Simulation of commutation spikes and measurement of the voltage distribution and interturn voltages in a synchronous generator due to rectifier loads

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Abstract - **This paper presents laboratory measurements made on a synchronous generator supplying a rectifier load. It shows the generation of notches and commutation voltage spikes due to the rectifier. The notches and the spikes obtained from measurements are then compared with simulations from EMTDC. The paper also presents transient voltage distribution measurements as well as interturn voltage measurements on the synchronous machine during thyristor commutation periods. This work shows that when subjected to commutations with thyristor bridge loading, the interturn transient voltage exceeds that expected from a linear load in the steady state.**

Keywords: Synchronous generator, rectifier, thyristor bridge, transient voltage distribution, EMTDC.

1.Introduction

The distortion of the terminal voltage waveform of a synchronous generator supplying a rectifier load has been studied [1]. Distortion in the form of notching occurs during the commutation of load current from one thyristor to the next. This does not occur instantaneously due to the synchronous generator's inductance. A notch can be treated as a short duration pulse superimposed on a sinusoidal waveform. In some applications, for example offshore drilling rigs, large dc motor drives are supplied by thyristor rectifiers which are connected to a generator. There is a large shunt capacitance in parallel with the generator due to the number of cables on an offshore platform. The natural frequency of the shunt capacitance of the system and that of the snubber circuit in the thyristor bridge and the system inductances can be excited by the trailing edge of the notch (or step-function) produced by thyristor commutation. This results in commutation voltage spikes appearing on the system voltage waveshapes [2].

Previous studies have looked at the generation of harmonics and notches by thyristor drives and models have been developed to assess the distortion level from a power system point of view [3]. Studies have not yet considered the impact of the sharp leading edges of notches on the windings of a synchronous generator.

In this paper notches in the generator waveform are shown. The commutation spikes in the notches are presented. Simulations of the spikes were performed using the time domain EMTDC package. A comparison between the measurements and simulation results is presented. The notches are represented as steep-fronted transient pulses similar to chopped impulse waveforms in the high voltage testing. The distribution of the transients along the generator winding as well as the interturn voltages produced during the transients are also presented.

2.The notches and the spikes from a thyristor bridge

Notches in the AC voltage waveform at a generator are caused by commutations of current in a thyristor bridge. An individual notch can be treated as a transient pulse superimposed on the AC voltage waveform. Mathematically, the notch is produced by the summation of two unit step functions. One is a negative step function and the other is a positive step function. The notch position depends on the firing angle of the bridge. At the end of a commutation, there is a high frequency spike on the trailing edge of the notch. This spike is caused by the excitation of the stray capacitances and the system inductances by a unit step function. The stray capacitances come from the cable capacitance and the capacitor of the snubber circuit for each thyristor in the thyristor bridge. The system inductances are dominated by the generator inductance and the cable inductance.

Laboratory experiments were set up by connecting a three phase, 16 kVA, 415 V, P.F. 0.8, synchronous generator via a 20 m lead cable to a thyristor bridge. The star point of the generator was not connected to ground. The generator was specially made with taps on one coil of the armature winding. These taps allow the measurement of voltages along the winding. The thyristor bridge was operated at a firing angle of 60° so that the notches occurred at the peak of the line to star point generator voltage waveform. The thyristor bridge was loaded by an inductance in series with a resistive load to give an output of 2.8 kW from the generator. The phase voltage waveform (phase R to the star point) at the generator terminals as well as the line to line voltage waveform between phase R and Y were recorded. Figures 1, 2 and 3 show the results obtained .

Figure 1 shows that there are 4 notches in the generator phase voltage waveform while 6 notches appear in the generator line to line voltage waveform. In Figure 2, a notch in the phase voltage waveform (line to star point) is zoomed in and it can be seen that there is a high frequency spike at the trailing edge of the notch. The notches at the positive peak and negative peak of an AC sinusoidal generator phase voltage waveform are shown in Figure 3.

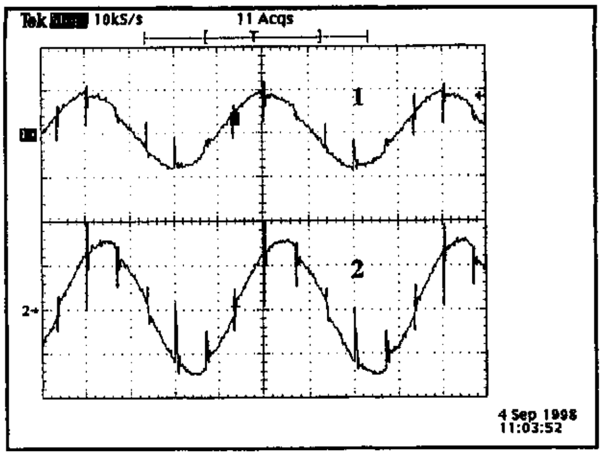

Figure 1. (1) The phase voltage (R-star point)
(2) The line to line voltage (R-Y)
(2x200 V/div, 5 ms/div)

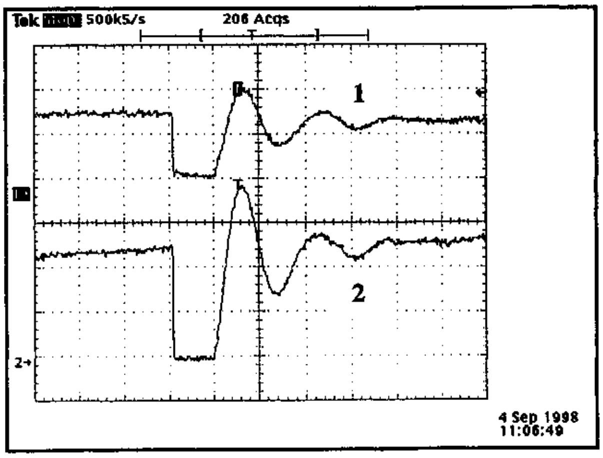

Figure 2. A spike at the trailing edge of a notch
(1) measured from phase voltage waveform
(2) measured from line to line voltage waveform
(1x200 V/div, 100 μs/div)

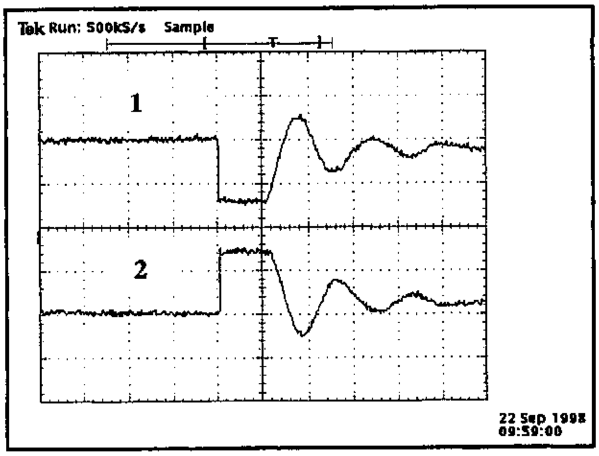

Figure 3. (1) Zoom of the notch at the positive peak of the phase voltage
(2) Zoom of the notch at the negative peak of the phase voltage
(1x200 V/div, 100 μs/div)

It can be seen from Figure 3 that a notch in the waveform can be treated as a short duration pulse superimposed on an AC sinusoidal waveform. The amplitude of the pulse is exactly the notch depth. The pulse has a steep wavefront and is similar to a chopped impulse waveshape as used for high voltage testing. The notch on the positive peak of the phase voltage waveform can be represented by a negative pulse while that on the negative peak can be represented by a positive pulse. The leading edge of the notch or the wavefront of the pulse corresponds to the start of a commutation process while the trailing edge relates to the end of the commutation period.

Simulations were performed in order to verify the experimental results obtained. The laboratory system was modelled on EMTDC which is a time domain analysis tool. A synchronous generator was represented by a constant voltage source in series with a resistance and an inductance. The resistance value in the model was the AC resistance of a stator phase winding at 50 Hz, and the inductance value was derived from $(X_d''+X_q'')/2$ [3]. The thyristor model in EMTDC allows users to define values of a RC snubber circuit. The values provided by the thyristor bridge manufacture were 68 Ω and 47 nF. The load at the DC side of the thyristor bridge was simulated as a 20 mH inductance in series with 30.5 Ω so that the generator output of 2.8 kW was obtained. The firing angle of the thyristor bridge was set at 60°. It was found that the inductance of the cable connected between the generator and the bridge was much less than that of the generator, and the shunt capacitance of the cable was again much less than that of the snubber circuit. As a result of this the inductance and capacitance of the cable were ignored in the simulation model. The cable resistance was connected in series with the generator in the model. The results obtained from EMTDC are shown in Figures 4, 5 and 6.

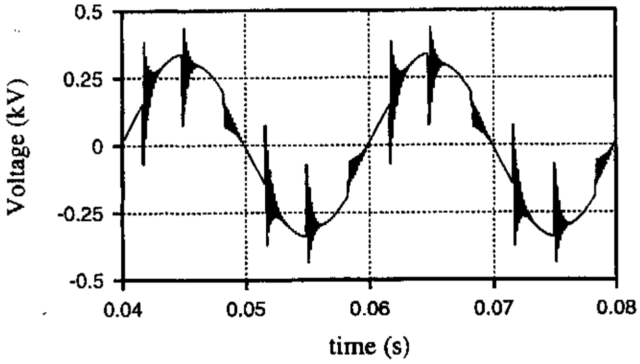

Figure 4. Phase voltage waveform

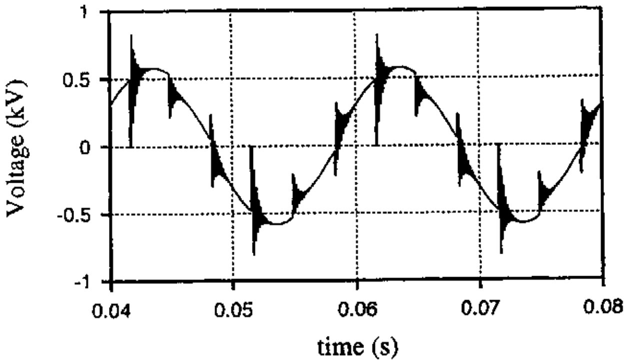

Figure 5. Line to line voltage waveform

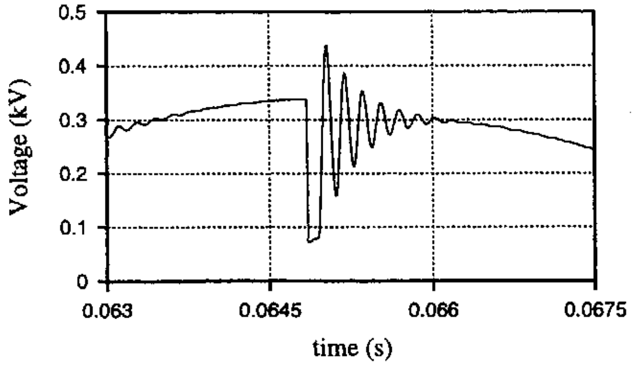

Figure 6. A commutation spike in a phase voltage waveform

It can be seen from Figures 4, 5 and 6 that the oscillation frequency, the peak amplitude of the spike, the notch depth and the notch width are close to those from the experiments. However, the decay time for the spike from the simulation is relatively long compared with that from the experiment. Simulations were performed using EMTDC with three different values of the time step (1 μs, 10 μs and 25 μs). It was found that the decay time in three cases was the same; the long decay time of the oscillation did not occur from choosing an inappropriate time step. The reason for the long decay time should come from that the damping factors which are the resistance in snubber circuits and the generator resistance have different values at the fundamental frequency (50Hz) and at the oscillation frequency (5.71 kHz). The generator resistance in the model was represented by the fundamental frequency value which is relatively lower than that at the oscillation frequency. In order to obtain the correct damping the value of the RC snubber circuit in the simulation model had to be modified. It has been accepted that sometimes the actual values of the snubber circuit cannot be used in the time domain simulation processes, particularly a system dealing with switching in capacitive and inductive circuits. An artificial snubber has to be used so that the correct results can be acquired [4].

To provide a reasonable damping factor, an equivalent circuit at the end of a commutation is studied. Figures 7 and 8 show the equivalent circuit at the end of a commutation process from thyristor no.1 to thyristor no.3. In Figure 7, thyristors no. 2 and no. 3 are conducting, while the others are open circuits.

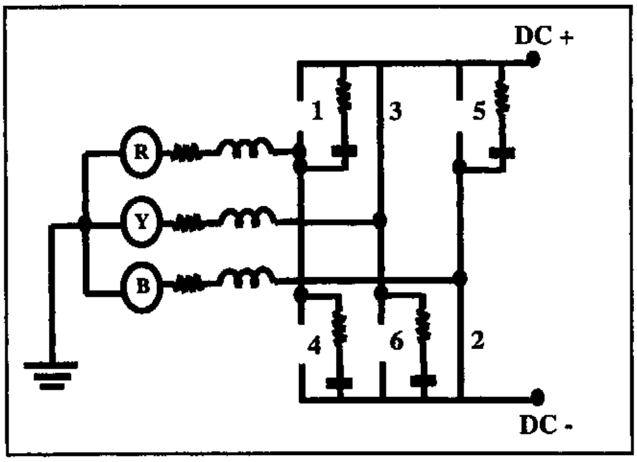

Figure 7 A thyristor bridge at the end of a commutation from thyristor no.1 to thyristor no.3

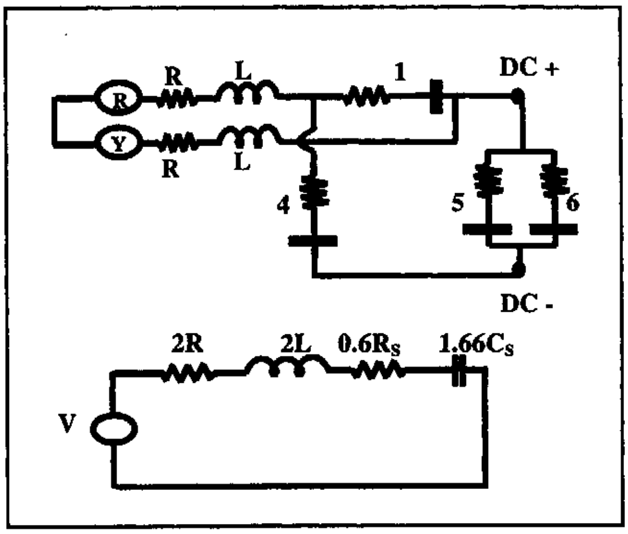

Figure 8. A RLC equivalent circuit of the bridge at the end of commutation

From Figure 8, the generation of commutation spikes at the trailing edge of a notch can be approximately calculated by switching a voltage source across a series RLC circuit. The value of the voltage source is the value of line to line voltage (in this case V_{RY}) at the instant that the commutation finishes. It can be concluded that:

1.)The oscillation frequency is given by:

$$f = \frac{1}{2\pi\sqrt{(2L)(1.66C_S)}} \qquad (1)$$

where,

L = generator inductance derived from $(X_d'' + X_q'')/2$

C_S = snubber capacitance

2.)The damping factor = $2R+0.6R_S$ (2)

where,

R = the summation of generator resistance and cable resistance

R_S = snubber resistance

The generator resistance and the cable resistance were measured at the fundamental frequency (50Hz) and at the frequency of oscillation (5.71 Hz). It was found that there was a variation in their values, while the snubber resistance was treated as a constant value.

The artificial values of the RC snubber can be calculated as follows:

1.)Substituting R and R_S into Equation 2 by their values at the frequency of oscillation, the damping factor at the oscillation frequency can be obtained as 82.46 Ω.

2.)From Equation 2, substituting R and R_S by their values at the fundamental frequency, the artificial snubber resistance which provides the same damping factor as 82.46 Ω can be determined. The artificial snubber resistance is equal to 131.6 Ω.

Simulations were performed on EMTDC again, but using the value of the artificial resistance in the snubber circuit. The results are shown in Figures 9 and 10. It was found that the oscillation of the spike decayed more quickly when compared with the simulation results using the real value of snubber resistance.

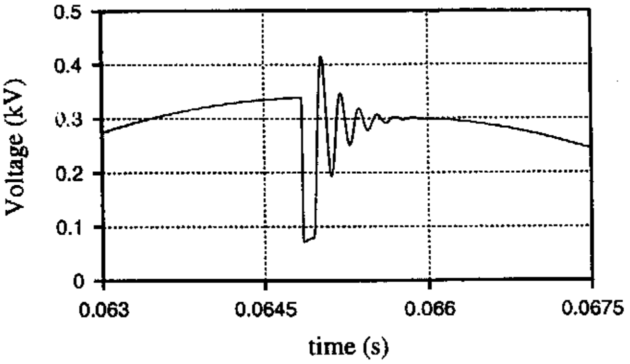

Figure 9. A commutation spike in a phase voltage obtained by simulations using artificial values of RC snubber circuits

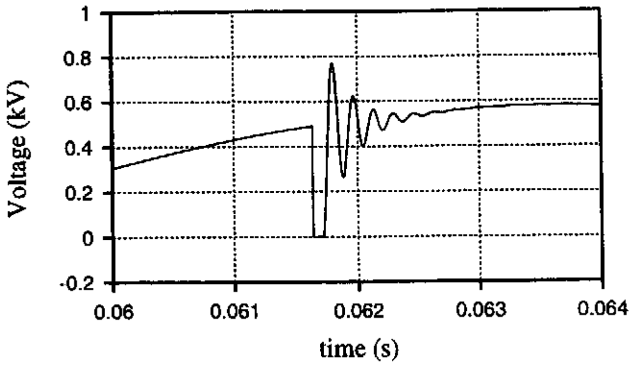

Figure 10. A commutation spike in a line to line voltage obtained by simulations using artificial values of RC snubber circuits

Characteristics of a spike	Experiment	Simulation (real snubber)	Simulation (artificial snubber)
Notch width (μs)	110	92	93
f_{osc} (kHz)	5.71	5.88	5.85
Peak value (V)	400	438	415.5

Table 1. A comparison between experiment and simulations of a commutation spike in a phase voltage

Characteristics of a spike	Experiment	Simulation (real snubber)	Simulation (artificial snubber)
Notch width (μs)	110	121	125
f_{osc} (kHz)	6.45	6.06	6.1
Peak value (V)	800	826	773

Table 2. A comparison between experiment and simulations of a commutation spike in a line to line voltage

3.The effects of the lead cable on the notches

The presence of a cable between the synchronous generator and the thyristor bridge leads to a mismatch of the surge impedance of the cable and that of the generator. A similar investigation on the effects of a lead cable was carried out in an induction motor fed by a PWM drive, and it was found that the mismatch between both surge impedances contributed to the transient overvoltage at the motor [5]. Figure 11 shows the comparison between a leading edge of a notch located on a negative peak of the AC sinusoidal waveform measured at the bridge and that measured at the generator.

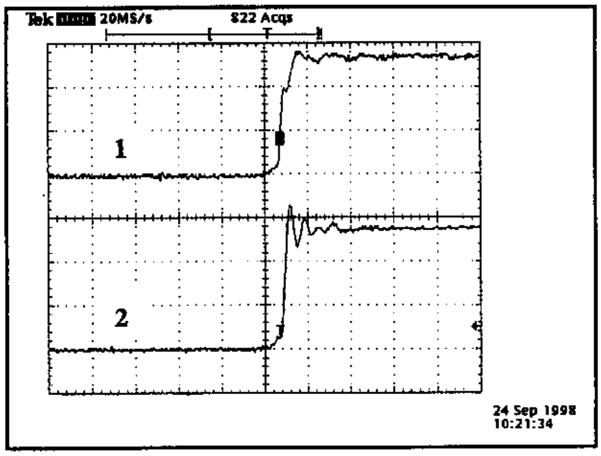

Figure 11. (1)The leading edge of a notch measured at the bridge
(2)The leading edge of a notch measured at the generator

The generator was connected to the bridge via a cable of 20 m in length

(1x100 V/div, 2.5 μs/div)

4.The voltage distribution along the winding

The voltage distribution in electrical machine windings due to the steep-fronted surge has been studied [6]. This study concentrated on the voltage distribution along the windings due to switching surges from switchgear operations. Recently, due to the use of power electronic converters with newly developed power semiconductor devices which produce fast wavefronts from their switching operations, studies have been extended to investigate the effects of switching operations of power electronic converters on electrical machines. The voltage distribution along a winding of an induction motor fed by a PWM drive has been carried out [7].

When a generator is loaded with a thyristor bridge, it has been found that the notches in the generator voltage waveform have sharp leading edges, and can be treated as steep-fronted transients. Experiments were performed in order to study the distribution of such transients along a winding of a synchronous generator. The generator had a star connection with a floating neutral. Voltages between the taps and the star point were recorded. Each coil of the winding comprises 3 groups, and there are 22 turns in each group, so there are 66 turns in a coil. One phase winding consists of two series connections of two parallel coils. The coil arrangement of the generator is shown in Figure 12 while Figure 13 shows the voltage distribution along the winding from the generator terminals to turn no.22, no.44, and no.66.

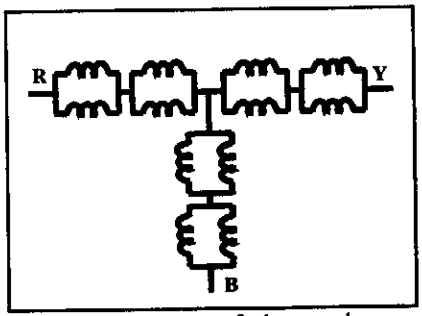

Figure 12. An arrangement of the synchronous generator

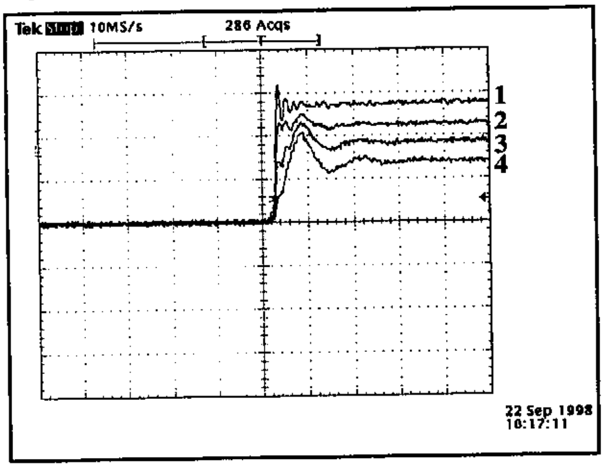

Figure 13. Voltage distribution along the first coil of the synchronous generator during the commutation
(1) the generator terminals (2) turn no.22
(3) turn no.44 (4) turn no.66
(0.5x200 V/div, 5 μs/div)

The distribution of the transient along the generator winding at an instant time of 1.25 μs after starting a commutation is shown in Figure 14.

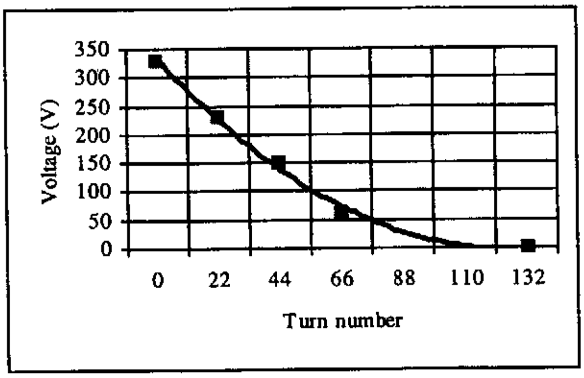

Figure 14. Peak voltage (notch depth) distribution along the winding at t = 1.25 μs after starting a commutation (turn no.0 = terminal)

5.The interturn voltages

The voltage distribution of the steep-fronted transient is nonlinear. Most of the voltage drop is produced at the first few turns of the line end coil, so the interturn insulation in that area is stressed by a higher voltage. The interturn voltage waveform due to the nonlinear voltage distribution, therefore, is another important factor to be studied to determine whether the amplitude is higher than the acceptable range of the interturn insulation. The voltage across the first turn as well as the interturn voltage waveforms between turn no.1-2, no.2-3, and no.3-4 were recorded. The results are shown in Figure 15.

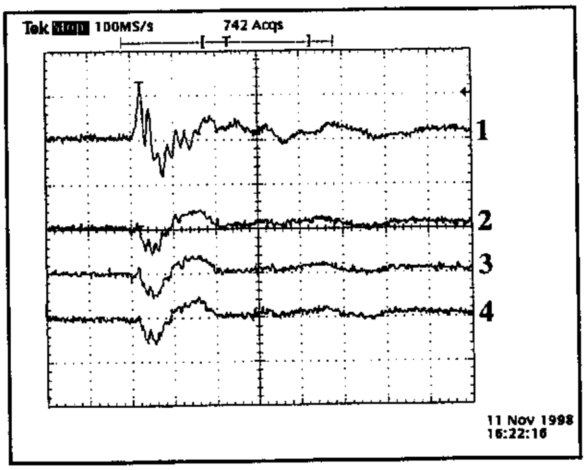

Figure 15. The interturn voltage waveforms
(1) Voltage across turn 1
(2) Interturn voltage between turn no.1 and 2
(3) Interturn voltage between turn no.2 and 3
(4) Interturn voltage between turn no.3 and 4
(0.1x200 V/div, 500 ns/div)

6.Conclusion

A notch in a generator voltage waveform due to commutation in a thyristor bridge load has two characteristics; a steep-fronted leading edge and a spike superimposed on a trailing edge. The commutation spike is caused by the excitation of system inductances and capacitances. In the present test system, the system inductance was that of the generator while the system capacitance came from the RC snubber circuit. The values of inductance and capacitance of the cable connected between the thyristor bridge and the generator were very small and neglected in simulations. However, the cable provided additional damping for the decay of the commutation spike.

Using the EMTDC package, it was found that the value of the RC snubber circuit had to be modified so that the actual damping factor was obtained. A method for determining a value of an artificial snubber resistance was proposed, and the simulation results obtained were reasonable.

A notch in the generator voltage waveform can be represented by a steep-fronted pulse superimposed on the sinusoidal waveform; either by a positive pulse or by a negative pulse depending on the position of the notch. The pulse waveshape can have its waveshape modified due to the presence of the lead cable between a synchronous generator and a thyristor bridge. It was found that the peak amplitude of the pulse was increased. For the lead cable of 20 m in length, at the generator terminals, the peak amplitude of the pulse was 330 V while that measured at the bridge was 280 V.

The steep-fronted leading edge of the notch can cause a nonlinear voltage distribution along the generator winding. Figure 14 shows that most of the voltage drops across the first coil (the first 66 turns) during the transient period. This nonlinear distribution causes the interturn voltage to be higher during the transients than the normal steady state value. The generator used in the experiments has two series connected parallel coils, i.e. 132 turns per phase. In normal operation, to produce 240 V the turn to turn voltage should be around 1.8 V_{rms} or around 2.6 V_{peak}. It can be seen from Figure 15 that the peak of the interturn voltage during the transient duration is around 10 V, and can be up to 20 V across the first turn. This transient voltage may lead to a deterioration of the electrical machine interturn insulation by partial discharge in the interturn insulation.

It has been shown that EMTDC is capable of simulating the generator terminal waveform with commutation spikes. Further work will develop a high frequency model of an electrical machine winding on EMTDC. The model will be used to investigate the transient voltage distribution in the machine winding. Other studies are being carried out to study the effects of the firing angle and the DC load current on the voltage distribution, and also interturn voltage during the transient period due to the commutation of rectifier loads.

7.Acknowledgements

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9.Appendix

Synchronous generator parameters
1)X_d''= 0.18 p.u.
2)X_q''= 0.10 p.u.
3)R (50Hz) = 1.45 Ω
4)R (5.71kHz) = 20.45 Ω