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Introduction

High voltage medium frequency and pulse transformers are used in a wide range of power electronics applications from switched-mode and resonant power supplies to power modulators delivering nanosecond short pulses in radars and kickers to millisecond pulses in klystron amplifiers for particle accelerators. The design process of these devices need an accurate modelling approach on an extended frequency range because they highly influence the operation, control and switch rating of the power converters. The influence of the parasitic capacitances and leakage inductances is increased by the high voltage transformer insulation constraints and the design of a transformer with a frequency response imposed by the specifications is a difficult task. The dynamic behavior of the transformer over a large bandwidth is not precisely represented by the conventional low order lumped equivalent circuit [1].

This paper presents a specific methodology to derive high order generalized equivalent circuits. The order of this equivalent circuit can be adapted to a specified bandwidth by identification procedures based on electromagnetic finite elements analysis (FEA) of the transformer structure. This modeling approach is useful for the designer on one hand to predict transient internal overvoltages and determine the insulation constraints and on the other hand to precisely control the resonance and anti resonance frequencies in the transformer dynamic model during the early steps of the design process. The proposed method can also efficiently provide a realistic high frequency equivalent circuit netlist that can be implemented in conventional simulation tools by the power electronics designer, if the transformer topological structure and dimensions are available. This is also an interesting tool to determine the transformer model structure and provide an initial guess of the parameters during an experimental identification procedure [2]. The generalized high order equivalent circuits together with their FEA identification methodology are presented in the following paragraph. Several application examples and an experimental validation are also presented.

Conventional Medium Frequency transformer model

The conventional model of a Medium Frequency (MF) transformer is based on a lumped-element equivalent circuit with a reduced order. Its parameters can be derived from experimental or FEA identification procedures.

Conventional MF transformer equivalent circuit

The equivalent circuit presented in Fig. 1 a) is using three lumped capacitances, two leakage inductances, two windings resistors and a magnetizing inductance. This simple model is proposed for example in the pulse transformer IEEE standard [1]. The magnetic part of the T-circuit with the three inductances can be also represented by a coupled-inductors circuit.

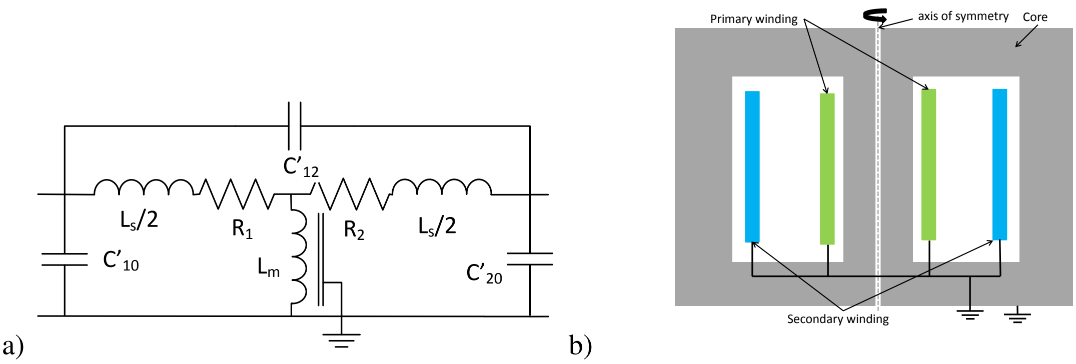

Figure 1: a) Conventional MF transformer T-equivalent circuit b) Coss-sectional view of a pot-core transformer

FEA identification of conventional MF transformer equivalent circuit

For transformer design purpose, the elements of the conventional equivalent circuit can be derived from the transformer dimensions and material characteristics by simplified analytical dimensioning models or by specific-FEA based identification procedures [3]. The three lumped capacitances are derived from three electrostatic FEA simulations where the windings are supplied at rated voltage or grounded [3]. In the case of pulse transformers, one takes account of the voltage distribution along the winding height during these simulation tests to derive more accurate values of the three capacitances [4]. One assumes that this distribution is linear. The inductances and coupling factors are identified by two magnetostatic or time-harmonic magnetic FEA simulations of the transformer no-load and short-circuit operations [3].

Impedance frequency response and pulse response of MF transformer

The blue waveform of Fig. 2 a) presents the no-load impedance vs frequency characteristic of the Pot-Core single phase transformer illustrated on Fig. 1 b) derived from the conventional reduced order equivalent circuit. The blue waveform of Fig. 2 a) presents the output voltage pulse applied to the transformer rated resistive load when a square voltage pulse is applied on the primary side. These two characteristics will be used in the paper to compare the performances of the different transformer equivalent circuits.

High order generalized MF transformer model

With the reduced order conventional equivalent circuit topology, it is difficult to quantify the influence of the detailed local structure of the transformer in terms of winding configuration, winding coil shape or insulation shields on the transformer dynamics. These local structural details as well as the external series and/or parallel connections of the different coils can lead to very different instantaneous voltage internal distribution in the windings during transient voltage operation in pulse transformers for example or to different resonant frequencies with pwm voltage waveforms in switched-mode power supplies. It is mandatory for the designer to consider high order equivalent circuits for this purpose [5] [6].

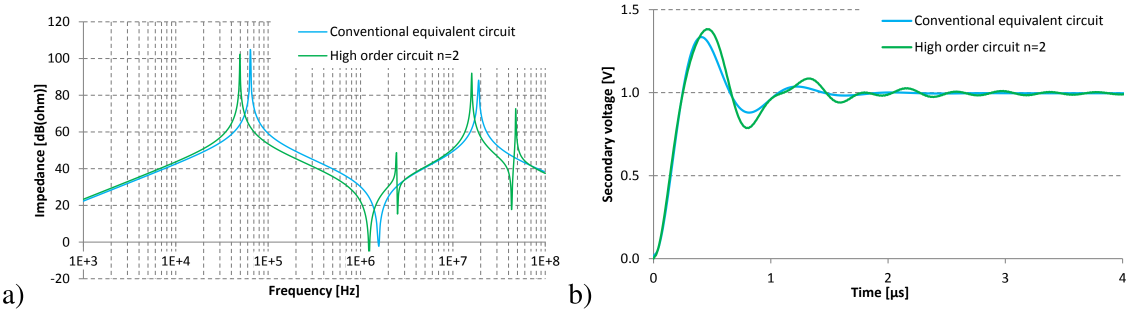

Figure 2: a) No-load impedance vs frequency characteristic b) Impulse response of reduced order conventional equivalent circuit and second order generalized equivalent circuit (n=2)

Generalized MF transformer equivalent circuit

For the same transformer topology, equivalent circuits of different orders can be identified by splitting the main windings in an arbitrary number n of elementary windings. With such an approach, each elementary winding is considered as a lumped element with its own inductance and magnetic couplings with the other elements, and with its own capacitance and capacitive influence coefficients with the other elements (Fig. 3). The lumped characteristics of each elementary winding are mainly based on the assumption that there is a constant voltage inside it. The generalized equivalent circuit order can be chosen according to the transformer size and the operational frequency range. The minimal elementary winding is a single coil turn. The elementary capacitance, inductance and coupling factors are derived from specific identification techniques based on experimental tests or FEA simulations.

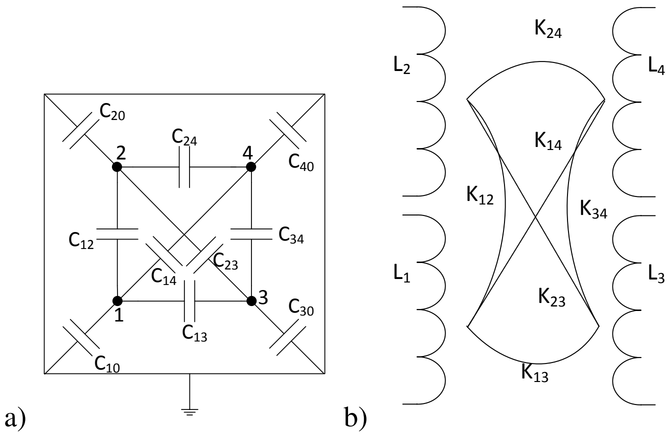

Figure 3: a) Capacitor network between 4 electrodes and ground b) Coupled-inductors network for 4 windings

FEA identification of generalized equivalent circuit capacitances

The capacitive part of the generalized equivalent circuit is based on a capacitance matrix [C] with positive coefficients:

$$[C] = \begin{pmatrix} C_{11} & \dots & -C_{1m} \\ \dots & \dots & \dots \\ -C_{n1} & \dots & C_{nm} \end{pmatrix} \quad (1)$$

Each elementary winding is considered as a conductor with a uniform voltage. The different capacitive coefficients can be systematically derived from FEA electrostatic simulation tests. The method is based on the evaluation of the induced electrical charge. A voltage V_i is imposed on conductor i. The charge

Q_j induced on every conductor including conductor i is computed by integration of the electrical field and application of the Gauss law. The capacitive coefficients between conductors i and j become:

$$C_{ij} = \frac{Q_j}{V_i} \tag{2}$$

With this method, m simulations must be performed if m conductors are present in the domain [8] [9]. Fig. 4 presents the four FEA electrical identification simulations for a Pot-Core single phase transformer with an equivalent circuit of order two. A network of capacitances linking each conductor including the grounded core and tank is then determined [8] [9]. The Fig. 3 a) presents an example of a capacitor network for a grounded system with four conductors supplied by independent voltages. The mutual capacitors between the conductors and the capacitance between conductor and ground are represented.

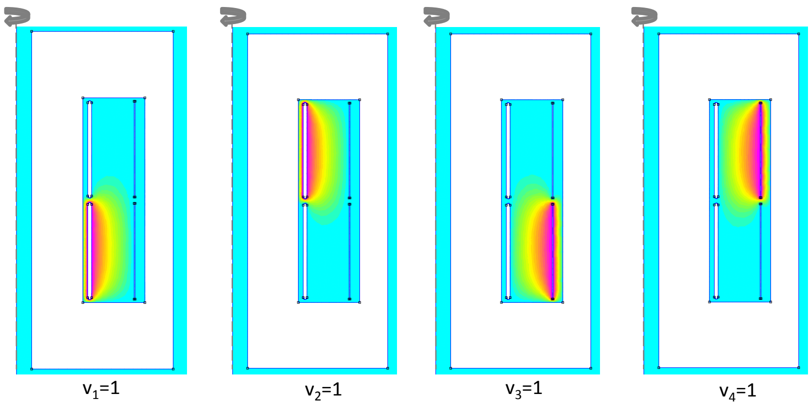

Figure 4: FEA Electrostatic identification tests of order 2 capacitance matrix for a Pot Core single phase transformer (n=2)

FEA identification of generalized equivalent circuit coupled inductors

The magnetic part of the generalized equivalent circuit is based on a coupled-inductors network that can be represented by an inductance matrix [L] with self and mutual inductances and a magnetic coupling matrix [K]:

$$a)\,[L] = \begin{pmatrix} L_{11} & \dots & L_{1m} \\ \dots & \dots & \dots \\ L_{n1} & \dots & L_{nm} \end{pmatrix} \quad b)\,[K] = \begin{pmatrix} 1 & \dots & k_{1m} \\ \dots & \dots & \dots \\ k_{n1} & \dots & 1 \end{pmatrix} \quad with\ \ k_{ij} = \frac{L_{ij}}{\sqrt{L_{ii}L_{jj}}} \tag{3}$$

The different coefficients of the inductance matrix can be systematically derived from FEA magnetostatic simulation tests. The inductive coefficients and coupling factors are computed by integration of the magnetic flux. Fig. 5 presents the FEA identification simulations for the Pot-Core single phase transformer transformer with a circuit of order two (i.e. a total number of four coupled inductors). A current i_i is imposed on one coil and the magnetic flux Φ_j are measured in all coils. The inductive coefficients are determined from:

$$L_{ij} = \frac{\Phi_j}{i_i} \tag{4}$$

The coupling coefficients k_{ij} can then be derived from eq. 3 b. The coupled-inductors network with four elementary windings is presented on Fig. 3. Because the primary and secondary windings are respectively split in two elementary windings, the coils 1,2 and 3,4 must be connected in series respectively.

Generation of generalized equivalent circuit netlist

The matrix coefficients are used in the netlist building procedure presented in Fig. 6 for a n order transformer equivalent circuit with both primary and secondary windings divided in n sub-windings. The netlist generated by the procedure can be implemented in a circuit simulation software to compute the impedance frequency response and the pulse response of the generalized transformer equivalent circuit.

The green waveform of Fig. 2 a) presents the no-load impedance vs frequency characteristic of the Pot-Core transformer of Fig. 1 b) derived from the generalized transformer equivalent circuit of order n=2. The green waveform of Fig. 2 a) presents the output voltage pulse applied to the rated resistive load when a square voltage pulse is applied on the primary side. One can notice that the performance characteristics of the conventional equivalent circuit and the second order generalized equivalent circuit are different. These differences will be discussed in the next part of the paper.

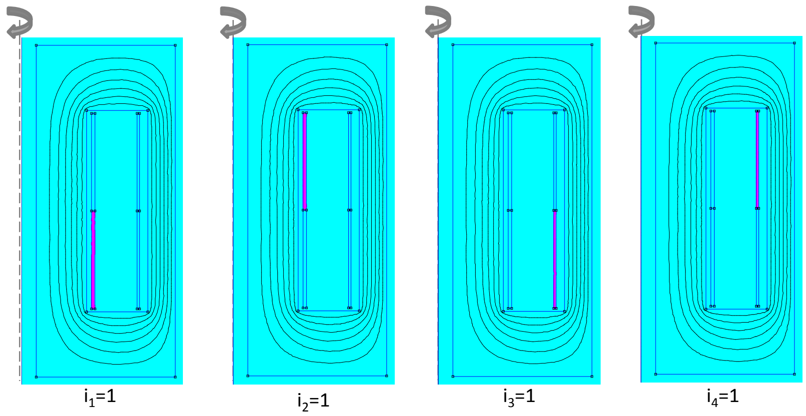

Figure 5: FEA Magnetostatic identification tests of order 2 inductance matrix for a Pot Core single phase transformer (n=2)

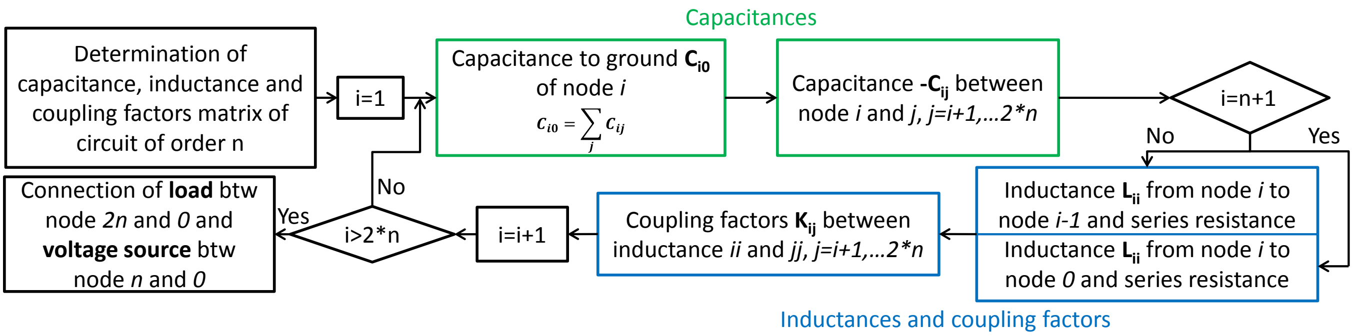

Figure 6: Flowchart of netlist generation procedure of a n order single phase transformer equivalent circuit

Applications of High order generalized MF transformer model

Two applications of the proposed modeling methodology and an experimental validation on a prototype of ferrite Pot Core transformer are presented.

Comparative analysis of pulse transformer equivalent circuits with different orders

The modeling methodology is applied to the 27 MW/10kV/100kV pulse transformer presented in Fig. 7 a). This structure with single primary and secondary windings on the same core leg has been designed with the CAD environment developed in [3]. Its specifications are presented on Table I. The primary and secondary windings are grounded with the core. The no-load impedance vs frequency characteristics derived from the conventional equivalent circuit and from equivalent circuits with different orders n=1,2, 4 and 8 are presented on (Fig. 8). The parameters of the four equivalent circuits have been identified with the FEA techniques presented in the first part of the paper. The FEA simulations were performed with the FEMM 4.2 code [7].

With the capacitive part of the generalized equivalent circuit, it is also possible to compute the voltage distribution along the primary coil height when a 10kV pulse is applied at time t=0. One can notice on Fig. 7 b) that the linear voltage distribution simplifying assumption used to identify the conventional equivalent circuit is not realistic. When the order is increased, the distributed character of the proposed high order equivalent circuit is emerging and the voltage profile is becoming more and more consistent with the high frequency electromagnetic theory.

Table I: Specifications of the pulse transformers with different winding configurations

Specification	Value	Unit
Peak output power	27	MW
Primary nominal voltage	10	kV
Secondary nominal voltage	180	kV
Pulse length	140	μs
Voltage pulse rise time	< 8	μs
Material specifications	**Value**	**Unit**
Breakdown field of insulating material	6	MV/m
Relative permittivity of insulating material	3	-
Relative permeability of magnetic material	4000	-
Saturation flux density of magnetic material	1.15	T

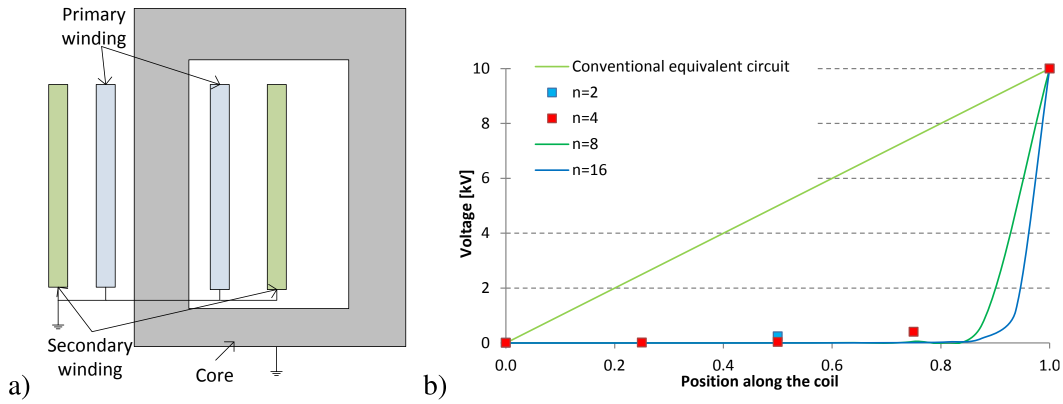

Figure 7: a) Coss-sectional view of 10MW pulse transformer with single primary and secondary windings on the same core leg b) Voltage distribution along the primary coil height when a 10kV pulse is applied at time t=0

According to the results obtained on the initial voltage profile, one can notice on the impedance vs frequency characteristics of Fig. 8, that the low order resonances are progressively shifted to higher frequencies when the order of the circuit is increased. For higher order values they are converging to specific values that are different from the values obtained with the conventional equivalent circuit assuming a linear initial voltage distribution.

The pulse response of the different equivalent circuits in Fig. 8 b) exhibit more oscillations, the rise time and the settling time are greatly influenced by the circuit order. These results can be explained by the additional resonance values due to the order increase. In practice, these high frequency oscillations are damped by the dissipative effects. In this application we have demonstrated and quantified the limits of the conventional electrical equivalent circuits in terms of pulse rise time prediction. It is mandatory to use the high order equivalent circuits during the pulse transformer design process.

Comparative performances of pulse transformers with different winding configurations

In this example, we consider two pulse transformers with one primary and one secondary windings on both legs. The primary windings of both transformers are connected in parallel, but the secondary windings are connected in series in the first transformer and in parallel in the second transformer (Fig. 9). The CAD environment developed in [3] has been used to design these pulse transformers with the same specifications listed on Table I and identical conventional equivalent circuit parameters that are detailed on Table II. Consequently, the no-load impedance vs frequency characteristics of both transformers derived from the conventional equivalent circuit are also identical (Fig. 10). One can also notice on Table II, that the transformer dimensions are slightly different.

Their no-load impedance vs frequency characteristics are now derived with a four order equivalent circuit and compared. The transformer with the secondary in series has one more resonance. The capacitive coupling is more important between windings on the same leg as they share larger and closer parallel surfaces. When the secondary windings are connected in parallel, the transformer is symmetric and windings on both legs have the same resonance peaks. When the secondary windings are in series, the insulation distance between the coils on the right and left legs are different because the secondary winding voltage are different. The resonance peaks on the left and right legs are different and superposed in the global impedance. This can be noticed with the two similar resonances at 360 kHz and 412 kHz. There are globally more resonances in the configurations with the secondary windings in series. The most noticeable supplementary resonance ignored by the conventional equivalent circuit model is at 231 kHz on the series configuration and only 131 kHz on the parallel configuration.

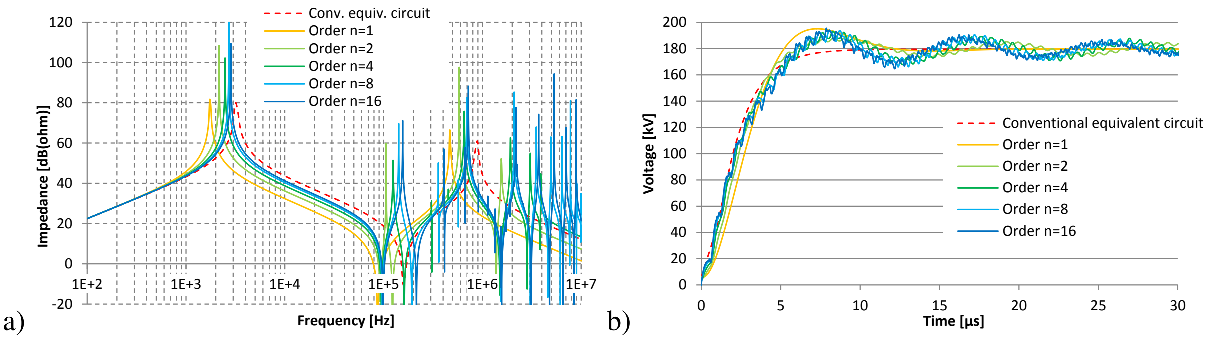

Figure 8: a) No-load impedance vs frequency characteristics of conventional equivalent circuit and equivalent circuits with different orders n=1,2, 4 and 8 b) Impulse response of conventional equivalent circuit and equivalent circuits with different orders n=1,2, 4 and 8

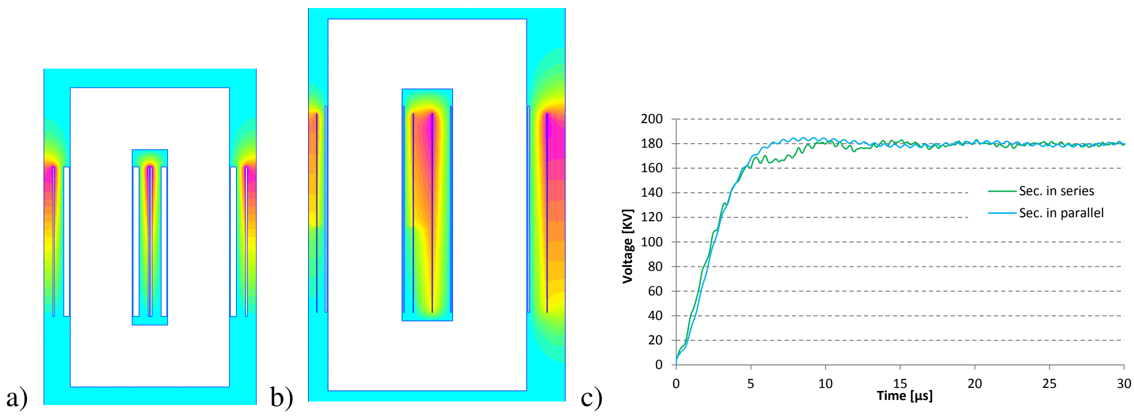

Figure 9: Compared cross-sectional view of pulse transformers with parallel primary windings, identical conventional equivalent circuit and different secondary winding configurations: two secondary windings in parallel (a) or in series (b) c) Comparison of the pulse response of transformers with secondary windings respectively in series and in parallel

In this second example the limits of the conventional equivalent circuits have been also highlighted in terms of prediction of the dynamic behavior. The transformers have identical conventional equivalent circuits but their no-load impedance vs frequency characteristics and pulse responses simulated with order four equivalent circuit presented in Fig. 9 c) are different. The high order equivalent circuits are more sensitive to the differences in winding configurations and transformer internal structure.

Winding internal overvoltage

The four order equivalent circuit of the second pulse transformer with the secondary windings in series was used to investigate possible internal overvoltages due to the resonances of the transformer impedance with the voltage supply harmonics. On can see on Fig. 11 that with a fundamental voltage supply at 13.8 kHz with a tenth harmonic, one can get an amplification of the tenth harmonic internal voltage on the middle of the primary coil. This kind of internal voltage amplification due to specific resonant frequencies of the transformer can lead to insulation defaults. With a conventional equivalent circuit, such a danger cannot be predicted. This kind of problem can be only detected by use of high order equivalent circuits.

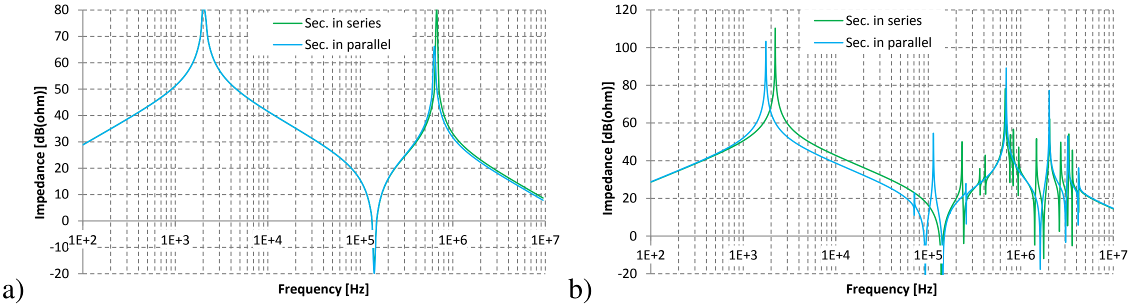

Figure 10: a) Identical no-load impedance vs frequency characteristics derived from conventional equivalent circuit b) No-load impedance vs frequency characteristics of high order circuit of order n=4

Table II: Characteristics of the transformers with parallel and series secondary coupling

Specification	**Unit**	**secondary in series**	**secondary in parallel**
Number of turns per primary winding	–	16	16
Number of turns per secondary winding	–	144	226
Core width	m	0.108	0.097
Dimensions width x height x length	m	0.374 x 0.577 x 0.463	0.333 x 0.468 x 0.584
Total volume	m^3	0.100	0.091
Equivalent circuit parameter	**Unit**	**Value for both configurations**	
Primary capacitance C'_{10}	nF	-1.7	
Secondary capacitance C'_{20}	nF	138	
Inter-windings capacitance C'_{12}	nF	6.51	
Magnetizing inductance L_m	mH	44.1	
Leakage inductance L_s	μH	8.69	

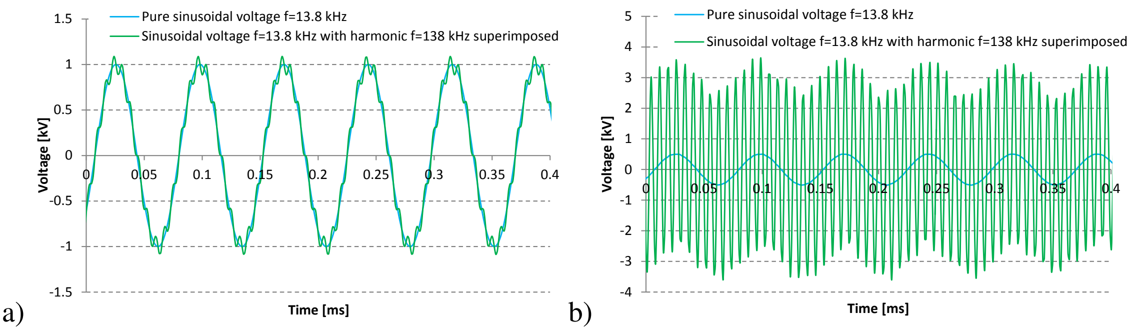

Figure 11: a) Primary voltage with and without harmonic b) Voltage at the middle of the primary coil with and without harmonic

Experimental validation on ferrite Pot Core transformer

A transformer prototype using a ferrite Pot Core has been designed and realized: the detailed characteristics of the prototype are presented on Fig. 12 and on Table III. The core cylindrical symmetry is well adapted to a 2D FEA simulation tool. Fig. 13 presents the experimental and simulated no-load impedance vs frequency characteristics. One can notice that the resonance modes predicted by the high order equivalent circuit are consistent with the experimental results. With the conventional equivalent circuit, it was not possible to predict the resonance measured at 3.6 MHz. The performance of the proposed methodology is demonstrated.

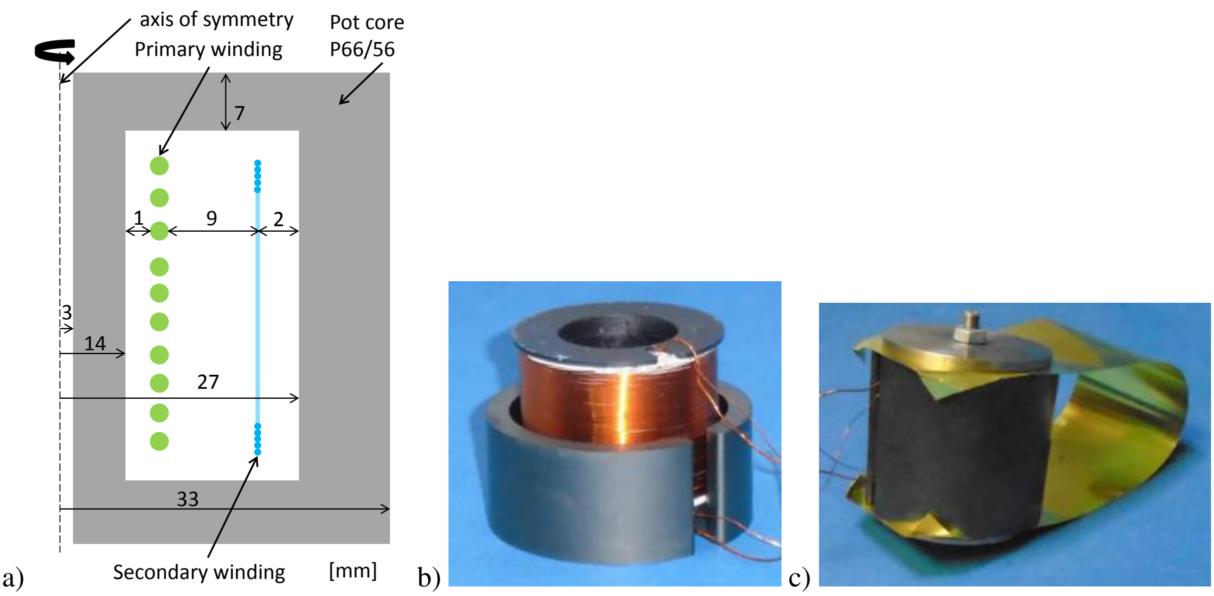

Figure 12: a) Pot Core transformer prototype dimensions b) View of the internal winding configurations c) Assembled prototype under test with grounded core shield

Table III: Characteristics of the experimental pot-core transformer

Parameter	Unit	Value
Number of turns of primary winding	10	
Primary winding Wire Gauge	AWG20	
Number of turns of secondary winding	130	
Secondary winding Wire Gauge	AWG30	
Pot-core	P66/56	
Core material	ferrite 3C91	

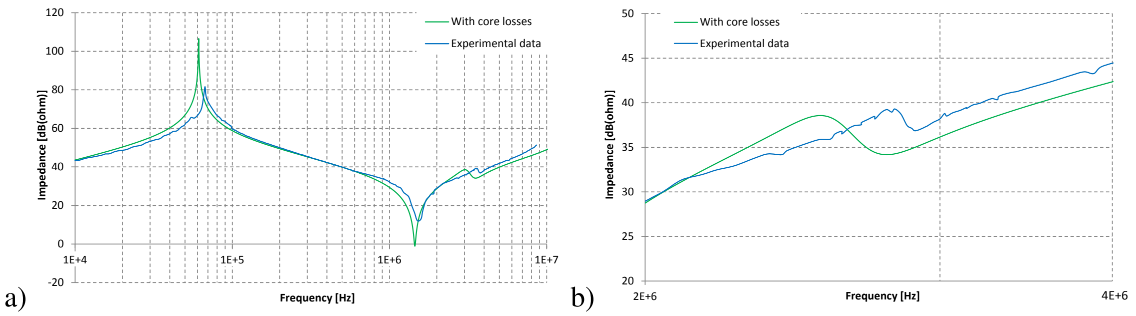

Figure 13: No-load impedance vs frequency characteristics: experimental and high order equivalent circuit simulation results, Zoom on the 3.6 MHz resonance predicted by the high order equivalent circuit of order n=8

Conclusion

A specific methodology to derive high order generalized equivalent circuits of high voltage medium frequency and pulse transformers from FEA identification tests has been presented and validated on a prototype. With this approach, an improved transformer dynamic model over a large bandwidth can be easily obtained and the order of the generalized equivalent circuit can be adapted to a specified bandwidth. The limits of the conventional reduced order equivalent circuits have been demonstrated on application examples. This efficient tool can be used by the designer to quantify the influence of the transformer local structure and winding configuration on its dynamic behavior.

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