Chap 3 - Digital Voltmeter

Digital voltmeter parameters

- range
- resolution
- accuracy
- input impedance

Digital voltmeter types

- CC – continuous current
- AC – alternative current
- vector type

Accuracy specification

Three type of accuracy specification for DMM

- ppm of U_X + ppm of U_{CS}
- % of U_X + % of U_{CS}
- % of U_X + Least significant digit

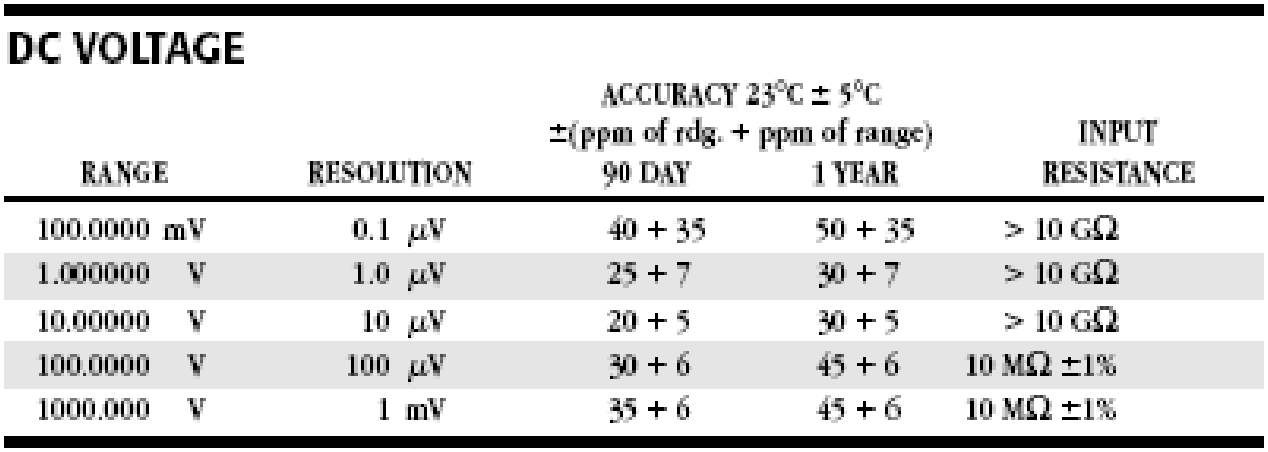
Reminder: $\varepsilon_r = \dfrac{e_{abs}}{U_X}$ $\varepsilon_{RAP} = \dfrac{e_{abs}}{U_{CS}}$

Absolute error: $e_U = \varepsilon_r(\%) \cdot U_X + \varepsilon_{RAP}(\%) \cdot U_{CS}$

$$e_U = \varepsilon_r(\mathrm{ppm}) \cdot U_X + \varepsilon_{RAP}(\mathrm{ppm}) \cdot U_{CS}$$

$$e_U = \varepsilon_r(\%) \cdot U_X + e_{LSD}$$

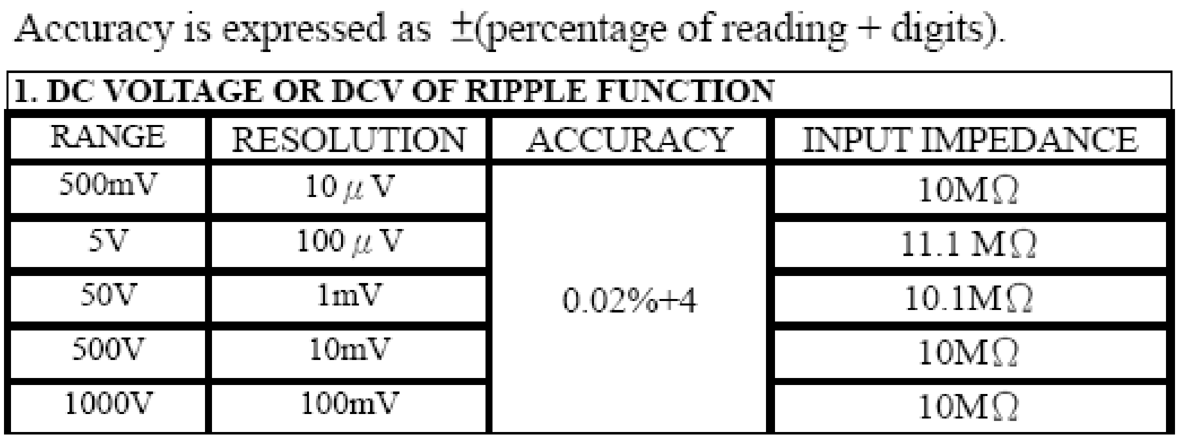
Performances specification types



DC VOLTAGE

RANGE	RESOLUTION	ACCURACY 23°C ± 5°C ±(ppm of rdg. + ppm of range) 90 DAY	 1 YEAR	INPUT RESISTANCE
100.0000 mV	0.1 μV	40 + 35	50 + 35	> 10 GΩ
1.000000 V	1.0 μV	25 + 7	30 + 7	> 10 GΩ
10.00000 V	10 μV	20 + 5	30 + 5	> 10 GΩ
100.0000 V	100 μV	30 + 6	45 + 6	10 MΩ ±1%
1000.000 V	1 mV	35 + 6	45 + 6	10 MΩ ±1%

Keithley



Accuracy is expressed as ±(percentage of reading + digits).

1. DC VOLTAGE OR DCV OF RIPPLE FUNCTION

RANGE	RESOLUTION	ACCURACY	INPUT IMPEDANCE
500mV	10 μV	0.02%+4	10MΩ
5V	100 μV		11.1 MΩ
50V	1mV		10.1MΩ
500V	10mV		10MΩ
1000V	100mV		10MΩ

GW-Instek

Relation between digits number (DMM) and bits number (DAC)

- ideal case

DMM display	N – digit number	ΔV – display resolution
DAC	n – bits number	δV – conversion resol.

$$U_{CS} = U_{REF} \Rightarrow \Delta V = \frac{U_{REF}}{10^N} \quad ; \quad \delta V = \frac{U_{REF}}{2^n} \ ; \ \text{cond: } \Delta V = \delta V$$

Exp: $\begin{cases} U_{CS} = 20\text{V} \\ \Delta V = 10\mu\text{V} \end{cases} \Rightarrow N = \log_{10}\left(\frac{U_{CS}}{\Delta V}\right) = 5.3 \rightarrow 5\tfrac{1}{2} \ ; \ n = \log_2\left(\frac{U_{CS}}{\delta V}\right) = 17.6\text{bits} \ ;$

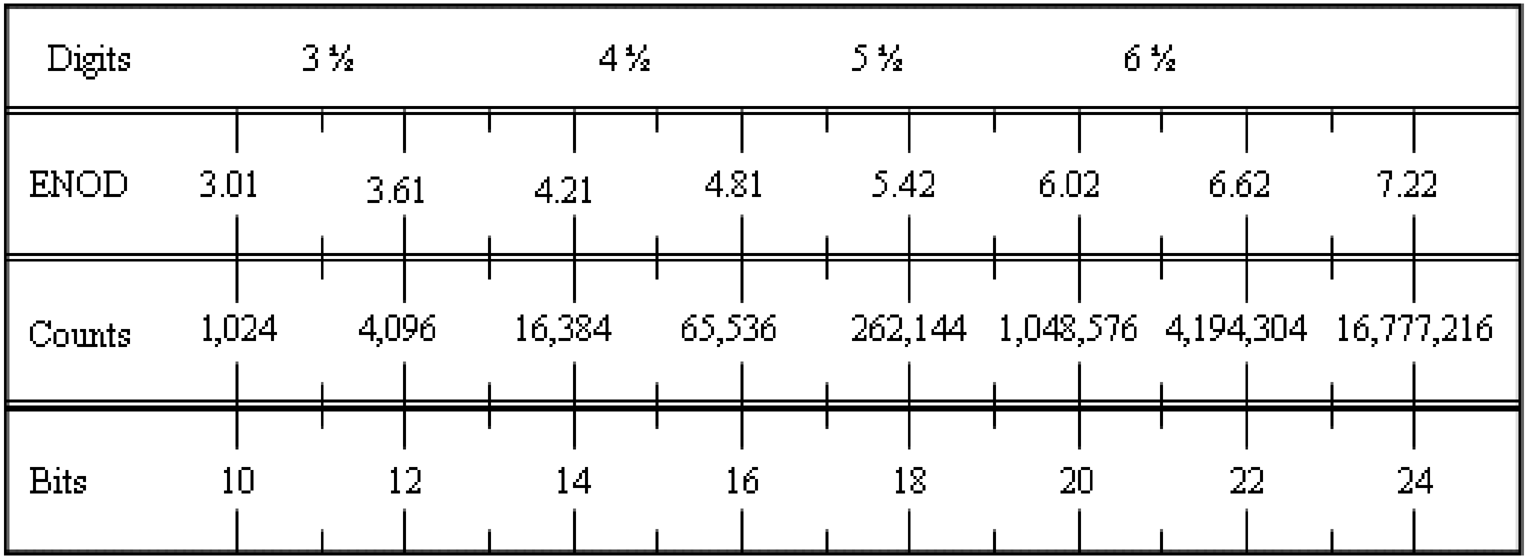
- noisily case : $U_{RMS\_noise} = \frac{U_{noise\_MAX}}{\sqrt{12}}$, if $U_{noise\_MAX} > \Delta V \rightarrow \Delta V$ unreliable

It uses $\Delta V_{ech} = U_{RMS\_noise} \cdot \sqrt{12}$

Exp: $U_{RMS\_noise} = 70\mu\text{V} \rightarrow \Delta V_{ech} = 70\sqrt{12}\ \mu\text{V} = 242.5\mu\text{V} = \delta V_{\text{ech}}$

$$N = \log_{10}\left(\frac{U_{CS}}{\Delta V_{ech}}\right) = 4.92 \rightarrow 5 \ ; \ n = \log_2\left(\frac{U_{CS}}{\delta V_{ech}}\right) = 16.33\text{bits}$$

- **Digital voltmeter type**

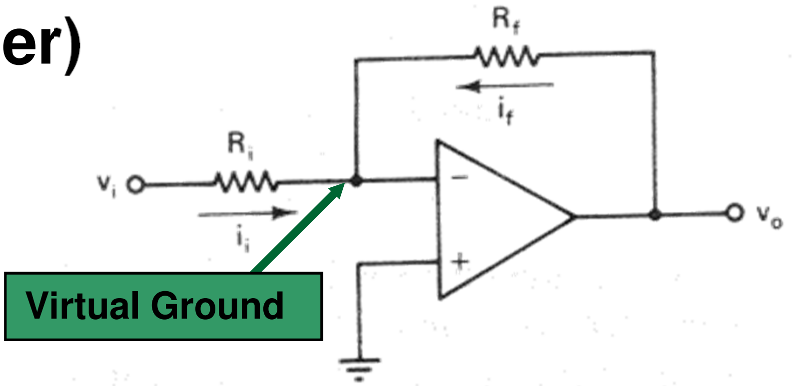


Digits		3 ½	4 ½		5 ½	6 ½		
ENOD	3.01	3.61	4.21	4.81	5.42	6.02	6.62	7.22
Counts	1,024	4,096	16,384	65,536	262,144	1,048,576	4,194,304	16,777,216
Bits	10	12	14	16	18	20	22	24

AO basic circuit (CIA remember)

Inverting amplifier

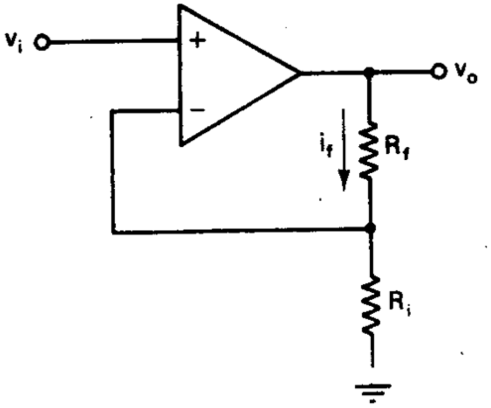
$$a_U = \frac{V_0}{V_{in}} = -\frac{R_f}{R_i} \quad ; \quad R_{IN} = \frac{V_i}{I_i} = R_i \ ; \quad R_{out} = 0$$



Virtual Ground

Non-inverting amplifier

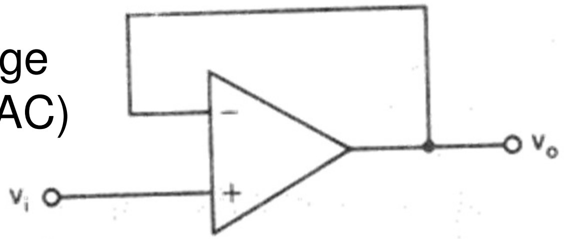
$$a_U = \frac{V_0}{V_{in}} = 1 + \frac{R_f}{R_i} \quad ; \quad R_{IN} \to \infty \ ; \quad R_{out} = 0$$



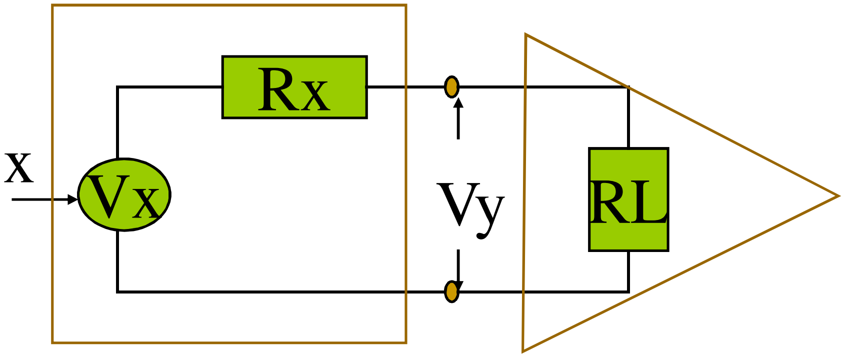
$$V_0 = V_{in} \quad ; \quad R_{IN} \to \infty \qquad \Rightarrow \text{ buffer function}$$

Applications

- Isolate one circuit from the loading effects of a following stage
- Impedance converter - Data conversion System (ADC or DAC) where constant impedance or high impedance is required



AO basic circuit (CIA remember)



- open loop output: V_X
- Voltage drop by load: V_Y

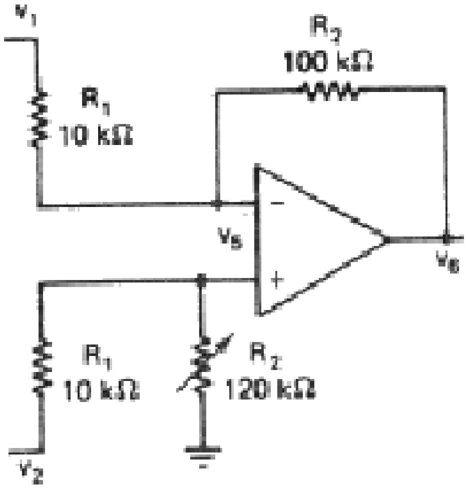
$$V_Y = V_X - V_X \frac{R_X}{R_L + R_X} = V_X \frac{R_L}{R_L + R_X}$$

$$R_L >> R_X \quad \Rightarrow \quad V_Y \approx V_X$$

Ideal: R_X low, R_L very large

Differential amplifiers

$$\left.\begin{aligned} V_5 &= V_2 \frac{R_2}{R_1 + R_2} \\ V_5 &= V_1 - R_1 I_1 \\ V_5 &= V_6 + I_1 R_2 \end{aligned}\right\} \Rightarrow V_6 = \left(V_2 - V_1\right)\frac{R_2}{R_1}$$

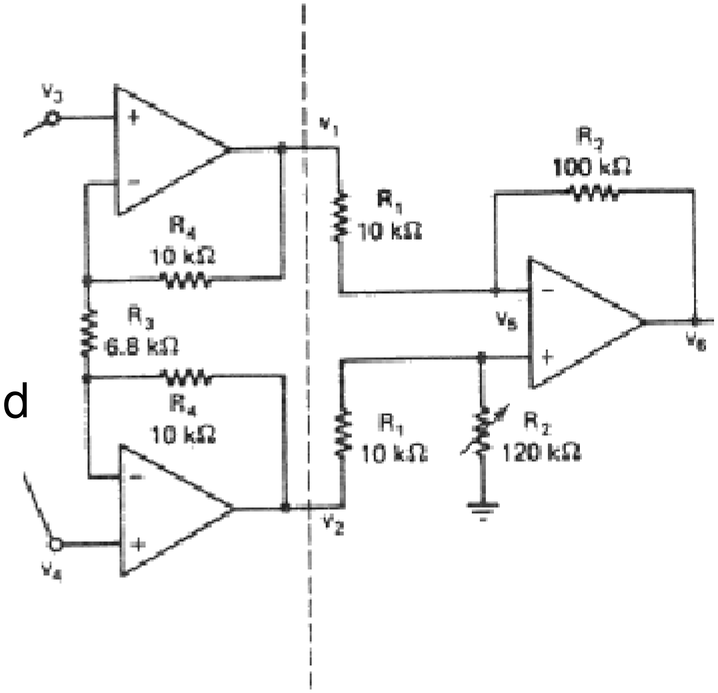


AO basic circuit (CIA remember)

- CMG = 0 (V_1=V_2 V_6=0V)
- DG = R_2/R_1
- CMRR = DG/CMG (large)
- not high input impedance ()

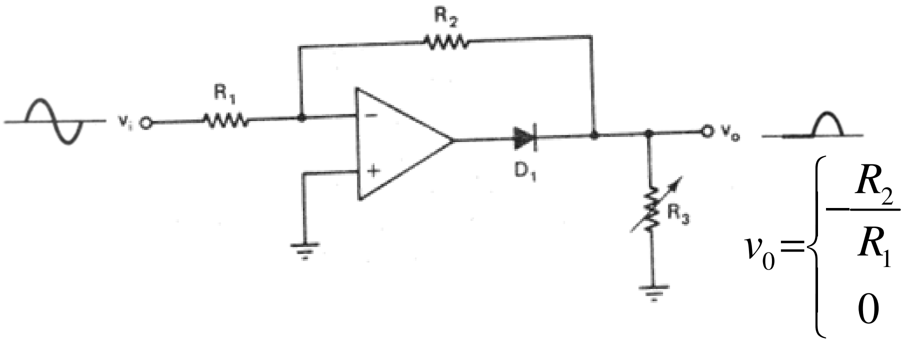
Instrumentation amplifier

- Two Noninvering Amp + One Differential Amp
- Differential Amp with High Input Impedance and Low Output Impedance



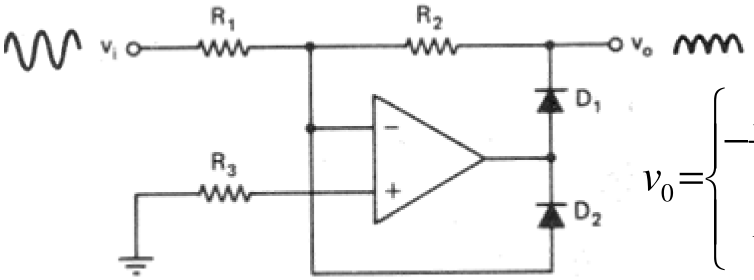
Rectifiers

Precision half wave rectifier



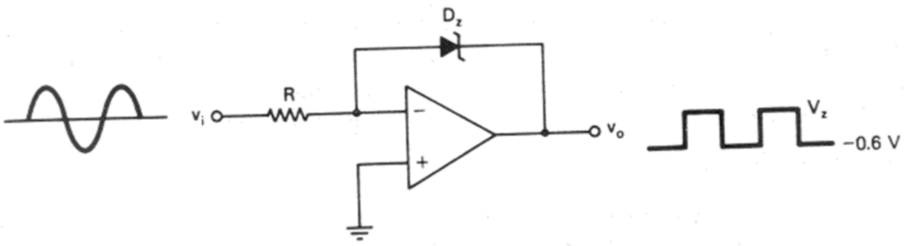
$$v_0=\begin{cases} -\dfrac{R_2}{R_1}v_i\,, & v_i\le 0\\ 0\;, & v_i>0\end{cases}$$

Precision full wave rectifier

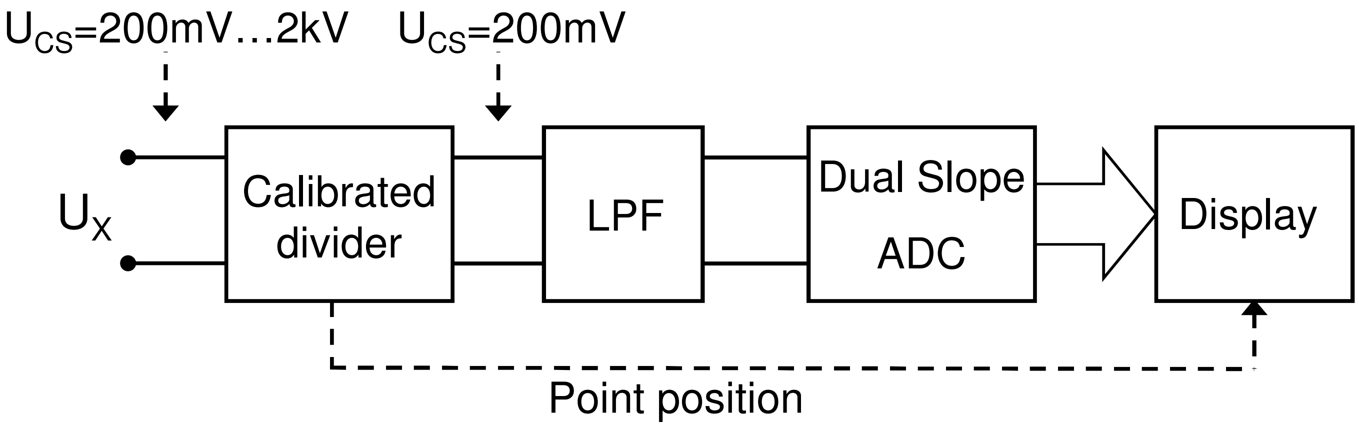


$$v_0=\begin{cases} -\dfrac{R_2}{R_1}v_i\,, & v_i\le 0\\ v_i\;, & v_i>0\end{cases}$$

Limiters

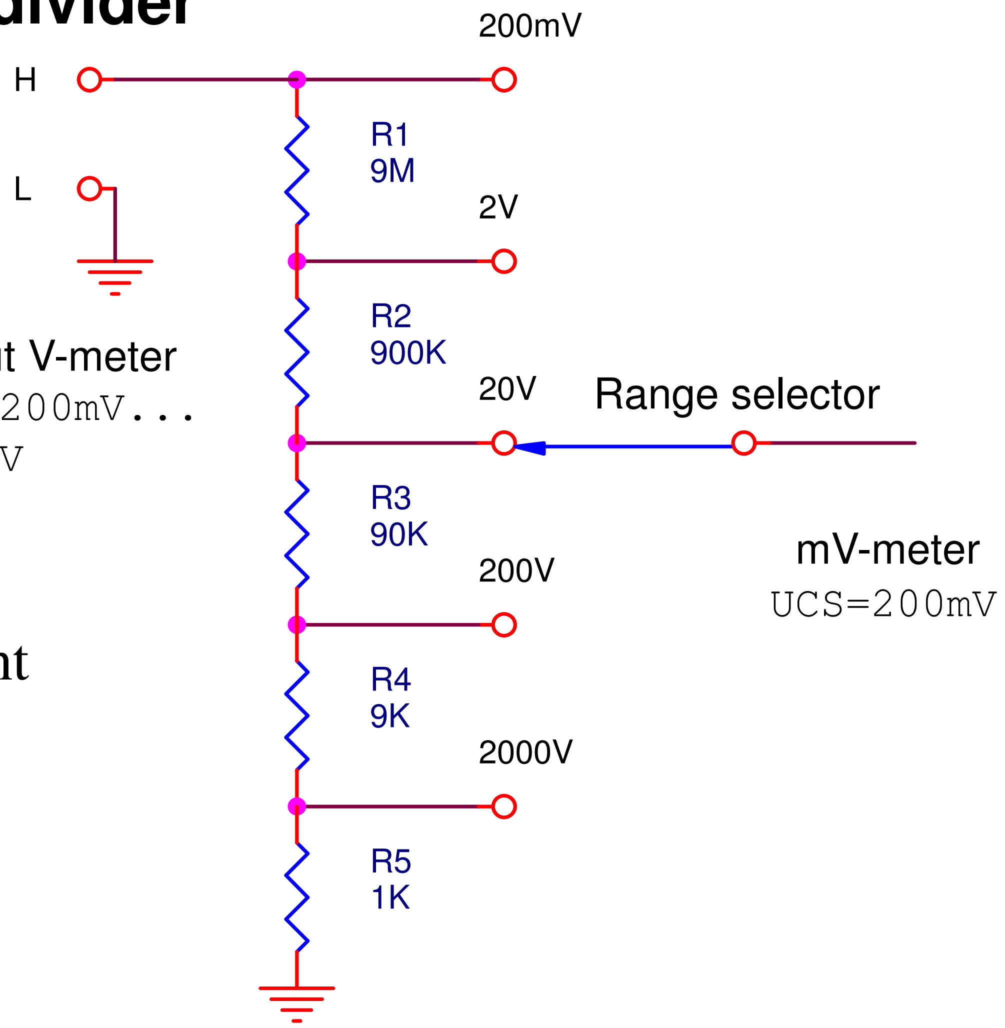


- **D.C. digital voltmeter**



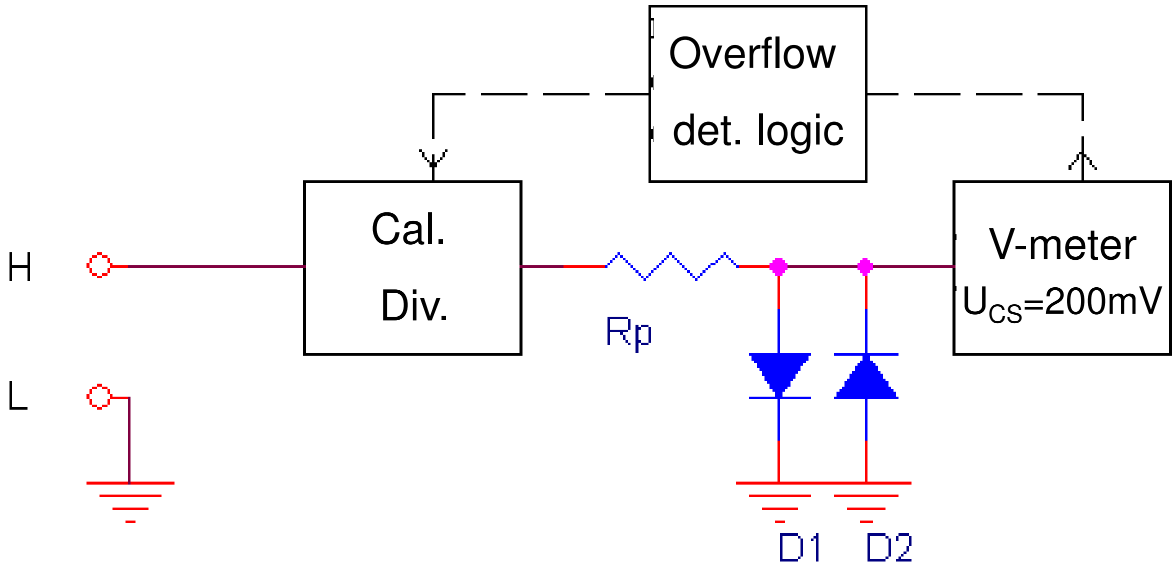
U_{CS} (dual slope ADC)=200mV

Calibrated voltmeter divider



$R_{IN} = 10\text{M}\Omega$ - constant

- **Auto-range digital d.c. voltmeter**



Cal. divider electronic switch

Range: U_{CS} = 200mV – 2V – 20V etc (range overlapping)

increasing: U_{IN} = 0..200mV ⇒ U_{CS} = 200mV

U_{IN} = 200mV.. 2V ⇒ U_{CS} = 2V

decreasing: U_{IN} = 2V.. 180mV ⇒ U_{CS} = 2V (decision hysteresis)

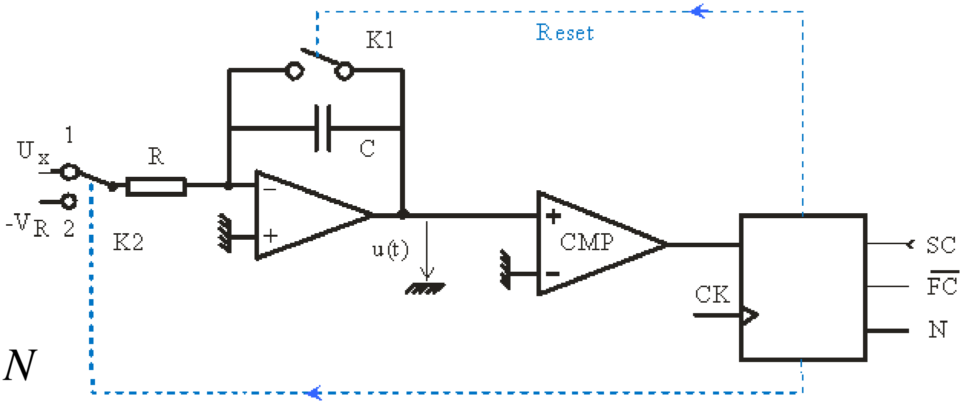
Dual slope ADC

- **Example of schema for positive voltage**

$$T_1=2^nT_{CK} \quad , \quad t_x=N'\cdot T_{CK}$$

$$\frac{1}{RC}\int_0^{T_1}U_x(t)\mathrm{d}t = \frac{1}{RC}\int_{T_1}^{T_1+t_X}V_\mathrm{R}\mathrm{d}t$$

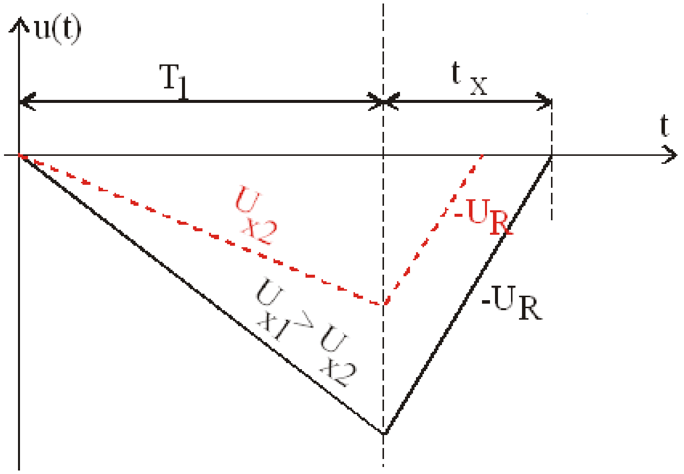
$$\frac{\overline{U_x(t)}}{V_R}=\frac{t_x}{T_1}=\frac{N'}{2^n} \quad \Rightarrow \overline{U_x(t)}=V_R\cdot\sum_{i=1}^{n}b_i2^{-i}=V_R\cdot N$$



- Absolute values of R and C don’t affect operation
- Conversion time is given by:

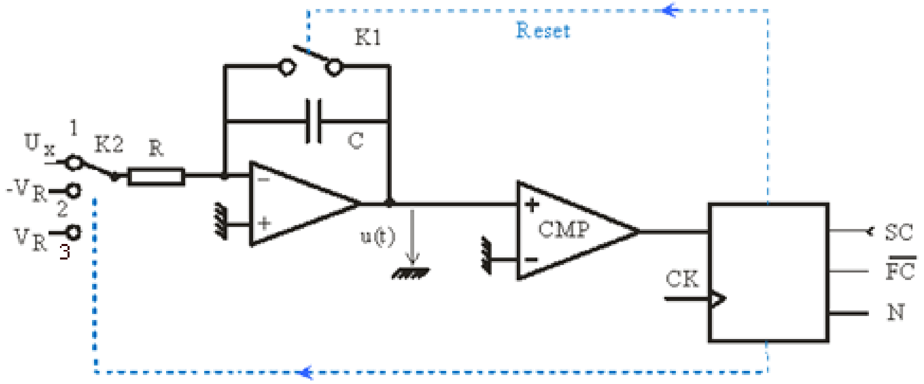
$$T_{conv}=\left(2^n+N'\right)T_{CK} \le 2^{n+1}T_{CK}$$

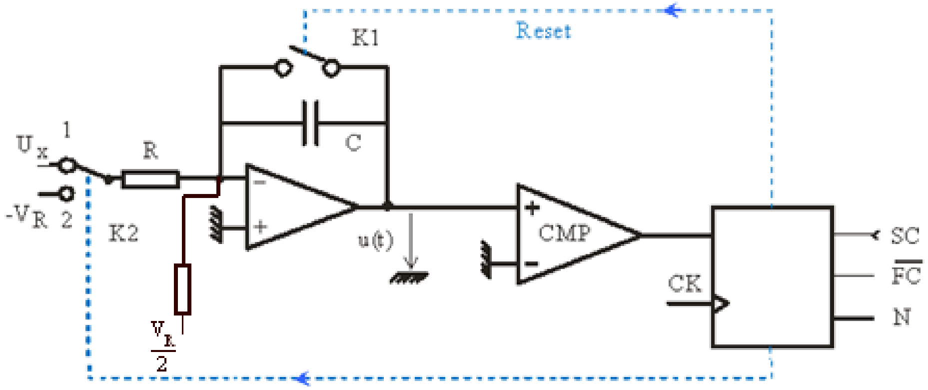
- Digital output word gives average value of *U_X* during first integration phase



Dual slope ADC

- **Examples of scheme for bipolar voltage**





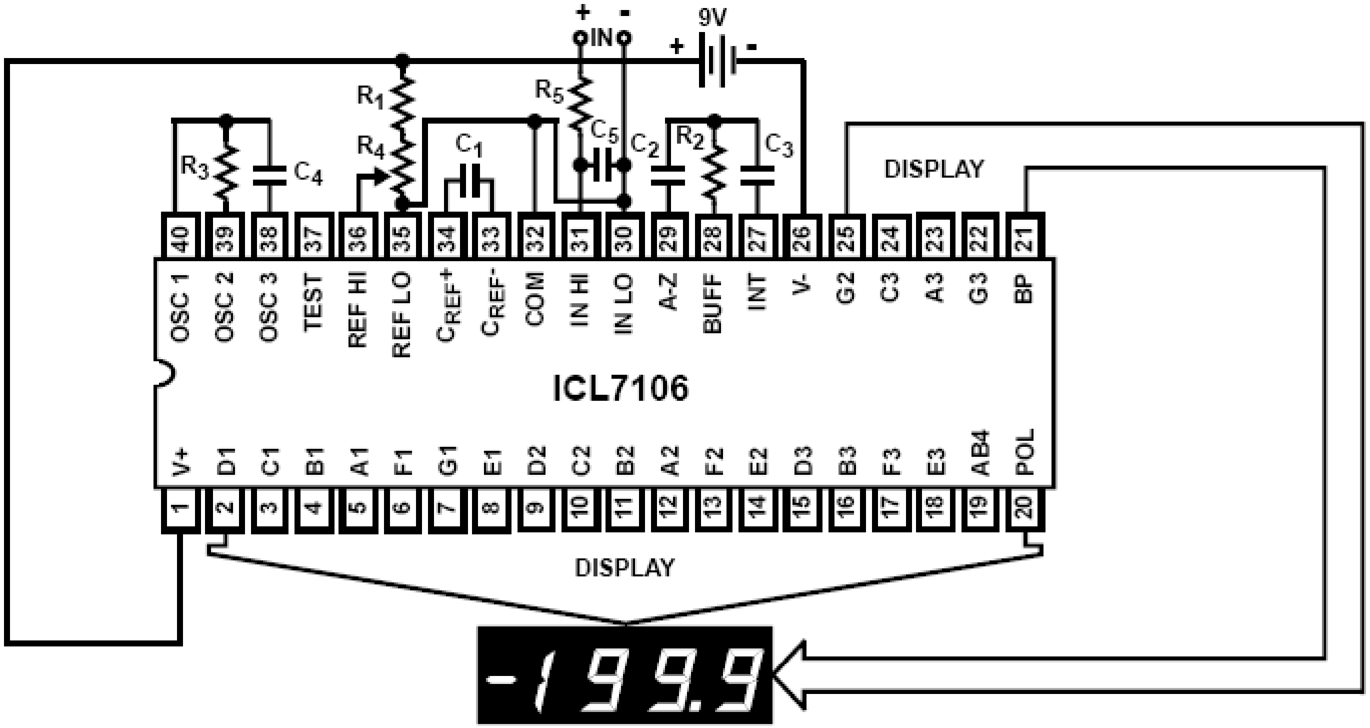
$T_1 = 2^n T_{CK}$, $t_x = N' \cdot T_{CK}$

$$-\frac{1}{RC}\int_0^{T_1} U_x(t) + \frac{V_R}{2}\,\mathrm{d}t = -\frac{1}{RC}\int_{T_1}^{T_1+t_X} -V_R + \frac{V_R}{2}\,\mathrm{d}t \Rightarrow \frac{V_R}{2}\cdot\frac{t_x}{RC} = \left(U_x + \frac{V_R}{2}\right)\frac{T_1}{RC}$$

$$U_x = V_R\,\frac{t_x - T_1}{2_1} \Rightarrow \begin{cases} U_x = 0 & \text{for } t_x = T_1 \\ U_x = -0{,}5\cdot V_R & \text{for } t_x = 0 \\ U_x = 0{,}5\cdot V_R & \text{for } t_x = 2T_1 \end{cases}$$

- **Example of digital voltmeter with dual slope ADC**

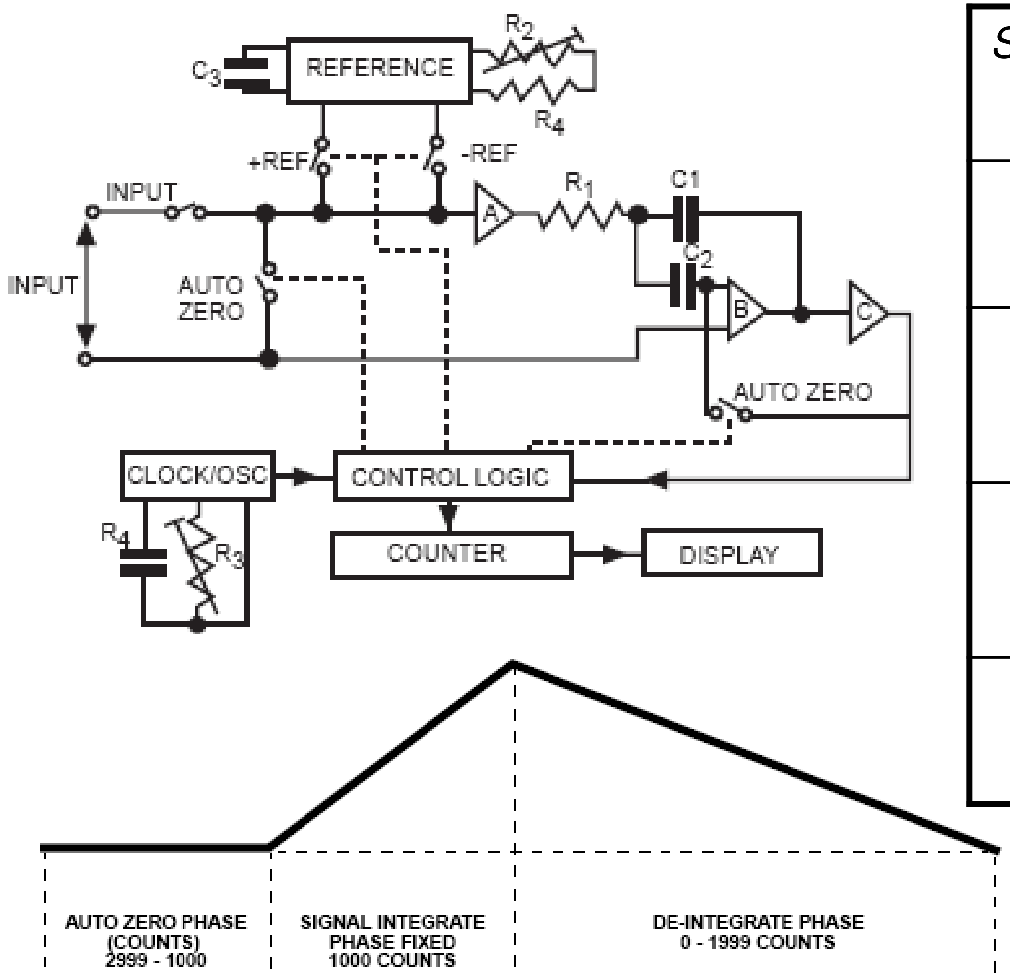
U_x



$C_1 = 0.1\mu F$
$C_2 = 0.47\mu F$
$C_3 = 0.22\mu F$
$C_4 = 100pF$
$C_5 = 0.02\mu F$
$R_1 = 24k\Omega$
$R_2 = 47k\Omega$
$R_3 = 100k\Omega$
$R_4 = 1k\Omega$
$R_5 = 1M\Omega$

Functioning principle – ICL7106

U_x



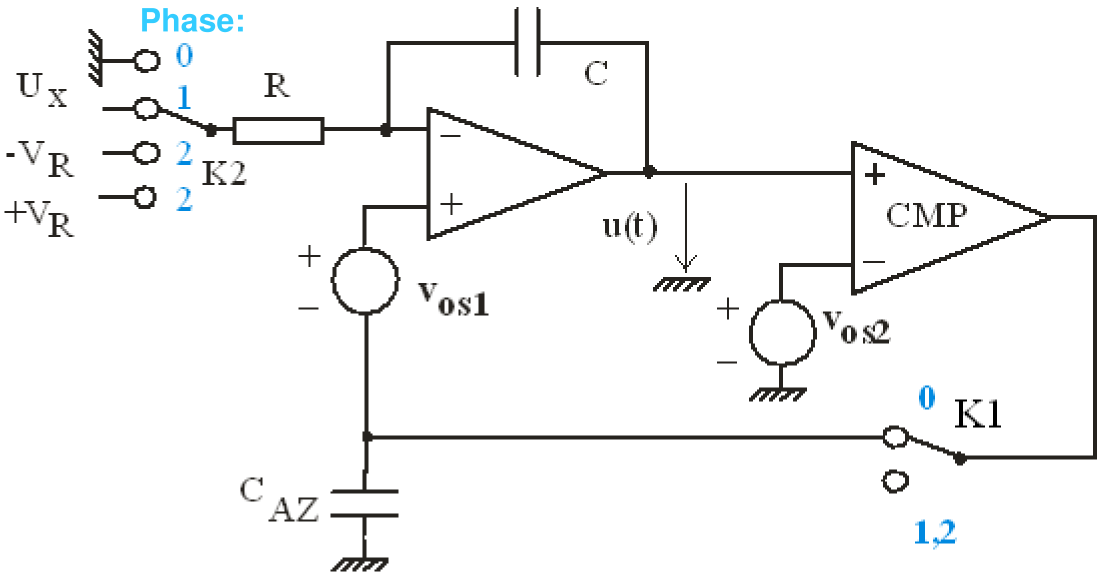
Switches	Phase 0 (AZ)	Phase 1	Phase 2
INPUT	open	close	open
+REF	open	open	funct. of V_{in} sign
-REF	open	open	funct. of V_{in} sign
AUTO-ZERO	close	open	open

Techniques for perturbation reduction

- Phase 1 – auto zero (K_1=0, K_2=0)

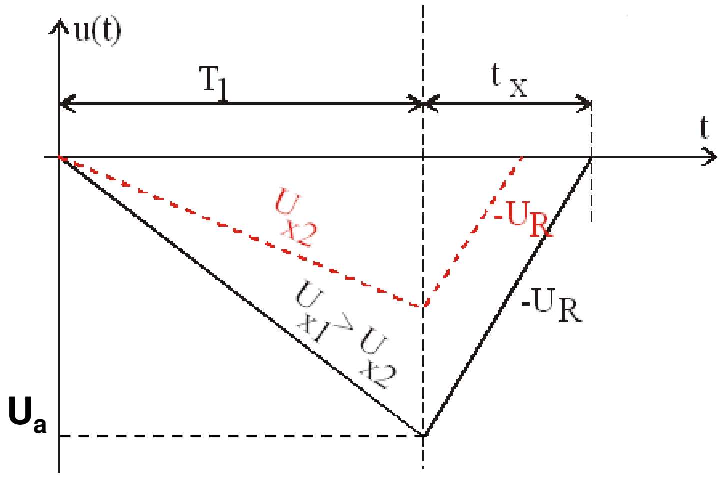
•Phase 2 – unknown voltage integrating (K_1=1, K_2=1)

•Phase 3 - reference voltage integrating (K1=2, K2=2)



Techniques for perturbation reduction

- selecting integration time in DS - ADC



$$U_x = U_{x0} + u_{ps}(t) = U_{x0} + U_{ps}\cos(\omega t + \phi)$$

$$U_a = -\frac{1}{\tau}\int_0^{T_1} U_x(t)dt = -\frac{1}{\tau}\int_0^{T_1} U_{x0} + u_{ps}(t)dt$$

$$= -U_{x0}\frac{T_1}{\tau} - \frac{U_{ps}}{\tau\omega}\left[\sin(\omega T_1 + \phi) - \sin(\phi)\right]$$

$$= U_{a\_0} + \frac{2U_{ps}}{\tau\omega}\cdot\sin\left(\frac{\omega T_1}{2}\right)\cdot\cos\left(\frac{\omega T_1}{2} + \phi\right)$$

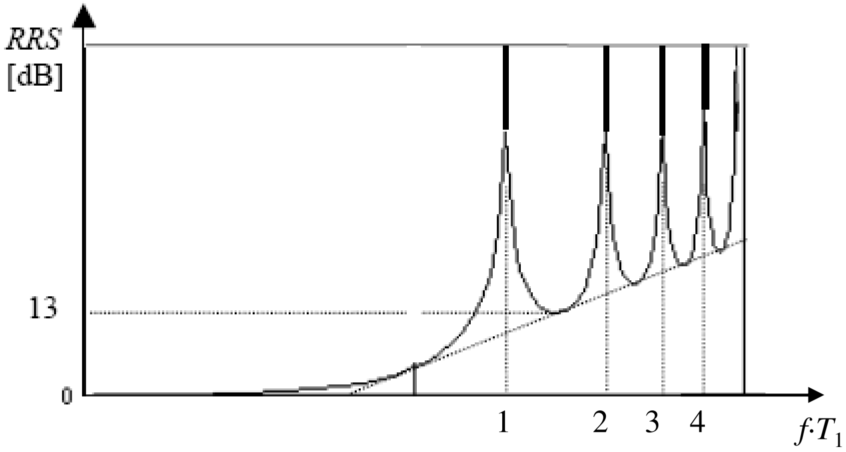
$$\varepsilon_{\mathrm{U_x}} = \left|\frac{U_x - U_{x0}}{U_{x0}}\right| = \left|\frac{U_a - U_{a\_0}}{U_{a\_0}}\right| = \left|\frac{\frac{2U_{ps}}{\tau\omega}\cdot\sin\left(\frac{\omega T_1}{2}\right)\cdot\cos\left(\frac{\omega T_1}{2} + \phi\right)}{U_{x0}\frac{T_1}{\tau}}\right| = \left|\frac{U_{ps}\cdot\sin\left(\frac{\omega t_1}{2}\right)}{\frac{\omega t_1}{2}U_{x0}}\right| \le \left|\frac{U_{ps}}{U_{x0}}\cdot\mathrm{sinc}\left(\frac{\omega T_1}{2}\right)\right|$$

Techniques for perturbation reduction

SRR – Serial Rejection Ratio

$$SRR\Big|_{\mathrm{dB}} = -20\log\left(\varepsilon_{U_x}\right)\Big|_{U_{ps}=U_{x0}} = -20\cdot\log\left|\mathrm{sinc}(\pi f\cdot T_1)\right|$$

$$\text{For } f = \frac{k}{T_1} \Rightarrow SRR\Big|_{\mathrm{dB}} \to \infty$$



Most important perturbation - supply voltage (f_{alim}=50Hz);

chose T_1 = 1/f_{alim}= 20ms

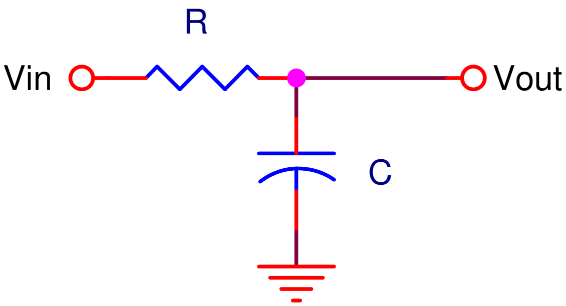
Exp: $f_{ps} \in$ [4950Hz, 5050Hz]

$$SRR\Big|_{\mathrm{dB}} \geq -20\cdot\log\left|\frac{1}{\pi f t_1}\right| \approx 50\mathrm{dB}$$

- disadvantage: increase measurement time

Techniques for perturbation reduction

- Low pass filter design



$$H(j\omega)=\frac{1}{1+j\omega RC}=\frac{1}{1+j\omega\tau}$$

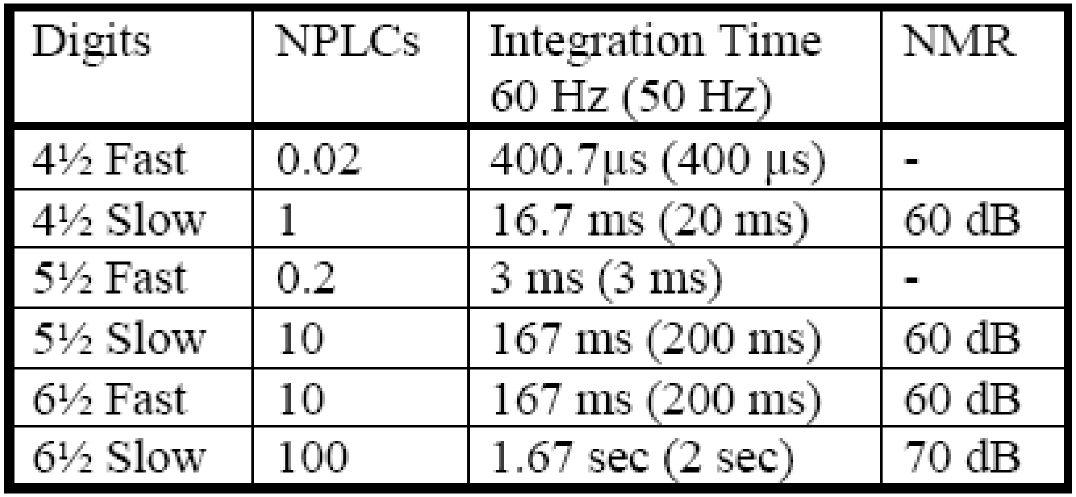
$$RRS_F\big|_{\mathrm{dB}}\geq 20\cdot\log\left|\frac{U_{PS}}{U_{PS}\cdot H(j\omega)}\right|=-20\cdot\log\left|H(j\omega)\right|$$

$$\tau=100\mathrm{ms}\quad\Rightarrow\quad \mathrm{RRS_F}=14\mathrm{dB}\ \left(f_{\mathrm{alim}}=50\mathrm{Hz}\right)$$

$$RRS_{Tot}\big|_{\mathrm{dB}}=RRS_F\big|_{\mathrm{dB}}+RRS\big|_{\mathrm{dB}}$$

$\mathrm{SRR}_{\mathrm{tot}}$ increases equivalent CMRR

Exp: Agilent 34401A



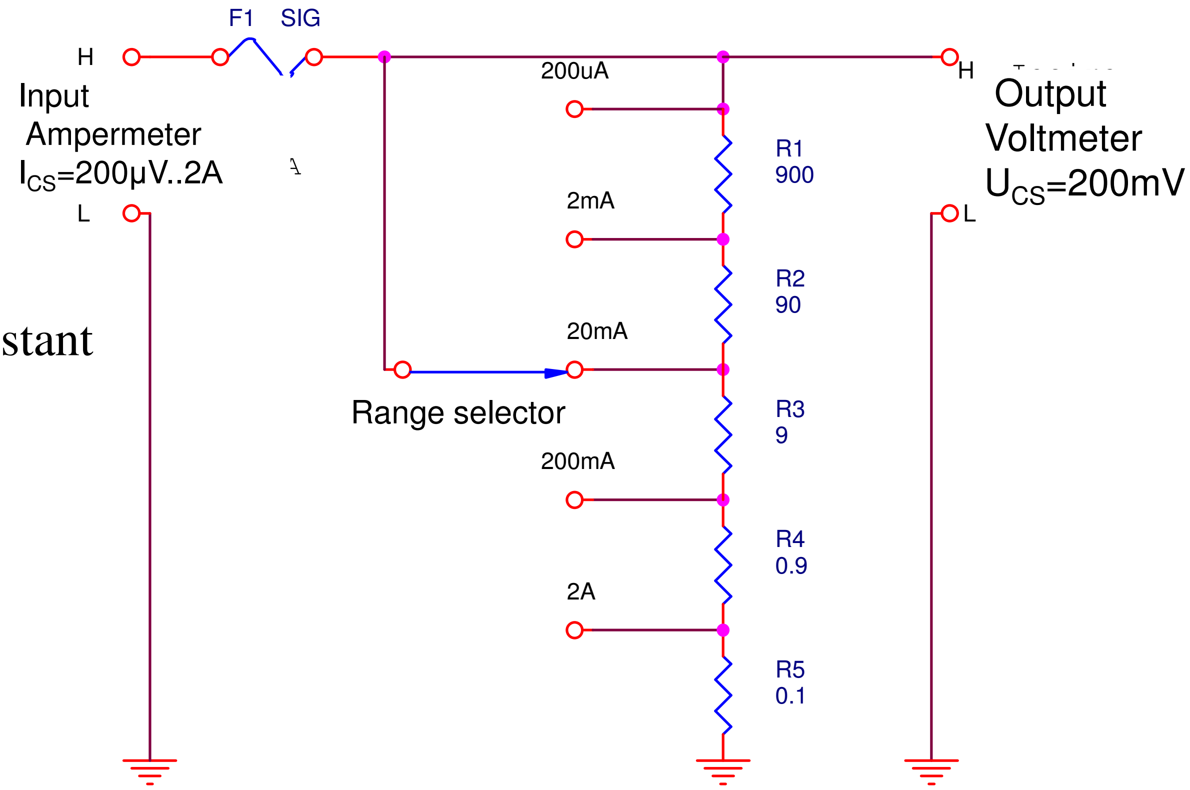
Digits	NPLCs	Integration Time 60 Hz (50 Hz)	NMR
4½ Fast	0.02	400.7µs (400 µs)	-
4½ Slow	1	16.7 ms (20 ms)	60 dB
5½ Fast	0.2	3 ms (3 ms)	-
5½ Slow	10	167 ms (200 ms)	60 dB
6½ Fast	10	167 ms (200 ms)	60 dB
6½ Slow	100	1.67 sec (2 sec)	70 dB

RRS (NMRR sau NMR) pentru Agilent 34401A

NPLCs = *Number of Power Line Cycles* for 50/60Hz.

Obs: network frequency automating detection

I-U converter module (DMM)

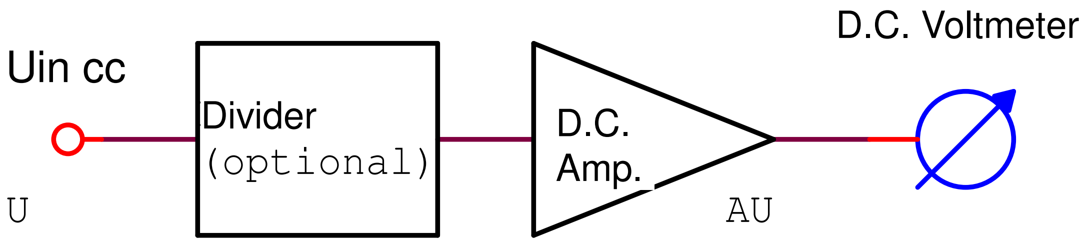


$$R_{OUT\ \ voltmeter} = 10\text{M}\Omega \quad \text{- constant}$$

$$R_{IN\ \ ampermeter} \neq \ \text{constant}$$

Small signal d.c. voltmeter (milivoltmeter)

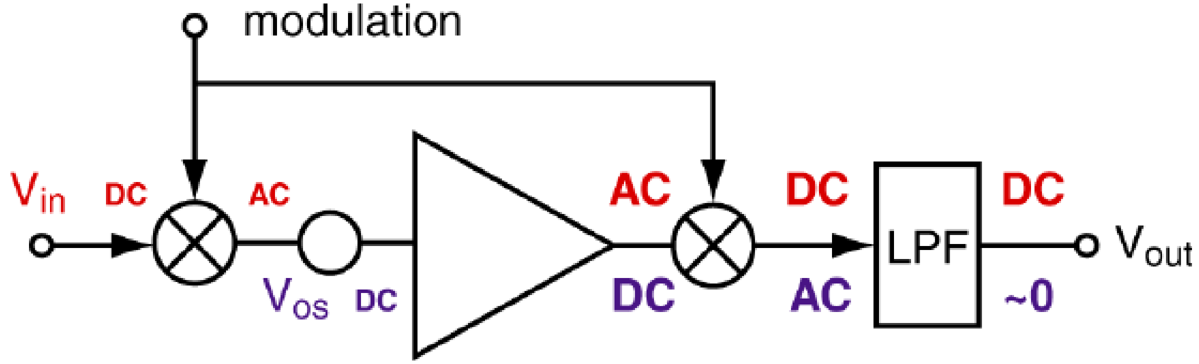
Typical scheme



d.c. amplifiers disadvantages:

- self noise
- selt offset voltage
- thermal leeway

- **D.C. amplifiers with chopper**



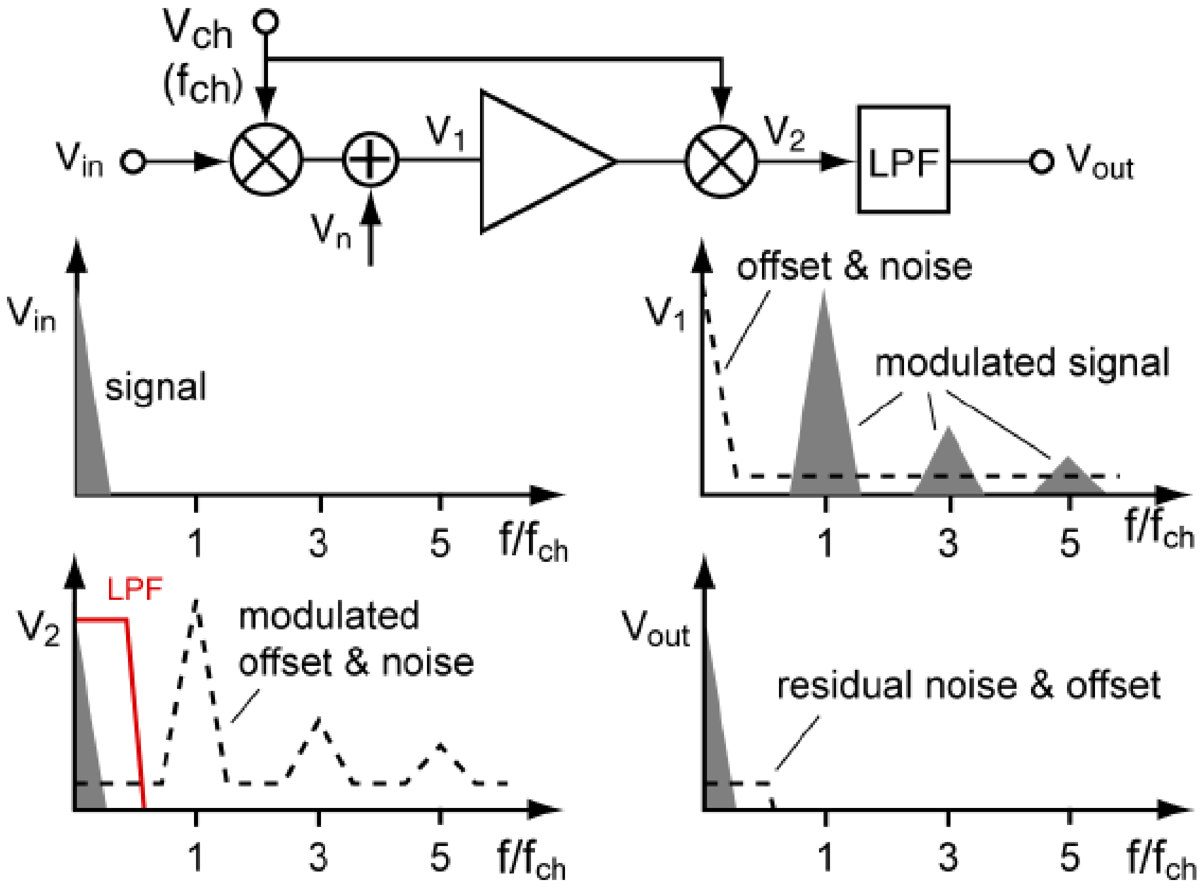
Upper way - util voltage: V_{IN}

Lower way - offset voltage V_{OS} (is rejected):

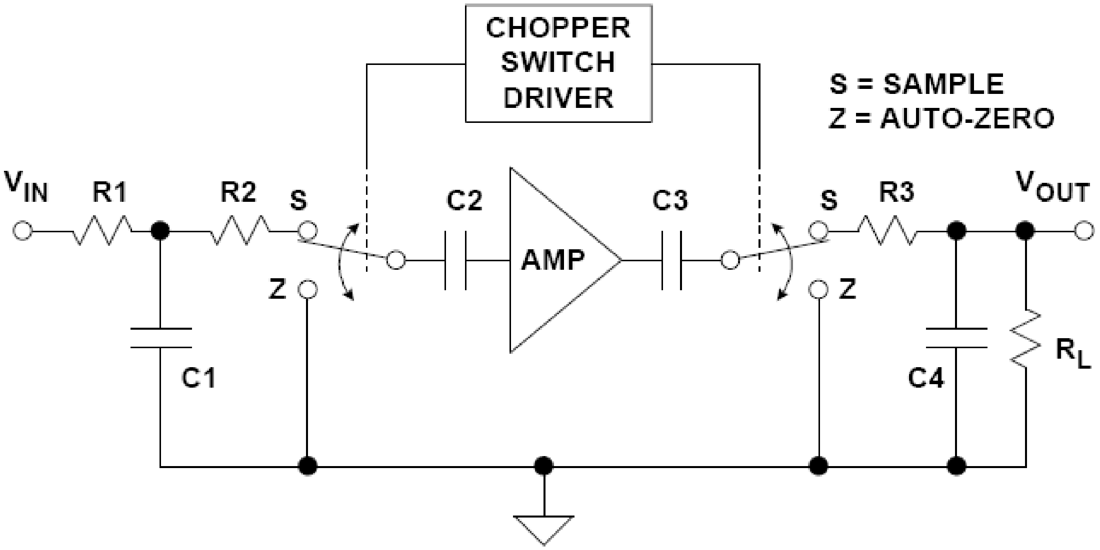
- Used for d.c. and a.c. low frequency
- Operation: DC → AC conversion (modulation), AC amplifier,

AC → DC conversion (demodulation + LPF)

- **D.C. amplifiers with chopper** - frequency domain



- **D.C. amplifiers with chopper**

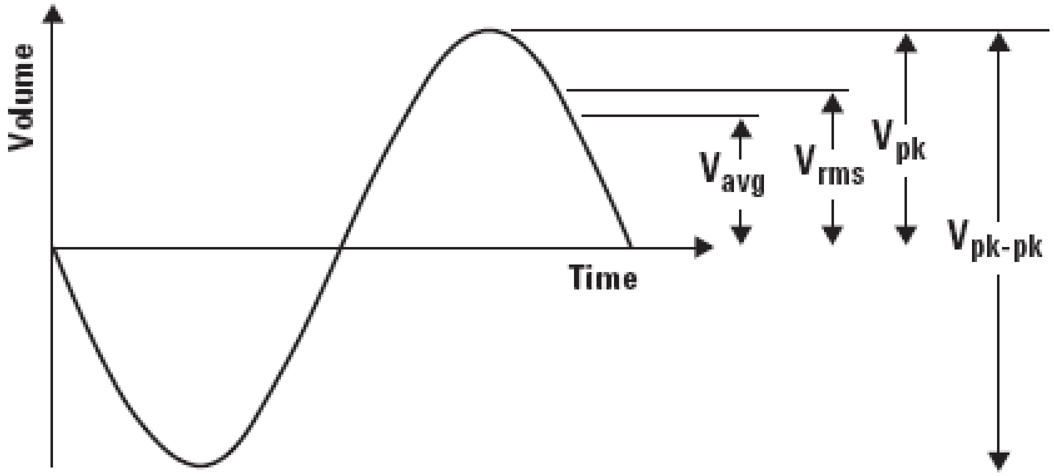


Variant: rectangular modulation/demodulation signal.

- Switch=Z : C2 şi C3 charges with offset voltage
- switch=S: C2, C3 voltage compensate offset voltage
- R1, C1 = antialiasing LPF
- R3, C4 = output LPF

EIM Chap 3 – Digital Voltmeter

- **A.C signal (METc remember)**



- For $u(t)=U \sin \omega t$:

$V_{med} = 0$ (unused)

$V_{ma} = V_{avg} = 2U/\pi$ (full-wave rect.)

$V_{ef} = V_{rms} = U/\sqrt{2} = 0.707U$

$V_V = V_{PK} = U$

$V_{VV} = V_{PP} = V_{Pk\text{-}Pk} = 2U$

$K_F = U_{ef}/U_{ma} = \pi / \sqrt{2} = 1.11$

$K_V = U_v/U_{ef} = \sqrt{2}$

- **A.C voltmeter types**

Obs: All a.c. voltmeter have gradation for sin wave rms

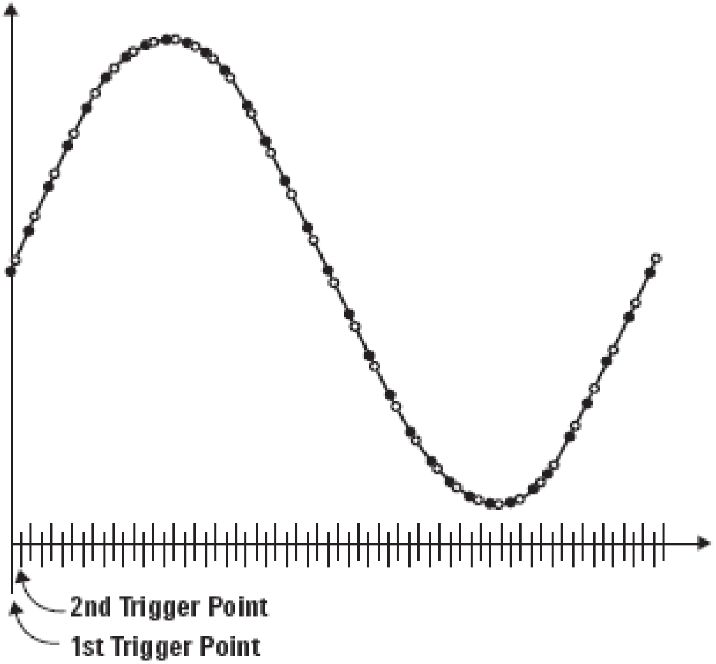
Types:

- a.m. voltmeter gradated in rms value $\mathbf{V_{rms} = V_{ma} \cdot 1.11}$ (introduce important systematic error for non sin wave signals)
- Peak detector voltmeter gradated in rms value $\mathbf{V_{rms} = V_{ma} \cdot 0.707}$
- True rms voltmeter – correct indication for all wave forms

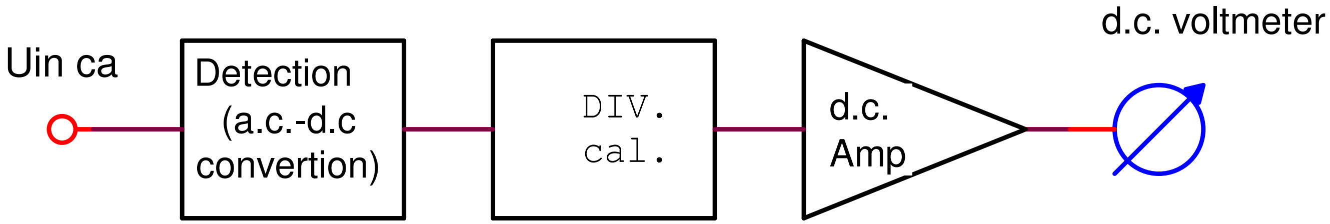
A.C. True rms voltmeter

- thermal effect - thermocouple (slowly, very sensitive of environment factors)
- analog multipliers (ex: Agilent 34405A)
- sampling and digital uP computing (only for repetitive signals)

(ex: Agilent 34410A, TDS 1001 Oscilloscope – measurement menu)



A.C. voltmeter with D.C. amplifier



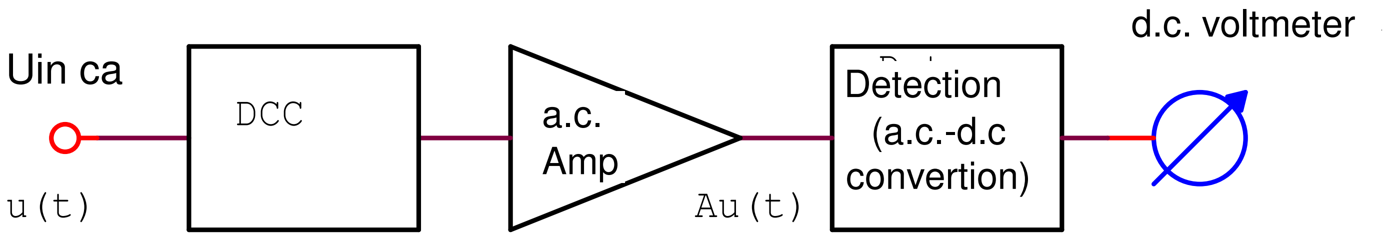
Advantages:

- High bandwidth (GHz)
- Small C_{IN}
- Detector : peak, absolute mean, etc;

Disadvantages:

- Small R_{IN}
- Small sensitivity (x10 mV); nonlinear for small signals
- D.C. amplif. gain limited by self noise and thermal leeway

A.C. voltmeter with a.c. amplifier



Advantages:

- high sensitivity (due a.c. amplifier), better linearity;
- High R_{IN} , small C_{IN}
- Detector : peak, absolute mean, etc;

Disadvantages:

- Medium bandwidth (MHz)
- DCC must be compensated

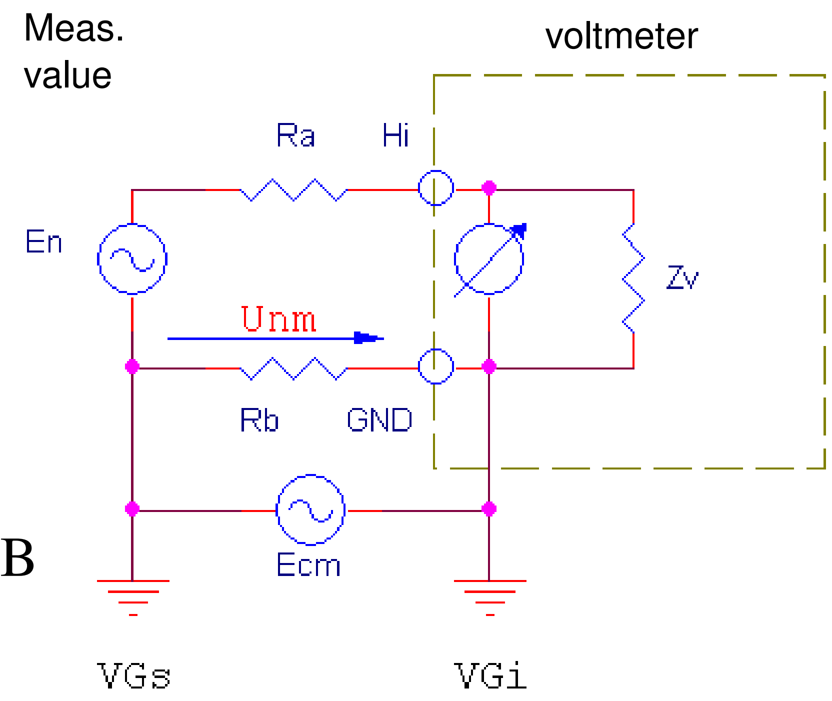
Cabling – two terminal configuration (Hi, Lo)

$$E_{cm} = V_{Gs} - V_{Gi}$$

After E_n passivization, measured value

$$U_{nm} = E_{cm}$$

$$CMRR = \frac{E_{cm}}{U_{nm}} = 1 \quad \Rightarrow \quad CMRR_{\mathrm{dB}} = 0\,\mathrm{dB}$$



Cabling – three wire configuration (Hi, Lo, GND)

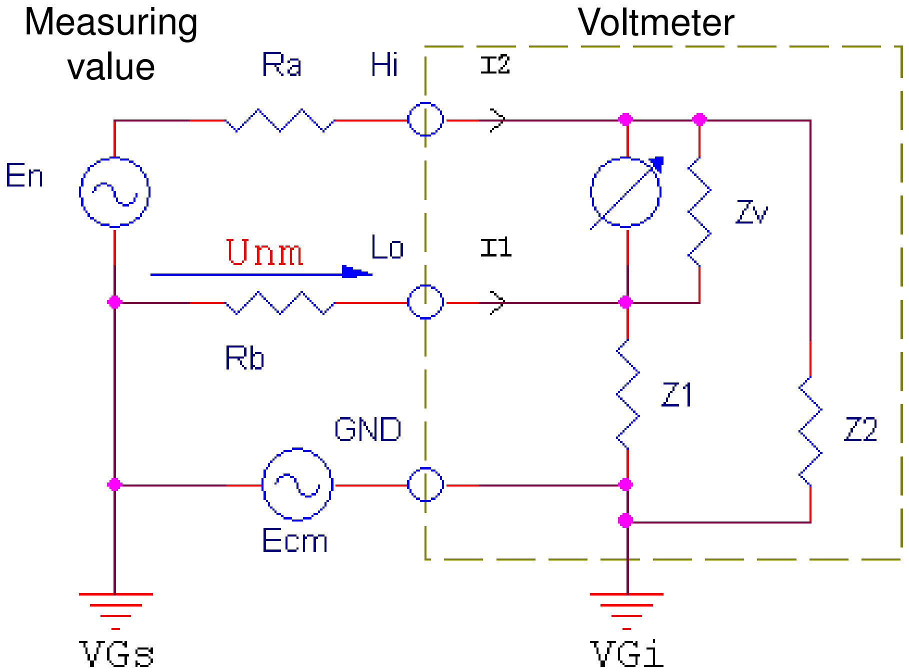
$$E_{cm} = V_{Gs} - V_{Gi}$$

$$U_{nm} = E_{cm}\frac{R_b}{Z_1 + R_b}$$

$$CMRR = \frac{E_{cm}}{U_{nm}} = \frac{Z_1 + R_b}{R_b} \cong \frac{Z_1}{R_b}$$

$$Z_1 << Z_2 \quad , \quad I_1 >> I_2$$

U_{nm} on R_a is neglected



Exp: R_b = 1kΩ; Z_1 =R_1||C_1 (R_1=109 Ω, C_1=2.5 nF)

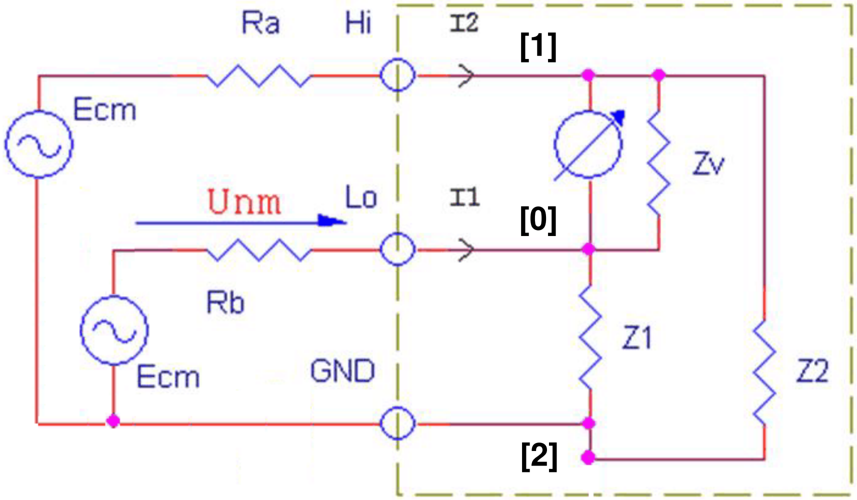
typically d.c. CMRR = 120dB a.c. (f=50Hz) CMRR = 62dB

- **Cabling – three wire configuration (Hi, Lo, GND)**

$$U_{nm} = E_{cm}\frac{Z_1}{Z_1 + R_b}$$

$$\underline{V_2}\left(\frac{1}{r_a}+\frac{1}{r_b}+\frac{1}{Z_1}+\frac{1}{Z_2}\right)-\underline{V_1}\left(\frac{1}{r_a}+\frac{1}{Z_2}\right)=-\frac{\underline{\underline{E_{cm}}}}{r_a}-\frac{\underline{\underline{E_{cm}}}}{r_b}$$

$$\underline{V_1}\left(\frac{1}{r_a}+\frac{1}{Z_V}+\frac{1}{Z_2}\right)-\underline{V_2}\left(\frac{1}{r_a}+\frac{1}{Z_2}\right)=\frac{\underline{\underline{E_{cm}}}}{r_a}$$



$$\underline{V_1}=\underline{E_{cm}}\frac{\frac{1}{r_a}\left(\frac{1}{r_b}+\frac{1}{Z_1}\right)-\frac{1}{r_b}\left(\frac{1}{r_a}+\frac{1}{Z_2}\right)}{\left(\frac{1}{r_a}+\frac{1}{Z_V}+\frac{1}{Z_2}\right)\cdot\left(\frac{1}{r_b}+\frac{1}{Z_1}\right)+\left(\frac{1}{r_a}+\frac{1}{Z_1}\right)\cdot\frac{1}{Z_V}}$$

$$\cong \underline{E_{cm}}\frac{\frac{1}{r_aZ_1}-\frac{1}{r_bZ_2}}{\frac{1}{r_ar_b}+\frac{1}{r_aZ_V}}\cong \underline{E_{cm}}\left(\frac{r_b}{Z_1}-\frac{r_a}{Z_2}\right)$$

using $|Z_1|\ ,\ |Z_2|\ ,\ |Z_V| >> r_a\ ,\ r_b$

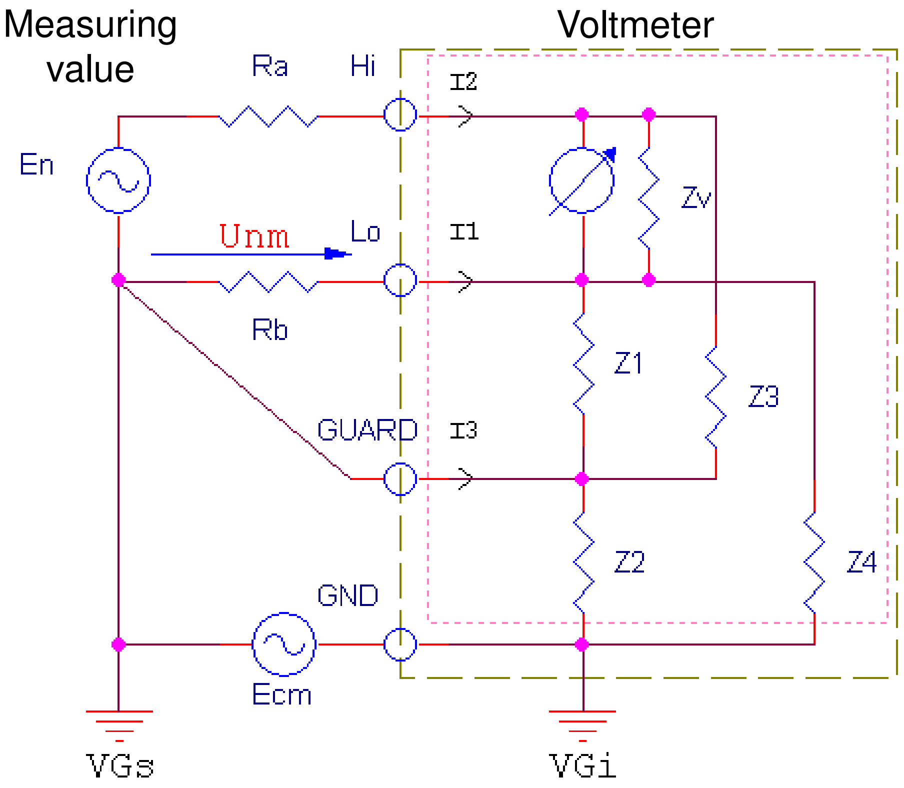
U_{nm} on R_a is neglected

Cabling - four wire configuration

$$E_{cm} = V_{Gs} - V_{Gi}$$

$$U_{nm} = E_{cm} \frac{Z_4}{Z_4 + R_b}$$

$$CMRR = \frac{E_{cm}}{U_{nm}} = \frac{Z_4 + R_b}{R_b} \cong \frac{Z_4}{R_b}$$



Exp: R_b = 1kΩ; $Z_1=R_1||C_1$:(R_1=109 Ω, C_1=2.5 nF); Z4 : R4=1011 Ω, C4=2.5pF

typically d.c. CMRR = 120dB a.c. (f=50Hz) CMRR = 120dB

Bibliography

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