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VOLTAGE DISTRIBUTION OF STEEP FRONTED TRANSIENTS IN STATOR WINDINGS – MODELLING, SIMULATION AND EXPERIMENTAL VERIFICATION

D.V.S.S. Siva Sarma,* B. Basavaraja,** C. Venkataseshaiah,*** and S.S. Yegnanarayanan****

Abstract

Steep fronted surge voltages are produced at H.T. motor terminals due to various switching operations. These are distributed within the stator winding coils and turns of the phases in a highly non-uniform manner leading to frequent insulation failures. There has been considerable interest in the development of the computational methods for analysing such phenomenon. This paper presents the development of a circuit model to predict the interturn voltage distribution and its validation through comparison of the results of simulation using EMTP with those obtained experimentally on sample coils for a specific three phase 6.6 kV, 400 KW H.T. motor. The correlation between the experimental and simulation results is found to be good.

Key Words

Steep fronted transients, voltage distribution, stator windings, modelling and simulation

1. Introduction

The results of a survey on failure of H.T. AC motors indicate that stator related failures account for about one-third of the total failures. Among these, the dominant failure mode is found to be the inter turn insulation failure. The major cause of such failure is considered to be the high interturn insulation stresses caused by steep fronted switching surges which result in non-uniform surge voltage distribution in the winding. Recent trends in power engineering such as increased use of low loss cables between the motor and switchgear, increased use of vacuum switchgear and continuing reduction in safety margin in the design of modern machines, have lead to situations where steep fronted surges are more often encountered than in the past. There has been considerable interest in the last decade in the development of suitable computational methods for analysing steep fronted surge voltage distribution in the stator winding [1–13].

It was initially assumed that under surge conditions, the lineend coils of the motor phase winding and their first turns are stressed more as in the case of transformer windings. But several authors [1, 3, 11, 12, 14–16, 18–21] through experimental investigations have shown that it is not the first turn but the last turn of the line end coil that is stressed more. Cornick and Thompson [2] confirmed this by tests carried out on a 6.6 kV induction motor and he observed that 100% of the crest voltage of the applied steep fronted surge can appear across the line end coil. Vincenzo Tucci [3, 11], Timothy Humiston and Pillay [19] and Dick *et al.* [20] presented an analysis of the voltage distribution inside the winding treating each coil as a series connection of five multi-conductor transmission lines using travelling wave theory and scatter matrix methods. Their study showed that the surge propagation through coils occur both in longitudinal and transverse manner. Narang *et al.* [4] reported the development of a lossless distribution in the line end coil of the winding, under steep fronted surge conditions. Guardado and Cornick [5] presented a computer model for predicting the distribution of steep fronted switching surges in the line end coils of the machine windings based on multi-conductor transmission line theory and model analysis. The use of the multi-conductor transmission line models given in the above methods requires large computational effort as computation of eigen vectors is involved. The objective of this paper is to present a simple circuit model which requires less computational effort, but enables the prediction of interturn voltage waveforms which closely match with those obtained experimentally on sample coils. This model combines certain aspects of the models previously reported to achieve simplification of solution. Experimental results obtained on sample coils of 6.6 kV, 400 kW motor have been used to validate the model developed.

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(paper no. 205-4870)

2. Experimental Study of Interturn Voltage Distribution in Sample Coils

Generally a H.T. motor winding consists of a number of coils in series per phase with each coil made up of number of turns. To carry out the studies on internal voltage distribution, it is first necessary to decide on the proper number of coils to be used for simulation without affecting the accuracy of the results, as simulation of all the coils involves very large computational effort. To do this meaningfully and simultaneously get an insight into the phenomenon of non-uniform distribution of surge voltage in the coils, experimental investigations have been carried out first. For this study, sample coils of a 6.6 kV, 400 kW squirrel cage induction motor were used. Each coil has 11 turns. The turn conductors of the coil were exposed by removing the insulation at the nose of the coil to facilitate the measurements. The slot environment of the actual machine winding was simulated by wrapping an aluminium foil around each coil in its slot portions. The aluminium foil is connected to the ground lead of the signal source. The measurements were recorded with a Tektronix (7834) 200 MHz analog storage oscilloscope. First, two identical probes were used to measure the differential voltage. However, it was found that there was considerable waveform distortion which was largely attributed to stray field effects. Considerable time and effort have been spent to minimize these effects. Finally, the following special arrangement was found to give satisfactory performance i.e., the measuring leads were made of two thin insulated high resistance wires twisted one over the other and enclosed in a metallic pipe and the metallic pipe was connected to the ground point of the signal source. Lead lengths of all connections were kept as short as possible. First, the measurements were made on the first coil of a four coil group. The source was connected to the beginning of the first turn of the first coil and ground. The applied surge has a flat topped ramp waveshape with a rise time of 100 ns. Its magnitude was adjusted to 10 V. Figure 1(a) shows the experimentally obtained waveforms of interturn

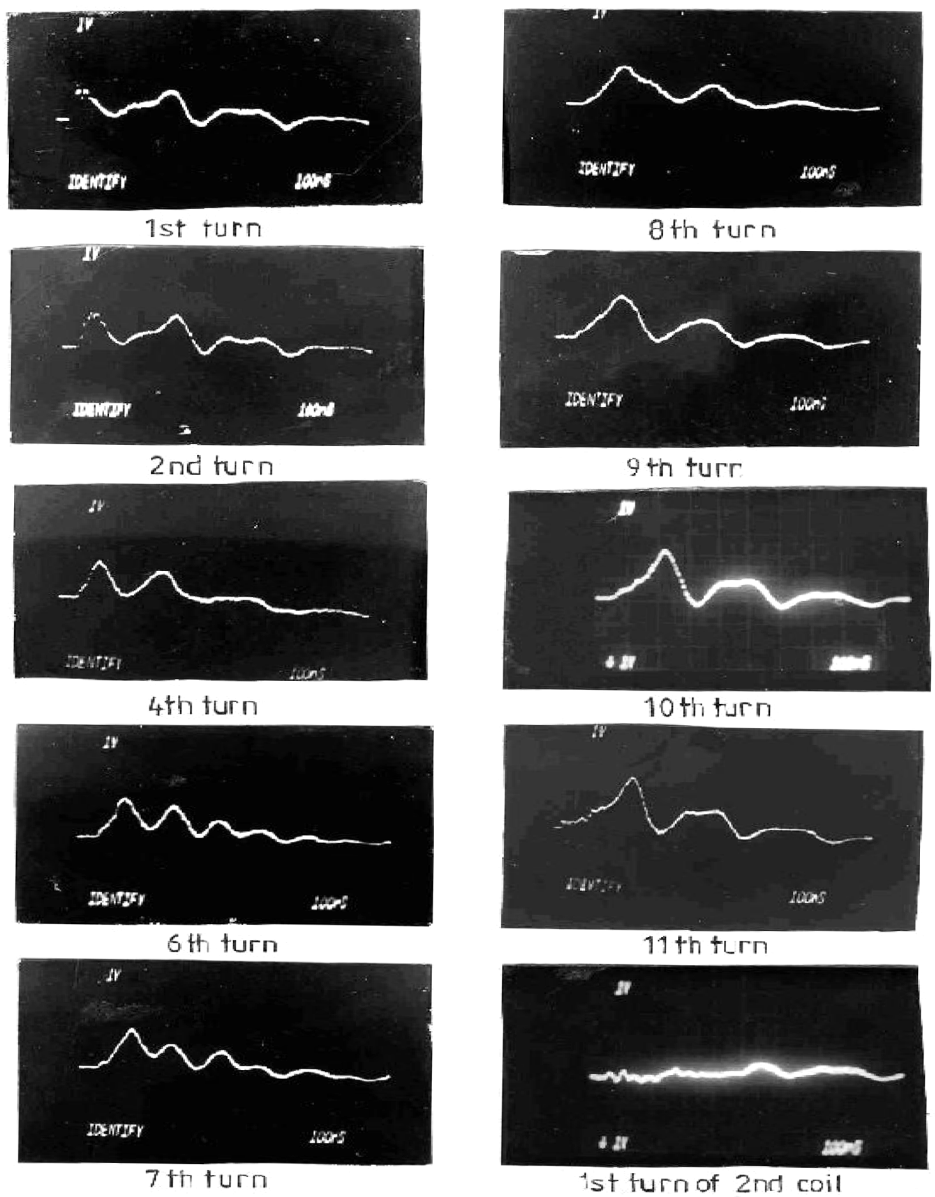

Figure 1. Interturn voltage waveforms across 11 turns.

voltages from first turn to 11th turn. It has been observed that there is a delay of approximately 20 ns between the peaks of the successive interturn voltage waveforms. This indicates that the applied surge propagates along the coil of surge along one turn, the velocity of surge propagation may be estimated as 120 m/μs for the winding containing 11 turns/coil with a mean length of turn of 2.38 m. This agrees well with the velocity of propagation estimated from $v = c/\sqrt{\epsilon_r \mu_r}$ where c is velocity of light and ϵ_r is the relative permittivity of the insulation material.

It can also be seen that the peak magnitude of the interturn voltage is higher for the last turn than that for the first turn; 13.6% of the applied surge is appearing across the first turn whereas around 19.5% of the applied surge appears across the last turn of the first coil. Figure 2 shows the waveforms of the applied surge and surge voltage across the first coil. It can be noticed that initially almost the full surge appears across the first coil. To study the effect of the number of coils connected to the first coil on its interturn voltage distribution, the interturn voltage waveforms of the first coil were recorded with either two coils connected or four coils connected. Figure 3 shows a

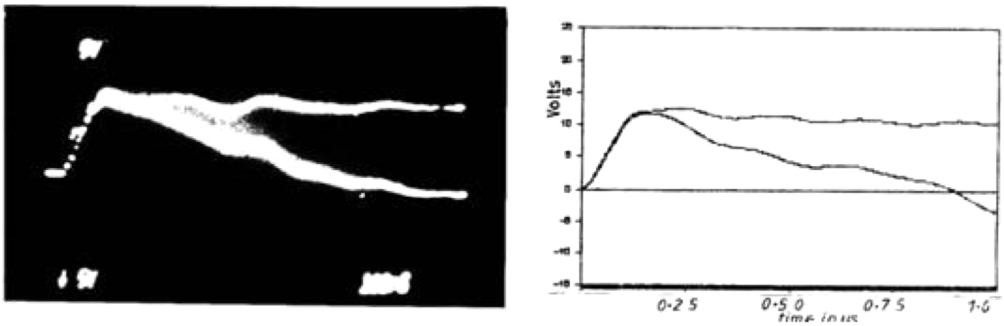

Figure 2. Voltage across the first coil by experiment and simulation.

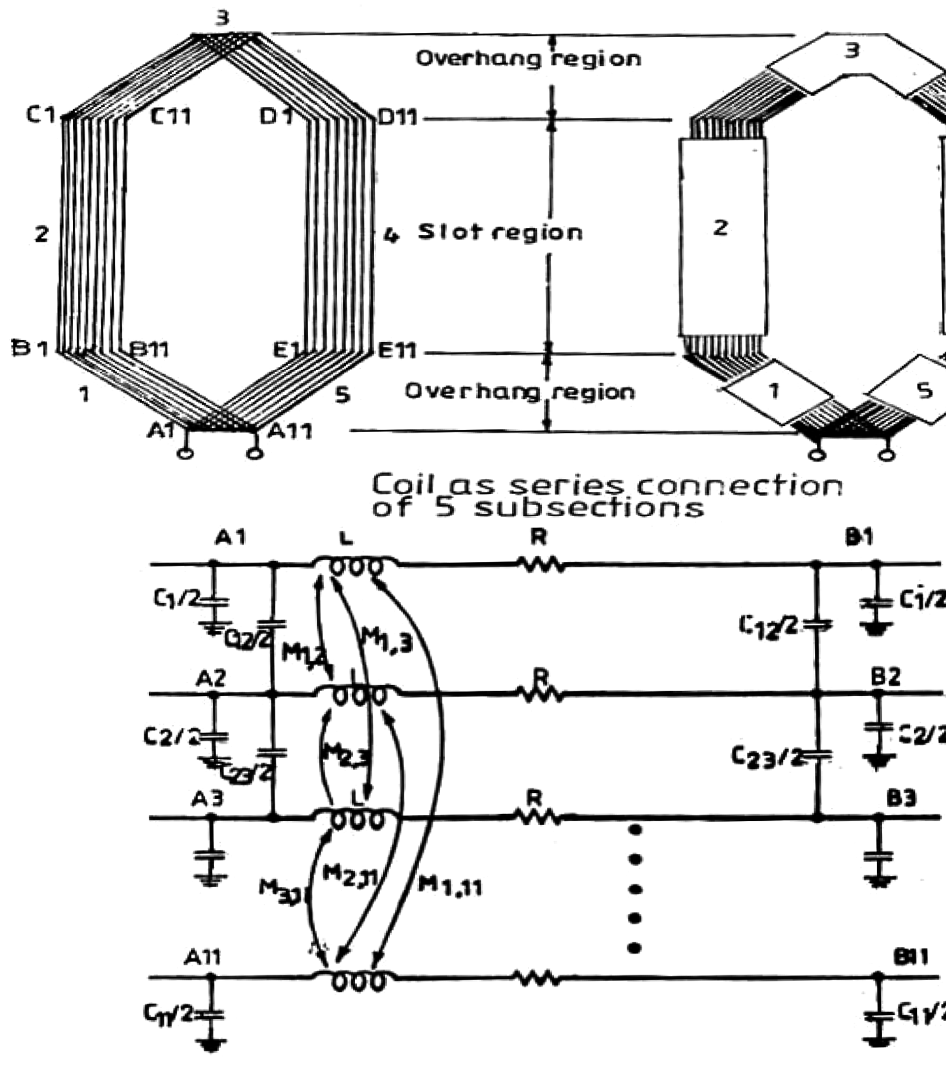

Figure 3. Sectionalization of the winding and equivalent circuit representation of each section.

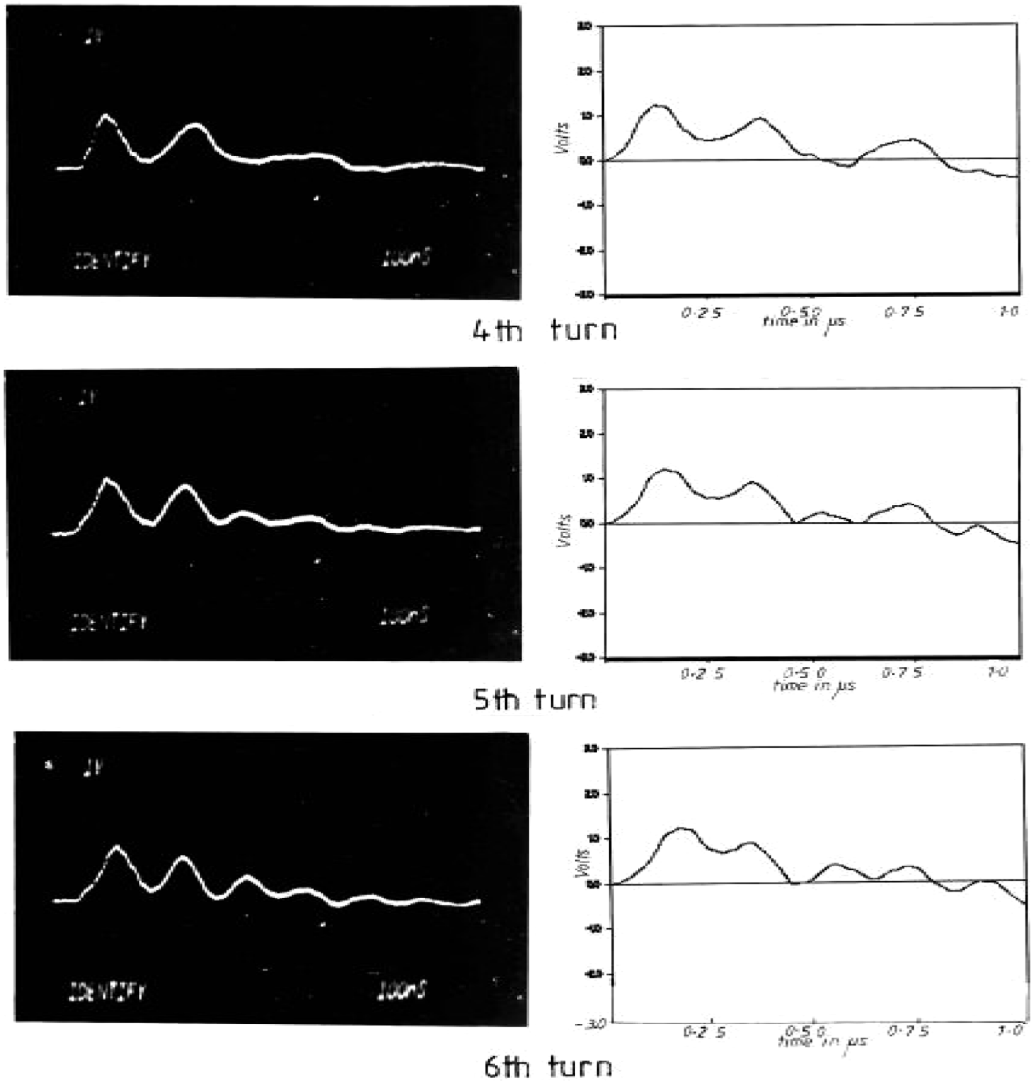

Figure 4(a). Comparison of experimental and simulation waveforms.

comparison of the 1st, 8th and 11th turn voltage waveforms with (a) two coils connected and (b) four coils connected. Upto about $0.5\,\mu$s time duration, both the waveforms are identical and there is a small deviation in the waveforms after $0.6\,\mu$s. Because the non-uniform voltage distribution within this time range is of interest, for the purpose of interturn voltage distribution study in the line end coil, it is sufficient to connect one more coil to it. It is thus enough to use two coils for computer simulation.

3. Development of the Winding Model

As in the case of transformer windings, a capacitance ladder network representation, descritizing the coil upto turn level, using turn to ground and turn to turn capacitances can be considered. But this does not take into account the differences in the surge propagation characteristics of the slot embedded and overhang portions of the coil. To overcome this deficiency, the discretization is extended beyond turn level by considering each turn as series connection of five subsections, two in the slot embedded portion and three in the overhang portion. The effect of ground capacitance and inductance per unit length and actual length of each subsection is modelled by an equivalent surge impedance and transit time representation for each subsection. Five such surge impedance/transit time branches are used for each turn. The interturn capacitances between the turns of each subsection are represented as lumped capacitances distributed at both ends of the concerned subsection. The surge impedance-transit time representation accounts for longitudinal propagation and the interturn capacitances approximately account for transverse propagation. But this model also did not give results matching with the experimental results. Therefore, a circuit approach was attempted.

In the circuit approach, each coil is considered as series connection of five subsections. Each subsection is considered as a multi-conductor transmission line. Unlike in the surge impedance approach, the circuit approach facilitates the consideration of both electromagnetic and electrostatic mutual coupling between the turns in terms of mutual inductance and capacitances. Each transmission line can be represented either by a distributed parameter

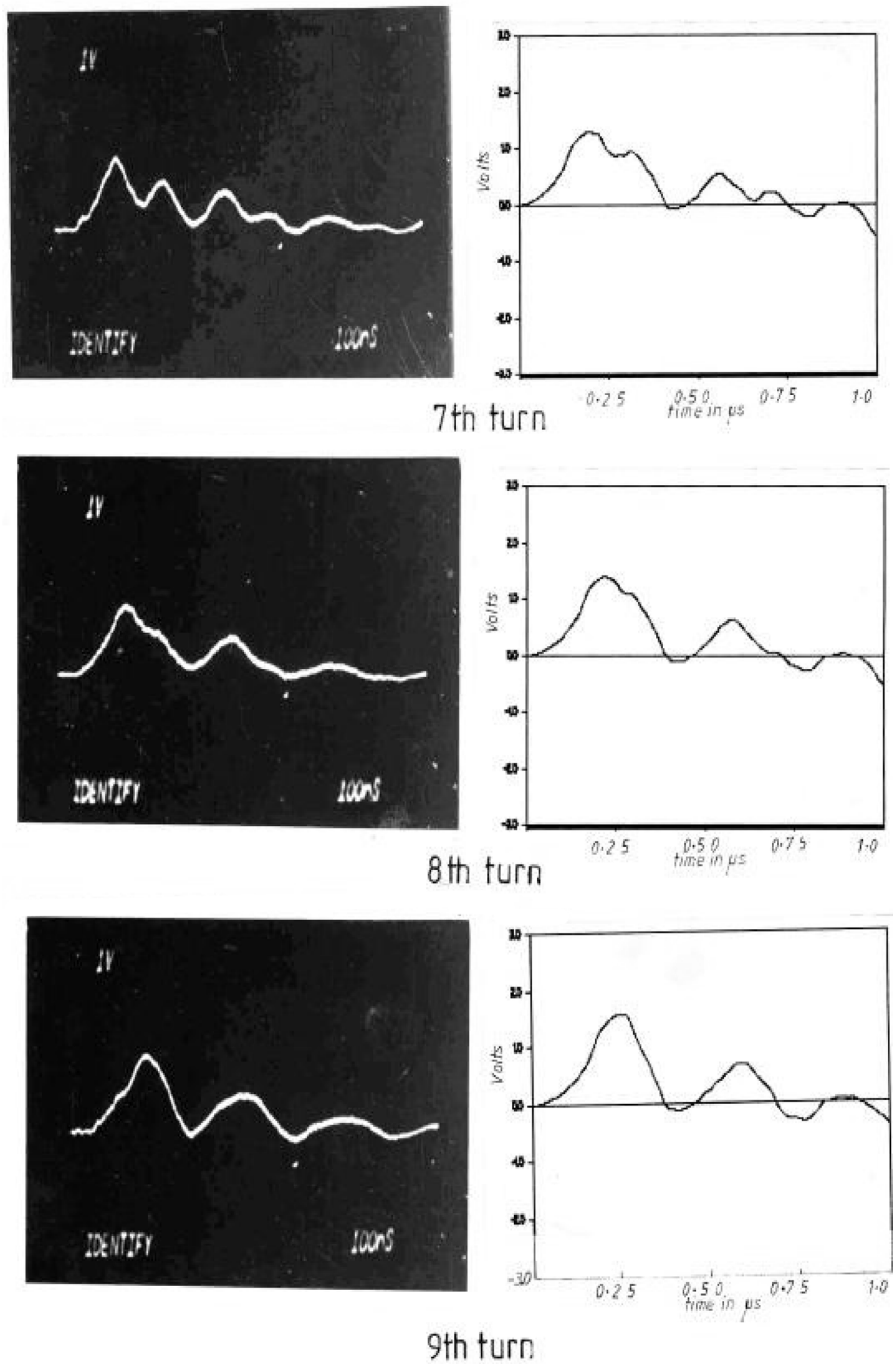

Figure 4(b). Comparison of experimental and simulation waveforms.

model or by its Pi equivalent circuit. For minimization of computational effort and simplicity, Pi equivalent circuit representation is considered. Figure 3 shows the coil model consisting of series connection of five subsections 1, 2, 3, 4 and 5. As the coil under consideration has 11 turns, each subsection is modelled as a mutually coupled Pi equivalent circuit. Figure 3 also shows the Pi equivalent circuit of a typical subsection. The model of the Pi equivalent circuit is same for all the subsections, except that the inductance and capacitance parameters of the equivalent circuit vary from one subsection to the other subsection. The differences in the equivalent circuit parameters are due to (i) the differences in the length of the coil in each subsection and (ii) the difference in the medium surrounding the coil i.e.,

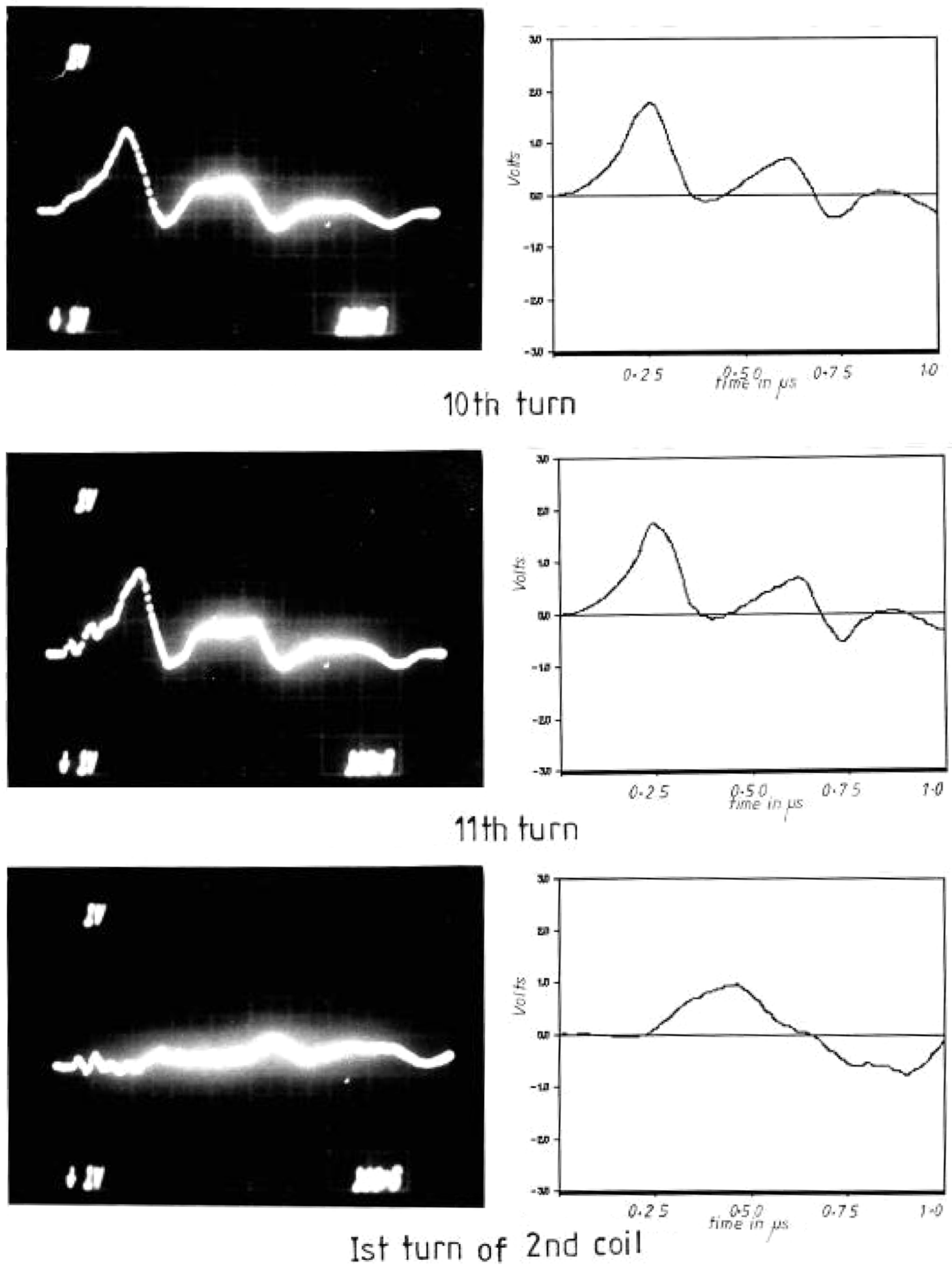

Figure 4(c). Comparison of experimental and simulation waveforms.

Table 1
Comparison of Experimental and Simulation Results

Turn No.		1	2	3	4	5	6	7	8	9	10	11
% Voltage Distribution	Experimental	12.3	12.5	12.6	12.5	12.2	12.4	13.0	14.1	15.8	17.7	17.6
	Simulation	13.6	13.6	15.4	15.4	14.5	15.4	16.3	16.3	16.8	19.1	19.5

whether it is overhang region or slot region of the coil. Figure 3 also shows the connection diagram of 11 phases of all the five subsections.

The end of the first phase of the 5th subsection is connected to the beginning of the third phase of the first subsection and so on. The end of the 11th phase of the 5th subsection is connected to the beginning of the third phase of the first subsection and so on. The end of the 11th phase of the 5th subsection of the first coil is connected to the beginning of the first phase of the first subsection of the second coil. However, as experimental results have shown that it is sufficient to consider the first two coils for the study of interturn voltage distribution in the first coil, only two coils were considered for simulation.

The inductance and capacitance parameters were estimated using the design data. The capacitance parameters were obtained by using the parallel plate capacitor formula and inductance parameters were obtained using the relation $[L][C]=1/v^2$ where v is the propagation velocity. The steepness of the surge is reported to have critical influence on the interturn voltage distribution [5–7, 11, 12, 14–17, 18–21]. Therefore, for satisfactory comparison of computer simulation results with those obtained experimentally, the simulated waveform of the surge (both amplitude and rise time) should be identical to that used in the experiments. This was taken into consideration while choosing the source model in the computer simulation. The magnitude and rise time of the surge provided by the source model at the entry point of the winding model was 10 V and 100 ns respectively.

4. Comparison of Experimental and Simulation Results

To validate the analytical modelling procedure, the interturn voltage waveforms obtained by simulation were compared with those obtained by experiments. In both the cases two coils connected in series were considered and the interturn voltage waveforms in the first coil were obtained. Figure 2 shows the applied sure waveform and the voltage across the first coil observed experimentally in comparison with the waveforms obtained with simulation. It can be observed that the waveforms obtained in both the cases closely agree with each other. The voltage across the first coil is nearly equal to the applied surge initially, and it diminishes slowly becoming almost zero after nearly 800 ns. Figure 4(a)–(c) shows the experimentally observed interturn voltage waveforms and the corresponding voltage waveforms obtained by simulation. An examination of the voltage waveforms across all the turns from first turn to last turn reveals a close agreement between the two. The surge propagation velocities estimated from the simulation waveforms is 116 m/μs whereas the corresponding value estimated from the experimental waveforms is 120 m/μs. In both the cases, the voltage across the last turn is maximum and is occurring nearly 200 ns after the surge is applied to the first turn. Table 1 shows the comparison of percentage voltage distribution across the various turns obtained by simulation and experiments. The correlation is good, thus validating the model. The maximum difference between the experimental and simulation results is 3%. Considering a measuring accuracy of about 2% in the oscilloscope, the agreement between predicted and experimentally observed results can be considered to be very satisfactory.

5. Conclusion

A simplified circuit model for predicting the interturn voltage distribution produced in the line end coil of a H.T. motor winding subjected to steep fronted surges is presented. This model involves representation of each coil as series connection of five subsections and each subsection as a multi-conductor mutually coupled transmission line with as many number of phases as the number of turns per coil. Each such transmission line subsection is represented by its Pi-equivalent circuit. The interturn voltage waveforms predicted using the above model show close agreement with those obtained by experimental measurements on sample coils. This confirms that the model faithfully represents the wave propagation and coupling characteristics of the coils. This model can be used for general design purposes for any H.T. motor winding as the derivation of the model is based on design data. One such application is the selection of suitable value of surge capacitor required to minimize the interturn voltage stresses.

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