Op-amp comparator/Schmitt (bipolar clamping)

Circuit description
Operational amplifiers used as comparators (or as level-sensing circuits when positive feedback is used for hysteresis) have output swings which vary with temperature and from unit to unit. Some amplifiers have access to the drive point of the output stage and this point may be clamped at selected positive and negative potentials by zener diodes or suitably biased transistors as shown. Clipping is at much lower current levels than if attempted directly at the output. Variable resistors R2 and R3 set the positive and negative clamping levels, R1 determines hysteresis at the clamping levels. Diodes provide base-emitter breakdown protection.

Basic Schmitt circuit

Circuit description
Emitter coupling between Tr1 and Tr2 introduces positive feedback causing a regenerative switching action into one of two states. When Vin is below threshold level V1, Tr1 is non-conducting and Tr2 conducts, the base voltage being determined by R1, R2 and R3. The emitter potential is then well-defined. As input voltage exceeds V1, Tr1 begins to conduct, reducing its collector potential, and hence that of the base and emitter of Tr2. This drop in potential is fed back to the emitter of Tr1, thus further increasing the conduction of Tr1 until Tr1 is on and Tr2 is off. A similar regenerative action occurs when the input voltage is reduced below the threshold level V2, returning the circuit to its original condition. A typical input-output voltage characteristic is shown above, where V1 - V2 is termed the hysteresis or backlash of the circuit.
Circuit modifications

- Diodes could be placed in series with the emitters of the transistors. This still provides base-emitter breakdown protection but the diodes then carry the larger emitter currents producing larger diode p.d.s.
- R1 and R2 could be connected as shown on left allowing the base potentials of both Tr1 and Tr2 to be set positive or negative independently. It would then be possible for Tr1 base to be positive and Tr2 base to be negative, which would allow excessive conduction in Tr1, Tr2.
- Fig. on right shows a modification which allows the mean level of VCE to be set positive or negative by the potentiometer with its peak-to-peak value still determined by ±3VBE.

Further reading

IC op.amp beats fets on input current, National Semiconductor application note AN-29, 1969, p.15.

Cross references

Series 2. cards 4 & 6.

Reference


Further reading


Cross references

Series 2. cards 3, 7 & 8.
Wireless World Circard

Complementary m.o.s. Schmitt

Circuit description
Two c.m.o.s. inverters are cascaded with positive feedback defined by ratio $R_f/R_i$. Provided this ratio is less than the forward gain in the inverters' linear region, switching follows the appropriate input changes. Output swing approaches supply lines and current from source is small as very high. The resistance of inverter allows $R_1$, $R_2$ to be large. With small hysteresis switching levels are near supply mid-point.

Series 2: Comparators & Schmitts–3

IC: CD4007AE (connected as triple inverter)
Supply: 10V
$R_1$: 1MΩ
$R_2$: 10MΩ
$V_1$: 5.9V
$V_2$: 5.1V
Output swing: 10V
Input current: ≤0.5μA

Component changes
- Any combination of inverters, gates or buffers giving voltage gain > +1 may be used. Examples: RCA CD4001AE, Motorola MC14001 quad 2-input NOR gates; CD4009AE hex buffer inverters.
- Supply voltage +3 to +15V (special versions down to 1.5V).
- $R_f/R_i$ may be varied between 1 and 100. At upper end of range positive feedback may be too little to guarantee switching. At lower end hysteresis is comparable to supply voltage.
- To minimize capacitive effects/hum pickup reduce $R_1$, $R_2$ to ~10kΩ. Lower values reduce output swing and accuracy of hysteresis, while increasing current from source.

Wireless World Circard

Series 2: Comparators & Schmitts–4

High-power comparator/Schmitt

Circuit description
The output swing of standard op-amps is significantly less than the supply voltage, particularly when the latter is low. The current available is also low. With some op-amps the current in the positive supply lead is large when the output voltage is positive and the output current is large but is small when the output voltage is negative. The negative supply current behaves similarly. The change in supply current as the input signal varies can be used to drive following transistors which may supply currents of several hundred milliamperes at a voltage very close to the supply voltage.

Performance data
IC: 741; Supplies ±5V
$T_1$: BFR41, $T_2$: BFR81
$R_1$, $R_2$: 220Ω, $R_3$: 270Ω
$R_4$, $R_5$: 68Ω, 3W
Minimum $V_{in}$ = 800mV
pk-pk
Max. ±V ±7V,
limited by $R_4$ and $R_5$.

With maximum permissible sinusoidal input of 8V pk-pk, $V_1$ and $V_2$ are both square waves swinging between -5 and +4.8V, and -5 and +5V respectively. $V_1$ and $V_2$ are in-phase while the currents in $R_4$ and $R_5$ are in anti-phase. Max. frequency 1kHz—waveform squareness is lost at higher frequencies.

Component changes
- To maximize output voltage swings $T_1$ and $T_2$ must be driven into saturation i.e. base currents of 5 to 10% of load current are required. Reducing $R_1$ will increase base current.
- Resistors $R_1$ and $R_2$ may need to be reduced for some op-amps having larger off-load currents (180Ω was found satisfactory for a 748).
Circuit modifications

- Buffer input with third inverter/gate increasing input resistance (typical input current ~ 10pA). Resistor \( R_1 \) may be dispensed with, the output resistance of buffer taking its place, with \( R_1 \) reduced to range 1 to 30kΩ. Resulting hysteresis in range 2.5 to 0.2V.
- Use spare inverter self-biased by large resistor \((~ 10MΩ)\) (see Fig.) to bias input terminal of first inverter via second resistor \((~ 10MΩ)\). This sets mean potential near to centre of linear region, assuming well-matched inverters. Signals may now be a.c. coupled and 200mV pk-pk typically triggers circuit over a range of supply voltage and temperature with no adjustment of bias level.

Further reading


Cross references

Series 2, cards 1, 2 & 8.
Unijunction-equivalent Schmitt

Circuit description
The transistors together have properties similar to those of a unijunction transistor. When $V_{in}$ is low $T_1$ and $T_2$ do not conduct and $V_r$ is defined by $R_3$. For $V_{in} \approx V_r + 1.3V$, $T_1$ and $T_2$ begin to conduct, regenerative switching via $T_2$ clamping $V_{out}$ close to 0V. Reversal of switching occurs when $V_{in}$ falls. Significant current is drawn from the source unless a limiting resistor ($R_1$) is included.

Typical performance
- Supply: ±5V
- $T_1$: BC126 $T_2$: BC125
- $R_1$, $R_2$: 1kΩ $R_3$: 4.7kΩ
- $V_{out}(on)$ = 0.04V
- $V_{out}(off)$ = $V_r$ = 2.5V
- $V_{in}(on)$ = 3.8V
- $V_{in}(off)$ = 3.0V
- Supply current: 8mA (on), 1mA (off)

Component changes
- $T_1$: any general purpose p-n-p silicon transistor.
- $T_2$: any general purpose n-p-n silicon transistor.
- Maximum useful frequency = 100kHz.
- Range of $V_r$ source resistance (seen by $T_1$ base): about 2.2kΩ to 33kΩ.
- $R_1$ (max) = 3.3kΩ. For large $R_1$ values $V_r$ source resistance must be increased for rapid switching action. The output can only be lightly loaded with large $V_r$ source resistance.

Variable hysteresis level detector

Circuit description
$V_{ref}$ adjusts the level at which the output switches without affecting hysteresis. Positive feedback path $R_2$ and $R_1$ provides hysteresis controllable by $R_3$. Sensitivity can be modified by changing input resistance $R_1$. Positive output swing is determined by the base-emitter voltage of the transistor and the negative output by the particular operational amplifier used. Diodes on the input provide breakdown protection of the op-amp against excessive input voltages.

Component data
- Supplies: ±15V
- $R_1$, $R_2$: 2.2kΩ
- $R_3$: 100kΩ
- $R_2$: 100MΩ
- $R_3$: 3.3kΩ
- $R_4$: 1kΩ
- $R_7$: 1kΩ
- $D_1$, $D_2$: general-purpose diodes.
- IC: 741
- $T_r$: ME4103 (in general determined by driving circuit).
- All resistors ±5%.

Component changes
- IC: 748 or LM301A.
  - For $V_{ref}$ of -1V to -14V, $R_3$ = 0, supplies: ±15V;
  - hysteresis: 180mV ±2%
  - trip level: $V_{ref} + 200$mV.
  - For $V_{ref}$ of -1V to -4V, $R_3$ = 0, supplies: ±5V;
  - hysteresis: 700mV ±5%
  - trip level: $V_{ref} + 100$mV.
  - Hysteresis: 10mV, $R_1$ - 1MΩ, supplies: ±10 to ±15V; trip level: $V_{ref} + 100$mV.
  - In general, hysteresis may be further increased by reducing $R_2 + R_3$. 

Wireless World Circard
Series 2: Comparators & Schmitts
Circuit modifications
If the input voltage is fed directly to Tr, emitter the circuit may be used to clamp it to a low level (about 0.7V with a 5V supply) when it exceeds some maximum permissible level. For example, V_f could be the output from a voltage regulator and V_in its input voltage. If V_in (regulator input) rises excessively the circuit will rapidly clamp the regulator input to a low value protecting the regulator and the circuitry it supplies during the time taken for the supply fuse to blow. The transistors require a current rating greater than the supply peak current on s.c. loading. R2 and R3 may then need to be reduced.

Further reading
Unijunction transistor timers and oscillators, Motorola application note AN-294 (appendix), 1967.

Cross references
Series 2, cards 2 & 12.

Circuit modifications
- If output voltage swing required at lower currents, Tr may be omitted and R2 reduced to zero. Hysteresis is then controlled by op-amp output swing.
- Alternative methods of defining output swing and hence hysteresis include series back-to-back zener diode or diode limiting circuits.
- For higher speed operation, IC may be any comparator.
- For higher output currents, Tr may be replaced by a Darlington pair. If only an indication of output state is required, most op-amps can deliver sufficient current to drive small light-emitting diodes.

Further reading

Cross references
Series 2, cards 9-11.
**High-speed Schmitt circuit**

![Circuit Diagram](image)

**Circuit description**
For maximum speed, Schmitt trigger circuits should operate with <i>all</i> transistors out of saturation at all times. A zener diode in the bias network can assist this. In this circuit, current levels are higher than in the basic Schmitt to maximize gain-bandwidth product. The inductors compensate for capacitive loading to optimize rise time. The upper and lower thresholds are negative and the hysteresis is variable but is not independent of the threshold levels.

**Typical performance**

- **Supplies:** ±5V
- **V<sub>1</sub>, V<sub>2</sub>:** 10V
- **V<sub>2</sub> (Tr1 on):** -0.3V
- **V<sub>2</sub> (Tr2 off):** 0.2V
- **Supply current:** +40mA, -50mA
- **Component changes**
  - Useful range of V<sub>2</sub>: 0 to ~1.47V
  - Corresponding hysteresis range: 2.9 to 1.64V
  - L<sub>1</sub> and L<sub>2</sub> can be adjusted to produce a required rise time with a defined overshoot for given capacitive loading. The same principle applies to the complementary Schmitt. With L<sub>1</sub> = L<sub>2</sub> = 0.12mH, rise time < 8ns with 3% overshoot at low switching rates.
  - The circuit functions to at least 40MHz with defined output levels although the waveform is rounded at high frequencies.
  - Careful printed circuit layout is necessary for good high-frequency operation.

**TTL Schmitt circuit**

![Circuit Diagram](image)

**Performance data**

- **Graph obtained with:** R<sub>1</sub>: 250Ω, R<sub>2</sub>: 30Ω
- **Supply:** 5V
- **ICs:** 7400
- **Frequency:** 0 to 1MHz

**Lower limit (1V as shown) is affected by R<sub>1</sub> and R<sub>2</sub>.**

- **With R<sub>1</sub> = 0 there is no positive feedback and switching is not clean.**
- **With R<sub>2</sub> = ∞ upper limit is reduced from 5V.**

**Circuit description**
Each NAND gate with one input gate disabled behaves as an inverter. The circuit with positive feedback via R<sub>1</sub> is very similar to the basic Schmitt trigger as each gate is essentially identical. This results in the potential across R<sub>1</sub> being constant and independent of which inverter is enabled. This results in an offset voltage compensated by R<sub>2</sub>.

**Component changes**
Any t.t.l. inverter may be used.

**Circuit modifications**
An alternative t.t.l. Schmitt is SN7413, produced by Texas, and has two in a single package. Typical characteristics are shown below. Frequencies up to several MHz can be handled, but ringing may occur beyond 100kHz if the circuit layout is poor.
Circuit modifications
Precise adjustment of the negative rail voltage allows the
output to be made truly t.t.l.-compatible with levels of 0V
and +5V. The output from Tr2 may be used to feed a high-
speed t.t.l. gate or an e.c.i. gate to "square up" the waveform
at high frequencies. Circuits of this type may be useful in
conjunction with t.t.l. or e.c.i. circuitry as they provide
alternative options of switching levels and hysteresis. To
assist supply decoupling at high frequencies, ferrite beads can
be added to the supply line wiring.

Further reading
MECL Integrated Circuit Schmitt Triggers, Motorola applica-
tion note AN-239.

Cross references
Series 2, card 2 & 8.
Low-voltage level sensor

Circuit description
Operation from single-ended supplies makes level-sensing of low voltages difficult (lower limit usually set by transistor $V_{BE}$). Taking signal and reference voltages with respect to opposite side of supply as shown allows much reduced triggering voltages. A long-tailed pair drives an inverting stage with positive feedback from the output to the non-inverting input. Input current is small, reducing to zero after switching. For positive-going signals, a complementary version using a positive supply voltage gives comparable results.

Supply: $-12V$
$V_{ref}$: $-1V$
$T_{1a}, T_{2a}, T_{1b}: BC125$
$T_{2b}: BC126$
Switching levels on: $-1.35V$
off: $-1.03V$

R1: 3.3kΩ
R2: 100kΩ
R3: 470kΩ
R4: 82kΩ
R5: 10kΩ

Component changes
- Supply voltage 5 to $-25V$, upper value depending on transistor breakdown. At lower voltages, switching levels become more supply sensitive. Reduce R1 at lower supply voltages to keep current in it to $\approx 120μA$.
- Reference voltage $-200mV$ to $-5V$.
- Load currents up to 100mA possible with no change in circuit. Replacing $T_{2a}$ by higher rating transistor, and scaling all resistors down by factor of 5 allows load currents of up to 0.5A (BFR41, BFY50 etc).
- $T_{1a}-T_{2a}$ replaced by any general-purpose silicon planar transistors results in comparable performance: matched pair at input reduces drift.

Reference-controlled hysteresis circuit

Circuit description
With a low $V_{in}$, $V_{out}$ is initially negative and the f.e.t. switch off. $V'$ is then given by $V_{in}/R_{f}(R_{1} + R_{2})$. Increasing $V'$ in until $V'$ is just greater than $V_{ref}$ causes $V_{out}$ to change sign, the f.e.t. then conducts and shorts out $R_{1}$ making $V''$ equal to $V_{in}$ and forcing $V_{out}$ to become even more positive. $V_{out}$ will only become negative again when $V_{in}$ is reduced below $V_{ref}$. The positive feedback does not come into action immediately $V_{out}$ starts to leave its saturated condition, so the output may lie between the saturated levels.

Performance data
Graphs obtained with Supplies $\pm 15V$
$T_{2}: \text{Motorola 2N4092}$
$D_{1}: \text{1N914, IC: 741}$
$R_{1}: 5.6kΩ \pm 5\%$
$R_{2}: 27kΩ \pm 5\%$
$C: 100pF$
Lower threshold (l.t.): $V_{ref}$
Upper (u.t.): $V_{ref}(R_{1} + R_{2})/R_{2}$
Hysteresis: $V_{ref} R_{1}/R_{2}$
Max. frequency: 300Hz
$V_{ref}$ must remain positive.

Component changes
Using a 748 op-amp the maximum frequency can be extended to 4kHz. National Semiconductor f.e.t. 2N3819/7127 may be used. $R_{1}$ is chosen such that the f.e.t. on-resistance is much lower than $R_{1}$ and the off-resistance is much higher than $R_{1}$. Varying $R_{2}$, $R_{1}$ and $R_{2}$ hysteresis of 0.1$V_{ref}$ and 10$V_{ref}$ can easily be obtained. Choice of diode and capacitor is not critical.
Circuit modifications
- Reference and signal inputs may be interchanged if minimum current drain from reference is required.
- Replacing $R_x$ by constant-current circuit minimizes shift of switching levels with varying supply voltage. Fig. shows a ring-of-two reference circuit biasing constant-current stage, and providing stable voltage across $R_s$ to act as switching-level reference. Replaced by potentiometer for variable reference.
- Tapping $R_s$ with a zener diode to 0-V line stabilizes hysteresis without limiting output voltage swing.
- For light loading $T_x$, may be omitted.

Further reading

Cross reference
Series 2, cards 6, 10 & 11.

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Circuit modifications
- With a negative $V_{ref}$, $V^*$ should be connected to the inverting input and $V_{ref}$ to the non-inverting input to obtain the positive feedback switching action.
- With a low reference voltage and low supply voltage (e.g. <1V with ±5V supply), f.e.t. pinch-off voltage causes unsatisfactory switching. The f.e.t. and its associated diode and capacitor may be replaced by a c.m.o.s. switch, left. The switch used was CD4016AE, the minimum $R_1$ in this case being about 10kΩ.
- For applications where $V_0$ is required to be positive, for positive $V_{ref}$ and small $V_{in}$, one may use the circuit on right, the resulting characteristic being as shown on right. The formulae for the upper and lower thresholds and the hysteresis are the same as those for the original circuit.

Further reading

Cross reference
Series 2, cards 4 & 6.

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Circuit description

A1 is a non-inverting comparator having a positive reference level \( V_r \) set by \( R_1 \) and \( R_2 \). Amplifier A2 is an inverting comparator having a negative reference \( V_n \) set by \( R_5 \) and \( R_6 \). Output \( V_{out} \) remains at a low level when \( V_r < V_{in} < V_n \), and A2 is capable of switching its output to \( +V_{OL} \) when \( V_{in} < V_n \). As the outputs of A1 and A2 are common, \( V_{out} = +V_{OL} \) when \( V_{in} < V_r \), or when \( V_{in} > V_r \). Hysteresis is introduced by the positive feedback on A1 (by \( R_1 \) and \( R_2 \)) and A2 (by \( R_5 \) and \( R_6 \)). See transfer characteristic above. From an output level viewpoint the circuit is t.t.l. compatible.

Component changes

Maximum useful frequency \( \approx 1 \text{MHz} \).

Function \( V_{OL} \) may be varied over the range \(+0.4 \text{ to } 4.4 \text{V} \) by setting \( V_{strobe} \) in the range \(+1 \text{ to } +5 \text{V} \). \( V_{OL} \) remains fixed at \(-0.4 \text{V} \).

Variation of \( R_1 \) and/or \( R_5 \) provides independent control of the positive and negative threshold levels. Minimum useful value of \( R_1 \) and/or \( R_5 \) \( \approx 700 \Omega \).

Minimum load resistance (for \( 10^{-9} \) reduction of \( V_{OL} \)) \( \approx 680 \Omega \).
Circuit modifications

- Where hysteresis is not required the positive feedback resistors may be omitted.
- A visible-light-emitting diode connected to output terminal through a limiting resistor gives visual indication when the input signal is outside the limits set by $V_i$ and $V_f$. Typically a resistance of 470Ω provides 5mA which is sufficient to illuminate the I.E.D. without excessively loading the IC.

Further reading


Cross references
Series 2, card 6.

Circuit modifications

A 47-Ω resistor included in series with the "free collector" of $T_2$ provides a complementary pulse output. These pulses typically have an amplitude of 0.6V (with a 12-V supply) i.e. sufficient to drive a following transistor or thyristor. $T_1$ will still saturate and $T_2$ will remain unsaturated. The value of this resistor may be considerably increased if it is returned to a separate negative supply. With a value $\leq R_1$ a second output is then available without significantly changing the circuit action.

Further reading


Cross references
Series 2, cards 2 & 5.