Теория

$$0 = \frac{d}{dt}\Psi(Hl) + L_н\cdot\left(\frac{d}{dt}i2\right) + R_н\cdot i2$$

$$Hl = i1\cdot w1 + i2\cdot w2 \qquad i2 = \frac{Hl - i1\cdot w1}{w2}$$

$$0 = \frac{d}{dt}\Psi(Hl(t)) + L_н\cdot\left(\frac{d}{dt}\frac{Hl(t) - i1(t)\cdot w1}{w2}\right) + R_н\cdot\frac{Hl - i1(t)\cdot w1}{w2}$$

$$L_н\cdot\frac{d}{dt}i2(t) = \frac{L_н}{w2}\cdot\frac{d}{dt}Hl(t) - L_н\cdot\frac{w1}{w2}\cdot\frac{d}{dt}i1(t)$$

$$0 = \frac{d}{dt}\Psi(Hl(t)) + L_н\cdot\left(\frac{d}{dt}i2(t)\right) + R_н\cdot i2(t)$$

$$0 = \frac{d}{dt}\Psi(Hl(t)) + \left(\frac{L_н}{w2}\cdot\frac{d}{dt}Hl(t) - L_н\cdot\frac{w1}{w2}\cdot\frac{d}{dt}i1(t)\right) + R_н\cdot\left(\frac{Hl(t)}{w2} - i1(t)\cdot\frac{w1}{w2}\right)$$

$$\frac{d}{dt}\Psi(Hl(t)) = -\left(\frac{L_н}{w2}\cdot\frac{d}{dt}Hl(t) - L_н\cdot\frac{w1}{w2}\cdot\frac{d}{dt}i1(t)\right) - R_н\cdot\left(\frac{Hl}{w2} - i1(t)\cdot\frac{w1}{w2}\right)$$

$$0 = \frac{d}{dHl}\Psi(Hl)\cdot\frac{d}{dt}Hl(t) + L_н\cdot\left(\frac{d}{dt}\frac{Hl(t) - i1(t)\cdot w1}{w2}\right) + R_н\cdot\frac{Hl - i1(t)\cdot w1}{w2}$$

$$\frac{d}{dt}Hl(t) = \left(\frac{d}{dHl}\Psi(Hl) + \frac{L_н}{w2}\right)^{-1}\cdot\left[\frac{w1}{w2}\cdot\left(R_н\cdot i1(t) + L_н\cdot\frac{d}{dt}i1(t)\right) - \frac{Hl\cdot R_н}{w2}\right]$$

Построение приблизительной ВАХ

$f := 50$

$\omega := 2\cdot\pi\cdot f = 314.159$

$K_{ном} := 30$ $\quad S_{ном} := 45$ ВА $\quad I2_{ном} := 5$ А $\quad R2 := 0.25$

$w1 := 1 \quad w2 := \frac{1000}{5} = 200$

Погрешности в нормальном режиме и режиме КЗ

$\delta_{норм} := 0.01 \quad \delta_{КЗ} := 0.1 \quad K_U := 0.7$

Приблизительный расчет индуктивности рассеяния

Собственное сопротивление вторичной обмотки

$$X22 = \frac{U_2}{I_2} = \frac{K_U\cdot K_{ном}\cdot R_{ном}\cdot I2_{ном}}{\delta_{норм}\cdot I2_{ном}} = \frac{K_U}{\delta_{норм}}\cdot\frac{K_{ном}\cdot S_{ном}}{I2_{ном}^2}$$

Известно, что сквозное сопротивление вычисляется по формуле

$$Xk = \left(1 - \alpha^2\right)\cdot X22$$

$$\alpha = \sqrt{1 - \frac{Xk}{X22}}$$

По аналогии с силовым трансформатором, пусть uk=5%, Ix=1%

$uk := 5 \qquad Ix := 1$

$$Xk = \frac{uk}{100}\cdot\frac{Uном^2}{Sном} \qquad X22 = \frac{100}{Ix}\cdot\frac{Uном^2}{Sном} \qquad \alpha = \sqrt{1-\frac{Xk}{X22}} = \sqrt{1-\frac{uk}{100}\cdot\frac{Ix}{100}}$$

$$L_{pac} = \frac{1}{\omega}\cdot(1-\alpha)\cdot X22 = \frac{1}{\omega}\cdot\left(1-\sqrt{1-\frac{uk}{100}\cdot\frac{Ix}{100}}\right)\cdot\frac{0.9}{0.03}\cdot\frac{Kном\cdot Sном}{I2ном^2}$$

$$L_{pac} := \frac{1}{\omega}\cdot\left(1-\sqrt{1-\frac{uk\cdot Ix}{100\cdot 100}}\right)\cdot\frac{K_U}{\delta_{норм}}\cdot\frac{Kном\cdot Sном}{I2ном^2} = 3.008\times 10^{-3}$$

Очевидно, что

$$\Psi(Hl) = \Psi'(Hl) + L_{pac}\cdot i2 = \Psi'(Hl) + \frac{L_{pac}}{w2}\cdot Hl$$

$$U2max = Kном\cdot Rном\cdot I2ном = Kном\cdot\frac{Sном}{I2ном}$$

$$U2max := 0.9\cdot Kном\cdot\frac{Sном}{I2ном} = 243 \quad \text{В}$$

$$U_2 := \sqrt{2}\cdot\left(-U2max \quad -K_U\cdot U2max \quad 0 \quad K_U\cdot U2max \quad U2max\right) = (-343.654 \quad -240.558 \quad 0 \quad 240.558 \quad 343.654)$$

$$I_2 := \sqrt{2}\cdot\left(-\delta_{K3}\cdot Kном\cdot I2ном \quad -\delta_{норм}\cdot I2ном \quad 0 \quad \delta_{норм}\cdot I2ном \quad \delta_{K3}\cdot Kном\cdot I2ном\right) = (-21.213 \quad -0.071 \quad 0 \quad 0.071 \quad 21.213)$$

$$\Psi_2 := \frac{1}{\omega}\cdot U_2 = (-1.094 \quad -0.766 \quad 0 \quad 0.766 \quad 1.094)$$

$$Hl_2 := w2\cdot I_2 = \left(-4.243\times 10^3 \quad -14.142 \quad 0 \quad 14.142 \quad 4.243\times 10^3\right)$$

$$\Psi_{max} := \frac{\sqrt{2}\cdot U2max}{\omega} = 1.094 \qquad k := \frac{\left(\frac{\sqrt{2}}{\omega}\cdot U2max\right)}{\left(\sqrt{2}\cdot\delta_{норм}\cdot I2ном\cdot w2\right)} = 0.077$$

$k0 := 0$

$P1 := 0.25 \qquad k1 := k$

$P2 := 0.25 \qquad k2 := k1\cdot 0.2$

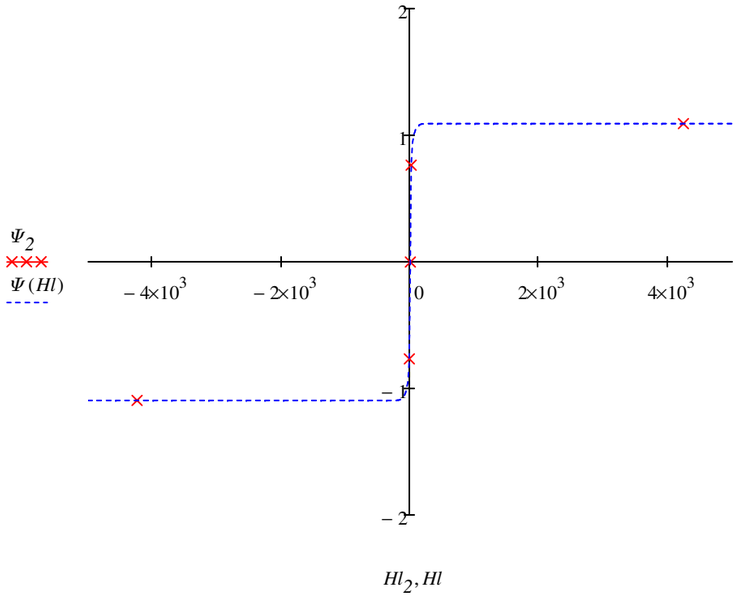
$P3 := 0.25 \qquad k3 := k1$

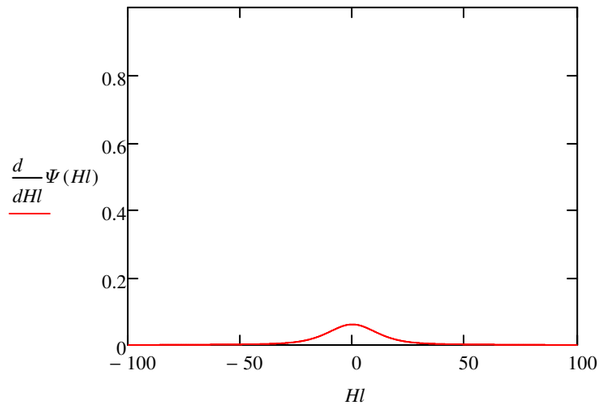
$P4 := 0.25 \qquad k4 := k1$

$$\Psi(Hl) := \left(k0\cdot Hl + P1\cdot\Psi_{max}\cdot tanh\left(\frac{k1}{\Psi_{max}}\cdot Hl\right) + P2\cdot\Psi_{max}\cdot tanh\left(\frac{k2}{\Psi_{max}}\cdot Hl\right) + P3\cdot\Psi_{max}\cdot tanh\left(\frac{k3}{\Psi_{max}}\cdot Hl\right) + P4\cdot\Psi_{max}\cdot tanh\left(\frac{k4}{\Psi_{max}}\cdot Hl\right)\right)$$

$$d\Psi(Hl) := k0 - P2\cdot k2\cdot tanh\left(\frac{Hl\cdot k2}{\Psi_{max}}\right)^2 - P3\cdot k3\cdot tanh\left(\frac{Hl\cdot k3}{\Psi_{max}}\right)^2 - P4\cdot k4\cdot tanh\left(\frac{Hl\cdot k4}{\Psi_{max}}\right)^2 - P1\cdot k1\cdot tanh\left(\frac{Hl\cdot k1}{\Psi_{max}}\right)^2 + P1\cdot k1 + P2\cdot k2 + P3\cdot k3 + P4\cdot k4$$

$H := -10000, -9999 .. 10000$





$R_H := 46.9614 \cdot \frac{1}{5^2} = 1.878$ $\qquad L_H := \frac{1.75 \cdot 0}{100 \cdot \pi}$

$X :=$

	0	1	2	3	4	5
0	1	0	-55	29	25	2
1	2	$1 \cdot 10^3$	-53	12	39	...

$n := rows(X) = 2.39 \times 10^3$

$k := 0 .. rows(X) - 1$

$t_{ALL_k} := X_{k,1} \cdot 10^{-6}$ $\qquad i_{ALL_k} := X_{k,2} \cdot 0.023041 \cdot \frac{1000}{5}$

$m := 0 .. 80$

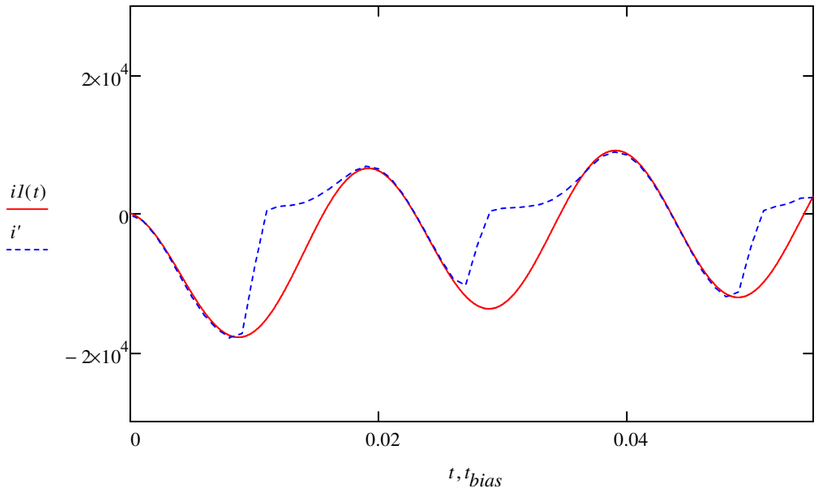
$t'_m := t_{ALL_{m+230}}$ $\qquad i'_m := i_{ALL_{m+230}}$

$\Delta t := 0.236$

$T := 0.022$ $\qquad \omega := 2 \cdot \pi \cdot 50$ $\qquad Im := 10920$ $\qquad \varphi := 108 \cdot \frac{\pi}{180}$ $\qquad Iexp := -Im \cdot sin(\varphi) - i_{ALL_{236}}$

$t_{bias_m} := t'_m - \Delta t$

$i1(t) := Im \cdot sin(\omega \cdot t + \varphi) + Iexp \cdot e^{\frac{-t}{T}}$



$$D(t,Hl) := \left(d\Psi(Hl) + \frac{L_н + L_{pac}}{w2}\right)^{-1} \cdot \left[\frac{w1}{w2}\cdot\left[(R2 + R_н)\cdot i1(t) + \left(L_н + L_{pac}\right)\cdot\frac{d}{dt}i1(t)\right] - \frac{Hl\cdot(R2 + R_н)}{w2}\right]$$

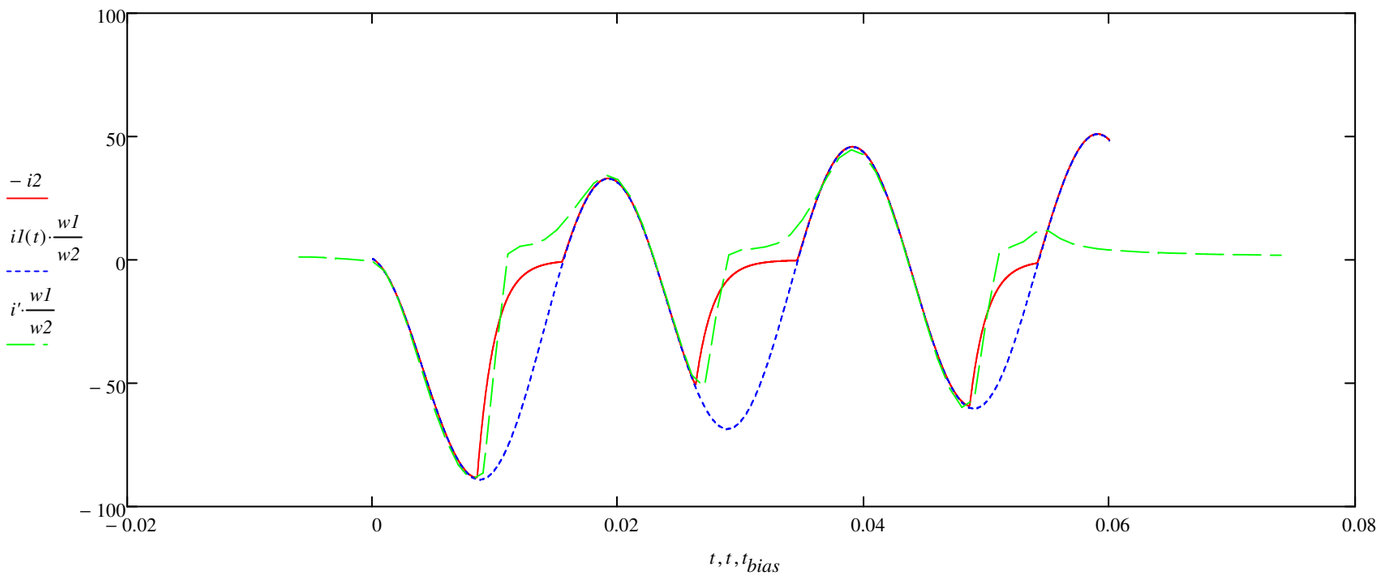
$Hl_{пред} := \delta_{КЗ}\cdot I2ном\cdot w2 = 100$

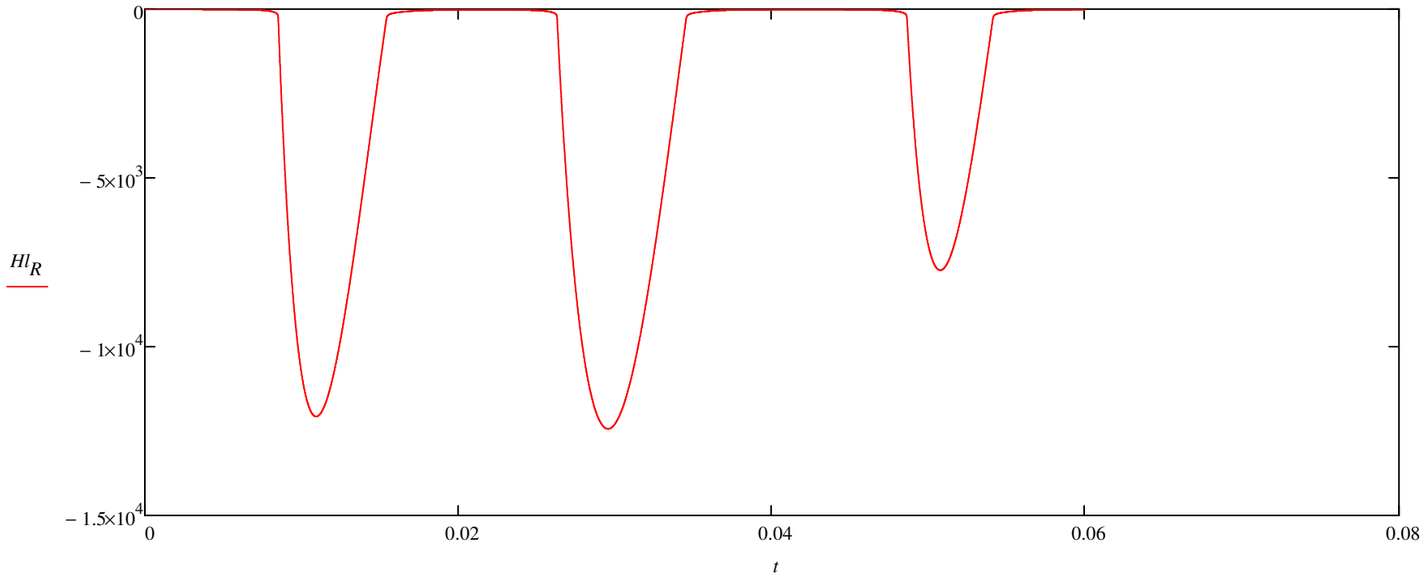
$Hl := 0\cdot Hl_{пред}$ $\qquad N := 6001 \qquad k := 0..N$

$t_{start} := 0 \qquad t_{end} := 0.06$

$Res := rkfixed\left(Hl, t_{start}, t_{end}, N, D\right)$

$t_k := Res_{k,0} \qquad Hl_{R_k} := Res_{k,1} \qquad i2_k := \dfrac{Hl_{R_k} - i1\left(t_k\right)\cdot w1}{w2}$





$$\Delta t := \frac{t_{end} - t_{start}}{N - 1} = 1 \times 10^{-5}$$

$$N_{per} := \frac{1}{f \cdot \Delta t} = 2 \times 10^{3}$$

$$N = 6.001 \times 10^{3}$$

$$j := \sqrt{-1}$$

$$DFT(value, N_{per}, N) := \left| \begin{array}{l} \text{for } n \in 0..N - N_{per} \\ \quad X_n \leftarrow \frac{2 \cdot j}{N_{per}} \cdot \sum_{k=n}^{N_{per}-1+n} \left(value_k \cdot exp(-j \cdot \omega \cdot \Delta t \cdot k)\right) \\ \text{return } X \end{array} \right.$$

$$ABS(value) := \left| \begin{array}{l} \text{for } n \in 0..last(value) \\ \quad Xabs_n \leftarrow \left|value_n\right| \\ \text{return } Xabs \end{array} \right.$$

$$ARG(value) := \left| \begin{array}{l} \text{for } n \in 0..last(value) \\ \quad Xarg_n \leftarrow arg\left(value_n\right) \cdot \frac{180}{\pi} \\ \text{return } Xarg \end{array} \right.$$

$$t_{dft} := \left| \begin{array}{l} \text{for } n \in 0..N - N_{per} \\ \quad t_{dft_n} \leftarrow \left(n \cdot \Delta t + N_{per} \cdot \Delta t\right) \\ \text{return } t_{dft} \end{array} \right.$$

$$ERR(x1, x2) := \left| \begin{array}{l} \frac{x1 - x2}{x2} \cdot 100 \quad \text{if } x2 \neq 0 \\ 0 \quad \text{otherwise} \end{array} \right.$$

$$I_{dft} := DFT(-i2, N_{per}, N) \qquad I_{dft.abs} := ABS\left(I_{dft}\right) \qquad I_{dft.arg} := ARG\left(I_{dft}\right)$$

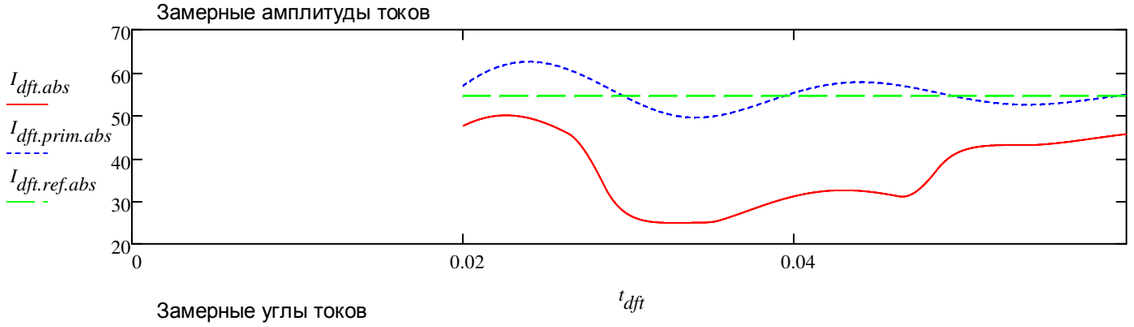
$$i1_{prim_k} := i1\left(t_k\right)$$

$$I_{dft.prim} := DFT\left(i1_{prim} \cdot \frac{w1}{w2}, N_{per}, N\right) \qquad I_{dft.prim.abs} := ABS\left(I_{dft.prim}\right) \qquad I_{dft.prim.arg} := ARG\left(I_{dft.prim}\right)$$

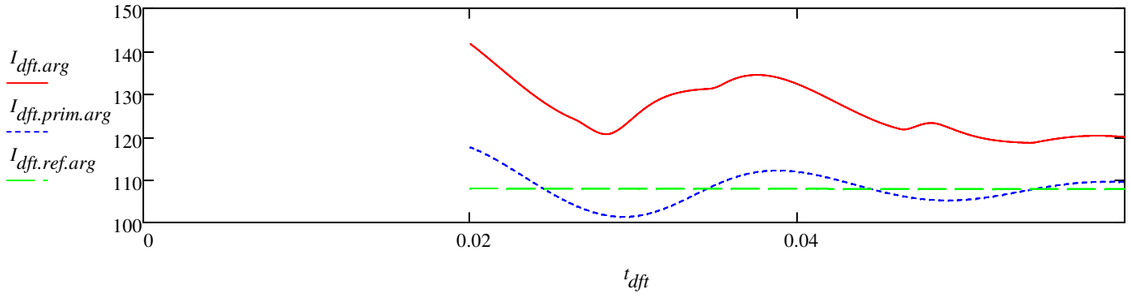
$$i1_{ref_k} := Im \cdot sin\left(\omega \cdot t_k + \varphi\right)$$

$$I_{dft.ref} := DFT\left(i1_{ref} \cdot \frac{w1}{w2}, N_{per}, N\right) \qquad I_{dft.ref.abs} := ABS\left(I_{dft.ref}\right) \qquad I_{dft.ref.arg} := ARG\left(I_{dft.ref}\right)$$

Замерные амплитуды токов



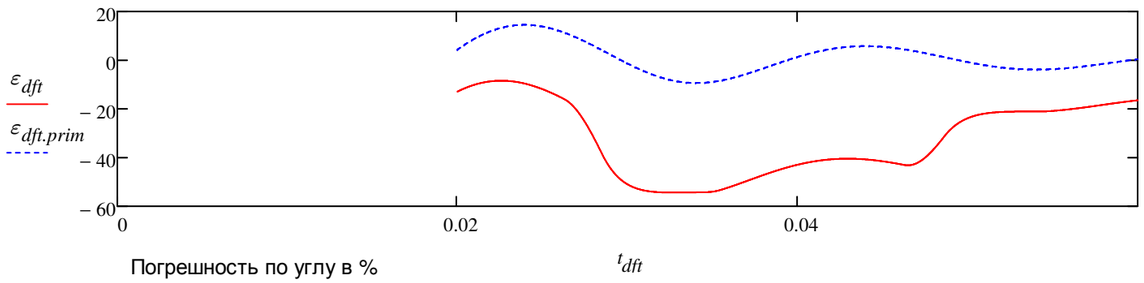
Замерные углы токов



$\varepsilon_{dft} := ERR(I_{dft.abs}, I_{dft.ref.abs})$ $\varepsilon_{dft.prim} := ERR(I_{dft.prim.abs}, I_{dft.ref.abs})$

$\delta_{dft} := ERR(I_{dft.arg}, I_{dft.ref.arg})$ $\delta_{dft.prim} := ERR(I_{dft.prim.arg}, I_{dft.ref.arg})$

Погрешность по модулю в %



Погрешность по углу в %