Hardware Protection Circuits

By Shimi Cohen

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POWER SUPPLY PROTECTION

Reverse Polarity Protection

MITIGATION

Prevents damage from incorrect power connection polarity.

EXPLANATION

When power connectors are wired backwards, reverse polarity can destroy ICs instantly. Protection circuits block reverse current while allowing forward current.

COMPONENTS USED

- **Schottky Diode**: Low forward drop (0.2-0.4V), fast switching
- **P-Channel MOSFET**: Near-zero voltage drop, higher efficiency
- **Ideal Diode Controller**: Active rectification with minimal loss

Protection Method	Voltage Drop	Power Loss	Cost	Complexity
Schottky Diode	0.2-0.4V	High	Low	Simple
P-Channel MOSFET	<0.1V	Very Low	Medium	Medium
Ideal Diode IC	<0.05V	Minimal	High	Complex

PRACTICAL EXAMPLE

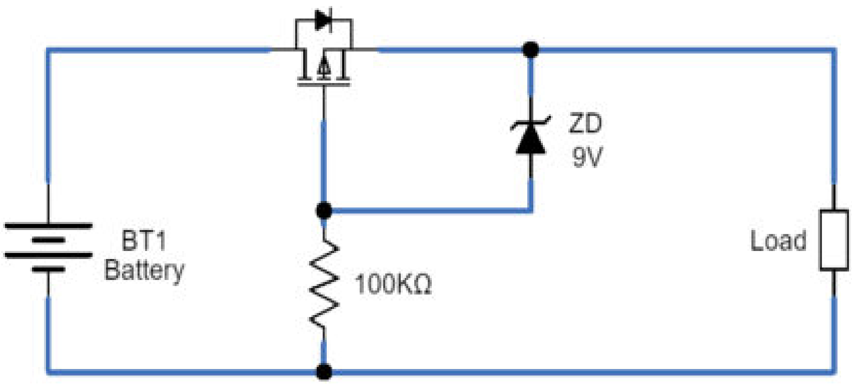
Battery Protection Circuit

Circuit

BAT in → [PMOS + Zener] → BAT out

Components

- PMOS
- Zener Diode



Overvoltage Protection (DC Input)

MITIGATION

Clamps input voltage to safe operating levels.

EXPLANATION

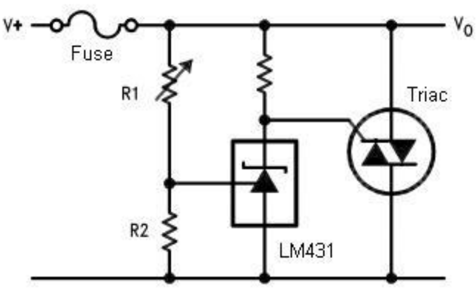
Transient overvoltage from power supplies, automotive load dumps, or industrial environments can exceed IC absolute maximum ratings. Protection circuits either clamp or crowbar excessive voltage.

COMPONENTS USED

- **TVS Diodes**: Fast response (<1ns), self-resetting
- **Zener Diodes**: Precise voltage clamping, lower cost
- **Crowbar Circuits**: SCR-based, triggers fuse/breaker

Component	Response Time	Clamping Accuracy	Energy Handling	Reset
TVS Diode	<1ns	±5%	400W-30kW	Automatic
Zener Diode	<10ns	±2%	1W-50W	Automatic
Crowbar SCR	<1μs	±10%	Very High	Manual

PRACTICAL EXAMPLE



24V Industrial Supply

Input

24V ±20% (19.2V - 28.8V)

Protection

SMBJ30A TVS (30V breakdown, 48.4V clamping)

Load

Sensitive 3.3V logic requiring <6V absolute max

Result

Any spike >30V gets clamped to <48V, triggering upstream fuse

Undervoltage Lockout Protection

MITIGATION

Prevents operation when supply voltage is insufficient.

EXPLANATION

Low supply voltages cause unpredictable digital logic states, corrupted memory, and potential system damage. UVLO circuits maintain reset until voltage reaches safe operating levels.

COMPONENTS USED

- **UVLO ICs**: Dedicated voltage supervisors with precise thresholds
- **PMIC Integration**: Power management ICs with built-in UVLO
- **Comparator Circuits**: Discrete implementations with hysteresis

PRACTICAL EXAMPLE

MCU System

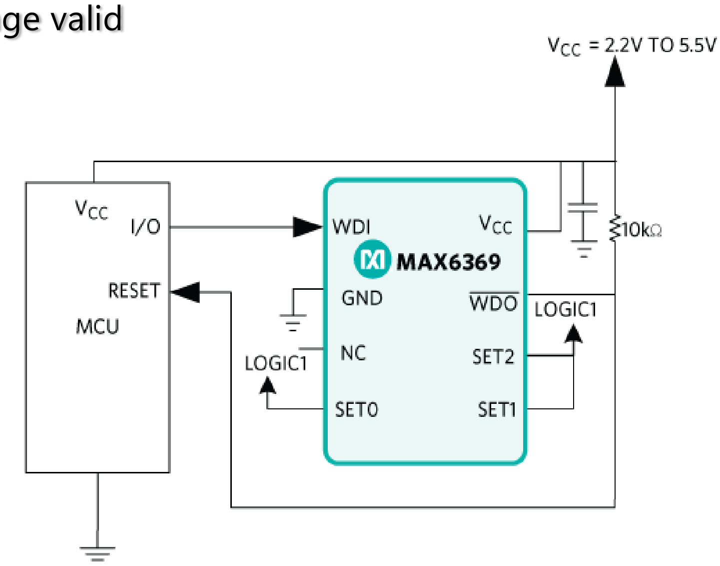
Application

ARM Cortex-M4 @ 3.3V

UVLO IC

MAX6369

- Rising threshold: 3.08V (typical)
- Falling threshold: 2.93V (typical)
- Hysteresis: 150mV prevents oscillation
- Reset delay: 200ms after voltage valid



Power Sequencing Protection

MITIGATION

Ensures correct power-up and power-down order.

EXPLANATION

Complex systems with multiple supply rails require specific sequencing to prevent latch-up, excessive current draw, or logic corruption.

COMPONENTS USED

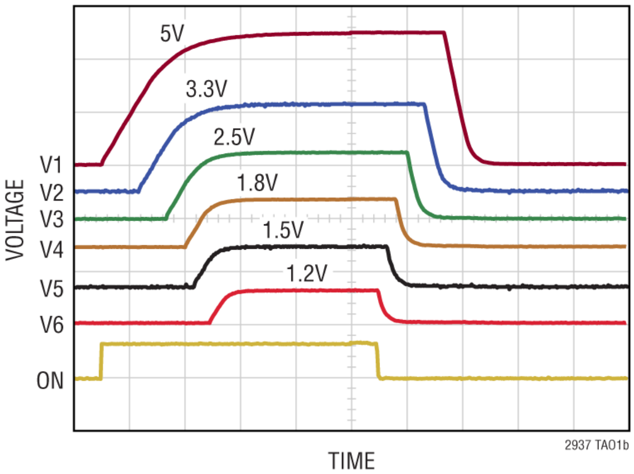
- **Sequencer ICs**: Programmable timing and thresholds
- **"Oring" Diodes**: Prevents reverse current between rails
- **Power MOSFETs**: Controlled rail switching

PRACTICAL EXAMPLE

FPGA Power System

Sequence Required

1. 5V First
2. 3.3V I/O
3. 2.5V Auxiliary
4. 1.8V Transceiver
5. 1.5V DDR memory
6. 1.2V Core Logic



Implementation

LTC2937 6-channel sequencer

- Monitors all rails with 0.8% accuracy
- Programmable delays via I2C
- Automatic shutdown on any rail fault

CURRENT PROTECTION

Overcurrent Protection

MITIGATION

Breaks circuit when current exceeds safe limits.

EXPLANATION

Excessive current causes component heating, trace damage, and potential fire hazards. Current limiting protects both the supply and load circuits.

COMPONENTS USED

- **Fuses**: One-time protection, very reliable
- **Circuit Breakers**: Resettable, mechanical operation
- **Current Limiters**: Active electronic limiting

Protection Type	Response Time	Reset Method	Accuracy	Cost
Fast-Blow Fuse	0.1-10ms	Replace	±20%	Very Low
Slow-Blow Fuse	1-100ms	Replace	±20%	Low
PTC Resettable	0.1-10s	Automatic	±30%	Medium
Electronic Limit	<1μs	Automatic	±5%	High

PRACTICAL EXAMPLE

USB Power Delivery:

Application

USB-C 5V/3A Power Supply

Primary

3.5A fast-blow fuse (automotive grade)

Secondary

MIC2097 current-limited switch

- 3.1A current limit (typical)
- 85mΩ on-resistance
- Thermal shutdown at 165°C
- Automatic retry after fault clears

Short Circuit Protection

MITIGATION

Rapidly disconnects power during short circuits.

EXPLANATION

Short circuits create near-infinite current demand, limited only by supply impedance and trace resistance. Protection must act within microseconds to prevent damage.

COMPONENTS USED

- **Poly-fuses (PPTC)**: Self-resetting, temperature activated
- **Current Switches**: Electronic, fast response
- **Magnetic Breakers**: Instantaneous trip on high current

PRACTICAL EXAMPLE

DC Motor Drive:

Application

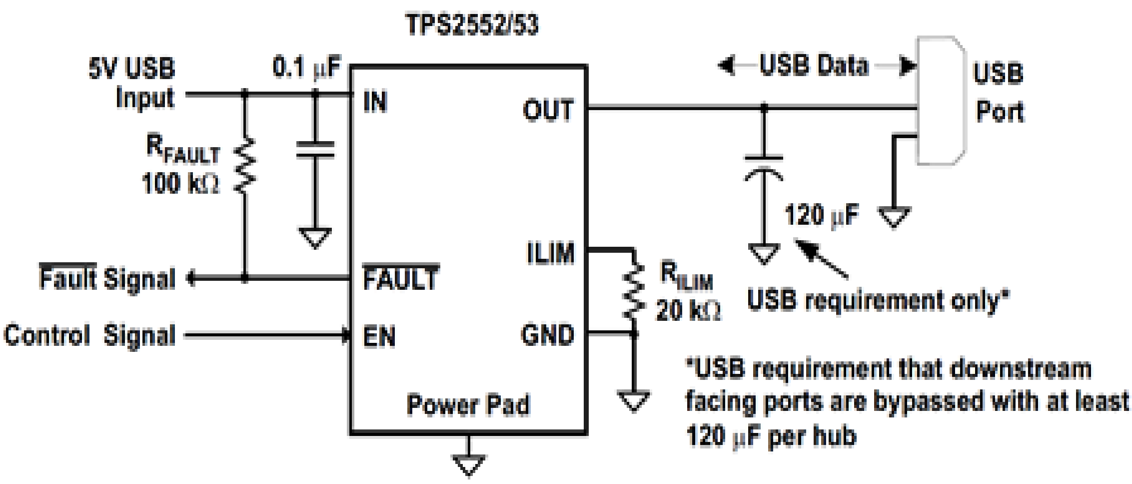
24V/10A Brushed DC Motor

Protection

Bourns MF-R300 PTC + TPS2065 Load Switch

PTC Spec

- Hold current 3.0A
- Trip current 6.0A
- Max voltage 30V



Inrush Current Limiting

MITIGATION

Controls surge current during power-up.

EXPLANATION

Capacitive loads create high inrush currents that can trip protection circuits or damage power supplies. Soft-start circuits gradually increase current.

COMPONENTS USED

- **NTC Thermistors**: Passive, temperature-dependent resistance
- **Soft-start ICs**: Active control with precise timing
- **Series Resistance**: Simple, constant limitation

PRACTICAL EXAMPLE

Switch-Mode Power Supply:

Application

100W SMPS with 2200µF Input Capacitor

Without Protection

50A+ inrush spike

With 5Ω NTC (B57364S0509M)

- Cold resistance: 5Ω (limits to 4.8A @ 24V)
- Hot resistance: 0.05Ω (minimal steady-state loss)
- Time constant: ~2 seconds to reach 10% resistance

Reverse Current Protection

MITIGATION

Prevents current flow in reverse direction.

EXPLANATION

Reverse current occurs during power-down, battery backup switching, or system faults. Can cause unexpected operation or component stress.

COMPONENTS USED

- **Schottky Diodes**: Low forward drop, fast recovery
- **Ideal Diode Controllers**: MOSFET-based, minimal loss
- **Body Diode Blocking**: Additional MOSFET in series

PRACTICAL EXAMPLE

Battery Backup System

Application

5V System with 6V Battery Backup

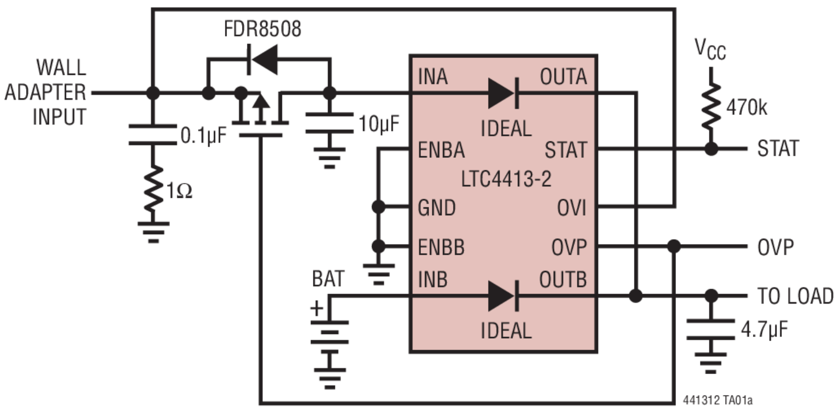
Main Supply

5V/2A switching regulator
Backup: 4x AA NiMH (4.8V nominal)

Protection

LTC4413 Dual Input Power Manager

- Automatic switchover at 4.5V main supply
- <25mV forward drop on both paths
- Prevents reverse current in both directions



SIGNAL INTEGRITY PROTECTION

Static Discharge (ESD) Protection

MITIGATION

Shunts electrostatic discharge to ground.

EXPLANATION

Human body can generate 15kV+ static charges. ESD events create nanosecond current spikes exceeding 30A, destroying junction interfaces in semiconductors.

COMPONENTS USED

- **TVS Diodes**: Bidirectional clamping for signal lines
- **ESD Arrays**: Multi-channel protection in single package
- **Series Resistors**: Current limiting during ESD events

ESD Standard	Test Voltage	Current Peak	Duration	Application
HBM (Human)	±8kV	30A	100ns	General handling
MM (Machine)	±800V	100A	10ns	Manufacturing
CDM (Device)	±2kV	20A	1ns	IC-level stress

PRACTICAL EXAMPLE

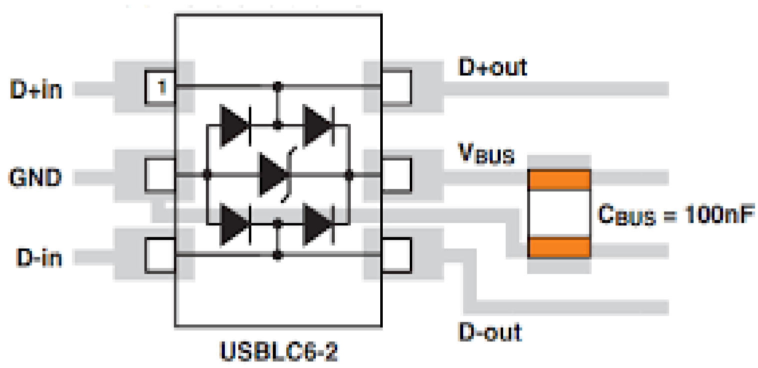
USB Interface Protection

Interface

USB 2.0 Data Lines (D+, D-)

ESD Protection

USBLC6-2SC6



Specifications

- Clamping voltage: 10V @ 1A
- Leakage current: <1µA
- Capacitance: 7pF (maintains signal integrity)
- ESD rating: ±15kV Contact, ±8kV Air Gap

Input Pin Overvoltage Protection

MITIGATION

Protects MCU and logic pins from voltage spikes.

EXPLANATION

Digital inputs typically tolerate VCC+0.3V maximum. External signals, long cables, or system faults can inject higher voltages causing latch-up or permanent damage.

COMPONENTS USED

- **Series Resistor**: Current limiting (1kΩ-10kΩ typical)
- **Zener Diodes (two)**: Precise voltage reference clamping

PRACTICAL EXAMPLE

Industrial 24V Input to 3.3V Logic

Signal Path

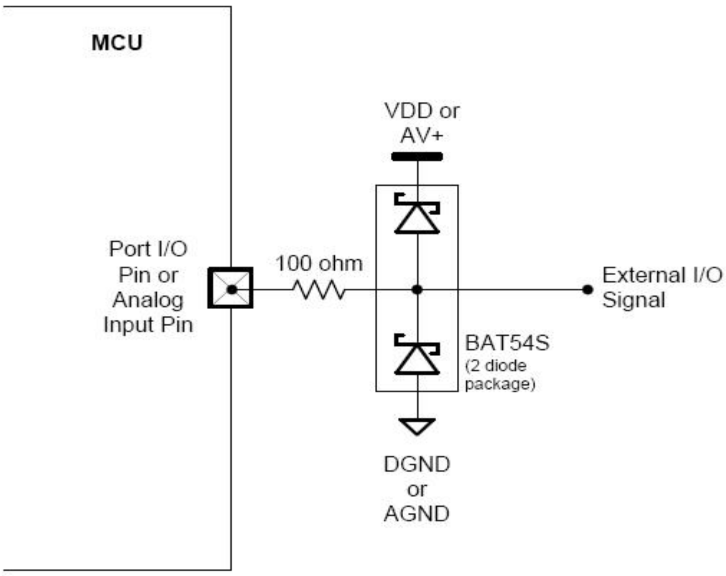
24V_SENSOR → Protection → MCU_GPIO

Protection Circuit

1. 100Ω series resistor (current limit)
2. Schottky to VCC (clamp positive)
3. Schottky to GND (clamp negative)

Result

Any input from -0.7V to +40V safely clamped to 0V-3.6V



Cross-talk Prevention

MITIGATION

Prevents signal interference between traces.

EXPLANATION

High-speed digital switching creates electromagnetic fields that couple into adjacent traces. Coupling increases with frequency, trace length, and proximity.

COMPONENTS USED

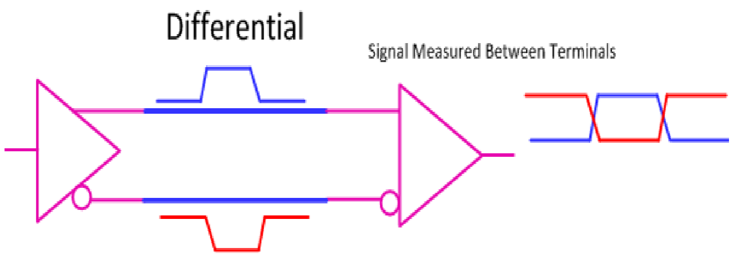
- **Ground Traces**: Shielding between sensitive signals
- **Differential Pairs**: Balanced signaling with noise immunity
- **Guard Rings**: Grounded traces surrounding critical signals

DESIGN RULES

- **3W Rule**: Space traces 3× trace width apart
- **Microstrip**: Controlled impedance with ground plane
- **Via Stitching**: Connect ground planes every λ/20

PRACTICAL EXAMPLE

High-Speed ADC Interface



Application

16-bit 1MSPS ADC with SPI

Critical Traces

CLK, MOSI, MISO (25MHz max)

Protection Method

- Differential clock pairs
- Ground traces between each signal
- Via stitching every 5mm
- Series termination: 33Ω resistors

Result

<5% amplitude coupling between adjacent channels

Data Line Protection

MITIGATION

Protects communication interfaces from transients.

EXPLANATION

Communication lines act as antennas for electromagnetic interference and provide paths for ESD injection. Protection must maintain signal integrity while clamping harmful voltages.

COMPONENTS USED

- **ESD Arrays**: Multi-channel protection for bus interfaces
- **Common Mode Chokes**: Differential noise filtering
- **Series Resistors**: Bandwidth limiting and current protection

PRACTICAL EXAMPLE

Automotive CAN Bus Protection

Interface

CAN High/Low Differential Bus

Environment:

12V automotive with load dump transients

Protection

1. NUP2105LT1G dual TVS array. Clamping: 24V @ 1A pulse. Capacitance: 85pF diff.

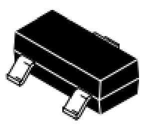
2. Common mode choke: 100µH

3. 120Ω termination with series 10Ω

Result

Passes ISO 10605 ESD testing (±25kV)

SOT–23
DUAL BIDIRECTIONAL
VOLTAGE SUPPRESSOR
350 W PEAK POWER



SOT–23

ELECTROMAGNETICS

Power Supply Spike Protection

MITIGATION

Filters transients from switching power supplies.

EXPLANATION

mode converters create high-frequency noise due to rapid current switching. Spikes couple through parasitic inductance and capacitance, affecting sensitive analog circuits.

COMPONENTS USED

- **Decoupling Capacitors**: High-frequency filtering (ceramic)
- **Bulk Capacitors**: Low-frequency energy storage (electrolytic)
- **Ferrite Beads**: Resistive at high frequencies

Frequency Range	Capacitor Type	Typical Value	ESR	Application
DC-100kHz	Electrolytic	100μF-1000μF	0.1Ω	Bulk storage
100kHz-10MHz	Tantalum	10μF-100μF	0.01Ω	Mid-frequency
10MHz-1GHz	Ceramic X7R	0.1μF-10μF	0.001Ω	High-frequency
>1GHz	Ceramic C0G	10pF-1000pF	<0.001Ω	Very Hi-Freq

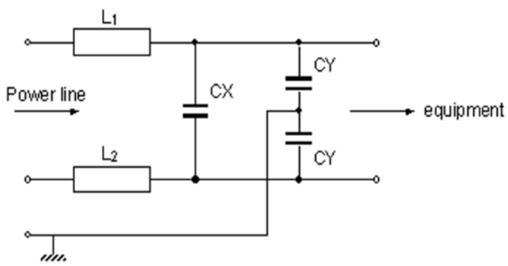
PRACTICAL EXAMPLE

Analog Front-End Power

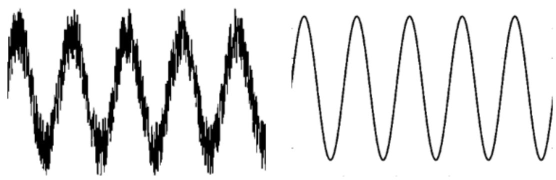
Application

24-bit ADC requiring <10μVpp noise with 5V supply (500KHz Switching)

Filter Network



1. 470μF electrolytic (bulk storage)
2. 10μF tantalum (medium frequency)
3. 0.1μF ceramic (switching noise)
4. 2 Ferrite beads: BLM21PG221SN1D
5. 10pF ceramic (VHF suppression)



Result

Power supply noise <2μVpp at ADC

High Frequency Noise Filtering

MITIGATION

Removes transient noise above useful signal bandwidth.

EXPLANATION

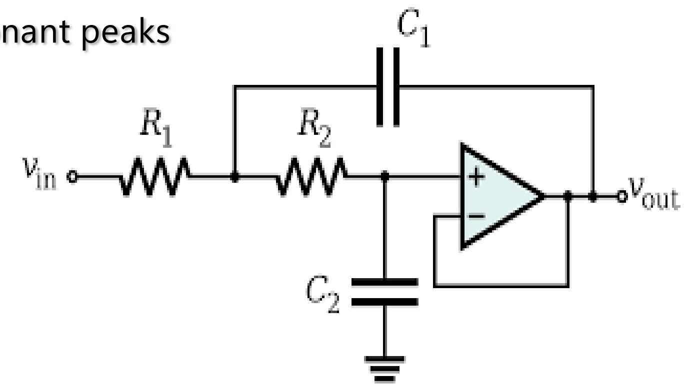
High-frequency noise degrades analog performance, causes digital logic errors, and increases EMI emissions. Filtering removes unwanted spectral content.

COMPONENTS USED

- **RC Filters**: Simple, predictable roll off characteristics
- **LC Filters**: Sharper roll off, resonant peaking possible
- **Ferrite Beads**: Resistive damping of high frequencies

FILTER DESIGN GUIDELINES

- **Cutoff Frequency**: 3-10× below noise frequency
- **Order**: Higher order = steeper roll-off
- **Q Factor**: Damping prevents resonant peaks



PRACTICAL EXAMPLE

Precision Voltage Reference:

Application

4.096V voltage reference for 18-bit ADC

Digital switching at 16MHz fundamental

Required Attenuation>60dB @ 16MHz

Implementation

- 3rd order Sallen-Key lowpass filter
- Cutoff frequency: 159kHz (-3dB)
- Components: R1=R2=1kΩ, C1=2.2nF, C2=1nF
- Op-amp: OPA827 (low noise, high PSRR)

Result

<1µVpp noise in measurement bandwidth

Input Filter Protection

MITIGATION

Protects against power line disturbances.

EXPLANATION

AC power lines carry transients from lightning, motor switching, and power factor correction circuits. Input filters prevent these from entering sensitive equipment.

COMPONENTS USED

- **π-Filters**: Capacitor-inductor-capacitor configuration
- **Common Mode Chokes**: Balanced filtering of both AC lines
- **Metal Oxide Varistors**: High-energy transient clamping

PRACTICAL EXAMPLE

Industrial Power Supply Input

Application

- 240VAC Industrial Environment
- Transient Spec required IEC 61000-4-5 (1.2/50µs, 4kV line-ground)

Filter Design

1. MOV: 20mm varistor (385V RMS, 6kA surge)
2. Common mode choke: 2×4.7mH (Würth 744823047)
3. Differential capacitor: 100nF X2-class
4. Common mode capacitors: 2×2.2nF Y2-class

Result

>40dB attenuation from 150kHz-30MHz

SYSTEM LEVEL PROTECTION

Inductive Kickback Protection

MITIGATION

Protects switching transistors from inductive voltage spikes.

EXPLANATION

When current is interrupted, stored magnetic energy creates voltage spikes following $V = L(di/dt)$. These spikes can exceed breakdown voltages.

COMPONENTS USED

- **Flyback Diodes**: Provides current path during switch-off
- **Snubber Circuits**: RC networks for gradual energy dissipation
- **TVS Diodes**: Fast clamping for high-energy spikes

PRACTICAL EXAMPLE

Relay Drive Circuit

Load

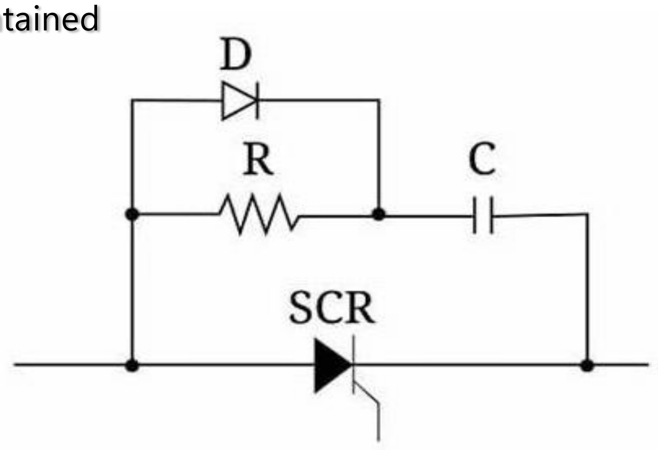
12V automotive relay (coil: 150mH, 80mA)

Protection

1N4148 flyback diode

Analysis

- No protection: Spike = 12V + L(di/dt) = 12V + 150mH×(80mA/10ns) = 1212V
- With flyback diode: Spike clamped to 12V + 0.7V = 12.7V
- MOSFET safe operating area maintained



Hot-Plugging Protection

MITIGATION

Prevents damage during live circuit connection.

EXPLANATION

Connecting circuits under power creates transients from capacitor charging, ground potential differences, and connector arcing. Protection circuits manage these transition events.

COMPONENTS USED

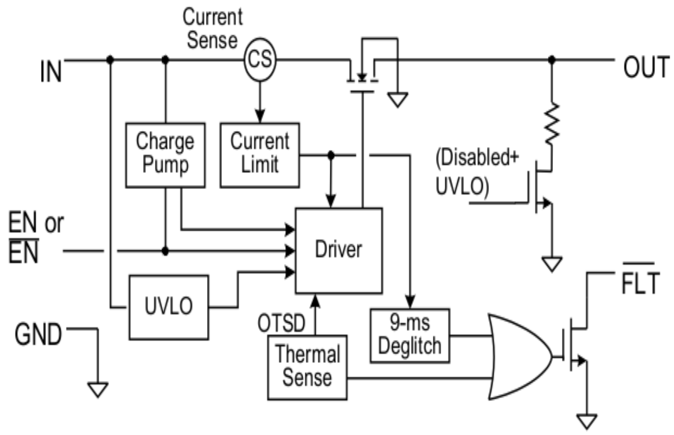
- **TVS Diodes**: Transient voltage suppression
- **Soft-start Circuits**: Controlled power application
- **Current Limiters**: Inrush current management

PRACTICAL EXAMPLE

PCIe Card Installation

Interface

PCIe x1 connector (3.3V, 12V supplies)



Protection Requirements

- Hot-plug compatible
- Inrush current <1.5A peak
- Connector wear <100 cycles

Implementation

1. TPS2065 hot-swap controller
2. Soft-start time: 10ms typical
3. Current limit: 1.5A with foldback
4. Undervoltage lockout: 2.9V threshold
5. Thermal shutdown: 150°C

Result

Clean power-up with <50mV supply droop

ADVANCED PROTECTION

High-Energy Surge Protection

MITIGATION

Diverts high-voltage, high-energy transients to ground.

EXPLANATION

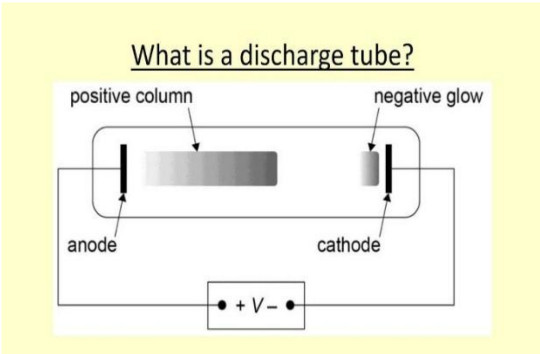
Lightning strikes and power system faults create kilovolt transients with joules of energy. Standard TVS diodes cannot handle these energy levels without coordination with other protective devices.

COMPONENTS USED

- **Gas Discharge Tubes**: High-voltage breakdown, high energy handling
- **Metal Oxide Varistors**: Fast response, moderate energy
- **Crowbar Circuits**: SCR-triggered, very high energy

Device Type	Breakdown	Energy Handling	Response Time	Applications
GDT	90V-10kV	10J-1000J	1-100μs	Telecom, outdoor
MOV	18V-1800V	0.1J-10J	<25ns	AC mains, automotive
TVS	5V-600V	1mJ-400J	<1ns	Signal lines, DC supply

PRACTICAL EXAMPLE



Outdoor Ethernet Installation

Application

POE in outdoor security camera.

Direct lightning exposure possible.

Protection Cascade

1. Primary: Gas discharge tube (230V breakdown, 5kA, 10J)
2. Secondary: 36V MOV (bidirectional, 6kA peak)
3. Tertiary: PESD5V0S1BL TVS array on data lines

Result

Survives IEC 61000-4-5 Level 4 (4kV/2kA) transients

Isolation Protection

MITIGATION

Eliminates ground loops and voltage differences between systems.

EXPLANATION

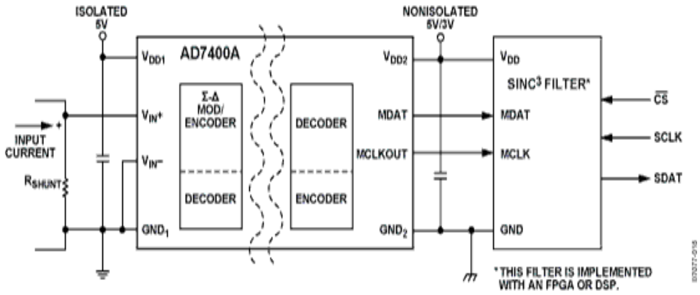
systems with different ground potentials creates current flow through signal connections. Isolation breaks the DC path while maintaining signal transfer.

COMPONENTS USED

- **Optocouplers**: LED-photodetector pairs for digital signals
- **Isolation Transformers**: Magnetic coupling for power and signals
- **Capacitive Isolators**: Electric field coupling for high-speed digital

PRACTICAL EXAMPLE

Industrial Process Control



Application

4-20mA sensor interface with 120VAC noise environment

Isolation Requirements

- 2.5kV isolation voltage (IEC 60601)
- <1% signal accuracy over temperature
- Common mode rejection >80dB @ 60Hz

Implementation

Analog Devices AD7400A Sigma-Delta Isolator

- Specifications: 2.5kV isolation, 20-bit resolution
- Common mode transient immunity: 25kV/µs
- Power consumption: 15mW total
- Accuracy: ±0.05% over -40°C to +125°C

Result

Noise-free measurement in harsh industrial environment

Watchdog Protection

MITIGATION

Resets system during software lockup or hardware failure.

EXPLANATION

Embedded systems can hang due to software bugs, memory corruption, or electromagnetic interference. Watchdog circuits monitor system activity and force reset when problems occur.

COMPONENTS USED

- **External Watchdog ICs**: Independent monitoring circuits
- **Window Watchdogs**: Monitor timing windows, not just timeouts
- **Supervisory ICs**: Combine voltage, temperature, and watchdog functions

PRACTICAL EXAMPLE

Medical Device Controller

Application

Insulin pump controller (safety-critical application)

Watchdog IC

MAX6369 with 1.6s timeout

Safety Requirements

- Independence of main processor
- Tamper-resistant design
- Fail-safe default state

Result

System recovers from SW failures