NOVEL HIGH FREQUENCY MODEL OF TRANSFORMERS OF ELECTRONIC DEVICES

PhD Theses

by

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1. INTRODUCTION

Impacts of over-voltages reaching transformers and transformer coils are already researched over a century. Transient over-voltages have different characteristics, like rise time, peak value, spectrum, energy, charge, etc. and different impacts on devices in turn, depending on the cause phenomenon: LEMP (Lightning Electromagnetic Pulse), SEMP (Switching Electromagnetic Pulse) sources of surges and bursts and electrostatic discharges (ESD).

The increasing electromagnetic noise level on electric networks and the even higher switching frequency of power supply units built into sensible electronic devices make necessary to have more precise modelling of transformers - for low voltage and low power transformers as well -, taking into account every wave propagation phenomena along the coils. A reliable but simple high frequency model of transformer shielding is necessary for the forecast of the interaction of different over-voltages and the shielding.

Several versions of SPICE based circuit simulator software are widely used for simulating electric and electronic circuits before, during and after manufacturing. An important task of these simulation sessions is to predict the behaviour of the circuits in case of over-voltages. Devices like transformers of electronic equipment becoming smaller and smaller and therefore more and more sensible against interference, have to be modelled for transient over-voltages with high frequency content like burst and ESD (Electrostatic Discharge). In case of small transformers built into electronic devices, quick over-voltages like bursts and electrostatic discharge are of interest as well.

Bursts and ESD have rather small electric charge absorbed by the capacitance of high voltage transformers but by small scale transformers not. They have a rise time of some nanoseconds and propagating through small transformers they can cause damages. In addition to those described above switching frequencies of supply units are near to the MHz range, so wave propagation is no more negligible either in small transformers. For a more precise high frequency modelling of transformers, a reliable model is needed. The known models do not take into account every electromagnetic wave propagation phenomena along the coils. The current path composed by the capacitance between the neighbouring turns not being negligible at high frequencies is taken into account only as capacitors connected directly in series with each-other. This is the case in longitudinal and radial directions as well. In these models certain voltage values appear with no delay at every locations of the capacitance chain, i.e. along the

whole length and whole radial dimension of the coil when applying the supply voltage at the input ports of the coil.

Shielding inserted between the coils of transformers have the task to conduct the electric charge of transient over-voltages to the earth avoiding so the propagation of over-voltages to the secondary coil of the transformer. However in case of fast transients with high frequency content this shielding is no more effective. Wound and cylinder type shielding has more or less inductance to the ground hindering the electric charges to reach the shielding, decreasing so the shielding efficiency. In case of over-voltages with very high frequency content no shielding is built into the transformers because their inefficiency.

A more precise simulation model for the shielding could help during the decision what type of shielding should be installed if any. The known shielding models do not take into account the capacitance of the shielding to the surrounding conductive bodies and the inductance in series with the shielding inside and outside of the transformer housing.

Objective of the research

The known high frequency transformer models are not able to simulate all aspects of the electromagnetic wave propagation along coils and transformers, neither in longitudinal nor in radial direction. In addition there is no known model for the shielding inserted between the coils of transformers taking into account the capacitance of the shielding to the surrounding conductive bodies and the inductance in series with the shielding inside and outside of the transformer housing. In the scope of the above shortage of the high frequency models of transformers the objectives of the present work are as follows.

(i) My purpose is to develop a novel high frequency model for one-layer, straight coils.

An inevitable part of a model of one-layer straight coils needed for high frequency examinations is the capacitance between turns along with the capacitance between the coil and the core and housing. There are several high frequency transformer models being applicable in certain cases, resulting no contradictions to each-other concerning the basic function of the transformer. Some models have lumped parameters determined e.g. by measurements, others are of "quasi" distributed parameters and of really distributed parameters taking into account wave propagation to a certain amount.

None of the known coil models is able to take into account electromagnetic wave propagation along the path composed by the turn-to-turn capacitance, because these capacitors are connected directly in series to each-other in the model according to the classic Wagner's theorem. In the case of these models certain voltage values appear with no delay at every locations of the capacitance chain, i.e. along the whole length of the coil when applying the supply voltage at the input ports (one end) of the coil.

For taking into account electromagnetic wave propagation along straight coils I would like to propose a length unit inductance connected in series to the length unit turn-to-turn capacitance within the distributed parameter model of one-layer straight coils proposed by Wagner. This inductance makes able the model to take into account the wave propagation along the turn-to-turn capacitance current path of the coil.

For an easier use of the model in a SPICE software I would like to develop a "quasi distributed parameter model" as well with proposed calculation methods of the parameters. This model contains several identical lumps for modelling the wave propagation but being easily applicable for the practical use.

For testing the model I would like to prove it by measurements, so a two meter long straight coil of copper wire with a diameter of 1 mm included the varnish insulation and the wire is densely wound onto a plastic protective pipe was tested. Measurements on the coil with an iron core have been realised with pulse generators and an oscilloscope to compare the results with those given by the model with the simulator software.

(ii) My purpose is to work out a novel high frequency model for multi-layer straight coils and coils on each-other.

The known high frequency coil and transformer models contain only capacitors between the turns of the neighbouring coil layers and coils, therefore these models are not able to take into account electromagnetic wave propagation along the layers of coils and between coils, because these capacitors are connected directly in series to each-other. In the case of these models certain voltage values appear without delay at every locations of the capacitance chain, i.e. along the whole radial dimension of the coil when applying the supply voltage at one bordering layer of the coil.

For taking into account electromagnetic wave propagation along multi-layer coils and transformers i.e. coils on each-other I want to propose a unit length inductance connected in series to the unit length layer-to-layer capacitance

within the distributed parameter model of the coils and transformers. This inductance makes able the model to take into account the wave propagation along the layer-to-layer capacitance current path in radial direction as well.

For an easier use of the model in a SPICE software I propose a "quasi distributed parameter model" as well with proposed calculation methods of the parameters. Because of the several identical lumps this model can take into account electromagnetic wave propagation, remaining meanwhile easily applicable in the practice.

To validate it I have developed a measurement for two meter long straight coils of copper wire with a diameter of 1 mm included the varnish insulation and the wire was densely wound onto plastic protective pipes. Measurements on the coils with and without an iron core has been realised with pulse generators and an oscilloscope to compare the results with those given by the model with the simulator software.

(iii) My purpose is to develop a novel high frequency model for the shielding between transformer coils.

Primary coils of small transformers with even less dimensions can no more absorb the rather low electric charges of bursts and electrostatic discharges, thus voltages being dangerous to electronic circuits can propagate to the secondary circuit. Shielding installed between the coils in small transformers should avoid the propagation of over-voltages to the secondary coil of the transformer. However because of the inductance existing always in series between the shielding and the electric charge source composed by the ground, the shielding is not so effective at high frequencies belonging to fast common mode transients like bursts and electrostatic discharges as at low frequencies belonging e.g. to surges.

A rather simple simulation model can help by the decision which art of shielding should be installed if any. The known shielding models do not take into account the capacitance of the shielding to the surrounding conductive bodies and the inductance in series with the shielding inside and outside of the transformer housing.

I would like to propose a high frequency SPICE model of transformer shielding built in a circuit simulator software for the use by the dimensioning of the transformers taking also into account the earth connection aspects of the shielding.

For testing the model I have realised a measurement on a PC supply unit transformer with signal generators to test the model. I would like to introduce an inductance in series to the ground of the shielding, yielding similar results as those of the measurements. A capacitance is introduced then in parallel to this inductance, both are then split into two parts each to obtain a reliable model for shielding between transformer coil.

The research focuses on coils with a structure in general use in transformers of electronic devices and to their behaviour during the first time period after applying voltage onto the coil, thus no core losses are taken into account during the investigations. The proposed models are not valid for high voltage transformers and other transformers with special structure.

2. APPLIED METHODS

Wagner's theorem

I would like to work out a novel one-layer distributed parameter coil model suitable for modelling electromagnetic wave propagation also along the current path composed by the turn-to-turn capacitance and I propose a lumped parameter model as well for the application with simulation software by introducing an inductance in series to the turn-to-turn capacitance in the model circuit.

The proposed distributed parameter model is based on Wagner's theorem and is a further development of it. Wagner's theorem is applicable for straight, one-layer, ideal coils with core and is based on the classic telegraph line equations. Wagner's theorem takes into account the turn-to-turn capacitances of coils, thus composing a basis for high frequency distributed parameter coil models being applicable in many practical cases. However Wagner's model is not able to take into account wave propagation along the current path composed by the turn-to-turn capacitance because of the capacitors in series to each-other. At he moment of applying the voltage to one end (input ports) of the coil a certain voltage value appears at every locations of the coil. This is impossible in the reality, a certain time in needed for the wave to propagate from one end to the other along the coil.

Turn reduction

A distributed parameter model would give perfect solution in case of fast transients but can not be realised in a SPICE software. When modelling a coil for a SPICE software the most precise results would be given by a lumped parameter circuit containing a model for each turn of the coil. In case of high voltage power transmission transformers this way can also be realised, with the help of a computer and the desired results can be quickly obtained. Coils of small transformers can however have several thousands of turns so this cannot be a suitable way for the practice.

The solution can be given by the use of the method of turn reduction used also in case of high voltage transformers, namely modelling several neighbouring turns in one lumped model. The principle of turn reduction means, that with adequate calculation less number of lumps can be used in the model maintaining meanwhile the necessary advantages of several lumps. Thus a "quasi distributed model" is achieved which is actually a lumped parameter model but made of several identical lumps.

Series Foster's circuit

The circuit elements in a high frequency model current is changing with the frequency, so the simplified series Foster's circuit is applied. The basic principle of the series Foster's circuit means, that more resistances are connected in series to the direct current resistance of the element and inductances are connected in parallel to them being calculated so that at low frequencies the inductive reactance values are negligible compared to the direct current resistance. With increasing frequency more and more further resistances will be effective modelling so the frequency dependence of the resistance.

If the first peak of the voltage has bees reached within a certain time period after the voltage pulse arrives the coil, this value can considered as a quarter period of pulse time corresponding to the maximum frequency of the voltage wave and the minimum skin depth and the surplus resistances can be calculated.

The inductance parallel to a surplus resistance have the task to short circuit the surplus resistance in case of low frequencies and to compose a much greater impedance at high frequencies. So the resistance of the lump can vary between two decades depending on the frequency. The value of the inductance must be chosen so, that its reactance is negligible compared to the surplus resistance, i.e. at least two decades lower than it.

Modelling time delays

A significant issue is to take into account the time delay of the induced voltage in the turns being apart from each-other if the electromagnetic field propagation has to be modelled as well. Time delays can be realised through several methods with the help of a circuit simulator software, using transmission lines, lossy transmission lines, ports or all pass filters. The only really distributed parameter element in a SPICE software is the so called "Lossy Transmission Line". In my investigation I have chosen for the use of ideal transmission lines because of their simplicity and less number of parameters. This transmission line serves only for time delay and the lossy character of the real coil is modelled by separate resistances. Using lossy transmission lines would not give the advantage of using a completely distributed parameter model, because it can model only a transmission line. In case of modelling coils it can be used only for time delay purposes like the normal transmission line, thus a lumped parameter model is to be used in a circuit simulator software with several identical lumps connected in series to each-other to maintain the ability of the circuit to model wave propagation.

3. THESES

Thesis 1

I have developed a novel high frequency distributed parameter model and a lumped parameter model for one-layer, straight coils. These models are able to take into account the electromagnetic wave propagation along the current path of the coil composed by the turn-to-turn capacitance as a result of an inductance inserted in series to this capacitance. Former models can not take this phenomenon into account, as they model this current path only by a capacitance chain, [1], [2], [3], [4].

a) I propose a novel high frequency distributed parameter model for one-layer straight coils on the basis of Wagner's model introducing an inductance of unit length in series with the reciprocal turn-to-turn capacitance of unit length. This distributed parameter circuit can model electromagnetic wave propagation along the current path of the coil composed by the turn-to-turn capacitance unlike the former models, because they model this path only by a capacitance chain, on which the voltage appears on its whole length with

no delay. Calculation of this inductance is based on that of coaxial cables depending on the dimension and materials of the coil.

b) I propose a novel high frequency lumped parameter model for one-layer straight coils for the use with circuit simulation software introducing an inductance in series with the turn-to-turn capacitance. With a model composed by an appropriate number of the developed identical lumps electromagnetic wave propagation along the current path of the coil composed by the turn-to-turn capacitance can be modelled.

Thesis 2

I have developed a novel high frequency distributed parameter model and a lumped parameter model for multi-layer coils and coils on each-other, i.e. for transformers of electronic devices. These models are able to take into account the electromagnetic wave propagation between coil layers and coils, i.e. in radial direction along the current path composed by the layer-to-layer capacitance as a result of an inductance inserted in series to this capacitance. Former models can not take this phenomenon into account, as they model this path only by a capacitance chain between the coil layers, [5].

a) I propose a novel high frequency distributed parameter model for multi-layer coils and coils on each-other, i.e. for transformers, introducing an inductance of unit length in series with the reciprocal layer-to-layer capacitance of unit length. Unlike the former models taking this path into account only by capacitance chain, on which the voltage appears without delay, this distributed parameter circuit can model electromagnetic wave propagation in radial direction, i.e. along the current path of the coil composed by the layer-to-layer capacitance. Calculation of this inductance between two layers for each layer pair is based on that of coaxial cables depending on the dimension and materials of the outer coil layer.

b) I propose a novel high frequency lumped parameter model for multi-layer coils and coils on each-other, i.e. for transformers for the use with circuit simulation software introducing an inductance in series with the layer-to-layer capacitance. With a model composed by an adequate number of the developed identical lumps electromagnetic wave propagation in radial direction, i.e. along the current path of the coil composed by the layer-to-layer capacitance can be modelled as well.

The above model is valid for transformers containing several turns densely wound near to each-other and layers being densely on each-other.

Thesis 3

I have developed a novel high frequency transformer shielding model for the shielding installed between the two - primary and secondary - coils of transformers of electronic devices. This model is able to take into account the dependence of the shielding efficiency on the internal and external characteristics of the transformer and its environment unlike former models being unable for this purpose, [7].

I propose a novel high frequency lumped parameter model for the shielding between the primary and secondary coils of transformers by introducing two inductances in series with each-other between the shielding and the grounding and two capacitances parallel to these inductances, one inductance-capacitance pair corresponding to the internal and the other pair corresponding to the external layout of the transformer and its environment. Unlike the former models this circuit can model the dependence of the shielding efficiency on the internal and external characteristics of the transformer and its environment.

The internal inductance and capacitance are to be calculated according to the dimensions and material characteristics inside the transformer to the connecting ports of it. The external inductance is to be calculated taking into account the inductance of the supply cable of the transformer and the inductance of the grounding circuit of the electrical installation in the room and building where the transformer is installed. The external capacitance is to be calculated between the transformer's primary coil resp. the housing of the transformer if exists and the surrounding conductive, grounded bodies.

4. FURTHER RESEARCH

Measurements realised on the one-layer coil give similar, robust results in case of repeating them with other signal generators and oscilloscopes. Simulation with the proposed quasi distributed parameter models are sensible to the parameters and give results with slightly other curve shapes at the investigated time period. A further research is necessary to make the model being able to give results nearer to the measured results.

The simulated transfer function curve for the shielding model is much more simple than the measured one, because the model is rather simple as well. The second peak value differs to a rather great amount from the measured one, it is

much slighter and smoother than that simulated. The reason of this fact is to be find.

Between 1 and 3 MHz there are a lot of local extreme values on the measured curve can not be find on the simulated curve. The reason of this can be the simplicity of the model circuit. A solution to model this phenomena could be a combination of the model principle developed in Karlsruhe or of other models with this model.

5. PUBLICATIONS

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