Determination of the high frequency parameters of the power transformer used in the railway substation

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Abstract— **The paper deals with the modeling method of the power transformers (three phases) used in the railway substation. In order to propose a high frequency model, which will be valid in the frequency band varying from 10 kHz to 30 MHz, it is necessary to identify the various impedances with a good accuracy. Often, these impedances are measured with an impedance analyzer, but for high power transformers, like those used in railway substation, these measurements are more difficult to carry out due to low power level delivered by the impedance analyzer. In this paper, we propose to use measurements in the time domain to identify the transformer impedances. These impedances can be obtained through measurements in various test configurations of the transformer. In the second part of the paper, a high frequency model, using the electrical equivalent circuit, is proposed and validated by the measurement data.**

Keywords: EMC, power transformer, Railway power system, time measurements, modeling.

I. INTRODUCTION

The work presented in this paper has been done in the context of a general study on electromagnetic compatibility (EMC) in railway power infrastructure as shown in Fig. 1.

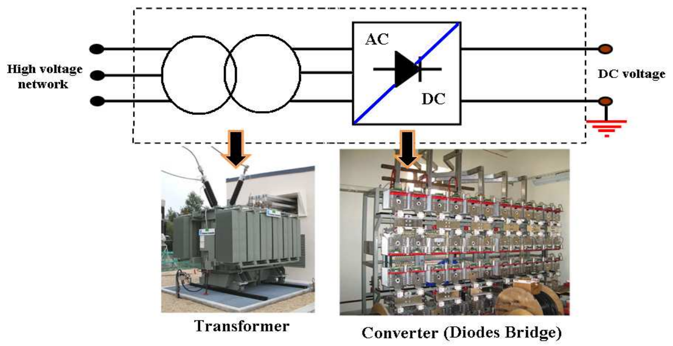

Figure 1. Example of a railway substation (transforner: 90kV/1.5kV and 7.3MVA)

According to the EMC standard, the rail systems should not disturb the immediate environment [1]. In fact, the measurement of the electromagnetic field radiated at 10 meters from the railway track shows resonance phenomena for some frequencies of the power supply. In addition, the new generation of rolling stock is equipped with safety communication systems with on board antennas which must not be disturbed neither. Most of these safety systems operate in frequency range from 10 kHz to 30 MHz. Thus, it becomes important to know which source can introduce the resonance phenomena. Besides, sensitivity of these telecommunication systems to the resonance could be evaluated.

The railway infrastructure could be divided in two parts as shown in Fig. 2.

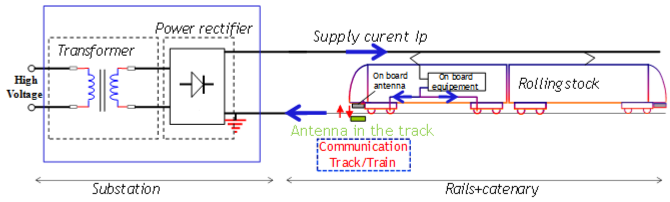

Figure 2. Simplified diagram of railway infrastructure

The rolling stock represents the first one and the railway power supply is the other part. In our study we will focus on the railway power supply infrastructure. Indeed, a frequency modeling of a railway power supply infrastructure in frequency band from 10 kHz – 30 MHz is useful to predict the EMC behavior of the railway system.

The railway power supply is generally composed by two main systems:

- The first one is the "lines system" constituted by the catenaries and the rails; this transmission line has already been modeled in a previous work [2], taken into account all important parameters in an EMC point of view (non uniformity and camber of the lines, multi-conductors structures, conductivity of the ballast, ...)

- The second main part is defined by the power supply substation which contains generally a power transformer, sometimes a converter, and wires, bus bars...etc.

The study of the power transformer which constitutes the heart of a substation is presented in this paper.

In order to propose a high frequency model of the whole system, it's necessary to determine a model for each element, especially of power transformer, which accuracy will be highly dependent of the accuracy of each primary model. The low

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frequency model of the transformer, defined at 50Hz, is not valuable when the frequency increases. Indeed, some phenomena can be predominant in high frequencies, for example the Eddy current, which depends on the variation of the magnetizing impedance and the winding resistance, but also the parasitic capacitances which appear between windings due to the insulated parts of the transformer. The analysis of the transformer behavior shows that it's possible to use an equivalent electrical model valid in the considered frequency band.

During the past decades, many models of power transformer have been studied for several applications. Most of those models, often in a reduced frequency band, are based on the representation of the transformer by an arrangement of resistive, inductive and capacitive elements which can take into account the physical behavior of power transformer [3]; some others are wide band models established using the black box principle [7]. Obviously, it’s also possible to apply the FEM (Finite Element Method) method to have a good model, but in this case, the exact constitution of the transformer must be known. Some additional difficulties are found in the studied problem: how to found the appropriate data sheet when the transformer is operated in the railway system since many years? In the following sections, we will present the proposed equivalent model and two techniques used to identify the transformer parameters.

II. HIGH FREQUENCY MODEL OF TRANSFORMER

A high frequency model of the power transformer, which takes into account the various physical phenomena, is presented in [4]. Figure 3 presents this model applied to a 15kVA three phase power transformer used in a laboratory test bench which represents a simplified scale railway substation. This model can be used to model a single phase transformer by using only the circuit for a phase.

Starting from an ideal transformer with coefficient ratio η, the proposed model takes into account, for each phase, the leakage inductance with the skin effects, the magnetizing impedance and the parasitic capacitances. This model is valid in the frequency band varying from 40 Hz to 30 MHz.

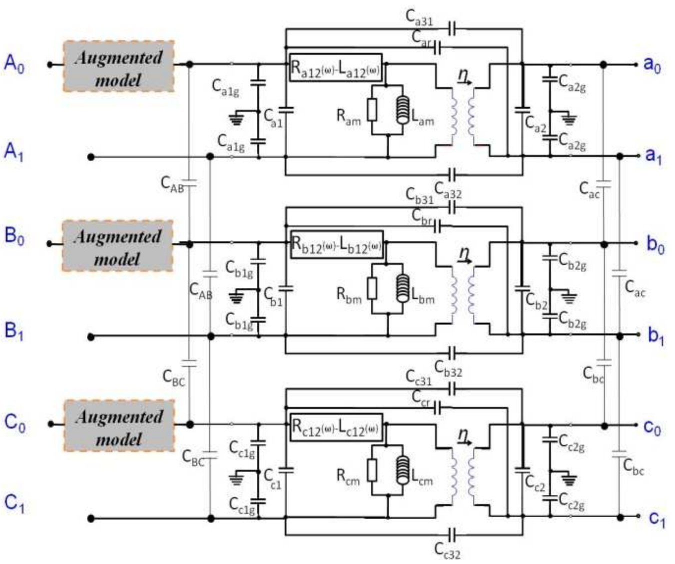


Figure 3. High frequency model of power transformer

If we consider one phase of the transformer (for example phase A0A1-a0a1), the block Ra12-La12 represents the leakage inductance with skin effects which is modeled by a ladder network circuit using resistances and inductances as shown in Fig. 4a.

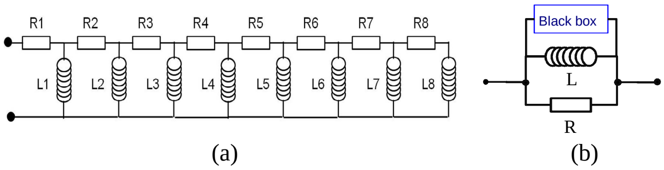


Figure 4. Ladder network circuit (a), augmented model block (b)

The magnetizing impedance is modelled thanks to a resistance (Ram) with an inductance in parallel (Lm).

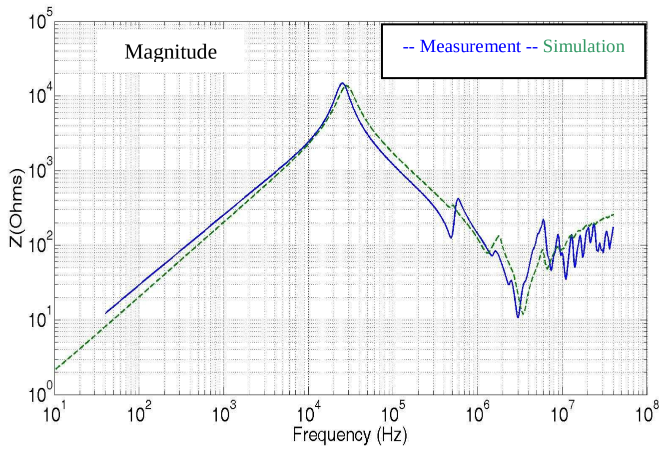
In the case of the phase A, shown in Fig. 3, C_{a1} and C_{a2} represent the turn-to-turn capacitances respectively of the primary and the secondary. The capacitance C_{a31} and C_{a32} are the capacitances between windings. Also, C_{ar} is the capacitance between input of the primary winding and the secondary. C_{a1g} and C_{a2g} are capacitances between windings and ground. For the three phase transformer, we add the capacitances between the phases (C_{AB}, C_{BC}, C_{ab}, C_{bc}). Details can be found in [8]. The phases B and C are described in the same way.

The impedance measurements (an example is given in Fig.5) show fast fluctuations above 10 MHz and their modeling using electric circuits can be time consuming. However, the use of macro model can be a good solution to take into account these fast variations at high frequency. These impedances are modeled using blocks named “augmented model” shown in Fig. 3 and detailed in Fig 4 in which the black box is defined by using vector fitting method, details are given in [4-5-6].

III. MODELING RESULTS

The experimental characterization, in time or in frequency domain presented in the next sections, allows to determine the various parameters of the model. Figure 5 shows an example of modeling results compared to experimental data in magnitude and phase.

In the next sections, we present the characterization method based on measurements in frequency and time domains.



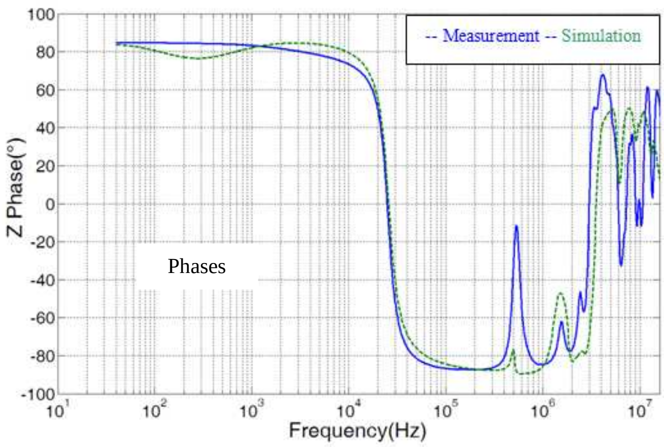


Figure 5. Comparison within measurements and model results (impedance of the primary winding, the secondary being open)

IV. CHARACTERISATION OF THE TRANSFORMER IN FREQUENCY DOMAIN

The determination of each parameter of the equivalent circuit of the transformer model is realized from impedance measurements, in frequency domain using an impedance analyzer, in various test configurations [7] [8]. The magnetizing impedance is estimated from the impedance measured on the primary winding when the secondary winding is open. The leakage impedance is measured with the secondary winding in short-circuited. The various capacitances can be determined by various measurements in various configurations, details can be found in [8] and the augmented model impedance is determined with fitting software which needs precise measurements at high frequency.

As we have seen before, the determination of the parameters of the proposed model is based on impedance measurements which can easily be done with impedance or network analyzer for low power transformer. The curve in figure 6, presents an example of impedance measurements realized when the source amplitude is equal to 1V max.

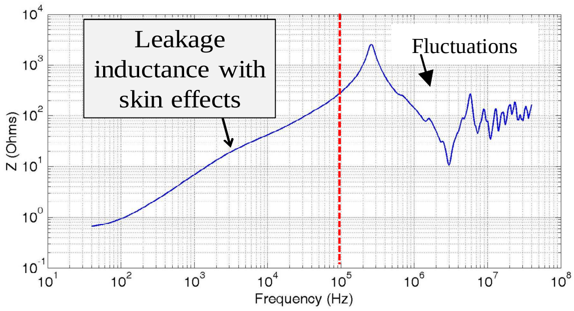


Figure 6. Primary impedance with secondary short circuited (phase A)

The problems to make this kind of measurement with very high power transformer as the ones used in railways substation, are the following:

- The connection between transformer and measurement apparatus (network or impedance analyzer) is not easy and some effects due to non ideal connection can be seen, especially at high frequency.
- The windings are often constituted with 'bus-bar' because the nominal power is high. Then, measurements with the previous apparatus are done with very low level signal compared to nominal power and can induce many errors (signal to noise ratio, non linearity effect).

In order to find a solution to these problems, we propose a measurement method, carried out in time domain and based on the injection of highest level signals in the transformer. The principle of the proposed method and the obtained results are presented in the next section.

V. CHARACTERISATION IN TIME DOMAIN

A. *Measurements principle*

A square voltage waveform is applied at terminals of the transformer in the various configuration tests. The input current and input voltage are measured in time domain and determined in frequency domain via Fourier transforms and then the corresponding impedance can be deduced.

This experimental method has been applied in reduced scale on the laboratory test bench, to characterize the 15kVA three phases transformer. For this characterization, a square signal of magnitude 30 V with a period equal to 30µs, duty cycle equal to 0.5 and the rise time and fall time equal to 10ns. A differential voltage probe (bandwidth: 100MHz) is used to measure the voltage at the generator terminals. The current is measured with a current probe (bandwidth: 100MHz). The connection wires between the generator and the transformer are chosen as short as possible. Figure 7 shows a diagram of the measurement bench; we can see the generator, one phase of the transformer and the position of measurements probes.

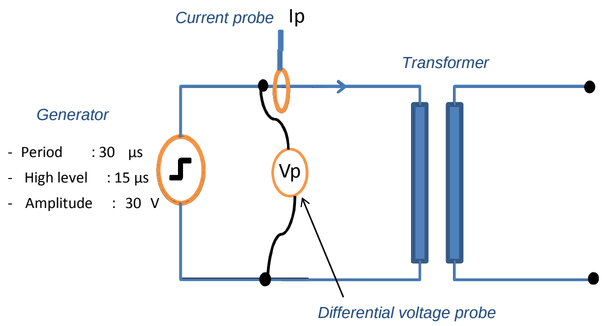


Figure 7. Measurement bench in time domain

Figure 8 and 9 show respectively the waveforms of the primary voltage and current of one phase of the transformer, in the configuration described in figure 7 when the voltage signal is applied at the primary winding with the secondary being open. These measurements allow to determine the magnetizing impedance. The sample frequency used for these measurements is 125 Msample/s.

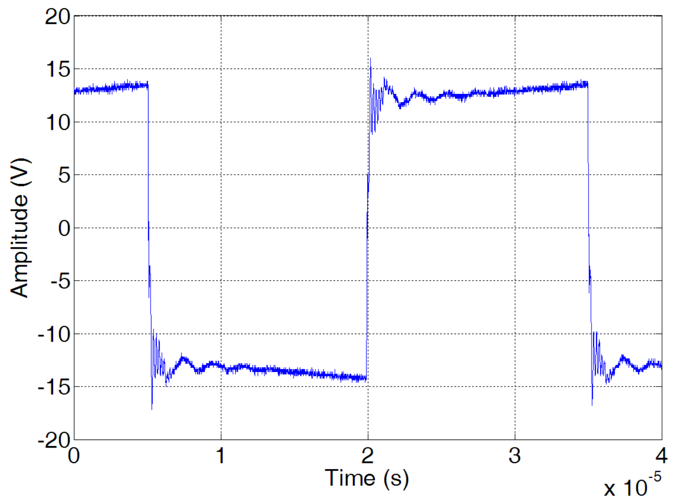


Figure 8. Voltage waveform in primary winding when the secondary is open

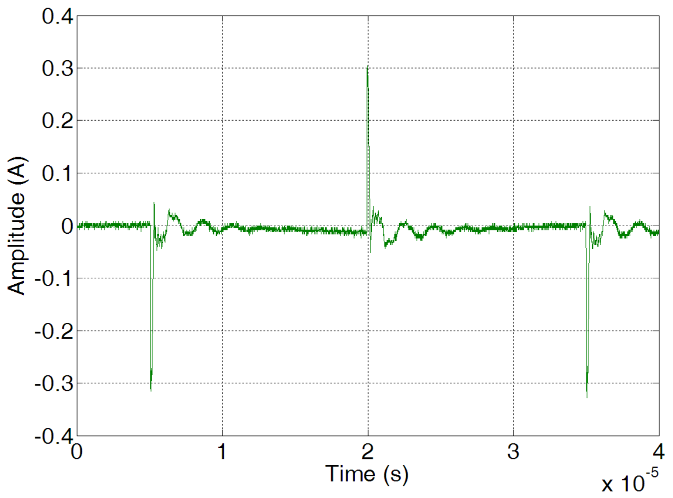


Figure 9. Current waveform in primary winding when the secondary is open

As an example, Fig. 10 shows the voltage measured at the primary winding when the secondary is short circuited.

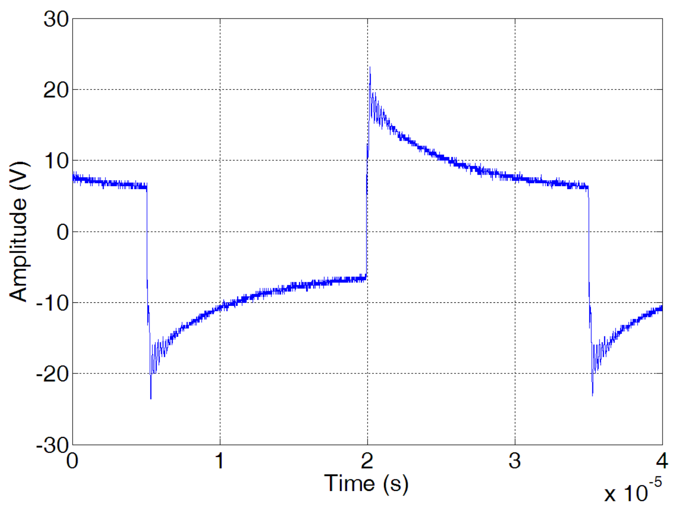


Figure 10. Voltage waveform at primary winding when the secondary is short-circuited

All impedances can then be measured with this technique, but now the data have to be processed.

B. *Data processing*

The measurements results in the time domain have to be studied in frequency domain. The impedance can be expressed as the ratio between the Fourier transforms of the voltage and the Fourier transform of the current which can be calculated through a FFT algorithm for all measurements. The various impedances of the equivalent circuit shown in Fig. 3 can then be determined through various configurations of the transformer.

Figures 11 and 12 how the comparison between the impedance measured directly in frequency domain with impedance analyzer and the impedance issued from the data processing applied to measurements in time domain. Figure 11 shows the impedance measured at the primary winding when the secondary is short circuited while figure 12 shows the results of comparison between the two methods when the secondary is open.

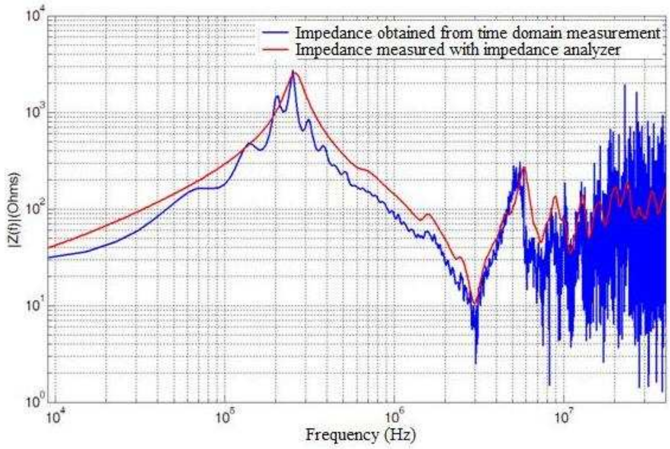


Figure 11. Comparison between measurement impedance in frequency domain and with temporal method applied to impedance of the primary winding, the secondary being short cicuited.

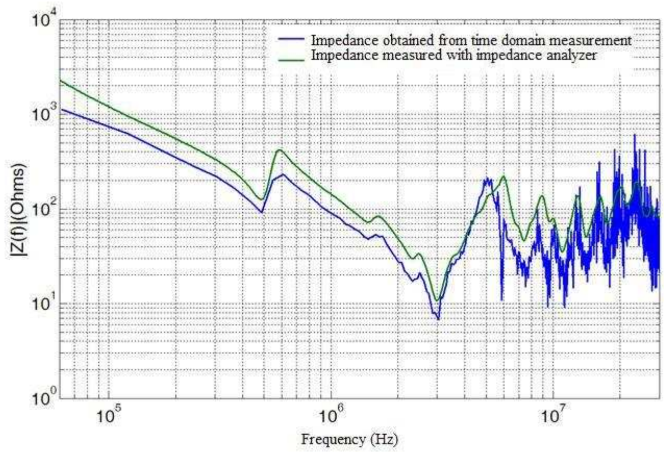


Figure 12. Comparison between measurement in frequency domain and with temporal method applied to impedance of the primary winding, the secondary being open

The obtained results show a good agreement between these methods. However, We note a small difference, in the impedance variation between these methods in low frequency, which may be due to two reasons: the low accuracy of measurement equipements in the time domain (oscilloscope, probes ...) and the behavior of the magnetic material at low frequency.

We can say that these results validate the proposed temporal method. This method is based on measurement of the voltage and current waveforms in the study system by reference to the method of Frequency Response Analysis FRA [9] which is based on the determination of the transfer function and voltage measurements. In the proposed method, the Injection of higher current values allows us to obtain the nominal operating of the transformer.

VI. CONCLUSION

These preliminary results obtained on a laboratory power transformer have shown a good agreement between calculated and measured results. The proposed model needs the determination of experimental parameters which can be measured in time or in frequency domain.

The measurements in frequency domain are often used and can give good results, depending on the application, other methods such as the Frequency Response Analysis FRA can be also used. Nevertheless, the power needed for these experimental determinations is low and can be a problem when the goal of the measurements is to define a model functioning at nominal high power level for a large frequency band.

The proposed experimental method, in time domain, allows making measurements with high injected power. The preliminary results, presented in this paper, obtained on a laboratory transformer are very interesting. In the future, in order to inject higher power signal, the source of square signal will replaced by a system based on the buck converter.

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