Section 3.2c Transformer Energization

Section 3.2.5 Saturation Compensation

The effects of the transformer inrush can be minimized by adding a preinsertion resistor. This resistor is an automated device that inserts segments of resistance in series with the transformer terminals. The first segment has the highest resistance value. The resistance is gradually reduced to zero at predetermined time steps. The preinsertion resistor minimizes the inrush by influencing the system response in two ways: it reduces the transient overvoltage at the moment of energization, thereby reducing the maximum core flux, and it increases system damping, causing the flux offset to decay more quickly. The interest in a preinsertion resistor study is to determine the correct timing of the resistor switching and the total energy dissipation into the resistor.

The preinsertion resistor in this simulation is defined as a time varying piece-wise linear resistor. The description is as follows:

Define the number of segments for the piece-wise linear representation of the preinsertion resistor.

$$M := 5$$

$$M := M - 1$$

Define the time and resistance at the knee of each segment.

$$ts := \begin{bmatrix} 0.0 \\ 0.03 \\ 0.06 \\ 0.09 \\ 0.15 \end{bmatrix} \mathbf{s} \qquad Rs := \begin{bmatrix} 80.0 \\ 30 \\ 20 \\ 10 \\ 5 \end{bmatrix} \boldsymbol{\Omega}$$

Use ramps to define the resistor functions.

$$m := 1, 2 .. M$$

Calculate the slope of each segment.

$$S_m := \frac{Rs_m - Rs_{m-1}}{ts_m - ts_{m-1}}$$

$$m := 2 .. M$$

The preinsertion resistor function is given by

$$r(x) := \Phi(x) \cdot x$$

$$Rp(x) := Rs_0 + S_1 \cdot r(x) + \sum_m \left(\left(S_m - S_{m-1}\right) \cdot r\left(x - ts_{m-1}\right)\right)$$

Plot the preinsertion resistor as a function of time.

$$x := 0.0\ \mathbf{s}, 0.003\ \mathbf{s} .. 0.15\ \mathbf{s}$$

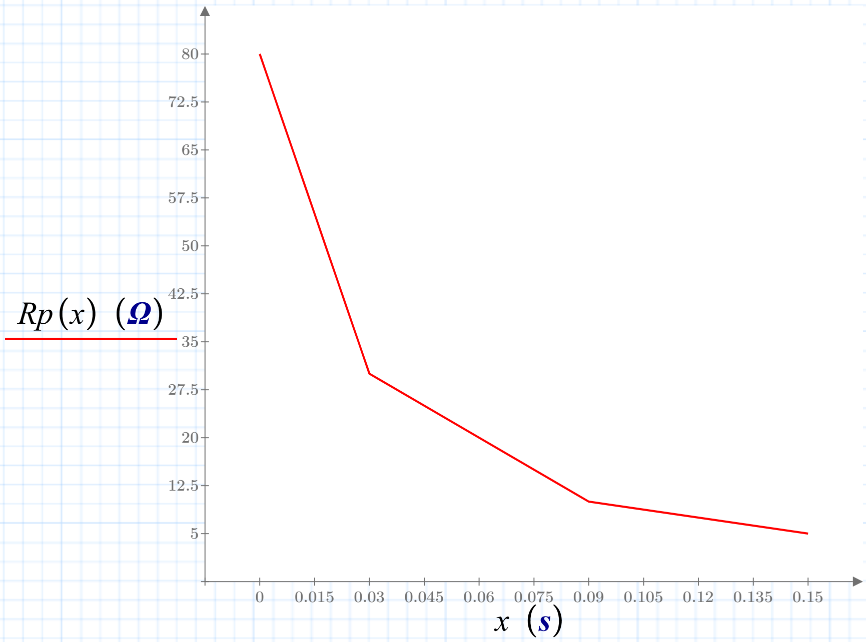

Fig. 3.2.9 Resistance as a function of time

The transformer saturation characteristic is defined as in the previous section:

$I_{mo} := 6\ \mathbf{A}$	steady-state magnetizing current in pu, under rated voltage
$X_s := 8\ \mathbf{\Omega}$	transformer leakage reactance in pu
$V_s := 7000\ \mathbf{V}$	rated primary voltage
$K_\sigma := 1.1$	transformer voltage at saturation knee-point in pu
$\omega := 377\ \dfrac{\mathbf{rad}}{\mathbf{s}}$	source frequency

$$L_m := \frac{\sqrt{\dfrac{2}{3}} \cdot V_s}{\omega \cdot I_{mo}} = 2.527\ \mathbf{H}$$

$$L_s := \frac{X_s}{\omega} \cdot 10 = 0.212\ \mathbf{H}$$

Determine the core flux at the knee point.

$$\lambda\sigma_\sigma := \frac{\sqrt{\frac{2}{3}} \cdot V_s \cdot K_\sigma}{\omega} = 16.676 \ \textbf{Wb}$$

Determine the magnetizing current at the knee point.

$$I_{m\sigma} := \frac{\lambda\sigma_\sigma}{L_m} = 6.6 \ \textbf{A}$$

$$I_m(x) := \left(\frac{1}{L_m}\right) \cdot \left(r\left(x + \lambda\sigma_\sigma\right) - r\left(x - \lambda\sigma_\sigma\right)\right) - \left(\frac{1}{L_s}\right) \cdot \left(r\left(-x - \lambda\sigma_\sigma\right) - r\left(x - \lambda\sigma_\sigma\right)\right) - I_{m\sigma}$$

Similarly the source data are

$Vs := 7000.0 \ \textbf{V}$ voltage amplitude

$\phi o_o := -10 \ \textbf{deg}$

$$V(t) := \sqrt{\frac{2}{3}} \cdot Vs \cdot \cos\left(\omega \cdot t + \phi o_o\right)$$

$\lambda o_o := 5 \ \textbf{Wb}$ residual flux

System data:

$R_L := 3.5 \ \boldsymbol{\Omega}$ line resistance

$X_L := 25 \ \boldsymbol{\Omega}$ line inductive reactance

$$L := \frac{X_L}{\omega} = 0.066 \ \textbf{H}$$

$X_C := 200 \ \boldsymbol{\Omega}$ shunt capacitive reactance

corresponding to

$$C := \frac{1}{\omega \cdot X_C} = \left(1.326 \cdot 10^{-5}\right) \ \textbf{F}$$

Define maximum simulation time.

$T := 0.2 \ \textbf{s}$ $dt := 0.3 \ \textbf{ms}$

$h_1 := 1.5 \cdot dt$ $h_2 := 0.5 \cdot dt$

$$N := \text{floor}\left(\frac{T}{dt}\right)$$

$k := 2 \,..\, N$ iteration counter

$$Dv_c\left(I_L, V_C\right) := \frac{I_L - I_m\left(V_C\right)}{C}$$ capacitor voltage derivative

Define the initial conditions for the system.

Initialize time.

$$t_0 := 0.0\ \boldsymbol{s}$$

$$t_1 := 0.0\ \boldsymbol{s}$$

Compute time at each interval.

$$t_k := k \cdot dt$$

Initialize the capacitor voltage. Assume fault condition in the system prior to energization.

$$v_{c_0} := 0.0\ \boldsymbol{V}$$

$$v_{c_1} := 0.0\ \boldsymbol{V}$$

Initialize the line current.

$$i_0 := 0.0\ \boldsymbol{A}$$

$$i_1 := 0.0\ \boldsymbol{A}$$

The initial value of core flux is the residual flux defined above.

$$\lambda_0 := \lambda o_o$$

$$\lambda_1 := \lambda o_o$$

Due to the presence of the preinsertion resistor the total system resistance is changed. This change affects the state equation of the line current. The new equation is

$$Di\left(I_L, V_C, t\right) := \frac{-\left(R_L + Rp(t)\right) \cdot I_L - V_C + V(t)}{L}$$

Assuming the same conditions as in Section 3.2.4, we obtain

$$\begin{bmatrix} i_k \\ v_{c_k} \\ \lambda_k \end{bmatrix} := \begin{bmatrix} i_{k-1} + h_1 \cdot Di\left(i_{k-1}, v_{c_{k-1}}, t_{k-1}\right) - h_2 \cdot Di\left(i_{k-2}, v_{c_{k-2}}, t_{k-2}\right) \\ v_{c_{k-1}} + h_1 \cdot Dv_c\left(i_{k-1}, \left(\lambda_{k-1}\right)\right) - h_2 \cdot Dv_c\left(i_{k-2}, \left(\lambda_{k-2}\right)\right) \\ \lambda_{k-1} + h_1 \cdot \left(v_{c_{k-1}}\right) - h_2 \cdot \left(v_{c_{k-2}}\right) \end{bmatrix}$$

The system response is shown below.

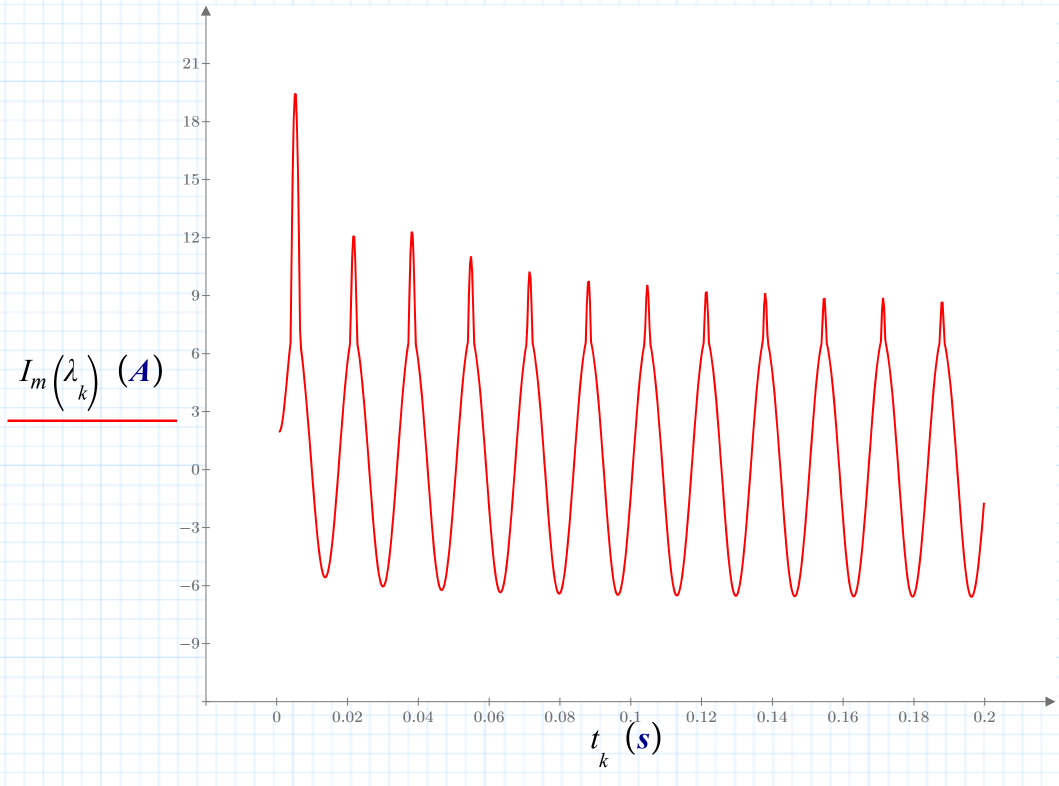

Fig. 3.2.10 Magnetizing current

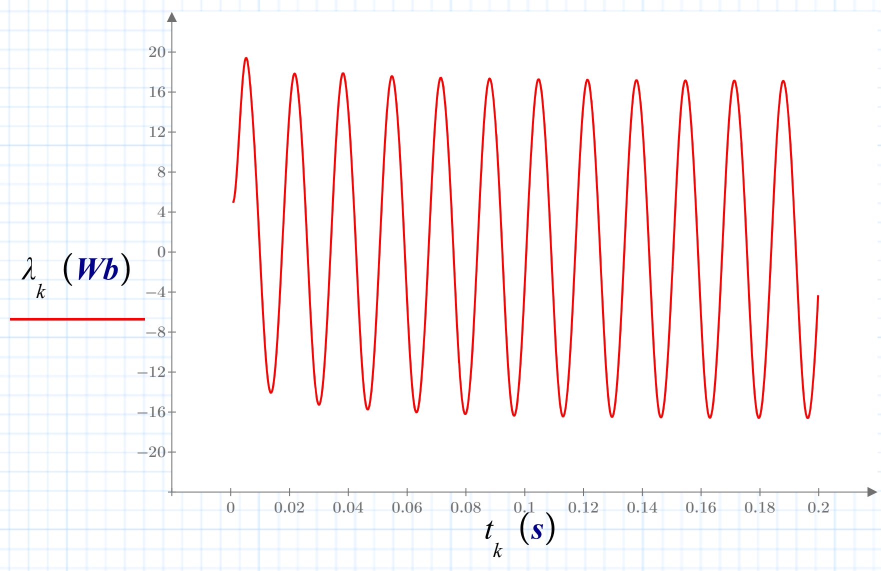

Fig. 3.2.11 Transformer flux response

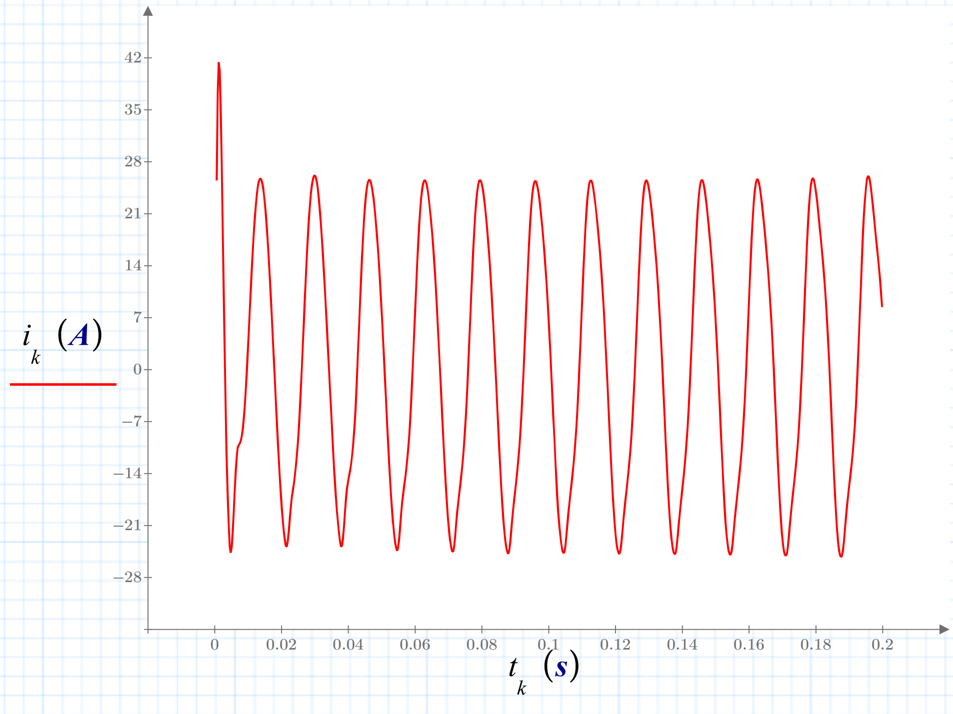

Fig. 3.2.12 Line current response

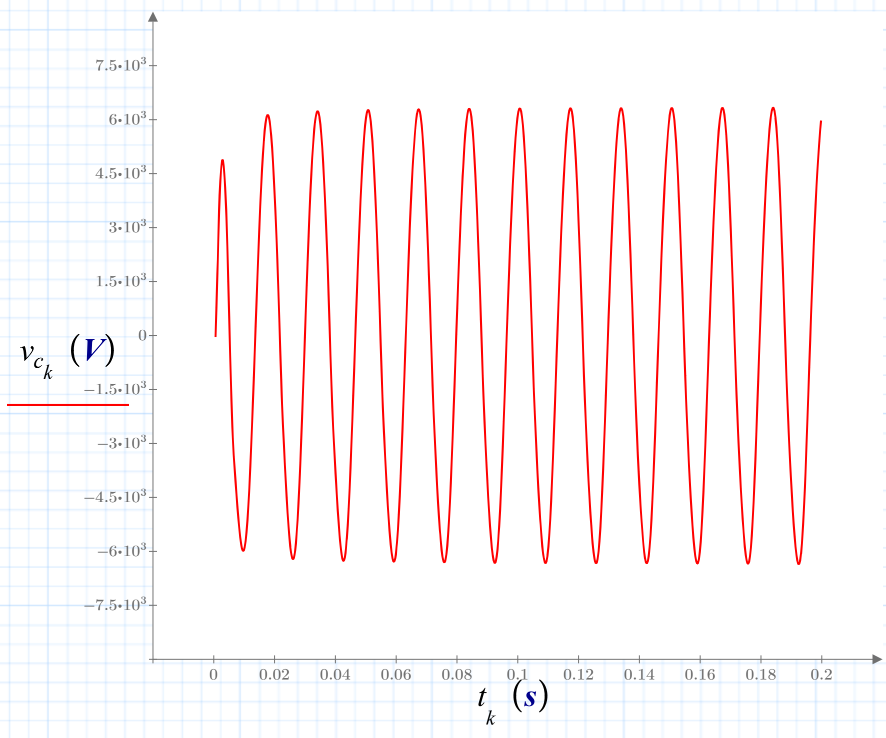

Fig. 3.2.13 Bus voltage response

The preinsertion resistor reduces the 2nd harmonic resonant effects. The initial case exhibited a harmonic instability around the second harmonic (120 Hz) - the uncompensated case is shown in **Section 3.2b**. The preinsertion resistor increases the system damping around this resonance, reducing the transient over-voltages and overcurrents seen in the first case.

When designing the preinsertion resistor, it's a good idea to know how much power it must dissipate, so that it will not be overstressed thermally. The energy dissipated in the preinsertion resistor is found as follows:

Initialize variable:

$$E_1 := 0.0\ J$$

Calculate energy at each time step:

$$E_k := E_{k-1} + Rp\left(t_k\right) \cdot \left(\left(i_k\right)^2\right) \cdot dt$$

The maximum energy dissipation is

$$E_N = \left(1.109 \cdot 10^3\right)\ J$$

The energy is shown as function of time below.

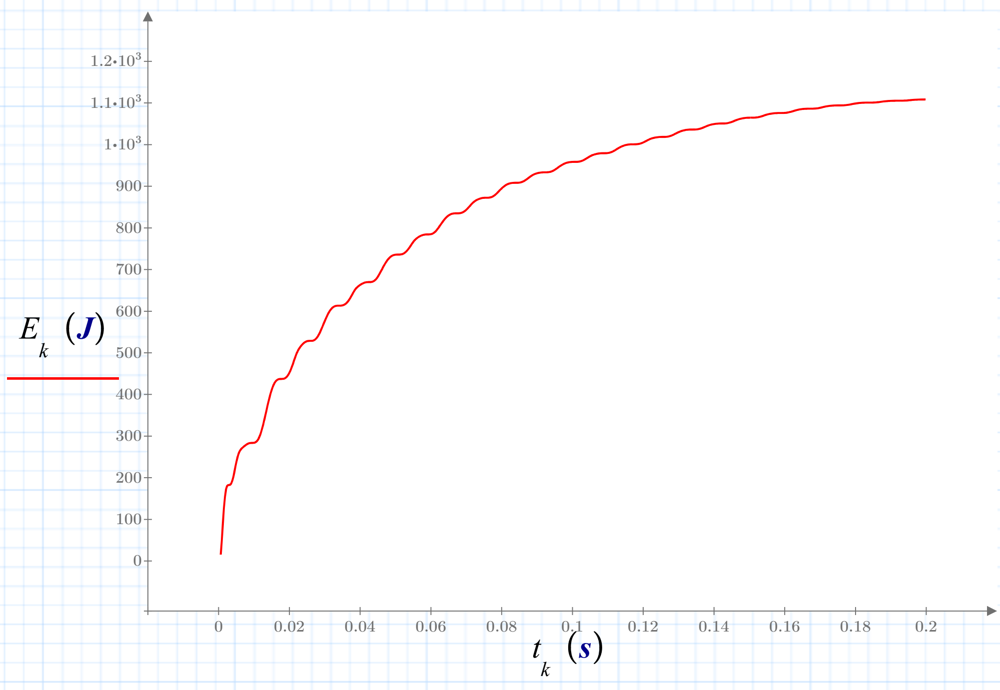

Fig. 3.2.14 Energy dissipation of the preinsertion resistor