A Wide Frequency Range Model For a MV/LV Core Transformer

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Abstract — **Analysing transients, harmonics, energization in power systems requires well adapted transformer models that remain difficult to implement. Some highly sophisticated models already exist at industrial frequency (model with saturation) or for a high frequency range, but their practical use is often impossible due to the lack of data and measurements.**
The purpose of this paper is to present a model of a power transformer on EMTP-ATP available from some kHz to some MHz, with an extension from Hz to kHz. The proposed model is black box type and is designed from impedance measurements and from the knowledge of core and winding geometrical ordering.
The general method to choose the model and to set parameters was already presented in part during IPST99, we now focuse on comparison with transmitted surge measurements and on low frequency modeling aspects. This paper is mainly about 100kVA-3150kVA oil immersed and core power transformers, but this approach could be extended to another type of transformer.

Keywords: Transformer model, high frequency model, ATP, EMTP, three-phase transformer, core type transformer, wide frequency range modeling.

I. INTRODUCTION

Transformers are of prime importance in a power system. Their first function is to modify at power frequency the voltage level: a certain volume of FeSi material is required, and also coils with a given number of turns. Other requirements such as dielectric strength or surge 1.2/50 withstand lead to particular geometrical arrangements and separation lengths between conductors. As a result every transformer will inherit a specific transient overvoltages characteristic [1], [2], [3], [4], [5], [6].

Our first paper about modeling the high frequency behaviour of transformers was based on small-signal impedance analyser HP4194A measurements [1]. This paper presents new small-signal gain-phase, low and high voltage surges transmission measurements. The previously presented model is both shown to yield satisfactory results and to only require parameters associated with a given design. It is insensitive to normal production differences.

Our message is that a general high frequency transformer model cannot be defined, but that a general procedure to find an adapted model could.

As in paper [1], MV/LV transformers (delta wye, oil immersed and core type) are studied. The impedance analyser was used between 100Hz up to 10MHz.

The proposed model of the black box type is implemented in EMTP - ATP. There are 8 external connections: delta (3), wye (4) and ground (1).

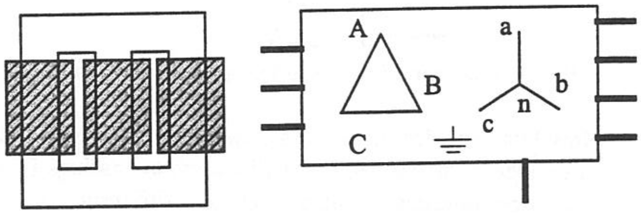

Fig. 1: black box model

In fact, small-signal measurements in the low frequency band (100Hz to some kHz) are not sufficient: FeSi material characteristic is non linear and frequency dependent. The resulting modeling problem is exposed in the paper.

Measurement part is first presented : impedance, gain-phase, surge test, low frequency. Then a comparison with some simulation results is given.

II. MEASUREMENT

A. *impedance measurement: frequency signature*

Lets consider three normally identical transformers (20kV/400V, 100kVA, same coil type). The impedance analyser yields the same resonant frequencies (Fig. 2).

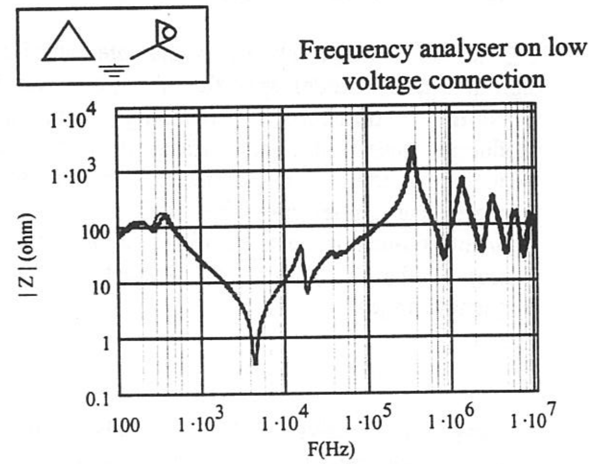

Fig. 2: open circuit impedance for 3 same transformers

Now lets consider three transformers of the same power, same type of windings, but different voltage ratings. The previous measurements now yield different resonant frequencies (Fig. 3).

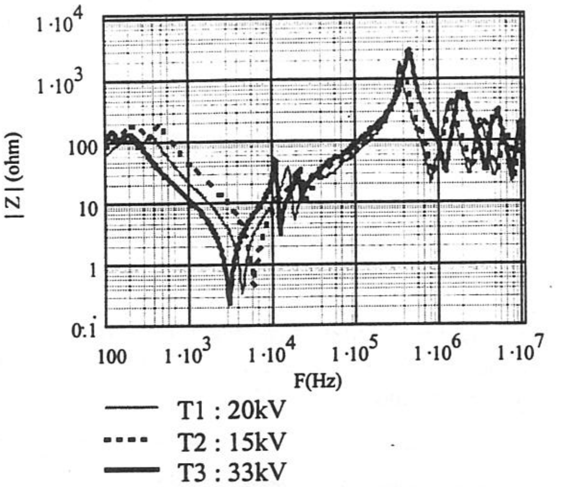

Fig. 3: open circuit impedance seeing from low voltage

Now lets consider three transformers of the same voltages, same type of windings, but different power ratings (Fig.4). The measurements also reveal different resonant frequencies.

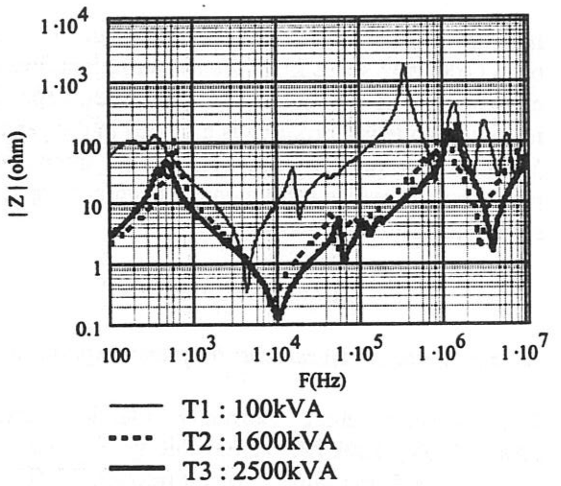

Fig. 4: open circuit impedance seeing from low voltage

This simple example shows us the interest of creating a high frequency model specific of a particular industrial transformer: transformers resulting from the same production unit and specifications have the same high frequency model. For different powers or different voltages, the model must be modified: the number of resonant frequencies can be different, leading to both a change in the model and its parameters (over a given frequency range).

B. *Gain – phase measurement*

The impedance analyser HP4194A is also equipped with a gain – phase measurement unit. This small-signal tool designed for small electronic filter covers a wide frequency spectrum (above 100MHz). In our case, the transformer is large, the conductors and the external connections are long: only a reduced band of frequencies can be taken into account between 100Hz and a few MHz. Testing with a long cable remains easy up to one MHz.

Fig. 5 shows the probe connections, but other internal ground connections are hidden inside the equipment.

Fig. 6 is the result for a 100kVA transformer. A transfer ratio V2/V1=0.0118 is found in that example for the concentric windings from 100Hz to about 10kHz. The two other windings share the voltage forced on the high voltage side between A and B, this is function of frequency:

1/ below some hundred of Herz, magnetic coupling by FeSi material is the strongest. Flux is preferentially flowing through the central leg, leading to a higher voltage on its windings.

2/ above some hundred of Herz, capacitive coupling becomes dominant. The symmetrical spreading of external windings leads to a lower voltage on the central leg.

Above 10kHz, the transfer ratio grows for the three windings and reaches a peak value between 300kHz and 400kHz. Above 1MHz, direct measurement results are unavailable.

It's important not to forget that these results are associated with small-signal measurements: higher voltages change equivalent inductances in the low frequencies, and so certainly modify the first resonant frequency.

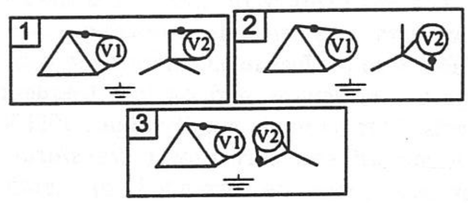

Fig. 5: diagram of transmission measurements

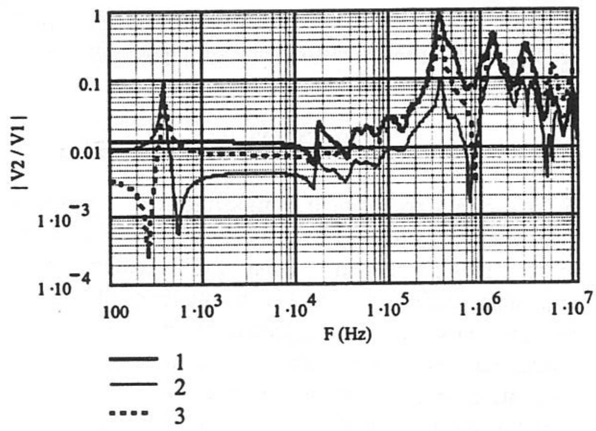

Fig. 6: transmission measurements

C. *Surge test*

A Marx generator is connected to the high voltage, point ① in Fig. 7: phase to ground surge. The voltage measurements are made between each indicated point and ground.

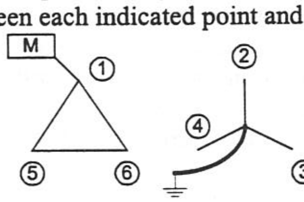

Fig. 7: diagram of surge test (a)

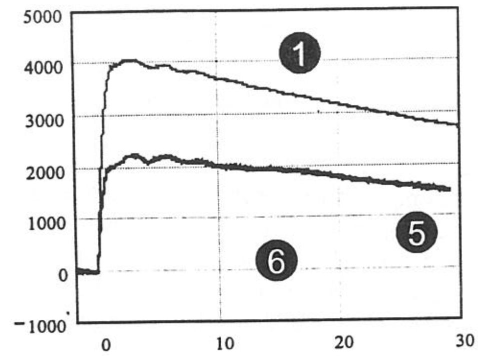

Fig. 8: high voltages for test (a): 4kV

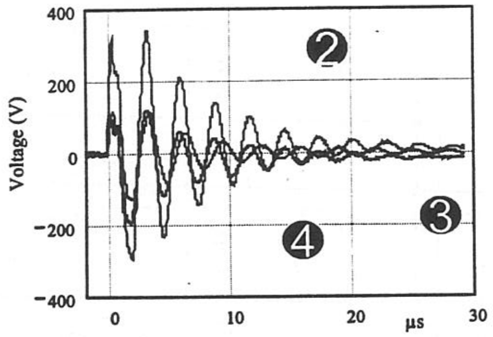

Fig. 9: low voltages for test (a)

Focusing on peak to peak value from high voltage to low voltage side, a ratio of 12.5 appears. A similar test, but with a 26kV peak voltage yields the same 12.5 ratio.

One of the main controlling parameters is the slope of voltage rise: an example is given with test (b) on Fig. 10: arresters are used to produce a steep slope with a peak voltage of 4kV.

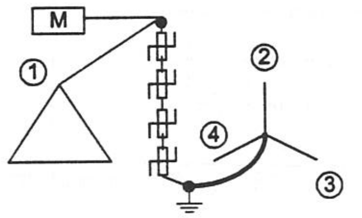

Fig. 10: diagram of surge test (b)

The peak to peak value now shows a ratio of 6.66: this case, as the case of 12.5 ratio, is far from the nominal ratio at power frequency of 1 / 0.0118 = 84.

Comparing Fig.9 with Fig.12 shows a double peak value on secondary even if primary sees the same 4kV peak value.

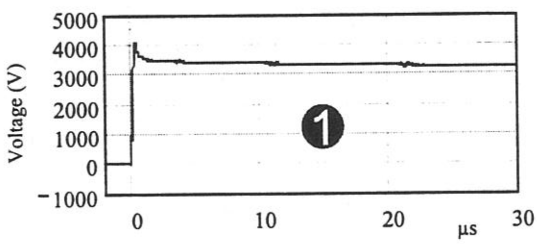

Fig. 11: high voltage for test (b): 4kV

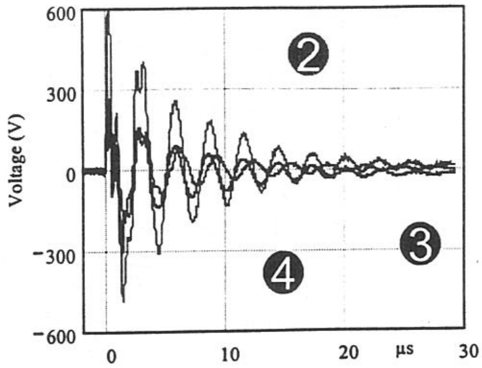

Fig. 12: low voltages for test (b)

D. *low frequency measurement*

A major problem over the low frequency range is the non linear behaviour of the magnetic material. Currently an Epstein test is used to analyse B(H) cycle. This approach allows one to identify two levels of difficulty:

1/ below a maximum induction of 1T, a simple (R//L) model can be used. However this couple depends on frequency and maximum induction values!

2/ above a maximum induction of 1T, saturation becomes important and equivalent R and L values must be changed during the cycle !

The following data on M5X oriented grain FeSi which is used in power transformers. Fig. 13 shows an example of the cycles at 50Hz.

When a low frequency signal below 5Hz is injected in the material, the B(H) cycle is independant of frequency: a quasistatic state is reached (Fig. 14). For any arbitrary frequency, the cycle may be divided into two components: the quasistatic cycle and the dynamical cycle.

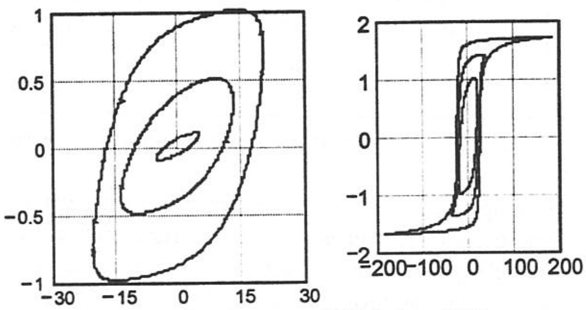

Fig. 13: B(T) versus H(A/m) at 50Hz

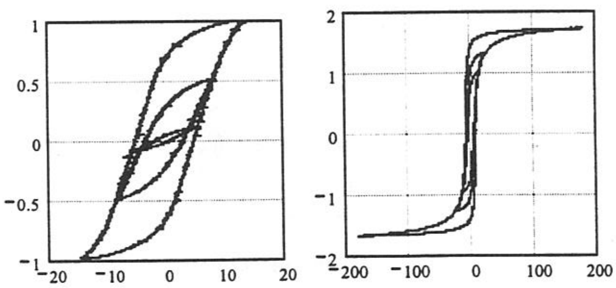

Fig. 14: B(T) versus H(A/m) at 1Hz

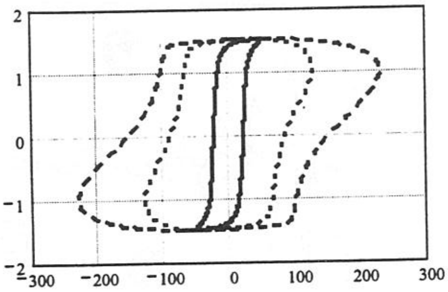

Fig. 15: B(T) versus H(A/m) at 50, 500 and 1000Hz

Fig. 15 shows the effects of a frequency rise: shape and area of the cycle are modified, area rising with frequency. This approach of B(H) cycle gives full information on the global average variations cycle by cycle, but there is a missing part about instantaneous variations of active and reactive energies.

Another problem is the transfer of Epstein results to a real transformer. In the production area, each transformer is checked in order to meet standards: for instance one of the tests concerns open circuit losses and current at power frequency. Some specific measurements have been done in these conditions not only for the nominal voltage, but for other values: a link between material measurement and transformer measurement is thus possible.

Several papers show that losses per weight unit are quite similar for Epstein test and open circuit transformers, although results on transformers are always a bit higher (Fig. 16). Losses on transformers (250kVA, 630kVA, 1000kVA) are measured with wattmeters and Epstein losses are calculated from cycle areas.

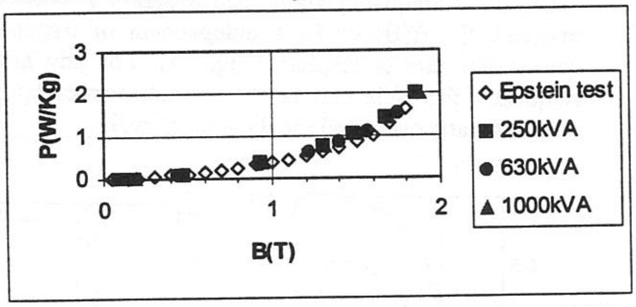

Fig. 16: open circuit losses per weight unit versus B(T)

For open circuit current, the comparison between Epstein and transformer measurements is more difficult and need a modeling step: results are shown in part II. Fig. 17 gives an example of currents recorded on the low voltage side for a 250kVA transformer (nominal current is around 360A).

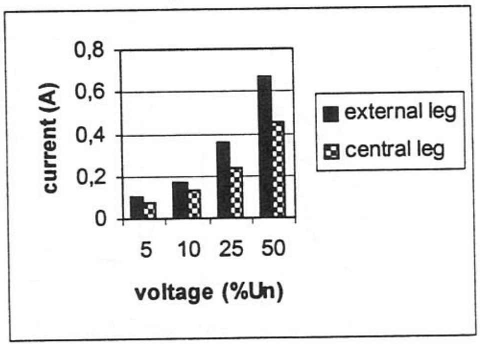

Fig. 17: open circuit current versus voltage (%Un)

II. SIMULATION

A. *High frequency electrical model*

The same procedure as described in [1] is used. As Zcc, Cps is composed of linear RLC components. The lumped RLC components are all of positive value and impedances are fitted manually. On Fig.19, Zcc acts mainly between 10kHz and 1MHz, and Cps above 1MHz. The transformer is 100kVA, 20kV/400V, but has a geometry different from the transformers of Fig. 2

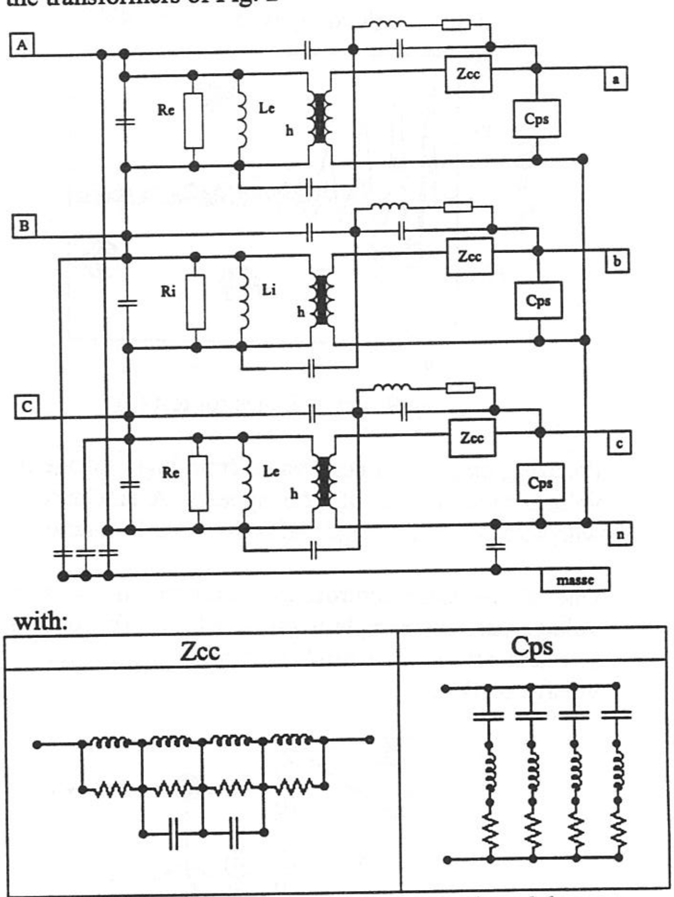

Fig. 18: high frequency electrical model

B. *High frequency electrical simulation*

As found in [1] impedance is valid. Comparison of Fig.19 with Fig.2 shows the importance of geometry.

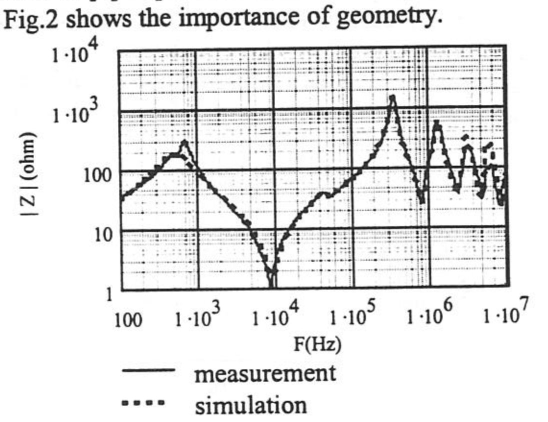

Fig. 19: open circuit impedance seeing from low voltage

An application of such a high frequency transformer model is given in [7], relative to a typical distribution network.

Fig.20 shows an example of injected voltage between phase B and ground, with voltages measured between phase a and neutral. Because of network capacitance, transfer ratio is low at low frequency. Between 1kHz and 100kHz, a near nominal ratio (0.0118) is observed. Above 100kHz, interpretations of the behaviour are complexes.

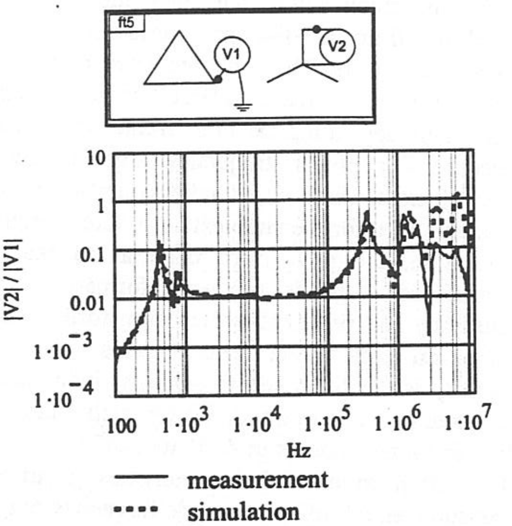

Fig. 20: transmission from high to low voltage

The transformer is unloaded in the surge test T8, whilst it is loaded with 47nF capacitance in T9 (Fig. 21). A surge wave 1.2/50µs is injected at point 1 as indicated in Fig. 22. Fig. 23 and 24 give similar result of measurement and simulation for the transmitted signal.

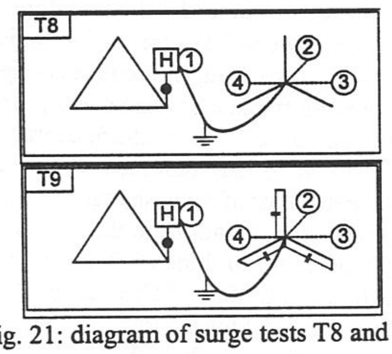

Fig. 21: diagram of surge tests T8 and T9

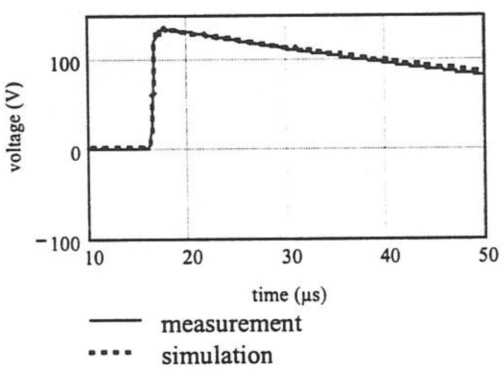

Fig. 22: result of surge tests T8 and T9 at point 1

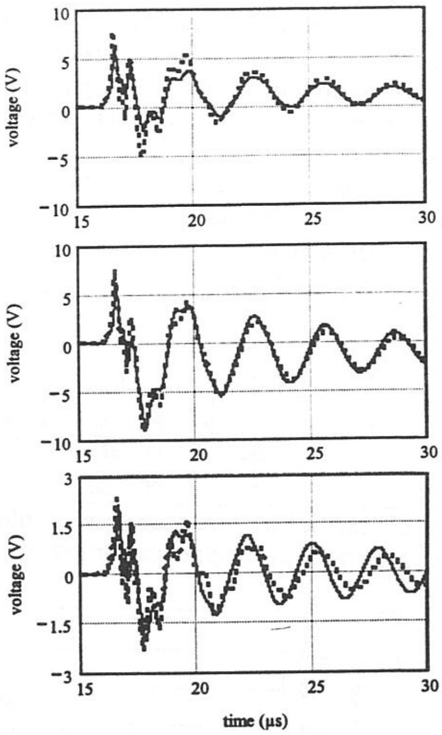

Fig. 23: result of surge test T8 at points 2, 3 and 4

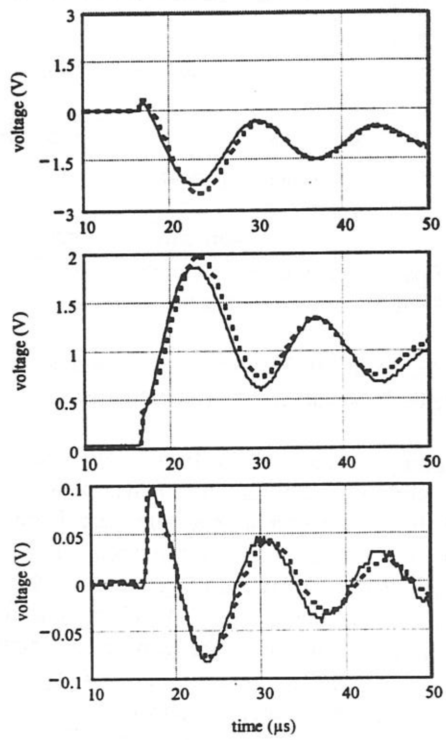

Fig. 24: result of surge test T9 at points 2, 3 and 4

C. *Low frequency electrical model*

To take into account the behaviour of the magnetic material at low frequencies, non-linear components must take the place of the high frequency components Re, Le, Ri and Li (Fig.18). A comprehensive model cannot be yet proposed, but two aspects are worth presenting:

1/ the use of Epstein results to model transformers

2/ introduction of a B(H) model within the electrical model. First measurements on transformer below saturation (voltage under 50% of the nominal value, see Fig. 17) are found from Epstein result. Air gap and equivalent capacitance must be taken into account, generally this data is difficult to obtain.
Fig. 25 and 26 present results for an external leg. The reluctance, associated to inductive current, is composed of two components: FeSi material and equivalent air gap.

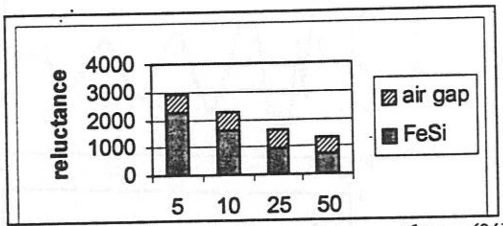

Fig. 25: External leg reluctance versus voltage (%Un) (air gap and FeSi components for inductive current)

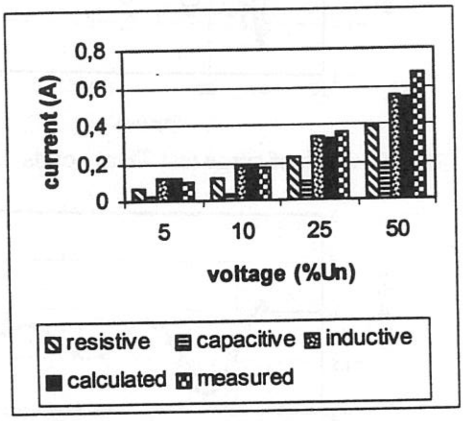

Fig. 26: no load current versus voltage
Epstein: calculated (resistive, capacitive, inductive)
Real transformer: measured (250kVA, as in Fig.17)

As shown in Fig.26, the model is already complex at low voltage. When saturation occurs, complexity increases.

Secondly, a method to find B(H) cycles step by step (adapted to a time simulation) has been found: quasistatic and dynamical components are calculated separately and then associated in a ATP_models. The integral of the voltage across the windings gives the induction (B), which involves a magnetic field (H) and so a current.
But how is composed the equivalent impedance step by step ? This question refers to how energy is lost or stored at each time step. Several models give an equivalent global result on the cycle: for instance STC or BCTRAN with added 98 card in ATP: resistance is supposed to be constant and a pseudo non linear reactor is defined. Measurements show that resistive component changes when saturation occurs, resistive and inductive components change versus frequency, what involves some difficulties for this way.
For a fixed frequency signal, a convenient solution in ATP is to use 96 card: inductive and resistive components are defined once and for all (no frequency dependence).

According to Epstein results, these low frequency models are not appropriate to represent both frequency and induction influence in the electrical system. Going from B(H) to a robust I(U) or Z(U) model remains a hard way.

III. CONCLUSION

The high frequency transformer modeling process proposed leads to an interesting result: not only the equivalent impedance seems to be correct over a wide range of frequencies, but also the transmitted signal resulting from small-signal measurements or transient overvoltage tests. The low frequency model, between Hz and some kHz, remains difficult to implement if a valid behaviour depending on both frequency and induction is needed. For power frequency signals, several models already exist which either take saturation into account or not. But even for the simplest case, fixed frequency and no saturation, the path from material to real transformer characteristics needs precise information on geometry. Currently the practical use of transformer model is still based on some direct measurements and the domain of validity is small limited to nominal induction and power frequency in open circuit. Under such conditions, current low frequency models in ATP are useful.
The path from material characteristics, geometry and some measurements leading to a wide frequency range black box model, valid from Hz to some MHz, remains very hard. This model would enable manufacturers to improve their offer and preserve proprietary information: it is still a challenge for the future

IV . REFERENCES

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