



ZÁPADOČESKÁ
UNIVERZITA
V PLZNI



Porovnání výsledků různých metodik výpočtu přechodných dějů na transformátoru a paradox odečítání proudové fáze při chodu nakrátko

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Parametry transformátoru

$$u_K = 10 \%$$

$$i_0 = 0.5 \%$$

$$U_N = 22 \text{ kV}$$

$$S_N = 100 \text{ MVA}$$

$$\Delta P_0 = 0.05 \%$$

$$\Delta P_K = 1 \%$$

$$R_k = (dP_k / 100) * (U_n^2 / S_n)$$

$$Z_k = (U_k / 100) * (U_n^2 / S_n)$$

$$X_s = \sqrt{Z_k^2 - R_k^2}$$

$$L_s = X_s / \omega$$

$$G_{fe} = (dP_0 / 100) * (S_n / U_n^2)$$

$$R_{fe} = 1 / G_{fe}$$

$$Y_g = (I_0 / 100) * (S_n / U_n^2)$$

$$X_h = 1 / \sqrt{Y_g^2 - G_{fe}^2}$$

$$L_h = X_h / \omega$$

Parametry transformátoru

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$$U_N = 22 \text{ kV}$$

$$S_N = 100 \text{ MVA}$$

$$\Delta P_0 = 0.05 \%$$

$$\Delta P_K = 1 \%$$

$$R_k = 0.0484$$

$$Z_k = 0.484$$

$$X_s = 0.48157$$

$$L_s = 0.0015329$$

$$R_{k1} = R_k/2 = 0.0242$$

$$L_{s1} = L_s/2 = 7.6645e-004$$

$$G_{fe} = 1.0331e-004$$

$$R_{fe} = 9680.0$$

$$Y_g = 0.0010331$$

$$X_h = 972.88$$

$$L_h = 3.0968$$

Chod naprázdno - MATLAB

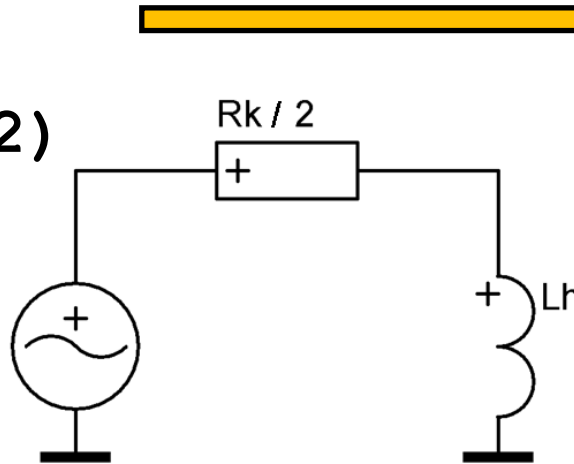
```
% Chod naprazdno
```

```
Z=sqrt(Rk1^2+Xh^2)
```

```
I0m=Um/Z
```

```
Tau=Lh/Rk1
```

```
Psi=atan(Xh/Rk1)
```



Z = 972.88

I0m = 18.464

Tau = 127.97

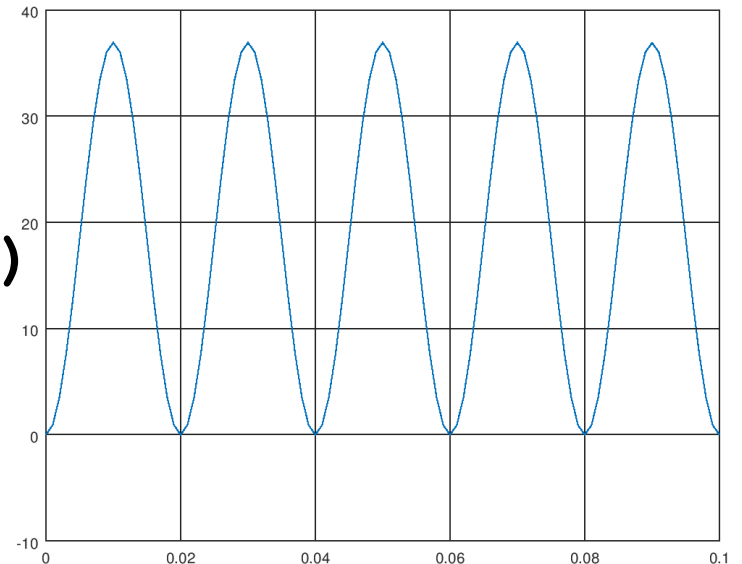
Psi = 1.5708

```
t=[0:0.001:0.1]';
```

```
I0t=I0m*(sin(Psi)*exp(-t/Tau)  
+sin(Omega*t-Psi));
```

```
plot(t,I0t);
```

```
grid on;
```



Chod naprázdno - MATLAB

```
% Chod naprazdno
```

```
In=Sn/ (sqrt (3) *Un)
```

```
I0mPom=In*I0/100*sqrt (2) *2
```

```
Z2=Rk1+i*Xs1+1/ (1/Rfe+1/ (i*Xh))
```

```
I0m2=Um/abs (Z2)
```

```
Psi2=atan (imag (Z2) /real (Z2) )
```

```
Zpozdeni=Psi2/pi*0.01
```

In = 2624.3

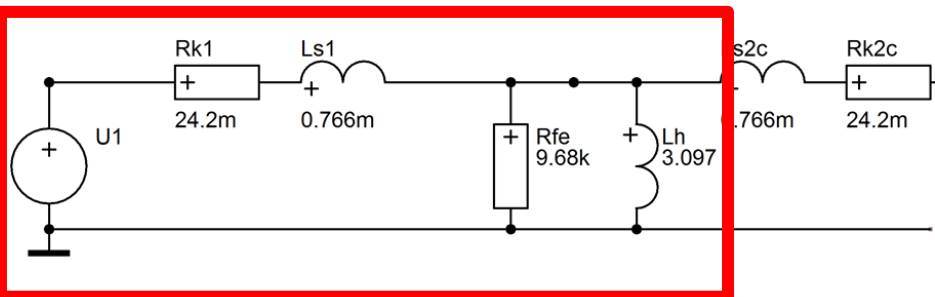
I0mPom = 37.113

Z2 = 96.824 + 963.389i

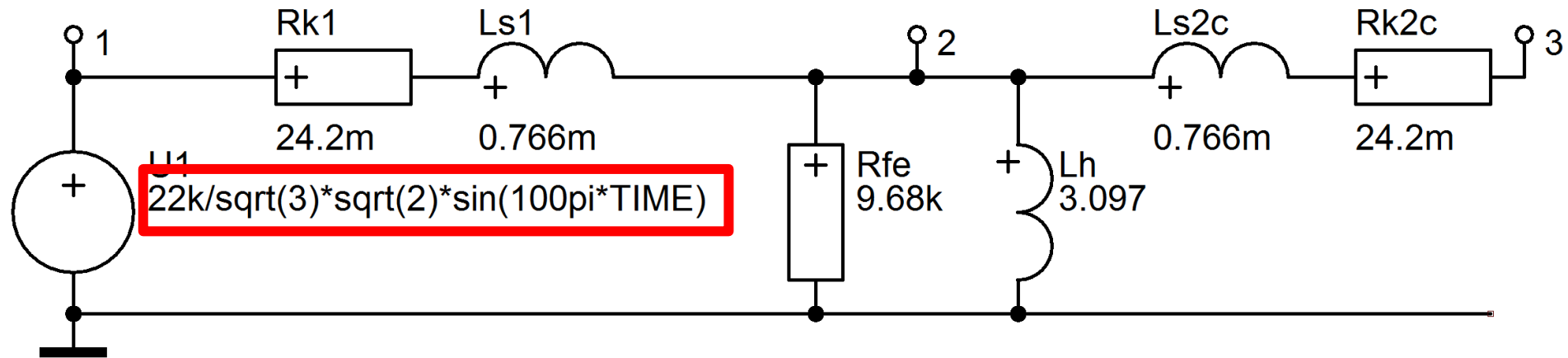
I0m2 = 18.552

Psi2 = 1.4706

Zpozdeni = 0.0046812



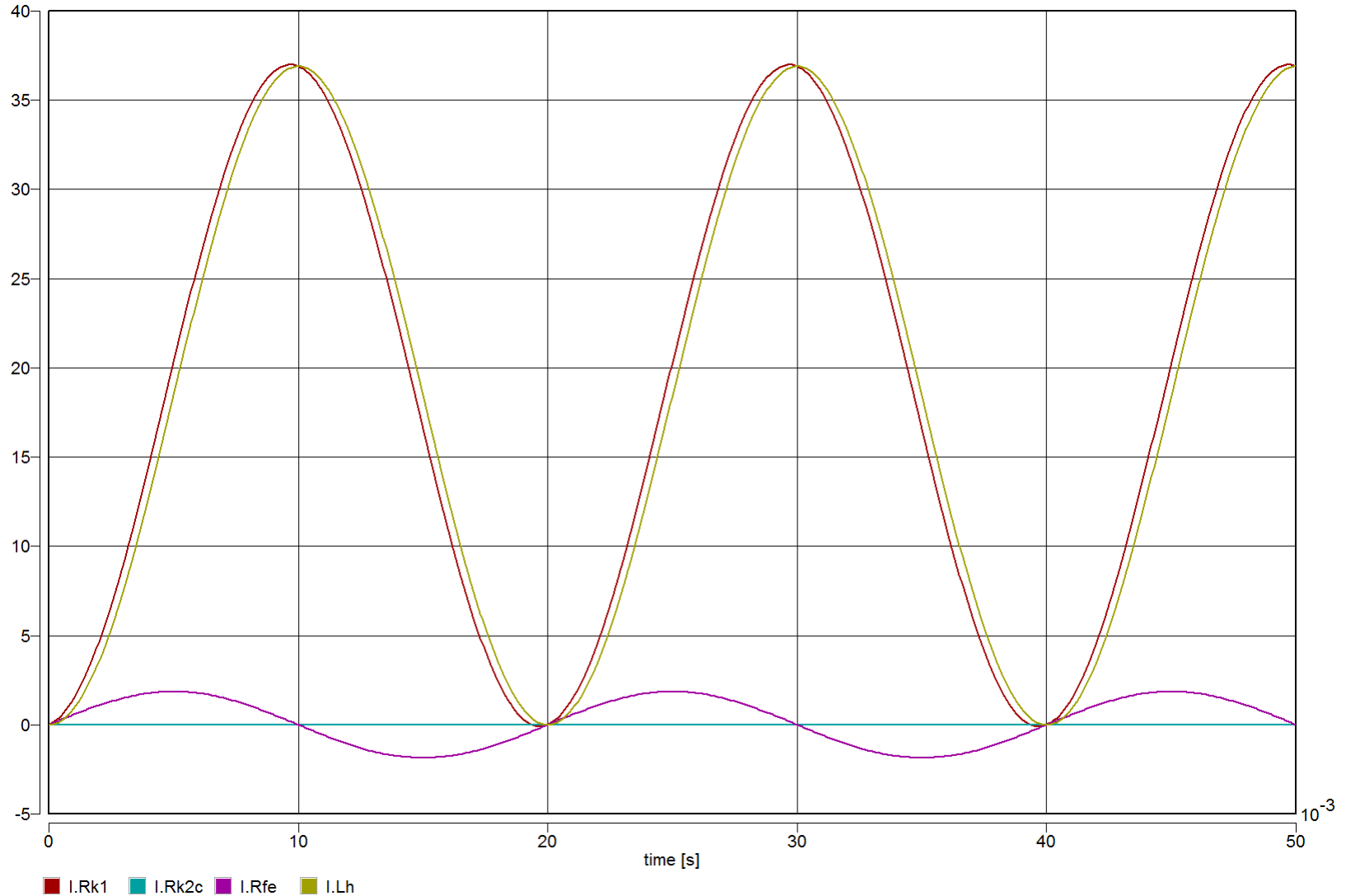
Chod naprázdno - DYNAST



<http://virtual.cvut.cz/dynast/>

Chod naprázdno - DYNAST

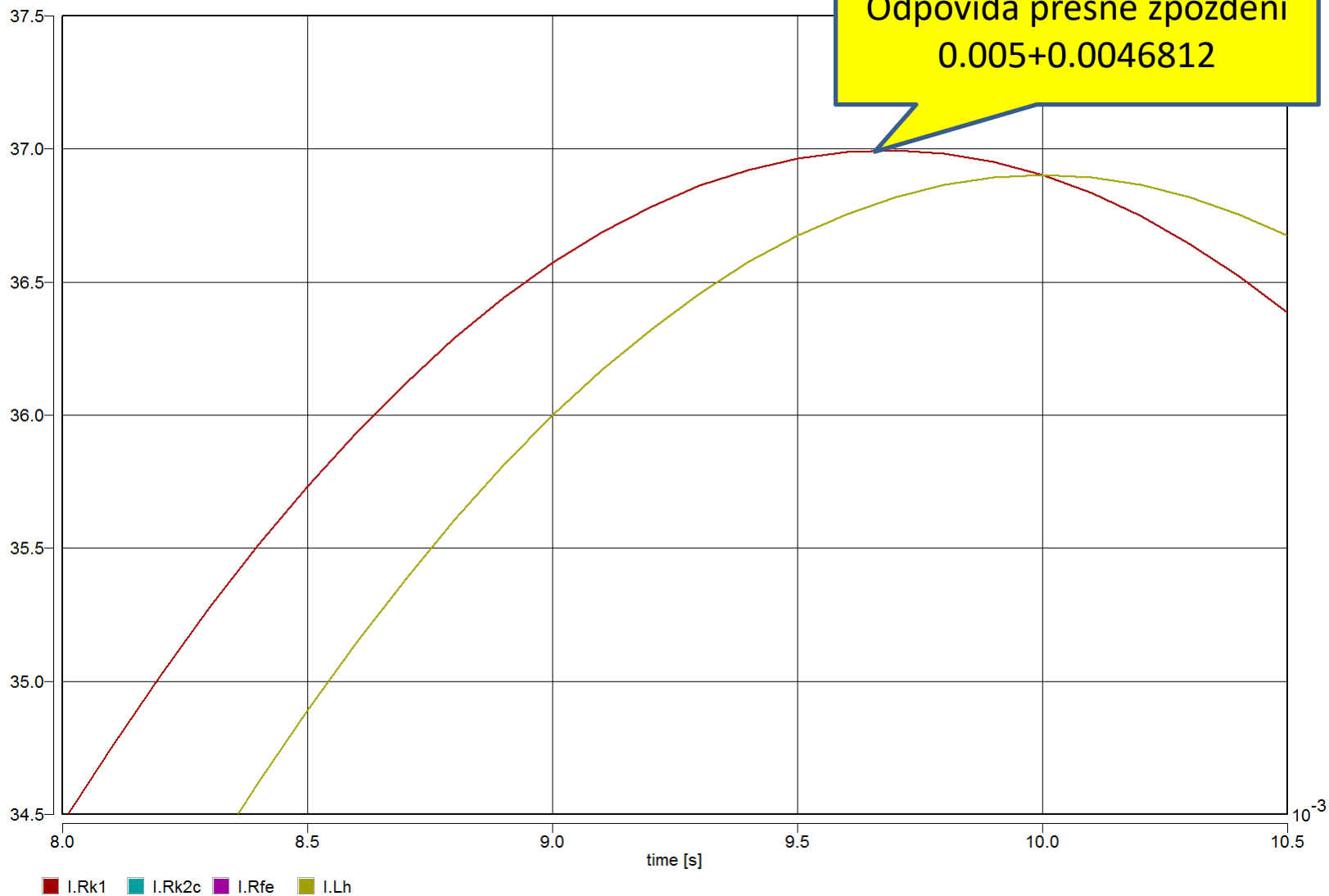
Transformator naprazdno Skupina 1 2017



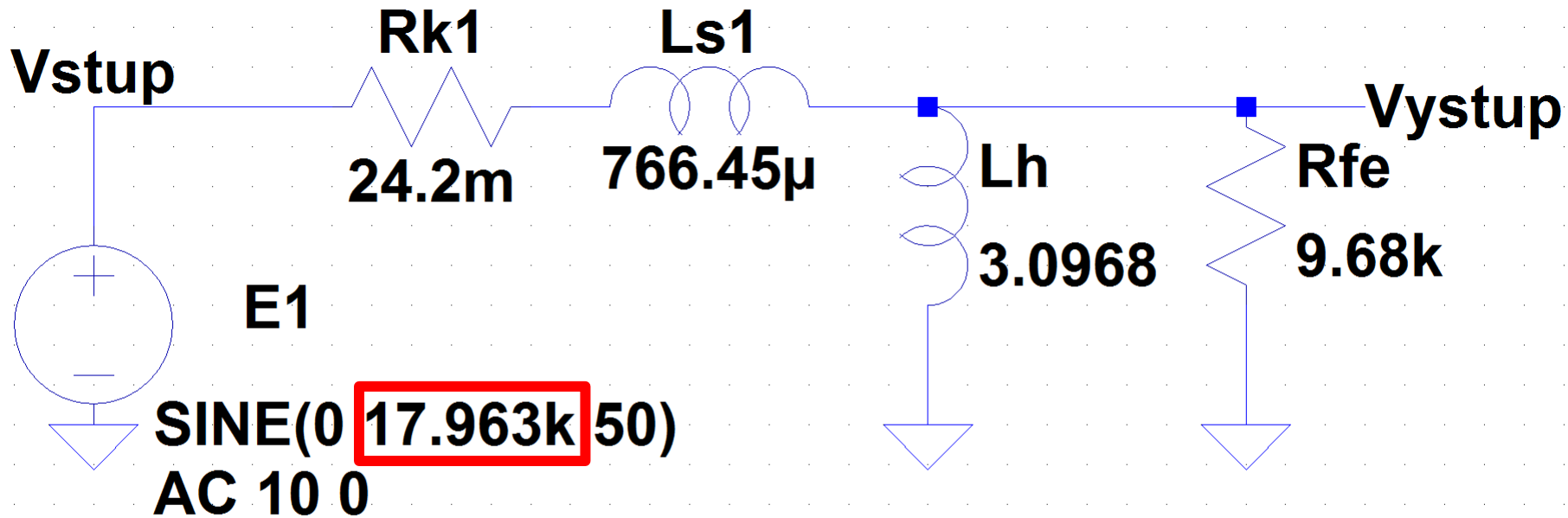
Chod naprázdno - DYNAST

Transformator naprazdno Skupina 1 2017

Odporová přesně zpoždění
 $0.005 + 0.0046812$

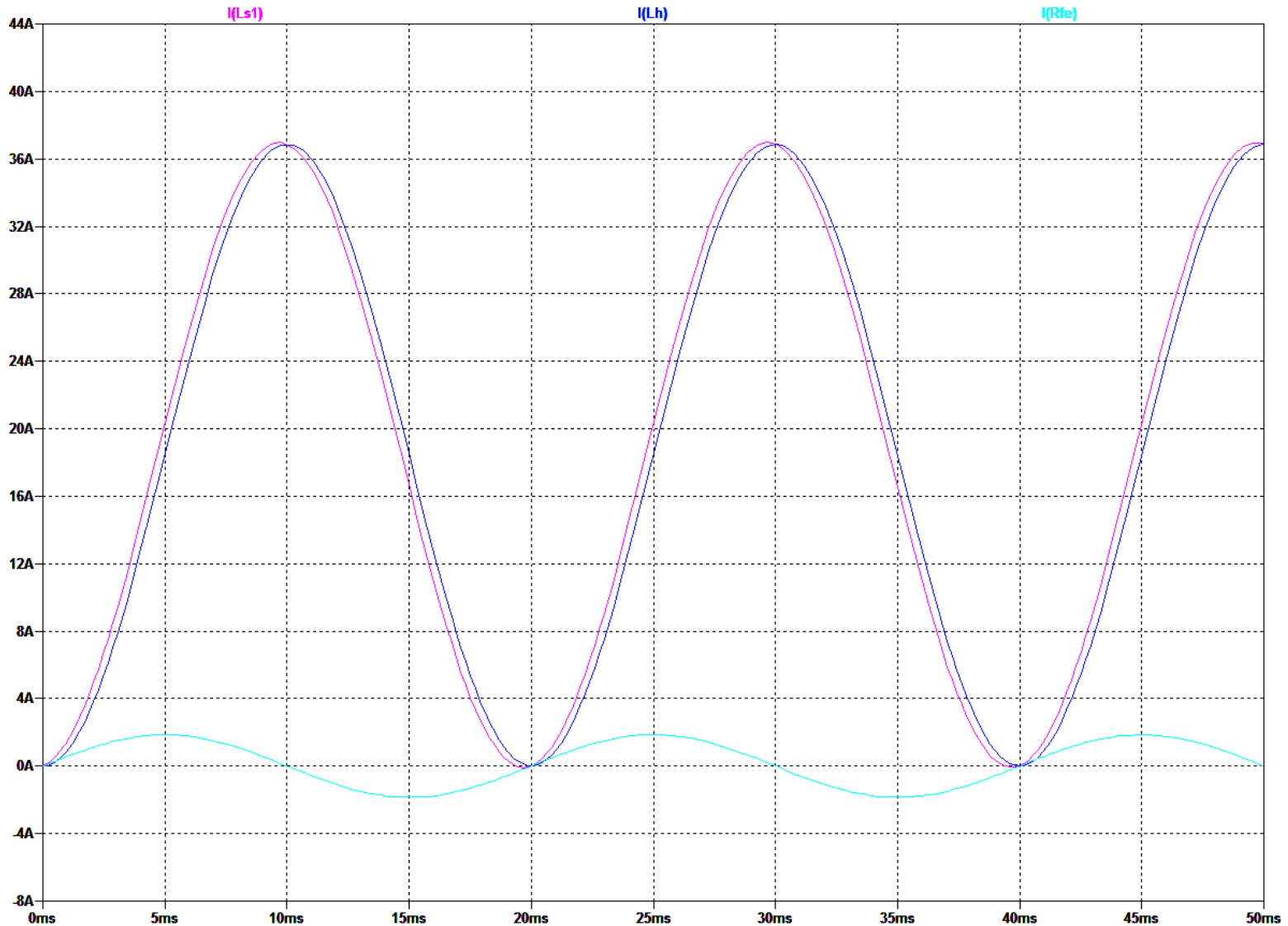


Chod naprázdno - LTspice

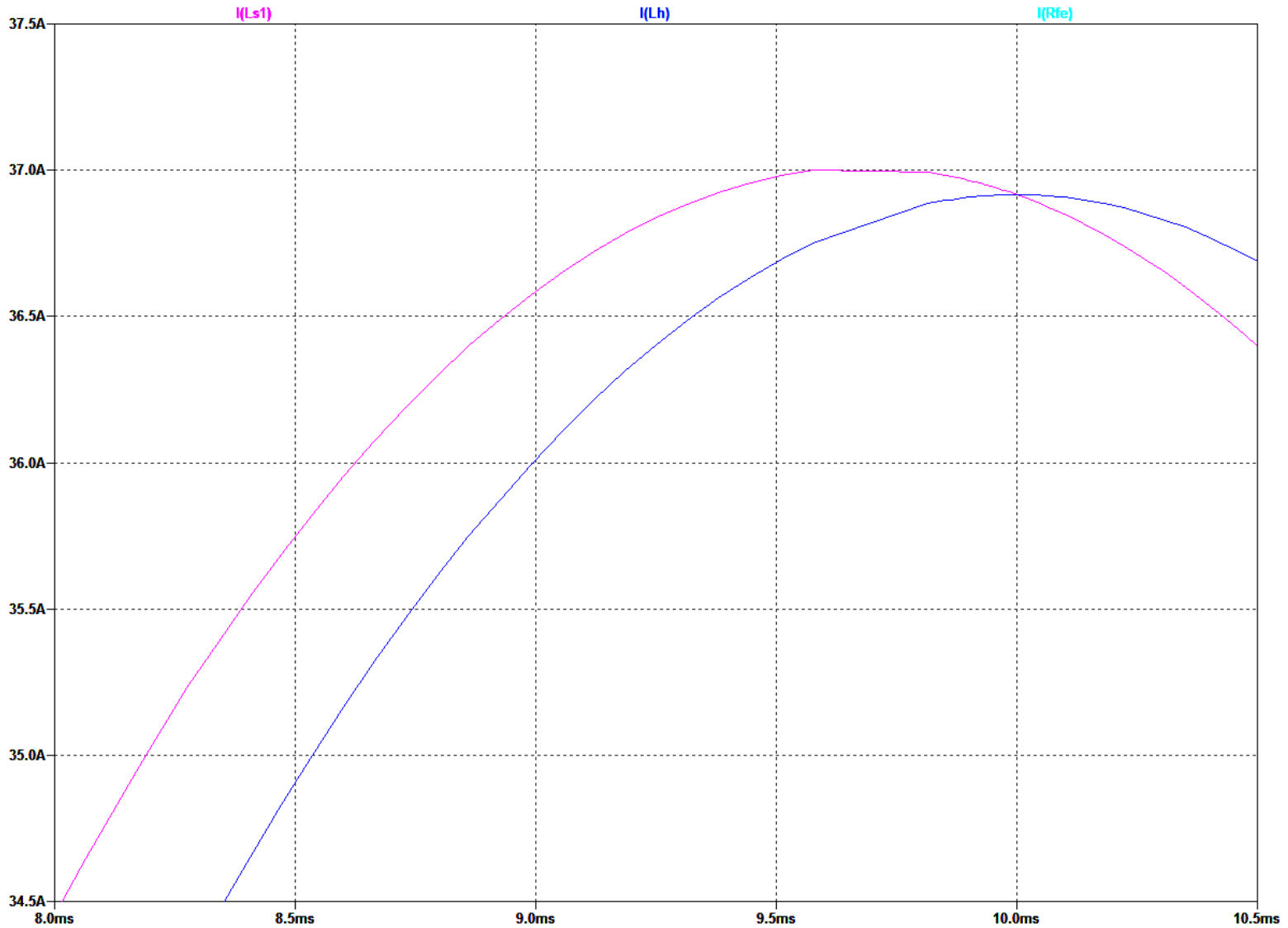


```
.tran 0 0.2 0 0.00001  
;ac oct 10 10 100
```

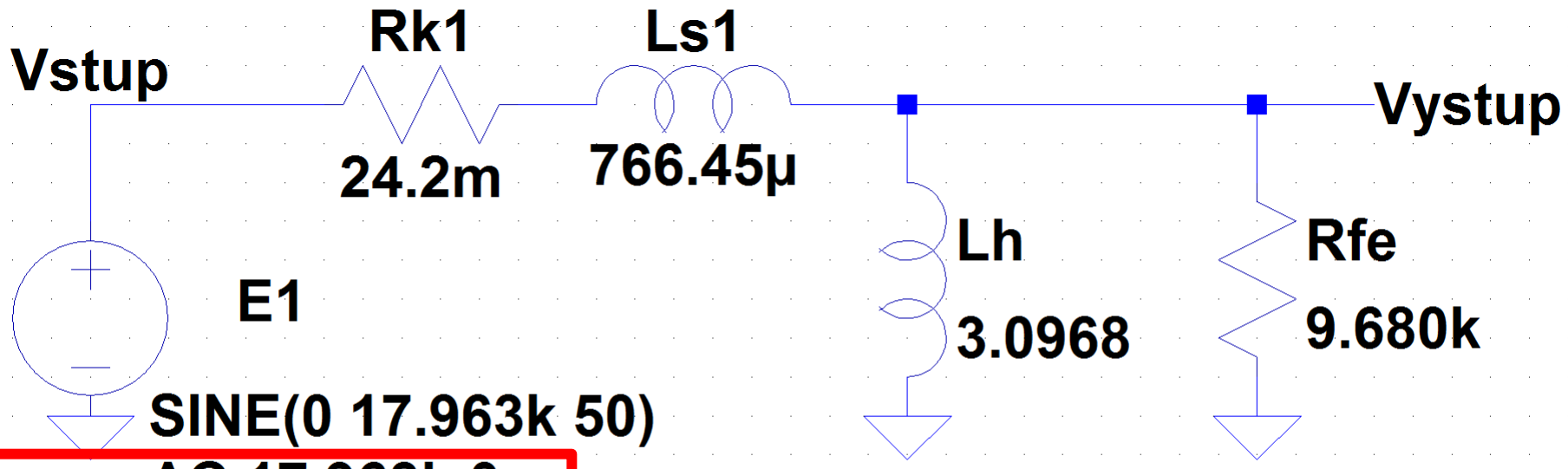
Chod naprázdno - LTspice



Chod naprázdno - LTspice



Chod naprázdno - LTspice



SINE(0 17.963k 50)

AC 17.963k 0

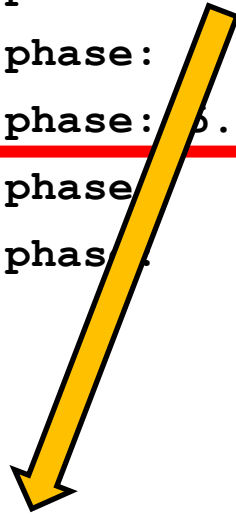
;tran 0.2

.ac lin 1 50 50

Chod naprázdno - LTspice

--- AC Analysis ---

frequency:	50	Hz		
V(n001):	mag:	17963	phase: 0.00142484°	voltage
V(vstup):	mag:	17963	phase: -7.25244e-016°	voltage
V(vystup):	mag:	17958.5	phase: 5.88434e-005°	voltage
I(Ls1):	mag:	18.552	phase: -84.2606°	device_current
I(Lh):	mag:	18.459	phase: -89.9999°	device_current
I(Rfe):	mag:	1.85522	phase: 5.88434e-005°	device_current
I(Rk1):	mag:	18.552	phase: 95.7394°	device_current
I(E1):	mag:	18.552	phase: 95.7394°	device_current



$$-84.2606^\circ / 180^\circ * \pi = -1.4706 \text{ rad}$$

Chod naprázdno – Solve Elec

The screenshot displays the Solve Elec software interface. The main window shows a circuit diagram on a grid background. The circuit consists of an AC voltage source E_1 on the left. A series combination of a resistor R_1 and an inductor L_1 follows. A parallel branch contains a resistor R_3 and an inductor L_3 . This is followed by another series combination of an inductor L_2 and a resistor R_2 . The circuit is terminated by a load consisting of a resistor R_2 and a voltage source U_2 . An ammeter I_1 is placed in series with the source, and a voltmeter U_1 is connected in parallel across the R_1 and L_1 branch. A voltmeter U_2 is connected in parallel across the load. The software's menu bar includes File, Edit, Circuit, Instruments, Report, Windows, and Documentation. The toolbar contains icons for Alternating current, Switch on, Solution, Equations, Graph, Equivalent circuit, Oscilloscope, Transfer function, and Frequency response. A left sidebar contains various circuit components. Below the circuit diagram, a 'Circuit properties' panel is visible, containing a table of component values and a table of calculated results.

<http://www.physicsbox.com/indexsolveelec2en.html>

Circuit properties

Phase reference	E_1				
Frequency	f	50.000	Hz		
R_1	24.200	mOhm			
R_2	24.200	mOhm			
R_3	9.6800	kOhm			
L_1	766.45	μ H			
L_2	766.45	μ H			
L_3	3.0968	H			
E_1	E_1 rms	12.702	kV	$\text{Phi}E_1$	0 rad
U_2	U_2 rms				
U_1	U_1 rms				
I_1	I_1 rms				

Chod naprázdno – Solve Elec

Circuit solved

$$\mathbf{I}_1 = \frac{\mathbf{E}_1 (\omega^2 L_1 L_3 - R_1 R_3) - j \omega \mathbf{E}_1 (L_1 R_3 + L_3 R_1)}{\omega^2 L_1^2 R_3 + 2 \omega^2 L_1 L_3 R_1 + \omega^2 L_1 L_3 R_3 - R_1^2 R_3 - j \omega (-\omega^2 L_1^2 L_3 + 2 L_1 R_1 R_3 + L_3 R_1^2 + L_3 R_1 R_3)}$$

$$I_{1rms} = \frac{\sqrt{(\mathbf{E}_1 (\omega^2 L_1 L_3 - R_1 R_3))^2 + (\omega \mathbf{E}_1 (L_1 R_3 + L_3 R_1))^2}}{\sqrt{(\omega^2 L_1^2 R_3 + 2 \omega^2 L_1 L_3 R_1 + \omega^2 L_1 L_3 R_3 - R_1^2 R_3)^2 + (\omega (-\omega^2 L_1^2 L_3 + 2 L_1 R_1 R_3 + L_3 R_1^2 + L_3 R_1 R_3))^2}}$$

$$I_{1rms} = 13.118 \text{ A}$$

$$\text{Phi}I_1 = -1.4706 \text{ rad}$$

$$\mathbf{U}_2 = \frac{L_3 R_3 \mathbf{E}_1}{L_1 R_3 + L_3 R_1 + L_3 R_3 + j \left(\omega L_1 L_3 - \frac{R_1 R_3}{\omega} \right)}$$

$$U_{2rms} = \frac{L_3 R_3 E_{1rms}}{\sqrt{(L_1 R_3 + L_3 R_1 + L_3 R_3)^2 + \left(\omega L_1 L_3 - \frac{R_1 R_3}{\omega} \right)^2}}$$

$$U_{2rms} = 12.699 \text{ kV}$$

$$\text{Phi}U_2 = -344.08e - 12 \text{ rad}$$

$$\mathbf{U}_1 = \mathbf{E}_1$$

$$U_{1rms} = E_{1rms}$$

$$U_{1rms} = 12.702 \text{ kV}$$

$$\text{Phi}U_1 = 0 \text{ rad}$$

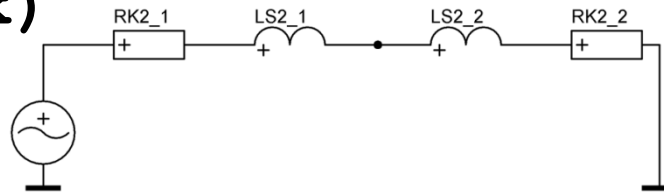
Chod nakrátko - MATLAB

```
% Chod nakratko
```

```
Ikm= (Uk/100) *Um/Zk
```

```
Tau3=Ls/Rk
```

```
Psi3=atan (Xs/Rk)
```



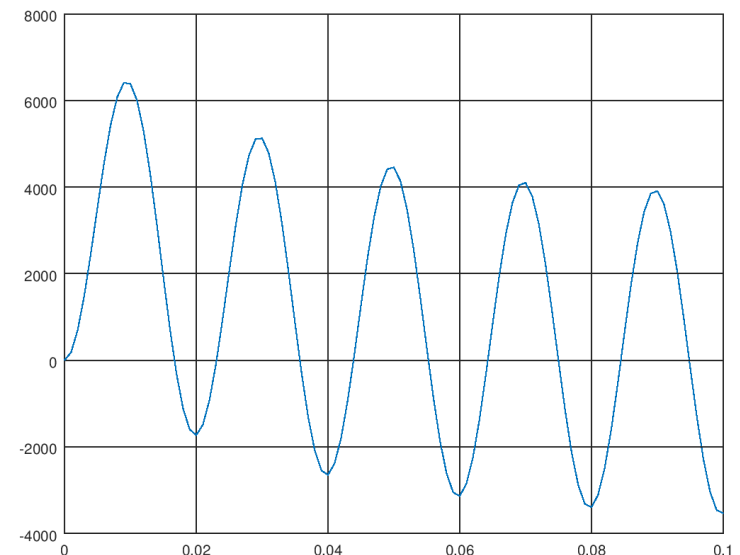
```
Ikm = 3711.3  
Tau3 = 0.031671  
Psi3 = 1.4706
```

```
t=[0:0.001:0.1]';
```

```
Ikt=Ikm*(sin(Psi3)*  
exp(-t/Tau3)+  
sin(Omega*t-Psi3));
```

```
plot(t,Ikt);
```

```
grid on;
```



Chod nakrátko - MATLAB

```
% Chod nakratko
```

```
IkmPom=In*sqrt(2)*2
```

```
Zk2=Rk1+i*Xs1+1/(1/Rfe+1/(i*Xh)  
+1/(Rk1+i*Xs1))
```

```
Ikm2=(Uk/100)*Um/abs(Zk2)
```

```
Psi4=atan(imag(Zk2)/real(Zk2))
```



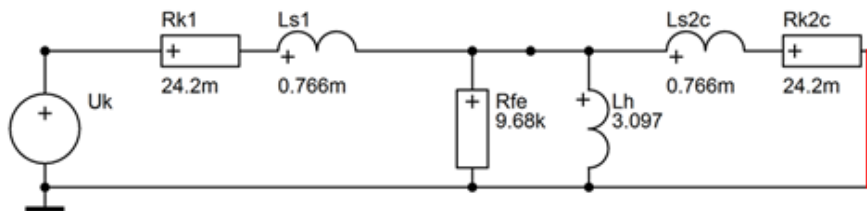
```
IkmPom = 7422.7
```

```
Zk2 = 0.048394 +  
0.481514i
```

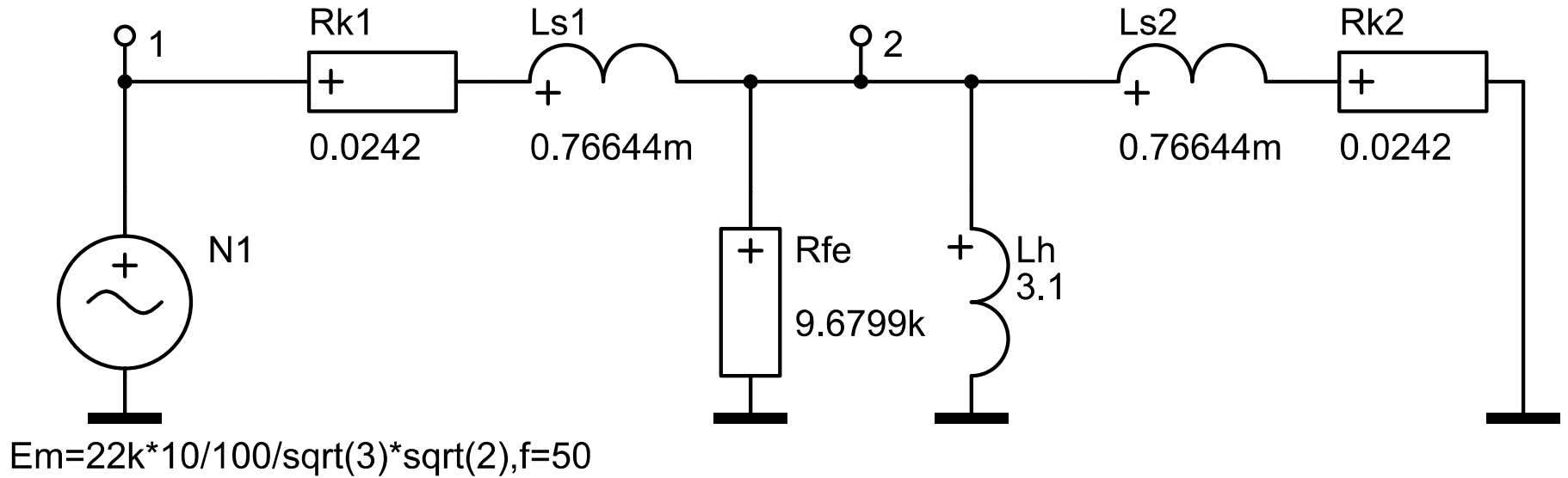
```
Ikm2 = 3711.8
```

```
Psi4 = 1.4706
```

```
Zpozdeni4 = 0.0046812
```

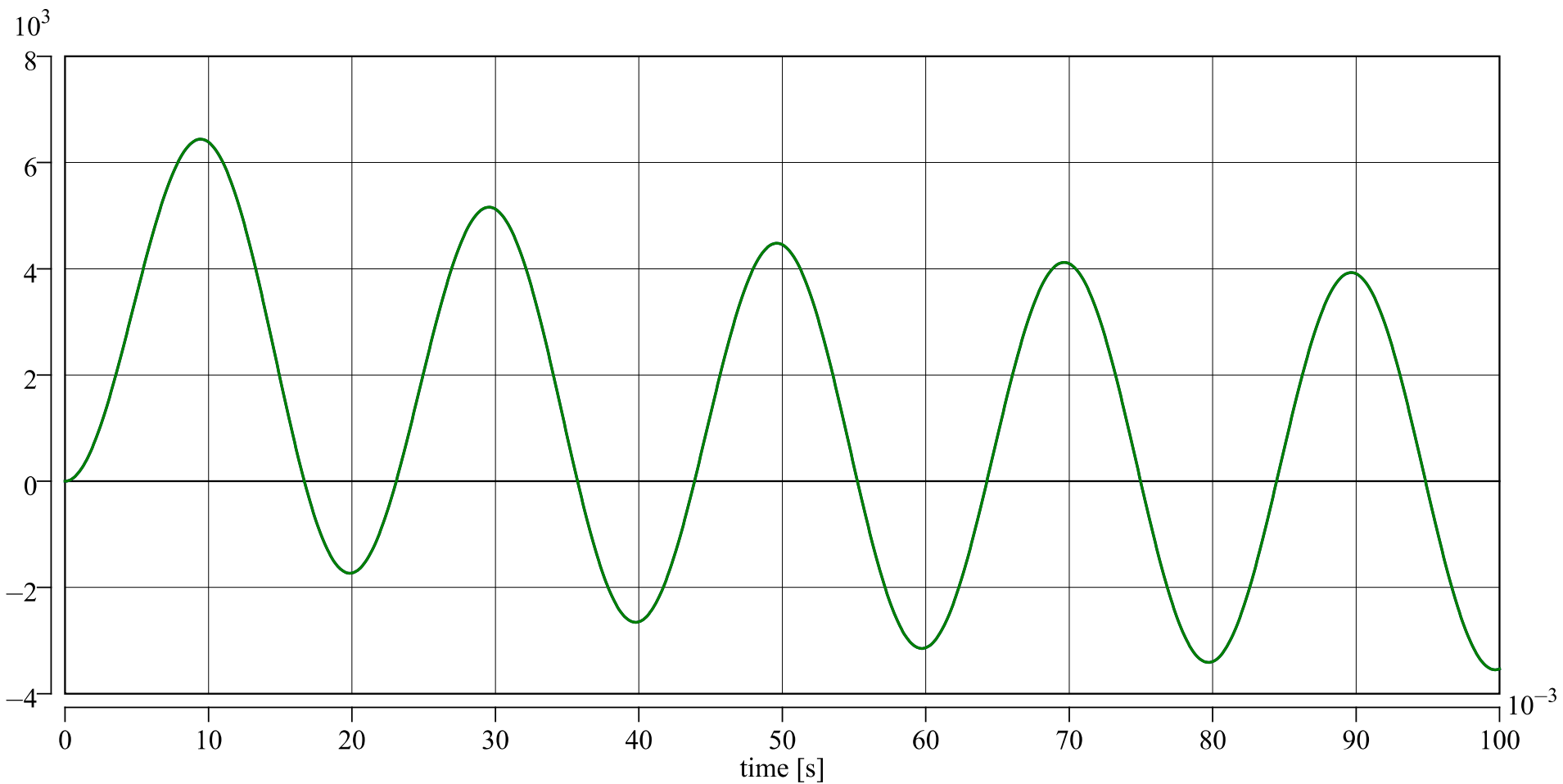


Chod nakrátko - DYNAST



<http://virtual.cvut.cz/dynast/>

Chod nakrátko – DYNAST

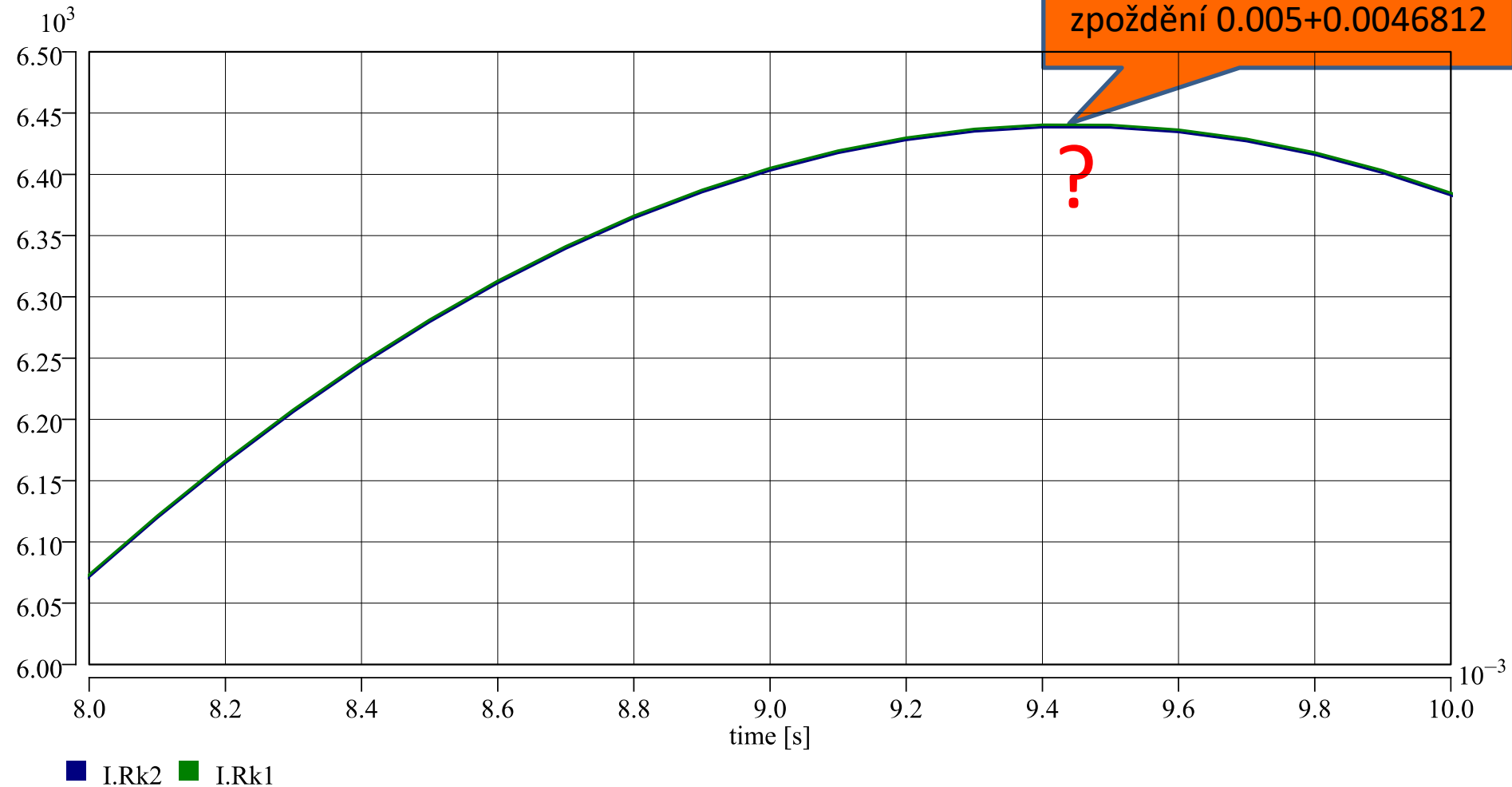


■ I.Rk2 ■ I.Rk1

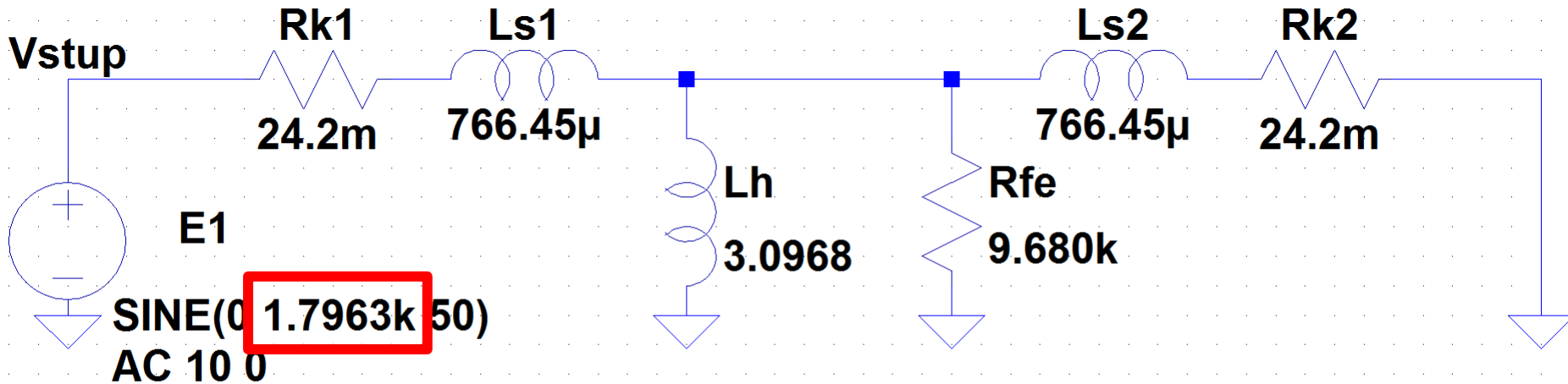
Chod nakrátko - DYNAST

NEodpovídá výrazně
zpoždění 0.005+0.0046812

?

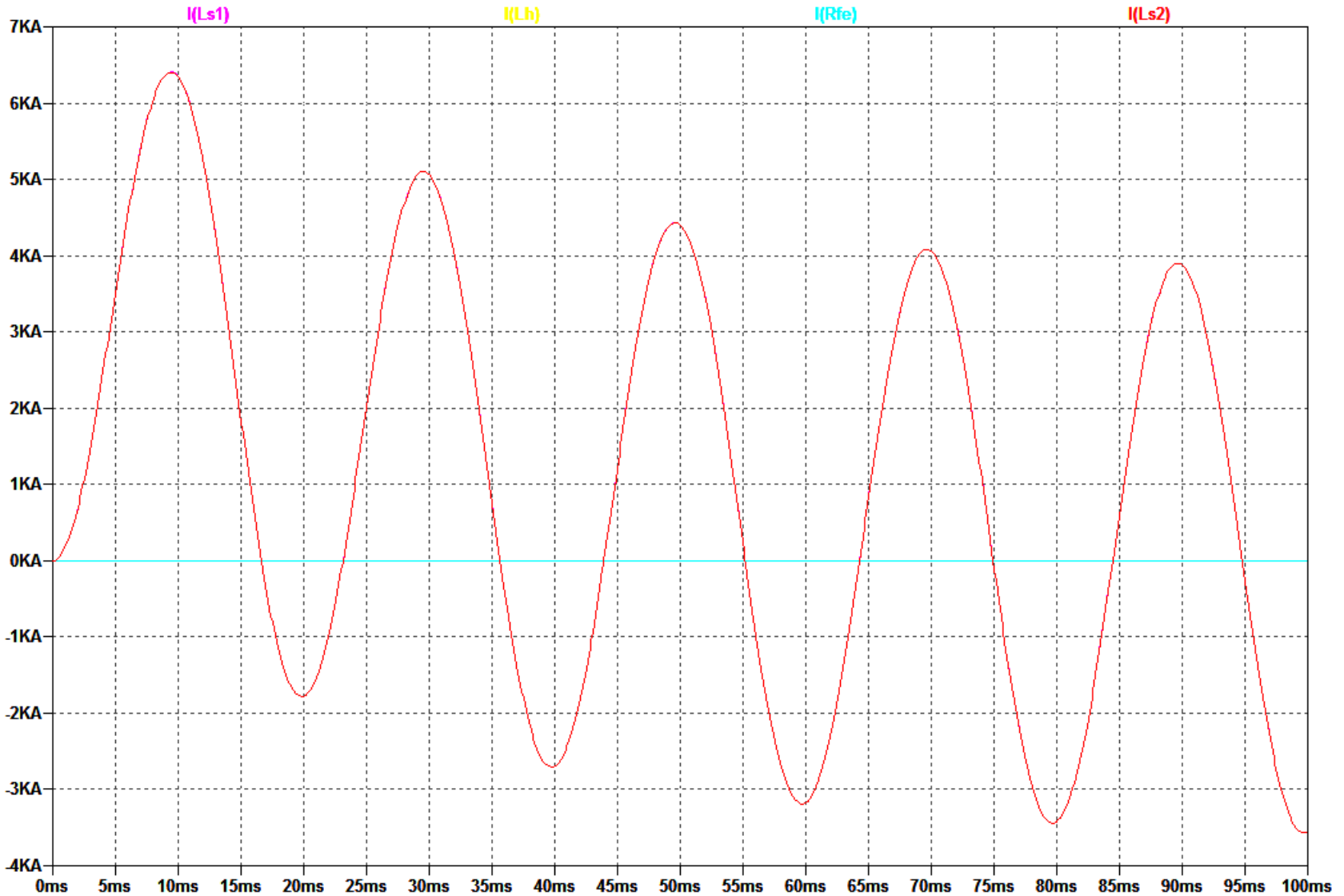


Chod nakrátko - LTspice

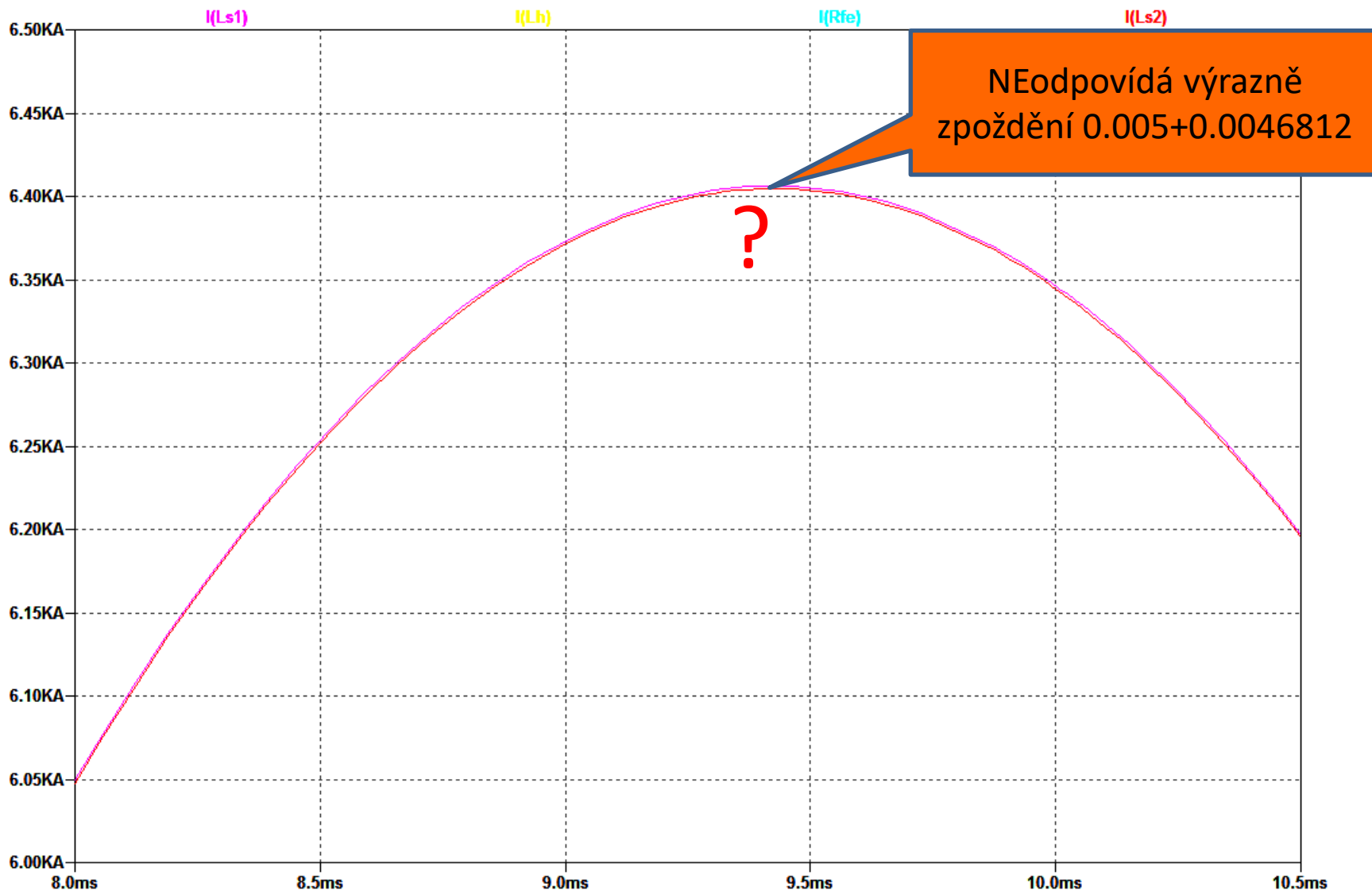


```
.tran 0 0.2 0 0.00001  
;ac oct 10 10 100
```

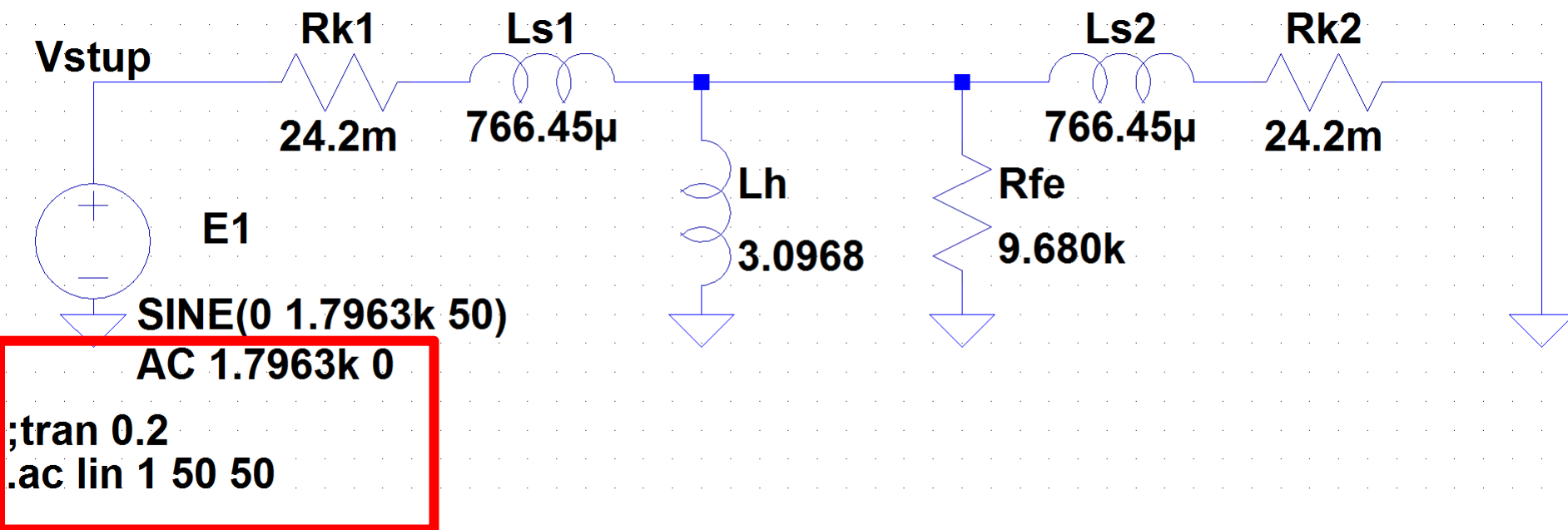
Chod nakrátko - LTspice



Chod nakrátko - LTspice



Chod nakrátko - LTspice



Chod nakrátko - LTspice

--- AC Analysis ---

frequency:	50	Hz		
V(n001):	mag:	1789.18	phase: 2.8609°	voltage
V(vstup):	mag:	1796.3	phase: 9.06555e-016°	voltage
V(n003):	mag:	89.7658	phase: -84.0253°	voltage
V(n002):	mag:	898.038	phase: 2.94254e-005°	voltage
I(Ls1):	mag:	3710.26	phase: -84.0254°	device_current
I(Ls2):	mag:	3709.33	phase: -84.0253°	device_current
I(Lh):	mag:	0.923063	phase: -89.9999°	device_current
I(Rfe):	mag:	0.0927725	phase: 2.94254e-005°	device_current
I(Rk2):	mag:	3709.33	phase: 95.9747°	device_current
I(Rk1):	mag:	3710.26	phase: 95.9746°	dev
I(E1):	mag:	3710.26	phase: 95.9746°	dev

$$-84.0254^\circ / 180^\circ * \pi = -1.4665 \text{ rad}$$

NEodpovídá přesně
-1.4706

Chod nakrátko – Solve Elec

Solve Elec: TrNakratkoSk1.e1n

File Edit Circuit Instruments Report Windows Documentation

Alternating current Switch off Solution Equations Graph Equivalent circuit Oscilloscope Transfer function

The circuit diagram shows an AC voltage source E_1 connected in series with an ammeter I_1 . A voltmeter U_1 is connected in parallel across the source. This is followed by a resistor R_1 and an inductor L_1 in series. A parallel branch contains a resistor R_3 and an inductor L_3 . This is followed by another inductor L_2 and a resistor R_2 in series, with an ammeter I_2 connected in parallel across the final resistor R_2 .

Circuit properties

Phase reference	E_1				
Frequency	f	50.000	Hz		
f / 10	f x 10				
R_1	24.200	mOhm			
R_2	24.200	mOhm			
R_3	9.6800	kOhm			
L_1	766.45	μ H			
L_2	766.45	μ H			
L_3	2.0068	μ H			
E_1	$E_{1,rms}$	1.2702	kV	$\text{Phi}E_1$	0 rad
U_1	$U_{1,rms}$	$\text{Phi}U_1$			
I_1	$I_{1,rms}$	$\text{Phi}I_1$			
I_2	$I_{2,rms}$	$\text{Phi}I_2$			

Chod nakrátko – Solve Elec

Circuit solved

$$I_{1rms} = 2.6247 \text{ kA}$$

$$\text{Phi}i_1 = -1.4706 \text{ rad}$$

$$I_2 = \frac{L_3 R_3 E_1}{-w^2 L_1 L_2 L_3 + L_1 R_2 R_3 + L_2 R_1 R_3 + L_3 R_1 R_2 + L_3 R_1 R_3 + L_3 R_2 R_3 + j \left(w L_1 L_2 R_3 + w L_1 L_3 R_2 + w L_1 L_3 R_3 + w L_2 L_3 R_1 + w L_2 L_3 R_3 - \frac{R_1 R_2 R_3}{w} \right)}$$

$$I_{2rms} = \frac{L_3 R_3 E_{1rms}}{\sqrt{\left(-w^2 L_1 L_2 L_3 + L_1 R_2 R_3 + L_2 R_1 R_3 + L_3 R_1 R_2 + L_3 R_1 R_3 + L_3 R_2 R_3 \right)^2 + \left(w L_1 L_2 R_3 + w L_1 L_3 R_2 + w L_1 L_3 R_3 + w L_2 L_3 R_1 + w L_2 L_3 R_3 - \frac{R_1 R_2 R_3}{w} \right)^2}}$$

$$I_{2rms} = 2.6240 \text{ kA}$$

$$\text{Phi}i_2 = -1.4706 \text{ rad}$$

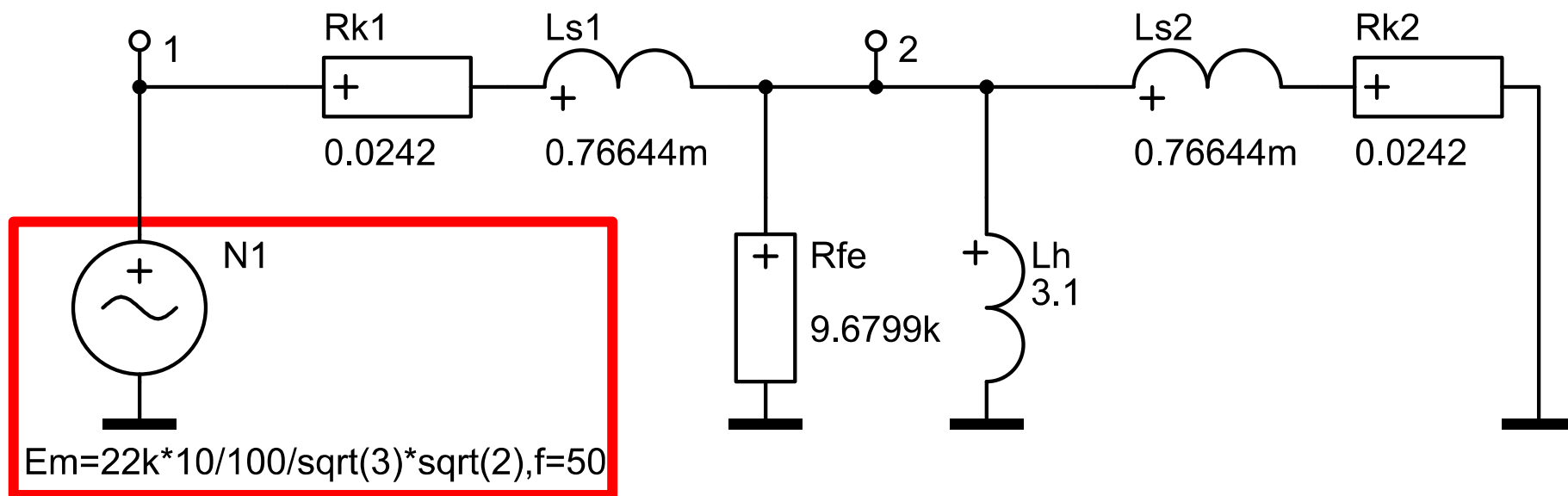
$$U_1 = E_1$$

$$U_{1rms} = E_{1rms}$$

$$U_{1rms} = 1.2702 \text{ kV}$$

$$\text{Phi}U_1 = 0 \text{ rad}$$

Chod nakrátko - DYNAST - SKM



<http://virtual.cvut.cz/dynast/>

Chod nakrátko - DYNAST - SKM

Transformator

X ... freq [Hz]
1 ... MOD.I.Rk1
2 ... RAD.I.Rk1
3 ... MOD.I.Rk2
4 ... RAD.I.Rk2

X	1	2	3	4
5.000000e+001	3.711853e+003	4.812558e+000	3.710926e+003	4.812558e+000

$$4.812558e+000 - 2 * \pi = -1.4706 \text{ rad}$$

Odpovídá přesně
-1.4706

Chod nakrátko - MATLAB

```
IkmPom = 7422.7
```

```
Zk2 = 0.048394 +  
      0.481514i
```

```
Ikm2 = 3711.8
```

```
Psi4 = 1.4706
```

```
Zpozdeni4 = 0.0046812
```

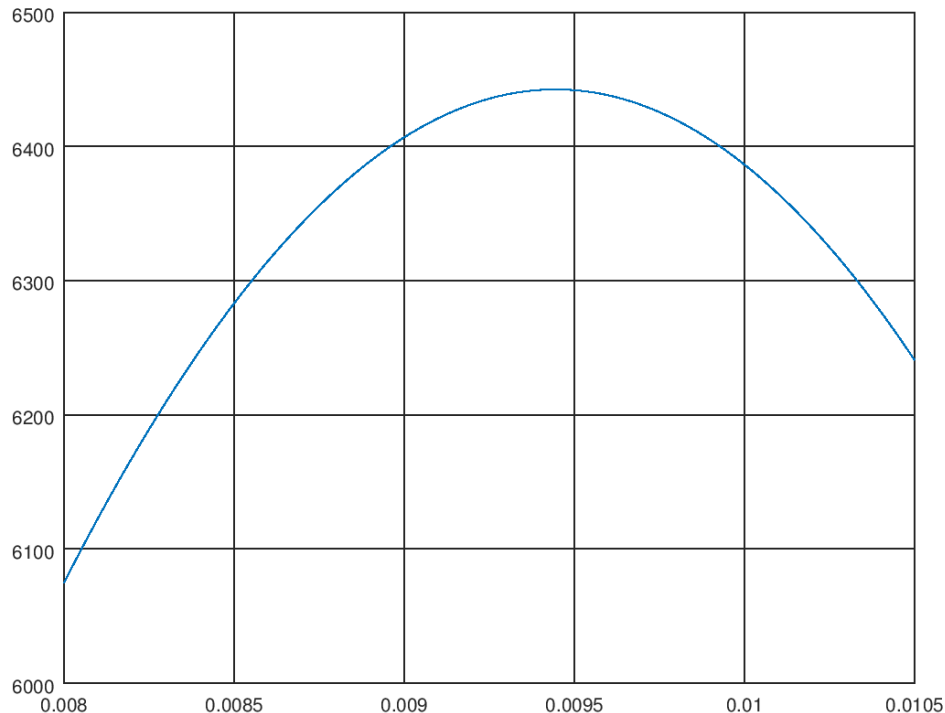
```
% Chod nakratko - detail
```

```
t=[0.008:0.00001:0.0105]';
```

```
Ikt2=Ikm2*(sin(Psi4)*exp(-t/Tau3)  
          +sin(Omega*t-Psi4));
```

```
plot(t,Ikt2);
```

```
grid on;
```



Chod nakrátko - MATLAB

```
t=[0.008:0.00001:0.0105]';
```

```
Ikt2=Ikm2*(sin(Psi4)*exp(-t/Tau3)  
+sin(Omega*t-Psi4));
```

```
Ikt3=Ikm2*(sin(Psi4)*exp(-0.0095/Tau3)  
+sin(Omega*t-Psi4));
```

```
plot(t,Ikt2,t,Ikt3);
```

