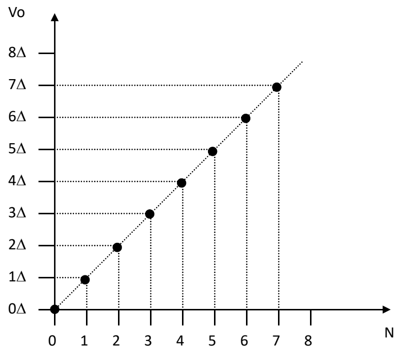
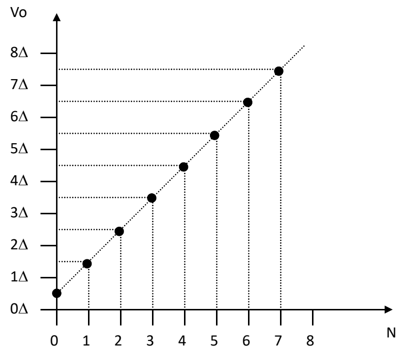
Digitalna elektronika
DA konverzija

Karakteristika konverzije





$$V_O = \Delta \cdot D + V_{ofset} = \Delta \sum_{i=0}^{n-1} b_i 2^i + V_{ofset}$$

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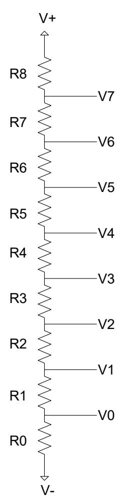
DA konverzija – DA konvertor sa naponskim nizom



$$V_O = V^- + R_0 \frac{V^+ - V^-}{\sum_i R_i} \qquad V_1 = V^- + (R_0 + R_1) \frac{V^+ - V^-}{\sum_i R_i}$$

$$V_k = V^- + (\sum_{i=0}^{k} R_i) \frac{V^+ - V^-}{\sum_i R_i}$$

$$V_k - V_{k-1} = V_1 - V_0 = V_2 - V_1 = \Delta \qquad R_1 = R_2 = \ldots = R_8 = R$$

$$\Delta = R \frac{V^+ - V^-}{8R + R_0}$$

$$V_{ofset} = V_0 = V^- + R_0 \frac{V^+ - V^-}{8R + R_0}$$

$$V_{ofset} = 0 \quad \Rightarrow \quad V^- = 0 = GND \quad \wedge \quad R_0 = 0$$

$$V_{ofset} = \frac{\Delta}{2} \quad \Rightarrow \quad V^- = 0 = GND \quad \wedge \quad R_0 = \frac{R}{2}$$ Koliko je R8?

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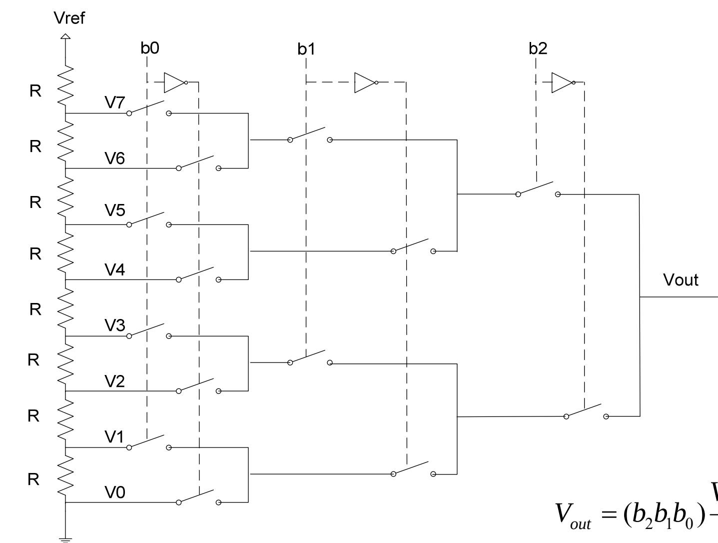
DA konverzija – DA konvertor sa naponskim nizom



$$V_{out} = (b_2 b_1 b_0)\frac{V_{ref}}{8}$$

Tačnost i preciznost Vref?

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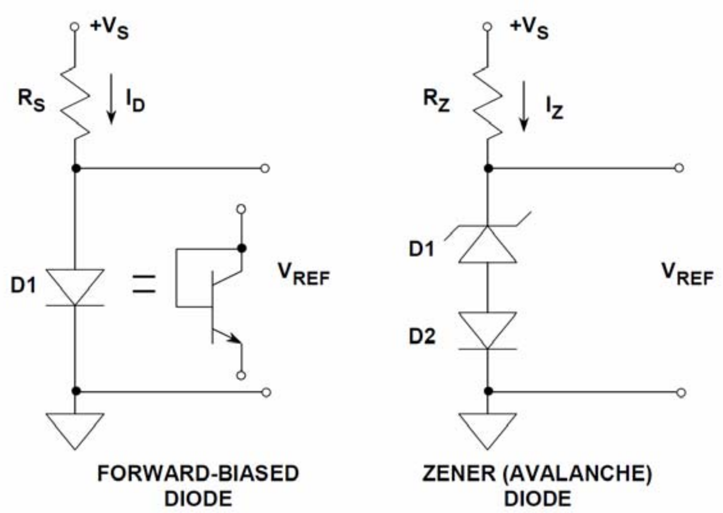
DA konverzija – Izvor referentnog napona



Fleksibilnost, temperaturna stabilnost?

Šum...

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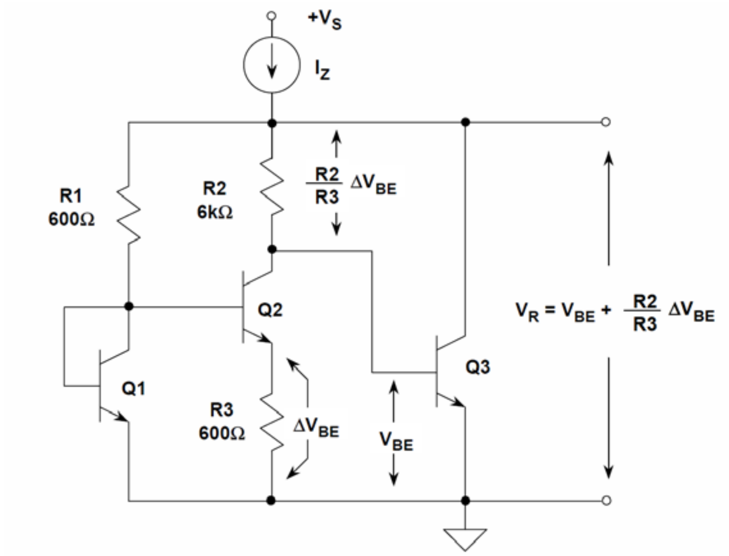
DA konverzija – Izvor referentnog napona



Bandgap reference

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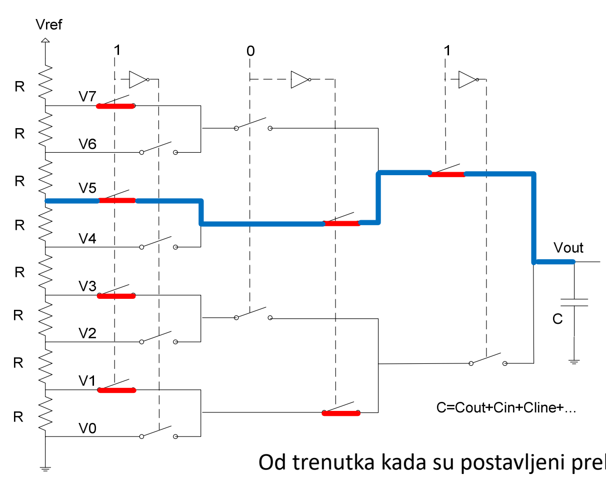
DA konverzija – DA konvertor sa naponskim nizom



$b_2b_1b_0 = 101 \quad \Rightarrow \quad V_{out} = 5\frac{V_{ref}}{8}$

$R_{out} = 5R \| 3R$

$\tau = R_{out}C$

Od trenutka kada su postavljeni prekidači do trenutka dok nije “važeći” izlaz

Brzina konverzije konvertora.

Ovde konkretno zavisi od koda.

DA konvertor = idealan naponski izvor

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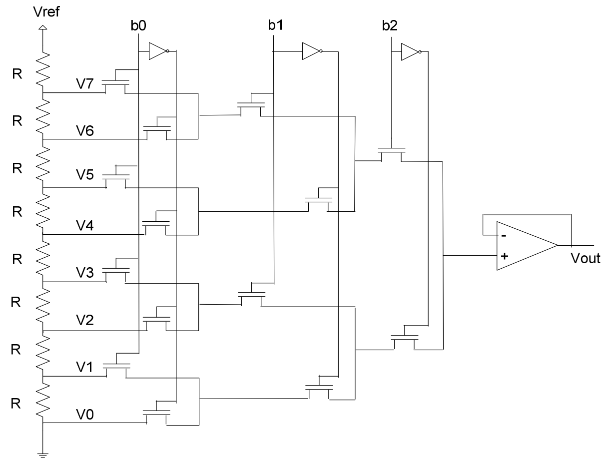
DA konverzija – DA konvertor sa naponskim nizom



Karakteristike operacionog pojačavača?

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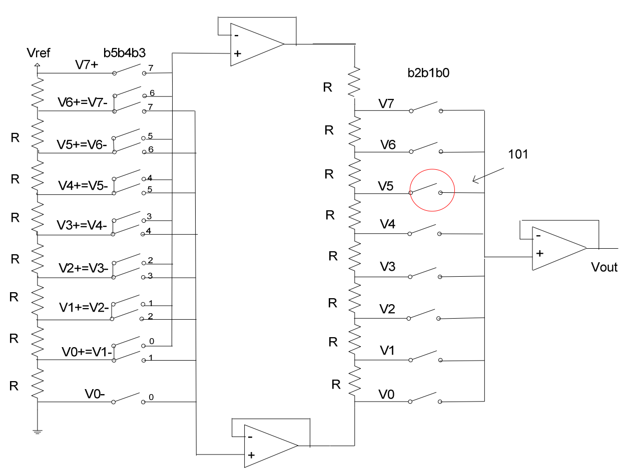
DA konverzija – DA konvertor sa naponskim nizom i interpolacijom

Velika rezolucija? Broj otpornika? Interpolacija!



$$V_{out} = V^{-} + (b_2 b_1 b_0)\frac{V^{+} - V^{-}}{8}$$

$$V^{+} - V^{-} = \frac{V_{ref}}{8}$$

$$V^{-} = (b_5 b_4 b_3)\frac{V_{ref}}{8}$$

$$V_{out} = (b_5 b_4 b_3)\frac{V_{ref}}{8} + (b_2 b_1 b_0)\frac{V_{ref}}{8 \cdot 8}$$

$$V_{out} = (b_5 b_4 b_3 b_2 b_1 b_0)\frac{V_{ref}}{64}$$

Umesto 64, 16.
Dodatak dva operaciona.
Kašnjenje? Ofseti?

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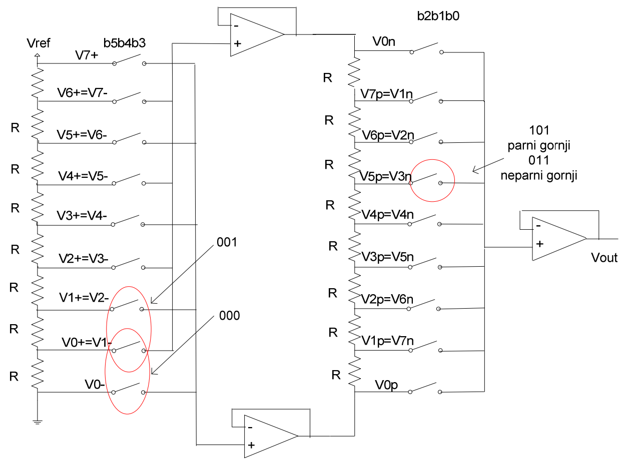
DA konverzija – DA konvertor sa naponskim nizom i interpolacijom

Presavijanje



$$V_{out} = V^- + (b_2 b_1 b_0)\frac{V^+ - V^-}{8}$$

$$V^+ - V^- = \frac{V_{ref}}{8}$$

$$V^- = (b_5 b_4 b_3)\frac{V_{ref}}{8}$$

$$V_{out} = (b_5 b_4 b_3)\frac{V_{ref}}{8} + (b_2 b_1 b_0)\frac{V_{ref}}{8 \cdot 8}$$

$$V_{out} = (b_5 b_4 b_3 b_2 b_1 b_0)\frac{V_{ref}}{64}$$

Zavisno od segmenta drugačije upravljanje desnim prekidačima

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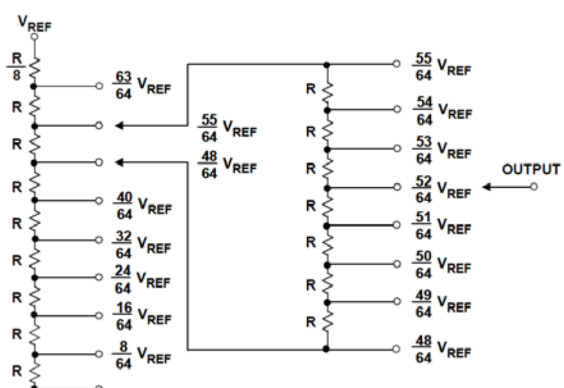
DA konverzija – DA konvertor sa naponskim nizom i interpolacijom

Triki!



Dennis Dempsey and Christopher Gorman, "Digital-to-Analog Converter," U.S. Patent 5,969,657, filed July 27, 1997, issued October 19, 1999.

$$R \| 7R = \frac{7R}{8}$$

Zato je najviši otpornik R/8

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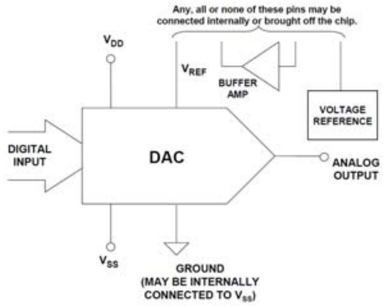
DA konverzija



Na šta mora da se obrati pažnja.

Referentni napon koliko dobar?
Izlazna otpornost izvora referentnog napona?
Uparenost otpornika?
Otpornici veliki ili mali?
Brzina i karakteristike prekidača?
Brzina potrebnih kombinacionih mreža?
Brzina, ofset, ... operacionih pojačavača?
Masa digitalna, masa analogna?

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DA konverzija – Kodovi

Unipolarni

Decimalna vrednost	Binarni	Grejov	Šetajuca jedinica	Termometarski
0	000	000	00000001	0000000
1	001	001	00000010	0000001
2	010	011	00000100	0000011
3	011	010	00001000	0000111
4	100	110	00010000	0001111
5	101	111	00100000	0011111
6	110	101	01000000	0111111
7	111	100	10000000	1111111

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DA konverzija – Kodovi

Bipolarni

Decimalna vrednost	Drugi komplement	Znak i apsolutna vrednost	Binarni ofset
-4	100		000
-3	101	111	001
-2	110	110	010
-1	111	101	011
0	000	100,000	100
1	001	001	101
2	010	010	110
3	011	011	111

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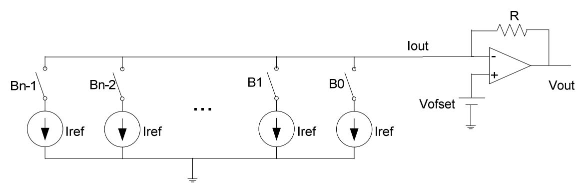
DA konverzija – sa strujnim izvorima

Termometarski kod



Jednake strujne izvore relativno lako pravimo.
Operacioni pojačavač je opcioni za integrisani konvertor;
možda je bolje da ostavimo korisniku da dodaje kakav mu za aplikaciju odgovara.
A onda može preko otpornika da podešava napon pune skale, odnosno vrednost napona 1LSB, dodaje ofset, itd....

$$I_{out} = \sum_{i=0}^{n-1} B_i I_{ref} = I_{ref} \sum_{i=0}^{n-1} B_i$$

$$V_{out} = V_{ofset} + RI_{out}$$

$$\Delta_I = I_{ref}$$

$$\Delta_U = RI_{ref}$$

Konačna otpornost strujnih izvora?
Jednakost strujnih izvora?
Brzina i karakteristike prekidača?
Brzina, ofset, ... operacionog pojačavača?

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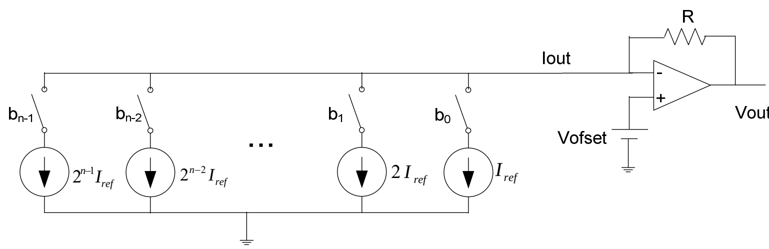
DA konverzija – sa strujnim izvorima

Binarni kod



$$I_{out} = \sum_{i=0}^{n-1} b_i 2^i I_{ref} = I_{ref} \sum_{i=0}^{n-1} b_i 2^i = I_{ref}\,(b_{n-1}...b_1 b_0)$$

$$V_{out} = V_{ofset} + RI_{out}$$

$$\Delta_I = I_{ref}$$

$$\Delta_U = RI_{ref}$$

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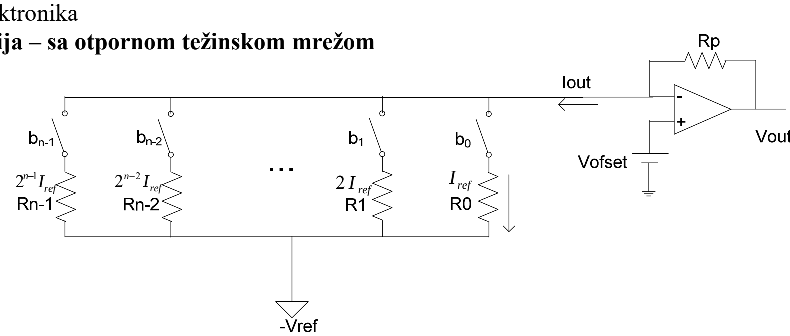
DA konverzija – sa otpornom težinskom mrežom

Binarni kod



$$I_{out} = \sum_{i=0}^{n-1} b_i \frac{V_{ref} + V_{ofset}}{R_i} = I_{ref} \sum_{i=0}^{n-1} b_i 2^i = I_{ref}\,(b_{n-1}...b_1 b_0)$$

$$R_0 = R \quad \Rightarrow \quad R_i = \frac{R}{2^i}$$

$$I_{ref} = \frac{V_{ref} + V_{ofset}}{R}$$

$$V_{out} = V_{ofset} + R_p I_{out}$$

$$\Delta_I = I_{ref}$$

$$\Delta_U = RI_{ref}$$

Kako u težinskoj mreži napraviti veliki opseg vrednosti

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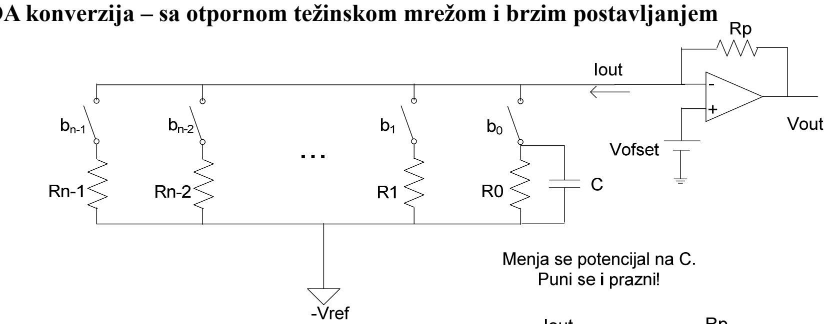
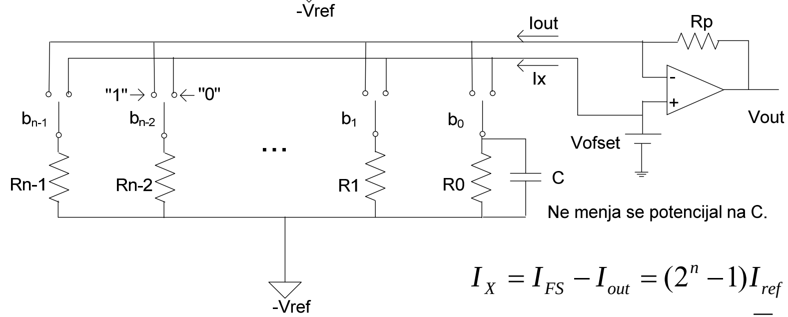
DA konverzija – sa otpornom težinskom mrežom i brzim postavljanjem





$$I_X = I_{FS} - I_{out} = (2^n - 1)I_{ref} - BI_{ref}$$

$$I_X = ((2^n - 1) - B)I_{ref} = \overline{B}I_{ref} = \overline{I}_{out}$$

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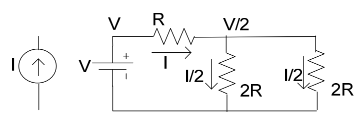
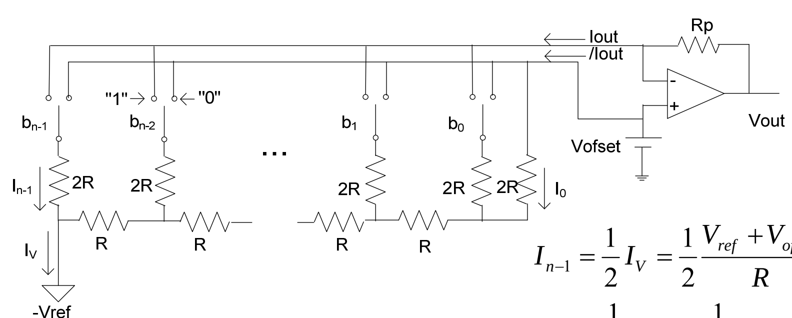
DA konverzija – sa otpornom lestvičastom mrežom





$$I_{n-1} = \frac{1}{2}I_V = \frac{1}{2}\frac{V_{ref} + V_{ofset}}{R}$$

$$I_{n-2} = \frac{1}{2}I_{n-1} = \frac{1}{2 \cdot 2}I_V$$

$$I_{n-k} = \frac{1}{2^k}I_V$$

$$I_0 = \Delta_I = \frac{1}{2^n}I_V$$

$$I_{out} = BI_0$$

$$\overline{I}_{out} = \left(2^n - B\right)I_0$$

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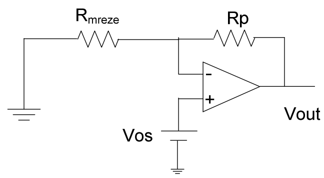
DA konverzija – greške konverzije

Vofset je do sada bio naponski izvor preko kojeg smo podešavali ofset karakterisike tj, pomerali je gde želimo.
A šta ako je to ofset operacionog pojačavača?
Znači nismo želeli da pomeramo karakteristiku ali u modelu postoji taj generator.



$$V_{out}^{os} = \frac{V_{os}}{R_{mreze}} R_p + V_{os} = V_{os}\left(1 + \frac{R_p}{R_{mreze}}\right)$$

R mreze je zavisno od koda, tako da je i uticaj na izlazu zavistan od koda!
Raste DNL i INL!

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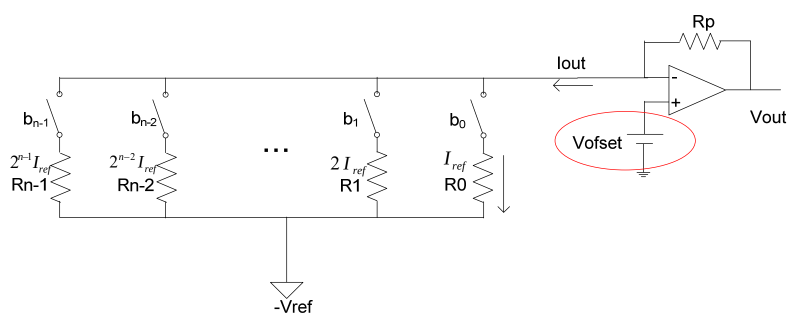
DA konverzija – greške konverzije

Računali za ovo ali sada smatramo Vofset neželjenim



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DA konverzija – greške konverzije

$$I_{out} = \sum_{i=0}^{n-1} b_i \frac{V_{ref}}{R_i} = I_{ref} \sum_{i=0}^{n-1} b_i 2^i = I_{ref}(b_{n-1}...b_1 b_0)$$

$$R_0 = R \quad \Rightarrow \quad R_i = \frac{R}{2^i}$$

$$I_{ref} = \frac{V_{ref}}{R}$$

Nema ofseta

$$V_{out} = R_p I_{out}$$

$$\Delta_I = I_{ref}$$

$$\Delta_U = RI_{ref}$$

$$I_{out}^{os} = \sum_{i=0}^{n-1} b_i \frac{V_{ref} + V_{ofset}}{R_i} = I_{ref}^{os} \sum_{i=0}^{n-1} b_i 2^i = I_{ref}^{os}(b_{n-1}...b_1 b_0)$$

$$R_0 = R \quad \Rightarrow \quad R_i = \frac{R}{2^i}$$

$$I_{ref}^{os} = \frac{V_{ref} + V_{ofset}}{R}$$

Računali kada ga ima

$$V_{out}^{os} = V_{ofset} + R_p I_{out}^{os}$$

$$\Delta_I^{os} = I_{ref}^{os}$$

$$\Delta_U^{os} = RI_{ref}^{os}$$

Greška na izlazu

$$\Delta V_{out} = V_{out} - V_{out}^{os} = R_p(I_{out} - I_{out}^{os}) - V_{ofset} = (b_{n-1}...b_1 b_0) R_p (I_{ref} - I_{ref}^{os}) - V_{ofset} =$$

$$= (b_{n-1}...b_1 b_0) R_p \left(\frac{V_{ref}}{R} - \frac{V_{ref} + V_{ofset}}{R}\right) - V_{ofset}$$

$$\Delta V_{out} = -V_{ofset}\left(1 + \frac{(b_{n-1}...b_1 b_0) R_p}{R}\right)$$

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DA konverzija – greške konverzije

Otpornik Rp nije tačan?
Otpornici Rk u mreži nisu tačni?
Kako to utiče u težinskoj a kako u lestvičastoj mreži?

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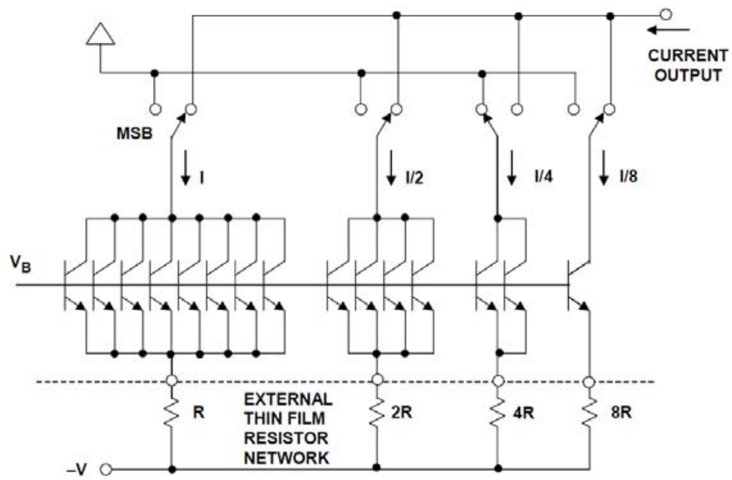
DA konverzija – strujni izvor sa velikom izlaznom otpornošću



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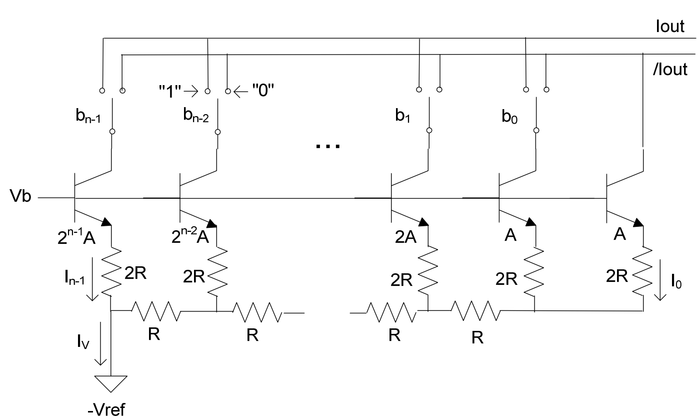
DA konverzija – strujni izvor sa velikom izlaznom otpornošću



Površine emitora?
Da bi tranzistori imali isto Vbe za različite struje, i površine moraju biti različite.
A isto Vbe treba da bi gornji krajevi otornika 2R bili na istim potencijalima. Da se ne narušava simetrija.

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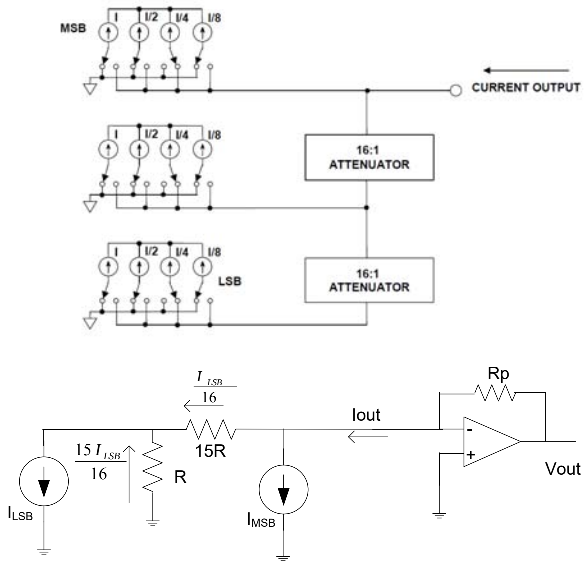
DA konverzija – kaskadna realizacija



I_{LSB} i I_{MSB} mreže napravljane na isti način.
Vrednosti bitskih strujnih izvora isti.

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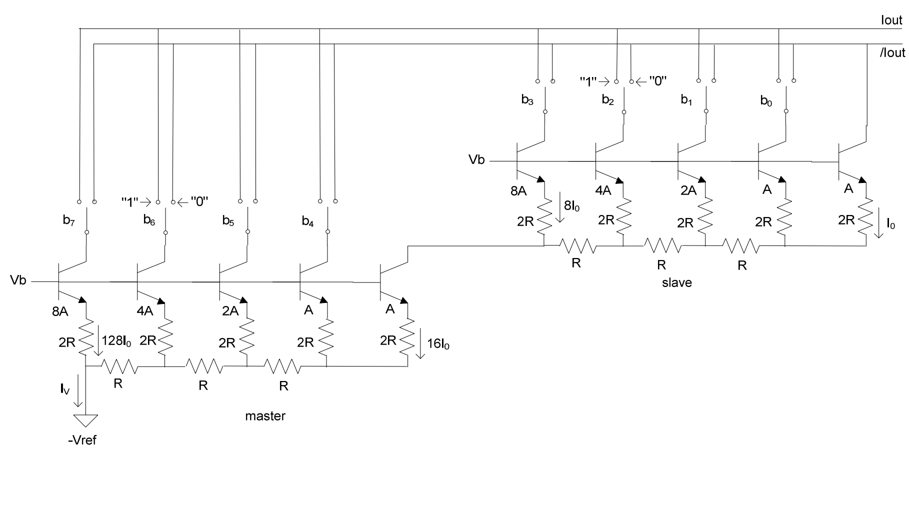
DA konverzija – master-slave konfiguracija



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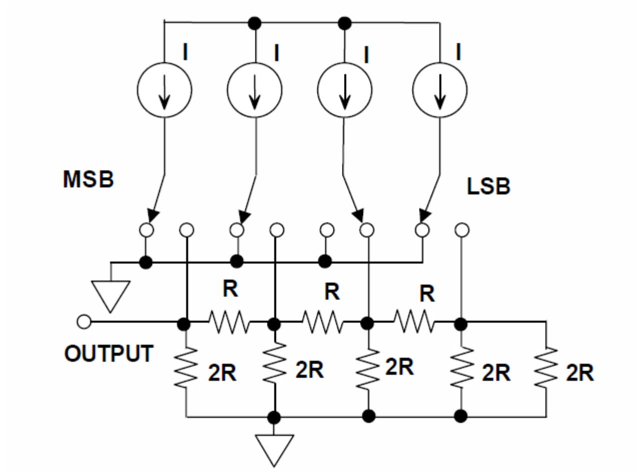
DA konverzija – iste vrednosti strujnih izvora u R-2R mreži



Naponski izlaz!

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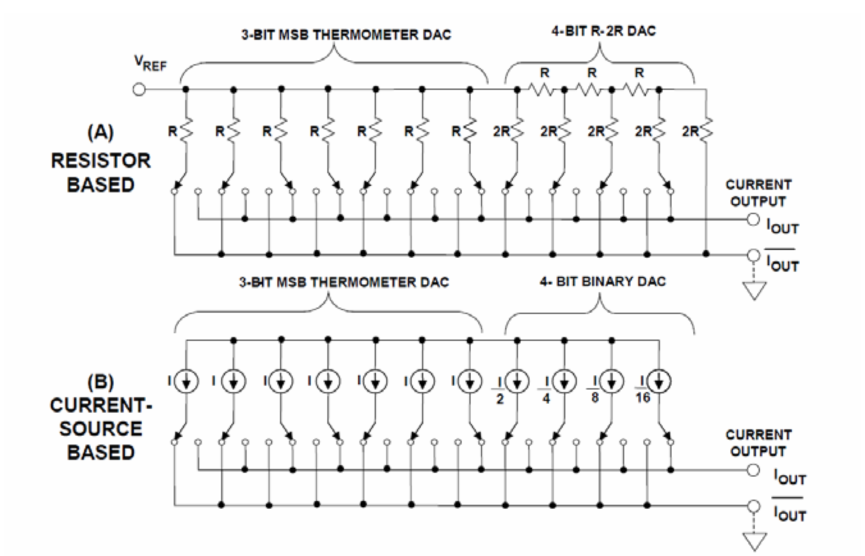
DA konverzija – segmentni

Monotonost karakteristike – kako obezbediti



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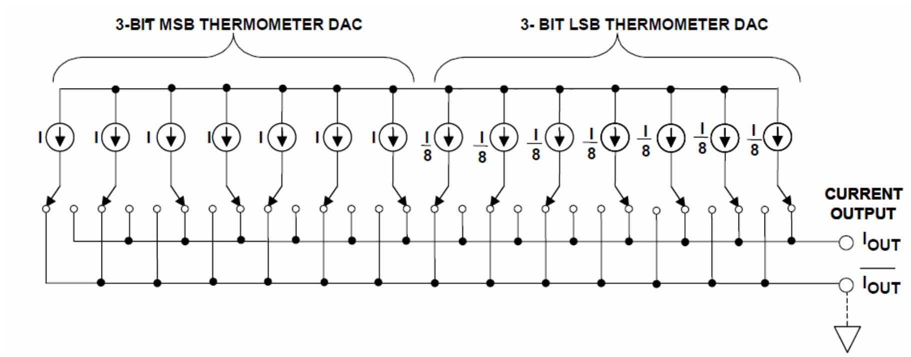
DA konverzija – segmentni



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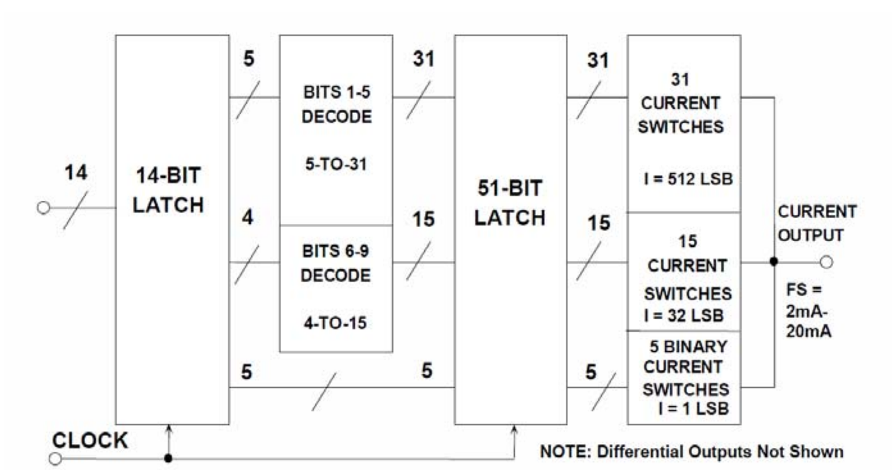
DA konverzija – AD9775



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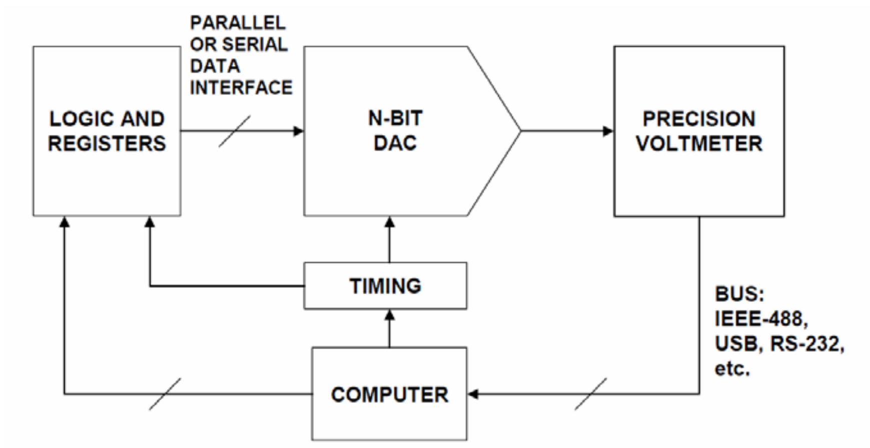
DA konverzija – snimanje statičke karakteristike



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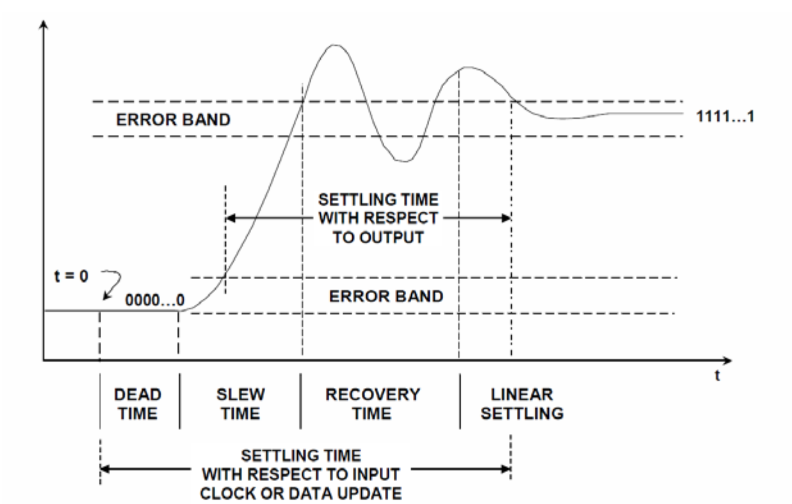
DA konverzija – vreme postavljanja

Vreme konverzije=vreme postavljanja=settling time



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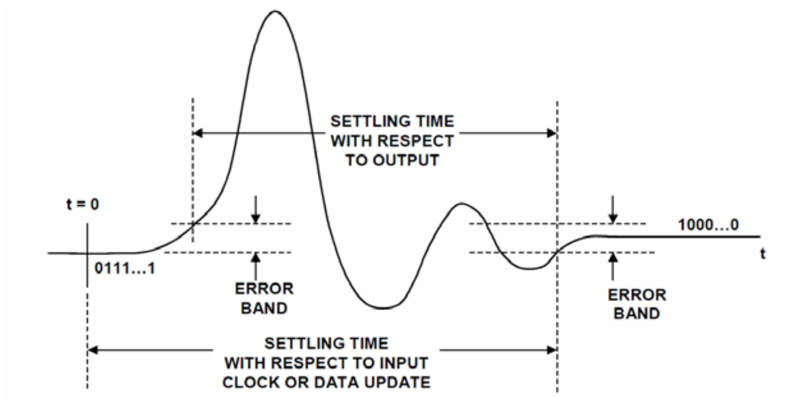
DA konverzija – glič

011..11 -> 100..00



011..11 -> 111...11 -> 100..00 pozitivan glič

011..11 -> 000...00 -> 100..00 negativan glič

I mnogo varijanti između

Termometarski kod?
Grejov kod?
Neki drugi?

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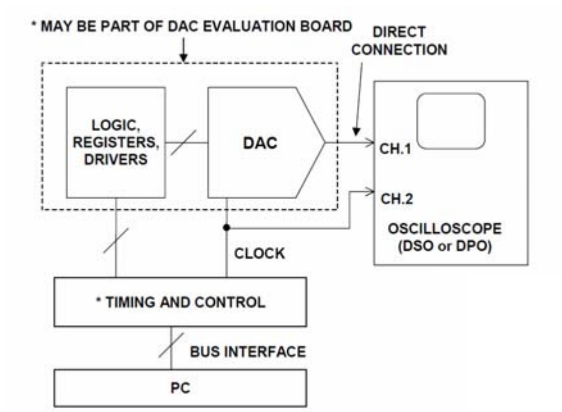
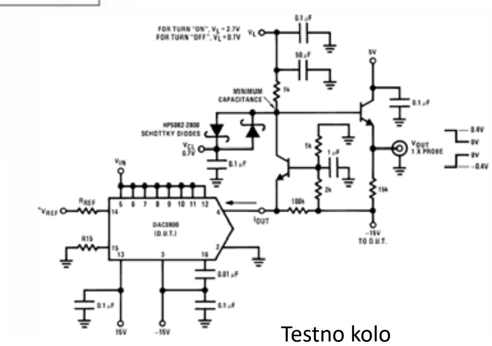
DA konverzija – merenje vremenskih karakteristika



Princip



Testno kolo

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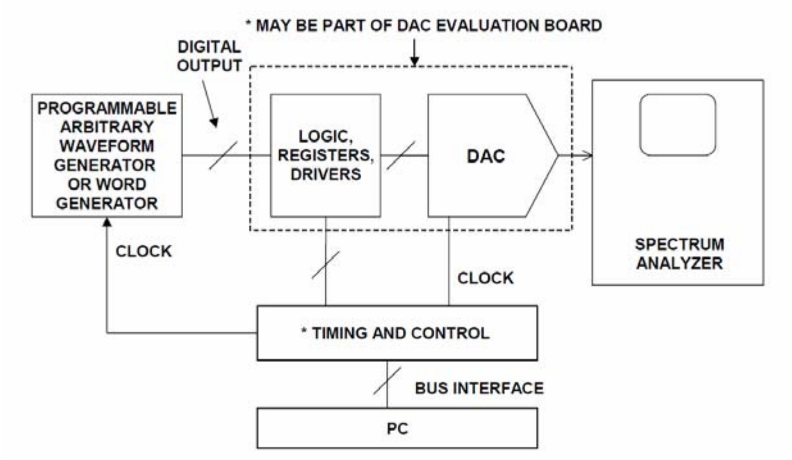
DA konverzija – merenje frekventnih karakteristika



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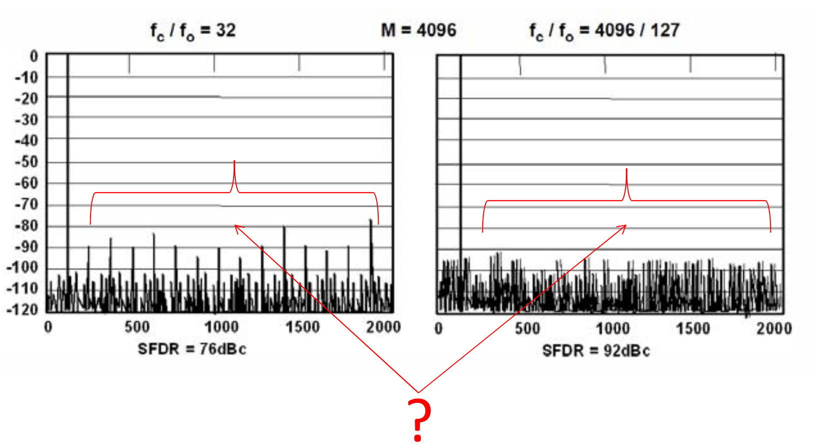
DA konverzija – merenje frekventnih karakteristika

4096/127=32.25



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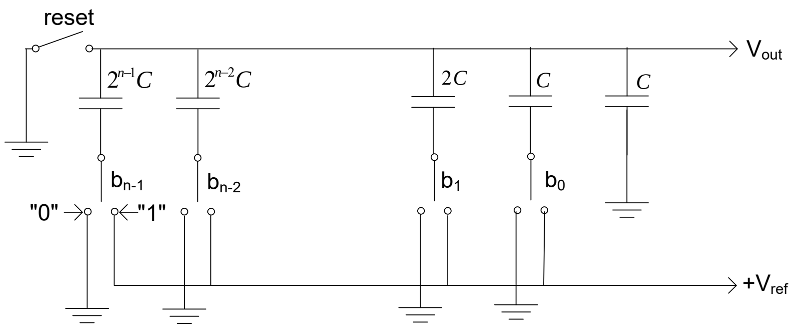
DA konverzija – kapacitivni DA konvertor



U toku resetne faze svi kondenzatori su na naponu 0.

b_i=/reset*B_i

U toku faze postavljanja prekidačima upravljaju bitske vrednosti.

/reset=1

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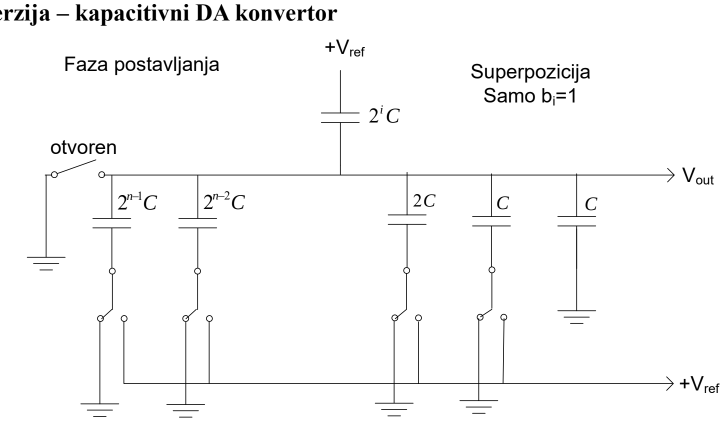

$$V_i = \frac{2^iC}{2^iC + \sum_{k=0,k\neq i}^{n-1} 2^kC + C} V_{ref} = \frac{2^iC}{2^iC + \left(\frac{2^n-1}{2-1}C - 2^iC\right) + C} = \frac{2^i}{2^n} V_{ref}$$

$$V_{out} = \frac{V_{ref}}{2^n} \sum_{i=0}^{n-1} b_i 2^i$$

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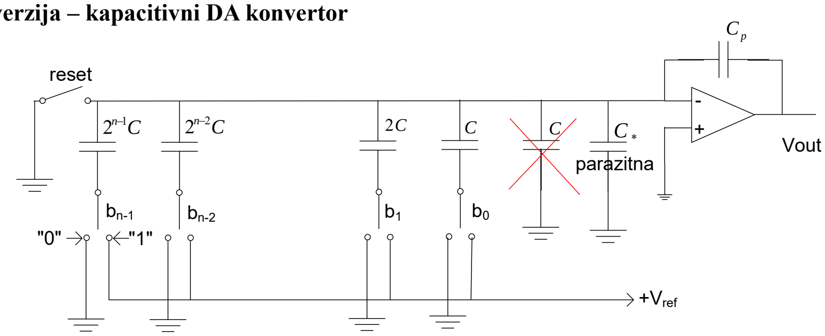

$$Q_i = b_i 2^i C V_{ref}$$

$$Q = \sum_{i=0}^{n-1} Q_i = C V_{ref} \sum_{i=0}^{n-1} b_i 2^i$$

$$V_{out} = -\frac{Q}{C_p} = -\frac{C}{C_p} V_{ref} \sum_{i=0}^{n-1} b_i 2^i$$

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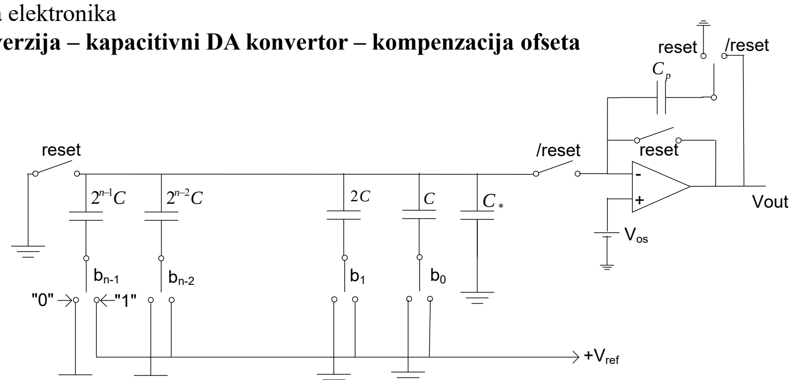
DA konverzija – kapacitivni DA konvertor – kompenzacija ofseta



U toku resetne faze

-prazne se sve kapacitivnosti u težinskoj mreži

-izlazna kapacitivnost se puni na napon V_{os}

U toku faze postavljanja

$$V_{C_p} = V_{os} + \frac{C}{C_p} V_{ref} \sum_{i=0}^{n-1} b_i 2^i$$

$$V_{out} = V_{os} - V_{C_p} = V_{os} - \left(V_{os} + \frac{C}{C_p} V_{ref} \sum_{i=0}^{n-1} b_i 2^i \right) = -\frac{C}{C_p} V_{ref} \sum_{i=0}^{n-1} b_i 2^i$$

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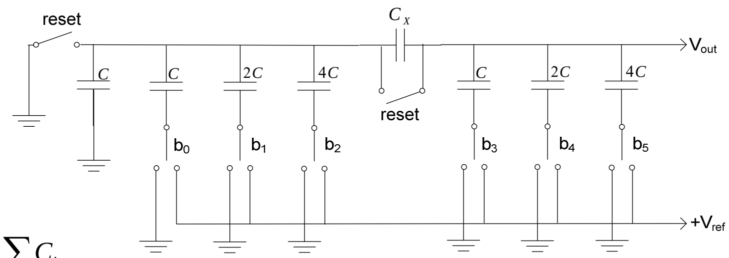
DA konverzija – kapacitivni DA konvertor – kaskadna realizacija



$$C_X = ?$$

$$LSB = \sum_{C_i \in LSB} C_i$$

$$MSB = \sum_{C_i \in MSB} C_i$$

$$\Delta_{iLSB} = \frac{2^i C}{LSB + \frac{C_X MSB}{C_X + MSB}} \frac{C_X}{C_X + MSB} V_{ref}$$

$$\Delta_{iMSB} = \frac{2^i C}{MSB + \frac{C_X LSB}{C_X + LSB}} V_{ref}$$

$$\Delta_{iMSB} = 2^k \Delta_{iLSB}, \quad k \text{ broj bita u LSB mrezi}$$

$$\frac{2^i C}{MSB + \frac{C_X LSB}{C_X + LSB}} V_{ref} =$$

$$= 2^k \frac{2^i C}{LSB + \frac{C_X MSB}{C_X + MSB}} \frac{C_X}{C_X + MSB} V_{ref}$$

$$\frac{C_X LSB}{C_X + LSB} = C \Rightarrow C_X = \frac{2^k}{2^k - 1} C$$

U primeru $C_X = \frac{8}{7} C$

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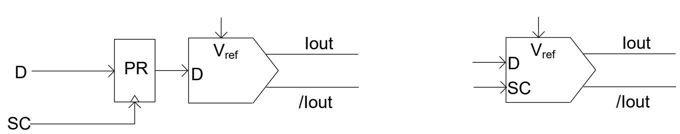
DA konverzija

registar za podatake koji upravljaju prekidačima često unutar DA konvertora

PIPO – parallel in parallel out = PR-prihvatni registar



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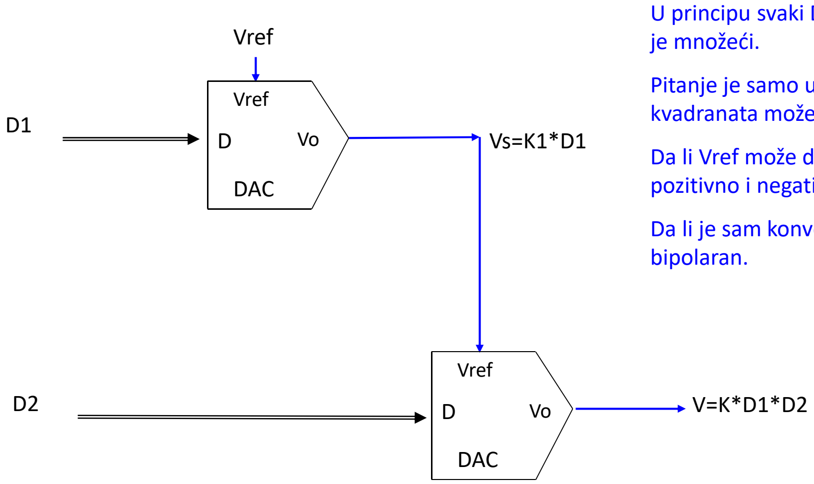
DA konverzija – množeći DA konvertor



U principu svaki DA konvertor je množeći.

Pitanje je samo u koliko kvadranata može da radi

Da li Vref može da bude i pozitivno i negativno.

Da li je sam konvertor bipolaran.

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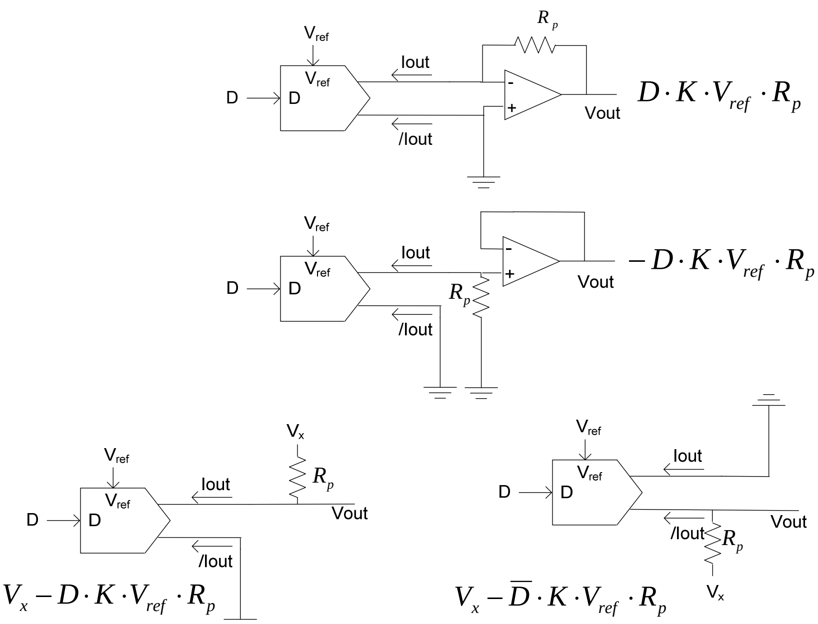
DA konverzija – unipolarna



$$D \cdot K \cdot V_{ref} \cdot R_p$$

$$-D \cdot K \cdot V_{ref} \cdot R_p$$

$$V_x - D \cdot K \cdot V_{ref} \cdot R_p$$

$$V_x - \overline{D} \cdot K \cdot V_{ref} \cdot R_p$$

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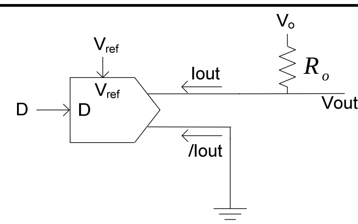
DA konverzija – bipolarna



$$V_{out} = V_o - D \cdot K \cdot V_{ref} \cdot R_o = V_x - D \cdot \Delta_I \cdot R_o$$

$$\Delta_U = -\Delta_I R_o$$

$$D = 0 \quad \Rightarrow \quad V_{out} = V_o = V_{max}$$

$$D = 2^n - 1 \quad \Rightarrow \quad V_{out} = V_o + \left(2^n - 1\right)\Delta_U = V_{min}$$

Sa ofsetom

MSB
0-pozitivni
1-negativni
Ofset dodajemo

$$D = 011...11 = 2^{n-1} - 1 \quad \Rightarrow \quad V_{out} = 0$$

$$0 = V_x + \left(2^{n-1} - 1\right)\Delta_U \quad \Rightarrow \quad V_x = -\left(2^{n-1} - 1\right)\Delta_U$$

$$D = 0 \quad \Rightarrow \quad V_{out} = -\left(2^{n-1} - 1\right)\Delta_U$$

$$D = 2^{n-1} - 1 \quad \Rightarrow \quad V_{out} = 0$$

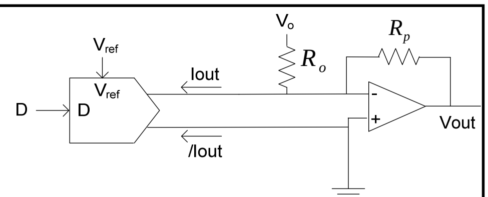
$$D = 2^n - 1 \quad \Rightarrow \quad V_{out} = -\left(2^{n-1} - 1\right)\Delta_U + \left(2^n - 1\right)\Delta_U = 2^{n-1}\Delta_U$$

$$V_{out} = \left(D - \left(2^{n-1} - 1\right)\right)\Delta_U$$

$$ofset = -\left(2^{n-1} - 1\right)$$

Digitalna elektronika

DA konverzija – bipolarna



$$V_{out} = R_p\left(I_{out} - \frac{V_o}{R_o}\right) = -V_o\frac{R_p}{R_o} + D \cdot \Delta_I \cdot R_p$$

$$\Delta_U = \Delta_I R_p$$

$$D = 0 \quad \Rightarrow \quad V_{out} = -V_o\frac{R_p}{R_o} = V_{min}$$

$$D = 2^n - 1 \quad \Rightarrow \quad V_{out} = -V_o\frac{R_p}{R_o} + \left(2^n - 1\right)\Delta_U = V_{max}$$

Sa ofsetom

MSB
0-negativni
1-pozitivni
Ofset dodajemo

$$D = 100...00 = 2^{n-1} \quad \Rightarrow \quad V_{out} = 0$$

$$0 = -V_o\frac{R_p}{R_o} + 2^{n-1}\Delta_U \quad \Rightarrow \quad V_o = \frac{R_o}{R_p}2^{n-1}\Delta_U = R_0 2^{n-1}\Delta_I$$

$$D = 0 \quad \Rightarrow \quad V_{out} = -2^{n-1}\Delta_U$$

$$D = 2^{n-1} \quad \Rightarrow \quad V_{out} = 0$$

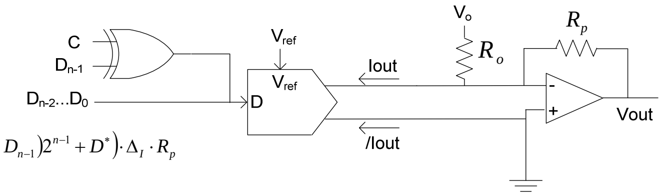
$$D = 2^n - 1 \quad \Rightarrow \quad V_{out} = -2^{n-1}\Delta_U + \left(2^n - 1\right)\Delta_U = (2^{n-1} - 1)\Delta_U$$

$$V_{out} = \left(D - 2^{n-1}\right)\Delta_U$$

$$ofset = -2^{n-1}$$

Digitalna elektronika

DA konverzija – bipolarna



$$V_{out} = R_p\left(I_{out} - \frac{V_o}{R_o}\right) = -V_o\frac{R_p}{R_o} + \left((C \oplus D_{n-1})2^{n-1} + D^*\right)\cdot \Delta_I \cdot R_p$$

$$\Delta_U = \Delta_I R_p$$

$$D^* = 0 \quad \wedge \quad (C \oplus D_{n-1}) = 0 \quad \Rightarrow \quad V_{out} = -V_o\frac{R_p}{R_o} = V_{\min}$$

$$D^* = 2^{n-1} - 1 \quad \wedge \quad (C \oplus D_{n-1}) = 1 \quad \Rightarrow \quad V_{out} = -V_o\frac{R_p}{R_o} + (2^n - 1)\Delta_U = V_{\max}$$

Sa ofsetom
ili
drugi komplement

$$D = (C \oplus D_{n-1})00\ldots00 = 2^{n-1} \quad \Rightarrow \quad V_{out} = 0$$

$$0 = -V_o\frac{R_p}{R_o} + 2^{n-1}\Delta_U \quad \Rightarrow \quad V_o = \frac{R_o}{R_p}2^{n-1}\Delta_U = R_0 2^{n-1}\Delta_I$$

$$D^* = 0 \quad \wedge \quad (C \oplus D_{n-1}) = 1 \quad \Rightarrow \quad V_{out} = 0$$

$$D^* = 0 \quad \wedge \quad (C \oplus D_{n-1}) = 0 \quad \Rightarrow \quad V_{out} = -2^{n-1}\Delta_U$$

$$D^* = 2^{n-2} - 1 \quad \wedge \quad (C \oplus D_{n-1}) = 1 \quad \Rightarrow \quad V_{out} = -2^{n-1}\Delta_U + (2^n - 1)\Delta_U = (2^{n-1} - 1)\Delta_U$$

$$V_{out} = \left((C \oplus D_{n-1})2^{n-1} + D^* - 2^{n-1}\right)\Delta_U$$

$$C = 0 \quad ofset = -2^{n-1}$$

$$C = 1 \quad drugi \quad komplement$$

Digitalna elektronika

DA konverzija – bipolarna

digresija

$$(C \oplus D_{n-1})2^{n-1} + D^* - 2^{n-1} = ?$$

$$C = 0 \quad \Rightarrow \quad (C \oplus D_{n-1})2^{n-1} + D^* - 2^{n-1} = D_{n-1}2^{n-1} + D^* - 2^{n-1} = D - 2^{n-1}$$

ofset

$$C = 1 \quad \Rightarrow \quad (C \oplus D_{n-1})2^{n-1} + D^* - 2^{n-1} = \overline{D}_{n-1}2^{n-1} + D^* - 2^{n-1}$$

$$\overline{D}_{n-1} = 1 - D_{n-1}$$

$$\overline{D}_{n-1}2^{n-1} + D^* - 2^{n-1} = -D_{n-1}2^{n-1} + D^*$$

drugi komplement

$$D_{n-1} = 0 \quad \Rightarrow \quad D_t = D^*$$

$$D_{n-1} = 1 \quad \Rightarrow \quad D_t = -D_{n-1}2^{n-1} + D^* = D_{n-1}2^{n-1} - 2^n + D^* = -(2^n - D)$$

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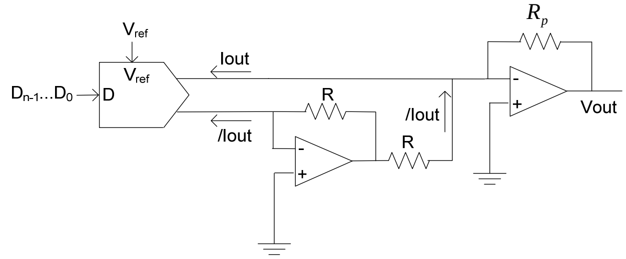
DA konverzija – bipolarna



$$V_{out} = R_p\left(I_{out} - \bar{I}_{out}\right) = \left(D - \overline{D}\right)\cdot \Delta_I \cdot R_p = \left(D - (2^n - D)\right)\cdot \Delta_I \cdot R_p =$$

$$= (2D - 2^n)\Delta_I \cdot R_p = (D - 2^{n-1})2\Delta_I \cdot R_p$$

$$\Delta_U = 2\Delta_I R_p$$

$$D = 0 \quad \Rightarrow \quad V_{out} = -2^{n-1}\Delta_U$$

$$D = 2^n - 1 \quad \Rightarrow \quad V_{out} = (2^{n-1} - 1)\Delta_U$$

$$D = 2^{n-1} \Rightarrow \quad V_{out} = 0$$

$$ofset = -2^{n-1}$$

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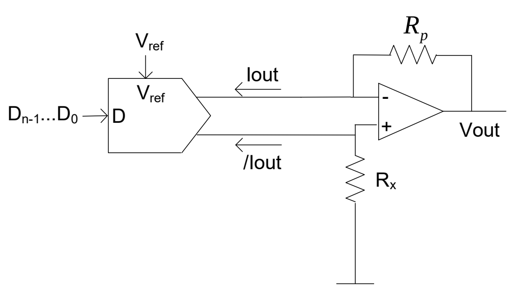
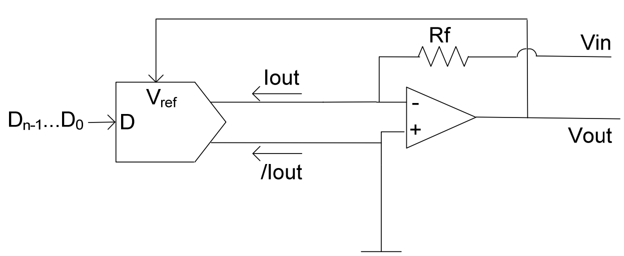
DA konverzija – ?



?

Rx=?



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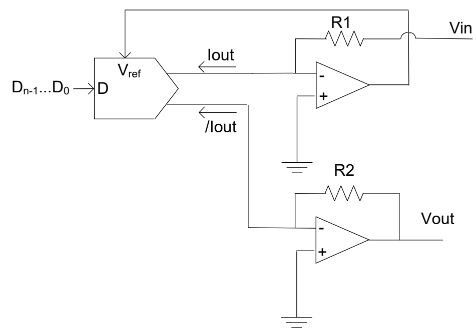
DA konverzija – ?



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