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PART
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Transient Response Study on Transformer Windings Under Impulse Voltage Stresses

Hendri Masdi, Norman Mariun

Abstract – *The study reported in this paper was aimed to investigate transient response of power transformer when lightning current pass through its winding. Analysis of distribution voltage at the winding taps was done, both by experimental and numerical simulation, by applying IEC-71 standard current surge (8/20 μs impulse current and 1.2/50 μs impulse voltage). Transformer's constants as: R, L, C were derived from the transformer construction, which consists of 9 winding layers at HV-side. The wave-shapes of the voltage across the winding sections were recorded. The response of the windings was then compared with results of a simulation using EMTDC/PSCAD. The simulation based on an RLC network model resulted in wave-shapes that are in good agreement to those of the experiment. Both results of the simulation and experiment show that the distribution of the impulse voltage across the windings is non linear, especially during the period of fraction of microseconds. Furthermore, results of the investigation show that a simple capacitance network model is sufficient for study of the impulse voltage distribution across transformer windings. **Copyright © 2010 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Transient Overvoltage, EMTDC/PSCAD, Transformer Model*

I. Introduction

Transient study in electric power system can nowadays be done by simulation with the help of software packages dedicated for that purpose, such as EMTDC/PSCAD and others.

Studies that involve substation require a good skill and knowledge in how to model more or less correctly the equipment included in substation's model. There has been a lot of discussion regarding transient model of substation's main equipment, such as: power transformer, Surge Arrester and others.

So far, the transient model of a power transformer consists of a circuit of capacitance that represent the capacitance of the winding insulation to ground, and the inter-turn capacitance. To model properly a power transformer that could reproduce the phenomenon close to real situation is very important, especially if one wishes to study the stresses borne by the winding during occurrence of transient overvoltage [1],[2],[3].

To realize that goal, we experiments and simulation were conducted on a distribution power transformer whose capacity was: 100kVA, 20.000V/400V. To experimentally simulate a lightning current Surge Current Generator from Schaffner Type NSG 857 was utilized, which can produce surge current up to 7,5 kA of 8x20 microsecond.

In the experiment, current of 5 kA was injected to the transformer winding, and then the over voltage between the transformer HV-terminal and ground and also between the transformer conductor layer to ground were measured. From the measurement, a waveform and voltage distribution along the winding can then be obtained [6].

Further, simulations were conducted, by applying the same current waveform. The simulation was performed using the EMTDC/PSCAD; and the transformer constants included in the simulation have been derived from the physical dimension of the transformer winding [7].

II. Transformer Construction and its Constants

Schematic drawing of the transformer investigated in the study can be seen in Figs. 1, where the HV-winding was constructed of 9 layers. The transformer was a three phase winding. In the experimental simulation, the surge current was injected to the tap 1 and the tap 9 connected to ground. These taps represent the HV-terminal and the neutral point of the transformer, respectively.

The transformer's constants have been calculated from the physical dimension. Each winding layer corresponds with one transformer winding segment of the transformer model, where uniformly distributed, so each layer can be represented by a lumped circuit component [4],[5],[6]. The inner-turn and winding-to-ground capacitance, inductance and resistance of transformer obtained from calculation based on physical dimension are shown in the Table I.

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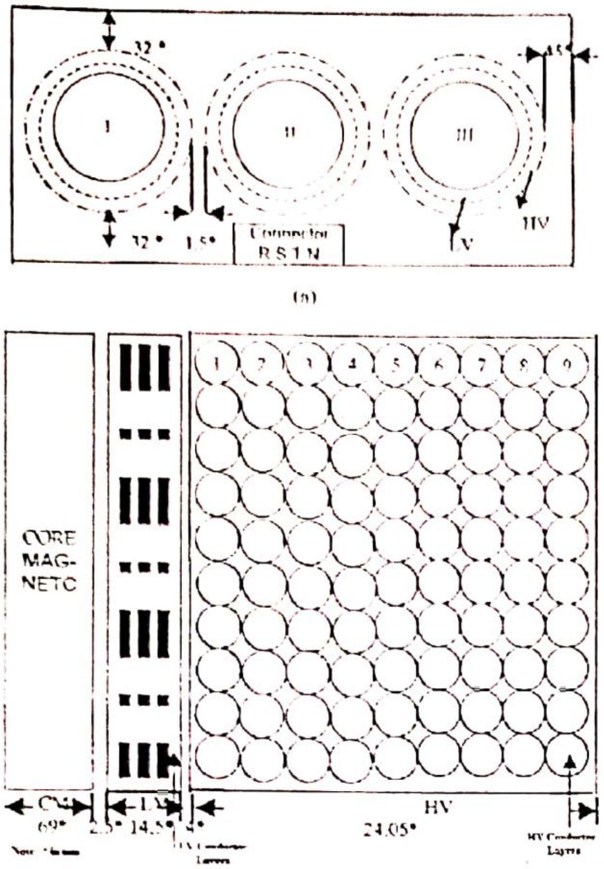


Figs. 1. Construction of the transformer (a) Transformer under study; (b) Inner construction of the transformer

These transformer constants were calculated using the principle of transformer modeling as proposed in the reference [6].

TABLE I
TRANSFORMER CONSTANTS

Conductor Layers	Capacitance (pF)		Inductance	Resistance
(from to)	Cs	Cg	(mH)	(Ohm)
$L_{1\text{-}1}$	-	$3,4\ 10^{4}$	-	-
$L_{1\text{-}2}$	$8,5\ 10^{1}$	$3,5\ 10^{4}$	1 1	1
$L_{1\text{-}3}$	$8,7\ 10^{1}$	$3,7\ 10^{4}$	1 1	1
$L_{1\text{-}4}$	$9,0\ 10^{1}$	$3,8\ 10^{4}$	1 1	1
$L_{1\text{-}5}$	$9,2\ 10^{1}$	$4,0\ 10^{4}$	1 1	1
$L_{1\text{-}6}$	$9,5\ 10^{1}$	$4,2\ 10^{4}$	1 1	1
$L_{1\text{-}7}$	$9,7\ 10^{1}$	$4,4\ 10^{4}$	1 1	1
$L_{1\text{-}8}$	$1,0\ 10^{2}$	$4,6\ 10^{4}$	1 1	1
$L_{1\text{-}9}$	$1,02\ 10^{2}$	$4,8\ 10^{4}$	1 1	1

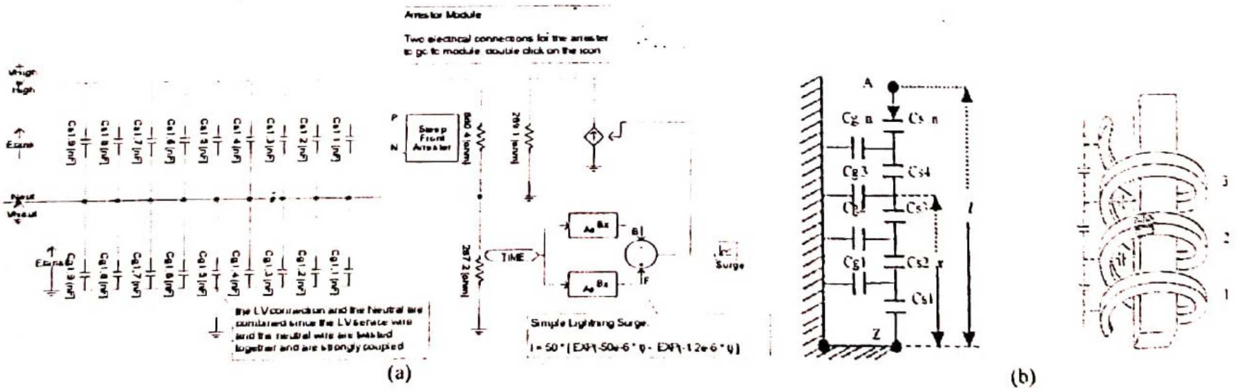
III. Circuit Model for EMTDC/PSCAD

In the numerical simulation, we applied the subroutine JMARTI SETUP where the transformer was considered as distributed and frequency-dependent parameters. The surge current used in the simulation was the type 15 of EMTDC/PSCAD.

In the simulation the following assumptions have also been adopted:

- The HV-winding under test was considered as isolated from the other two windings and from the LV-winding.
- The transformer was assumed as air-core transformer. This assumption was applied since the influence of iron only significant for the case of switching impulse.

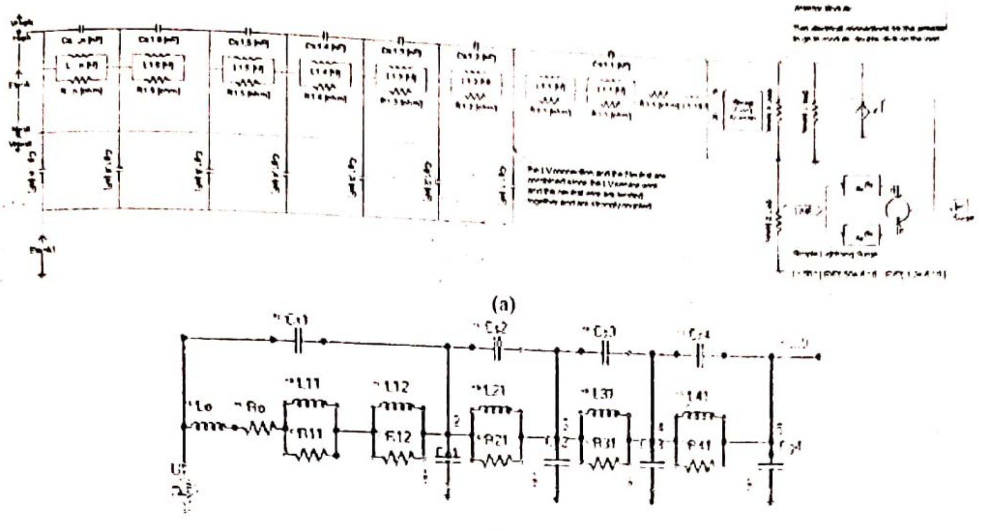
In the study, the simulation was conducted using two type of circuit model; the first model included the transformer's capacitances only, while in the second all transformers' constants were taken into account. Figs. 2 and Figs. 3 illustrate the transformer models 1 or 2 used in the simulation by EMTDC/PSCAD and figure 4 is the output from the system simulation.



Figs 2. Model 1, consisting of transformer's capacitances only. (a) Simulation Model 1, (b) Schematics Model 1

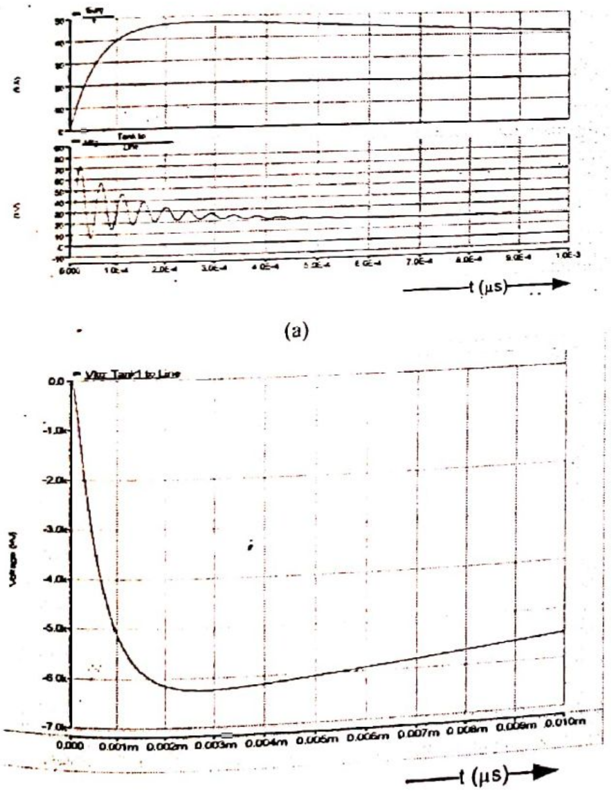
IV. Experimental Setup

The experimental measurement was carried out with help of the setup shown in Fig. 5. The surge current was generated from the generator "Shaffner NSG 587", which can produce impulse current up to 5 kA peak value, with different waveform. In this simulation, we applied current waveform of 8/20μs.



Figs. 3. Model 2, including all parameters R, L, C. (a) Simulation Model 2 and (b) Schematics Model 2

where:
Cg_1; Cg_2... : Capacitance between conductor layers to ground
Cs_1, Cs_2... : Capacitance between layers
L_{11}, L_{12}, : Inductance of each conductor layer
R_{11}, R_{12}, : Resistance of each conductor layer



Figs. 4. Output Simulation EMTDC/PSCAD Model 1, consisting of transformer's capacitances only. (a) Output Cs Simulation Model 1 and (b) Output Cg Simulation Model 1

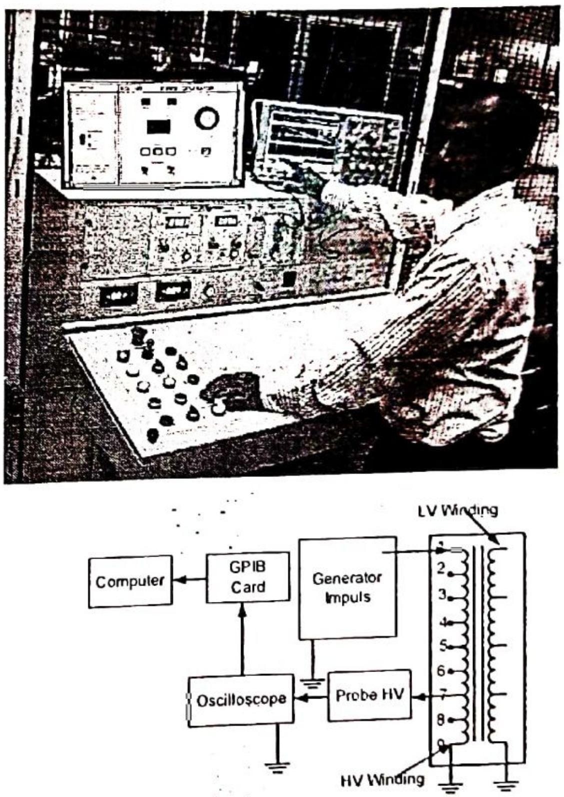


Fig. 5. Experimental Setup

The experiments were done by injecting current to the upper terminal of the transformer, and the lower terminal was grounded through a metal strip of copper. The voltages measured at the winding taps were recorded by PC, which was connected to the oscilloscope through GPIB card. During the test, the LV-winding was short-circuited and connected to ground, as well.

V. Results

Results of experimental measurement shown in the Fig. 6 indicate the behavior of the transformer, when surge current is injected to the HV terminal (at layer 1). The voltage measured at the conductor layers (L2, L5, L8) oscillate during the first 4 μs, where the highest voltage was at the layer L1 (the layer near to the transformer's HV terminal, the curve not presented in the Fig. 5). After 6μs the voltage at the layer tends to be stabilised.

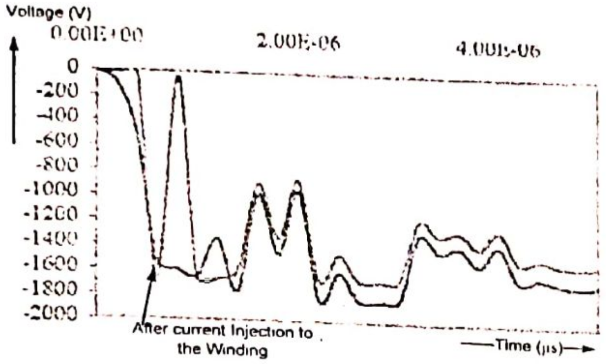


Fig. 6. Voltages at the layers L2, L5, L8 during 6 μs after current injection to the winding

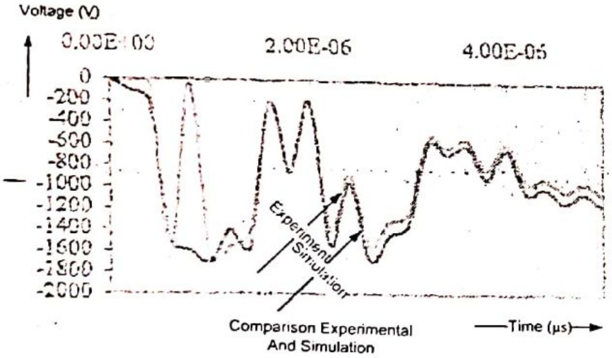


Fig. 7. Comparison between experimental measurement and numerical simulation

The Fig. 7 shows comparison between experimental measurement and numerical simulation. As can be seen, the discrepancy between the curves is important at t ≈ 1 μs. The curve obtained from the experimental measurement decreased toward zero.

After $t \approx 1$ μs, the simulation and experimental measurement curves were in good concordance that means the response of the transformer can be adequately simulated. The numerical simulation shown in the Fig. 5 was obtained by using the model 2. Simulation by using the model 1 was not presented in this report, it gave however similar characteristic.

Results of the study show that the numerical simulation could not follow the real phenomena at the beginning of transient period ($t < 1$μs), where at this time period the capacitances have important influence during transient.

As the capacitance at each layer applied in the EMTP simulation has been obtained through approximate calculation and also assumed as lumped component, the response at higher frequencies would not follow exactly the phenomena. This might be caused by stray capacitances of the layers to ground, which play an important role for higher frequencies. Experimental curves of the layers L1 up to L9, show a sharp decrease at $t \approx 1$ μs, which might eventually be due to reflection at ground terminal. Yet, this assumption is not very clear, and needs to be further investigated. The simulation curve shows in fact same decrease at that instance, but not very important.

From the comparison between experimental and numerical simulation it can be concluded that numerical calculation can simulate adequately transient characteristic of a transformer after some microseconds of surge current flowing through the winding. To simulate more or less precisely at $t \approx$ 0-1 μs proves to be difficult, since the estimation of the transformer capacitances could not be done precisely for higher frequency component of the surge currents.

However, from this study, it has been observed that the experimental measurements have given results, where the simulation curve is always higher than the measured ones. It means the simulation tends to result in more pessimistic values in overvoltage estimation.

Plot of voltage distribution at $t \approx 6$ μs, both of experimental and numerical simulation (model 1 and 2) is presented in the Fig. 8. As already known from theory, the voltage gradient at the upper turns (nearest to the HV terminal) will be the most important. Nearly 60% of the voltage is born by layer 1 and layer 2. Again, the simulation curve indicates more severe situation compared to the real condition.

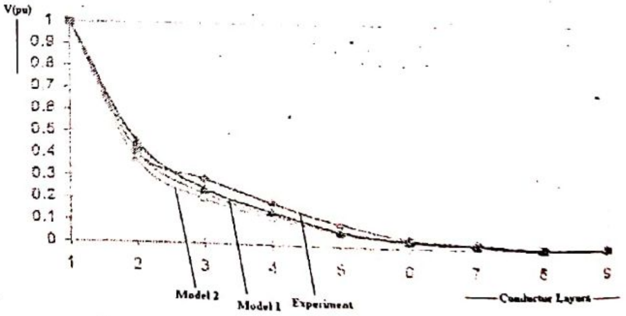


Fig. 8. Comparison of voltage distribution obtained from experimental measurement and simulation, along the transformer winding at t ≈ 6 μs

VI. Conclusion

Transformer model used for transient condition is normally represented by its capacitance to ground, the value of which is so for given based on approximated value depending on the rated voltage and power capacity of transformer [6],[8],[9]. This very simple model can sufficiently represent the transformer when rough prediction on transient overvoltage due to lightning surge current is needed [7],[11].

The study here presented shows that the more complete and detail model is sufficiently good for transient simulation. Somehow, the model could still not be quite precise when it concerns the first microseconds of the transient period. On the other hand, after some microseconds the concordance between the simulation and measurement curves is good.

The information obtained from this study which can justify the estimation of transient overvoltage by numerical simulation, is the fact that it resulted in more pessimistic overvoltage values compared to the real condition [10].

From the study, it has been discovered that transformer capacitances, especially those of conduction layer to ground, had the most important role in numerical simulation. Our study shows that there is only small discrepancy of voltage values obtained by using the model 1 and model 2.

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