Study Committee A2

Power transformers and reactors

A2_PS3_10356_2022

White-box Models Development for Insulation Design and Providing Transformers Withstand to High-Frequency Resonant Overvoltages

V.S. Larin[1], D.A. Matveev[2], M.V. Frolov[2]

[1]All-Russian Electrotechnical Institute (VEI – branch of RFNC-VNIITF), [2]Moscow Power Engineering Institute (NRU MPEI), Russian Federation

Motivation

Power transformers switching together with cable lines in renewable generation systems can be followed by high-frequency voltage oscillations affecting the insulation of that transformers.

One of the possible measures to prove the ability of transformers to withstand high-frequency overvoltages is numerical study using high-frequency transformer models which allow to determine dielectric stresses.

Method/Approach

- Experimental studying and measurements on power transformers.
- Numerical modelling using white-box models.

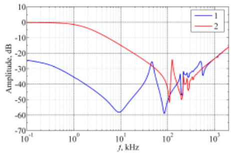
Objects of investigation

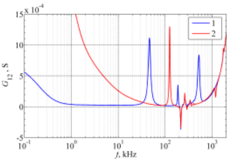
- 1600 kVA 6/0,4 kV cast-coil dry-type transformer;
- 630 kVA 10/0,4 kV cast-coil dry-type transformer with additional taps.

Main results:

1. Determination of natural frequencies and damping factors from winding frequency responses

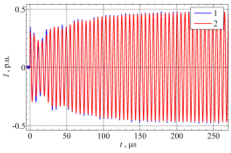
- Determination of natural frequencies by overlapping of active admittance G_{12} corresponding to OC and SC frequency responses;
- Determination of damping factors τ/T from resonance peaks half width of active part of neutral current or reactive part of node voltage transfer function.

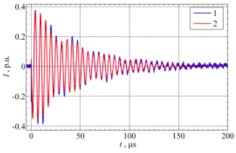




2. Determination of natural frequencies and damping factors via curve fitting of transient voltages and currents waveforms

- Least square fitting of voltage and current waveforms by analytical expressions describing high-frequency transients inside windings.



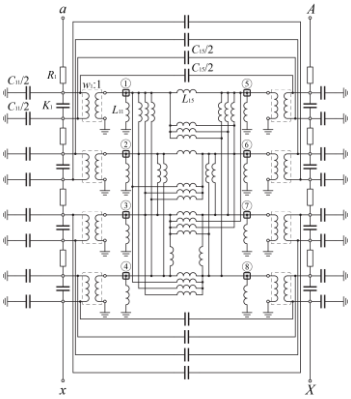


3. Approach to include experimentally obtained damping into white-box models

- Correction of system matric eigenvalues to take account of the frequency dependency of natural oscillations damping.
- Creation of black-box model form fitted white-box model.

4. Wideband transformer model

- Based on a detailed equivalent network of the transformer.
- Self and mutual inductances of winding parts are taken into account by means of series and shunt inductances which are calculated using inductive decoupling.



Conclusion

- For insulation design and providing transformers withstand to high-frequency resonant overvoltages it is necessary to use power transformers white-box models verified by comparison with experimental data on natural frequencies and damping factors.
- The approaches are presented to obtain the natural frequencies and damping factors of power transformer windings from voltage transfer functions of windings internal nodes, winding frequency responses and winding transient voltages and currents.
- Measured damping factors obtained experimentally can be included in numerical models of transformers via eigenvalues correction of matrix of equations system describing transients inside windings.
- An approach to the development of a wideband transformer model correct for both high-frequency and low-frequency transients as well as for steady-state modes is presented.

http://www.cigre.org

CIGRE PARIS 2022

Study Committee A2

Power transformers and reactors

A2_PS3_10356_2022

VNIITF ROSATOM

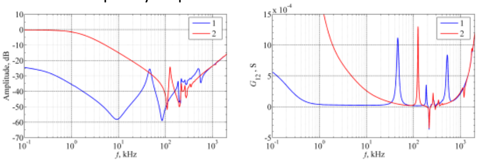
МЭИ

White-box Models Development for Insulation Design and Providing Transformers Withstand to High-Frequency Resonant Overvoltages

continued

1. Determination of natural frequencies and damping factors from winding frequency responses

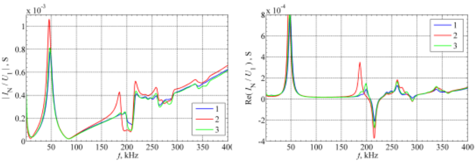
- Measurements of winding frequency responses (with OC and SC secondary winding);
- Determination of natural frequencies by overlapping of active admittance G_{12} corresponding to OC and SC frequency responses:



Frequency response and active admittance G_{12} (1 – HVOC, 2 - HVSC)

- Calculation of neutral current $I_N = (U_2/U_1)/50$ from frequency responses and its active part Re(I_N);
- Determine the damping factor τ/T from resonance peaks half width of Re(I_N) as well as reactive part of node voltage transfer function (e.g., DETC winding taps)

$$\frac{\tau}{T}=\frac{f_{res}}{\gamma}\approx\frac{f_{res}}{\Delta\omega}K_{\gamma}$$ where $$K_{\gamma}=2\sqrt{\sqrt{2}-1}\approx 1{,}3$$



Neutral current IN and its active part (1, 2 and 3 – phase U, V and W)

2. Determination of natural frequencies and damping factors via curve fitting of transient voltages and currents waveforms

- More accurate determination of natural frequencies and damping factors with the use of the approach based on registration and curve fitting of waveforms of transient voltages inside windings and neutral current.
- If internal nodes of power transformer winding, for instance, taps of DETC or OLTC, are available, registration of transient voltages inside winding under impact of undamped sinusoidal voltage source with frequency of interest can be performed.
- In time domain, expressions for voltage u(t) at winding internal node and neutral current i_N(t) can be expressed as follows:

$$u_k(t)=B_1\sin\omega t+B_2\cos\omega t+\sum_{j=1}^{n}\left(B_{2j+1}\sin\omega_j t+B_{2j+2}\cos\omega_j t\right)e^{-\gamma_j t}$$

$$i_N(t)=D_1\sin\omega t+D_2\cos\omega t+\sum_{j=1}^{n}\left(D_{2j+1}\sin\omega_j t+D_{2j+2}\cos\omega_j t\right)e^{-\gamma_j t}+D_0 e^{-\gamma_0 t}$$

Approach to fitting of transient voltages and currents:

1. Determination of forced oscillations frequency f_0 and corresponding amplitudes B_1 and B_2 using steady-state part of the waveform (least-squares fitting with f_0, B_1 and B_2 as independent variables).
2. Calculation of steady-state voltage approximation using determined values of f_0, B_1 and B_2 for the whole registered waveform of transient voltage:

$$u_{ss}(t)=B_1\sin(2\pi f_0 t)+B_2\cos(2\pi f_0 t)$$

3. Determination of free voltage component:

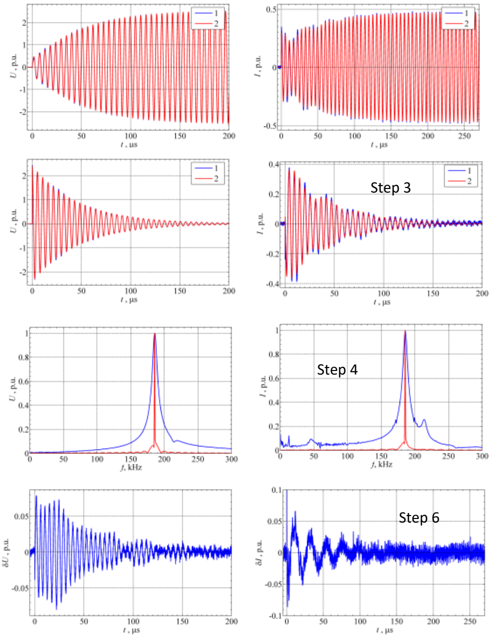
$$u_{free}(t)=u(t)-u_{ss}(t)$$

4. Spectral decomposition of free voltage component $u_{free}(t)$ using Fast Fourier Transform and determination of dominating natural frequencies as points of local maximums of the spectrum.
5. Determination of f_j, B_{2j+1} and γ_j values providing the best fitting of free component using least-squares method (j = 1÷n, where n being a number of used frequencies).

$$u_{free}(t)=\left(B_3\sin\omega_1 t+B_4\cos\omega_1 t\right)e^{-\gamma_1 t}+\left(B_5\sin\omega_2 t+B_6\cos\omega_2 t\right)e^{-\gamma_2 t}$$

6. Estimation of absolute fitting error and assessment of sufficiency of fitted frequencies number n.

$$\delta U(t)=u(t)-u_{ss}(t)-u_{free}(t)$$



Fitting the Voltage at DETC tap (left) and Neutral current (right) (1 – measured, 2 - fitted)

cigre PARIS 2022

Study Committee A2

Power transformers and reactors

A2_PS3_10356_2022

White-box Models Development for Insulation Design and Providing Transformers Withstand to High-Frequency Resonant Overvoltages

continued

Results of natural frequencies and damping factors determination (1600 kVA 6/0,4 kV transformer)

Parameters	Natural frequency number	
	1	3
Natural frequency, kHz, obtained from:		
- transient voltage approximation	185,8	214,4
- neutral current approximation	186,1	214,9
- active admittance G_{12}	186,7	214,3
Damping factors γ, 1/ms, obtained from:		
- transient voltage approximation	21,9	23,1
- neutral current approximation	21,1	23,9
τ / T ratio, obtained from:		
- transient voltage approximation	8,65	9,29
- neutral current approximation	8,80	8,97

3. Approach to include experimentally obtained damping into white-box models

- Undamped transients inside transformer windings can be described using the following system of ordinary differential equations:

$$\begin{cases} \dfrac{dU(t)}{dt} = -\mathbf{C}^{-1}\mathbf{T}^{T} I(t) - \mathbf{C}^{-1}\mathbf{C}_{\blacksquare}\dfrac{dU_{\blacksquare}(t)}{dt} \\ \dfrac{dI(t)}{dt} = \mathbf{L}^{-1}\mathbf{T}U(t) + \mathbf{L}^{-1}\mathbf{T}_{\blacksquare}U_{\blacksquare}(t) \end{cases}$$

$$\frac{d^2U(t)}{dt^2} = -\mathbf{C}^{-1}\mathbf{T}^{T}\mathbf{L}^{-1}\mathbf{T}U(t) - \mathbf{C}^{-1}\mathbf{T}^{T}\mathbf{L}^{-1}T_{\blacksquare}U_{\blacksquare}(t) - \mathbf{C}^{-1}\mathbf{C}_{\blacksquare}\frac{d^2U_{\blacksquare}(t)}{dt^2}$$

$$\lambda = \mathrm{eig}(\mathbf{M}) = \mathrm{eig}\left(-\mathbf{C}^{-1}\mathbf{T}^{T}\mathbf{L}^{-1}\mathbf{T}\right)$$

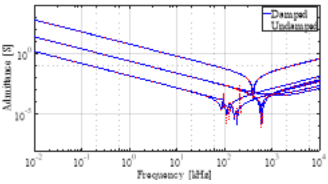
- Correction of **M** eigenvalues to take account of the frequency dependency of natural oscillations damping:

$$\lambda' = \left((\gamma/\omega)^2 - 1\right)|\lambda| - 2j(\gamma/\omega)|\lambda| \qquad \mathbf{M}' = \mathbf{V}\Lambda\mathbf{V}^{-1}$$

$$\begin{cases} j\omega\dot{U}(\omega) = -(\mathbf{C}')^{-1}\mathbf{T}^{T}\dot{I}(\omega) - j\omega(\mathbf{C}')^{-1}\mathbf{C}_{\blacksquare}\dot{U}_{\blacksquare}(\omega) \\ j\omega\dot{I}(\omega) = \mathbf{L}^{-1}\mathbf{T}\dot{U}(\omega) + \mathbf{L}^{-1}\mathbf{T}_{\blacksquare}\dot{U}_{\blacksquare}(\omega) \end{cases}$$

$$\mathbf{C}' = -(\mathbf{M}')^{-1}\mathbf{T}^{T}\mathbf{L}^{-1}\mathbf{T}$$

$$\dot{Y}_j(\omega) = j\omega\mathbf{C}_{\blacksquare}^{T}\dot{U}(\omega) + \mathbf{T}_{\blacksquare}^{T}\dot{I}(\omega)$$



Damped and undamped frequency responses of terminal admittance matrix of 630 kVA dry-type transformer

- Calculation of transfer function can be performed from equation:

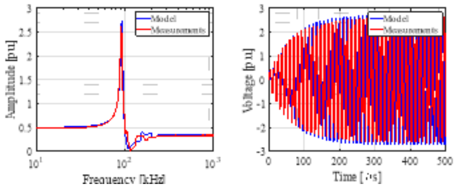
$$\dot{U}(\omega) = \left(\mathbf{M}' - \omega^2\mathbf{I}\right)^{-1}\left(\omega^2\mathbf{C}^{-1}\mathbf{C}_{\blacksquare} - \mathbf{C}^{-1}\mathbf{T}^{T}\mathbf{L}^{-1}\mathbf{T}_{\blacksquare}\right)\dot{U}_{\blacksquare}(\omega)$$

- Internal nodes voltages can be calculated using coefficient of transfer functions approximation:

$$\begin{cases} \dfrac{dX(t)}{dt} = \mathbf{A}X(t) + \mathbf{B}U_{\blacksquare}(t) \\ U_{\mathrm{int}}(t) = \mathbf{C}X(t) + \mathbf{D}U_{\blacksquare}(t) \end{cases}$$

Comparison of model and experimental data (630 kVA 10/0,4 kV transformer):

Parameter	Calc	Meas	Diff, %
First natural frequency, kHz	92,7	91,7	1,1
Resonant voltage rise at the first natural frequency, p.u.	2,73	2,62	4,2



Transfer function of voltage (left) and voltage waveform (right)

4. Wideband transformer model

- Based on a detailed equivalent network of the transformer.
- Self and mutual inductances of winding parts are taken into account by means of series and shunt inductances which are calculated using inductive decoupling.
- The set of series and shunt inductances represents the electric equivalent network of the magnetic circuit of the transformer; that network is separated from the rest of the equivalent circuit by ideal transformers.
- For convenience, inductances are referred to unity number of turns; this allows to use the number of turns of the element as the corresponding ideal transformer ratio.
- The equivalent circuit may be supplemented by resistances representing core losses.
- The distinctive feature of the suggested model is the fact that series and shunt inductances of equivalent circuit are considered with taking account of transformer core magnetization. As a results, the model turns out to be correct for the calculation of linear low-frequency transient and steady-state phenomena requiring the modeling of magnetization.
- This model is capable of correct representation of transformer natural frequencies; the more detailed the windings representation is, the higher are the natural frequencies that can be represented by the model.

http://www.cigre.org