A Frequency-Dependant Model For a MV/LV Transformer

C. Andrieu, E. Dauphant
Electrical System Analysis
Corporate Research & Development
Schneider Electric SA
38050 Grenoble France
(christophe_andrieu@mail.schneider.fr)

D. Boss
Research & Development
France Transfo
Schneider Electric SA
57211 Maizières-les-Metz France

Abstract — **To simulate an overvoltage surge transfer from medium voltage to low voltage, a high frequency model of a power transformer is necessary. The purpose of this paper is to build a model on EMTP-ATP available from a few kHz to one MHz. The proposed model is a black box designed from impedance measurements and from the knowledge of core and winding geometrical ordering.**
This paper presents a creative method of designing the model and setting the parameters, then EMTP-ATP simulations and measurements are compared. It has been applied on 250kVA-2500kVA transformers on a wide frequency range, and generalization is possible on a wider power range for oil transformers.

Keywords : Transformers, wide range frequency modeling, transient analysis, ATP, EMTP

I. INTRODUCTION

The wide frequency range modeling of transformers is difficult to do. This type of model is of a great importance both for transformer designers and electrical network designers.
Concerning transformer design, transient behaviour can interact with the development (geometry is a strong parameter) and knowing about this behaviour allows you to explain or to prevent some failures.
Concerning electrical network design, electrical stresses must be forecast everywhere in a large electrical network in order to choose the most suitable equipment.
Our goal is to present a MV/LV transformer model (delta wye, oil and core type), for a frequency range from a few kHz to one MHz.
This range allows us to study transmission or resonance phenomena when switching or lightning surges occur. In general these surges are spread over a wide frequency range.
The proposed model is a black box type and is used with EMTP. There are 8 connections : delta (3), wye (4) and ground (1).

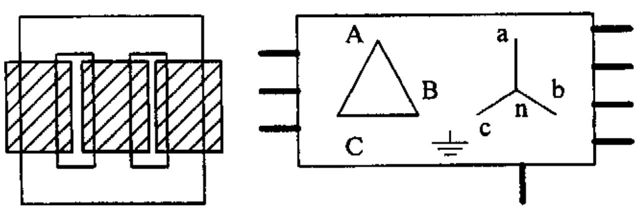


Fig. 1 : black box model

II. MODELING

A. *Model design*

50Hz or 60Hz transformer models are well-known. A basic model with saturation taken into account can be used with EMTP. This type of model (fig. 2), is composed of ideal transformers, series impedances (short-circuit losses (Rcc) and leakage inductance (Lcc)) and magnetizing impedance (open-circuit losses (Ri, Re) and magnetizing inductance (Li,Le)).
At low frequencies, from 50Hz to a few kHz, transformer modeling is very difficult to do : saturation (core material has a non linear behaviour) and frequency effects must be taken into account at the same time. Implementing such a model could improve the knowledge of transformer energization (ferroresonance) for instance.
Above a few kHz, magnetic induction inside the core sheets is significantly decreased. Transformer behaviour becomes linear in high frequency : small signal measurements can be used for higher currents and voltages. At the same time, the stray capacitances of transformer begin to act. They are divided in two types :

1) capacitance between two insulated conductors : MV to ground, MV to LV, and LV to ground. They can be easily measured at low frequency.
2) self-capacitance of windings : in the same conductor, geometrical spreading leads to an equivalent network of resistances, inductances and capacitances. At low frequency, the self-capacitance cannot be measured due to the short-circuit provoked by the inductances.

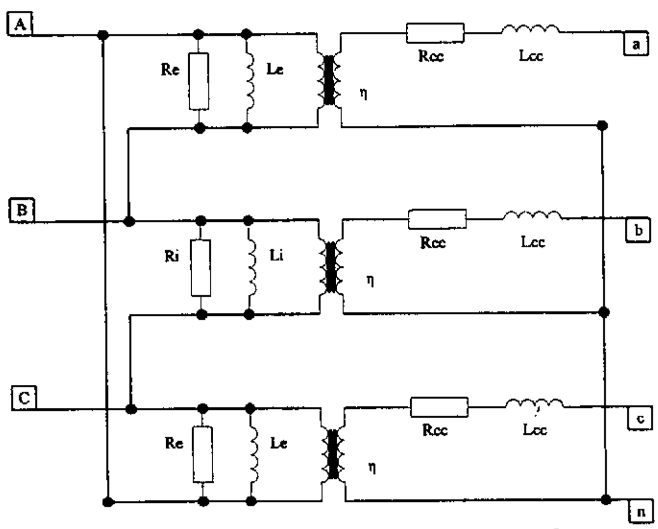


Fig. 2 : electrical diagram for a delta-wye transformer

For a few years, several research projects have been oriented to the design and the identification of the parameters of the high frequency transformer black box models, as in [2],[4],[5], and [6]. The model HFT in DCG/EPRI version of the EMTP leads to a nodal admittance matrix which is complex, symmetrical and frequency-dependent [7].
In ATP, this model does not exist but some papers show that accurate models can be achieved using a basic model combined with frequency dependent series branches and a network of capacitances [1], [3].

The theoretical number of capacitances to take into account between the 8 connections should be (9x8)/2=36 ! Actually some of these capacitances can be neglected, but the transformer model must be tailor-made.
Fig. 3 gives an exemple of a delta-wye transformer with pancake MV windings (delta) and concentric LV windings (wye).
Fig. 4 gives the reduced capacitance network corresponding. In the presented case, capacitances between neutral (n) connection and MV (A, B, C) connections are neglected, because these conductor surfaces are separated by other conductor surfaces.

Another purpose : series impedance depends on frequency. Foster circuit is used to model this dependency, as Zcc in Fig. 6. This component (RLC network) can change from a transformer to another (winding spreading dependent).

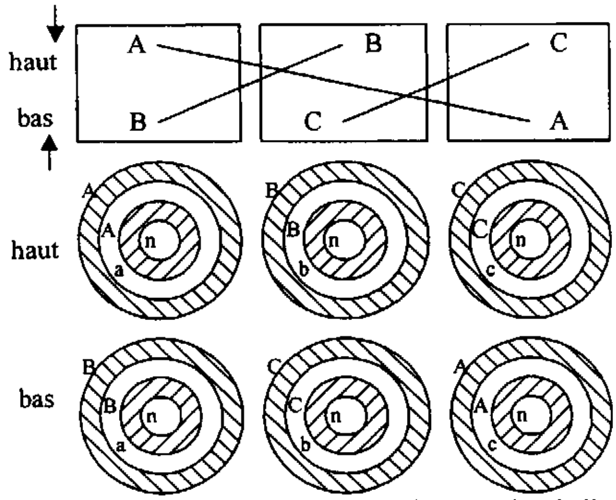


Fig. 3 : delta (pancake winding)-wye (concentric winding)

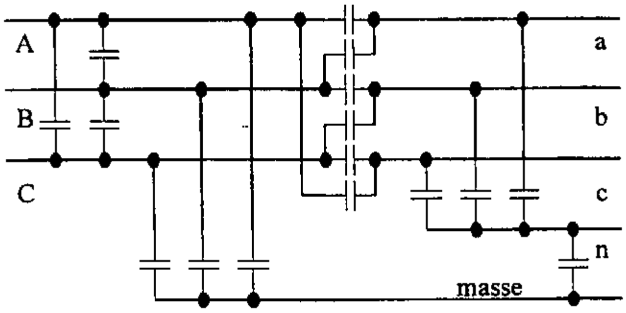


Fig. 4 : reduced capacitance network

B. *Measurements to identify the model parameters*

An HP4194A impedance analyser provided measurements from 100Hz to 10MHz. Results are magnitude (ohm) and phase (degree). The six measurements of Fig. 5 were made in order to evaluate the model parameters.
" A " is the analyser and cables between connections are drawn with bold-faced lines.
Measurements 1, 2 and 3 are useful in wide frequency ranges. The variations of the curves 1 and 2 are used to calculate the magnetizing impedance and the self-capacitance of MV windings. The variations of curve 3 are used to evaluate the series impedance (frequency dependent) and the self-capacitance of LV windings.
Measurements 4, 5 and 6 allow us to evaluate the capacitances between the three insulated parts : MV windings, LV windings and ground. Low frequency measurements could be sufficient.

Some measurements show very low inductances at high frequencies, about a few µH. These components are not modelled because they could come from cables between connections (3 meters sometimes), measurement cables or internal path of current in the transformer.

III. APPLICATION

Transformer : oil, core type, Dyn 1000kVA, 10kV/400V.
MV : concentric windings, LV : concentric windings

For all following curves :
X axes : f_Hz = frequency (Hz)
Y axes :
z_mesu, z_simu : measured, simulated modulus (ohm)
a_mesu, a_simu : measured, simulated phase (degree)
Rcc_mesu, simu : measured, simulated resistance (ohm)
Lcc_mesu, simu : measured, simulated inductance (µH)
C_nF : measured capacitance (nF)

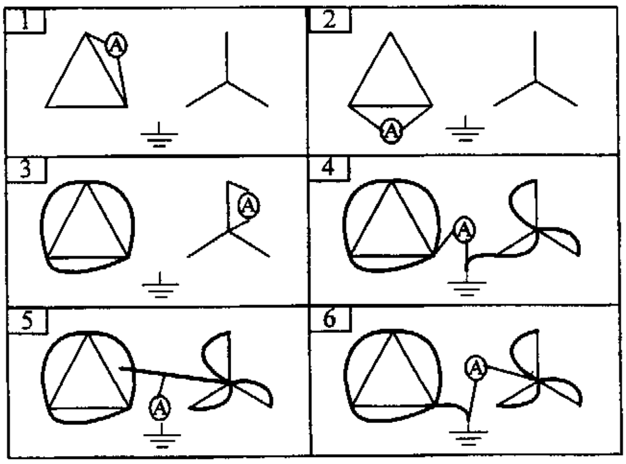
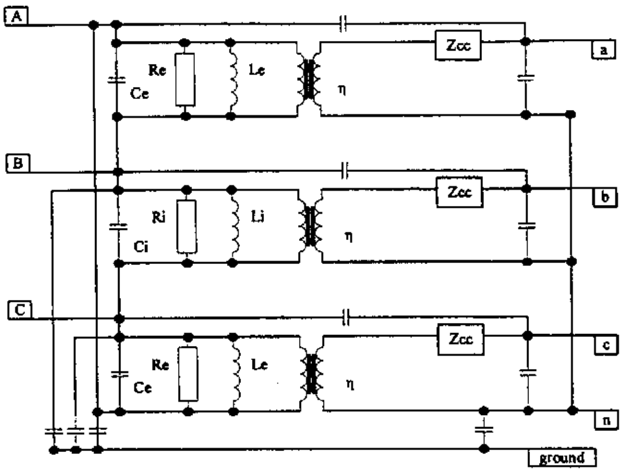


Fig. 5 : identification measurements

A. *Proposed model*

Due to geometrical spreading, Fig. 6 diagram is used.



with Zcc :

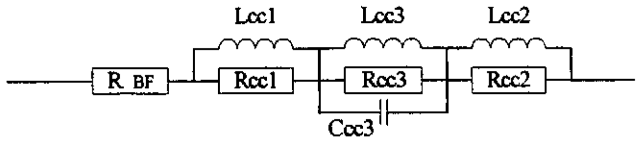


Fig. 6 : proposed model with Zcc detailed

B. *Parameters identification*

η is the nominal ratio HV/LV : η = 43.3

The following curves contain measured and simulated results in order to compare them at the same time. Curves 1 and 2 are very similar in shape, so that only curve 1 is reported in Fig. 7.

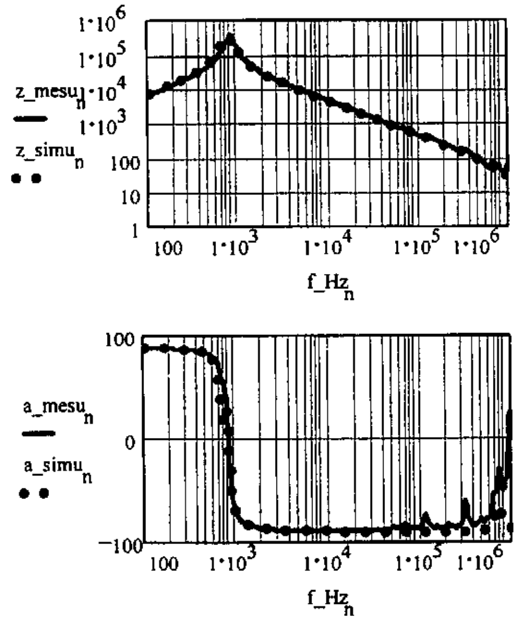


Fig. 7 : measurement and simulation n°1

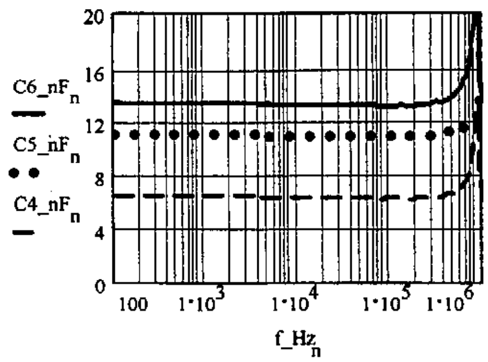


Fig. 8 : measurements n°4, 5 and 6

Measurements 1 and 2 show a difference between the winding in the middle and the winding on either side concerning the magnitude of the magnetizing impedance : Li = 29H, Le = 15H. The resonance frequency and magnitude give Ri, Re and MV self-capacitance :
Ri = 970kΩ, Re = 561kΩ, Ci = 1.7nF and Ce = 1.4nF.

Fig 8 gives three capacitances corresponding with two capacitances in parallel at each time.
So the total capacitances are :
MV - ground = 2nF
LV - ground = 8.8nF
MV-LV = 4.2nF
Then, these capacitances are shared out in the model.

Fig. 9 gives measurement n°3 fot Zcc and the LV self-capacitances. This measurement can be changed in equivalent inductance and resistance, as in Fig. 10, in order to understand the Zcc design.

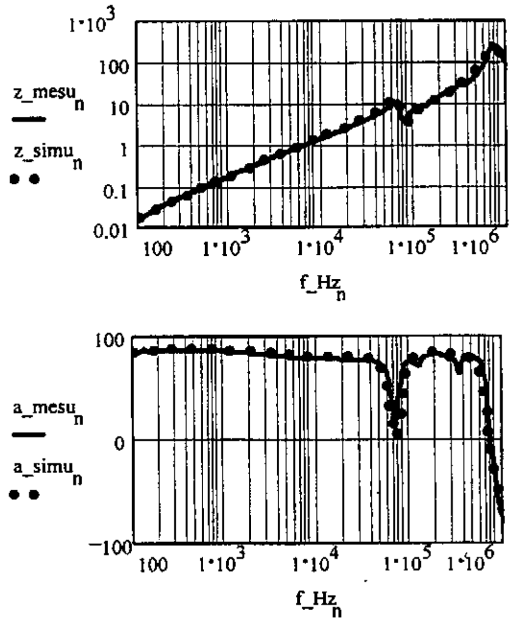


Fig. 9 : measurement and simulation n°3

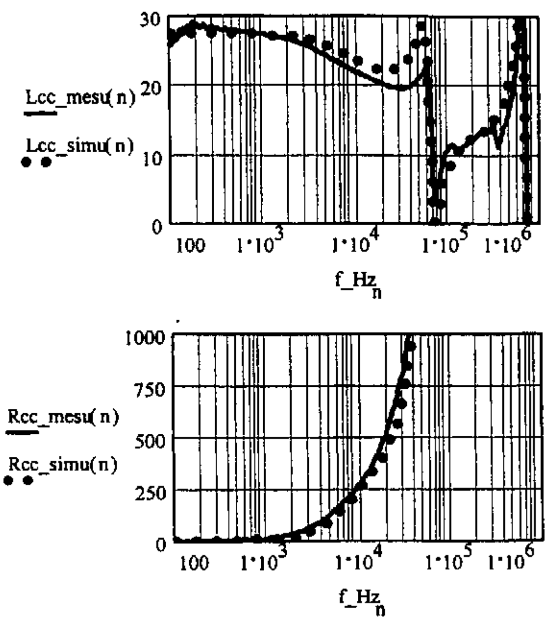


Fig. 10 : inductance and resistance of Zcc

Fig. 10 shows that Lcc is divided into three main steps : 27µH, 20µH, 13µH. That is why Lcc1=13µH, Lcc2=7µH and Lcc3=7µH are chosen.

The significant change at 70kHz is modelled by a series resonance with a capacitance Ccc3 = 0.8µF.

R_BF =2.2mΩ is evaluated from a short-circuit test at 50Hz or 60Hz. Rcc1, Rcc2 and Rcc3 are chosen in accordance with Lcc1, Lcc2, Lcc3 in order to find the right frequency variations of Zcc : Rcc1=280Ω, Rcc2=0.4Ω, Rcc3=11Ω.

C. Comparison measurement-simulation

From measurements 1 to 6, measurement and simulation with the model correspond. About twenty measurements were made in order to initiate this comparison : the simulation results also correspond with the measurements. Some representative results based on test diagrams of Fig. 11 are shown below in Fig. 12, 13, 14 and 15.

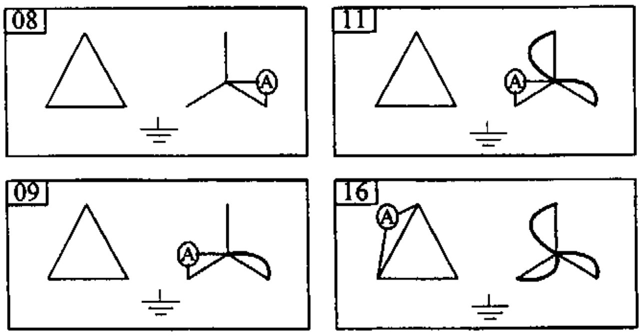


Fig. 11 : test diagrams n°8, 9, 11 et 16

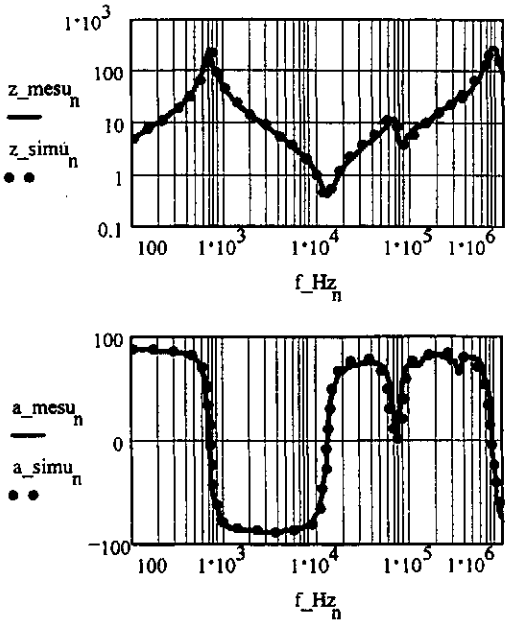


Fig. 12 : test n°08

Fig. 12 and Fig. 13 are quite similar in the result shape, except around 10kHz. These shapes are open-circuit type, viewed from the LV side.

Fig. 14 and Fig. 15 are quite different, but they are both short-circuit type. The difference comes from the point of view of the short-circuit :
Fig. 14 is view from LV side
Fig. 15 is view from MV side

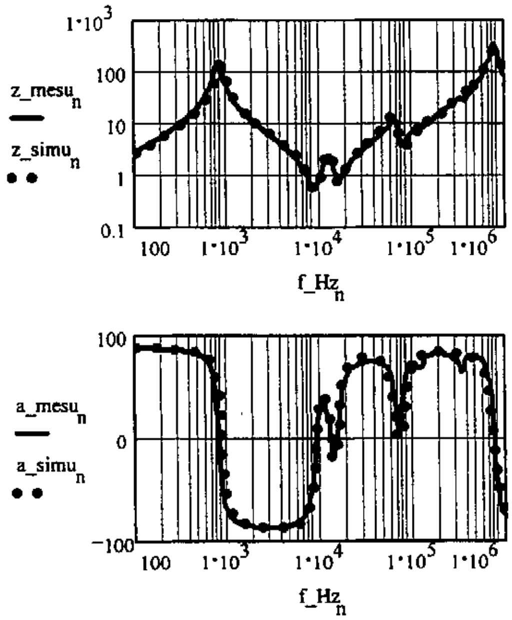


Fig. 13 : test n°09

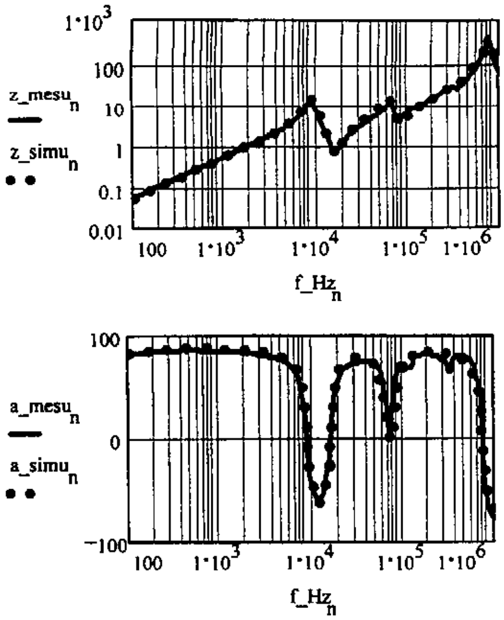


Fig. 14 : test °11

The verification of the electric strength of insulation of transformers is achieved through tests. Several types of tests are described in IEC 71-3. For one of them, the standard lightning impulse 1,2/50 μs is applied to a pair of MV windings, all the other connections being connected to the ground. Though data test is not available for this transformer, test simulations have been done and compared with the results on other transformers. The shape is correct : short current peak folllowing by a slow current increase.

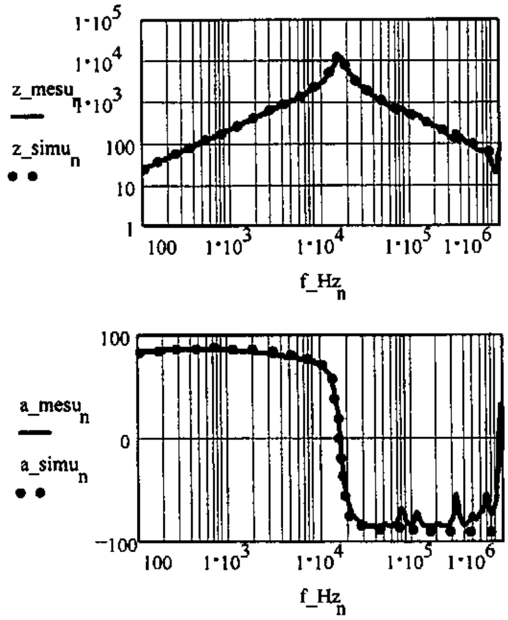


Fig. 15: test n°16

IV. PERSPECTIVES

A. Model verification for transmission

Additional experiments are expected in 1999 to validate the model. As described in [1], attention must be paid to the capacitive load behind the transformer during the tests. A test circuit with Marx generator will be used to investigate transmission of 1.2/50μs signal. Possible actual links between external connections must be taken into account : the capacitive equivalent network is changed, and thus the spreading of overvoltages too. Two main cases :

ground linked to neutral

ground insulated, definitely or partially, from neutral.

B. Wide frequency range model through low frequency

The high frequency and small signal model does not allow us to simulate the behaviour of transformers at nominal voltage in open circuits correctly. A way to improve the model is to measure dynamic hysteresis cycles at several frequencies and several magnetizing states for sinusoidal magnetic induction. But such results are not easy to use for implementing a simple EMTP model. You have to use the subroutine " models " in ATP.

Fig. 16 gives an example of frequency and magnetization dependency. The maximum induction (B1, B2 and B3 in Tesla) is 1.5T in the three cases. The X axis gives the magnetic field (A/m).

B1, H1 is the cycle at 50Hz

B2, H2 is the cycle at 500Hz

B3, H3 is the cycle at 1000Hz

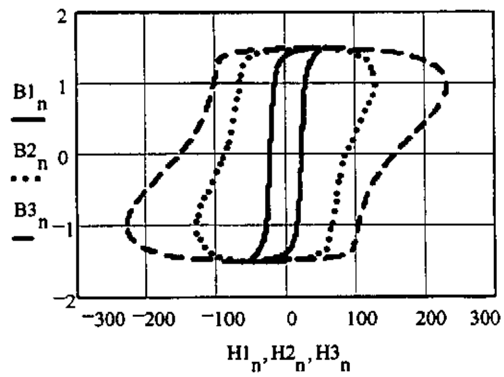


Fig. 16 : hysteresis cycles with an Epstein test

A useful solution for obtaining a model valid at 50Hz or 60Hz, and then for high frequencies, consists of using constant magnetizing parameters (Ri, Re, Li, Le) in accordance with nominal measurements : this model is called corrected model (z_corr and a_corr) in Fig. 17. So, power frequency signals and additional transients can be simulated at the same time. Nevertheless, designers must take care with the frequency spectrum in open circuit cases : model is not accurate in the range [50Hz, a few kHz].

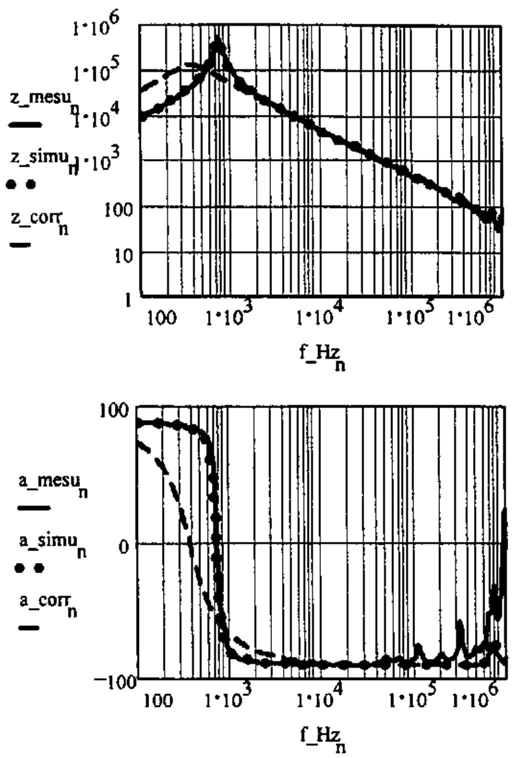


Fig. 17: small signal and corrected model

C. Wide frequency range model above MHz

Above one MHz, the measurements show an inductive component of a few µH. This component could be modelled (put into the model), but an unknown part of this value is due to measurement cables and cables between connections. Investigation on higher frequency ranges need special attention to what is around the transformer (HV cables, LV cables and loads, geometry of external connections) and also particular attention to equipment accuracy.
Our model used in higher frequency than one MHz becomes equivalent to the capacitive network of the model.

D. Dry type transformer modeling

Even if geometrical spreading of windings is quite similar, dry and oil transformers have different characteristics. The capacitive network is changed which acts on the several resonant frequencies of measurements. The proposed model seems to be not suited for the dry transformers. An additional investigation is needed.

E. Black box and detailed model of transformer

The proposed model can't give us any information about the internal constraints, but allows us to evaluate transient contraints at the external connections. EMTP is used to make these simulations on a wide network including lines ; cables, loads, equipment, and so on...
Then transformer designers can use a detailed model of the transformer to investigate the internal transient constraints : the external electrical network around the transformer becomes a black box !

V. CONCLUSION

Transformer modeling is difficult to do when saturation and frequency effects are taken into account. Some system analysis requires a simple and realistic model (memory, simulation time) in order to forecast surge transmission or resonance between transformers, feeders and loads. That is why a wide frequency range transformer model is investigated.
The proposed model presented in this paper is a black box model type that meets these requirements from a few kHz to one MHz, for oil transformers Dyn from a few kVA to a few MVA.

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