

Influence by parasitic capacitances on frequency response of a 380-150-50 kV transformer with shunt reactor

Citation for published version (APA):

Wu, L., Fonk, H., Wouters, P. A. A. F., & Steennis, E. F. (2013). Influence by parasitic capacitances on frequency response of a 380-150-50 kV transformer with shunt reactor. In *Proceedings of the 18th International Symposium on High Voltage Engineering (ISH 2013), August 25-30 2013, Seoul, Korea* (pp. 56-60).

Document status and date:

Published: 01/01/2013

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

INFLUENCE BY PARASITIC CAPACITANCES ON FREQUENCY RESPONSE OF A 380-150-50 KV TRANSFORMER WITH SHUNT REACTOR

L. Wu^{1*}, H. Fonk², P. A. A. F. Wouters¹, E. F. Steennis³

¹Eindhoven University of Technology, P.O.Box 513, 5600 MB, Eindhoven, the Netherlands

²SMIT transformers, Groenestraat 336, 6531 JC, Nijmegen, the Netherlands

³DNV KEMA, P.O.Box 9035, 6800 ET, Arnhem, the Netherlands

*Email: <lei.wu@tue.nl>

Abstract: Power transformers and shunt reactors in HV systems attract increasing attention for their transient behaviour as nowadays the systems grow more and more complex. Both devices are usually modelled by inductive components at low frequencies (e.g. 50 or 60 Hz): magnetizing and leakage inductances for transformers and phase inductances for shunt reactors. However, transients (high frequency phenomena) will boost the influence of the parasitic capacitances and require corresponding extension of their models. This paper analyzes the influence of the parasitic capacitances for a transformer (500 MVA, three-phase three-winding three-limb) and a shunt reactor (100 MVA) by building their models according to the datasheet followed by a comparison with the measurement of Sweep Frequency Response Analysis both on transformer and shunt reactor individually and on their combination.

1 INTRODUCTION

In a new Dutch HV transmission connection (Randstad380 project involving overhead lines and power cables at 380 kV [1]), power transformers are used to connect networks with different voltage levels. Since part of the connection consists of underground power cables, shunt reactors for reactive power compensation are applied. In the particular case of the south-ring in this connection, shunt reactors are connected to the low voltage (LV, tertiary) winding of the power transformer. Power transformers are important and expensive components in power transmission systems. They require accurate models to analyse their behaviour in either steady state or transient conditions to ensure safe operation. At steady state with fundamental frequency (50 or 60 Hz), power transformers are conveniently modelled by their magnetizing and leakage inductances; while shunt reactors are modelled by their inductances. However, the transient behaviour will be influenced by their parasitic capacitances, such as inter-winding capacitances, winding to ground capacitances, and so on.

The applied power transformer is a 500 MVA three-phase three-winding three-limb transformer with the vector group of YNYn0D5. Specifically, within the delta connection, series reactors are added to the LV winding in each phase. The applied shunt reactor is a 100 MVA air-core shunt reactor. Each winding is composed of 11 layers. Parameter values are given in the appendix.

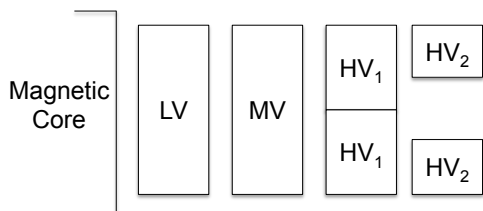
This paper describes the detailed configuration of the applied transformer and shunt reactor in

Section 2. The model of the transformer (with Unified Magnetic Equivalent Circuit approach, UMEC, [2-4]) and shunt reactor according to their datasheet is presented in Section 3. The influence caused by the parasitic capacitances is analysed based on the simulation with and without these capacitances together with the so-called Sweep Frequency Response Analysis (SFRA) measurement ranging from about 20 Hz to 1 MHz, [5].

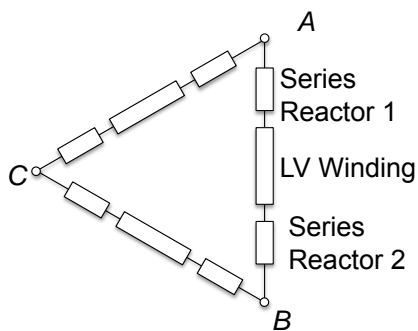
2 CONFIGURATION

Detailed configuration of the transformer and shunt reactor are shown in Figure 1 and Figure 2, respectively. In the transformer, the HV winding is composed of two parallel connected identical combinations of winding HV₁ and HV₂ (Figure 1-a); the LV winding has two built-in air-core series reactors connected to both sides (Figure 1-b). In the shunt reactor, the winding of each phase is constructed by connecting the 11 layers in series. Unlike the transformer, the shunt reactor has air-limb core with an earthed screen.

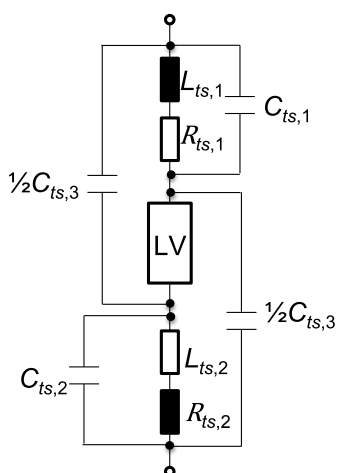
The related parasitic capacitances are: 1) cross-over capacitances of each winding (or layer); 2) inter-winding (or inter-layer) capacitance between each two neighboring windings (or layers); 3) winding-to-earth (or layer-to-earth) capacitance between LV winding of the transformer (or layer 1 of the shunt reactor) and earthed magnetic core (or screen).



(a)



(b)



(c)

Figure 1: Transformer configuration: Winding structure of the transformer in single-phase view (a); Connection of the built-in series reactors with LV windings: three-phase view (b), single-phase detailed view (c). Subscript “ts” refers to “transformer series reactor”

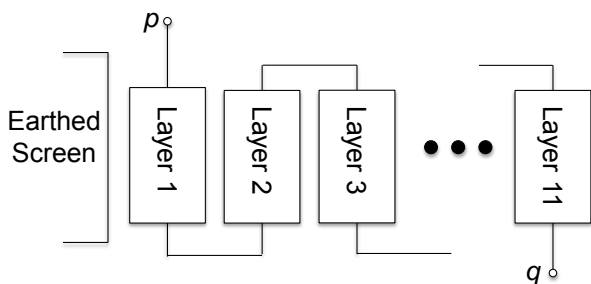


Figure 2: Configuration of shunt reactor in single-phase representation

3 MODELING METHODS

3.1 Transformer windings

Before including parasitic capacitances, the transformer windings are modelled by UMEC approach, see Figure 3, since it has the advantages of considering the magnetic coupling between different phases [2-4]. Particularly, Reference [4] shows that the permeances of a three-phase three-winding three-limb transformer have three contributions: 1) main path via limb (P_1) or yoke (P_3); 2) leakage path via air but only links to the winding itself; 3) zero-sequence path via air links to the windings on the same limb (P_4). Then, if number of windings (N) is known, the corresponding inductance (L) can be derived via:

$$L = N^2 P.$$

However, obtaining the values of N and P requires information (e.g. transformer core scheme) usually not publically available. The purpose of calculating P is to provide a relationship within all the windings. Therefore, to enable UMEC approach based on available data, a possible method is to 1) use the inductances given by no-load and short-circuit transformer tests to assign the number of turns (N_x) the rated voltage (V_x) of the winding x , ([2, 3]); 2) assume the leakage permeances of all windings are the same; 3) $P_4 = P_2$ ([3]).

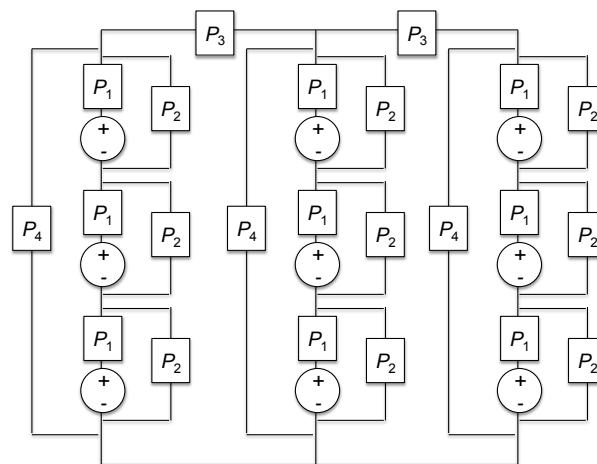


Figure 3: UMEC transformer model for three-winding three-phase three-limb transformer

Although P_1 can be obtained from no-load test on transformer, the corresponding formulas are different for the winding in the middle limb and side limbs, since their equivalent no-load magnetic loops are different. As a result, the formulas for P_1 to P_3 are:

$$P_{1,x \text{ on middle limb}} = \frac{3(3 + r_L/r_A)}{2\omega_0 V_{\text{rated},x} I_{\text{rated},x} l_m}$$

$$P_{1,x \text{ on side limb}} = \frac{3(1 + r_L/r_A)}{\omega_0 V_{\text{rated},x} I_{\text{rated},x} i_m} \left(1 + \frac{1}{2 + r_L/r_A} \right)$$

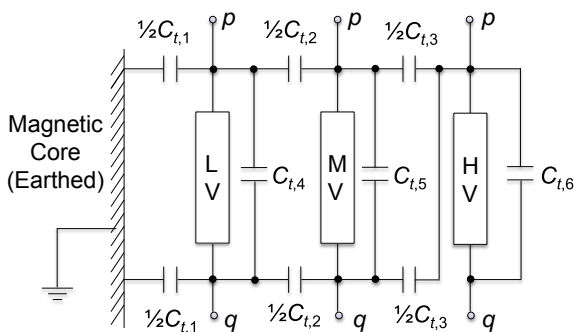
$$P_2 = \frac{6}{11} \frac{x_k}{\omega_0 V_{\text{rated},x} I_{\text{rated},x}}$$

$$P_3 = 3 \frac{r_L}{r_A} P_1$$

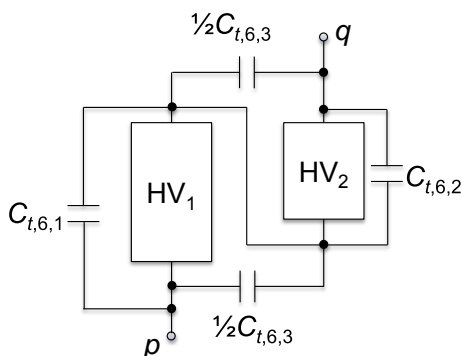
where: ω_0 refers to rated frequency;
 i_m is the magnetizing current at rated voltage in percentage (%);
 x_k is the leakage reactance in percentage (%);
 r_L and r_A are the ratios of the length and area of yoke and limb respectively.

3.2 Transformer parasitic capacitances

The parasitic capacitances for single phase are depicted in Figure 4-a. $C_{t,1}$ is the capacitance between LV winding to earth; $C_{t,2}$ and $C_{t,3}$ are the inter-capacitances of MV-LV and HV-MV respectively; $C_{t,4}$ to $C_{t,6}$ are the cross-over capacitances of winding LV, MV, and HV, respectively.



(a)



(b)

Figure 4: Parasitic capacitances of transformer: a) single-phase view of three windings; b) detailed capacitances between HV₁ and HV₂. Subscript “t” refers to “transformer”.

Particularly, the HV winding in Figure 1-a is equivalent to the four windings (two HV₁ and two HV₂, which can be approximately obtained according to Figure 4-b:

$$C_{t,6} \approx 2 \times \left[\frac{(C_{t,6,3}/2 + C_{t,6,1})(C_{t,6,3}/2 + C_{t,6,2})}{C_{t,6,1} + C_{t,6,2} + C_{t,6,3}} \right]$$

Note, that the terminals p and q of MV winding are equally close to the terminal p of HV winding, while the q terminal of HV winding is further away (Figure 1-a, Figure 4-b). Thus, the total capacitive coupling between HV and MV windings is represented by two identical capacitances from both terminals p and q of MV winding only to terminal p of HV winding, Figure 4-a.

3.3 Shunt Reactor

The shunt reactor can be modelled in a similar way to Figure 4-a, see Figure 5.

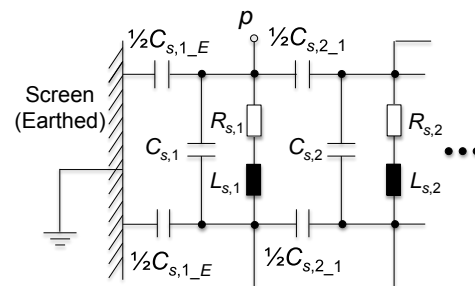


Figure 5: Parasitic capacitances of shunt reactor in single-phase view. Subscript “s” refers to “shunt reactor”.

The equivalent resistance and inductance of each layer are represented by $R_{s,k}$ and $L_{s,k}$ (lumped elements, $k = 1, \dots, 11$) respectively.

4 ANALYSIS BASED ON MEASUREMENT

The measurement scheme is depicted in Figure 6, where the tap-changer in the transformer is at maximum position (437 kV). Note that the transformer and shunt reactor in Figure 6-c are not the ones shown in Figure 6-a and Figure 6-b, but they are built with the same specification and share the same datasheet.

The investigated quantity is the absolute value of the transfer $H(f)$ between the input and output voltage values as a function of frequency:

$$|H(f)| = \left| \frac{V_{\text{out}}(f)}{V_{\text{in}}(f)} \right|$$

The results based on measurements and simulations (where all parameters are assumed to be frequency invariant) are shown in Figure 6.

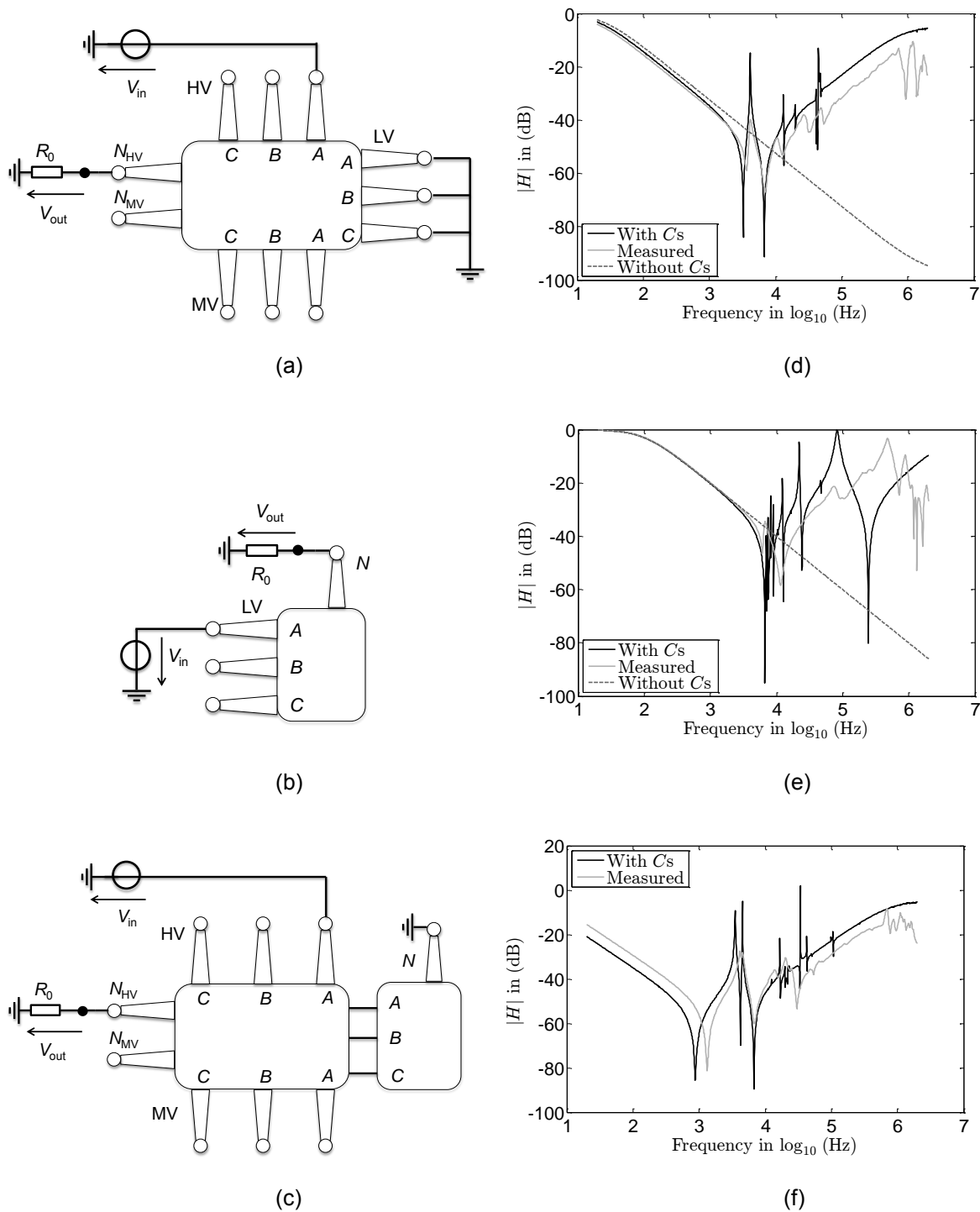


Figure 6: Comparison of measurement and simulation: a) on transformer only; b) on shunt reactor only; c) on transformer with shunt reactor connected to its LV winding. V_{in} (100 V) is the source voltage, V_{out} the measured voltage. R_0 (50 Ω) is the terminal resistor of the measuring device; d) - e) are the results corresponding to a) - c) respectively.

Figure 6-d shows that, for the transformer, the simulated curve based on the model with parasitic capacitances matches the shape of the measured curve, especially at frequencies below 10 kHz. Similar conclusion can be drawn for the model of shunt reactor according to Figure 6-e, but the deviation becomes larger for frequencies above 10-100 kHz. Extension of the model used in this paper is required for higher frequencies; e.g. the

capacitive coupling within the air-core limbed windings can be changed from layer-to-layer level (Figure 5) to turn-to-turn level. Figure 6-f confirms both models of transformer and shunt reactor, since the simulation has similar shape even though the measurement was performed on another transformer and shunt reactor (but with the same specifications). Moreover, in all cases, the resonances in the simulated results are less

damped than the measured ones. When the parasitic capacitances are ignored, models of both transformer and shunt reactor are purely inductive and their simulated curves continue going downwards as frequency increases. They start to lose accuracy as from around 3 kHz. Note that the measured values above about 1 MHz must be ignored since the accuracy of the measuring device is affected by the connection details to the transformer.

5 CONCLUSION

The influence of parasitic capacitances on the transient behaviour of transformer and shunt reactor has been investigated. The applied models, which are composed of frequency invariant parameters, include detailed configurations: 1) four sub-windings in HV winding of the transformer; 2) built-in series reactors at LV winding sides in the transformer; 3) the layer-profile of the shunt reactor (connecting the parallel constructed 11 layers in series).

Simulations including modelling parasitic capacitances represent the observed structures in SFRA measurements over almost the full frequency range (20 Hz to 1 MHz), and the model of the shunt reactor close to 100 kHz. Modification of the applied shunt reactor model is needed for higher frequencies. The deviation in simulation without parasitic capacitances emphasises the need to include them for frequencies exceeding about 3 kHz.

6 APPENDIX

Table 1: Transformer electrical rated properties

Parameter	Values
Power (MVA)	500/500/167
Voltage (kV)	380/150/50
No-load current (%)	0.032
No-load loss (kW)	130
r_L	0.5
r_A	1.0

Table 2: Transformer leakage reactances

Related Windings	Values (p.u.)
437 kV – 150 kV	0.213
150 kV – 50 kV	0.177
437 kV – 50 kV	0.414

Table 3: Transformer parasitic capacitances (nF)

$C_{t,1}$	8.6	$C_{t,5}$	0.054
$C_{t,2}$	5.0	$C_{t,6,1}$	0.37
$C_{t,3}$	5.0	$C_{t,6,2}$	4.3
$C_{t,4}$	0.017	$C_{t,6,3}$	2.4

Table 4: Transformer series reactor

$R_{ts,1} = R_{ts,2}$ (mΩ)	4.5
$L_{ts,1} = L_{ts,2}$ (mH)	1.9
$C_{ts,1}$ (pF)	20.0
$C_{ts,2}$ (pF)	25.8
$C_{ts,3}$ (nF)	3.1

Table 5: Shunt reactor electrical rated properties

Parameter	Values
Power (MVar)	100
Voltage (kV)	50
Resistance (mΩ, at 15 °C)	3.4

Table 6: Shunt reactor parasitic capacitances (nF)

$C_{s,1 E}$	8.6	$C_{s,1}$	0.047
$C_{s,2_1}$	31.1	$C_{s,2}$	0.049
$C_{s,3_2}$	32.6	$C_{s,3}$	0.051
$C_{s,4_3}$	34.1	$C_{s,4}$	0.054
$C_{s,5_4}$	35.6	$C_{s,5}$	0.056
$C_{s,6_5}$	37.1	$C_{s,6}$	0.058
$C_{s,7_6}$	38.6	$C_{s,7}$	0.061
$C_{s,8_7}$	40.1	$C_{s,8}$	0.063
$C_{s,9_8}$	41.6	$C_{s,9}$	0.065
$C_{s,10_9}$	43.0	$C_{s,10}$	0.068
$C_{s,11_10}$	44.5	$C_{s,11}$	0.070

7 REFERENCES

- [1] L. Wu, P. A. A. F. Wouters, E. F. Steennis: "Model of A Double Circuit with Parallel Cables for Each Phase in A HV Cable Connection", Power System Technology (POWERCON), 2012 IEEE International Conference on, Vol., no., pp. 1-5, Oct. 30 2012-Nov. 2 2012.
- [2] Manitoba HVDC Research Centre Inc.: EMTDC User's Guide, Vol. 4.7, fifth printing, February 2010.
- [3] W. Enright, O. B. Nayak, G. D. Irwin, J. Arrillaga: "An Electromagnetic Transients Model of Multi-limb Transformers Using Normalized Core Concept", IPST '97 Proceedings, Seattle, pp. 93-98, 1997.
- [4] L. M. R. Oliveira, A. J. M. Cardoso: "Three-Phase, Three-Limb, Steady-State Transformer Model: the Case of A YnZn Connection", Proceedings of the IASTED International Conference "Power and Energy Systems", pp. 467-472, Marbella, Spain, September 19-22, 2000.
- [5] CIGRE Working Group A2.26: "Mechanical-Condition Assessment of Transformer Windings Using Frequency Response Analysis (FRA)", Paris, France, April 2008.