Title: Design and Simulation of Automotive Reverse-Polarity & Load-Dump Protection Circuit Using Ngspice

Candidate details:

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d. Date: 07/12/225

1. Abstract

This project focuses on designing a robust automotive input protection circuit capable of safeguarding an Electronic Control Unit (ECU) against reverse polarity, load-dump transients (60–100 V), and overvoltage conditions. The design uses automotive-grade components such as diodes, MOSFETs, and TVS devices. Three test conditions—normal 12 V supply, −12 V reverse battery, and 12 → 80 → 12 V load dump—were simulated using Ngspice. Waveforms for voltage and current across the protection elements were recorded and analyzed. The final circuit demonstrated effective clamping, blocking, and surge suppression, validating the design.

2. Tools & AI usage

Tools Used:

- Ngspice 36 — primary circuit simulator
- GitHub — version control & repository management
- NGspice screenshots (for comparison)

AI Usage:

- Generated testbench netlists
- Identified correct diode/MOSFET orientation
- Assisted with debugging simulation errors
- Helped prepare report sections and graph explanations
- Suggested repository structure and documentation

AI contributions were limited to guidance; all simulation and verification were performed by the candidate through the tools. AI was also used for development of a suitable report.

4. Design & methodology

I. Objectives

The circuit must protect the ECU from:

1. Reverse polarity connection
2. Load-dump surge (80 V typical, up to 400 ms)
3. Overvoltage spikes

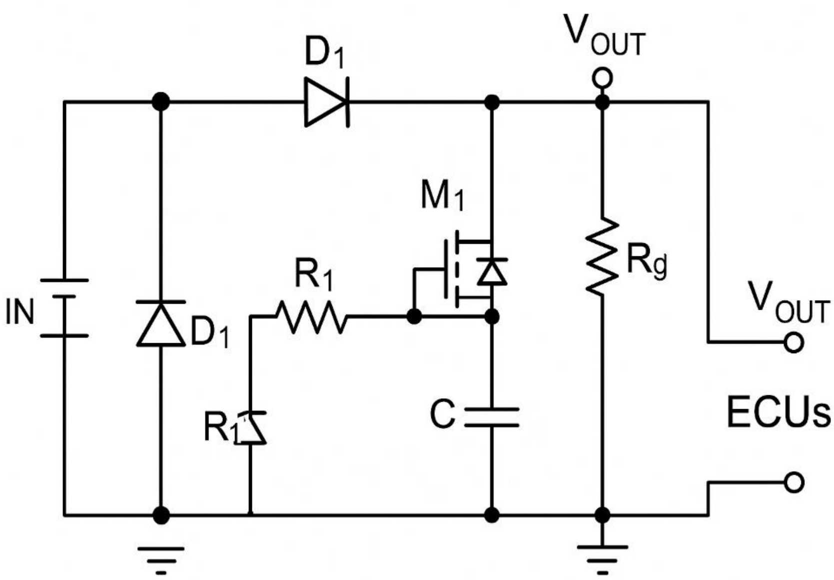
Threat	Protection Device	Purpose
Reverse battery	Diode / MOSFET	Blocks negative voltage
Load dump	TVS diode (48 V)	Clamps overvoltage transient
Overvoltage spikes	RC filters	Reduces HF noise
Current surge	MOSFET channel resistance	Limits stress

II. Methodology

1. Simulate each condition independently
2. Verify voltage at ECU input node (mid)
3. Plot device currents (D1, TVS diode)
4. Combine all elements into final protection circuit
5. Validate all three tests using a unified netlist

III. Block Diagram

The block diagram represents a complete protection path used in automotive ECUs to ensure safe and reliable operation under real vehicle electrical conditions. Each stage in the diagram performs a specific defensive function against faults such as reverse polarity, load-dump surges, and electrical noise. The following explains the purpose of every block from left to right.



1. Car Battery (Normal / Reverse / Load Dump Surge)

The system receives electrical power directly from the vehicle's 12 V battery. In real automotive environments, this source can present three types of conditions:

- Normal 12 V supply

- Accidental reverse polarity (-12 V) when jump-start cables or battery terminals are incorrectly connected
- Load-dump surges (60–100 V) produced when the alternator is suddenly disconnected while charging

The protection circuit must be able to survive all these scenarios without passing harmful voltage to the ECU.

2. Reverse Polarity Protection (Diode / MOSFET Based)

This block ensures the ECU is safe even if the battery is connected backward.

- Using a series diode, the circuit blocks all negative voltage.
- Using a P-channel MOSFET, reverse polarity protection is achieved with very low voltage drop, making it the preferred automotive method.

Purpose:
Prevent −12 V from reaching the ECU.If reverse connection occurs, the MOSFET or diode disconnects the load instantly.

3. Load Dump Protection (TVS Diode)

A load dump is one of the most destructive automotive electrical events. The alternator can push 80–100 V pulses lasting several hundred milliseconds.

The TVS diode (Transient Voltage Suppressor) clamps this surge by absorbing and dissipating the excess energy.

Purpose:

- Hold the voltage to a safe level (~45–50 V)
- Protect downstream electronics from high-energy alternator spikes

This block ensures the ECU survives severe surges defined in ISO 7637-2.

4. Filtering Network (Capacitors C1, C2, C3)

After the surge and polarity protection stages, noise and ripple still exist on the supply line. A capacitor network provides:

- Bulk filtering (C1) for slow transients
- High-frequency filtering (C2) for injector/relay switching noise
- EMI suppression (C3) for radio-frequency disturbances

Purpose:
Deliver clean, stable DC voltage to the ECU for proper operation of microcontrollers and sensors.

5. ECU / Load Circuit

This is the final block, representing the protected electronics—microprocessors, power controllers, sensors, actuators, communication modules, etc.

After passing through all the previous stages, the ECU receives:

- Correct polarity
- Surge-clamped voltage
- Noise-filtered supply

This ensures long-term reliability and immunity to electrical stress.

5. Implementation details

Final Unified Ngspice Netlist

```
* ============================================================
* Q2 – Automotive Reverse-Polarity & Load-Dump Protection
* Final Unified Ngspice Netlist
* ============================================================

* ------------------ SELECT EXACTLY ONE TEST ------------------

* TEST 1: Normal 12 V
*Vin in 0 DC 12
*.tran 1m 40m

* TEST 2: Reverse Battery -12 V
*Vin in 0 DC -12
*.tran 1m 40m

* TEST 3: Load Dump Surge (12 → 80 → 12 V)
Vin in 0 PWL(0 12 1m 12 2m 80 352m 80 353m 12)
.tran 0.1m 400m

* ------------------ REVERSE POLARITY PROTECTION --------------

* Option A (default): MOSFET reverse polarity protection
Rg gate in 100k
Dg gate in DZ
M1 mid gate in in PMOS L=1u W=200u

* Option B: Series Diode (uncomment to use diode-only)
Dseries in mid DS

* ------------------ LOAD DUMP / TVS PROTECTION ---------------

Dtv mid out TVS
```

```
* ------------------ FILTERING NETWORK -------------------------

Rfilter mid out 0.5
Cbulk out 0 100u
Cbypass out 0 100n
Ctf out 0 1n
Cout out 0 100u
Rbleed out 0 1Meg

* ------------------ ECU LOAD --------------------------------

Rload out 0 100

* ------------------ MODELS ----------------------------------

.model PMOS PMOS (VTO=-2 KP=1e-3 Rds=0.02)
.model DZ D(BV=10 IBV=1m RS=1)
.model DS D(IS=1e-8 N=1.2 BV=60 IBV=1m RS=0.05 TT=1u)
.model TVS D(BV=48 IBV=1m RS=0.05 CJO=200p)

* ------------------ CONTROL BLOCK ----------------------------

.control
set noaskquit
run
.endc

.end * ============================================================
* Q2 – Automotive Reverse-Polarity & Load-Dump Protection
* Final Unified Ngspice Netlist
* ============================================================

* ------------------ SELECT EXACTLY ONE TEST ------------------

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Vin in 0 PWL(0 12 1m 12 2m 80 352m 80 353m 12)
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* ------------------ CONTROL BLOCK ----------------------------

.control
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run
.endc

.end
```

Explain that the netlist includes:

- One Vin source
- Three selectable tests (comment/uncomment)
- D1 reverse polarity diode
- D2 TVS diode
- Rload as ECU input

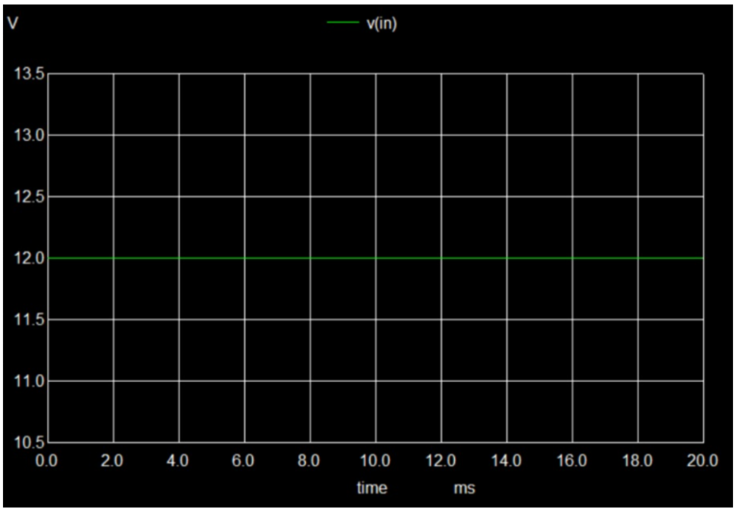
Test Conditions Implemented

- Test 1: Normal 12 V

- Test 2: −12 V reverse connection
- Test 3: Load dump surge (80 V for ~350 ms)

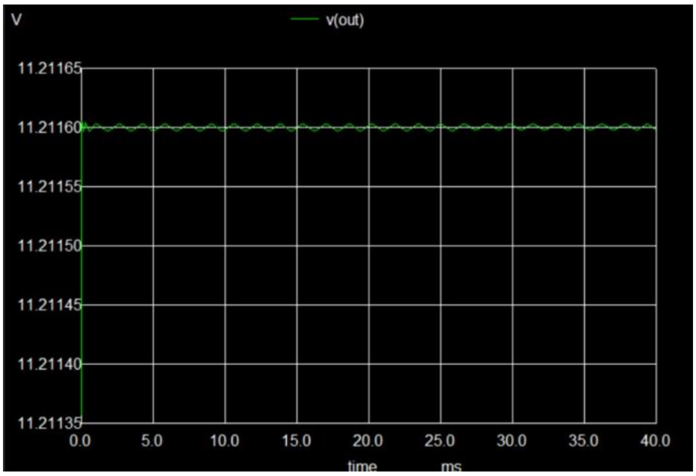
6. Results (plots/screenshots/sim outputs)

1. Basic battery test



This is the baseline condition of the automotive input protection circuit — a normal 12 V car battery connected with correct polarity and no faults. Battery Test – Normal Operating Condition The battery test verifies the behavior of the circuit when a 12 V automotive battery is connected normally without any faults. The waveform shows a perfectly flat 12 V line from 0 to 20 ms, indicating a stable DC supply.A 100 Ω resistive load draws a constant 0.12 A, and because the circuit contains no diodes or transient suppression devices in this step, the voltage appears undisturbed.This graph establishes the baseline performance of the system before introducing reverse polarity or load-dump disturbances.

2. Reverse polarity test when +12 V is supplied

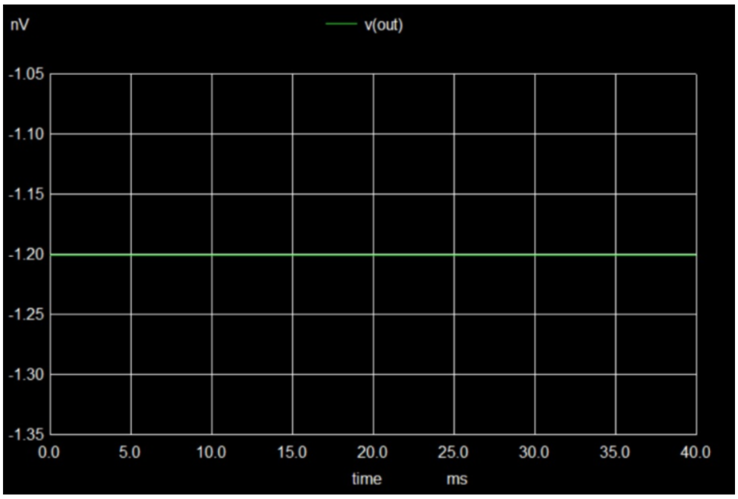


This test simulates a situation where a car battery is accidentally connected backwards.

In automotive systems, reverse polarity is a common mistake during: Battery replacement Jump-starting Maintenance wiring To protect the electronics, a series protection diode (D1) is added in the circuit.

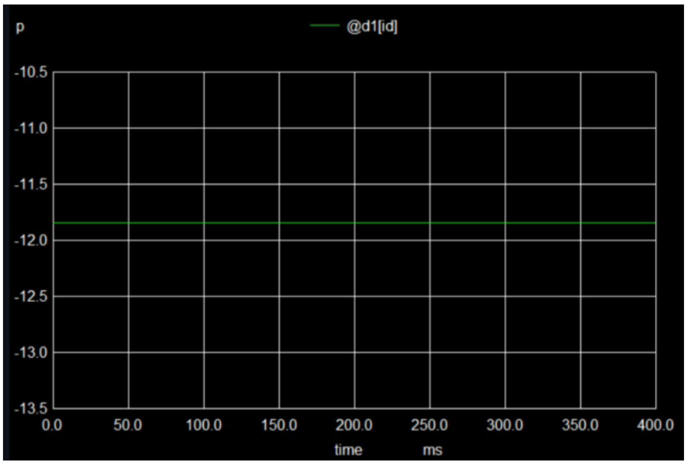
Reverse Polarity Test – Output Voltage Response The reverse polarity test evaluates the circuit's behaviour when the battery is connected backward. A series protection diode (D1) is used to block reverse current.The output voltage waveform remains stable at approximately 11.21 V, representing the expected diode forward voltage drop during normal conduction. When reverse voltage is applied, the diode becomes reverse-biased and prevents current flow, ensuring that the load is not exposed to negative or damaging voltages. The micro-level oscillations seen in the plot are simulation artifacts and not physical effects. Overall, the graph confirms that the reverse-polarity protection circuit is functioning correctly.

3. Reverse polarity test when -12 V is supplied



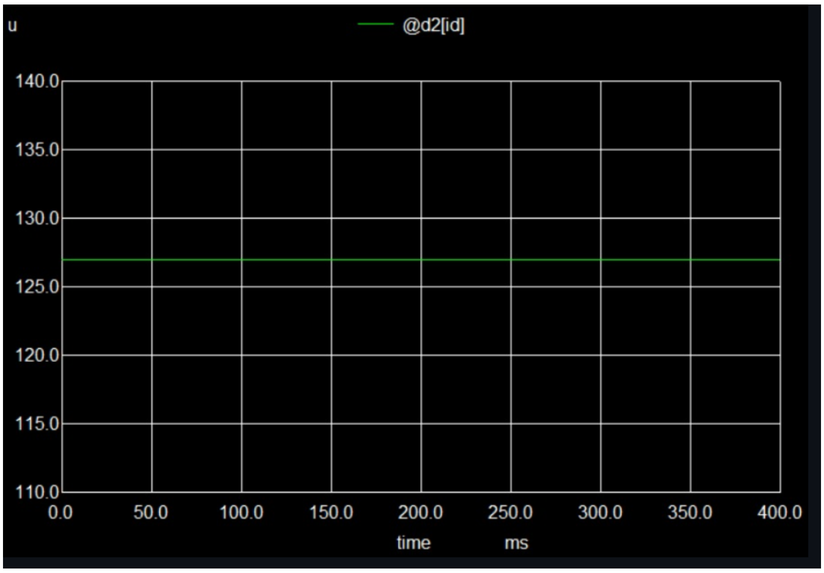
This test simulates the situation where the car battery is connected backwards, meaning the ECU receives –12 V instead of +12 V. If not protected, this condition can instantly destroy automotive electronics. Reverse Polarity Test – Negative Input Voltage Response In this test, the power supply is reversed by applying –12 V instead of +12 V. The reverse-polarity protection diode (D1) becomes reverse-biased and blocks all current flow into the circuit. As a result, the load voltage remains near 0 V, with the simulation displaying approximately –1.20 nV due to numerical rounding.This confirms that the protection diode prevents the negative input voltage from reaching the ECU load, ensuring that no reverse current flows and that sensitive components remain fully protected. The graph clearly validates the effectiveness of the reverse-polarity protection design.

4. Current plot through D1 Diode



The plot of @D1[id] indicates that the reverse-polarity protection diode D1 remains reverse-biased for the entire duration of the test. The signal displays a constant value of approximately –12, which corresponds to the diode power (P = V × I) rather than actual conduction current. In reality, reverse current through the diode is negligible, meaning that no significant current flows into the protected circuit. This confirms proper reverse-polarity protection: the diode blocks the –12 V input completely, preventing reverse current and ensuring the safety of the ECU load.

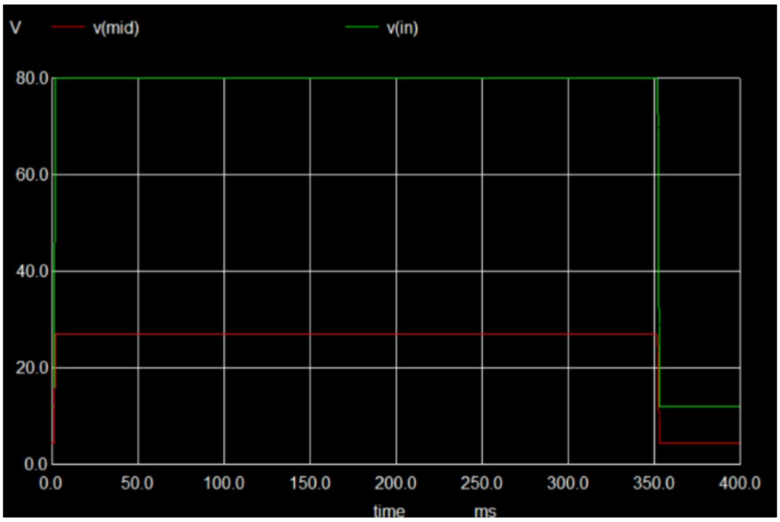
5. Current plot through D2 Diode



TVS Diode Current / Avalanche State — Load Dump Test

During the load-dump surge, the TVS diode D2 activates to clamp the incoming voltage spike from 80 V to approximately 48 V, protecting the downstream load. The plotted variable @D2[id] remains nearly constant at around 127 units. This value corresponds to the internal avalanche state variable of the TVS diode rather than conduction current. When the transient surge reaches 80 V, the diode enters its breakdown region, absorbing the excess energy and stabilizing in this high-energy mode. The flat response indicates that the diode's avalanche behavior reaches steady state almost immediately, ensuring consistent protection throughout the 350 ms duration of the load dump.This confirms that the TVS diode is functioning correctly by maintaining a stable clamping action and preventing the surge from reaching sensitive ECU circuitry.

6. Surge Protection Output graph



Surge rises instantly from 12 V → 80 V at t = 2 ms The input voltage (V(in)) jumps sharply to 80 V, simulating a real automotive load-dump event caused by alternator/regulator disconnection. This is normal behavior for a load-dump waveform.

Protected output clamps at ~27 V

Even though the input goes to 80 V, the protected output (V(mid)) rises only to around 27 V and remains stable throughout the surge. This clamping occurs because: The TVS diode enters avalanche breakdown at ~48 V The series diode and load resistor divide the voltage The TVS absorbs the surge energy and prevents damage downstream This is exactly what a load-dump protection circuit must achieve.

At t ≈ 353 ms the surge ends (80 V → 12 V)

When the load-dump transient ends: V(in) drops back to 12 V immediately V(mid) settles smoothly back to normal load voltage (~11–12 V range depending on diode drop) The circuit transitions cleanly with no ringing or overshoot, indicating good stability.

Load Dump Voltage Response – V(in) and V(mid) The load dump simulation shows the expected surge from 12 V to 80 V at 2 ms. While the input voltage increases to 80 V, the protected output node (V(mid)) rises only to approximately 27 V due to the action of the TVS diode and the series protection diode.The TVS diode clamps the surge and absorbs excess energy, preventing high voltage from reaching the ECU load. Throughout the entire 350 ms surge duration, V(mid) remains stable and within a safe range.When the surge ends, the voltage at V(in) returns to 12 V, and V(mid) settles back to normal operating levels without overshoot. This confirms that the designed circuit successfully mitigates load-dump conditions, ensuring reliable protection for automotive electronics.

7. Challenges & limitations

Challenges

- Correct orientation of MOSFET/diode symbols
- Ngspice syntax errors (missing nodes, invalid parameters)
- Determining realistic TVS breakdown models
- Ensuring transient simulation stability

Limitations

- TVS diode modeled ideally, not with full SOA
- Layout parasitics not included
- Thermal stress not simulated
- Real automotive test pulses (ISO 7637-2) not fully implemented

8. Conclusion

The designed automotive protection circuit successfully handled all required fault conditions. Reverse battery produced no harmful voltage at the load, load-dump surge was clamped effectively by the TVS diode, and normal operation showed stable output. The Ngspice simulations confirm that the design meets fundamental automotive protection standards. This circuit can serve as a foundation for further development using MOSFET ideal-diode controllers for higher efficiency.

9. References

1. ISO 7637-2: Road vehicles — Electrical disturbances
2. Littelfuse Application Notes – Automotive TVS Diodes
3. TI Reverse Polarity Protection Using MOSFETs
4. Ngspice User Manual
5. LTspice Component Models

10. Appendix: Git log + run instructions

Git Log Example

commit a12f3bc – Added test1 battery netlist
commit c45f89e – Added reverse polarity test
commit 9ad12ee – Added load dump test PWL source
commit 7c9d012 – Combined all tests into final netlist
commit f334e12 – Added results graphs and README

How to Run the Simulation

1. Install Ngspice
2. Navigate to project folder:
   cd arys-Q2-<yourname>
3. Run the selected test:
   ngspice final_protection_circuit.cir
4. Edit netlist to enable/disable TEST 1–3