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Analysis of transformer frequency response deviations using white-box modelling

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Introduction

- The white-box models are being used for many years in transformer design for simulation of impulse transients in the windings of power transformers and shunt reactors.
- In the recent years these models have been increasingly used in the studies of transformers interaction with an external network: in the network design process and for the analysis of failure accidents caused by the resonance phenomenon in transformer windings.
- Another application of the white-box models is the calculation of the frequency response characteristics of transformers (at high frequencies) for research and qualitative analysis of the effect of transformer internal faults and damages on frequency response. Thus they can be used for the Frequency Response Analysis (FRA) results interpretation.

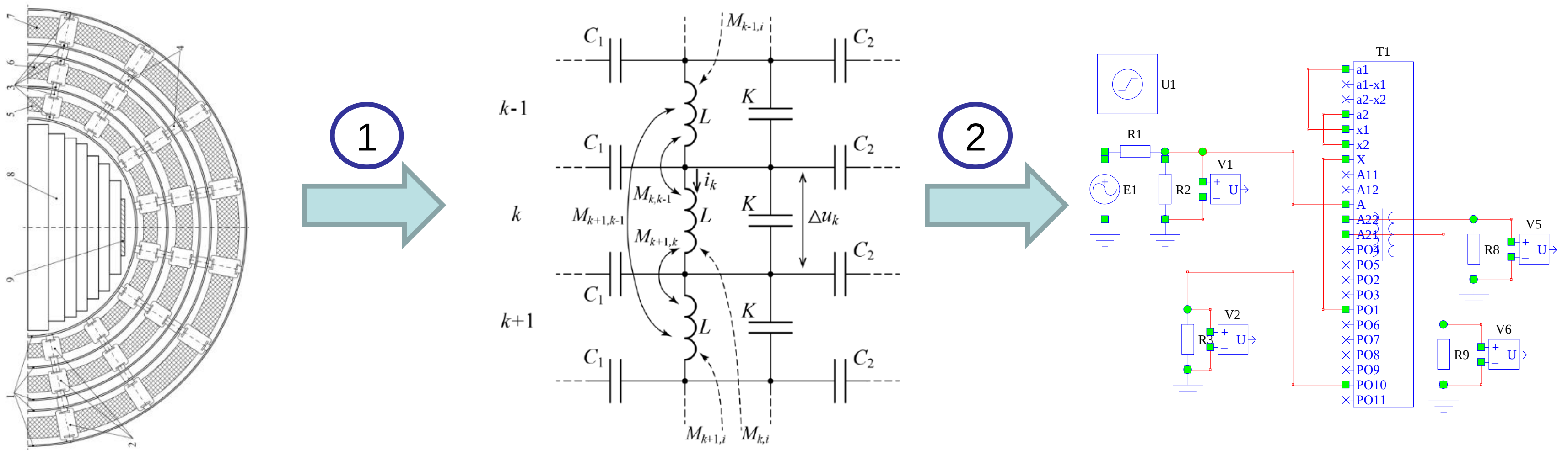
White-box modelling specifics (1)

- White-box models are being in scope of CIGRE JWG A2-C4.52 "High-Frequency Transformer and Reactor Models for Network Studies".
- Disc-by-disc and turn-by-turn winding representation.
- White-box model is completely defined by five matrices namely R, L and C, the matrix of interconnections T, and the matrix of labeled nodes N.
- The resistances in the transformer equivalent circuit are strongly frequency dependent, but calculation of this dependency constitutes one of the most complicated problems in transformer numerical modelling.
- The simplified approach consists in the calculation of the resistances at the power frequency with further multiplication of the obtained values by the factor accounting for the increase of losses at high-frequencies.

White-box modelling specifics (2)

Transformer windings frequency responses can be evaluated from white-box model using combination of two types of software:

1. Software for generation of high-frequency models of windings based on the equivalent circuits with lumped parameters which further can be imported via R-L-C-T-(N) matrices.
2. EMTP-type tools to connect the transformer windings with measuring circuit and to calculate the frequency responses and transfer functions using a frequency analyzer simulation.



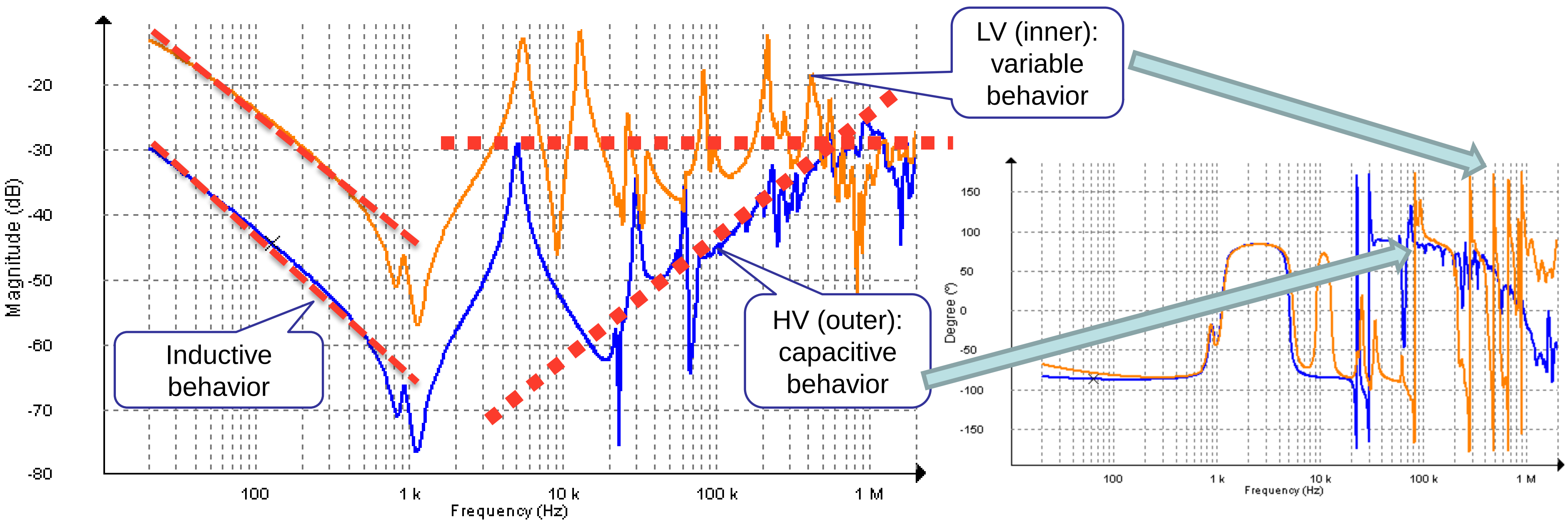
White-box modelling specifics (3)

- Frequency response obtained from white-box models differs a priori from the measured response:
  - **Different goal:** white-box models based on equivalent circuits with lumped parameters which were originally intended for the simulation of impulse overvoltages in transformer windings and are based on a number of assumptions.
  - **Frequency-dependent parameters:** Frequency dependence of the losses in the windings is usually not taken into account. This is due to the fact that in the calculation of impulse overvoltages it is not necessary to reproduce the transient attenuation with high accuracy. In the majority of white-box models the values of the winding element resistances (the R-matrix) are determined at some fixed frequency.
- Despite these differences the white-box model is very useful for qualitative analysis and explanation of winding frequency-response nature and deviations.

Case 1 - Frequency responses of inner LV and outer HV windings

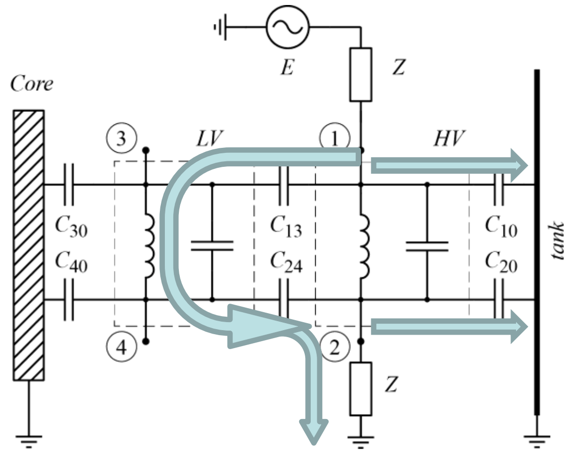
Frequency responses of LV and HV windings typically have some basic differences:

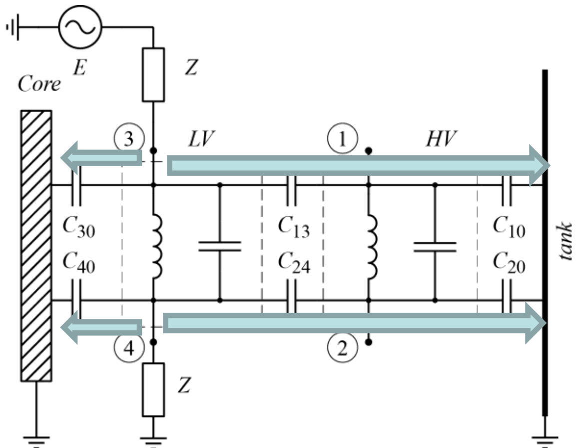
- Frequency response of LV winding typically goes higher, especially at low and medium frequencies (smaller number of turns, inductance and electric length of LV winding compared to HV winding);
- Outer HV windings often have a pronounced V-shaped frequency response (obvious capacitive behavior in high-frequency range).



Case 1: reasons of capacitive behavior of frequency response

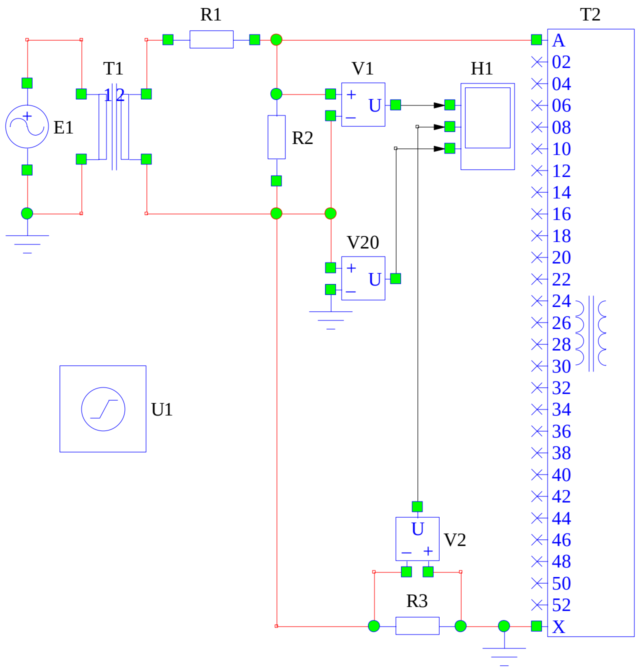
- In case of winding with high series capacitance (e.g. fully interleaved) the capacitive behavior at frequencies higher than 100 kHz can be explained by series capacitance itself.
- But in case of continuous disc windings having relatively low series capacitance there should be another reason.
- One of reasons is that current throw instrument impedance is combination of currents flowing throw winding itself and inter-winding capacitances. The latter has different paths for inner LV and outer HV windings due to different winding admittances and capacitances to earth.

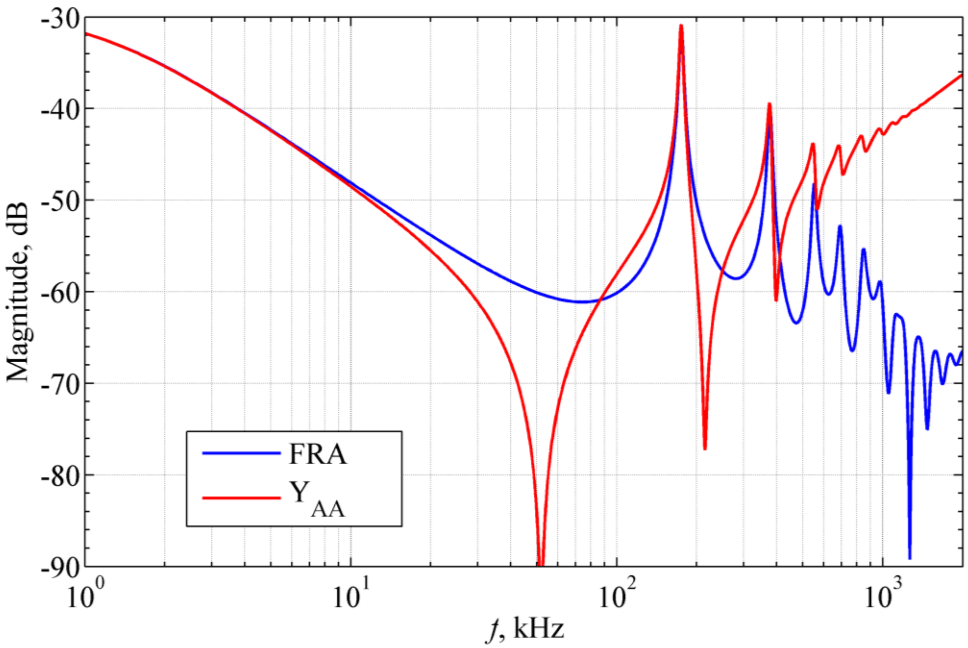




Case 1: white-box modelling

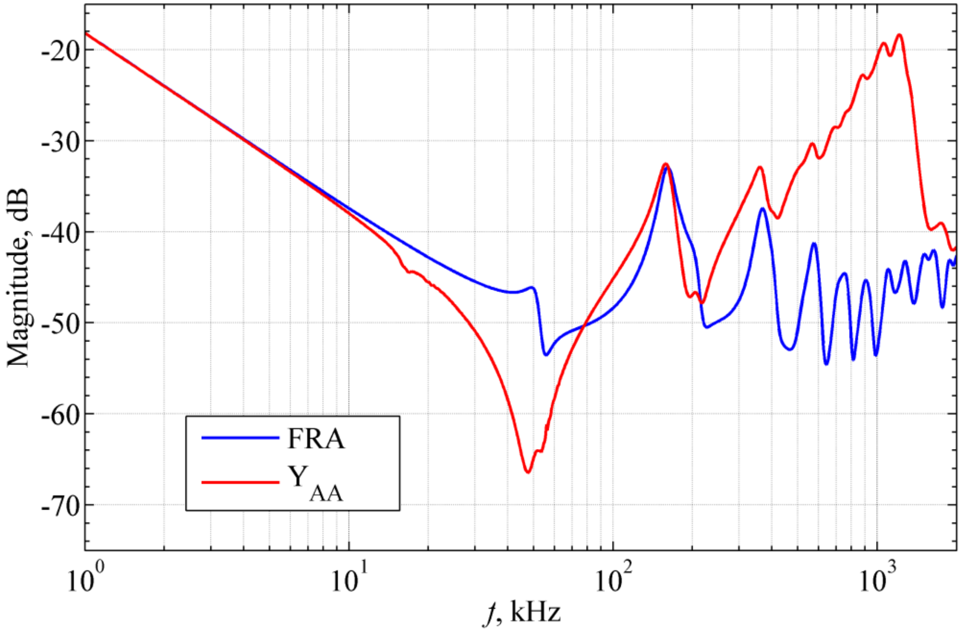
- This effect may be simulated by white-box model by creation the models with and without LV winding.
- The effect can also be shown by using non-standard measuring scheme such as scheme for measuring diagonal elements of the admittance matrix (e.g.,Y_{AA}) when the ground of the FRA instrument is decoupled from transformer ground and whole capacitive current to ground returns throw measuring impedance.
- Example: white-box modelling of single continuous disc winding (core-type reactor):





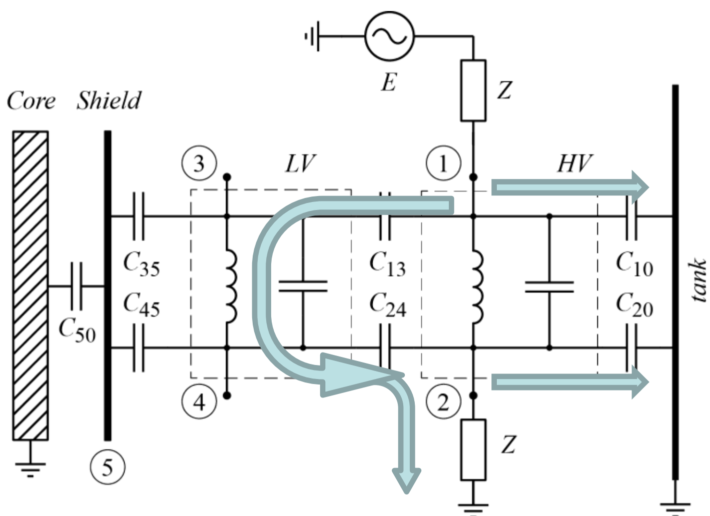
Case 1: results from measurement

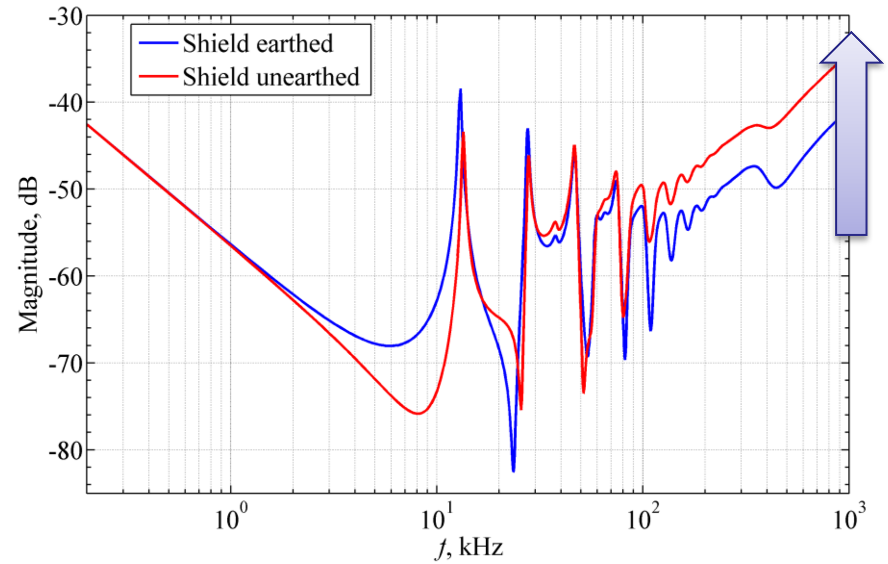
- Experimentally measured frequency-response characteristics of single winding (reactor with two core legs and two identical windings)



Case 2 – Effect of unearthed core shield

- Core shield may be unearthed due to fault in earthing circuit (e.g., burn-out or bad contact of lead to core shield) or missed earthing (e.g. after insulation resistance measurement).
- Modelled frequency-response characteristics:





- Unearthing of the core shield yields to a decrease of coupling of LV winding to the ground, an increase in the induced potentials at nodes 3 and 4 of this winding, in the potential difference between nodes 2 and 4 and in the capacitive current flowing through the measuring impedance.
- In the case where C_{35} and C_{45} are comparable to C_{13} and C_{24} the unearthing of shield should lead to an upward shift of the HV winding frequency response.

Conclusion

1. White-box models are suitable for qualitative evaluation of frequency response characteristics of transformer windings and can be useful for the interpretation of FRA results.

2. One of reasons of differences in the frequency responses of the inner LV and outer HV windings (V-shape and capacitive behavior in high-frequency range for HV) is due to additional capacitive current flowing through the measuring impedance from inter-winding capacitances and LV winding.

3. The unearthing of core shield yields to redistribution of capacitive currents throw LV and HV windings thus it can be detected by shift of frequency response of outer HV winding while its natural frequencies remain almost the same.

Thank you for attention!