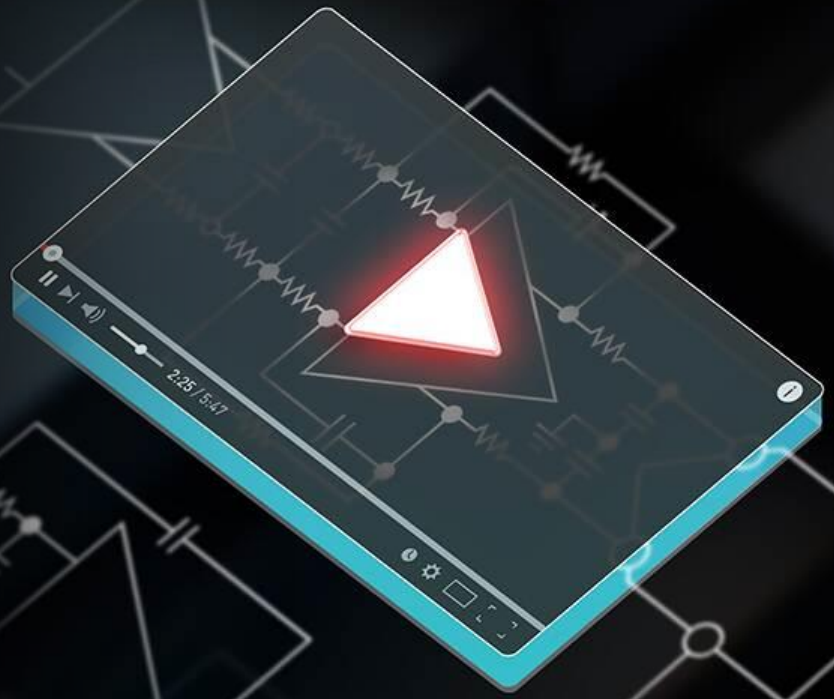
TI Precision Labs Seminar

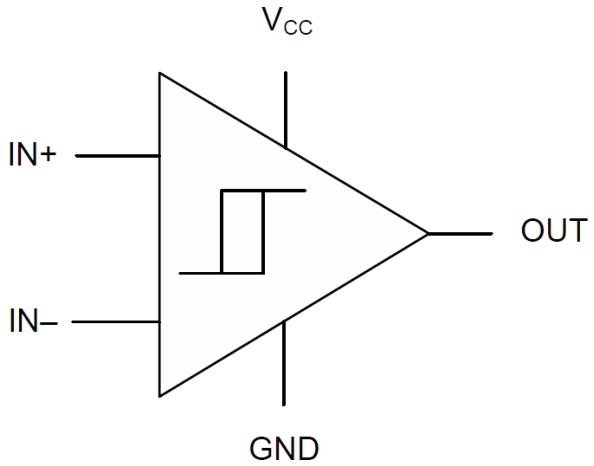
Comparator applications



Agenda

- Comparator differentiation from amplifiers
- Output types
- DC specifications & features
- AC specifications
- Applications/use cases
- Why come to TI for comparators?

Comparators…



Simple, *right* ???

Texas Instruments

Key difference from amps - common mode range

- Similar structure to amplifier and share key specs like, Vos, Iq, etc

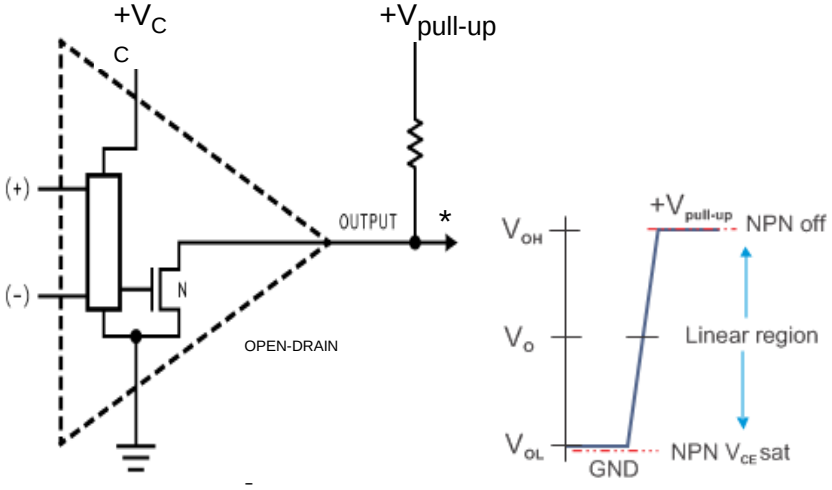
Key difference:

- Amps have negative feedback which creates “virtual” short across inputs
- Comparators do not have this behavior
- Frequently operated with inputs several volts apart for detection

Comparator output types

Open-drain/open-collector output

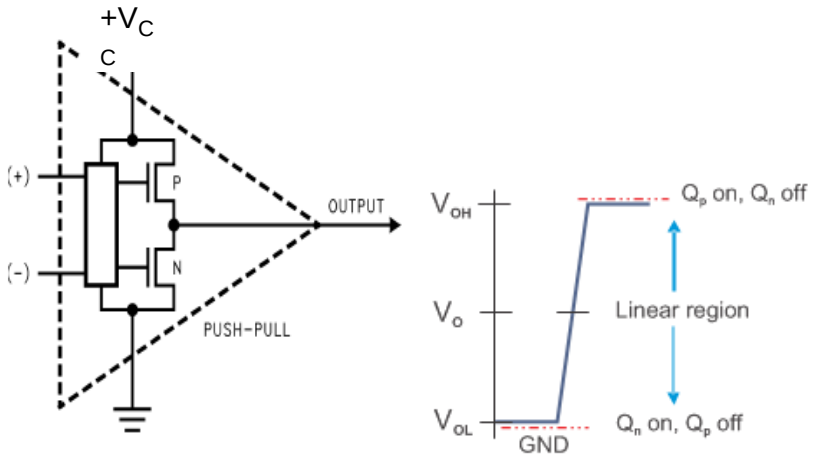
Requires pull-up resistor - useful for wired-OR output applications



* ESD not present on devices that allow $V_{PULL-UP} > V_S$, such as TLV170x, LMC677x or LMx39/x93 series.

Push-pull (also called R-R or Totem Pole) output

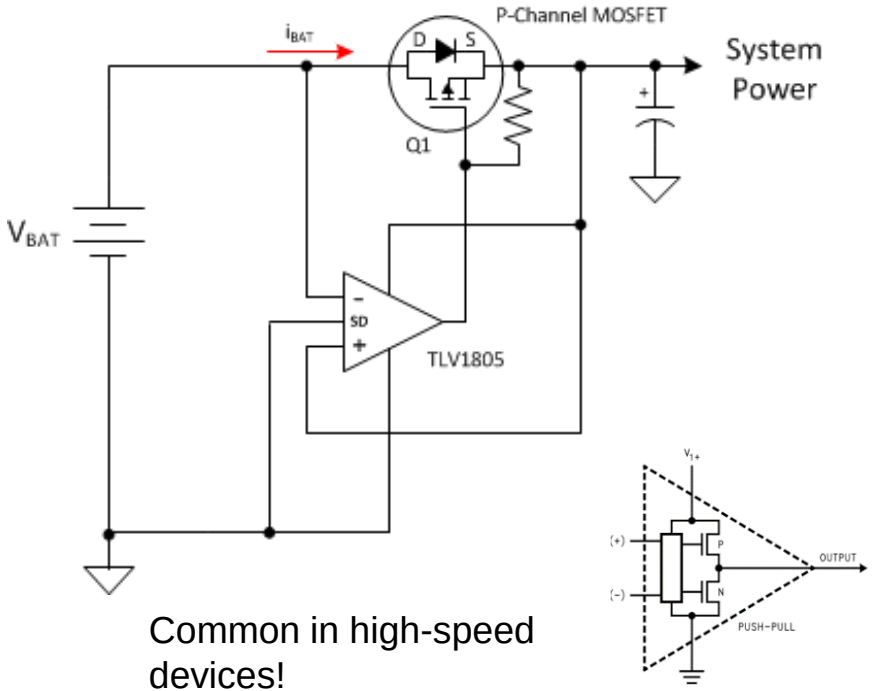
No pull-up resistor required – cannot tie outputs together



Texas Instruments

Output type usage examples

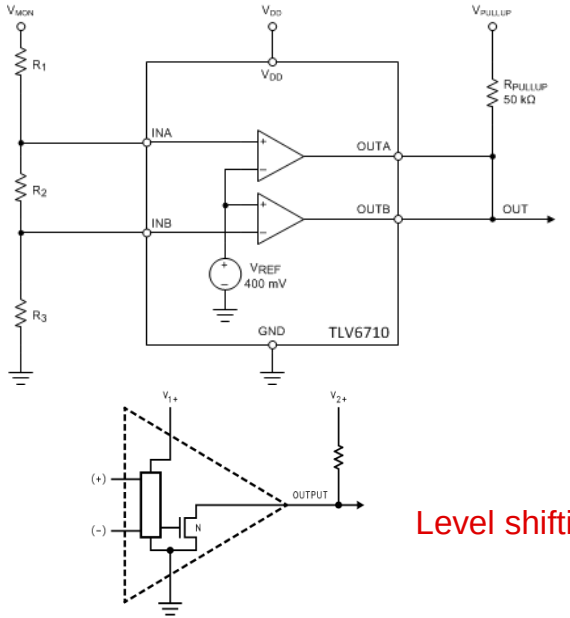
Push-pull output



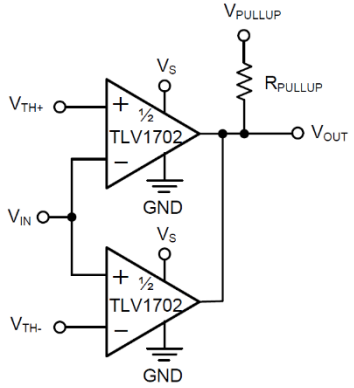
Common in high-speed devices!

Open drain output

Window comparators



Output OR'ing

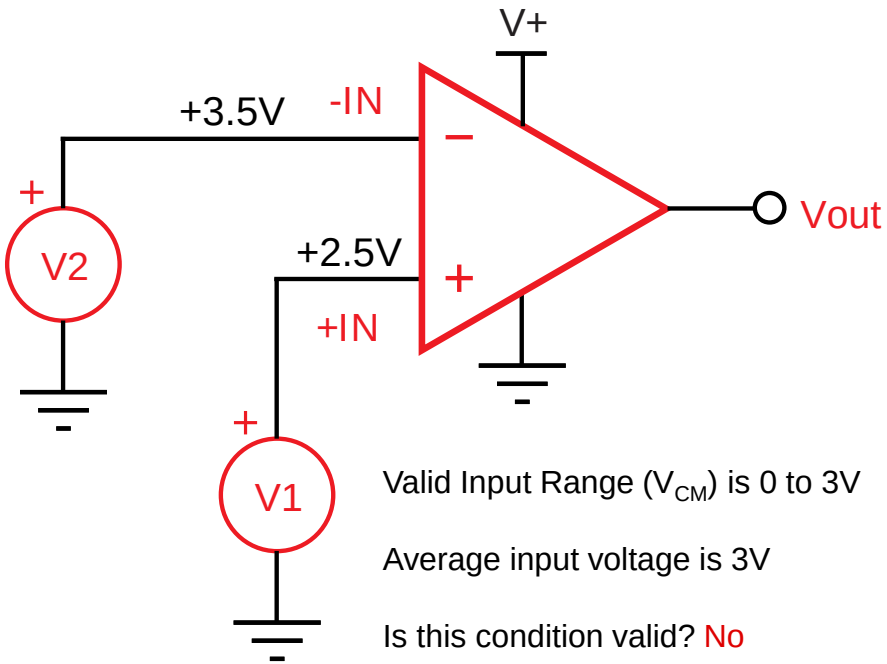


Level shifting

Texas Instruments

Comparator DC parameters - common mode range

- Common mode voltage is commonly defined as “the average of the two input voltages”
  - Only true for Operational Amplifiers under feedback
  - **Not true for comparators**
- Input voltage range specification is **per input**
- Do **not** “average” – look at each input voltage separately for Comparators
- Newer SPICE models will force output to half supply when specs are violated.

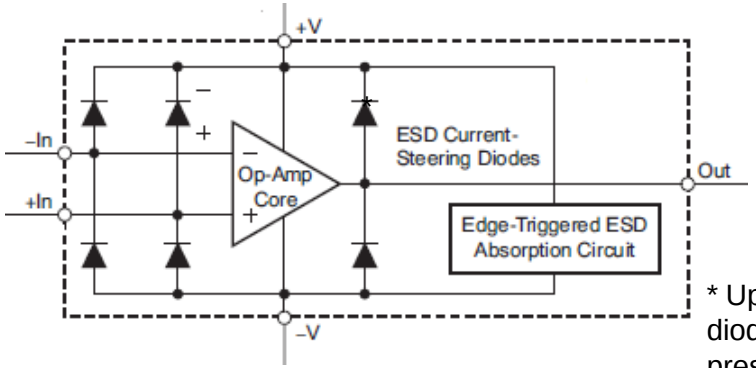


Technical article: Solving top comparator challenges: Violating input common-mode range

Texas Instruments

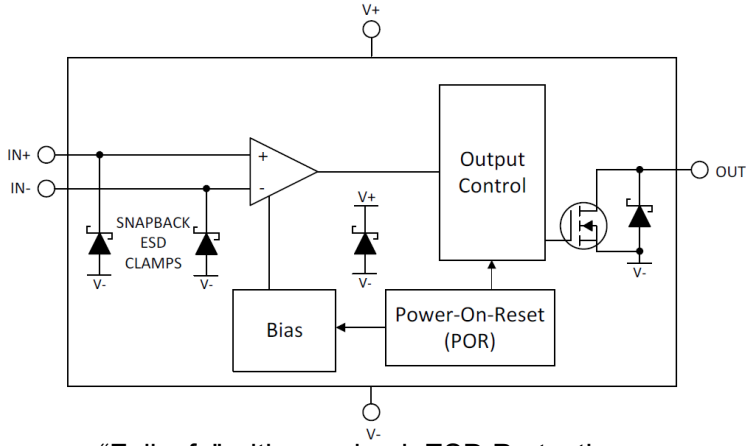
Exceeding input common mode voltage (V_{CM})

- Common question: *"What if I expect the input voltage to exceed the rails?"*
- Most low-voltage and CMOS devices have ESD clamping diodes to supplies on all pins
- Diodes will clamp to supply when input exceeds supply by >500mV
- ESD diodes are not designed for continuous power dissipation
- "Failsafe" inputs do not have top diode, and allow the input voltage to exceed V+



Conventional ESD Protection

* Upper output ESD diode may not be present on Open Collector Outputs



"Failsafe" with snapback ESD Protection

Texas Instruments

Integrated Fail-Safe Inputs

AEC Q100

Feature Highlight

Problem: Input pins are dependent on power supply

Designing with input pins that are dependent on the power supply can lead to system damages in cases where the power supply ramps down faster than the input supply or during start-up where the input supply ramps faster than the output supply.

Solution: Make input pins independent of power supply

By giving the input pins their own absolute maximum ratings independent of the power supply, users can have more flexibility in designing without worrying about damage to the input pins.

System Care Abouts:

- High Input Impedance in absence of supply
- Input signal can go well beyond the supply voltage of the comparator as defined by Absolute Maximum Table

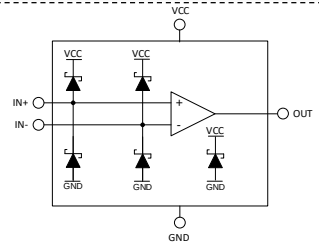
Without Fail-Safe Inputs

Absolute Maximum Ratings

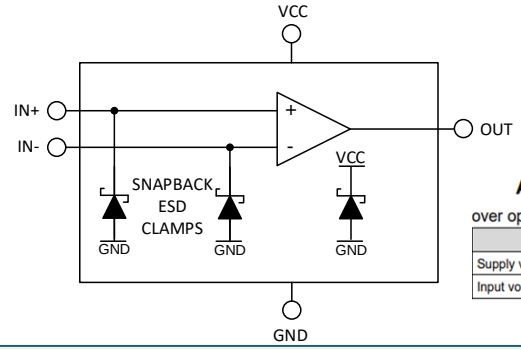
over operating free-air temperature range (unless otherwise noted)(1)

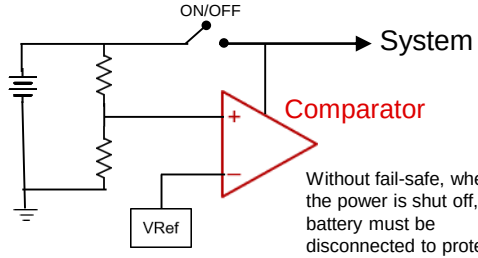
		MIN	MAX	UNIT
Voltage	Supply voltage		7	V
	Signal input pins(2)	–0.5	(VCC) + 0.5	

*Input limited by VCC



With Fail-Safe Inputs





Without fail-safe, when the power is shut off, the battery must be disconnected to protect the comparator.

Absolute Maximum Ratings

over operating free-air temperature range (unless otherwise noted)(1)

	MIN	MAX	UNIT
Supply voltage: V_S = (V+) – (V–)	–0.3	6	V
Input voltage (IN) from (V–) (2)	–0.3	6	V

*Input independent of VCC

Comparators with Fail Safe

	I_Q	V_{OS}	t_{PD}	Supply Range
Q100 LM393LV/LM339LV	25µA	0.4mV	600ns	1.65V to 5.5V
Q100 TLV90X2/4	16µA	0.3mV	100ns	1.65V to 5.5V
TLV701X/2X	5µA	8mV	260ns	1.6V to 6.5V
Q100 TLV703X/4X	315nA	8mV	3µS	1.6V to 6.5V
TLV40X1	2µA	-	360ns	1.6V to 5.5V

Benefits:

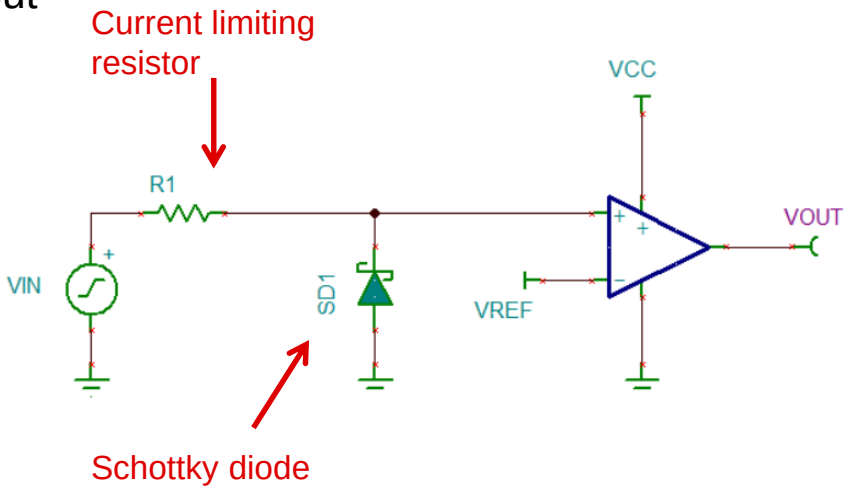
- You don't have to disconnect monitored signal from comparator input when powering down
- You don't have to worry about power supply sequencing
- You don't have to level-shift comparator output

Want to learn more? Check out these links:

- [FAQ] How to the apply inputs before powering the supply of my comparator?

Exceeding input common mode voltage (V_{CM})

- Current must be limited to under Abs Max input current (TI recommends <10% of Abs Max)
- Add current limiting resistor
  - 1k per volt of expected overvoltage
- Add external Schottky diode
- Output condition may be incorrect if > V_{CM}
  - Cannot warranty behavior outside of V_{CM} range

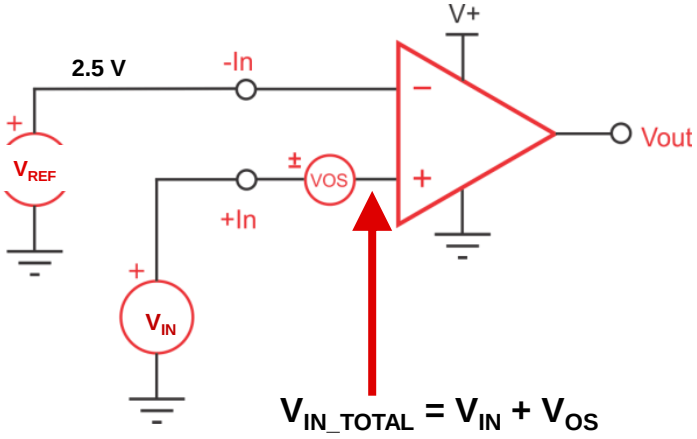


Application note: Application design guidelines for LM339, LM393, TL331 family comparators including the new B-versions

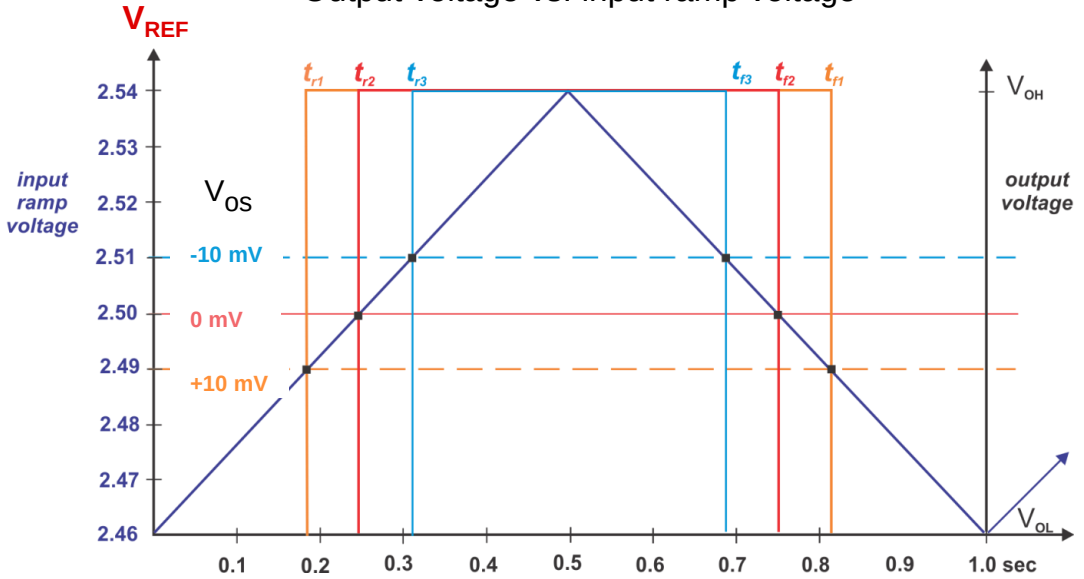
Technical article: Solving top comparator challenges: Negative inputs and phase reversal

Texas Instruments

Comparator DC parameters – offset voltage (V_{OS})



Output voltage vs. input ramp voltage



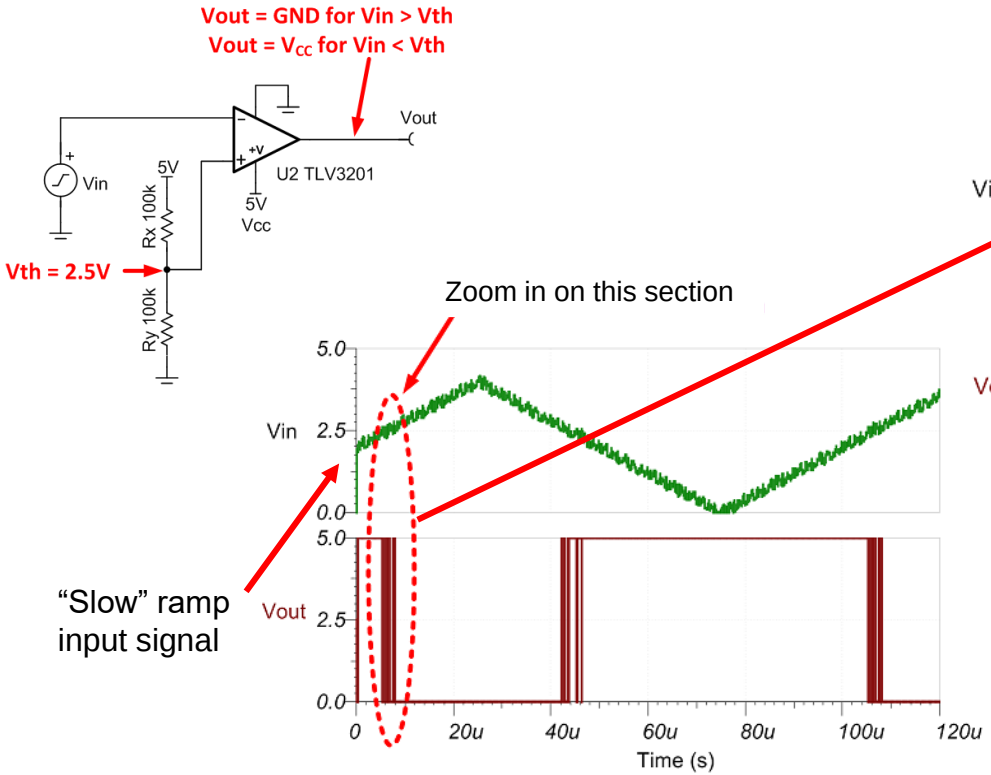
The maximum V_{OS} of a comparator ranges from about **±0.5 mV** up to **±15 mV**

- Offset appears in series with positive input.
- "Suppresses" actual input signal

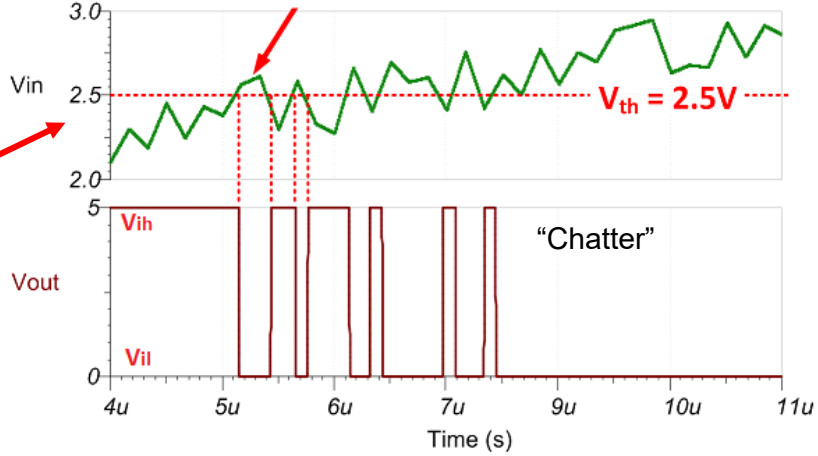
Example application: Zero crossing detection using comparator circuit

Texas Instruments

Noise effect on comparator output – “chatter”



Vout momentarily transitions from Vih to Vil as Vin crosses above the 2.5V Vth level

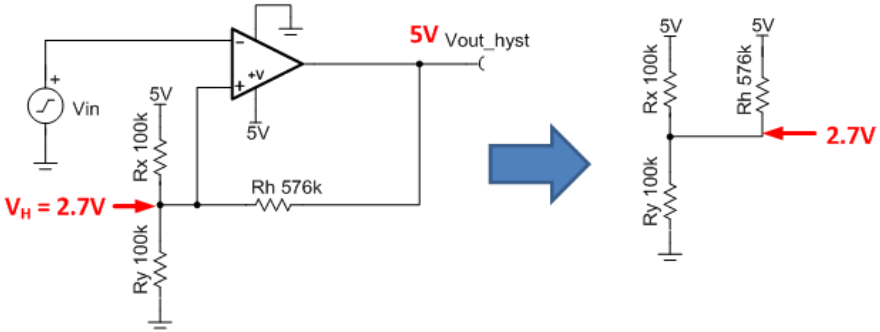


Comparator output rapidly changes state near the threshold point in response to the noise peaks.

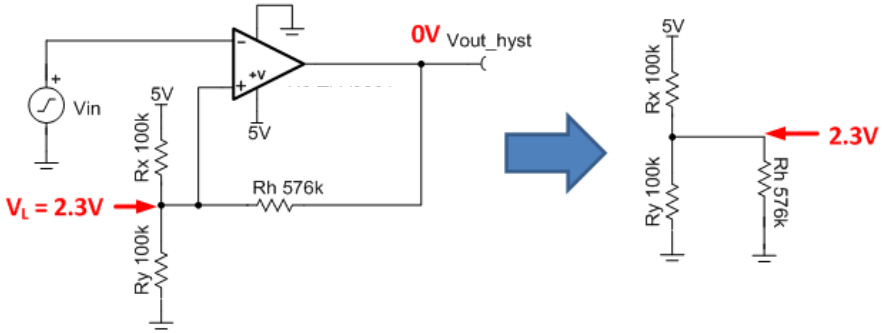
Texas Instruments

Reducing noise sensitivity with hysteresis

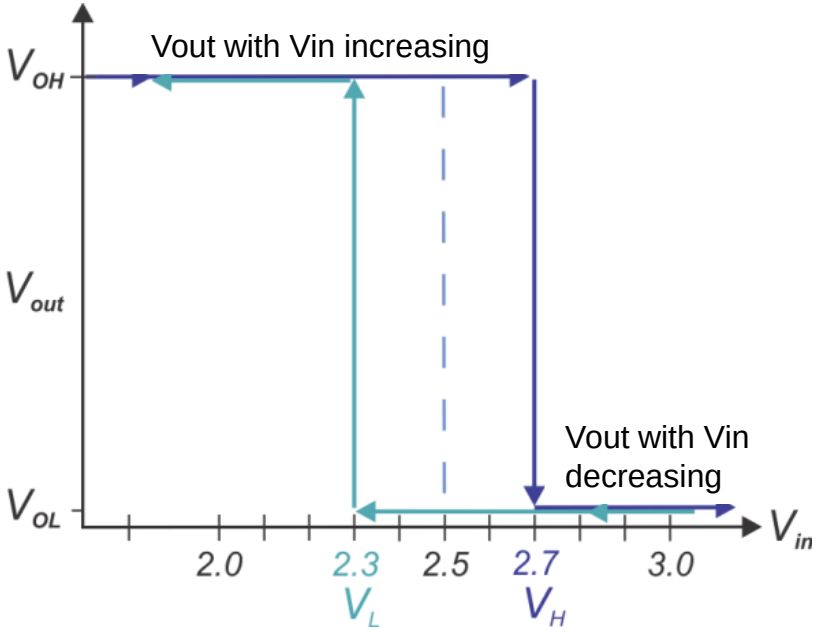
Vin > 2.7V causes Vout to transition to 0V



Vin < 2.3 V causes Vout to transition to 5 V

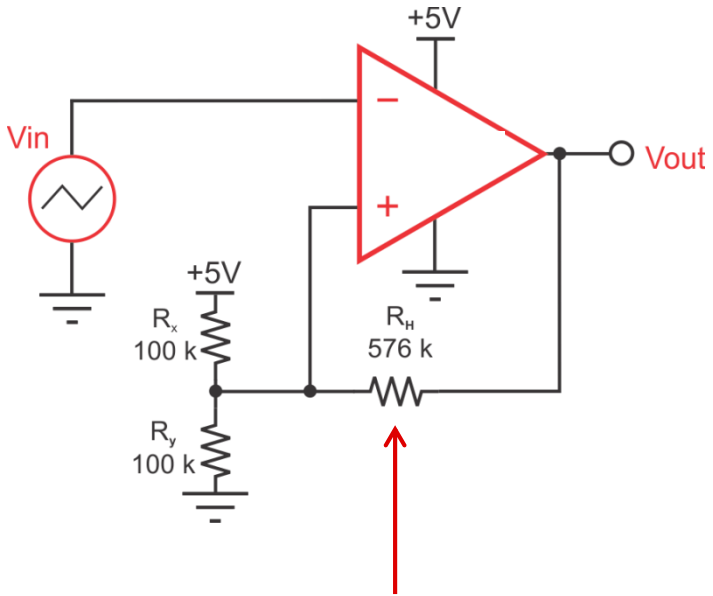


Vout vs Vin with 400 mV of hysteresis

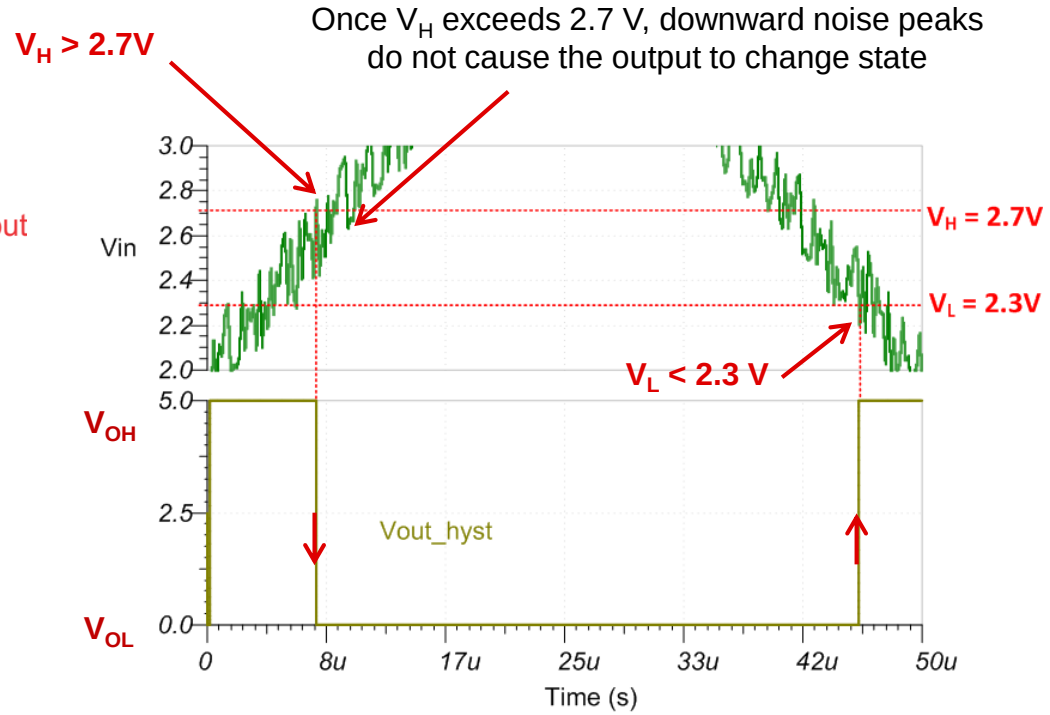


Texas Instruments

Reducing noise sensitivity with hysteresis



Positive feedback or “hysteresis”



Texas Instruments

Some comparators have internal hysteresis

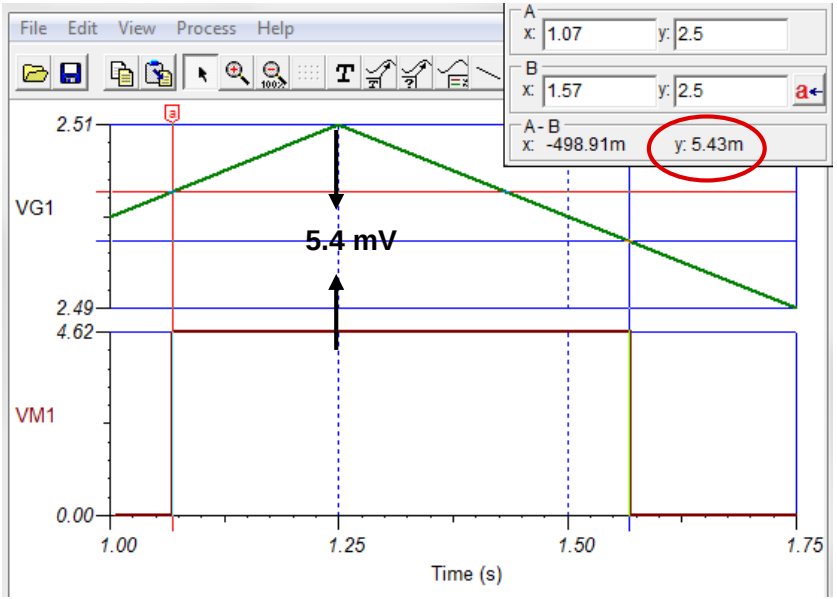
TI comparators with internal (built-in) hysteresis:

- **TLV3501** – 4.5 ns, V_{HYST} 5.4 mV typ.
- **TLV3601/2/5** – 2.5 ns, V_{HYST} 3 mV typ.
- **TLV3603** – 2.5 ns, resistor programmable V_{HYST} up to 60 mV.
- **TLV38x1** – 225ps, V_{HYST} 2 mV typ.
- **TLV40x1** – 450 ns V_{HYST} 20 mV typ.
- **TLV701/2x** – 3 us, V_{HYST} 6.5 mV typ.

External hysteresis can still be applied

- Total hysteresis = Internal hysteresis + External hysteresis

TLV3501 simulation model with built-in hysteresis



Texas Instruments

Chatter and hysteresis resources

Technical article: Solving Top Comparator Challenges: Chatter



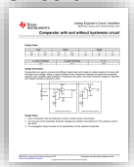
Circuit Cookbook → SBOA313: Non-Inverting Comparator with Hysteresis



TI training video: How to Add External Hysteresis to a High Speed LVDS Comparator



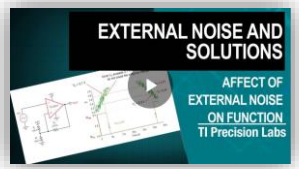
Application note → SBOA219A: Comparator with and without Hysteresis Circuit



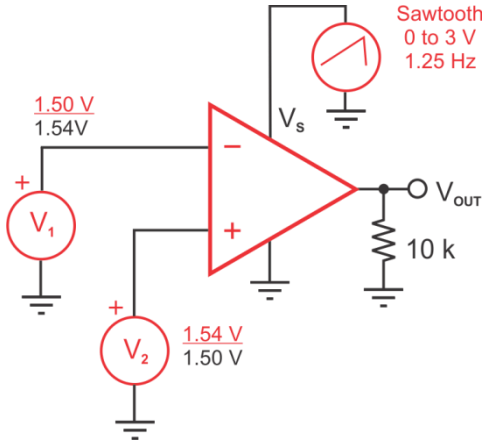
Circuit Cookbook → SNOA997: Inverting Comparator with Hysteresis



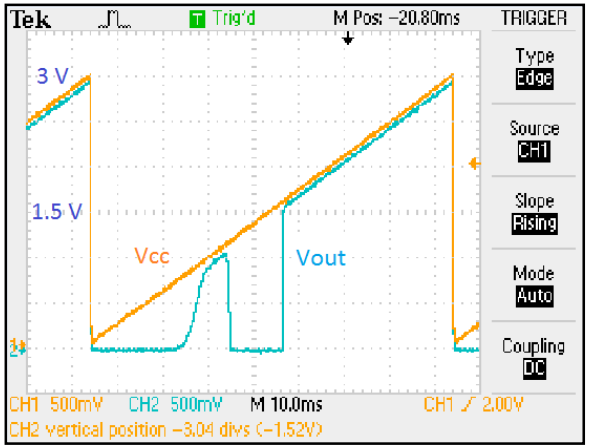
TI training video: How to Solve Comparator Noise Problems with Hysteresis



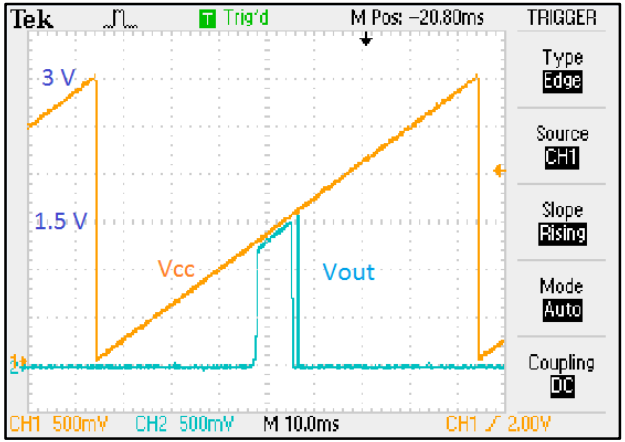
Start-up output state uncertainty



V_1 = 1.50V, V_2 = 1.54V
(Output should be high)



V_1 = 1.54V, V_2 = 1.50V
(Output should be low)



The comparator output flips state as it is powering up.
This is a common behavior for comparators.

Texas Instruments

Comparators with known start-up conditions

Problem:

Start-up uncertainty creates a false output on start-up, or even shut-down.

Solution:

Integrated power-on-reset (POR) circuitry

	I_Q	t_{PD}	Supply range
TLV3601/2/3	6mA	2.5ns	2.4V to 5.5V
TLV181x/2x	7µA	400ns	2.4V to 40V
TLV1805	135µA	250ns	3.3V to 40V
LM393LV/LM339LV	25µA	600ns	1.65V to 5.5V
TLV902x/3x	16µA	100ns	1.65V to 5.5V
TLV701x/2x	5µA	260ns	1.6V to 6.5V
TLV703x/4x	315nA	3µS	1.6V to 6.5V
TLV40X1	2µA	360ns	1.6V to 5.5V
TLV185x/6x	560nA	30µs	1.8V t0 40V
TLV183x/4x	100µa	50ns	2.4V t0 40V

Without POR

IN+ > IN-

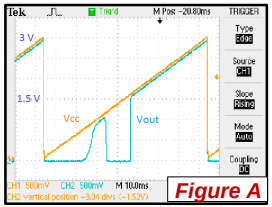


Figure A

*IN- > IN+

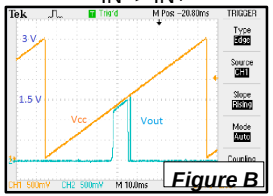


Figure B

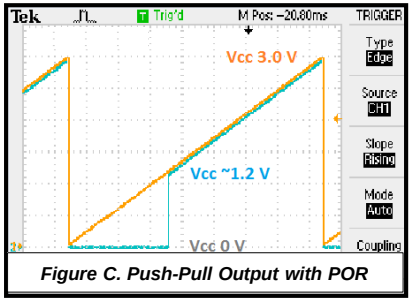


Figure C. Push-Pull Output with POR

For a push-pull comparator, the output is held low until the minimum operating voltage is reached

*IN+ > IN-

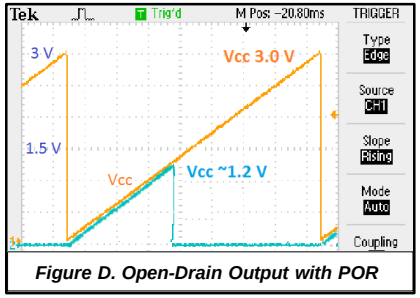


Figure D. Open-Drain Output with POR

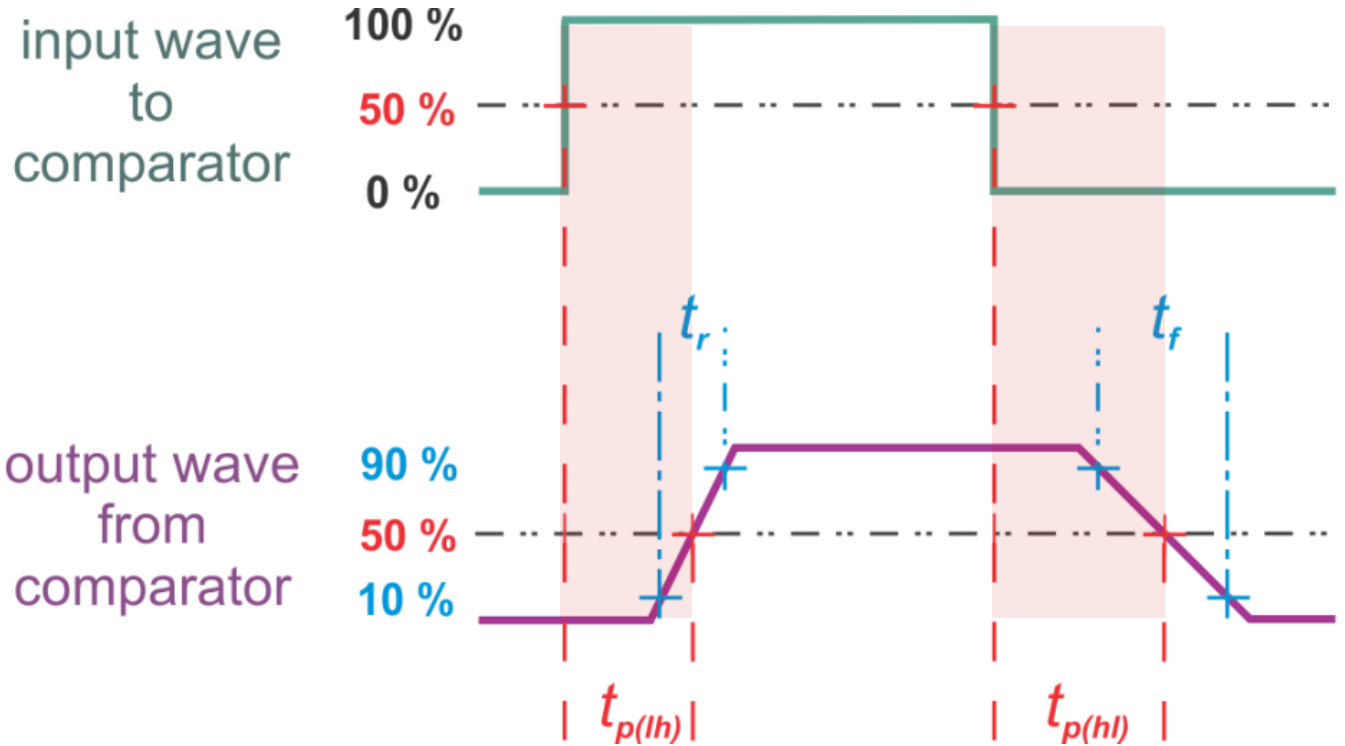
For an open-drain comparator, the output follows the supply until the minimum operating voltage is reached

*IN- > IN+

Benefits:

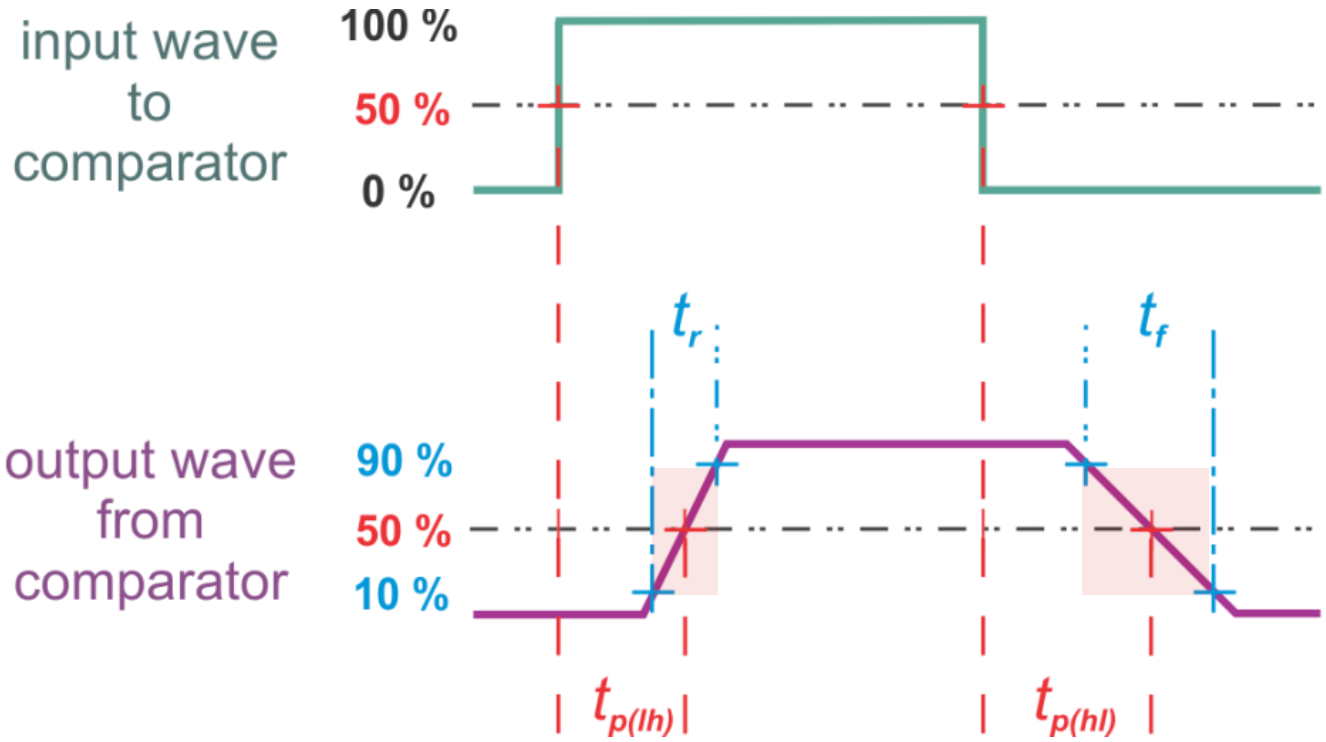
- Allows comparator to consistently remain in a known state (POR state or reflective of input)
- Minimizes impact of brownout conditions by protecting against accidental change in state
- Avoid false output conditions which can cause systems to not start properly

Comparator AC parameters - propagation delay



Texas Instruments

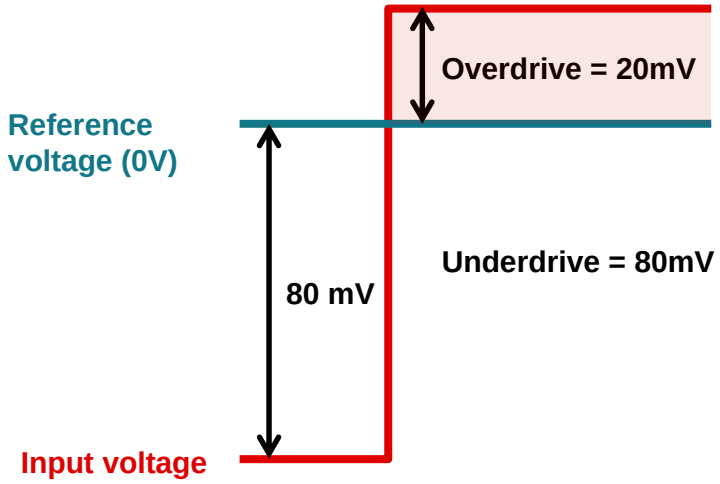
Comparator AC parameters - rise and fall time



Texas Instruments

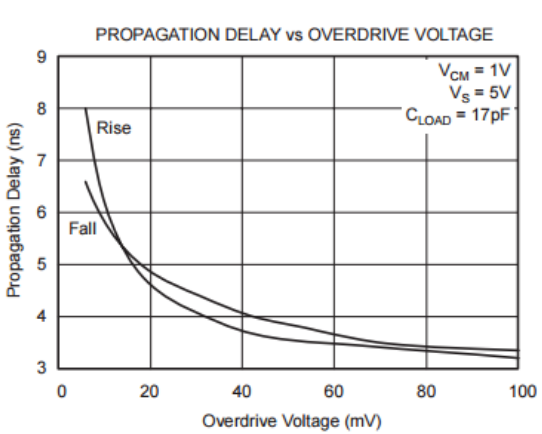
Comparator AC parameters - input overdrive

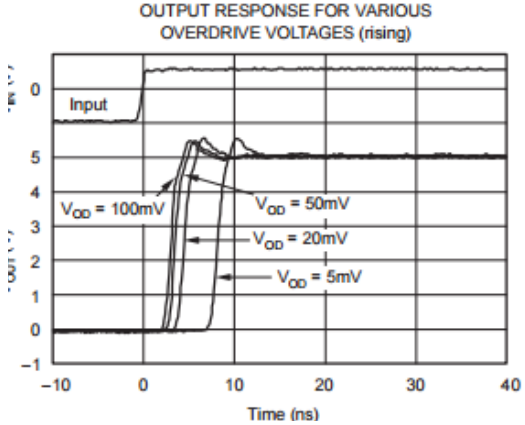
- A commonly misunderstood specification
- Overdrive is not the total change in input voltage
- Overdrive is defined as the amount of differential input voltage exceeding the reference voltage



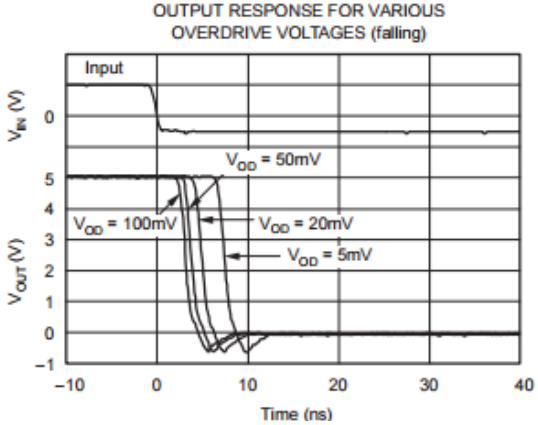
Example:
100mVpp input step with 20mV overdrive

Input overdrive influences propagation delay

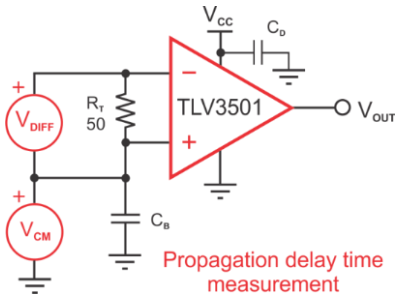




Prop delay $t_{P(LH)}$



Prop delay $t_{P(HL)}$



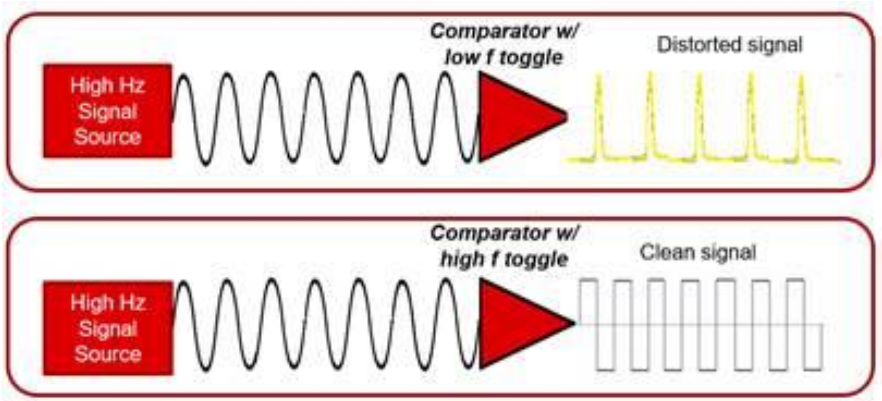
Temp	Overdrive	Typical	Maximum
25°C	5 mV	7.5 ns	10 ns
-40°C to 85°C			12 ns
25°C	20 mV	4.5 ns	6.4 ns
-40°C to 85C			7 ns

Propagation delay t_{PD} , ΔVin = 100 mV

Texas Instruments

Comparator AC parameters - maximum toggle frequency

- Maximum switching frequency of the comparator
- Overall “speed” of a comparator
- Rule of thumb:
  - Ftoggle_max = 1 / (tr + TPLH + TPHL + tf)
  - Does not account for output fidelity
- Do not try to “push” the speed of the comparator
  - Output can distort or “shrink”
  - Variation over process / lot / temperature
  - Chance of missing pulses
  - Better to use a faster comparator
    - Recommend at least 2x prop delay as absolute minimum, and 10x for best output fidelity

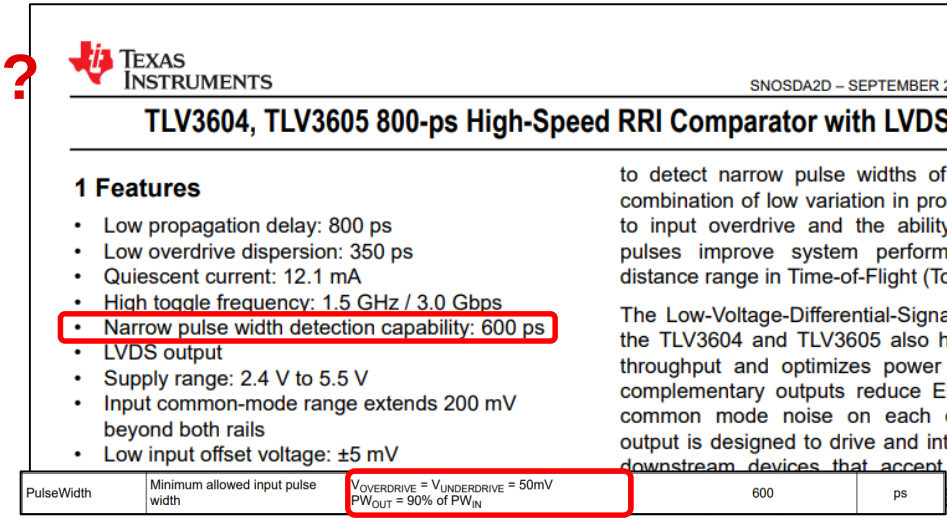


Texas Instruments

What is Minimum Pulse Width?

Minimum pulse width: smallest pulse size (measured in seconds) that will produce a high output state on the comparator

A pulse that is too narrow will not be detected, as the pulses will disappear before the comparator can transition its output



Texas Instruments

SNOSDA2D – SEPTEMBER 2

TLV3604, TLV3605 800-ps High-Speed RRI Comparator with LVDS

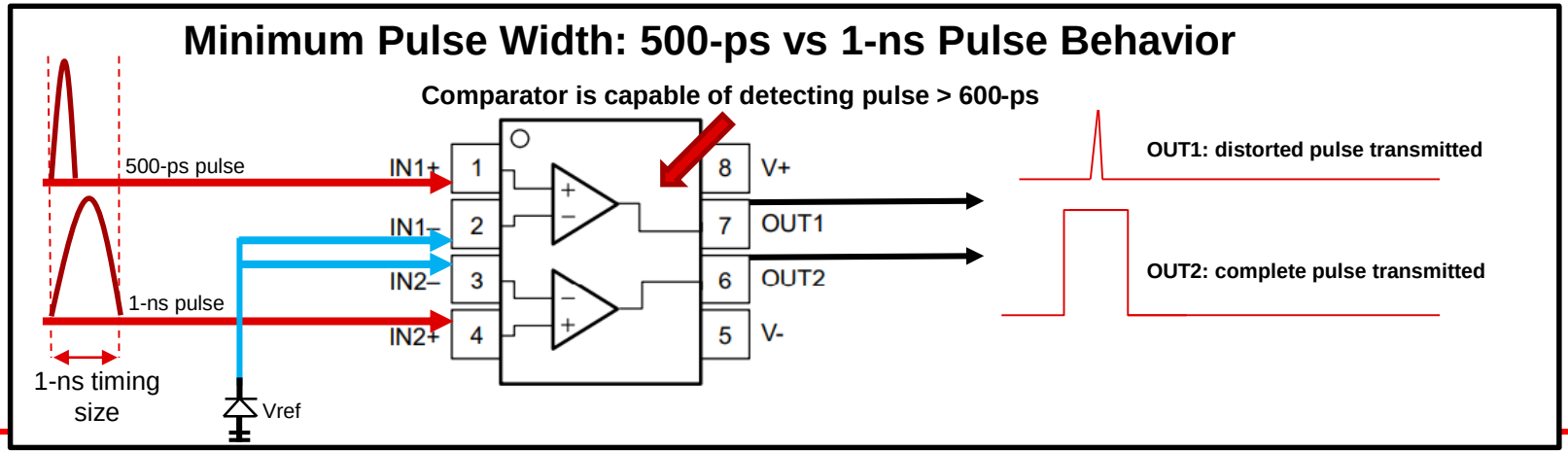
1 Features

- Low propagation delay: 800 ps
- Low overdrive dispersion: 350 ps
- Quiescent current: 12.1 mA
- High toggle frequency: 1.5 GHz / 3.0 Gbps
- Narrow pulse width detection capability: 600 ps
- LVDS output
- Supply range: 2.4 V to 5.5 V
- Input common-mode range extends 200 mV beyond both rails
- Low input offset voltage: ±5 mV

to detect narrow pulse widths of
combination of low variation in pro
to input overdrive and the ability
pulses improve system perform
distance range in Time-of-Flight (To

The Low-Voltage-Differential-Signa
the TLV3604 and TLV3605 also h
throughput and optimizes power
complementary outputs reduce E
common mode noise on each
output is designed to drive and int
downstream devices that accept

PulseWidth	Minimum allowed input pulse width	$V_{OVERDRIVE} = V_{UNDERDRIVE} = 50mV$ $PW_{OUT} = 90\%$ of PW_{IN}	600	ps

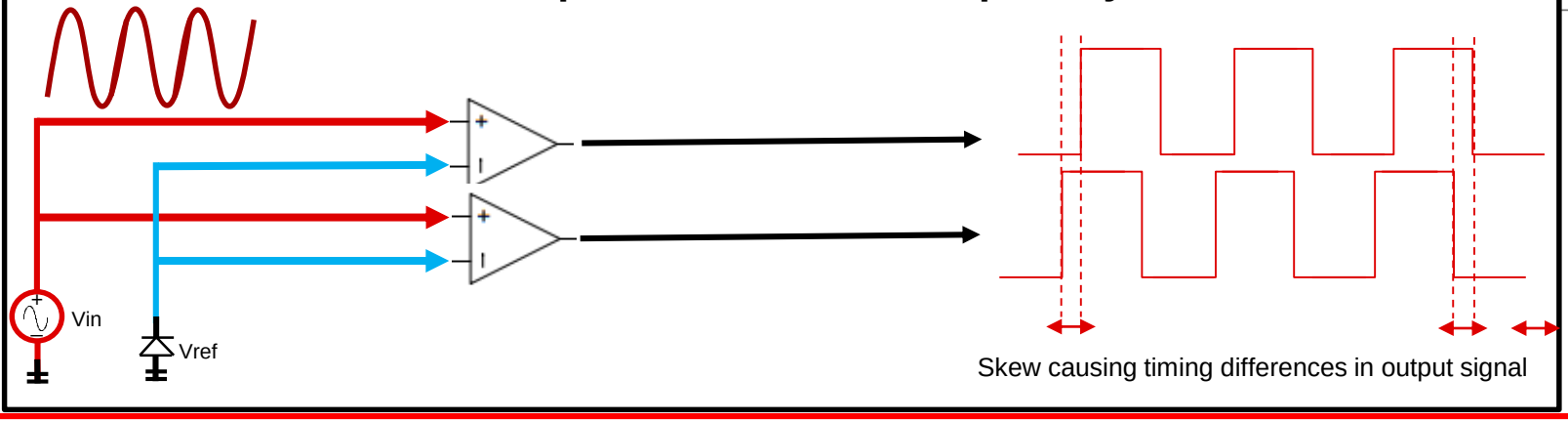


What is t_{PD} Channel-to-channel Skew (matching)?

Channel-to-channel skew (often called “matching”) refers to the **variation in response time between two or more channels** when receiving the same input signal

AC Characteristics					
t_{PD}	Propagation delay	$V_{OVERDRIVE}$ = $V_{UNDERDRIVE}$ = 50mV	2.5	3.5(1)	ns
t_{PD}	Propagation delay	$V_{OVERDRIVE}$ = $V_{UNDERDRIVE}$ = 50mV T_A = –40°C to +125°C		4.5(1)	ns
Δt_{PD} (TLV3602 only)	Channel-to-channel propagation delay skew(2)	V_{CM} = V_{CC}/2, $V_{OVERDRIVE}$ = $V_{UNDERDRIVE}$ = 50mV, 50 MHz Squarewave	24		ps
$t_{CM_DISPERSION}$	Common dispersion	V_{CM} varied from V_{EE} to V_{CC}	80		ps
$t_{OD_DISPERSION}$	Overdrive dispersion	Overdrive varied from 10 mV to 125 mV	600		ps
$t_{UD_DISPERSION}$	Underdrive dispersion	Underdrive varied from 10mV to 125 mV	330		ps
t_R	Rise time	10% to 90%	0.75		ns
t_F	Fall time	90% to 10%	0.75		ns
t_{JITTER}	RMS Jitter	V_{IN} = 100mV$_{P-P}$, f_{IN} = 100MHz, Jitter BW = 10Hz – 50MHz	4		ps
f_{TOGGLE}	Input toggle frequency	V_{IN} = 200 mV$_{PP}$ Sine Wave, When output high reaches 90% of V_{CC} - V_{EE}	325		MHz
					ns

Overdrive Dispersion Effect on Prop Delay



Comparator applications/ use cases

Texas Instruments

Power supply monitoring

Comparator usage cases

Under-voltage detection:

Devices such as the MCU need to know when the power supply reaches a nominal operating voltage to ensure proper operation. Standard comparators are frequently used because a reference voltage is already available in the system, otherwise comparators with an integrated REF can be used for higher precision and lower power consumption.

System Care Abouts:

- Low Offset | Low Power | Low Operating Voltage

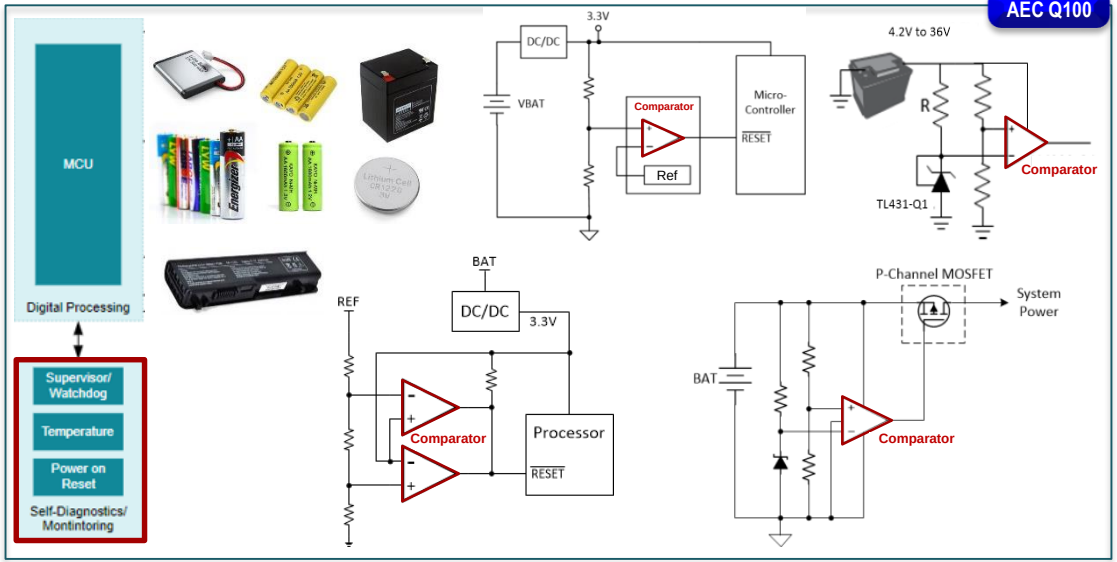
Over-voltage detection:

High voltage sources are resistor divided down and compared against a reference voltage to protect the system. Protection is provided by disabling the power source or disconnecting the system from the source. If powered by the source that is being monitored, the comparator's max operating voltage must be greater than the highest supply voltage.

System Care Abouts:

- Low Offset | Propagation Delay | Max Operating Voltage

Standard comparators	Precision comparators
Q100 **LM2903B** → Standard DUAL comparator; best price guaranteed	Q100 **TLV90XX** → 100ns, 16uA
Q100 **TLV1805** → 40V operation with push-pull output stage is well-suited to drive a MOSFET switch	Q100 **TLV301X / TLV40XX** → Integrated 1% REF
	Q100 **TLV170X** → 36V operation with IQ of 55uA and low offset;
	Q100 **TLV70XX** → Power sensitive applications



Benefits:

- Integrated reference saves board space and reduces BOM count
- Push-pull output eliminates the need for a pull-up resistor, thus saving power and decreasing the time it takes to switch off or alert the system of undervoltage/overvoltage conditions
- Inverting/non-inverting options allow for more flexibility in design

Want to learn more? Check out these links:

- Overvoltage Protection with Comparator Circuit
- Non-Inverting Comparator with Hysteresis Circuit
- High-Side Inverting Comparator with Hysteresis Circuit
- Analog Engineers Cookbook: Op Amps & Comparators

Current Sense

Comparator usage cases

Bi-directional current sense of the motor:

When the shunt resistor is placed in series with a phase lead of a motor, the current sensing requirement is bi-directional. A current sense amplifier will bias its output at mid-supply and a window comparator will alert the system if the current ever goes outside the desired range.

System Care Abouts:

- Low Offset | Propagation Delay | Output Configuration

High-side & low-side current sensing

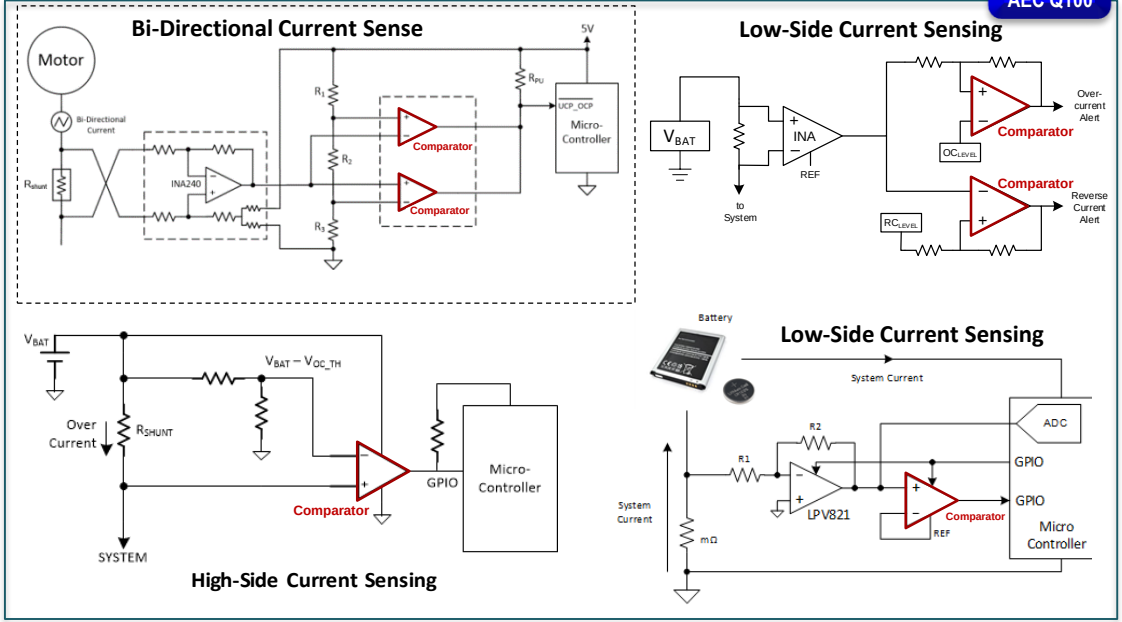
High and low side current sensing have current flowing in one direction. The voltage across the shunt can be directly monitored by a comparator or a current sense amplifier can be used when higher precision is required. An alert signal is generated by the comparator when an over-current event occurs.

System Care Abouts:

- Low Offset | Propagation Delay | Input Common Mode Range

High-voltage current sensing	Highspeed current sensing
Q100 **LM2903B** → Standard dual comparator	Q100 **TLV90XX** → 16µA, 100ns delay, best for low power application in bi-directional current sensing
Q100 **TLV170x** → 36V operation with IQ of 55uA and RRI; best for low power application in high-side current sensing	Q100 **TLV320X** → 40ns delay, 40uA supply current for high speed OC alert
Q100 **TLV1805** → 40V operation with push-pull output stage is well-suited to drive a MOSFET switch.	• **TLV360X** → 800-ps prop delay, 350-ps overdrive dispersion
	Q100 **TL331B/2903B** → 2.5mv offset voltage, 2V to 36V supply range, 1µs prop delay

AEC Q100



Benefits:

- Low offset increases accuracy of current detection
- Low propagation delay allows the comparator to send a fast alert signal
- Simplifies design and monitors hardware

Want to learn more? Check out these links:

- Bidirectional Current Sensing with a Window Comparator Circuit
- Analog Engineers Cookbook: Op Amps & Comparators
- High-side Current Sensing with Comparator Circuit
- Precision Over-Current Latch Circuit
- High-Side Fast-response Over-Current Detection Circuit

Signal Restoration

Comparator usage cases

Receiver interface: noise suppression and rebuffing

Many factors can cause signal deterioration (attenuation, distortion, etc.), prohibiting devices such as an FPGA from reading data reliably. A comparator can be used to recover the clock and/or data signal integrity and convert it to a full scale output.

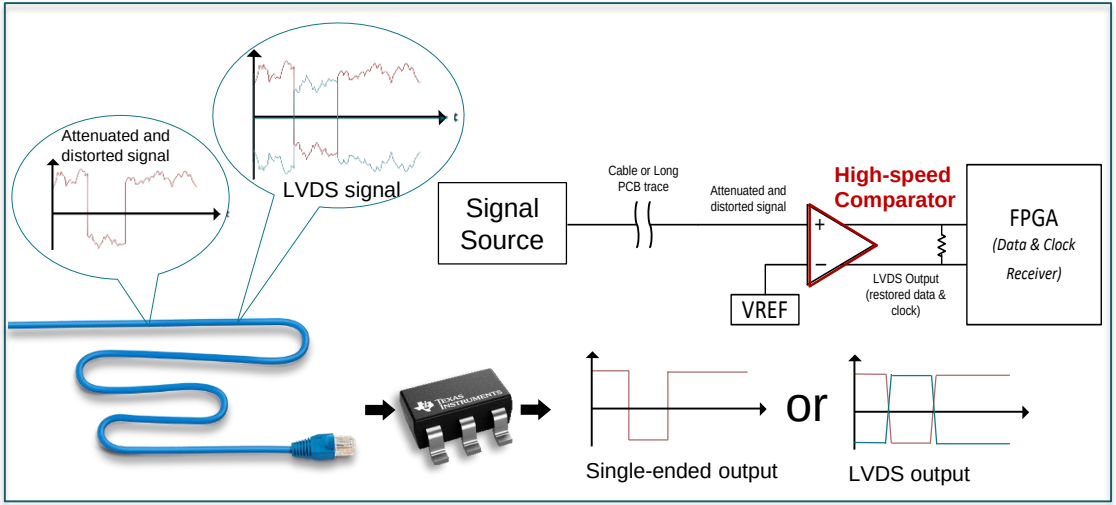
The comparator needs to

- remove the common mode noise
- sometimes needs to convert differential signal to single ended signal and drive the next stage

System care about:

- Toggle frequency | Dispersion | Adjustable hysteresis.

LVDS comparators	High speed comparators
TLV3801 → • 225 ps propagation delay • 5 ps overdrive dispersion • 3 GHz toggle frequency • 1.5mV hysteresis	**TLV3603 →** • 2.5/3.3/5V power supply • 325 MHz data frequency with push pull output; • On-chip adjustable hysteresis • 5V input signal range
TLV3604/5 → • 2.5/3.3/5V power supply • 1.5GHz data frequency with LVDS output • on-chip adjustable hysteresis • 5V input signal range	**TLV3601 →** • 2.5/3.3/5V power supply • 325 MHz data frequency with push pull output; • Fixed hysteresis • 5V input signal range



Benefits:

- Adjustable hysteresis allows for more threshold control and saves board space by eliminating external feedback loop
- Small size makes it ideal for space-constrained designs
- Fast toggle frequency and low dispersion preserves signal integrity

Want to learn more? Check out these links:

- Analog Engineers Cookbook: Op Amps & Comparators
- Signal and Clock Recovery Comparator Circuit
- LVDS data and clock recovery circuit with high-speed comparators

Temperature Detection

AEC Q100

Comparator usage cases

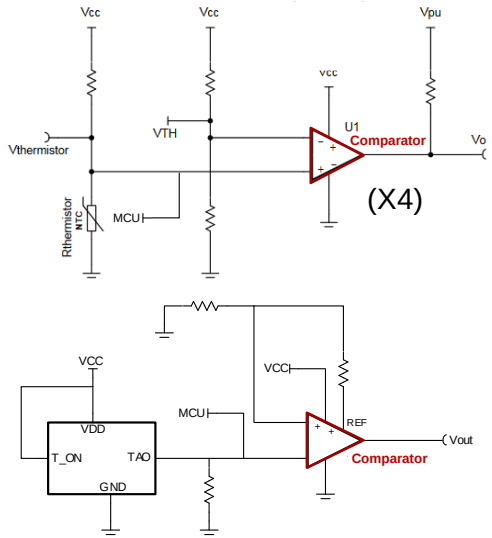
Detect when system reaches critical temperature:

Over-temperature detection is required to protect systems from excessive temperatures during operation; note that no fixed reference is required with integrated reference comparator solution.

System care about:

- Low quiescent current
- Low input offset voltage
- Integrated hysteresis
- Rail-to-rail inputs
- Multichannel options for measuring multiple temperatures
- Known startup condition

Standard	Specialized
Q100 **TLV703X/4X** → Nanopower, best when need low power in high-side current sensing, 0.8 mm × 0.8 mm, Q100 **TL331B/TL391B** → operating voltage up to 36V, Low input offset	Q100 **TLV3011/TLV3012**→ Power on Reset circuit, Externally available precision 1.2V reference, ±1% accuracy • **TLV4031R1**→ Power on Reset circuit, precision 1.2V reference, ±1% accuracy, 0.73 mm × 0.73 mm size package





Benefits:

- Offers analog backup protection when placed in parallel with microcontroller
- Hysteresis and low V_{OS} eliminate false output transitions for slow temperature transitions
- Rail to rail inputs allow for monitoring temperature over a wider range
- In the presence of a POR circuit, the output is in a known state during startup

Want to learn more? Check out these links:

- Thermal Switch with a Comparator
- Analog Engineers Cookbook: Op Amps & Comparators

Why TI? Investment in special features

- Known startup condition (power on reset circuit)
- Fail-safe Inputs
- Integrated references and application specific standard products
- Reverse battery protection
- Over-the-rail operation
- Split-supply input operation with ground reference outputs
- Hysteresis pin
- Self-latching
- 65V operation

Comparators web portal – ti.com/comparators

Browse by category

Select by parametric specification

High-speed comparators (t_{PD} <100 ns)

Our lightning-fast comparators provide a performance advantage with optimized power and response times as low as 210 ps

- 5 to 100-ns propagation delay
- <5-ns propagation delay

Low-power comparators (I_Q/ch < 10 µA)

Power-efficient comparators with quiescent current as low as 75 nA for extending battery life

- 1 to 10-µA I_Q
- <1-µA I_Q

High-voltage comparators (V_{CC} >12 V)

Robust, high-voltage and fast-response-time comparators from 0.9 V to 40 V

- 12 to 30-V supply voltage
- >30-V supply voltage

Small-size comparators

High-performance comparators in packages as small as 0.7mm x 0.7mm

- Find your device

Automotive comparators

AEC-Q100 Grade 0 and Grade 1 qualified comparators with robust 2-kV ESD

- Find your device

Standard comparators

Standard comparators from the industry's largest and highest-quality comparator portfolio

- Find your device

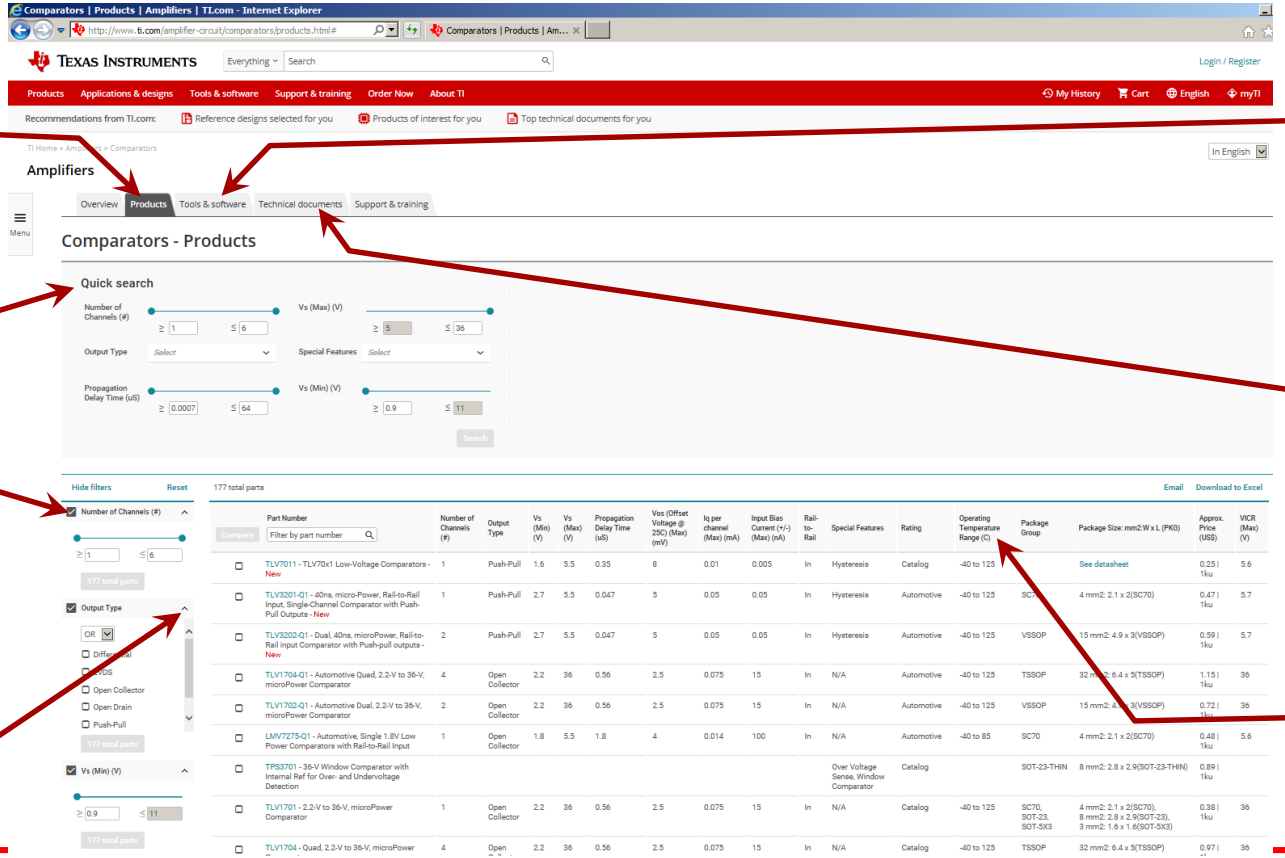
Comparators web portal – ti.com/comparators

Click “Products” tab for parametric table

Quick search

Selectable filters for more detailed search

Click on arrow to expand filter selections



Tools and software tab for selguide, crossref and TINA

Technical documents tab for application notes and selection guides

Click on headers to toggle sorting

Texas Instruments

Questions?

Texas Instruments

To find more technical resources on comparators and search for products, visit **ti.com/comparators**.



© Copyright 2024 Texas Instruments Incorporated. All rights reserved.

This material is provided strictly “as-is,” for informational purposes only, and without any warranty.
Use of this material is subject to TI’s **Terms of Use**, viewable at TI.com

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATA SHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI’s products are provided subject to TI’s Terms of Sale or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI’s provision of these resources does not expand or otherwise alter TI’s applicable warranties or warranty disclaimers for TI products.

TI objects to and rejects any additional or different terms you may have proposed.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2024, Texas Instruments Incorporated