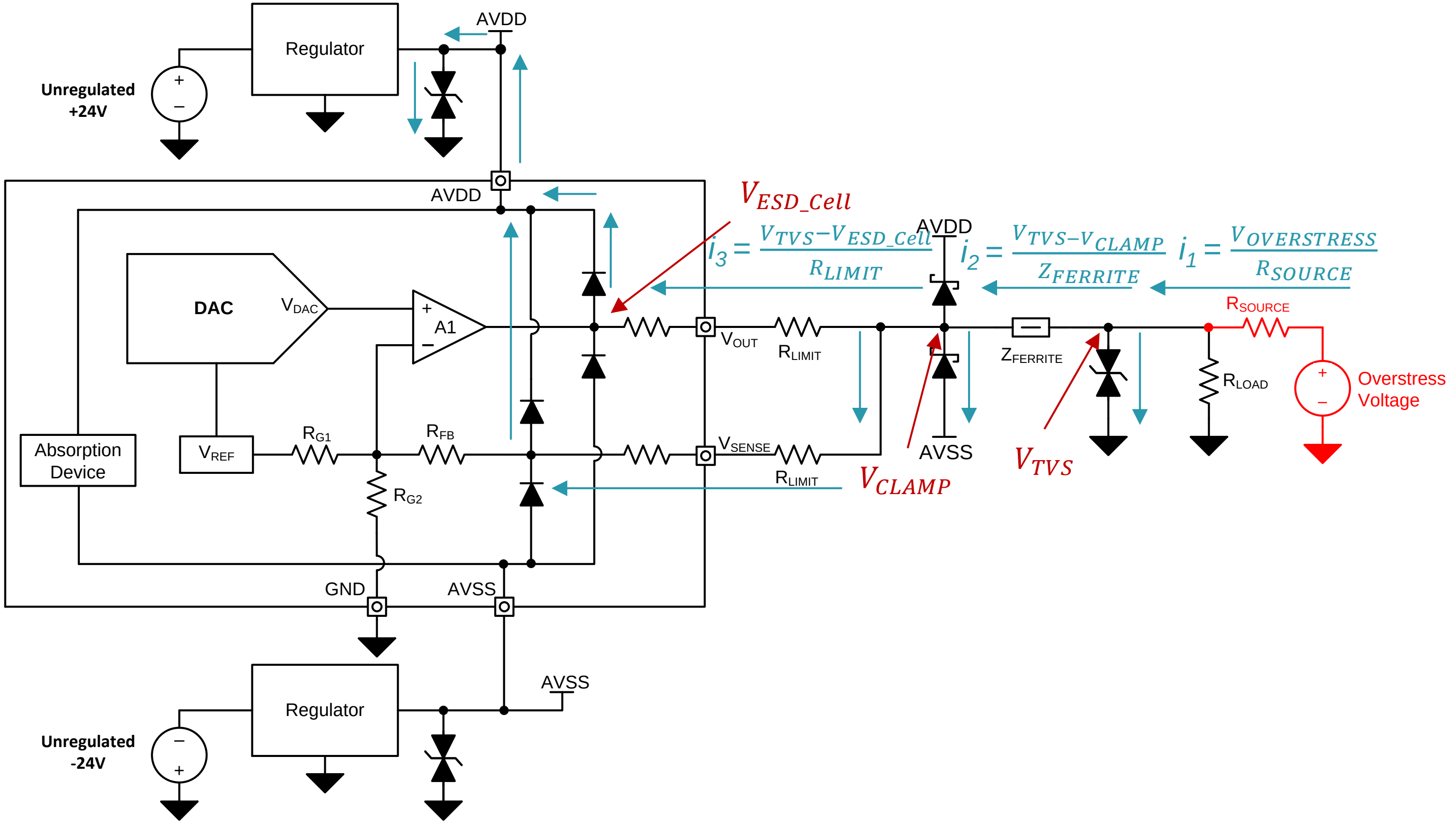
# TVS Diodes on Output and Supplies



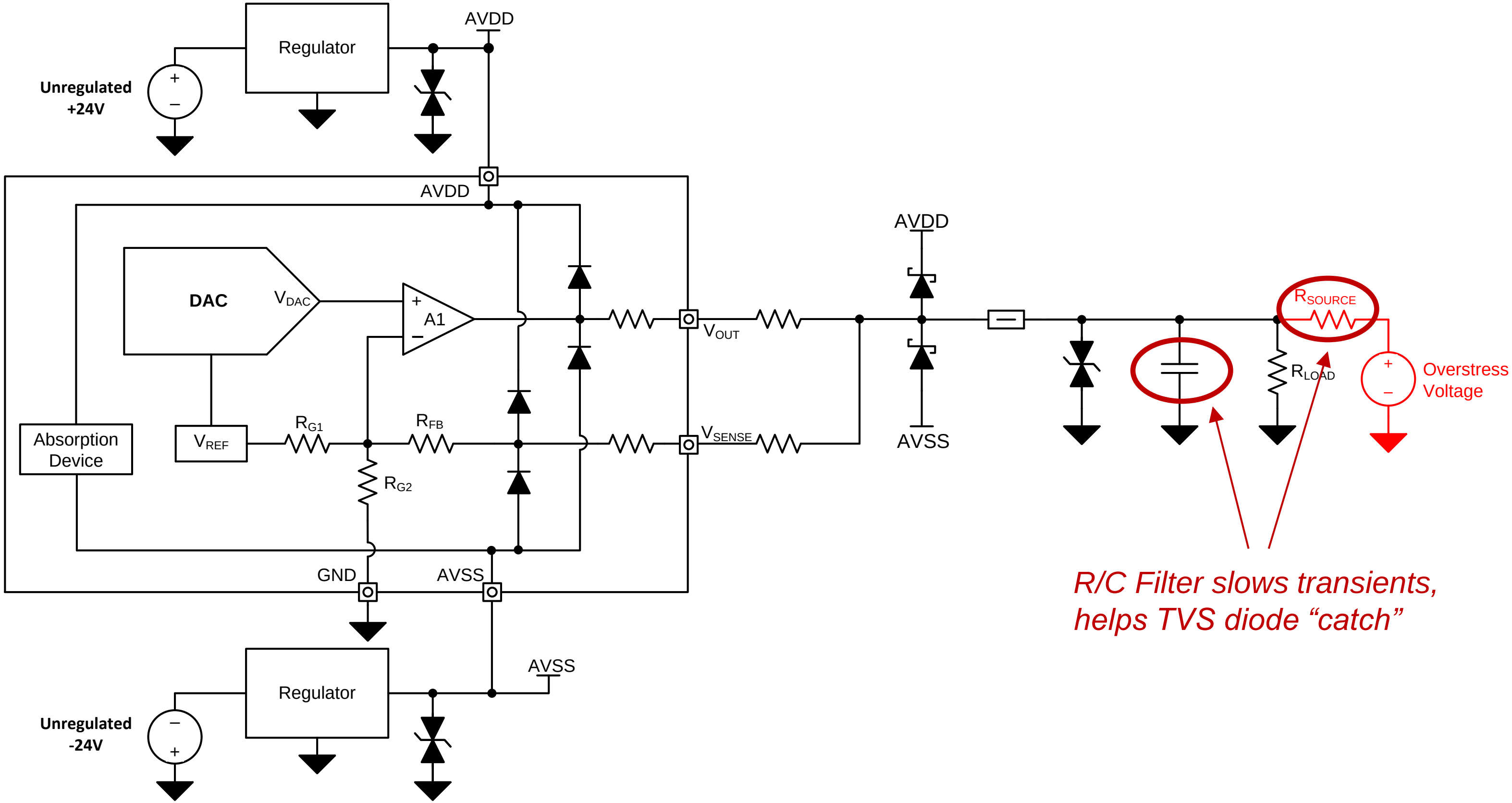
# TVS Diodes & Pass Elements



# TVS Diodes, Clamp-to-Rail, & Pass Elements



# Complete Protection Circuit



# Supporting Collateral

- TI Precision Designs
  - TIPD101: Low-Side Voltage-to-Current Converter
  - TIPD102: High-Side Voltage-to-Current Converter
  - TIPD119: Single Channel Shared Voltage/Current Output Terminal
  - TIPD125: Bipolar +/-10V from a Unipolar DAC
  - TIPD126: Bridge Sensor Conditioner with 2-wire 4-20mA Transmitter, EMC/EMI Tested
  - TIPD153: Single-Channel 3-wire Voltage/Current Output, EMC/EMI Tested
  - TIPD155: Dual Channel Shared Bipolar Voltage/Current Output Terminal
  - TIPD158: Low Cost 2-wire 4-20mA Transmitter, EMC/EMI Tested
  - TIPD160: Analog Linearized 3-Wire PT100 RTD to 2-Wire 4-20mA Current Loop Transmitter Reference Design
  - TIPD190: 2-wire, 4-20mA Transmitter, EMC/EMI Tested Reference Design
  - TIPD202: Analog Linearized 3-Wire PT1000 RTD to 2-Wire 4-20mA Current Loop Transmitter Reference Design
  - TIPD215: Less Than 1-W, Quad-Channel, Analog Output Module w/ Adaptive Power
  - TIPD216: Quad-Channel Industrial Voltage and Current Output Driver, EMC/EMI Tested
- Blog Posts
  - Industrial DACs – Kevin Duke
    - Part I, Part II, Part III, Part IV, Part V, Part VI
  - Input Isolation for 3-wire Analog Outputs – Kevin Duke
  - 4-wire 4-20mA Transmitters
    - Part I, Part II, Part III, Part IV
  - Two-Wire 4-20mA Transmitters: Background & Common Issues – Collin Wells
    - Part I, Part II, Part III, Part IV, Part V, Part VI
  - Electrical Overstress in a nut shell – Art Kay
    - Part I, Part II, Part III
  - Get CerTIfied, not certi-FRIED! Electromagnetic Compatibility Testing Explained – Ian Williams
    - Part I, Part II, Part III, Part IV