Projektovanje elektronskih kola

Sadržaj:

1. Uvod - osnovni pojmovi
2. Stilovi projektovanja i izrade prototipova
3. **Projektovanje analognih kola**
4. **Osnove fizičkog projektovanja (projektovanje štampanih ploča)**
5. **Projektovanje digitalnih kola (vežbe)**

Analiza kola

Tipovi analize?

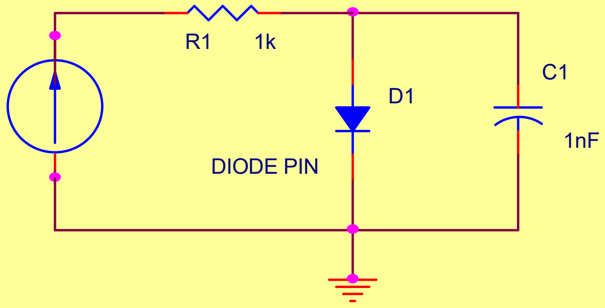
Zavisno od vrste pobude, ima smisla analizirati ponašanje kola u

1. jednosmernom domenu (određivanje položaja jednosmerne radne tačke kola).
2. frekvencijskom domenu (frekvencijska karakteristika kola – amplitudska, fazna)
3. vremenskom domenu (talasni oblik napona/struja na izlazu kola pobuđenog impulsima poznatog talasnog oblika)

Tipovi analize kola

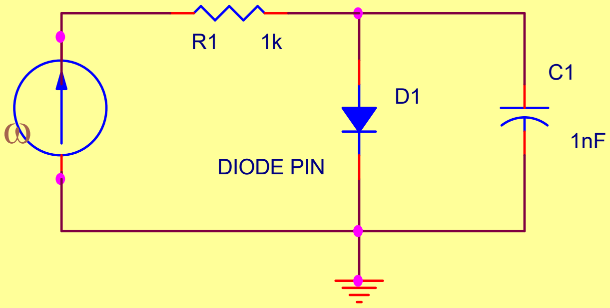
1. **Jednosmerni domen (DC analiza)**

$I=5mA$



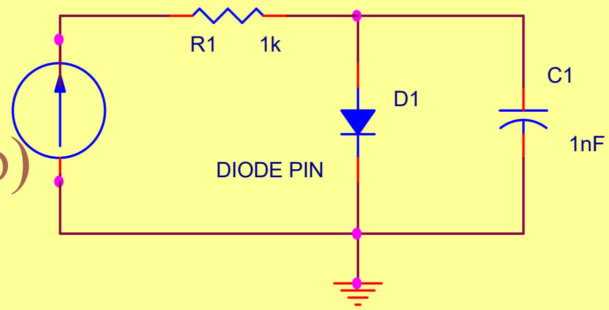
2. **Frekvencijski domen (AC analiza)**

$i(\omega)=5\cdot 10^{-3}e^{j\omega}$



3. **Vremenski domen (TR analiza)**

$i(t)=510^{-3}\cos(2\pi ft+\varphi)$



Analiza kola

Tipovi analize?

Zavisno od vrste elemenata od kojih se kolo sastoji, različiti tip problema i metoda za analizu

1. **Linearna otporna kola (R, linearni generatori, nezavisni i kontrolisani)**
2. **Linearna reaktivna kola (R, L, C, m, ...)**
3. **Nelinearna otporna (poluprovodničke komponente, R, ...)**
4. **Nelinearna reaktivna (poluprovodničke komponente, R, L, C,...)**

Tipovi elektronskih kola

1. Linearna otporna
   R
2. Linearna reaktivna
   L, C, m, ...
3. Nelinearna otporna
   dioda, tranzistor, R, ...
4. Nelinearna reaktivna
   dioda, tranzistor, R, L, C,...

Tipovi analize kola

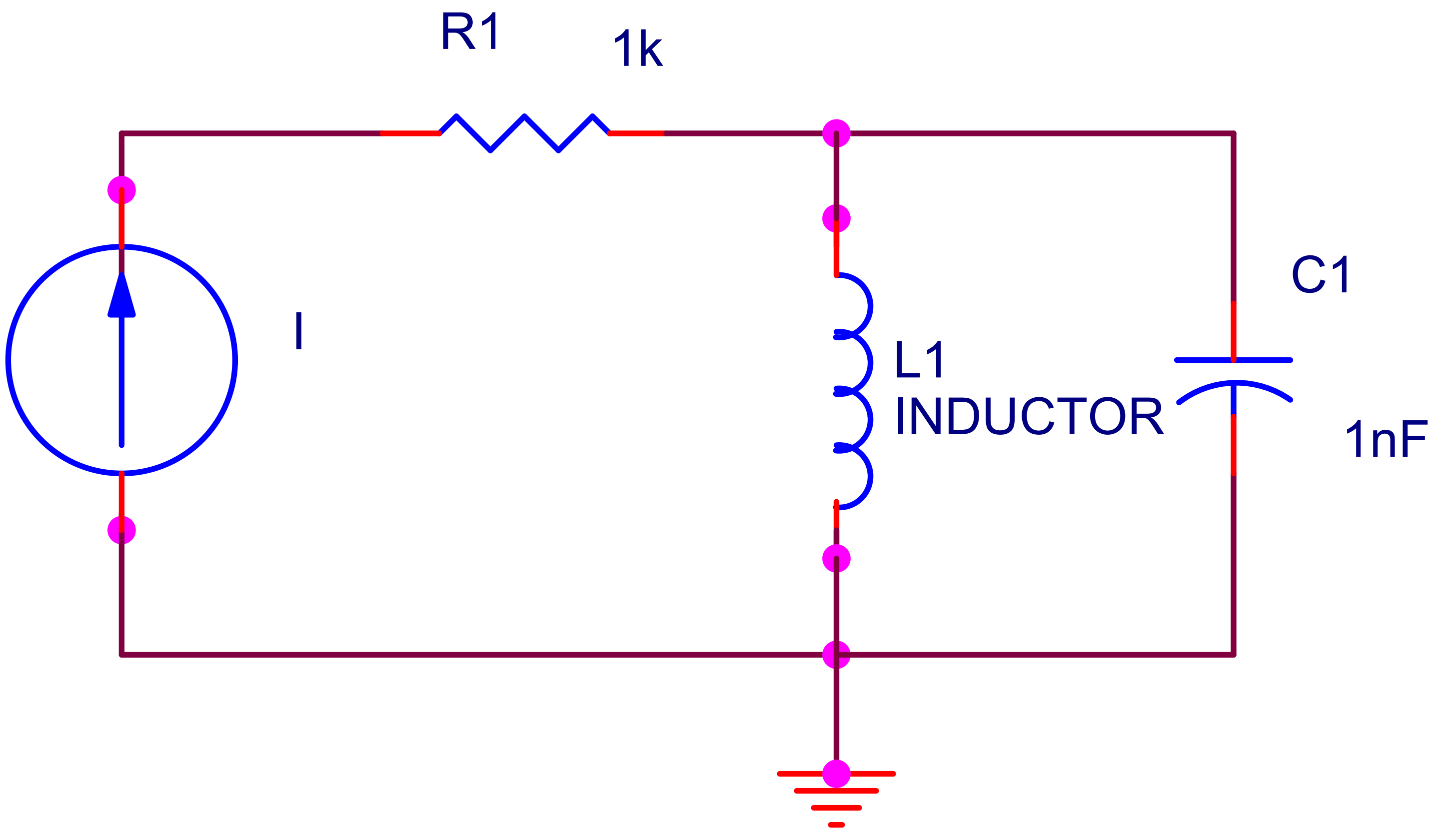
1. Jednosmerni domen (DC analiza)
2. Frekvencijski domen (AC analiza)
3. Vremenski domen (TR analiza)

Analiza elektronskih kola

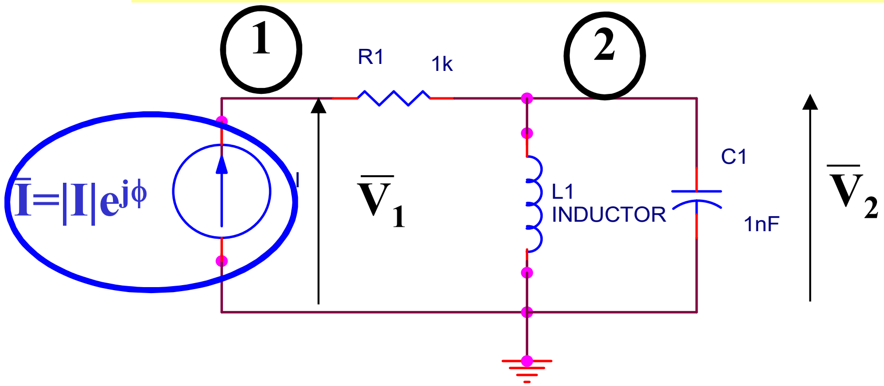
1. Uvod
2. Analiza linearnih kola u DC domenu (jednosmerni režim)
3. Analiza linearnih kola u AC domenu (frekvencijski domen)
4. Analiza linearnih kola u TR domenu (vremenski domen)
5. Analiza nelinearnih kola u DC domenu
6. Analiza nelinearnih kola u TR domenu

Analiza elektronskih kola

1. Uvod
2. Analiza linearnih kola u DC domenu (jednosmerni režim)
3. Analiza linearnih kola u AC domenu (frekvencijski domen)
4. Analiza linearnih kola u TR domenu (vremenski domen)
5. Analiza nelinearnih kola u DC domenu
6. Analiza nelinearnih kola u TR domenu


R1
1k
I
L1
INDUCTOR
C1
1nF

Ponašanje linearnih reaktivnih kola u frekvencijskom domenu opisuje se sistemom linearnih algebarskih jednačina sa kompleksnim koeficijentima



$$\frac{\bar{V}_1-\bar{V}_2}{R_1}=\bar{I}$$

$$\frac{\bar{V}_2-\bar{V}_1}{R_1}+\frac{\bar{V}_2}{j\omega\cdot L_1}+j\omega\cdot C_1\bar{V}_2=0$$

Tip kola i analize

2. Linearna reaktivna u AC domenu

Matematički model

2. Linearne algebarske jednačine sa kompleksnim koeficijentima

Matematički model

2. Linearne jednačine kompleksne

3. Linearne diferencijalne jednačine

4. Nelinearne algebarske jednačine

5. Nelinearne diferencijalne jednačine

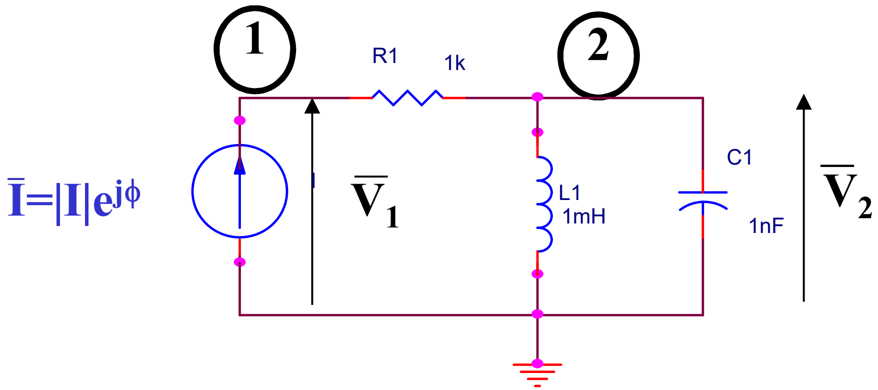
Način rešavanja sistema j-na

2. LU faktorizacija (Gauss)

3. Numeričko integraljenje - diskretizacija - svođenje na linearne algebarske (Euler)

4. Linearizacija - Iterativno svođenje na linearne algebarske (Newton-Kantorovič)

5. Diskretizacija - svođenje na nelinearne algebarske i linearizacija - Iterativno svođenje na linearne algebarske



$$\frac{\overline{V}_1-\overline{V}_2}{R_1}=\overline{I}$$

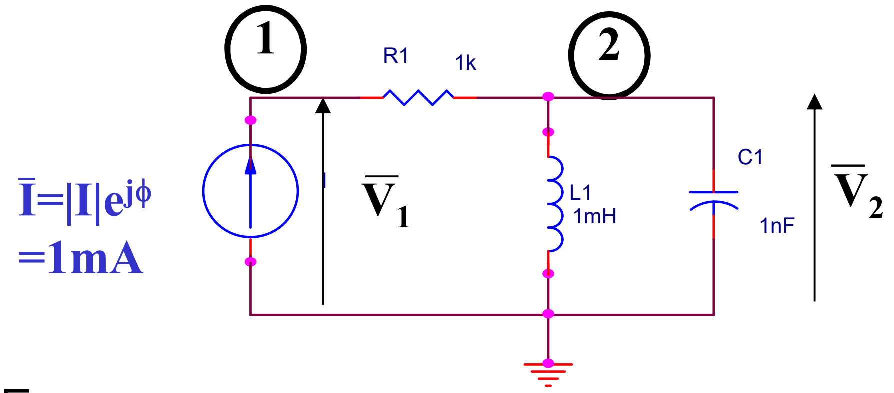
$$\frac{\overline{V}_2-\overline{V}_1}{R_1}+\frac{\overline{V}_2}{j\omega\cdot L_1}+j\omega\cdot C_1\overline{V}_2=0$$

$$\mathbf{\frac{1}{R_1}\overline{V}_1-\frac{1}{R_1}\overline{V}_2=\overline{I}}$$

$$\mathbf{-\frac{1}{R_1}\overline{V}_1+\left(\frac{1}{R_1}+\frac{1}{j\omega\cdot L_1}+j\omega\cdot C_1\right)\overline{V}_2=0}$$

$$\mathbf{10^{-3}\overline{V}_1-10^{-3}\overline{V}_2=\overline{I}}$$

$$\mathbf{-10^{-3}\overline{V}_1+\left(10^{-3}+\frac{1}{j\omega\cdot 10^{-3}}+j\omega\cdot 10^{-9}\right)\overline{V}_2=0}$$

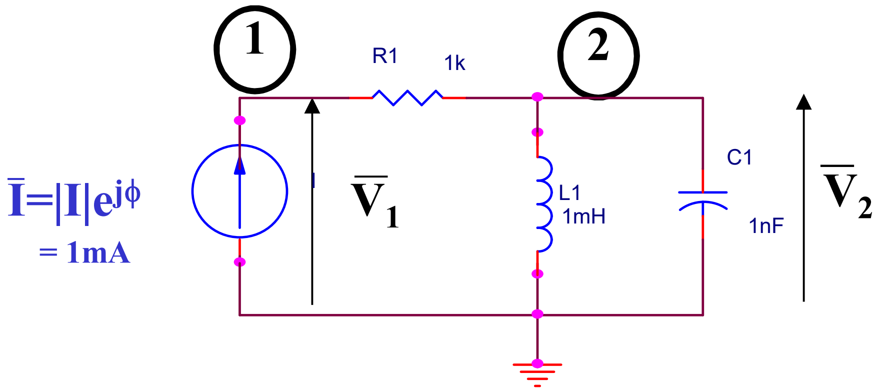


$$\frac{\overline{V}_1-\overline{V}_2}{R_1}=\bar{I}$$

$$\frac{\overline{V}_2-\overline{V}_1}{R_1}+\frac{\overline{V}_2}{j\omega\cdot L_1}+j\omega\cdot C_1\overline{V}_2=0$$

$$\begin{bmatrix}\frac{1}{R_1} & -\frac{1}{R_1}\\ -\frac{1}{R_1} & \frac{1}{R_1}+\frac{1}{j\omega\cdot L_1}+j\omega\cdot C_1\end{bmatrix}\begin{bmatrix}\overline{V}_1\\ \overline{V}_2\end{bmatrix}=\begin{bmatrix}\bar{I}\\ 0\end{bmatrix}\qquad \underset{\sim}{Y}\cdot\overline{\underline{v}}=\bar{\underline{i}}$$

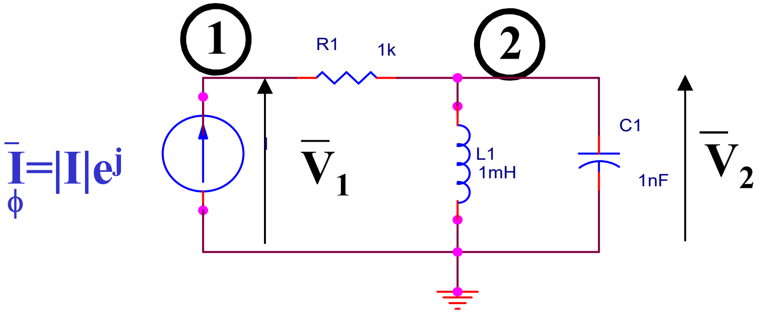
$$\begin{bmatrix}10^{-3} & -10^{-3}\\ -10^{-3} & 10^{-3}-\frac{j}{\omega\cdot 10^{-3}}+j\omega\cdot 10^{-9}\end{bmatrix}\cdot\begin{bmatrix}\overline{V}_1\\ \overline{V}_2\end{bmatrix}=\begin{bmatrix}10^{-3}\\ 0\end{bmatrix}$$



$$\begin{bmatrix} \frac{1}{R_1} & -\frac{1}{R_1} \\ -\frac{1}{R_1} & \frac{1}{R_1}+\frac{1}{j\omega\cdot L_1}+j\omega\cdot C_1 \end{bmatrix} \begin{bmatrix} \overline{V}_1 \\ \overline{V}_2 \end{bmatrix} = \begin{bmatrix} \overline{I} \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} \frac{1}{R_1} & -\frac{1}{R_1} \\ -\frac{1}{R_1} & \frac{1}{R_1}+j(\omega\cdot C_1-\frac{1}{\omega\cdot L_1}) \end{bmatrix} \begin{bmatrix} V_{1r}+jV_{1i} \\ V_{2r}+jV_{2i} \end{bmatrix} = \begin{bmatrix} I_r+jI_i \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} 10^{-3} & -10^{-3} \\ -10^{-3} & 10^{-3}+j(\omega\cdot 10^{-9}-\frac{1}{\omega\cdot 10^{-3}}) \end{bmatrix} \cdot \begin{bmatrix} V_{1r}+jV_{1i} \\ V_{2r}+jV_{2i} \end{bmatrix} = \begin{bmatrix} 10^{-3}+j0 \\ 0 \end{bmatrix}$$

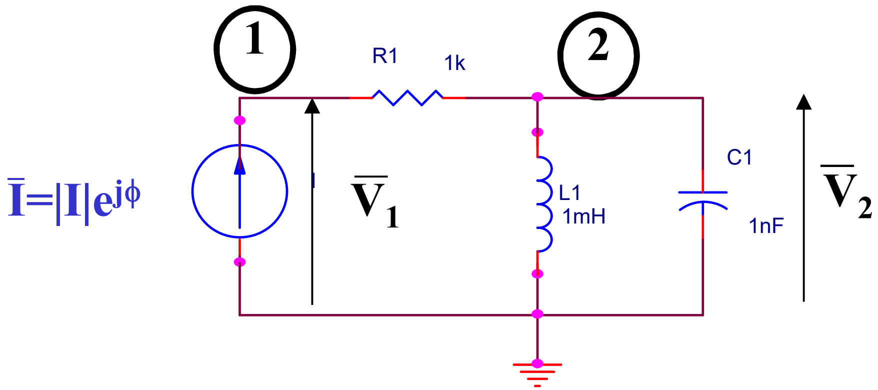


$$\begin{bmatrix} \frac{1}{R_1} & -\frac{1}{R_1} \\ -\frac{1}{R_1} & \frac{1}{R_1} + j(\omega \cdot C_1 - \frac{1}{\omega \cdot L_1}) \end{bmatrix} \begin{bmatrix} V_{1r} + jV_{1i} \\ V_{2r} + jV_{2i} \end{bmatrix} = \begin{bmatrix} I_r + jI_i \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} y_{11r} + j \cdot y_{11i} & y_{12r} + j \cdot y_{12i} \\ y_{21r} + j \cdot y_{21i} & y_{22r} + j \cdot y_{22i} \end{bmatrix} \cdot \begin{bmatrix} V_{1r} + j \cdot V_{1i} \\ V_{2r} + j \cdot V_{2i} \end{bmatrix} = \begin{bmatrix} I_r + j \cdot I_i \\ 0 \end{bmatrix}$$

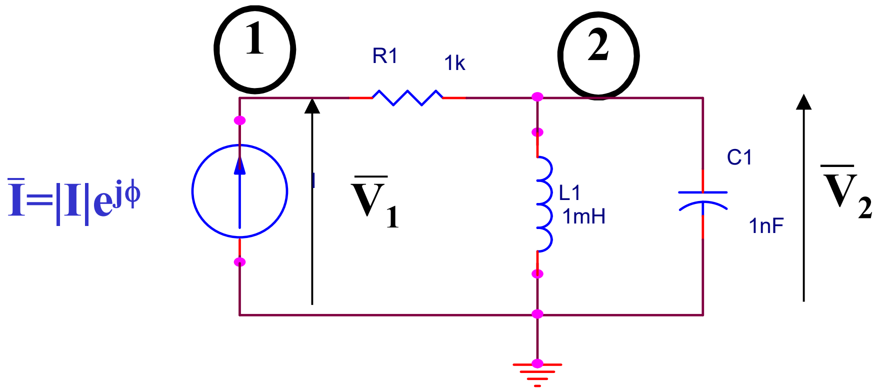
$$(\underset{\sim}{Y}_r + j \cdot \underset{\sim}{Y}_i) \cdot (\underline{v}_r + j \cdot \underline{v}_i) = \underline{i}_r + j \cdot \underline{i}_i$$

$$\begin{bmatrix} \underset{\sim}{Y}_r & -\underset{\sim}{Y}_i \\ \underset{\sim}{Y}_i & \underset{\sim}{Y}_r \end{bmatrix} \cdot \begin{bmatrix} \underline{v}_r \\ \underline{v}_i \end{bmatrix} = \begin{bmatrix} \underline{i}_r \\ \underline{i}_i \end{bmatrix}; \quad \text{ili} \quad \begin{bmatrix} -\underset{\sim}{Y}_i & \underset{\sim}{Y}_r \\ \underset{\sim}{Y}_r & \underset{\sim}{Y}_i \end{bmatrix} \cdot \begin{bmatrix} \underline{v}_i \\ \underline{v}_r \end{bmatrix} = \begin{bmatrix} \underline{i}_r \\ \underline{i}_i \end{bmatrix}$$



$$\begin{bmatrix} 10^{-3} & -10^{-3} \\ -10^{-3} & 10^{-3} + j(\omega \cdot 10^{-9} - \dfrac{1}{\omega \cdot 10^{-3}}) \end{bmatrix} \cdot \begin{bmatrix} V_{1r} + jV_{1i} \\ V_{2r} + jV_{2i} \end{bmatrix} = \begin{bmatrix} 10^{-3} + j0 \\ 0 \end{bmatrix}$$

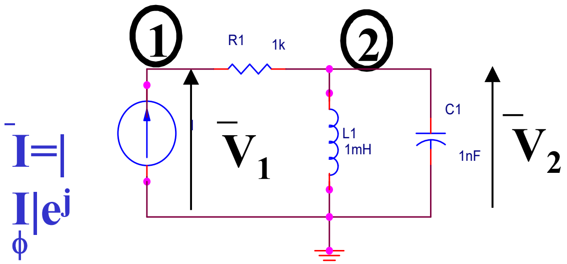
$$\underset{\sim}{\mathbf{Y}}_r = \begin{bmatrix} 10^{-3} & -10^{-3} \\ -10^{-3} & 10^{-3} \end{bmatrix} \quad \text{i} \quad \underset{\sim}{\mathbf{Y}}_i = \begin{bmatrix} 0 & 0 \\ 0 & j(\omega \cdot 10^{-9} - \dfrac{1}{\omega \cdot 10^{-3}}) \end{bmatrix}$$



$$\begin{bmatrix} \underset{\sim}{Y}_r & -\underset{\sim}{Y}_i \\ \underset{\sim}{Y}_i & \underset{\sim}{Y}_r \end{bmatrix} \cdot \begin{bmatrix} \underline{v_r} \\ \underline{v_i} \end{bmatrix} = \begin{bmatrix} \underline{i_r} \\ \underline{i_i} \end{bmatrix}$$

$$\left[\begin{array}{cc|cc} 10^{-3} & -10^{-3} & 0 & 0 \\ -10^{-3} & 10^{-3} & 0 & -(\omega \cdot 10^{-9} - \dfrac{1}{\omega \cdot 10^{-3}}) \\ \hline 0 & 0 & 10^{-3} & -10^{-3} \\ 0 & (\omega \cdot 10^{-9} - \dfrac{1}{\omega \cdot 10^{-3}}) & -10^{-3} & 10^{-3} \end{array}\right] \cdot \begin{bmatrix} v_{1r} \\ v_{2r} \\ v_{1i} \\ v_{2i} \end{bmatrix} = \begin{bmatrix} 10^{-3} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Red matrice 2x veći, ali je gustina matrice manja



Za $\omega=10^3$rad/s

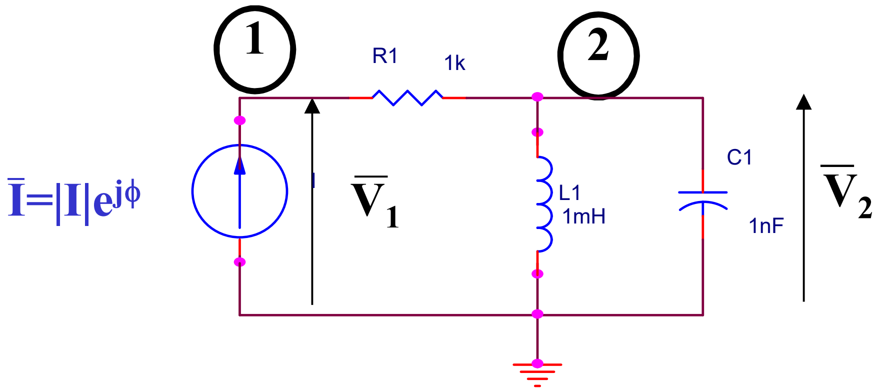
$$\begin{bmatrix} 10^{-3} & -10^{-3} & 0 & 0 \\ -10^{-3} & 10^{-3} & 0 & -(10^{-6}-1) \\ 0 & 0 & 10^{-3} & -10^{-3} \\ 0 & (10^{-6}-1) & -10^{-3} & 10^{-3} \end{bmatrix} \cdot \begin{bmatrix} v_{1r} \\ v_{2r} \\ v_{1i} \\ v_{2i} \end{bmatrix} = \begin{bmatrix} 10^{-3} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Za $\omega=10^6$rad/s

$$\begin{bmatrix} 10^{-3} & -10^{-3} & 0 & 0 \\ -10^{-3} & 10^{-3} & 0 & -(0) \\ 0 & 0 & 10^{-3} & -10^{-3} \\ 0 & (0) & -10^{-3} & 10^{-3} \end{bmatrix} \cdot \begin{bmatrix} v_{1r} \\ v_{2r} \\ v_{1i} \\ v_{2i} \end{bmatrix} = \begin{bmatrix} 10^{-3} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

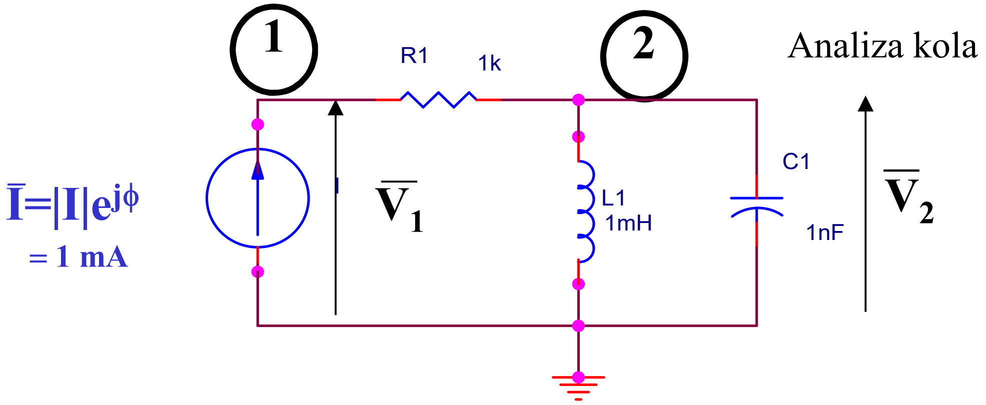
Za $\omega=10^9$rad/s

$$\begin{bmatrix} 10^{-3} & -10^{-3} & 0 & 0 \\ -10^{-3} & 10^{-3} & 0 & -(1-10^{6}) \\ 0 & 0 & 10^{-3} & -10^{-3} \\ 0 & (1-10^{6}) & -10^{-3} & 10^{-3} \end{bmatrix} \cdot \begin{bmatrix} v_{1r} \\ v_{2r} \\ v_{1i} \\ v_{2i} \end{bmatrix} = \begin{bmatrix} 10^{-3} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$



$$\begin{bmatrix} -\underset{\sim}{Y}_i & \underset{\sim}{Y}_r \\ \underset{\sim}{Y}_r & \underset{\sim}{Y}_i \end{bmatrix} \cdot \begin{bmatrix} \underline{v_i} \\ \underline{v_r} \end{bmatrix} = \begin{bmatrix} \underline{i_r} \\ \underline{i_i} \end{bmatrix}$$

$$\left[\begin{array}{cc|cc} 0 & 0 & 10^{-3} & -10^{-3} \\ 0 & -(\omega \cdot 10^{-9} - \frac{1}{\omega \cdot 10^{-3}}) & -10^{-3} & 10^{-3} \\ \hline 10^{-3} & -10^{-3} & 0 & 0 \\ -10^{-3} & 10^{-3} & 0 & (\omega \cdot 10^{-9} - \frac{1}{\omega \cdot 10^{-3}}) \end{array}\right] \cdot \begin{bmatrix} v_{1i} \\ v_{2i} \\ v_{1r} \\ v_{2r} \end{bmatrix} = \begin{bmatrix} 10^{-3} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

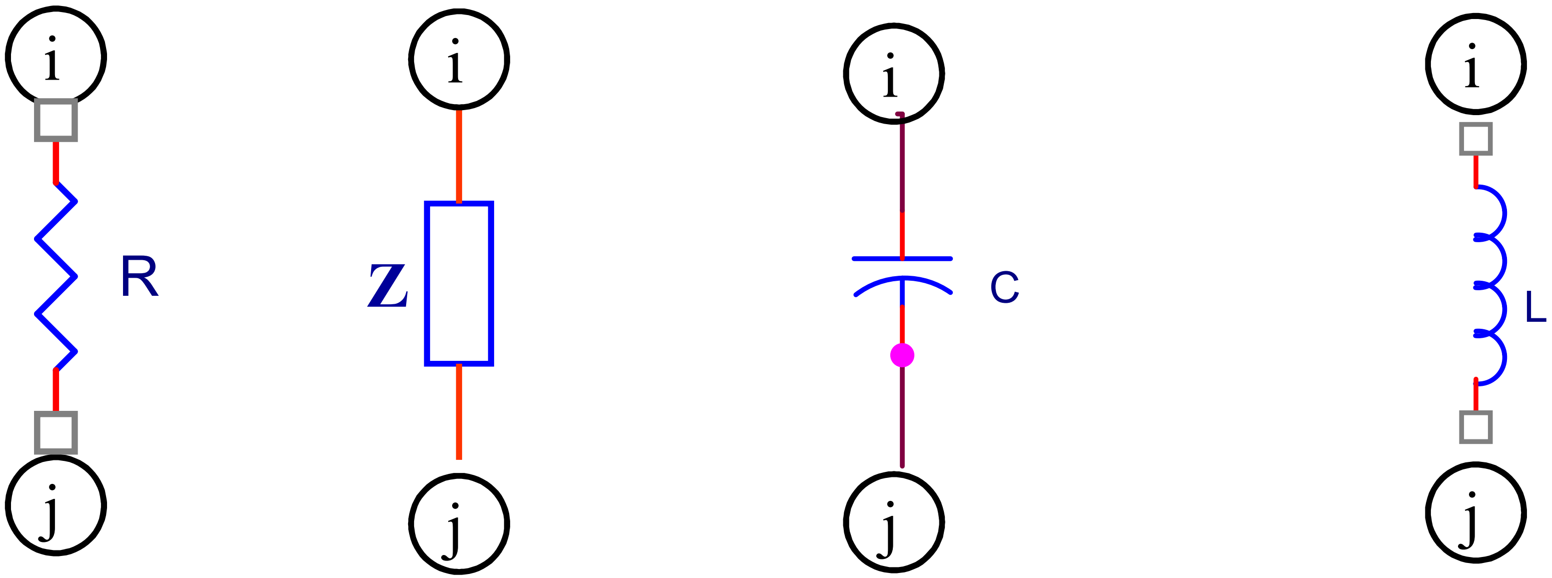


Za $\omega=10^6$rad/s

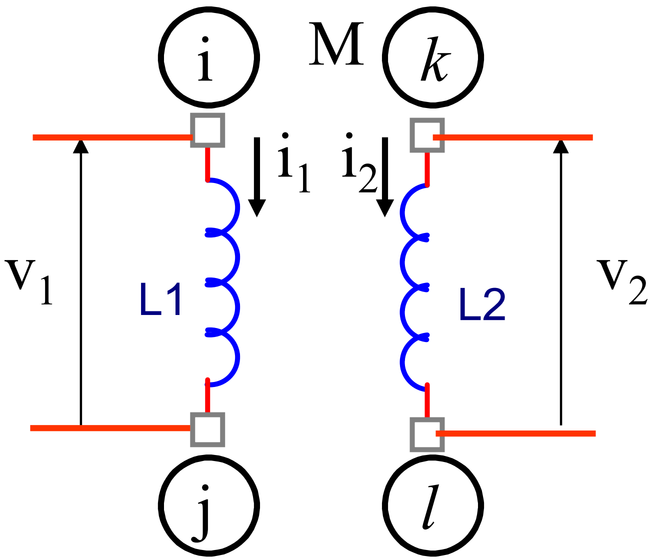
$$\begin{bmatrix} 0 & 0 & 10^{-3} & -10^{-3} \\ 0 & -(0) & -10^{-3} & 10^{-3} \\ 10^{-3} & -10^{-3} & 0 & 0 \\ -10^{-3} & 10^{-3} & 0 & (0) \end{bmatrix} \cdot \begin{bmatrix} v_{1i} \\ v_{2i} \\ v_{1r} \\ v_{2r} \end{bmatrix} = \begin{bmatrix} 10^{-3} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Postoji potpuna korespodencija sa elementima linearnih otpornih kola

$$\mathbf{Z_C=1/j\omega C} \qquad \mathbf{Z_L=j\omega L}$$

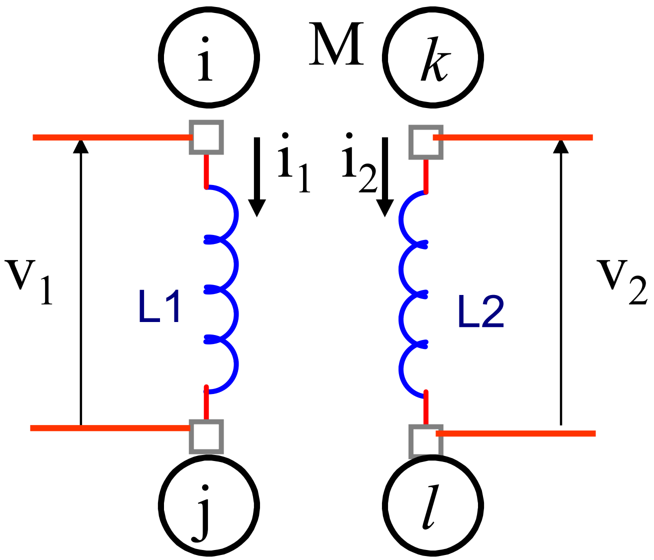


Spregnute induktivnosti



$$\mathbf{V_1} = \mathbf{j\omega L_1 i_1} + \mathbf{j\omega M i}_2$$
$$\mathbf{V}_2 = \mathbf{j\omega M i_1} + \mathbf{j\omega L_2 i}_2$$
$$\begin{bmatrix} \mathbf{V_1} \\ \mathbf{V_2} \end{bmatrix} = \begin{bmatrix} \mathbf{j\omega L_1} & \mathbf{j\omega M} \\ \mathbf{j\omega M} & \mathbf{j\omega L_2} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{i_1} \\ \mathbf{i_2} \end{bmatrix}$$

Spregnute induktivnosti

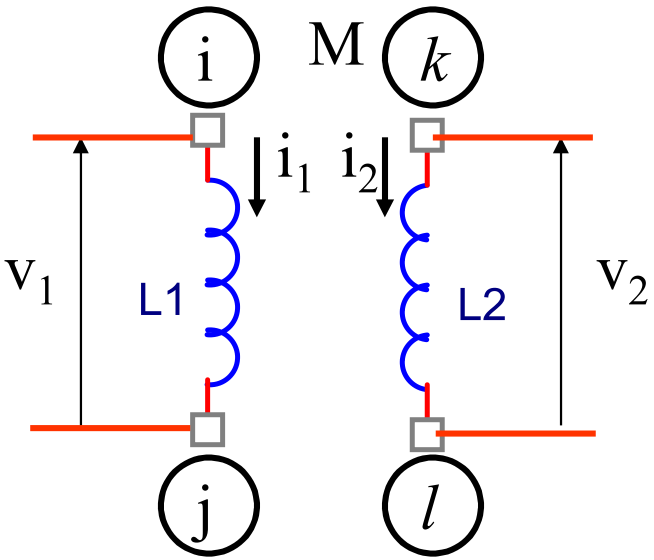


$$\begin{bmatrix} \mathbf{i_1} \\ \mathbf{i_2} \end{bmatrix} = \frac{1}{j\omega} \begin{bmatrix} \mathbf{L_1} & \mathbf{M} \\ \mathbf{M} & \mathbf{L_2} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \mathbf{V_1} \\ \mathbf{V_2} \end{bmatrix} =$$

$$\begin{bmatrix} \mathbf{i_1} \\ \mathbf{i_2} \end{bmatrix} = \frac{1}{j\omega(\mathbf{L_1 L_2} - \mathbf{M}^2)} \begin{bmatrix} \mathbf{L_2} & -\mathbf{M} \\ -\mathbf{M} & \mathbf{L_1} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{V_1} \\ \mathbf{V_2} \end{bmatrix}$$

Automatizacija formulacije jednačina

Spregnute induktivnosti



$$\mathbf{i}_1 = \frac{1}{\mathbf{j\omega L_{11}}}\mathbf{V}_1 - \frac{1}{\mathbf{Z}}\mathbf{V}_2$$

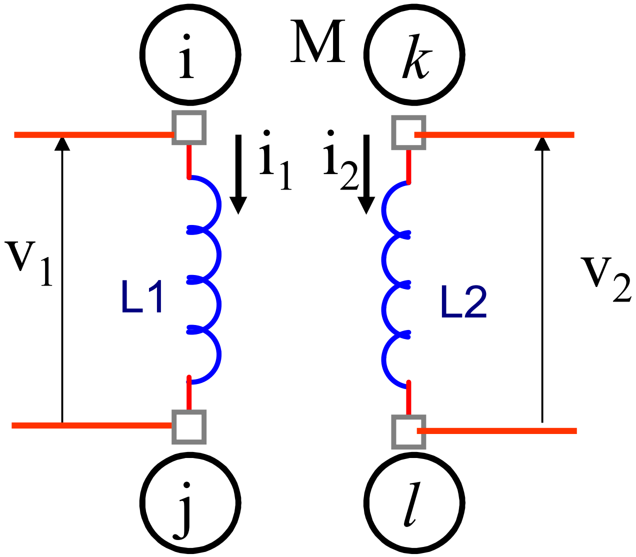
$$\mathbf{i}_2 = -\frac{1}{\mathbf{Z}}\mathbf{V}_1 + \frac{1}{\mathbf{j\omega L_{22}}}\mathbf{V}_2$$

$$\mathbf{L_{11}} = \frac{\mathbf{L_1L_2 - M}^2}{\mathbf{L_2}}$$

$$\mathbf{L_{22}} = \frac{\mathbf{L_1L_2 - M}^2}{\mathbf{L_1}}$$

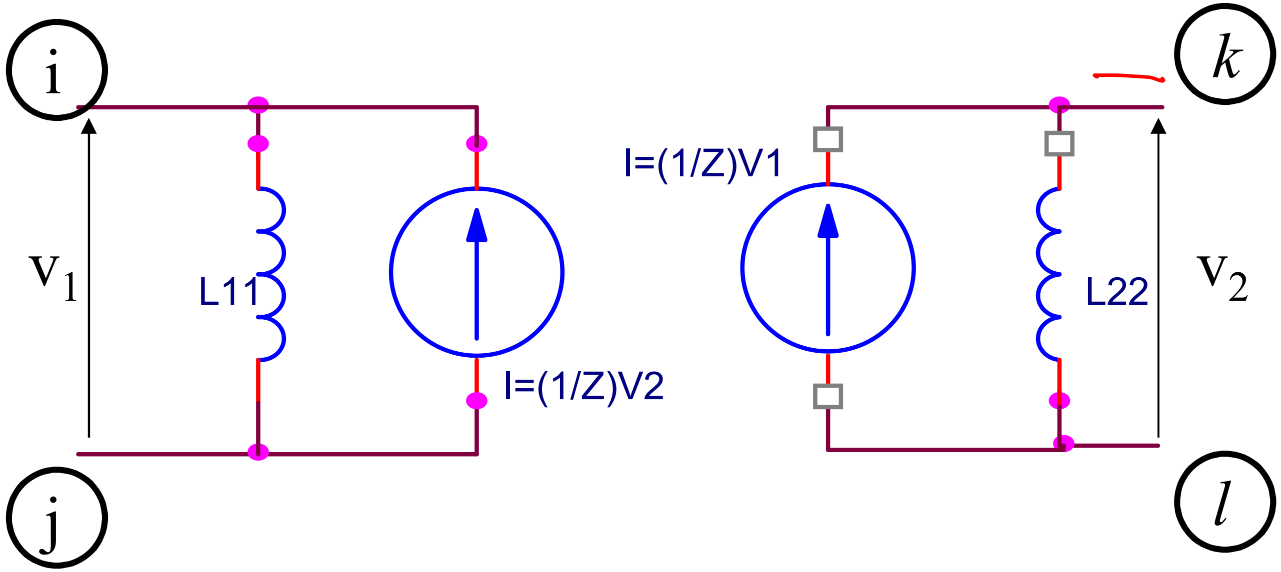
$$\mathbf{Z} = \mathbf{j\omega}\frac{\mathbf{L_1L_2 - M}^2}{\mathbf{M}}$$

Spregnute induktivnosti

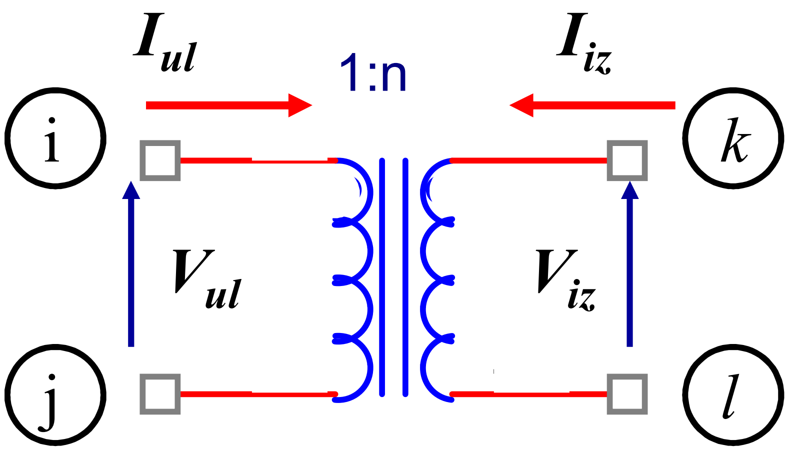


$$\mathbf{i}_1 = \frac{1}{\mathbf{j\omega L_{11}}}\mathbf{V}_1 - \frac{1}{\mathbf{Z}}\mathbf{V}_2$$

$$\mathbf{i}_2 = -\frac{1}{\mathbf{Z}}\mathbf{V}_1 + \frac{1}{\mathbf{j\omega L_{22}}}\mathbf{V}_2$$



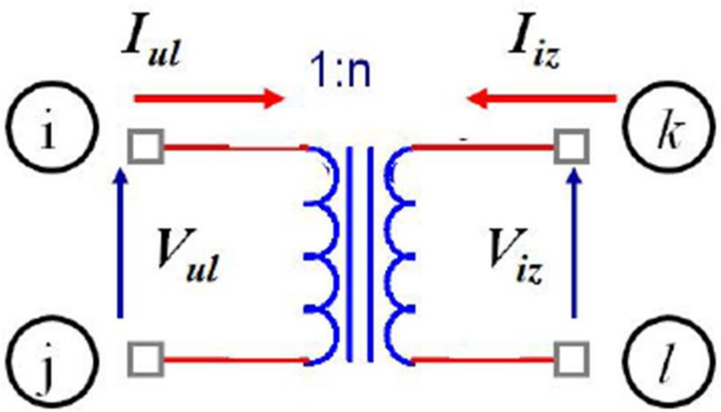
Transformator



$$I_{ul} = -nI_{iz}$$

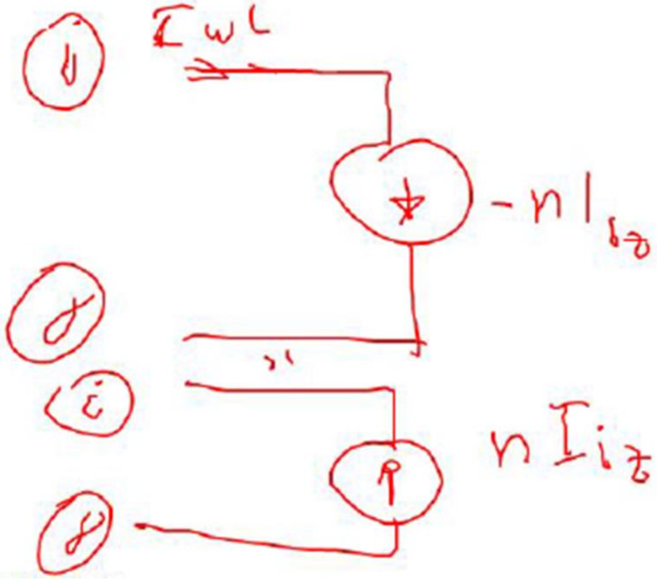
$$n(V_i - V_j) = V_k - V_l$$

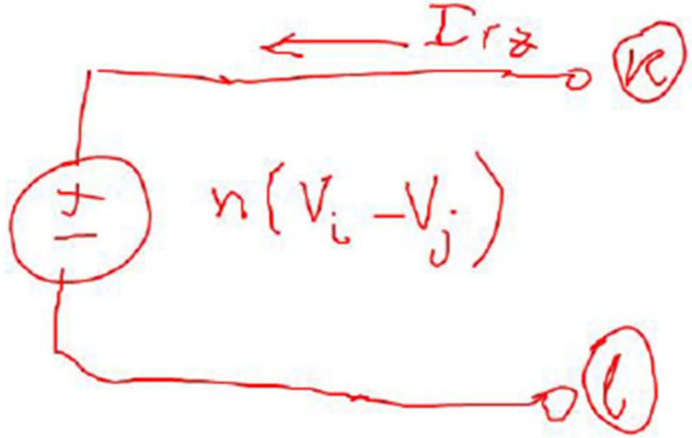
Transformator



$$I_{ul} = -nI_{iz}$$

$$n(V_i - V_j) = V_k - V_l$$





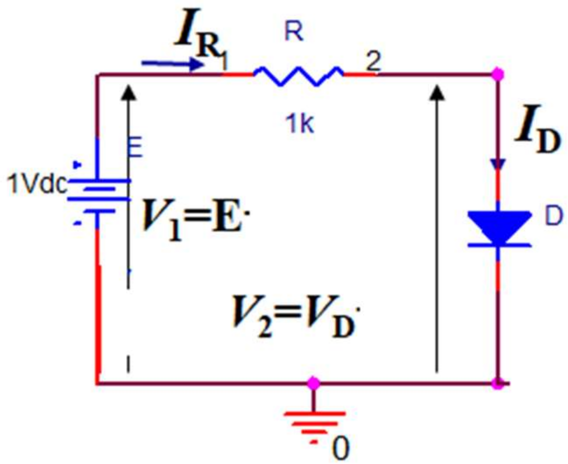
Kako se predstavljaju nelinearne komponente:

- Diode
- BJT
- MOST

pri AC analizi?

Predstavljaju se modelima za male signale (kako mali signal vidi nelinearnu karakteristiku)

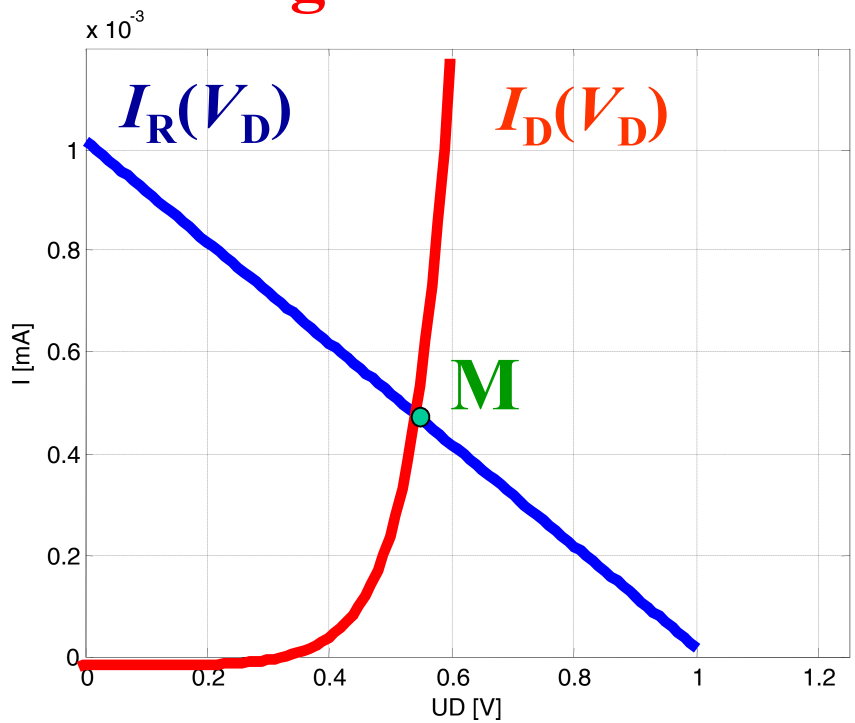
-Dioda u elektronskom kolu



Model diode – nelinearan – za velike signale

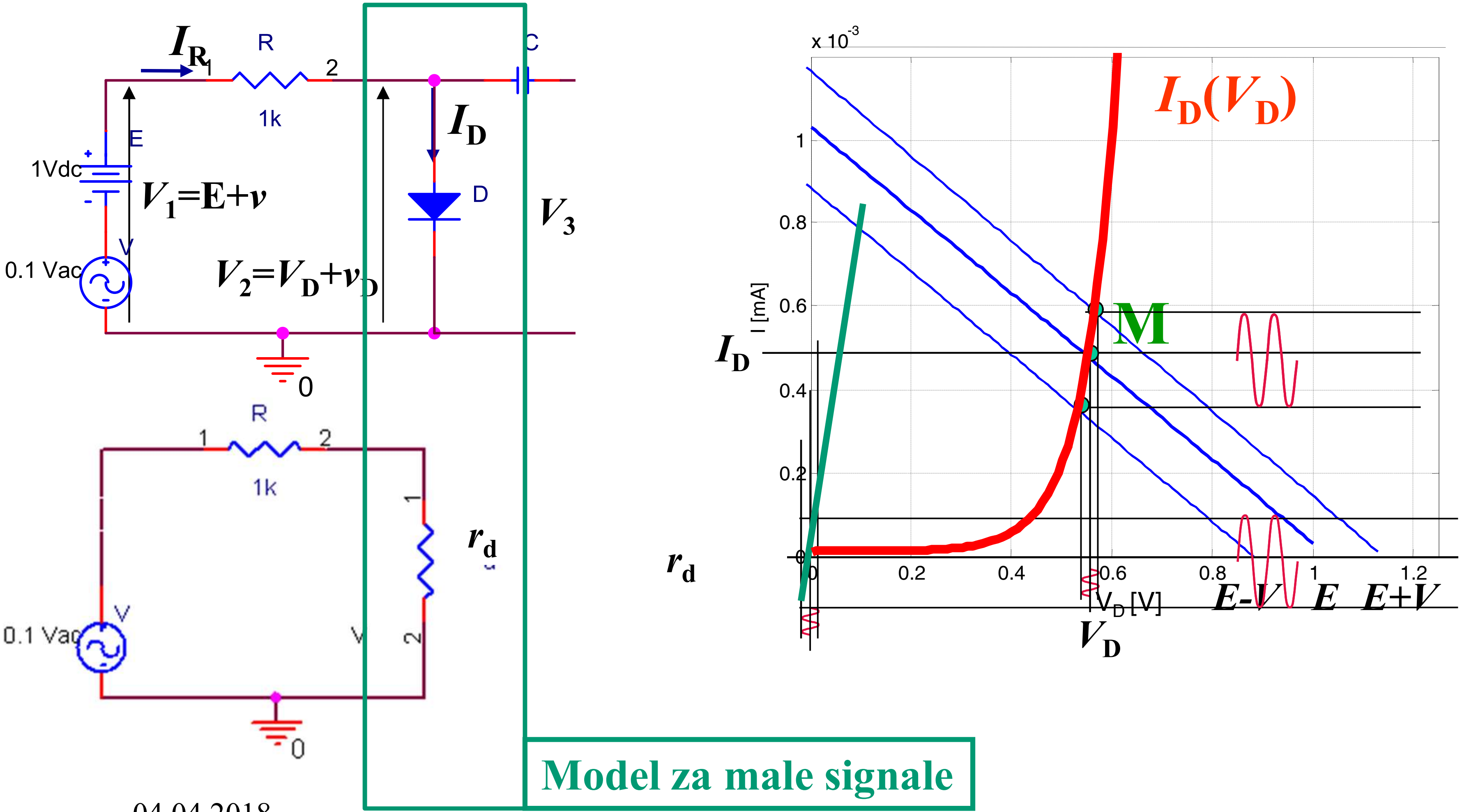
$$\boxed{\frac{\mathbf{E}-V_{\mathbf{D}}}{R}=I_{\mathbf{R}}}$$

$$\boxed{I_{\mathbf{D}}=\mathbf{I}_{\mathbf{S}}(\mathbf{e}^{\frac{V_{\mathbf{D}}}{\mathbf{V_T}}}-1)}$$

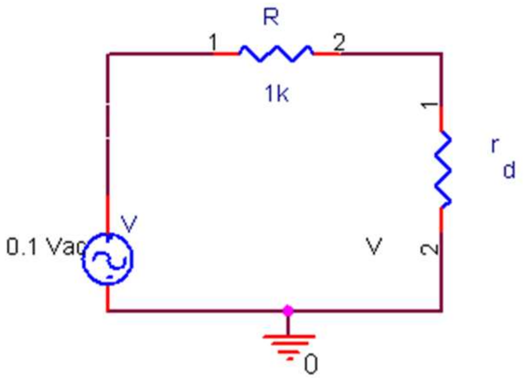


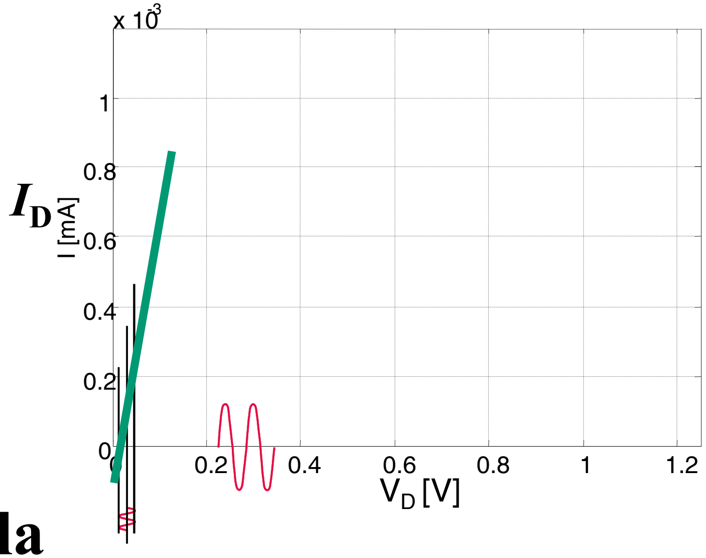
Dioda

-Dioda u elektronskom kolu   Grafička interpretacija problema



Dioda **VAŽNO model za male signale**





koristi se u analizi ponašanja kola pobuđenih malim naizmeničnim signalima.

$$r_d = \frac{dV_D}{dI_D} \approx \frac{\Delta V_D}{\Delta I_D}$$

Tada se svi elementi kola zamenjuju ***dinamičkim parametrima***

$$r_d = \frac{1}{\frac{dI_D}{dV_D}} \approx \frac{1}{\frac{\boxed{I_S e^{V_D/V_T}}}{V_T}}$$

Dinamički parametar diode jeste ***unutrašnja otpornost*** **diode u radnoj tački.**

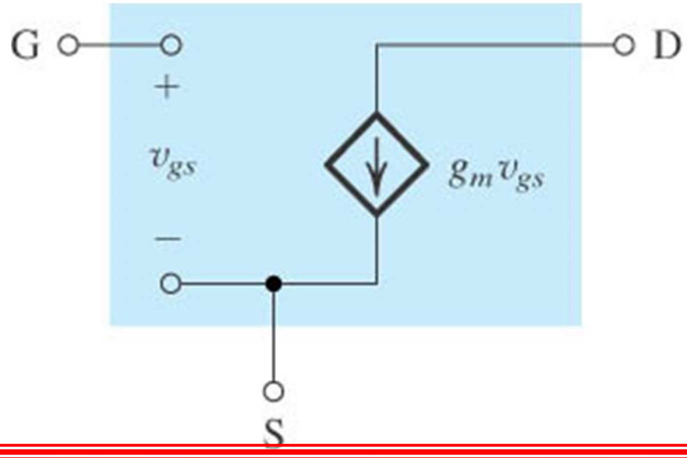
$$r_d \approx \frac{V_T}{\boxed{I_D}}$$

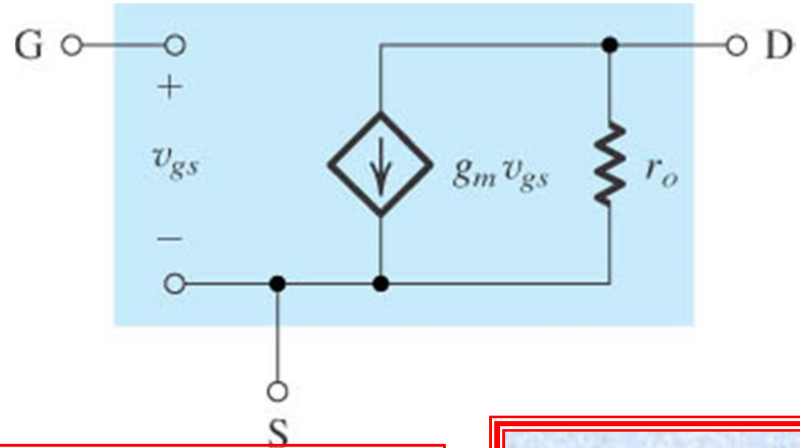
Dioda Spice model

Diode SPICE parameters

Symbol	Name	Parameter	Units	Default
I_S	IS	Saturation current (diode equation)	A	1E-14
R_S	RS	Parsitic resistance (series resistance)	Ω	0
n	N	Emission coefficient, 1 to 2	-	1
τ_D	TT	Transit time	s	0
$C_D(0)$	CJO	Zero-bias junction capacitance	F	0
φ_0	VJ	Junction potential	V	1
m	M	Junction grading coefficient	-	0.5
-	-	0.33 for linearly graded junction	-	-
-	-	0.5 for abrupt junction	-	-
E_g	EG	Activation energy:	eV	1.11
-	-	Si: 1.11	-	-
-	-	Ge: 0.67	-	-
-	-	Schottky: 0.69	-	-
p_i	XTI	IS temperature exponent	-	3.0
-	-	pn junction: 3.0	-	-
-	-	Schottky: 2.0	-	-
k_f	KF	Flicker noise coefficient	-	0
a_f	AF	Flicker noise exponent	-	1
FC	FC	Forward bias depletion capacitance coefficient	-	0.5
BV	BV	Reverse breakdown voltage	V	∞
IBV	IBV	Reverse breakdown current	A	1E-3

Model MOS tranzistora za male signale





$$g_m = \mu_n C'_{ox} \frac{W}{L}(V_{GS} - V_t) = \frac{2I_D}{(V_{GS} - V_t)} = \frac{2I_D}{V_{OV}}$$

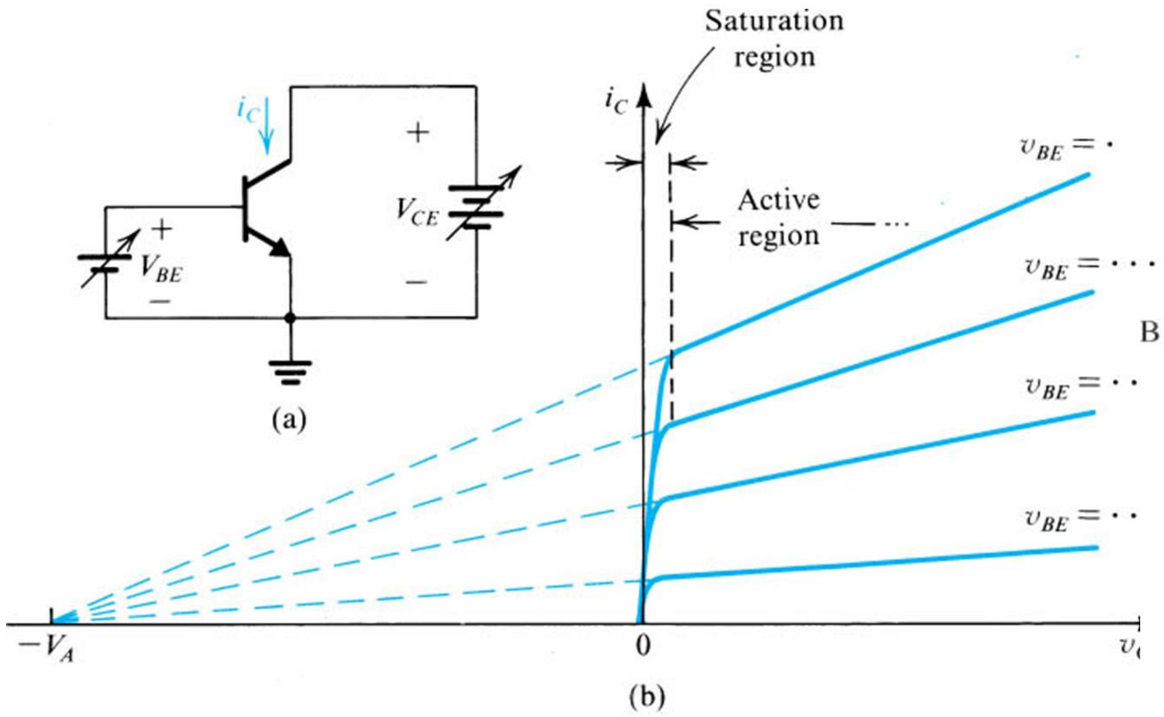
$$r_0 = \frac{V_A}{I_D}$$

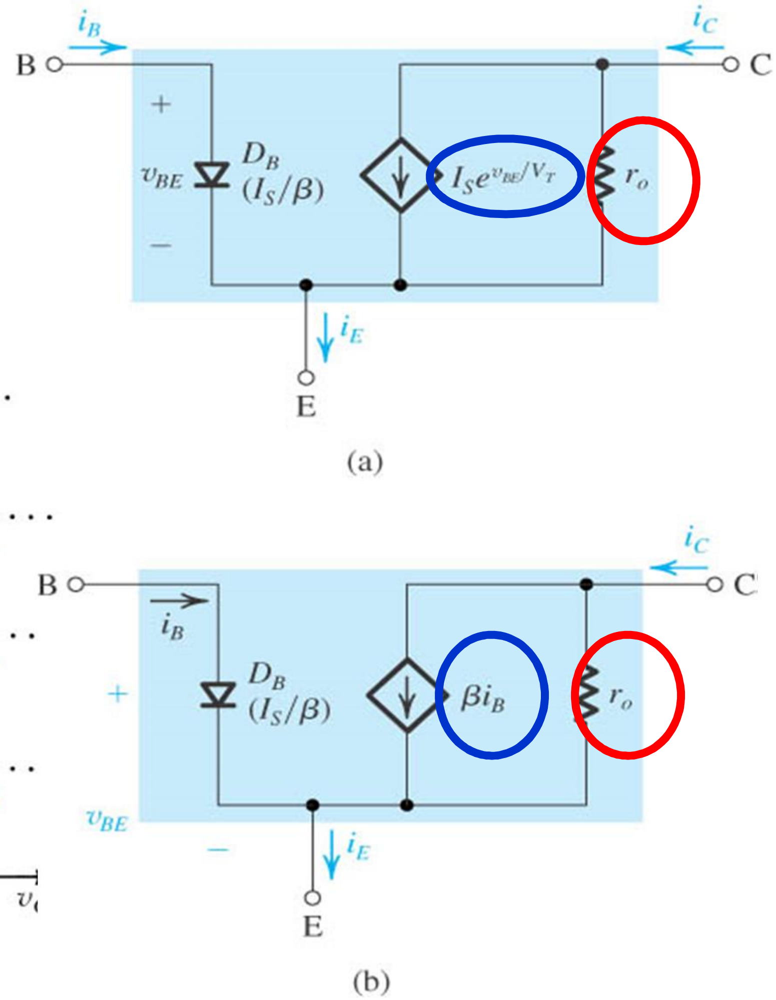
$$\left(g_m r_o \equiv \mu = \frac{\partial I_D}{\partial V_{GS}} \frac{\partial V_{DS}}{\partial I_D} = \frac{\partial V_{DS}}{\partial V_{GS}} = \frac{2V_A}{(V_{GS} - V_t)} \right) \quad (r_o \equiv R_i)$$

MOS tranzistor Spice model

04.04.2018.

Tranzistor


i_C
V_{BE}
V_{CE}
(a)
Saturation region
Active region
$v_{BE} = \cdot$
$v_{BE} = \cdots$
$-V_A$
0
(b)


i_B
i_C
B
C
v_{BE}
D_B
(I_S/β)
$I_S e^{v_{BE}/V_T}$
r_o
i_E
E
(a)
βi_B
(b)

BJT Spice model

Pri AC analizi sve komponente se zamenjuju linearnim modelima!

– AC podrazumeva analizu LINEARNIH kola
– Sadrže reaktivne komponente (L i C)

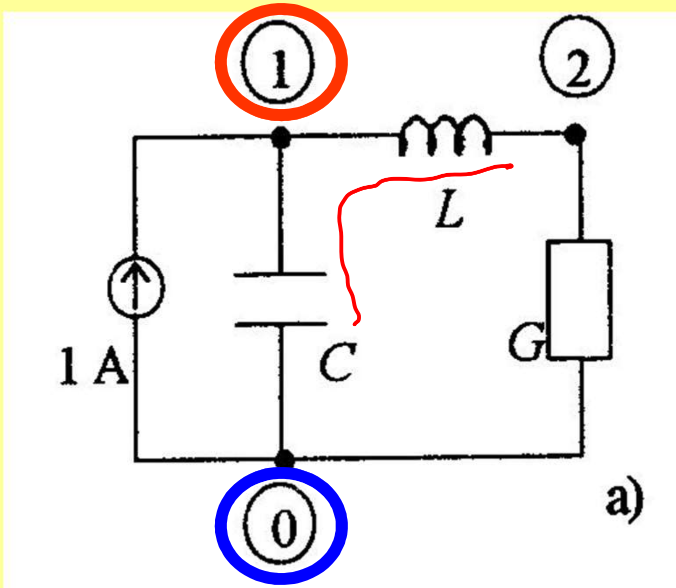
Njih opisuje sistem linearnih algebarskih jednačina sa kompleksnim koeficijentima.

Rešavaju se LU faktorizacijom (Gaus)

Izazovi i specifičnosti AC analize?

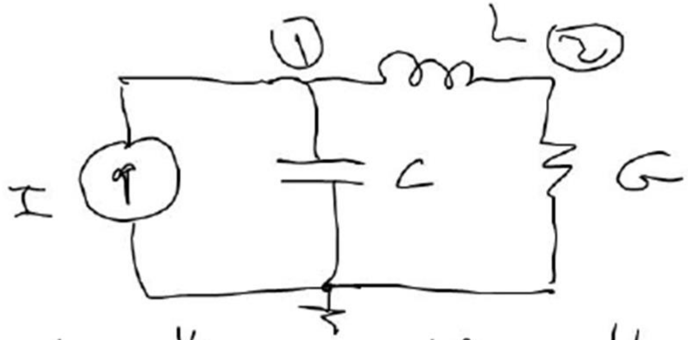
Izazovi i specifičnosti AC analize?

Primer



$$\begin{bmatrix} j\omega C - j\frac{1}{\omega L} & j\frac{1}{\omega L} \\ j\frac{1}{\omega L} & G - j\frac{1}{\omega L} \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

Izazovi i specifičnosti AC analize?



	V_1	V_2	
1	$j\omega C + \frac{j}{\omega L}$	$+\frac{j}{j\omega L}$	I
2	$+j/\omega L$	$-\frac{j}{\omega L} + G$	

$$Y_l = \begin{bmatrix} j\omega C - \frac{j}{\omega L} & +\frac{j}{\omega L} \\ j/\omega L & -\frac{j}{\omega L} \end{bmatrix}$$

$$Y_r = \begin{bmatrix} 0 & 0 \\ 0 & G \end{bmatrix}$$

$$\omega = \omega_0 = \frac{1}{\sqrt{LC}}$$

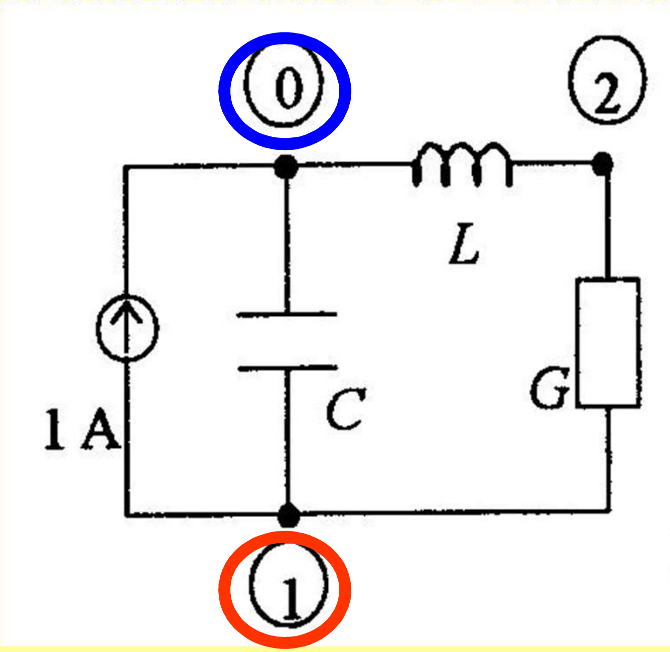
$$V_C = V_1$$

$$V_L = V_1 - V_2$$

$$V_G = V_2$$

Izazovi i specifičnosti AC analize?

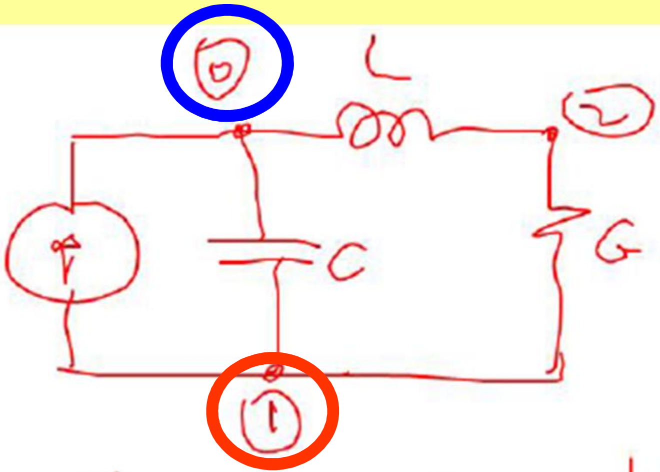
Primer



$$\begin{bmatrix} j\omega \cdot C + G & -G \\ -G & G - \dfrac{j}{\omega \cdot L} \end{bmatrix} \begin{bmatrix} \overline{V_1} \\ \overline{V_2} \end{bmatrix} = \begin{bmatrix} -\bar{I} \\ 0 \end{bmatrix}$$

Izazovi i specifičnosti AC analize?

Primer



$V_G = V_2 - V_1$

$V_L = -V_2$

$V_C = -V_1$

	V_1	V_2	
1	$j\omega C + G$	$-G$	$-I$
2	$-G$	$-\frac{j}{\omega L} + G$	

Karakteristike analize u AC domenu:

Analiza od f_d do f_g

Voditi računa o veličini koraka i veličini propusnog opsega kola koje se analizira.

Svi modeli poluprovodničkih komponenata su linearni i malosignalni. U Spice-u uvek se najpre obavi DC analiza, da bi se odredio položaj radne tačke, a zatim se izračunavaju parametri modela.

Izbor koraka frekvencije

Logaritamska skala

Broj tačaka po dekadi/oktavi

Linearna skala

$$\Delta_f=(f_g-f_d)/N$$

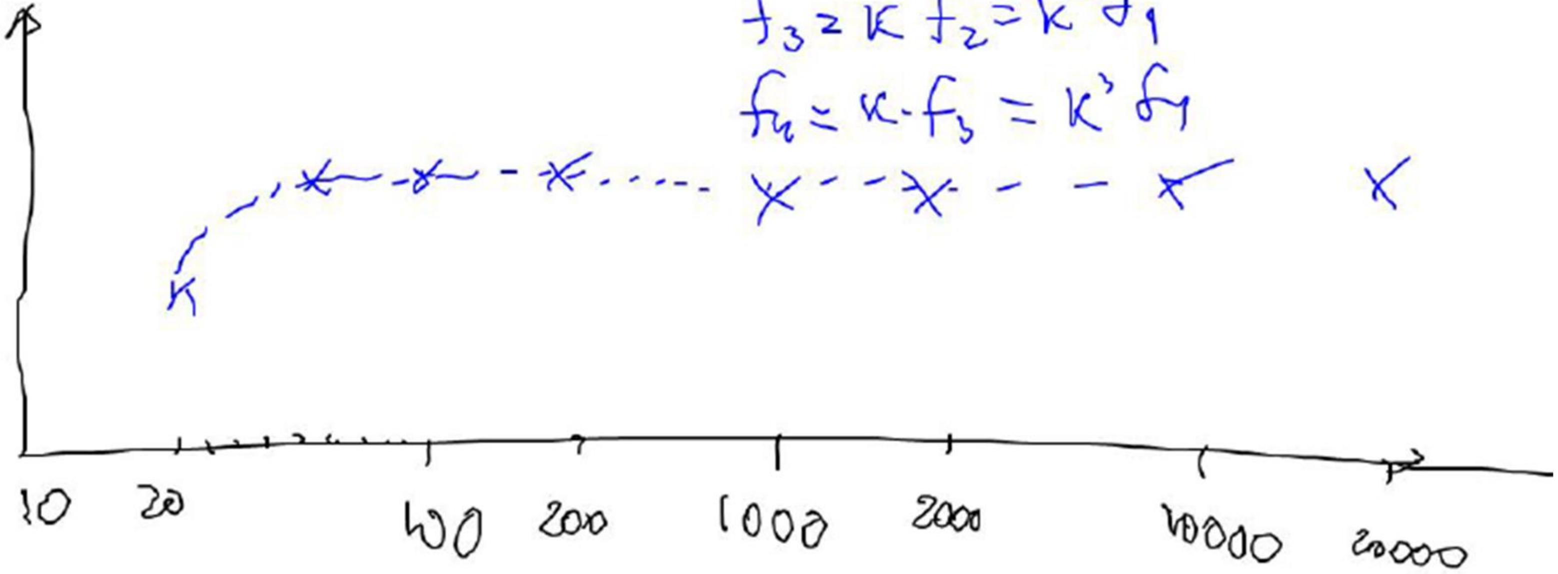
$f_d = 20\,Hz$

$f_g = 20\,kHz$

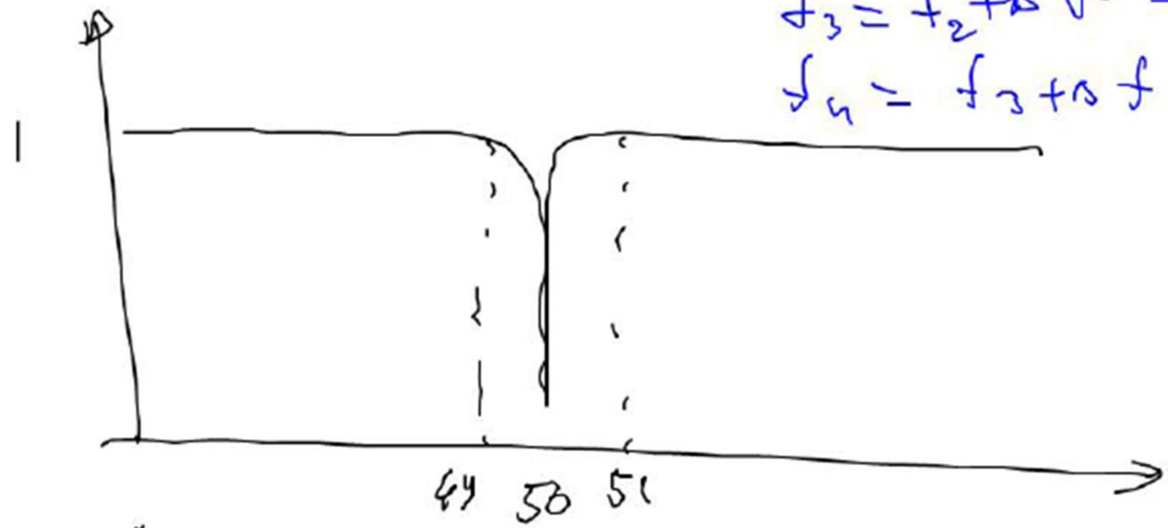
$f_2 = k \cdot f_1$

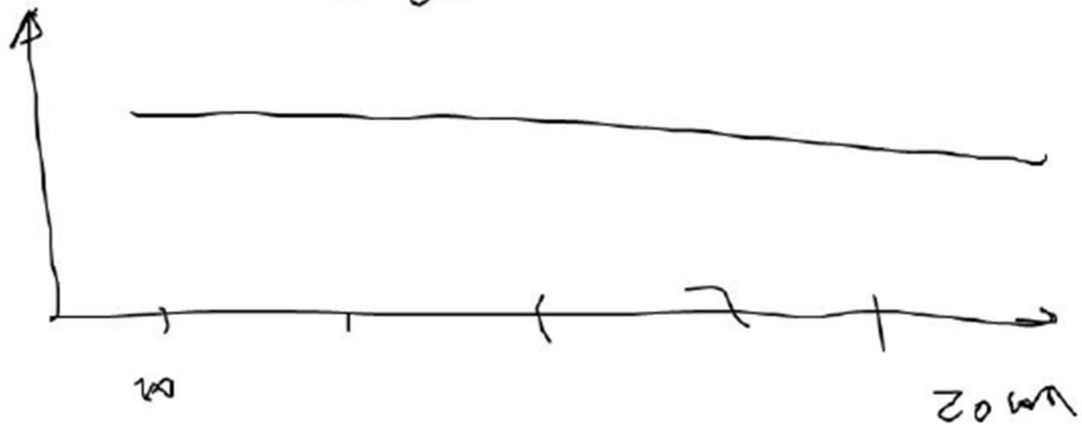
$f_3 = k\, f_2 = k^2 f_1$

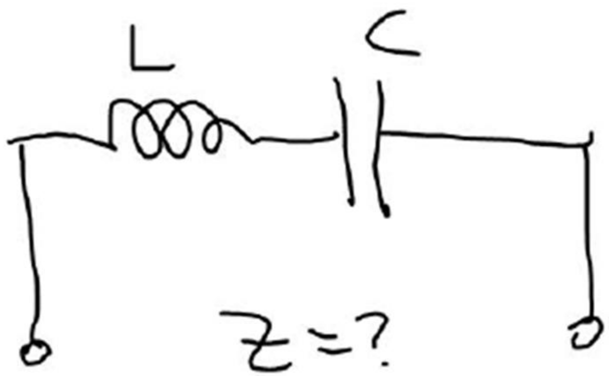
$f_4 = k \cdot f_3 = k^3 f_1$



$$f_2 = f_1 + \Delta f$$
$$f_3 = f_2 + \Delta f = f_1 + 2\Delta f$$
$$f_4 = f_3 + \Delta f = f_1 + 3\Delta f$$



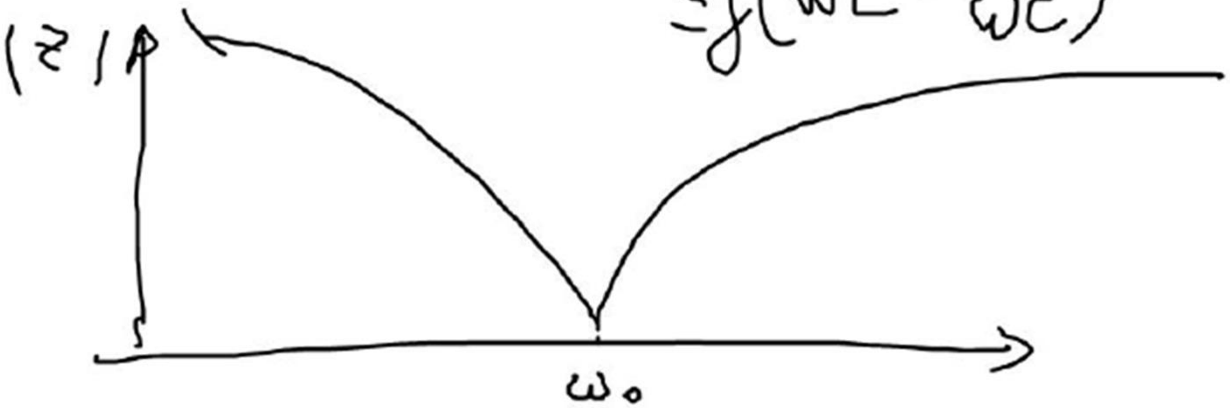




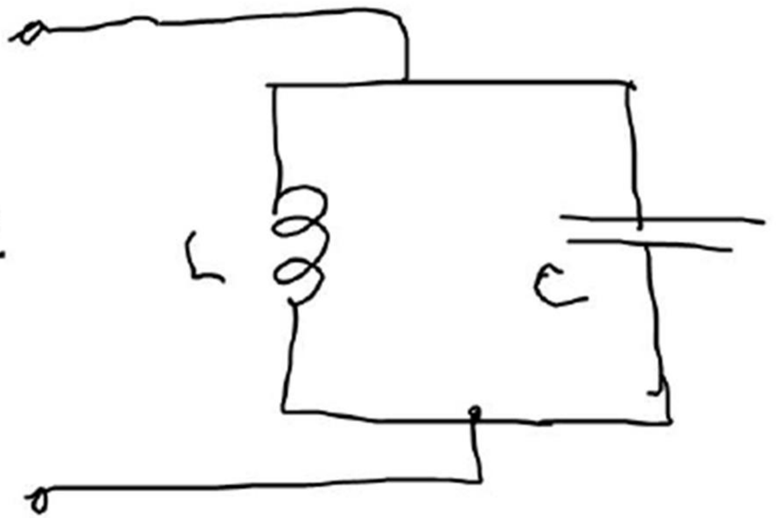
$$\boxed{\begin{aligned} \omega_0 L &= \frac{1}{\omega_0 C} \\ \omega_0 &= \frac{1}{\sqrt{LC}} \end{aligned}}$$

$$Z = j\omega L + \frac{1}{j\omega C} = j\omega L - j\frac{1}{\omega C} =$$

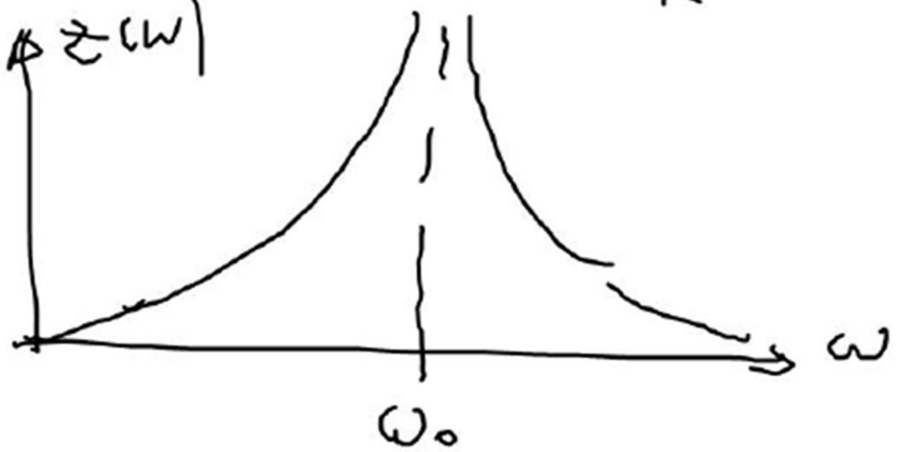
$$= j\left(\omega L - \frac{1}{\omega C}\right)$$



$Z \rightarrow ?$

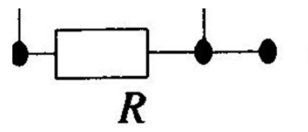


$$Z = \frac{Z_L \cdot Z_C}{Z_L + Z_C} = \frac{j\omega L \,\frac{1}{j\omega C}}{j\omega L - j\,\frac{1}{\omega C}} = \frac{\frac{L}{C}}{j\left(\omega L - \frac{1}{\omega C}\right)}$$

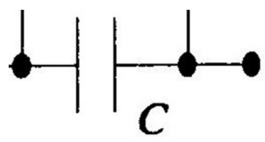


Analiza VF kola - parazitni efekti

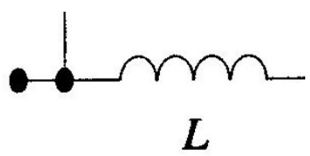
R



C

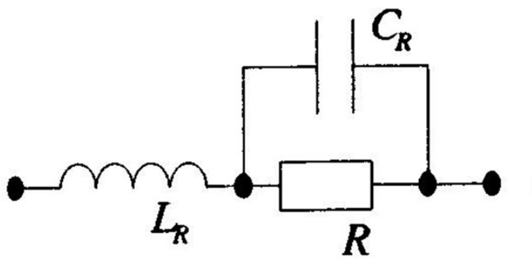


L

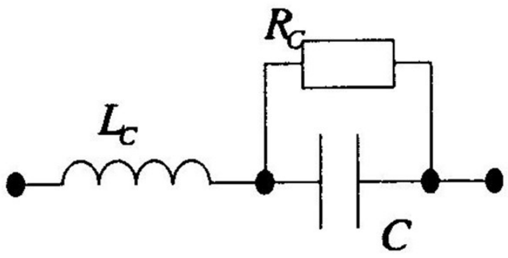


Analiza VF kola - parazitni efekti

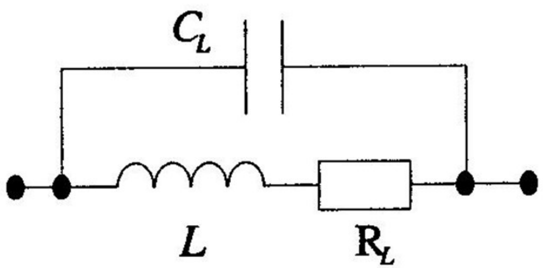
R

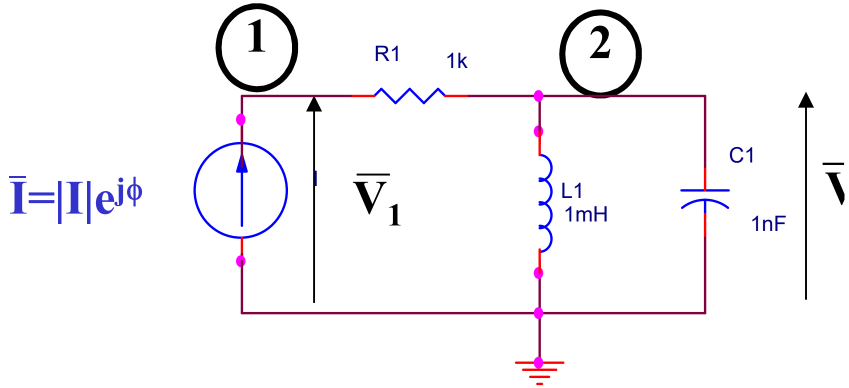


C



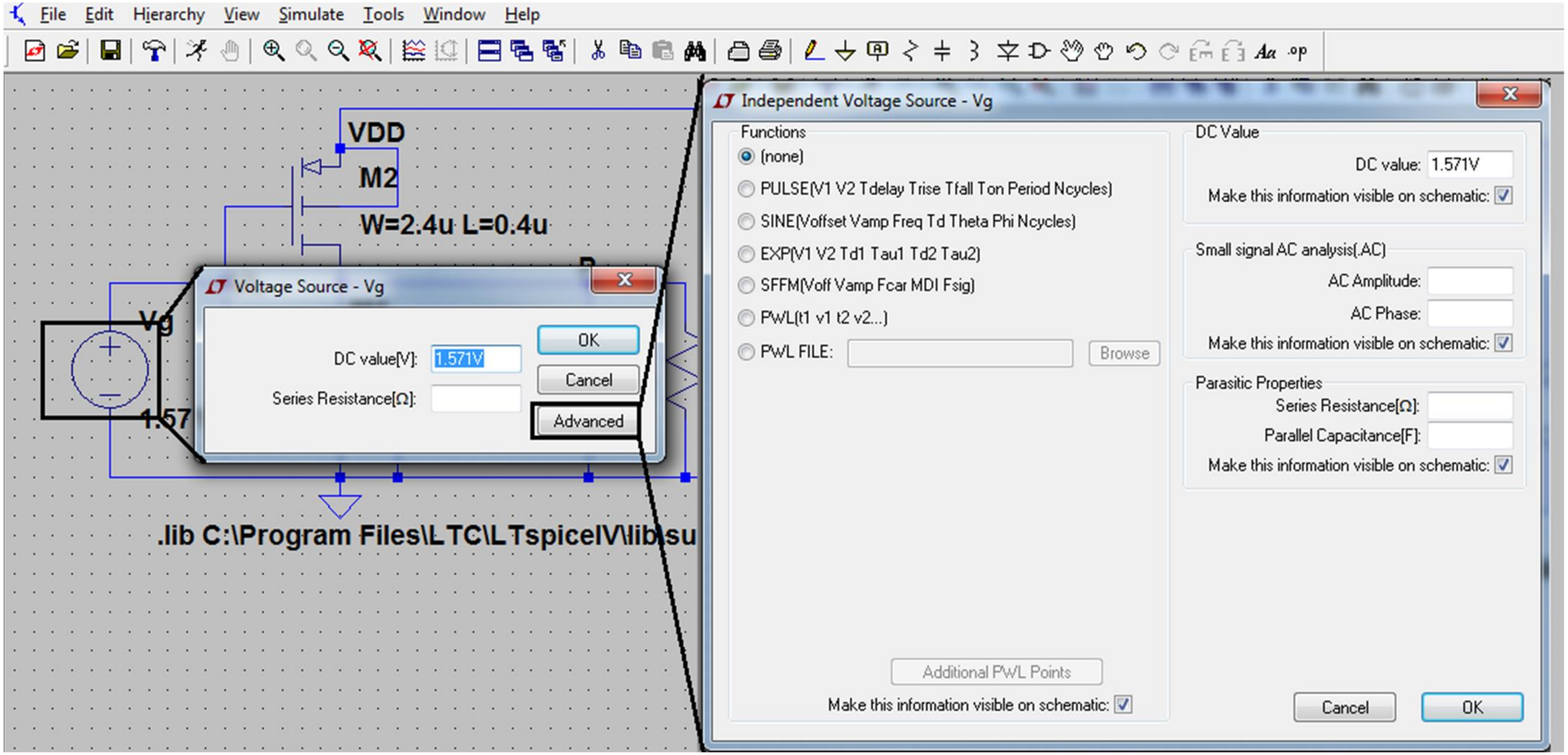
L



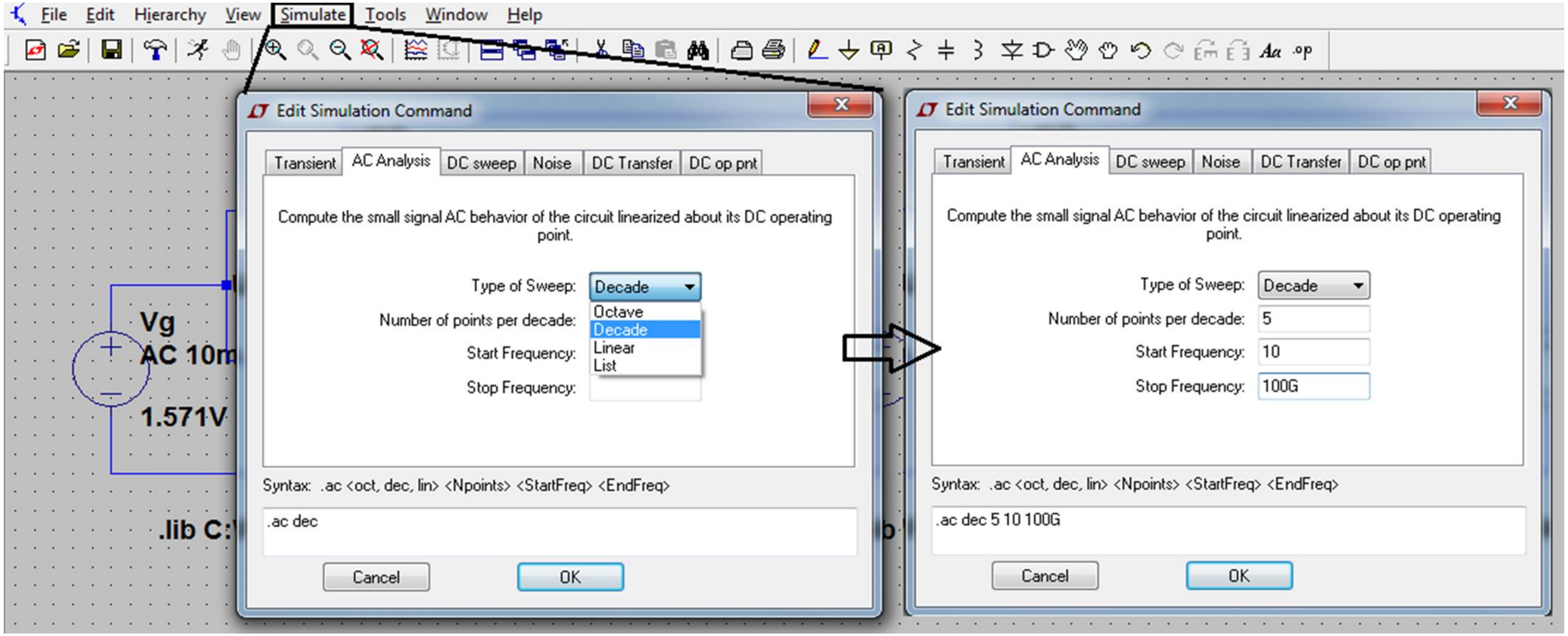


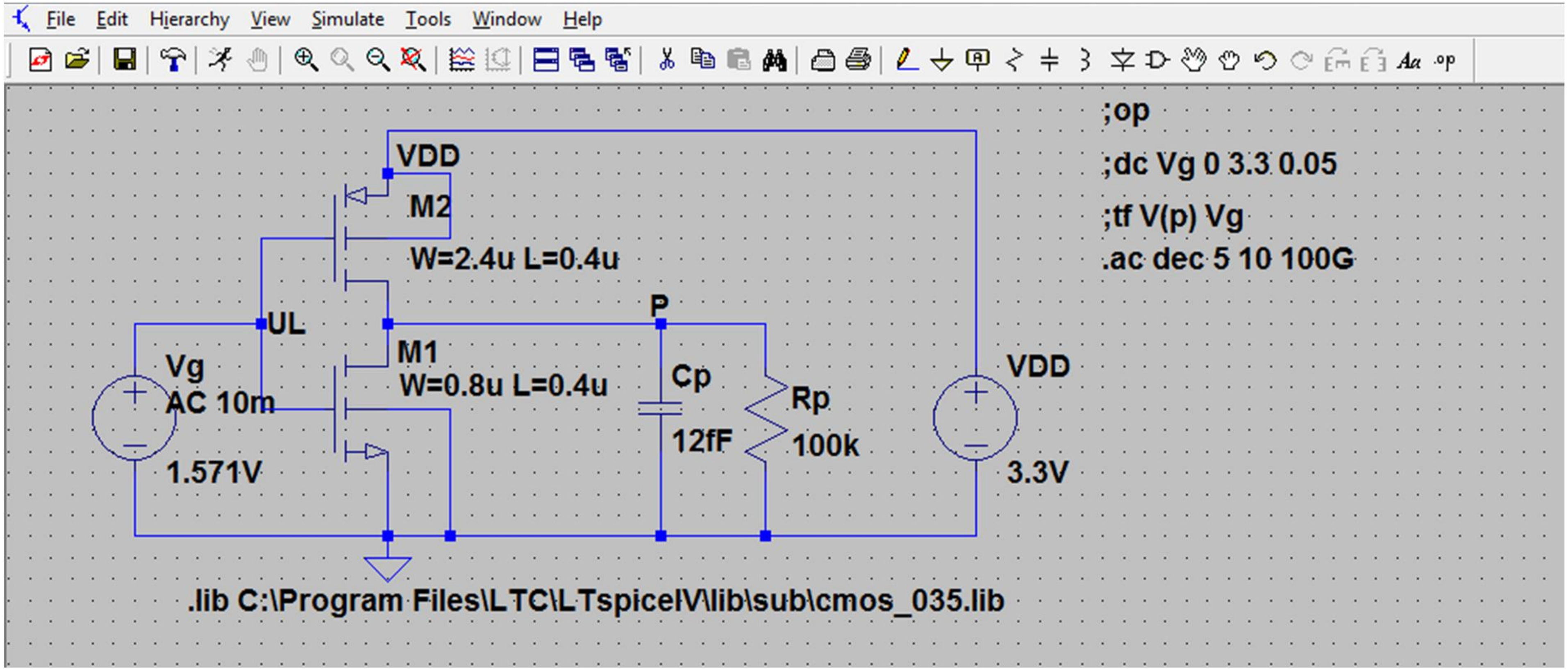
Spice:
Koje parametre treba zadati da bi se kolo analiziralo u AC domenu?

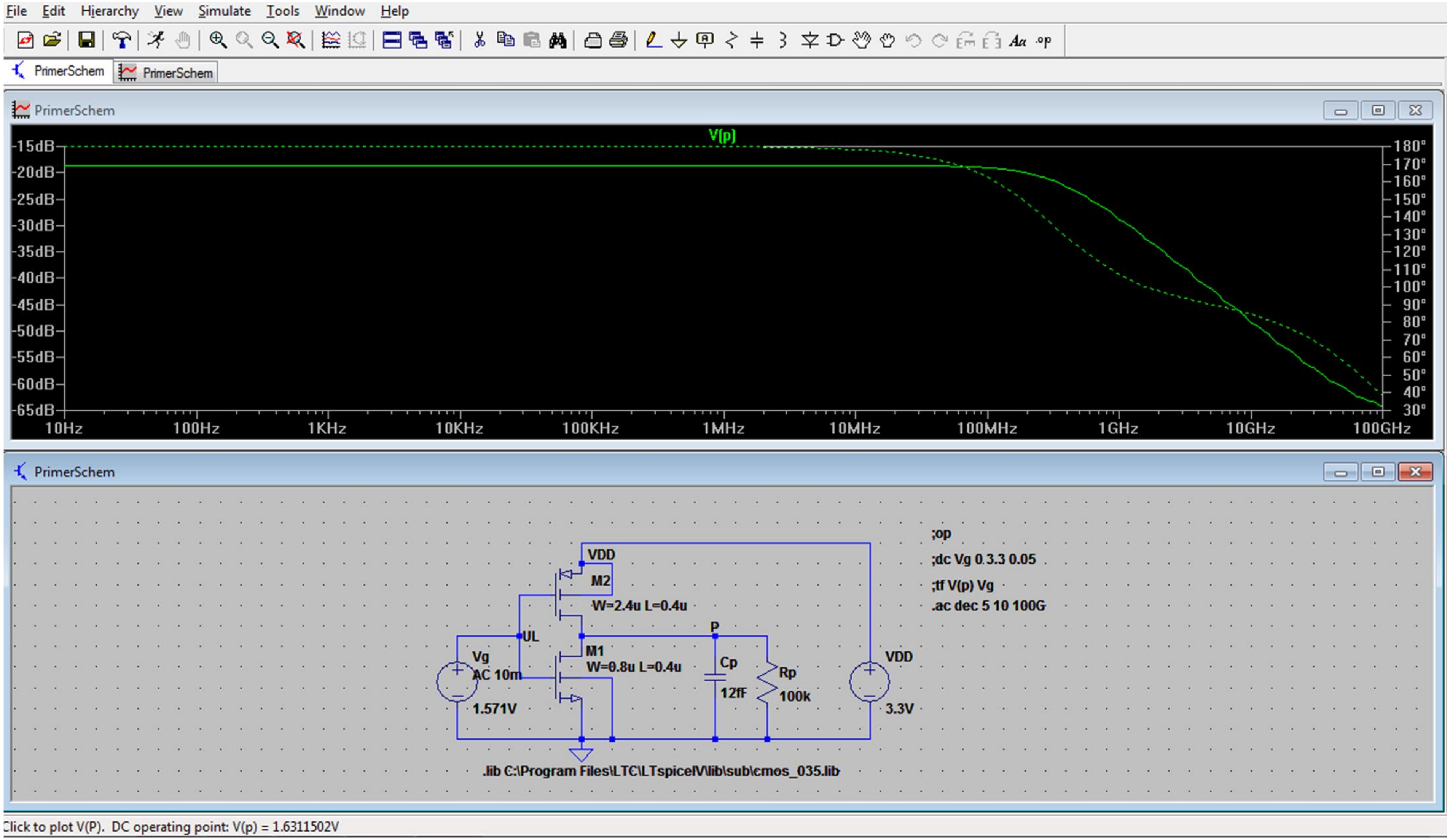
- Tip analize: AC
- Parametri generatora: magnituda i faza
- Donja granična frekvencija
- Gornja granična frekvencija
- Broj tačaka:
  - Linearno
  - Logaritamski
  - (po dekadi)
  - (po oktavi)

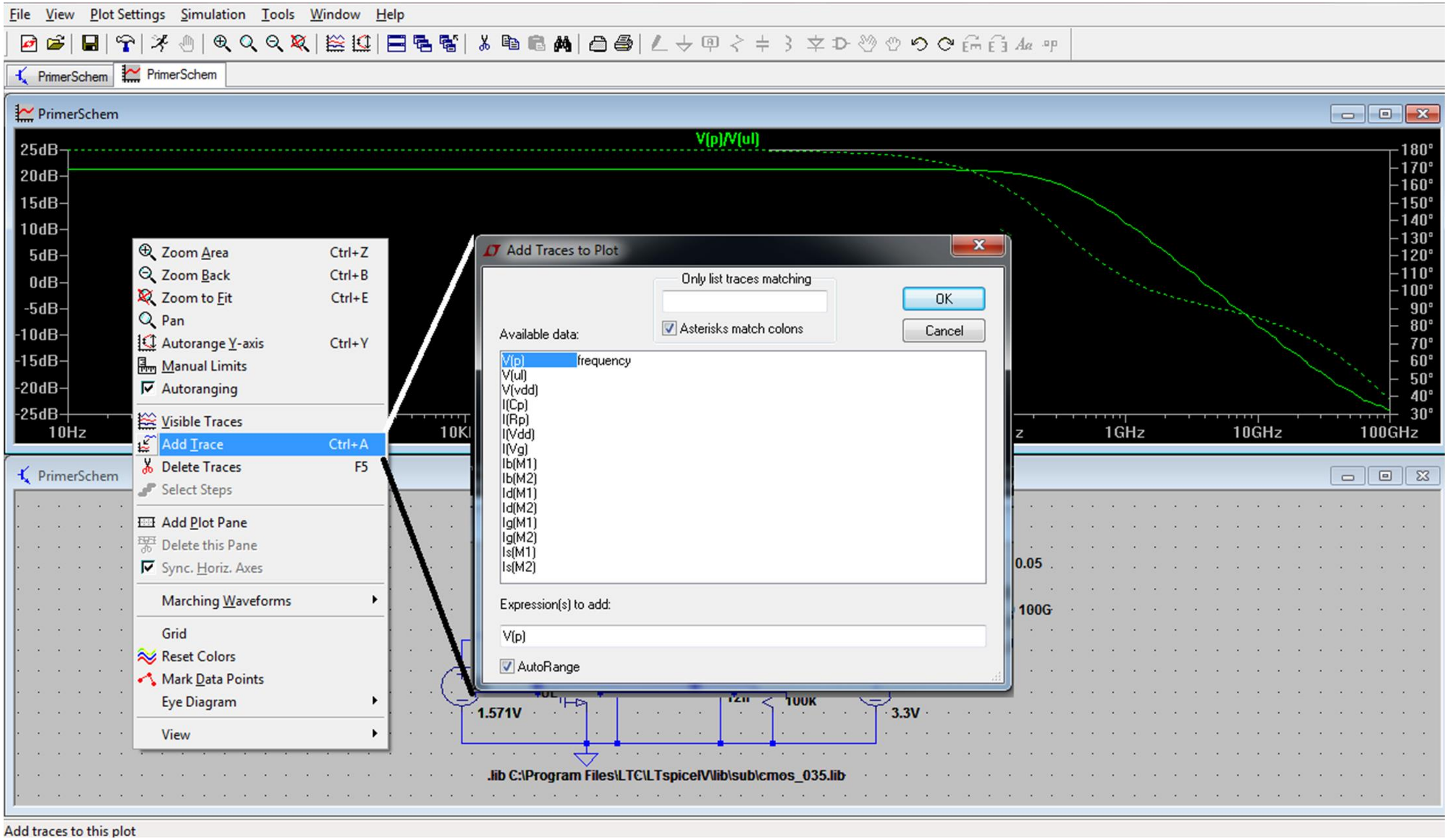


File Edit Hierarchy View Simulate Tools Window Help
VDD
M2
W=2.4u L=0.4u
Vg
1.57
.lib C:\Program Files\LTC\LTspiceIV\lib\su
Voltage Source - Vg
DC value[V]: 1.571V
Series Resistance[Ω]:
OK
Cancel
Advanced
Independent Voltage Source - Vg
Functions
(none)
PULSE(V1 V2 Tdelay Trise Tfall Ton Period Ncycles)
SINE(Voffset Vamp Freq Td Theta Phi Ncycles)
EXP(V1 V2 Td1 Tau1 Td2 Tau2)
SFFM(Voff Vamp Fcar MDI Fsig)
PWL(t1 v1 t2 v2...)
PWL FILE:
Browse
Additional PWL Points
Make this information visible on schematic:
DC Value
DC value: 1.571V
Make this information visible on schematic:
Small signal AC analysis(.AC)
AC Amplitude:
AC Phase:
Make this information visible on schematic:
Parasitic Properties
Series Resistance[Ω]:
Parallel Capacitance[F]:
Make this information visible on schematic:
Cancel
OK

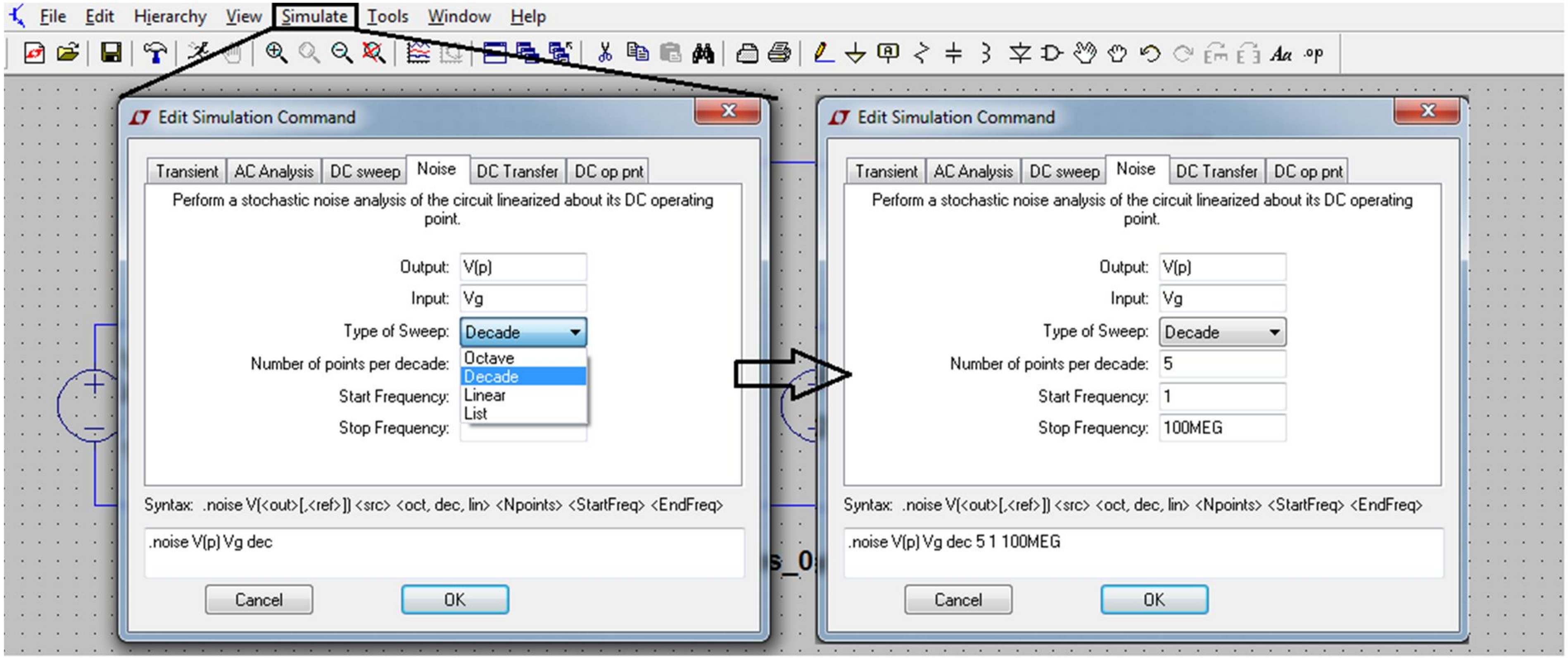

File Edit Hierarchy View Simulate Tools Window Help
Edit Simulation Command
Transient AC Analysis DC sweep Noise DC Transfer DC op pnt
Compute the small signal AC behavior of the circuit linearized about its DC operating point.
Type of Sweep: Decade
Octave
Decade
Linear
List
Number of points per decade:
Start Frequency:
Stop Frequency:
Syntax: .ac <oct, dec, lin> <Npoints> <StartFreq> <EndFreq>
.ac dec
Cancel
OK
Vg
AC 10m
1.571V
.lib C:
Edit Simulation Command
Transient AC Analysis DC sweep Noise DC Transfer DC op pnt
Compute the small signal AC behavior of the circuit linearized about its DC operating point.
Type of Sweep: Decade
Number of points per decade: 5
Start Frequency: 10
Stop Frequency: 100G
Syntax: .ac <oct, dec, lin> <Npoints> <StartFreq> <EndFreq>
.ac dec 5 10 100G
Cancel
OK

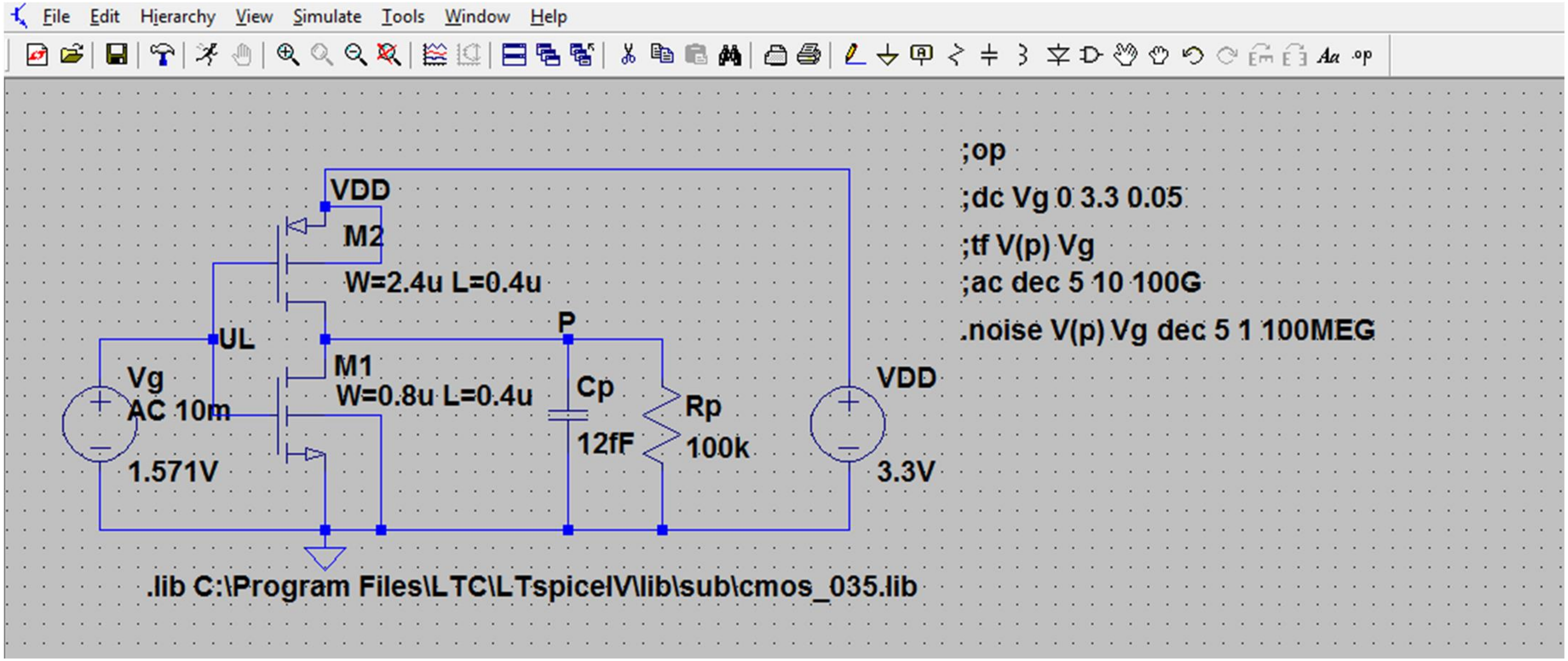

File Edit Hierarchy View Simulate Tools Window Help
;op
;dc Vg 0 3.3 0.05
;tf V(p) Vg
.ac dec 5 10 100G
VDD
M2
W=2.4u L=0.4u
P
UL
M1
W=0.8u L=0.4u
Vg
AC 10m
1.571V
Cp
12fF
Rp
100k
VDD
3.3V
.lib C:\Program Files\LTC\LTspiceIV\lib\sub\cmos_035.lib

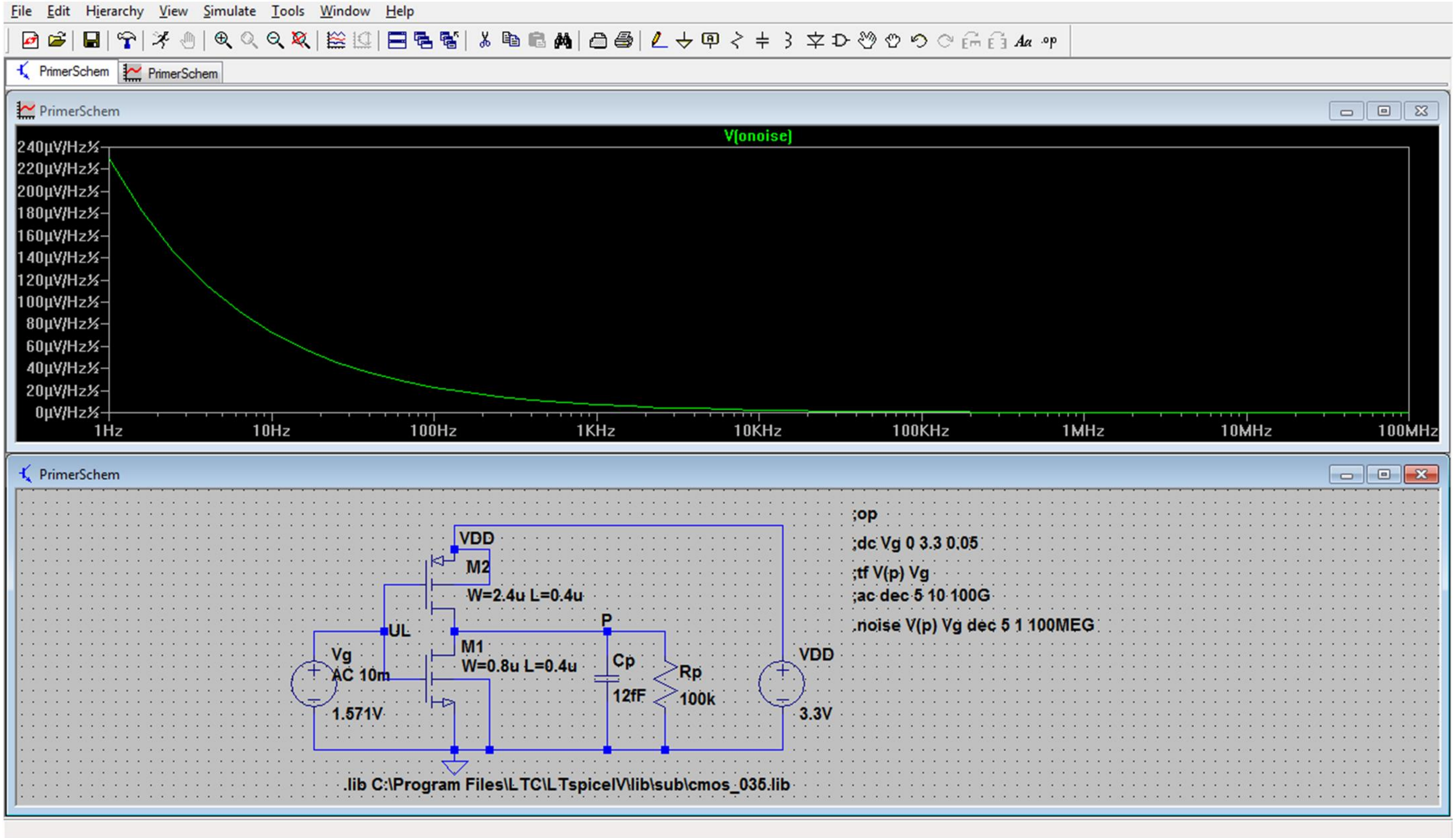

File Edit Hierarchy View Simulate Tools Window Help
PrimerSchem
PrimerSchem
V(p)
-15dB
-20dB
-25dB
-30dB
-35dB
-40dB
-45dB
-50dB
-55dB
-60dB
-65dB
180°
170°
160°
150°
140°
130°
120°
110°
100°
90°
80°
70°
60°
50°
40°
30°
10Hz
100Hz
1KHz
10KHz
100KHz
1MHz
10MHz
100MHz
1GHz
10GHz
100GHz
VDD
M2
W=2.4u L=0.4u
P
UL
M1
W=0.8u L=0.4u
Vg
AC 10m
1.571V
Cp
12fF
Rp
100k
VDD
3.3V
;op
;dc Vg 0 3.3 0.05
;tf V(p) Vg
.ac dec 5 10 100G
.lib C:\Program Files\LTC\LTspiceIV\lib\sub\cmos_035.lib
Click to plot V(P). DC operating point: V(p) = 1.6311502V



File View Plot Settings Simulation Tools Window Help
PrimerSchem
V(p)/V(ul)
Zoom Area Ctrl+Z
Zoom Back Ctrl+B
Zoom to Fit Ctrl+E
Pan
Autorange Y-axis Ctrl+Y
Manual Limits
Autoranging
Visible Traces
Add Trace Ctrl+A
Delete Traces F5
Select Steps
Add Plot Pane
Delete this Pane
Sync. Horiz. Axes
Marching Waveforms
Grid
Reset Colors
Mark Data Points
Eye Diagram
View
Add Traces to Plot
Only list traces matching
Asterisks match colons
OK
Cancel
Available data:
V(p) frequency
V(ul)
V(vdd)
I(Cp)
I(Rp)
I(Vdd)
I(Vg)
Ib(M1)
Ib(M2)
Id(M1)
Id(M2)
Ig(M1)
Ig(M2)
Is(M1)
Is(M2)
Expression(s) to add:
V(p)
AutoRange
1.571V
3.3V
100K
0.05
100G
.lib C:\Program Files\LTC\LTspiceIV\lib\sub\cmos_035.lib
Add traces to this plot


File Edit Hierarchy View Simulate Tools Window Help
Edit Simulation Command
Transient AC Analysis DC sweep Noise DC Transfer DC op pnt
Perform a stochastic noise analysis of the circuit linearized about its DC operating point.
Output: V(p)
Input: Vg
Type of Sweep: Decade
Number of points per decade:
Start Frequency:
Stop Frequency:
Octave
Decade
Linear
List
Syntax: .noise V(<out>[,<ref>]) <src> <oct, dec, lin> <Npoints> <StartFreq> <EndFreq>
.noise V(p) Vg dec
Cancel
OK
Edit Simulation Command
Transient AC Analysis DC sweep Noise DC Transfer DC op pnt
Perform a stochastic noise analysis of the circuit linearized about its DC operating point.
Output: V(p)
Input: Vg
Type of Sweep: Decade
Number of points per decade: 5
Start Frequency: 1
Stop Frequency: 100MEG
Syntax: .noise V(<out>[,<ref>]) <src> <oct, dec, lin> <Npoints> <StartFreq> <EndFreq>
.noise V(p) Vg dec 5 1 100MEG
Cancel
OK


File Edit Hierarchy View Simulate Tools Window Help
;op
;dc Vg 0 3.3 0.05
;tf V(p) Vg
;ac dec 5 10 100G
.noise V(p) Vg dec 5 1 100MEG
VDD
M2
W=2.4u L=0.4u
P
UL
M1
W=0.8u L=0.4u
Vg
AC 10m
1.571V
Cp
12fF
Rp
100k
VDD
3.3V
.lib C:\Program Files\LTC\LTspiceIV\lib\sub\cmos_035.lib



File Edit Hierarchy View Simulate Tools Window Help
PrimerSchem
V(onoise)
240µV/Hz½
220µV/Hz½
200µV/Hz½
180µV/Hz½
160µV/Hz½
140µV/Hz½
120µV/Hz½
100µV/Hz½
80µV/Hz½
60µV/Hz½
40µV/Hz½
20µV/Hz½
0µV/Hz½
1Hz
10Hz
100Hz
1KHz
10KHz
100KHz
1MHz
10MHz
100MHz
VDD
M2
W=2.4u L=0.4u
UL
M1
W=0.8u L=0.4u
P
Vg
AC 10m
1.571V
Cp
12fF
Rp
100k
VDD
3.3V
;op
;dc Vg 0 3.3 0.05
;tf V(p) Vg
;ac dec 5 10 100G
.noise V(p) Vg dec 5 1 100MEG
.lib C:\Program Files\LTC\LTspiceIV\lib\sub\cmos_035.lib

Analiza linearnih kola u DC domenu

Šta treba da znamo?

Elementarno (za potpis)

Šta se dobija kao rezultat analize u frekvencijskom domenu?

Osnovna (za 6)

1. **Koje parametre treba zadati da bi se u programu Spice analiziralo kolo u frekvencijskom domonu?**
2. **Kakvi se modeli poluprovodničkih komponenta koriste pri AC analizi?**

Ispitna pitanja

a) Koliko puta se formira i rešava sistem jednačina pri jednoj analizi kola u AC režimu ukoliko se traži analiza u 4 tačke po dekadi u opsegu od 5Hz do 50kHz/Koliko puta se formira i rešava sistem jednačina pri jednoj analizi kola u AC režimu ukoliko se traži analiza u 2 tačke po oktavi u opsegu od 5Hz do 50kHz?

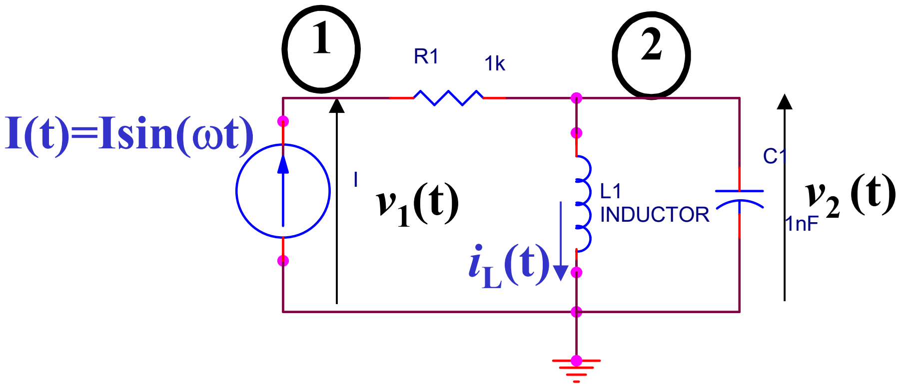
b) Koji su karakteristični problemi vezani za zadavanje koraka u AC analizi?

c) Koji su karakteristični problemi vezani za rezonantnu frekvenciju u AC analizi? Kako ih izbeći?

Analiza elektronskih kola

1. Uvod
2. Analiza linearnih kola u DC domenu (jednosmerni režim)
3. Analiza linearnih kola u AC domenu (frekvencijski domen)
4. Analiza linearnih kola u TR domenu (vremenski domen)
5. Analiza nelinearnih kola u DC domenu
6. Analiza nelinearnih kola u TR domenu

Matematički model	**Način rešavanja sistema j-na**
1. i 2. Linearne jednačine (realne i kompleksne)	1. i 2. LU faktorizacija (Gauss)
3. Linearne diferencijalne jednačine	3. Numeričko integraljenje - diskretizacija - svođenje na linearne algebarske (Euler)
4. Nelinearne algebarske jednačine	4. Linearizacija - Iterativno svođenje na linearne algebarske (Newton-Kantorovič)
5. Nelinearne diferencijalne jednačine	5. Diskretizacija - svođenje na nelinearne algebarske i linearizacija - Iterativno svođenje na linearne algebarske



$$\frac{v_1(t)-v_2(t)}{R_1}=i(t)$$

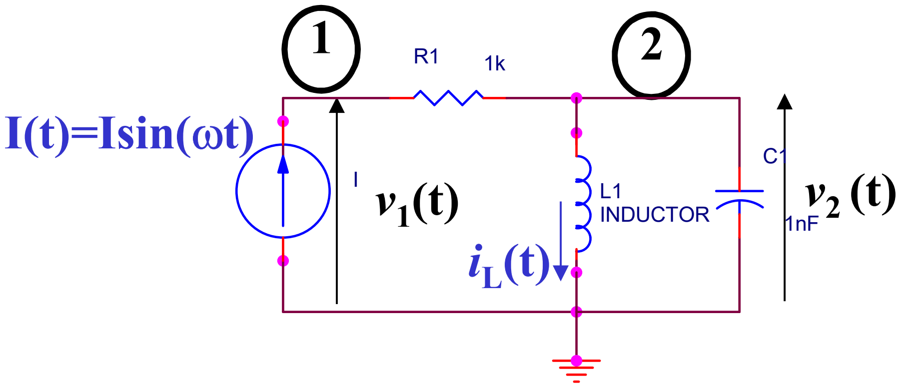
$$\frac{v_2(t)-v_1(t)}{R_1}+i_L(t)+C_1\frac{\partial v_2(t)}{\partial t}=0$$

$$v_2(t)-L\frac{\partial i(t)}{\partial t}=0$$

$$\dot{x}=\frac{dx}{dt}=f(x)$$

Diskretizacija vremenske ose

$$\dot{\mathbf{x}}(\mathbf{t}_{n+1})=\frac{\mathbf{x}(\mathbf{t}_{n+1})-\mathbf{x}(\mathbf{t}_n)}{\mathbf{t}_{n+1}-\mathbf{t}_n}=\frac{\mathbf{x}(\mathbf{t}_{n+1})-\mathbf{x}(\mathbf{t}_n)}{\mathbf{h}}=\frac{\mathbf{x}^{n+1}-\mathbf{x}^{n}}{\mathbf{h}}$$



$$\frac{v_1(t)-v_2(t)}{R_1}=i(t)$$

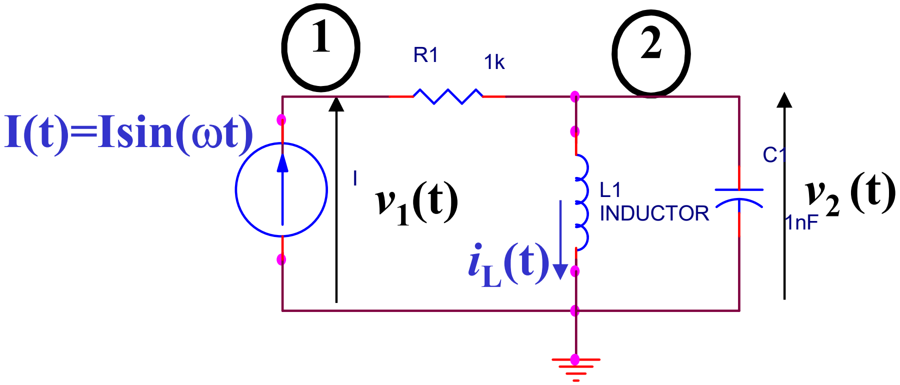
$$\frac{v_2(t)-v_1(t)}{R_1}+i_L(t)+C_1\frac{\partial v_2(t)}{\partial t}=0$$

$$v_2(t)-L\frac{\partial i(t)}{\partial t}=0$$

$$\frac{v_1(t_{n+1})-v_2(t_{n+1})}{R_1}=i(t_{n+1})$$

$$\frac{v_2(t_{n+1})-v_1(t_{n+1})}{R_1}+i_L(t_{n+1})+C_1\frac{v_2(t_{n+1})-v_2(t_n)}{h}=0$$

$$v_2(t_{n+1})-L\frac{i_L(t_{n+1})-i_L(t_n)}{h}=0$$



$$\frac{1}{R_1}v_1^{n+1} - \frac{1}{R_1}v_2^{n+1} = i^{n+1}$$

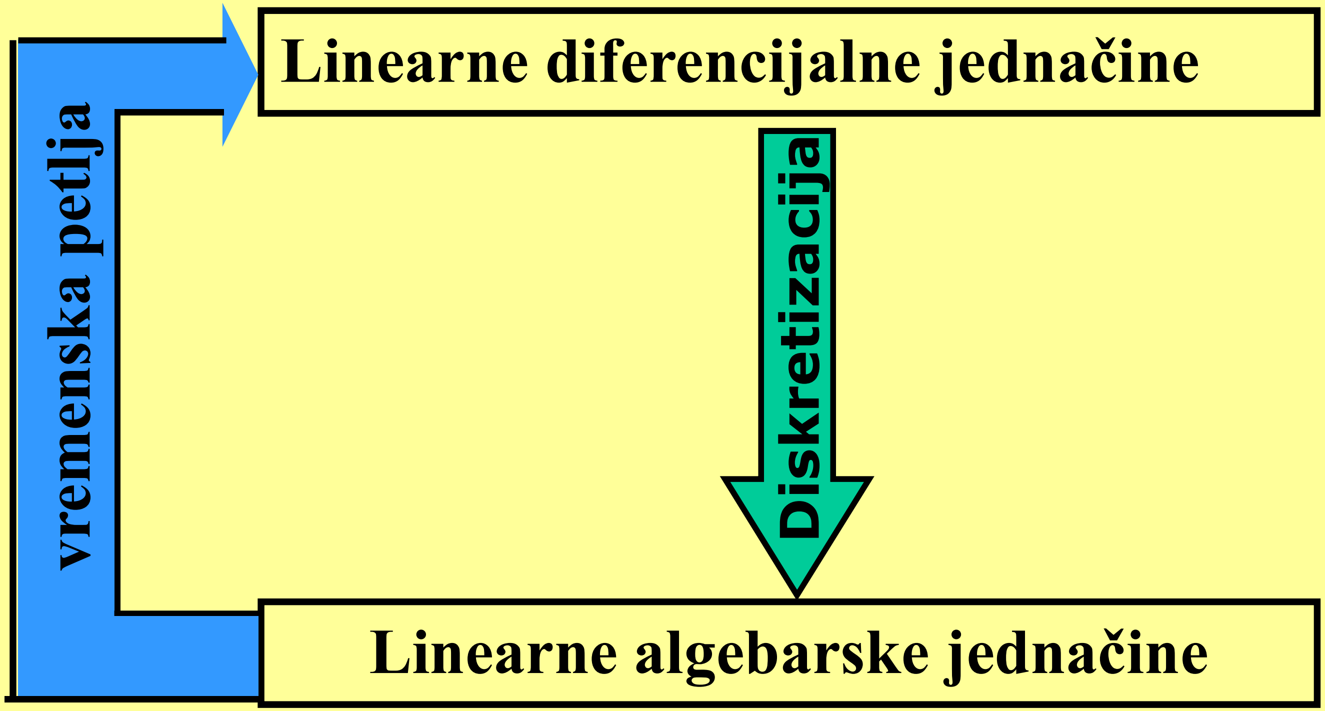
$$-\frac{1}{R_1}v_1^{n+1} + \left(\frac{1}{R_1} + \frac{C_1}{h}\right)v_2^{n+1} + i_L^{n+1} = \frac{C_1}{h}v_2^n$$

$$v_2^{n+1} - \frac{L}{h}i_L^{n+1} = -\frac{L}{h}i_L^n$$

Sistem linearnih jednačina

$$\begin{bmatrix} \frac{1}{R_1} & -\frac{1}{R_1} & 0 \\ -\frac{1}{R_1} & \frac{1}{R_1} + \frac{C_1}{h} & 1 \\ 0 & 1 & -\frac{L_1}{h} \end{bmatrix} \cdot \begin{bmatrix} v_1^{n+1} \\ v_2^{n+1} \\ i_L^{n+1} \end{bmatrix} = \begin{bmatrix} i^{n+1} \\ \frac{C_1}{h}v_2^n \\ -\frac{L_1}{h}i_L^n \end{bmatrix}$$

$$\underset{\sim}{\mathbf{G}} \cdot \underline{\mathbf{v}^{n+1}} = \underline{\mathbf{i}}^n$$


Linearne diferencijalne jednačine
Diskretizacija
Linearne algebarske jednačine
vremenska petlja

Diskretizacija vremenske ose.

Da bi se našlo rešenje u trenutku $t=t_{n+1}$, potrebno je da se zna rešenje za trenutak $t=t_n$.

Potrebno je definisati granične uslove za t=0.

Za analizu kola u intervalu do 50ms sa korakom 5μs potrebno je formirati i rešiti sistem linearnih algebarskih jednačina 10 000 puta!

Diskretizacija vremenske ose.

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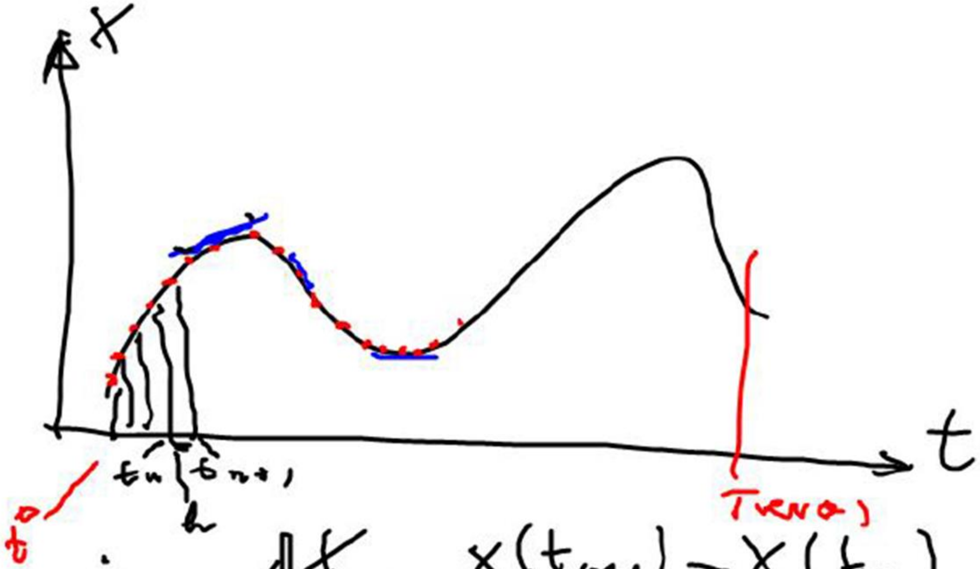


5 μs

50 ms

$\frac{50000}{5} = 10000$

$$\dot{x} = \frac{dx}{dt} \approx \frac{x(t_{n+1}) - x(t_n)}{t_{n+1} - t_n} = \frac{x^{n+1} - x^{n}}{h}$$

$$h = t_{n+1} - t_n$$

Primena Eulerove formule na kapacitivnu granu

$$i_C = C\frac{dv_C}{dt}$$

$$i_C^{\,n+1} = C\frac{(v_C^{\,n+1} - v_C^{\,n})}{h}$$

$$i_C^{\,n+1} = \frac{C}{h}(v_C^{\,n+1} - v_C^{\,n})$$

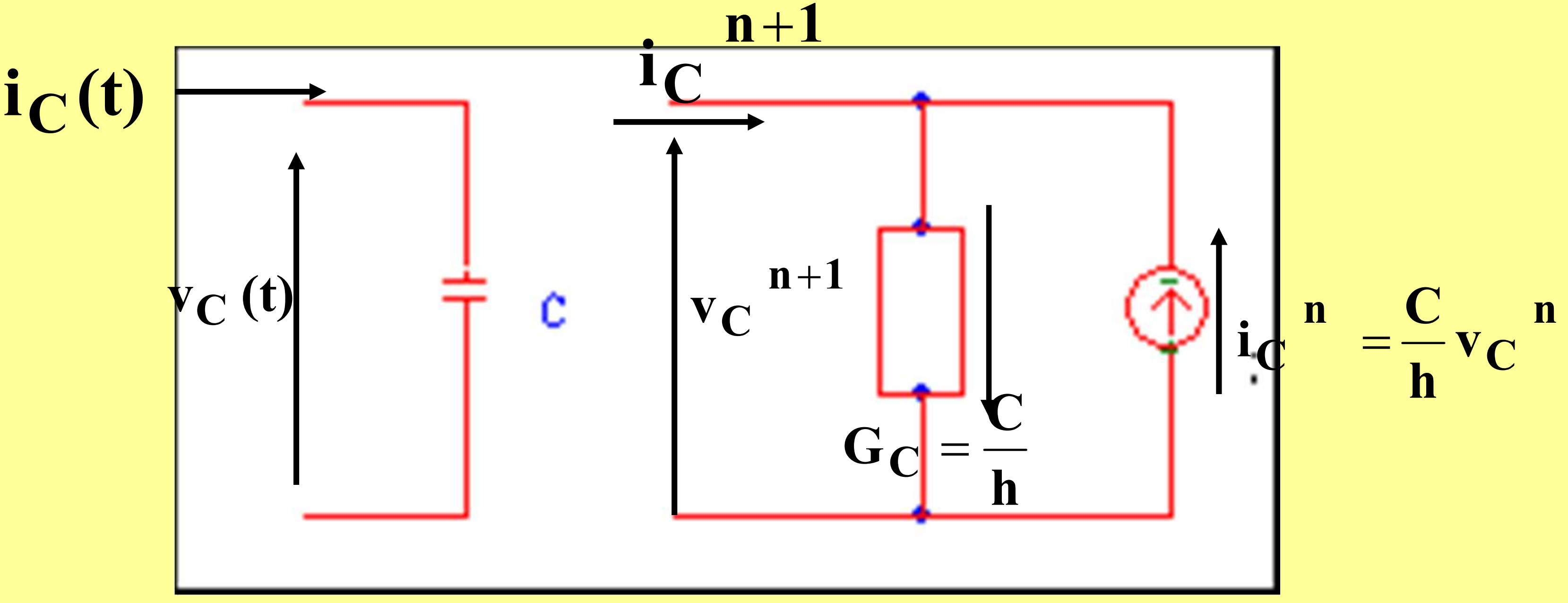
$$i_C^{\,n+1} = \frac{C}{h}v_C^{\,n+1} - \frac{C}{h}v_C^{\,n}$$

Primena Eulerove formule na kapacitivnu granu

$$i_C^{\,n+1} = \frac{C}{h} v_C^{\,n+1} - \frac{C}{h} v_C^{\,n}$$

Struja $i_C(t_n+1)$ ima dve komponente:

Jedna zavisi od napona $v_C\ (t_n+1)$ a druga od $v_C(t_n)$



Analiza greške diskretizacije

Intuitivno je jasno (a znanja iz numeričke matematike to potvrđuju) da diskretizacija unesi određenu grešku, i da može da se očekuje da greška bude manja ako je korak diskretizacije manji i ako je promena sporija.

Želimo da utvrdimo

-koliko iznosi greška i

-od čega zavisi.

Analiza greške diskretizacije

Neka je $x(t_{n+1})$ tačna vrednost

a x^{n+1} izračunata vrednost pomenljive x.

Tada je lokalna greška zaokruživanja

(Local trncation Error, LTE)

$$\varepsilon_{Tx} = x(t_{n+1}) - x^{n+1}$$

Analiza greške diskretizacije

Razvojem funkcije x(t) u Tajlorov red u okolini tačke $t=t_{n+1}$ dobija se

$$x(t) = x(t_{n+1}) + (t - t_{n+1})\dot{x}\big|_{t=t_{n+1}} + \frac{1}{2}(t - t_{n+1})^2 \ddot{x}\big|_{t=t_{n+1}} + \ldots$$

$$\text{za } t = t_n$$

$$x(t_n) = x(t_{n+1}) + (t_n - t_{n+1})\dot{x}\big|_{t=t_{n+1}} + \frac{1}{2}(t_n - t_{n+1})^2 \ddot{x}\big|_{t=t_{n+1}} + \ldots$$

$$h = t_{n+1} - t_n,$$

$$x(t_n) = x(t_{n+1}) - h\dot{x}\big|_{t=t_{n+1}} + \frac{1}{2}h^2 \ddot{x}\big|_{t=t_{n+1}} + \ldots$$

$$x(t_{n+1}) = x(t_n) + h\dot{x}\big|_{t=t_{n+1}} - \frac{1}{2}h^2 \ddot{x}\big|_{t=t_{n+1}} - \ldots$$

Analiza greške diskretizacije

Na osnovu

$$\dot{x}(t_{n+1}) = \frac{x(t_{n+1}) - x(t_n)}{t_{n+1} - t_n} = \frac{x(t_{n+1}) - x(t_n)}{h} = \frac{x^{n+1} - x^{n}}{h}$$

sledi da je približna vrednost promenljive x u trenutku $t=t^{n+1}$

$$x^{n+1} = x^{n} + h\dot{x}\big|_{t=t_{n+1}}$$

$$\left(x(t_{n+1}) \cong x(t_n) + h\dot{x}\big|_{t=t_{n+1}} - \frac{1}{2}h^2\ddot{x}\big|_{t=t_{n+1}} \right)$$

Ako se pretpostavi da je u $t=t_n$, poznato tačno rešenje i da je $x(t_n)=x^n$, tada je

$$\varepsilon_{Tx} = x(t_{n+1}) - x^{n+1}$$

$$\varepsilon_{Tx} = \left(x(t_n) + h\dot{x}\big|_{t=t_{n+1}} - \frac{1}{2}h^2\ddot{x}\big|_{t=t_{n+1}} \right) - \left(x^{n} + h\dot{x}\big|_{t=t_{n+1}} \right) = \boxed{-\frac{1}{2}h^2\ddot{x}\big|_{t=t_{n+1}}}$$

Analiza greške diskretizacije

$$\varepsilon_{Tx} = x(t_{n+1}) - x^{n+1} = -\frac{1}{2} h^2 \ddot{x}\Big|_{t=t_{n+1}}$$

Lokalna greška zaokruživanja (local truncation error LTE) proporcionalna je kvadratu veličine koraka h i brzini promene signala

Vremenski korak h $\searrow$
Promena brzine odziva $\searrow$ $\Rightarrow$ **LTE** $\searrow$

Analiza greške diskretizacije

Tokom izračunavanja izvoda pravi se, takođe, lokalna greška zaokruživanja izvoda

$$\varepsilon_{Td} = \dot{x}(t_{n+1}) - \dot{x}^{n+1}$$

$$x(t) = x(t_{n+1}) + (t - t_{n+1})\dot{x}\big|_{t=t_{n+1}} + \frac{1}{2}(t - t_{n+1})^2 \ddot{x}\big|_{t=t_{n+1}} + \ldots$$

$$\text{za } t = t_n$$

$$x(t_n) = x(t_{n+1}) + (t_n - t_{n+1})\dot{x}\big|_{t=t_{n+1}} + \frac{1}{2}(t_n - t_{n+1})^2 \ddot{x}\big|_{t=t_{n+1}} + \ldots$$

$$h = t_{n+1} - t_n,$$

$$\dot{x}\big|_{t=t_{n+1}} = \dot{x}(t_{n+1}) = \frac{x(t_{n+1}) - x(t_n)}{h} + \frac{1}{2}h\ddot{x}\big|_{t=t_{n+1}} + \ldots$$

Analiza greške diskretizacije

Znajući da je

$$\dot{x}^{n+1} = \frac{x(t_{n+1}) - x(t_n)}{h}$$

sledi

$$\varepsilon_{Td} = \dot{x}(t_{n+1}) - \dot{x}^{n+1}$$

$$\varepsilon_{Td} = \frac{x(t_{n+1}) - x(t_n)}{h} + \frac{1}{2} h \ddot{x}\Big|_{t=t_{n+1}} + \ldots - \frac{x(t_{n+1}) - x(t_n)}{h}$$

$$\varepsilon_{Td} = \frac{1}{2} h \ddot{x}\Big|_{t=t_{n+1}} + \ldots$$

$$\varepsilon_{Td} \approx \frac{1}{2} h \ddot{x}\Big|_{t=t_{n+1}}$$

Analiza greške diskretizacije

Lokalna greška zaokruživanja izvoda (LTE izvoda)
proporcionalna je veličini koraka h i
brzini promene signala

Vremenski korak h ↘
Promena brzine odziva ↘ ⇒ **LTE izvoda** ↘

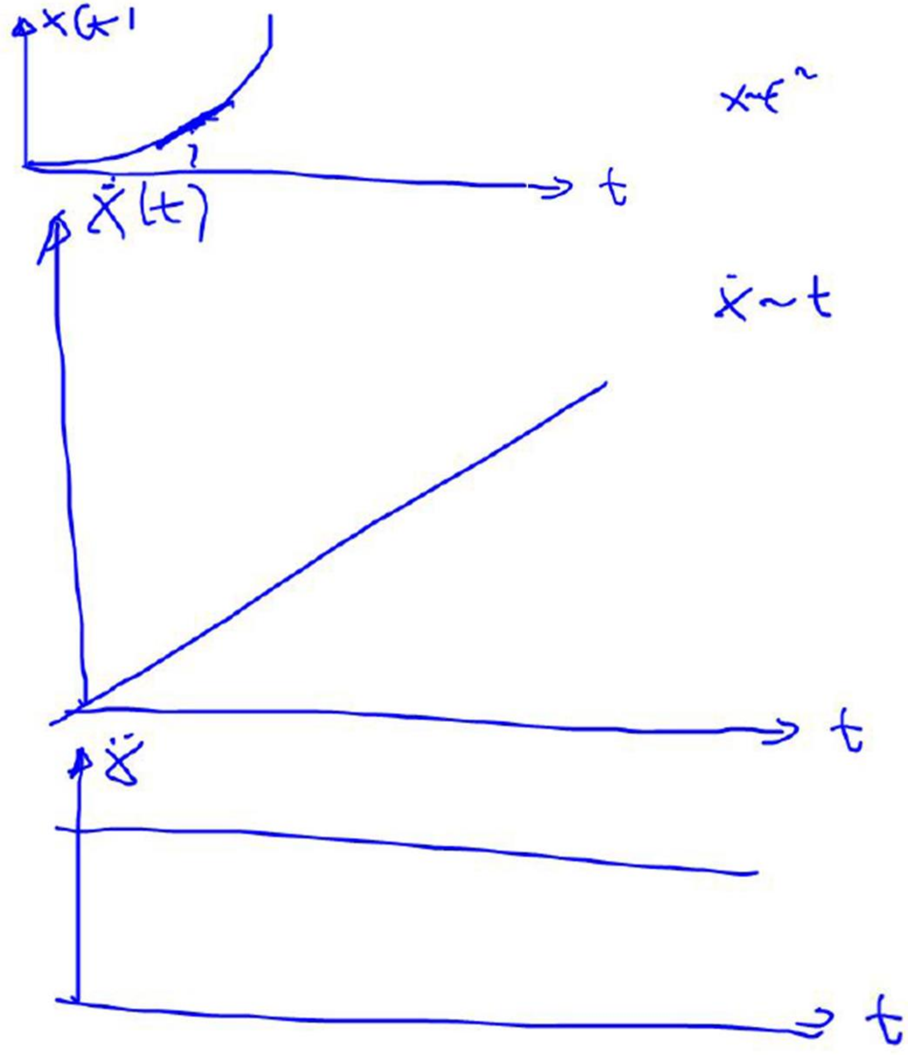
Analiza greške diskretizacije

$$\varepsilon_{Tx} = x(t_{n+1}) - x^{n+1} = -\frac{1}{2} h^{2} \ddot{x}\Big|_{t=t_{n+1}}$$

$$\varepsilon_{Td} = \frac{1}{2} h \ddot{x}\Big|_{t=t_{n+1}}$$

Greška je manja za monotone odzive jer se izvod aproksimira pravom linijom

Da se podsetimo: prvi i drugi izvod funkcije



Funkcija $x=t^2$

$$\dot{x} = \frac{dx}{dt} = 2 \cdot t$$

$$\ddot{x} = \frac{d\dot{x}}{dt} = 2$$

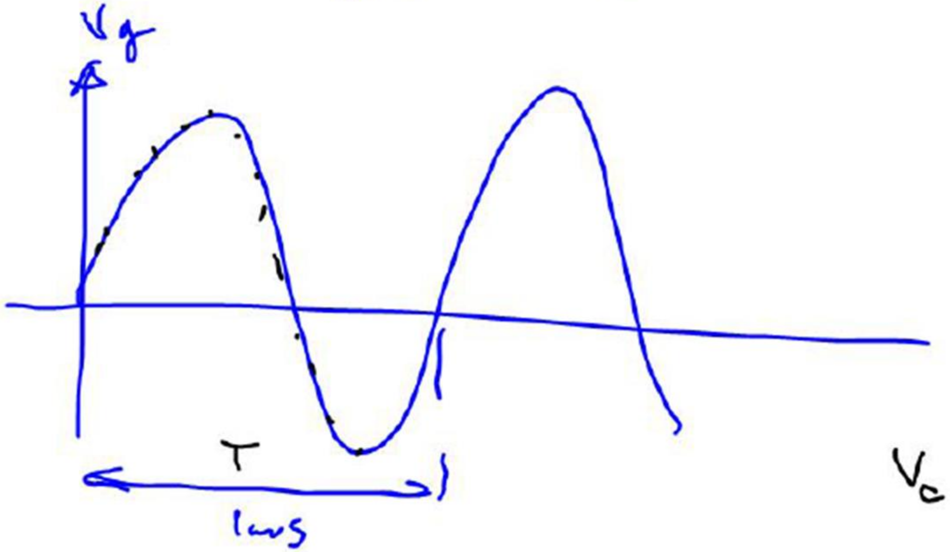
Izbor koraka diskretizacije

Kako izabrati pravu veličinu koraka?

Korak se bira na osnovu vrednosti elemenata kola i/ili na osnovu brzine promene signala pobude.

Izbor vremena završetka analize

$f = 1kHz$



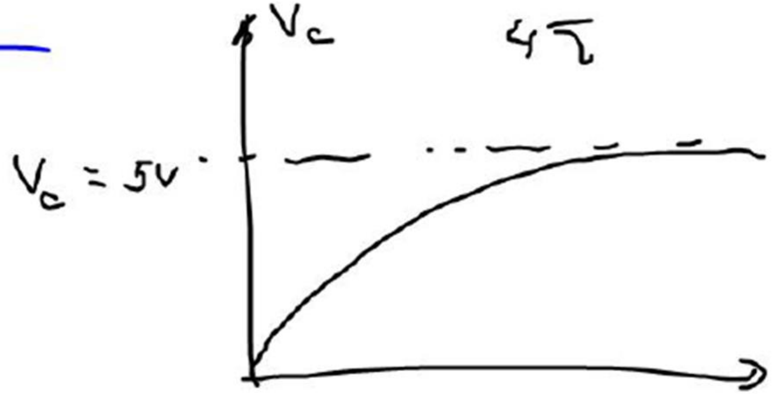
$h = \frac{T}{10} = 100\mu s$

Zavisi od pobude
(recimo 10 tačaka po periodi)

$C = 10mF$

$R = 10\Omega$

4τ



$\tau = \frac{1}{RC} = \frac{1}{10 \cdot 10^{-3} \cdot 10} = 0.1s$

$T_{kraj} = 0.4s$

Zavisi od očekivanog odziva
Da bi se C napunio treba najmanje 4τ

Analiza greške diskretizacije

Brzina promene signala u kolu zavisi od vrednosti vremenskih konstanti u kolu.

Dobra je praksa da se izabere korak h < τ/100 gde je τ lokalna vremenska konstanta.

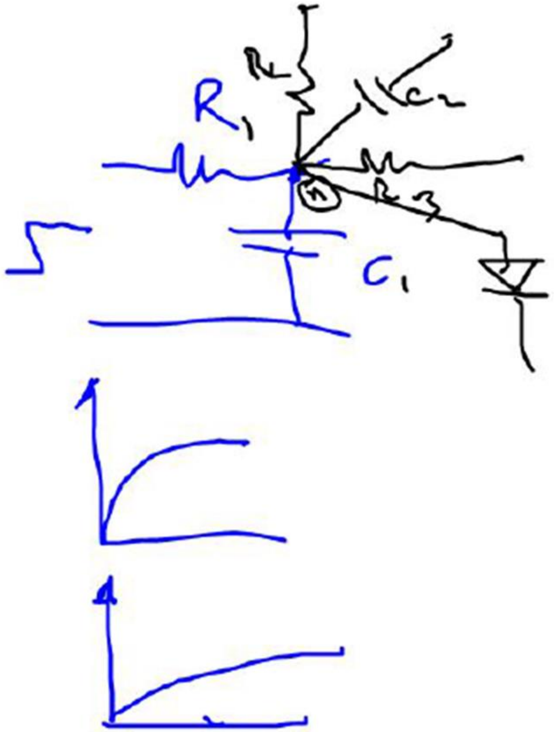
Bira se najmanji korak

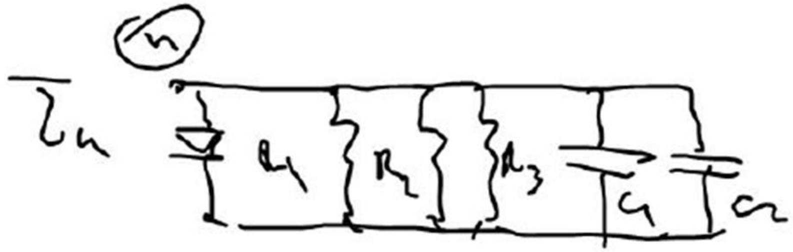
04.04.2018.

Naravno, ako je ograničavajuća promena u kolu diktirana brzinom pobude, tada se izabere korak koji je u stanju da prati pobudu.

Veličina koraka analize h<τ/100

τ_n lokalna vremenska konstanta za čvor *n*



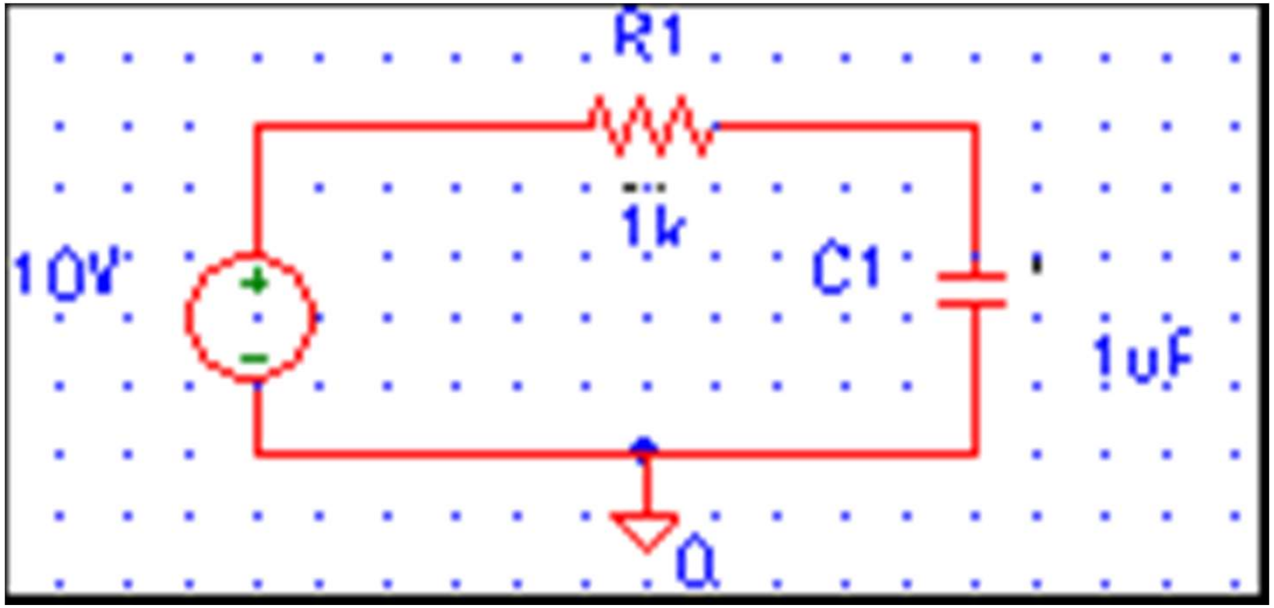


$$\tau_n = \frac{1}{(R_1 \| R_2 \| R_3)(C_1 + C_2)}$$

Otpornost diode – r_d – menja se u zavisnosti od režima

Primer

RC kolo τ=1ms

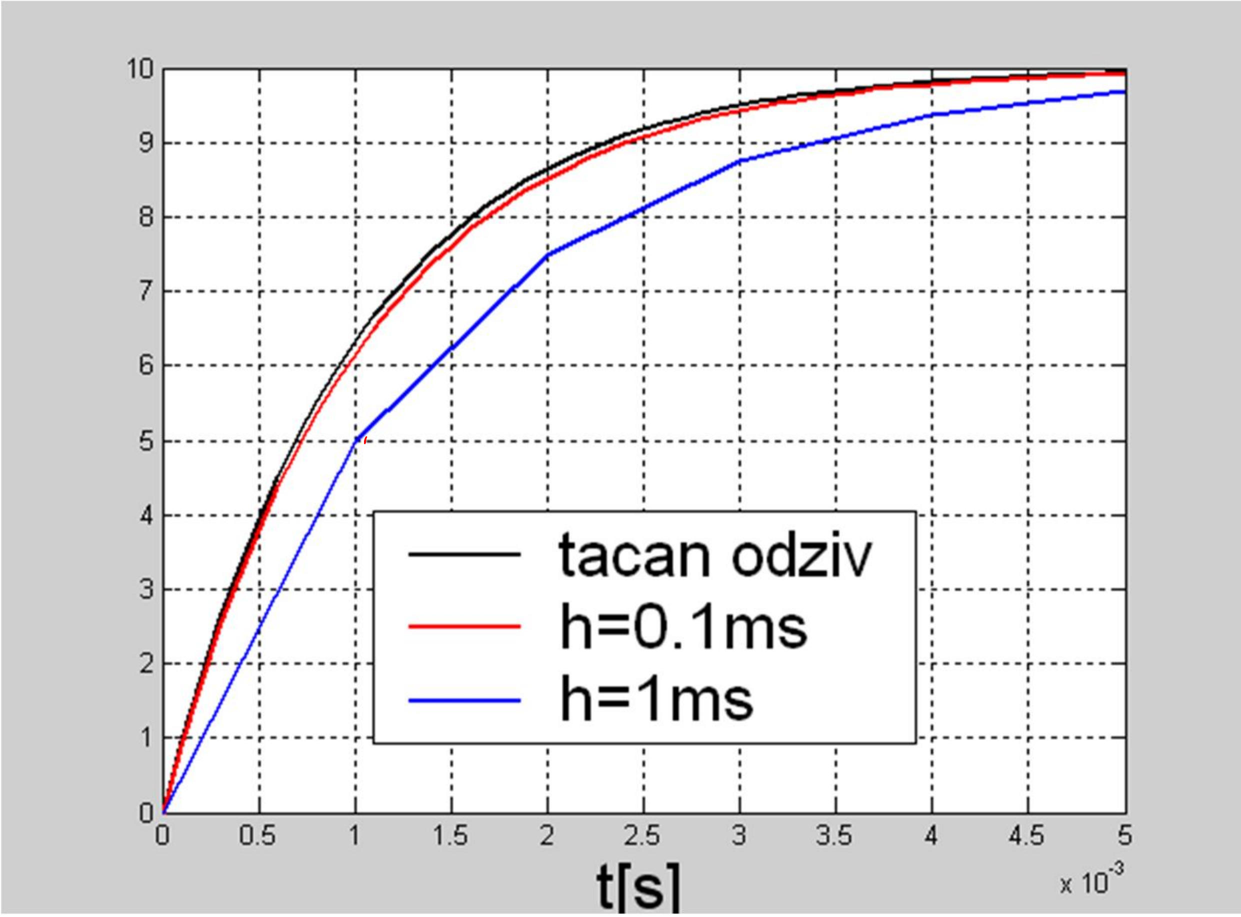


Primer

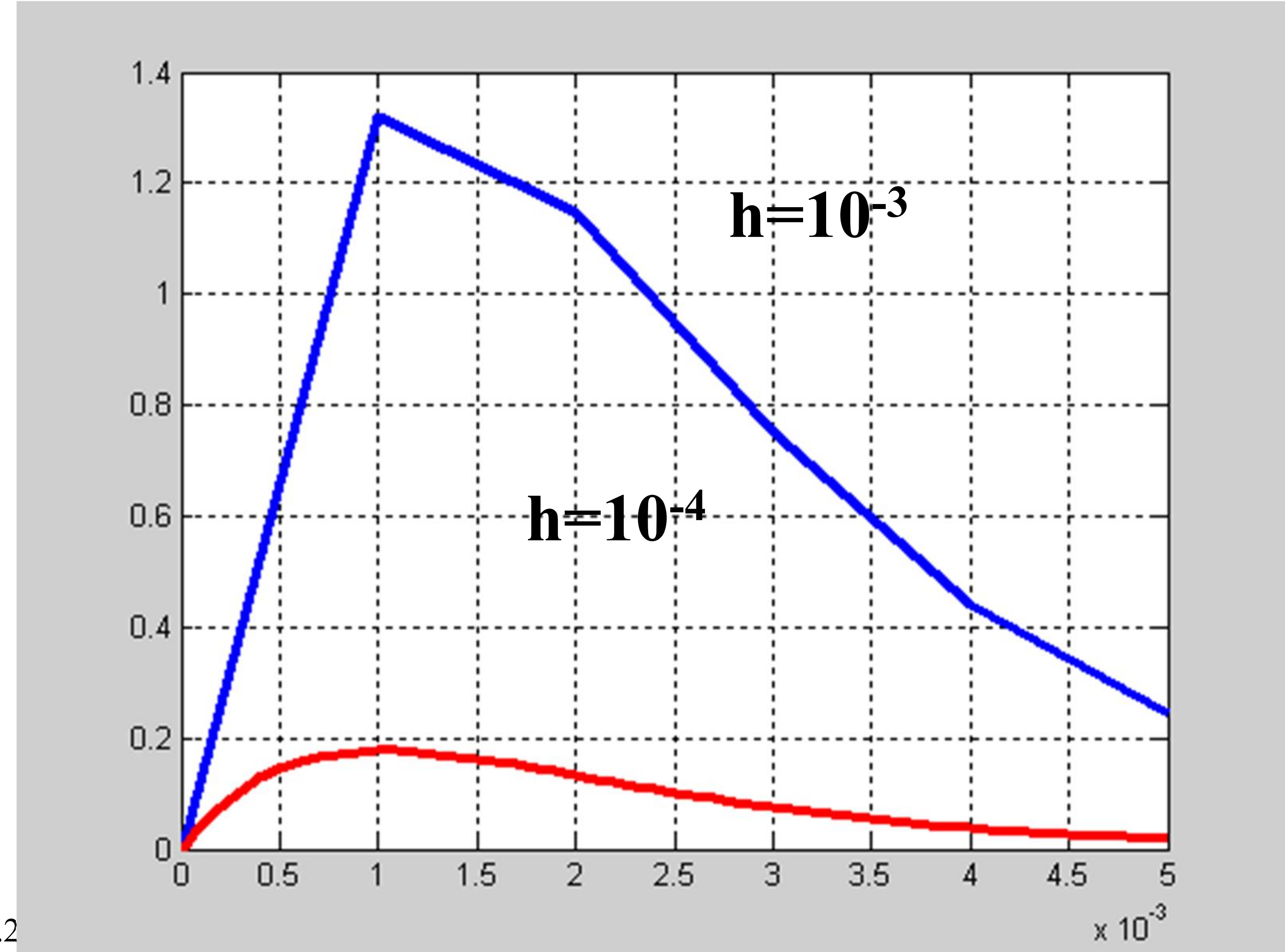
RC kolo τ=1ms

t	tačno	h=0.01ms	h=0.1ms	h=1ms
0	0	0	0	0
1E-5	9.900498	9.0099		
1E-4	9.04837	9.05287	9.09091	
1E-3	3.67879	3.69711	3.85543	5.00000

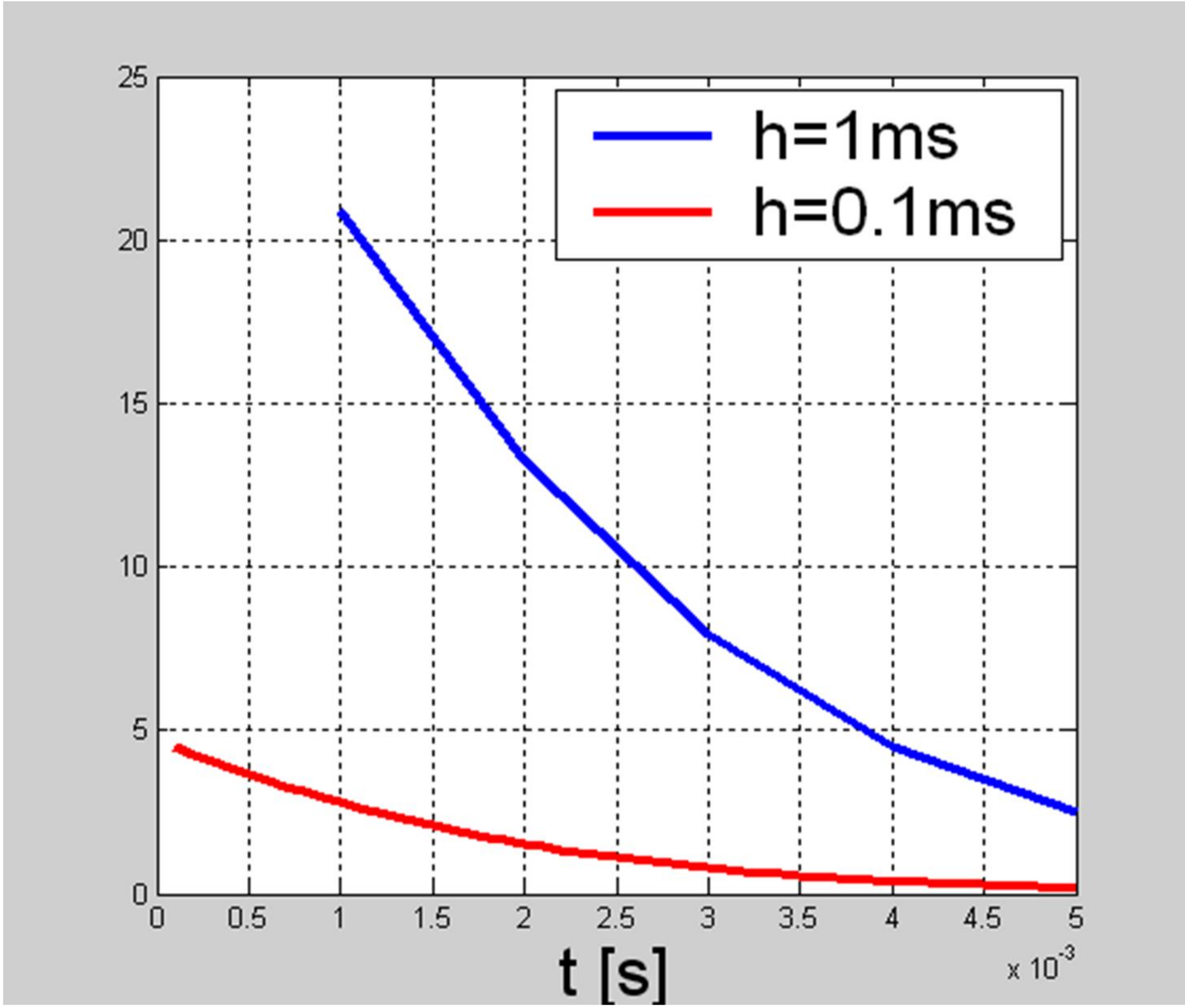
Odziv RC kola τ=1ms



apsolutna greška



relativna greška



Analiza greške diskretizacije

Greška je proporcionalna veličini koraka h i brzini promene $\dot{x}$ signala

Da bi se zadržala konstantna greška, treba smanjiti korak tamo gde je brzina promene signala veća i obrnuto.

Ovo je iskorišćeno u algoritmima za automatsku kontrolu koraka (Spice)

Gde je prvi izvod najveći za sinusnu pobudu?

Kako zavisi od frekvencije?

Analiza greške diskretizacije

Primer:

Neka je odziv sinusna funkcija sa amplitudom V=4V i periodom T=5ms. Odrediti minimalni korak da bi maksimalna LTE bila $\varepsilon_{Tx}= 10^{-4}$V dobija se:

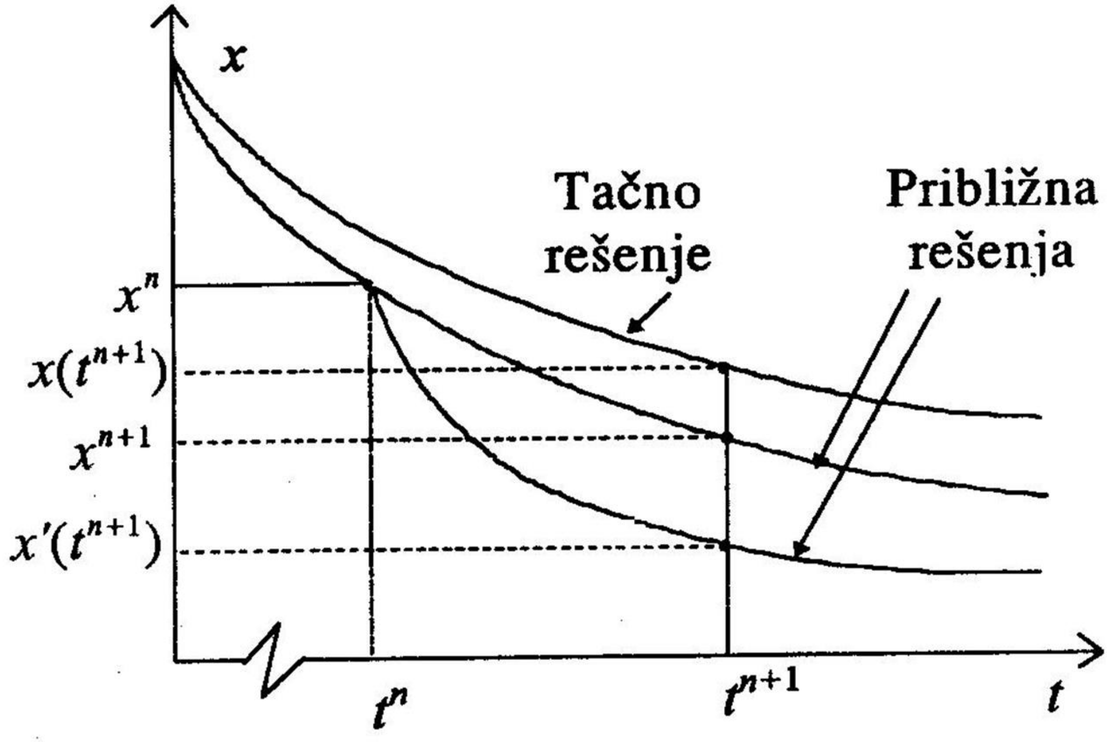
$$h_{min} = \sqrt{\frac{2\varepsilon_{Tx}}{\ddot{x}}}$$

$$\ddot{x} = 4\left(\frac{2\pi}{T}\right)^2 \sin\frac{2\pi}{T}t = 6{,}3\cdot 10^6\,\mathrm{V/s^2} \quad \Rightarrow \quad h_{min} = 5{,}6\mu s$$

$$N = \frac{T}{h} = \frac{5ms}{5{,}6\mu s} \approx 892$$

Za jednu periodu !!!

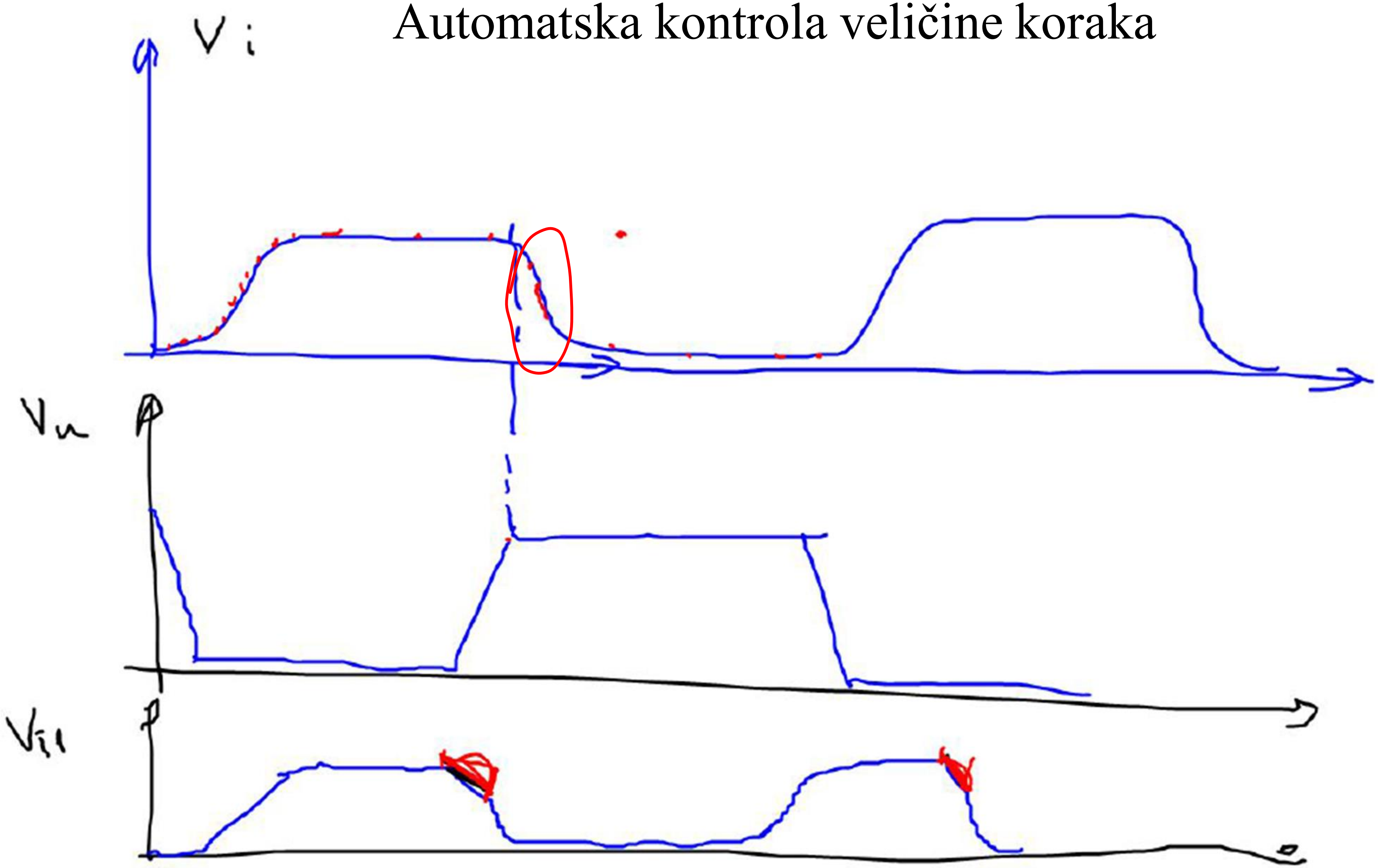
Analiza greške diskretizacije

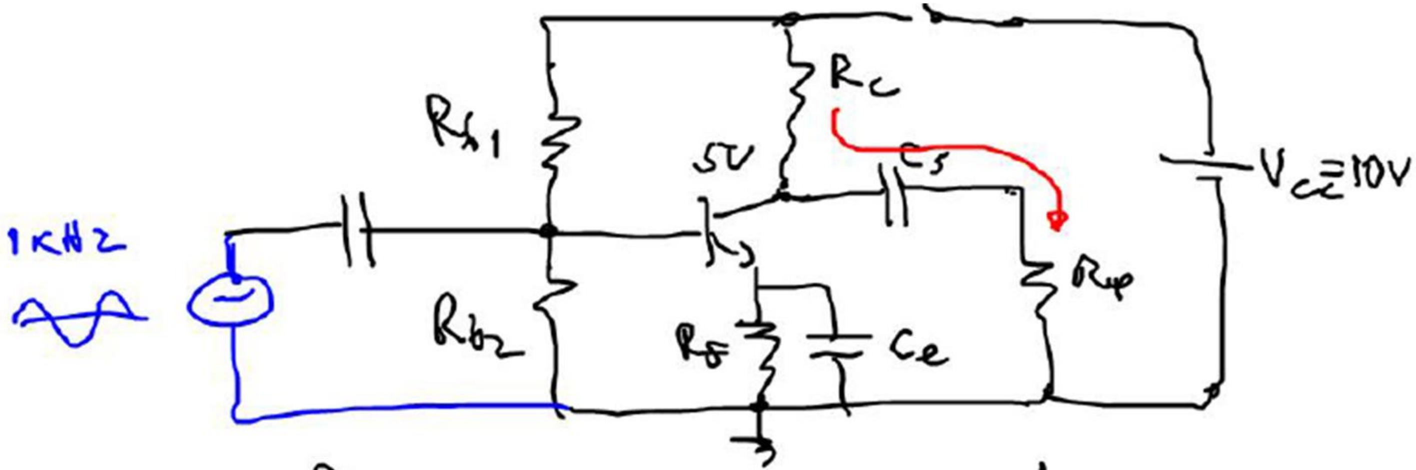


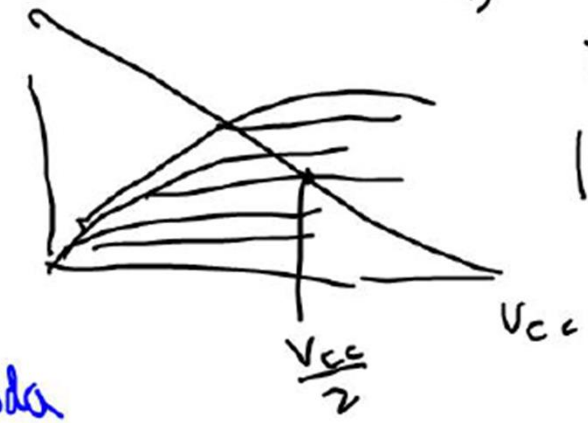
Greška može da se nagomilava

Ukoliko se ne povećava greška kaže se da je rešenje stabilno

Automatska kontrola veličine koraka







$$X_{Cs} = \frac{1}{j\omega C} << 10\Omega$$

$$|X_{C_s}| = \frac{1}{20 \cdot 2\pi \cdot C} << 10\Omega$$

$$C >> \frac{1}{20 \cdot 10 \cdot 2 \cdot \pi} =$$

$$>> \frac{1}{400\pi} =$$

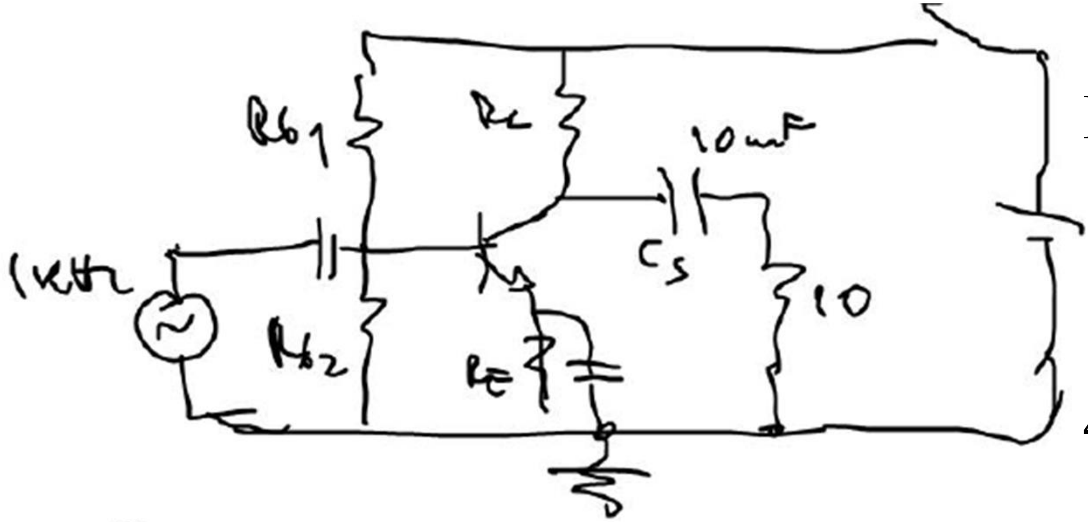
$$>> \frac{1}{1200} \approx 1mF$$

$$C > 10mF$$

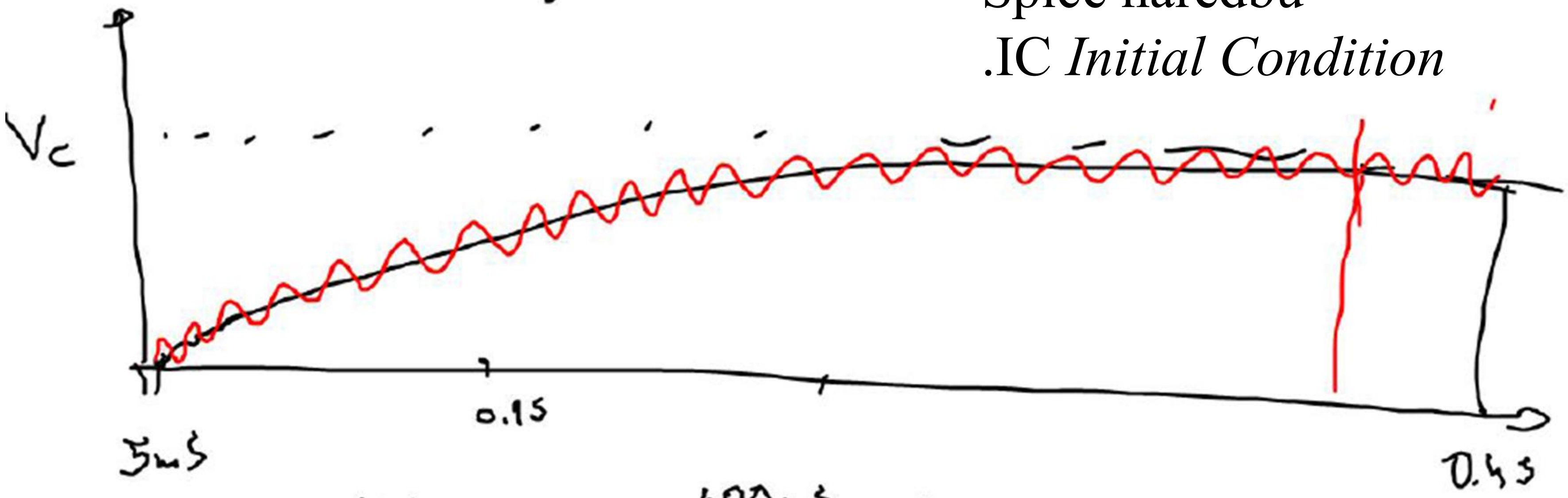
$n = 5$ perioda

$$T_{kraj} = 5 \frac{1}{1kHz} = 5ms$$

1 F
0.1 F
10 mF
1 mF
100 μF
10 μF
1 μF
100 nF
10 nF
1 nF
100 pF
10 pF
1 pF
100 fF
10 fF
1 fF



Da ne bismo „čekali“ da se uspostavi stacionarno stanje (C napunjen na DC, 4τ=0.4s, što je za pobudu od 1kHz 400 perioda) treba koristiti Spice naredbu .IC *Initial Condition*



50 koraka x0.1ms

$\frac{400ms}{0.1ms} = \underline{4000}$

$\underline{.IC}$

Analiza linearnih kola u DC domenu

Šta treba da znamo?

Elementarno (za potpis)

Šta se dobija kao rezultat analize u vremenskom domenu?

Osnovna (za 6)

1. **Koje parametre treba zadati da bi se u programu Spice analiziralo kolo u TR domonu?**

Ispitna pitanja

a) **Od čega zavisi lokalna greška zaokruživanja pri TR analizi?**

b) **Odrediti minimalni korak diskretizacije da bi maksimalna LTE bila $\varepsilon_{Tx}= 10^{-3}$V, ako je odziv sinusna funkcija sa amplitudom V=4V i periodom T=5ms.**

c) **Koje parametre treba zadati pobudnim generatorima za analizu kolu u TR režimu pomoću programa Spice?**