Verification of the Effectiveness of ELCID on a Hydrogenerator Stator Core

ABSTRACT

Electromagnetic Core Imperfection Detection (EL CID) was developed in the late 1970's by the Central Electricity Generating Board (CEGB) in the UK. The technology is now well established in many parts of the world as an easier means than the traditional ring flux test of checking the integrity of interlaminar insulation for stator cores of large rotating electrical machines. EL CID requires only a low voltage supply to excite the core to approximately 4% of rated magnetic induction. The application to turbogenerators has been very successful and has presented few interpretative problems. Application to hydrogenerators however has presented a number of unique effects and parameters that require a specialised approach to qualitative and quantitative analysis. A lack of familiarity with these effects and of information and training on special techniques has raised a number of questions on the application of ELCID within certain sectors of the hydrogeneration industry. This paper presents the findings of a study conducted on a large hydrogenerator in Northern California. Through the co-operation of the machine owner and the contractor an opportunity was presented to allow EL CID tests and evaluations on this machine in a controlled environment. The instrumentation, measurement technique and the interpretation of data collected will be described. The paper will specifically address issues surrounding the split section of a hydrogenerator core and comparison of results with traditional ring flux tests.

Introduction

The electromagnetic core lamination fault detection technique, now universally known as EL CID, was originally developed around 1980 by the then Central Electricity Generating Board (CEGB) in the UK to solve certain current test requirements on turbogenerators. Since that time the technique has been used increasingly world-wide on generators and large motors. Details of the test theory and application are outlined in a paper by John Sutton (Reference 1) which also provides other references to the early work.

The other and long established method of testing the integrity of magnetic core laminations is by means of a high power loop or rated flux test, often referred to as a High Flux Ring test or various permutations of these words, carried out with the rotor of the generator removed. With the Ring Flux test the core is excited to or near to the full rated flux of core by means of a single phase high voltage winding through the bore and around the outside of the stator. The rated flux produces fault currents similar in level to those which flow when the generator is in operation and therefore in theory will also produce similar hot spots and temperature rises, subject to discrepancies resulting from different operating conditions such as inoperative cooling system, etc.

The EL CID test uses a similar excitation winding but at a very low flux level, typically four percent of rated flux. Hence the heat produced by faults is negligible and not detectable, but the fault current is detectable by electromagnetic means and it is this fault current, when scaled up to the appropriate rated flux level, which would give rise to the local generation of heat and associated hot spots.

There potentially exists therefore a small theoretical difference between the two methods associated with the assumed distribution of the heat produced. Although heat produced by the detected EL CID fault current, in conjunction with the test excitation voltage along the length of the fault, will be representative of the power dissipation to be expected in a Ring Flux test, the precise location of heat within the fault current loop is not defined. This difference is not normally of practical significance but may sometimes need to be considered when analysing changes in deep faults with complex fault current paths.

The two forms of tests may be considered complementary to some extent and the appropriate method will often be dictated by the prevailing circumstances. Advantageous features of EL CID testing are covered elsewhere, such as in Reference 2 referred to again below, and more recently the tendency to reduce major outages has given rise to EL CID tests being carried out without removal of the rotor, where Ring Flux tests are not possible.

Studies of the correlation between the test results of both methods provide a basis for confidence in EL CID test effectiveness itself and also for continued monitoring of earlier Ring Flux detected faults. A comprehensive comparative analysis of the test methods applied to turbogenerators was carried out and reported in 1985 by Shelton and Reichman in Reference 2.

Although the EL CID method has been readily adopted by many users for testing hydrogenerators for some time, a number of differences in the relative machine design compared with turbogenerators has given rise to reservations. Test results on hydrogenerators often exhibit spurious phenomena which are rare on turbogenerators. Studies to analyse and predict these effects have been carried out to maintain confidence in EL CID testing for these applications, as outlined by G.K.Ridley in References 3 and 4. However the absence of comparative analysis with Ring Flux testing to include hydrogenerators has restricted wider acceptance for hydrogenerator applications.

This paper therefore describes a comparison EL CID and Ring Flux tests on a split core hydrogenerator during a routine refurbishment and also the utilisation of specific EL CID techniques to enhance fault detection in areas of flux distortion around core splits, not normally encountered with turbogenerators.

Background to Correlation Study

The opportunity to carry out a study was presented by a hydrogenerator rewind scheduled to be carried out at the Woodleaf Generating Station in California in September 1997. The machine owner, the rewind contractor and the EL CID manufacturer co-operated to include a comparative study of core test methods into the routine tests performed as part of the rewind schedule.

A decision had been taken to re-stack the top two packets, about four inches, of one of the sections (180º) of the two section core, partly with new laminations. This provided the opportunity to insert a number of artificial faults in this top section before carrying out both EL CID and Ring Flux tests on the complete core prior to the work. The core had previously been subjected to some local repair. Machine core height was 62 ins., with inside and outside core diameters of 160 and 190 ins. respectively. Details of the machine ratings are given in Table A.

Table A: Machine Ratings contained in the ELCID Test Header File

Date	22-09-97
Station	Woodleaf
Unit Number	1
Manufacturer	Allis Chalmers
Rated Power (MW)	65.5
Rated Voltage (kV)	13.8
Length of Core (m)	1.57
Number of Slots	180
Excitation Turns	20
Excitation Current (A)	12
Single turn Voltage (V)	2.9
Series Turns/Phase (T_p)	60

The normal pressures of timescale associated with refurbishment of an operational unit prevailed which resulted in some changes to the planned schedule and expediting of tests but useful comparative data was obtained.

Insertion of Artificial Faults

The artificial faults were made within the top four inches of the core for around half its circumference between the two core splits, corresponding to slots numbered from 30 to 120, there being 180 slots in total. The main laminations of the core were in segments of ten teeth, providing nine full slots and two half slots. Four lamination segments identified as A B C (slots 30 to 60) and D (slots 110 to 120) were used for the faults. Fault positions were selected on the tooth top surface and also on the side walls and bottom of both normal slots and slots on splits, with further faults in the back iron at the top outside end.

Faults on segments B and C were duplicated to enable comparison of test results with and without stator conductor bars and the associated wedges in place. Five conductor bars were therefore placed in segment B, visually masking faults B2, B3 and B4 (Slots 43 to 47) (*N.B. Although the EL CID tests were carried out with the bars in place they were unavoidably removed prior to the thermal tests to enable the maintenance schedule to continue*).

Figure 1, shown below, illustrates the position of the faults on the four segments, shown on one lamination outline for simplicity.

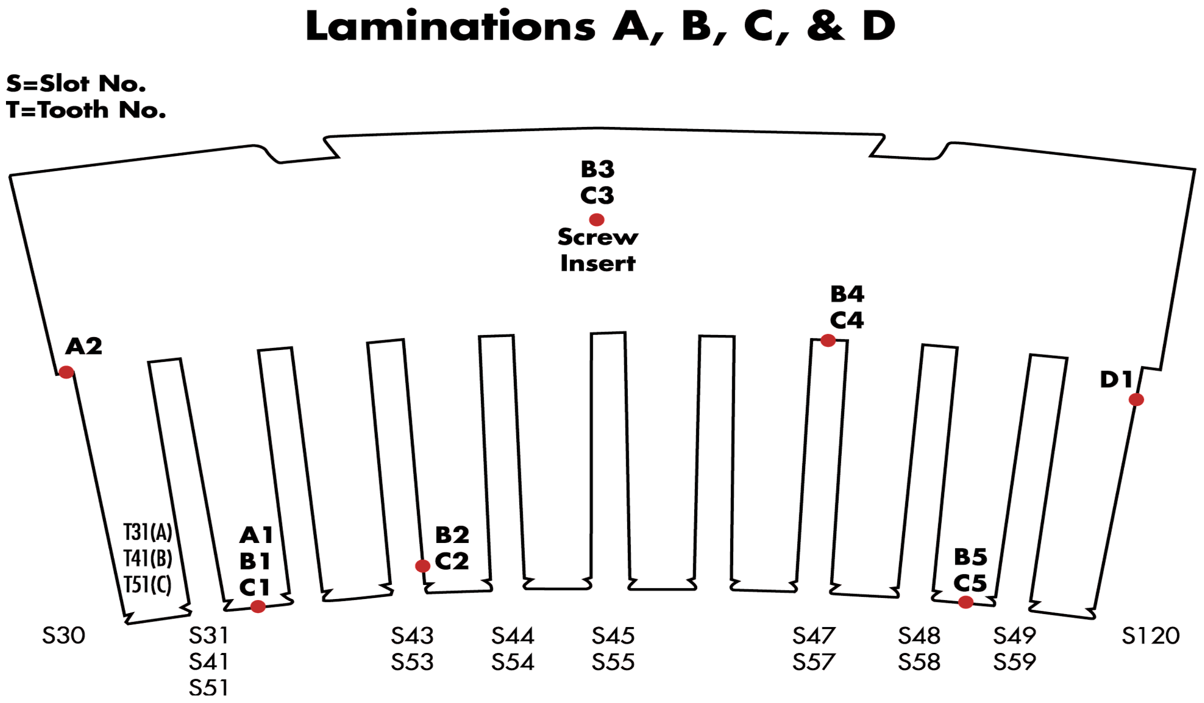


Figure 1. Location Template for Artificial Faults

Most faults were produced by spot welds (of then currently unknown effectiveness). Fault D1 was made by screw compression of a short copper strip into the laminations on the tooth wall of slot 120 and faults B3 and C3 screwed into the back iron of the top surface of the core behind slots 45 and 55. Table B shows the location of the faults by slot number.

Table B: Location of Artificial Faults by Slot No.

Slot No.	Fault Position				
	Slot Bottom	Centre of Tooth Tip	Tooth Wall	Backiron Screw	Sidewall Brace
30 (split)	A2				
31/32		A1			
41/42		B1			
43			B2		
45				B3	
47	B4				
48/49		B5			
51/52		C1			
53			C2		
55				C3	
57	C4				
58/59		C5			
120 (split)					D1

Test Schedule and ELCID Test Details

The following schedule of events relating to the test study was carried out.

- Rotor was pulled from the machine and the old windings removed
- The core was cleaned using a walnut-shell blasting technique
- Artificial faults added to top packets of core (second packet from the top)
- Selected bars and associated wedges replaced (lamination B)
- EL CID tests performed
- Thermal Ring Flux tests and refurbishing work (with bars removed)

The stator core was manufactured in two halves and therefore had two splits. The twenty turns used for core excitation were divided into two groups of 10 turns, each positioned approximately midway between core splits.

A Digital EL CID type 601 instrument was used for the tests together with a Robotic Inspection Tractor type 702 to carry the EL CID sense coil. Scans of the whole length of the slots were made in one sweep from the bottom to the top.

Core splits were at the bottom of slots and the excitation flux across the gaps at these splits resulted in the usual high magnetic potential and leakage flux in these regions. During the course of a normal EL CID test the Chattock sensing coil will bridge the split and consequently measure this very high level excitation signal. The excitation flux in the area of the core split will be composed of flux flowing circumferencially in the iron and that in fringe fields within the bore, not necessarily of the same phase. Any variation in the phase of the signal with respect to the reference phase will therefore produce a significant unwanted quadrature component providing spurious high background indications in the associated QUAD readings.

In order to reduce this effect it is therefore desirable to re-define the reference phase angle to that of the excitation flux across the split. The PHASE ANGLE RESET facility of the EL CID 601 instrument was therefore used to modify the reference phase angle of the EL CID discriminator to that of the flux in the region of the split for this purpose. Resetting of the reference phase was carried out with the Chattock sense coil across the core split at a position along the slot where fairly constant readings along the core were obtained. Auxiliary traces were then taken at the split slots. The EL CID SPU indicated that the change of phase of the excitation flux at the core splits compared with the central core was approximately 25º.

Subsequent evaluation of the test results indicated that traces for slots adjacent to the split slot would have been improved by resetting the phase on these slots also, precluded in this instance by time constraints. This would be expected to reduce the effect of perturbations in the flux such as those associated with cooling ducts, plainly visible as regular signals on some traces (e.g. slot 121 in fig 2).

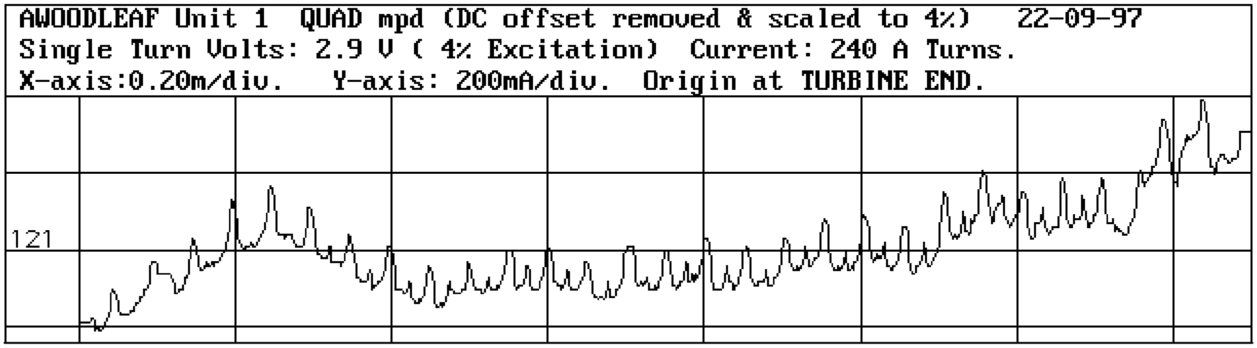


Figure 2: Flux disturbance associated with cooling ducts.

The opportunity was taken to evaluate briefly a number of experimental test coils in the region of the splits. Although useful evaluation test information was obtained, further work would be required to produce better results than that expected from careful application of the phase resetting technique.

Summary of ELCID Test Results

A table of signal responses for the artificial faults is included in Table C. Although with more time available for the test the opportunity may have been taken to repeat some traces which appear truncated or to have spurious noise effects preventing easy recognition, most faults have indications close to or exceeding the standard threshold level of 100 mA normally taken as warranting further investigation. Exceptions are surface fault C5, where incomplete traces provided little signal above noise, and B3 where a 75 mA signal was not readily discernible above noise. The presence of stator bars over the sub surface faults on B did not appear to affect detection compared with segment C, although some of the traces were less satisfactory for other reasons.

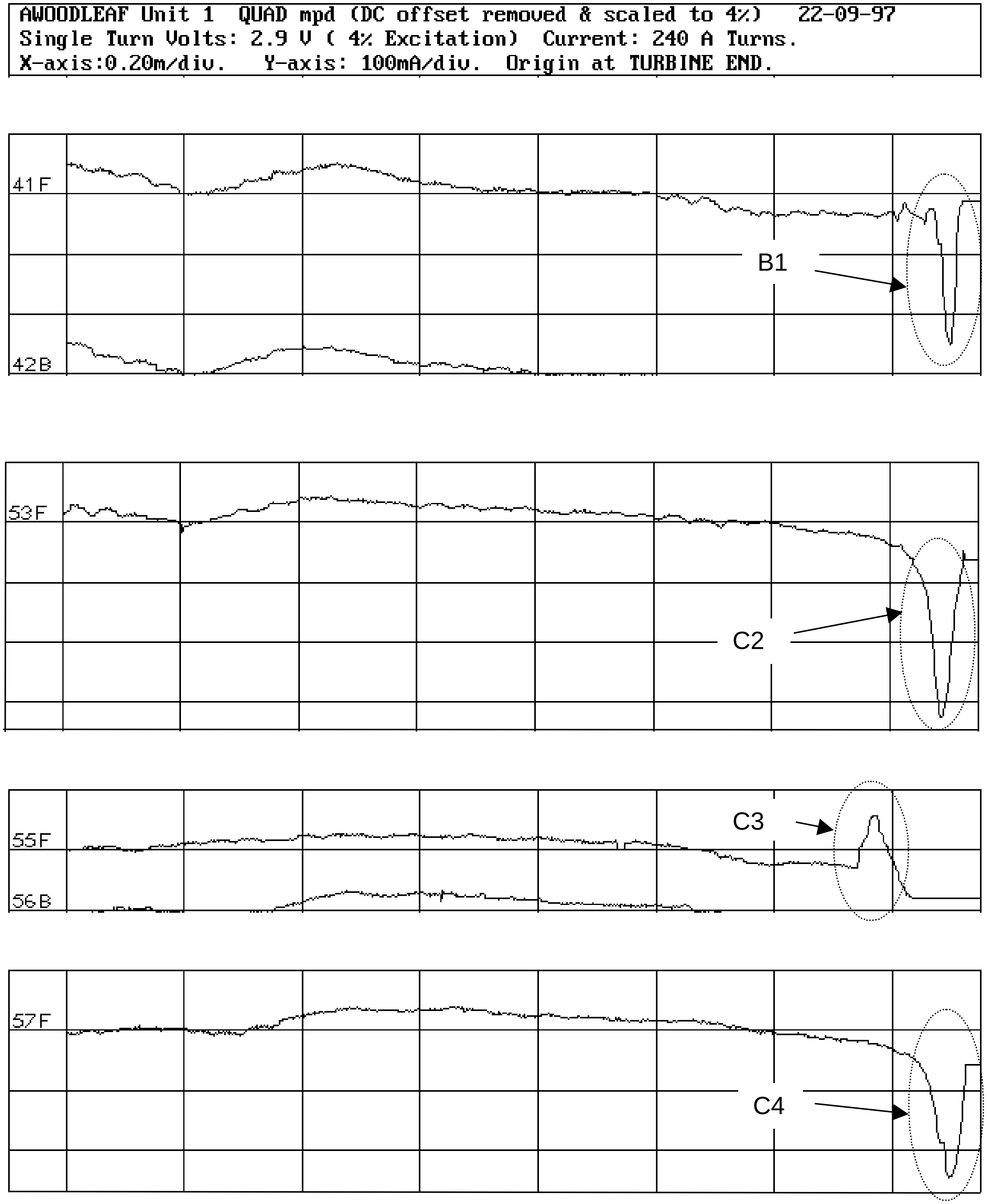
The test traces were also examined for indications of possible damage in areas where faults had not been inserted. The largest indication is at the beginning (lower end) of slot 165. Signal level is 150 mA for the initial 7 cms, rapidly reducing to zero on this slot, but not present either side. This non-artificial fault signal is included in Table C also.

The remainder of the core in general provided only slow variations in background level associated with excitation cables and other spurious effects which in general appeared over groups of slots. Exceptions included:

- Slot 68: change in level of 100 mA over a short distance at beginning of trace.
- Slot 25: 100 mA signal at end of traces centred around this slot.
- Slot 35: 150 mA signals on rising ramp at trace end.
- Slot 68: 100 mA change in level over shorter distance than other background variations

These signals would normally warrant closer inspection of the core including use of normal EL CID local test procedures with a miniature Chattock coil, or time permitting, careful repeat of these traces.

Figure 3 demonstrates typical signals from the different artificial types of fault B1, C2, C3 and C4.



AWOODLEAF Unit 1 QUAD mpd (DC offset removed & scaled to 4%)   22-09-97
Single Turn Volts: 2.9 V (4% Excitation) Current: 240 A Turns.
X-axis:0.20m/div.   Y-axis: 100mA/div. Origin at TURBINE END.

Figure 3: Indications for Artificial Faults B1,C2, C3, and C4

Figures 4 and 5 of slot 120 shows the very high magnetic potential across the core split in this slot (PHASE trace) together with the associated unusable QUAD trace from the initial Global test. It may be seen that the QUAD signal follows that of the PHASE signal (i.e., consistent P/Q ratio).

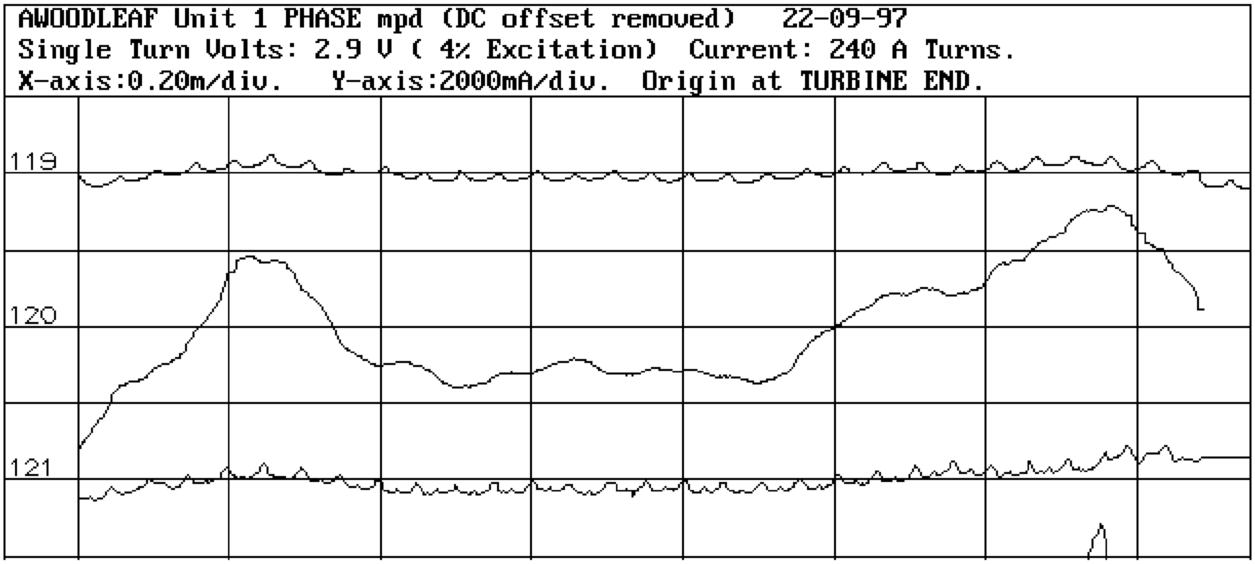


Figure 4: High Phase Signal in Region of Split

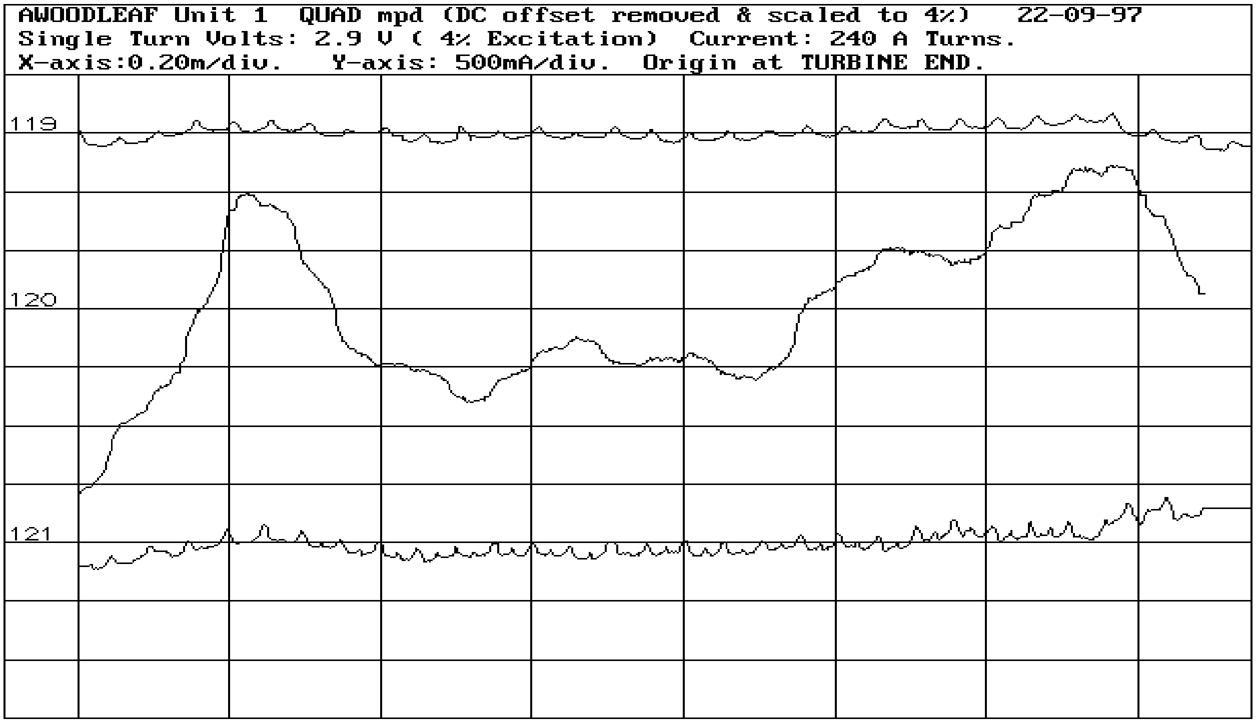


Figure 5: Global Test QUAD Signal in region of Split.

QUAD traces obtained after reset of the reference angle of the Phase Reference are shown for slot 120 in Figure 6, together with that of slot 30. Differences between PHASE signal traces before and after resetting the reference phase are not readily discernable. However, the effect of phase distortion of the high PHASE signal is still present on the QUAD traces but much reduced. Although sufficient rejection has not been obtained, the fault signals are discernible against other spurious signals of similar amplitude. Improved rejection of the phase signal is necessary for fault signals of this level but major faults would be more readily identifiable.

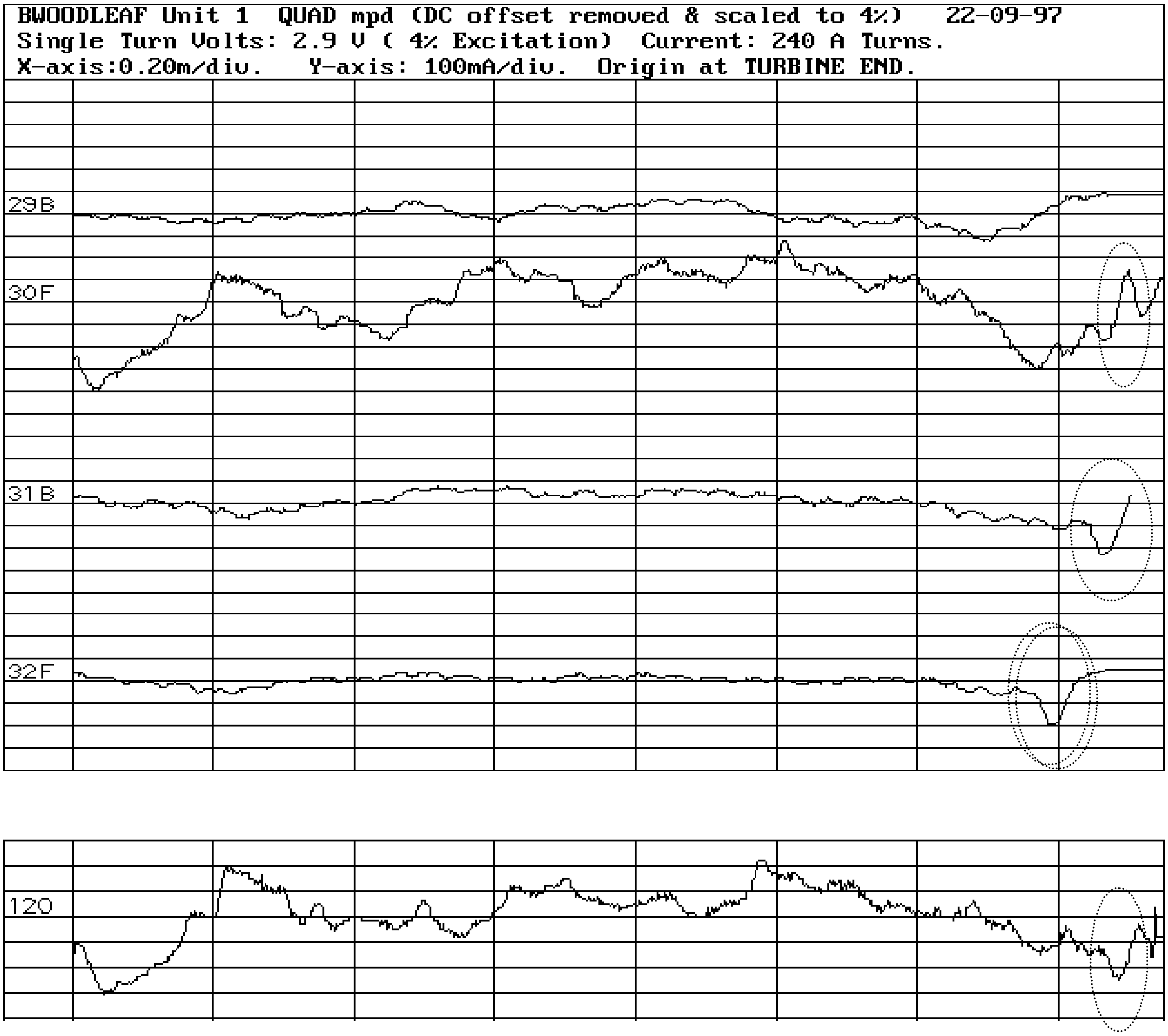
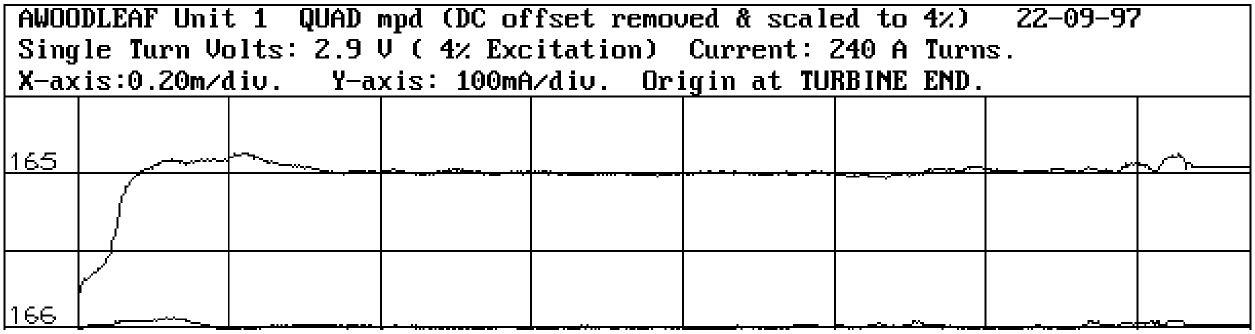


Figure 6: QUAD Signals on Splits after Phase Reset at Split

Figure 7 shows the abnormal QUAD signal at the beginning of slot 165.



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AWOODLEAF Unit 1  QUAD mpd (DC offset removed & scaled to 4%)   22-09-97
Single Turn Volts: 2.9 V ( 4% Excitation)  Current: 240 A Turns.
X-axis:0.20m/div.   Y-axis: 100mA/div.  Origin at TURBINE END.
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Figure 7: Non-Artificial Fault Indication

Thermal Ring Flux Test Details (Loop Test)

A thermal loop test was conducted September 23, 1997 on the clean unwound core generally in accordance with IEEE 56-1982. The excitation loop was energized by a portable diesel generator rated at 1.0 MVA, 3 phase, 480 volt. The loops around the stator core were wound in 4 parallels of 500 mcm insulated flexible cable. Each parallel had 5.5 turns. The loops were positioned in two groups 180 degrees apart, away from the core splits. Two phases of the generator were connected to the excitation loop cable. When energized this arrangement produced 68.0 volts on a single loop search coil with 1185 amps and 420 volts at the diesel generator terminals. This level of excitation represents approximately 90% of rated flux.

The loop was energized for one hour and the average core temperature increased by approximately 40 degrees C. The core temperature was monitored by an Inframetrics 760 thermovision camera. The camera provided a colour video image of the temperature on the core surface which was video taped. The energized core produced a very loud transformer like noise which diminished as the core temperature increased.

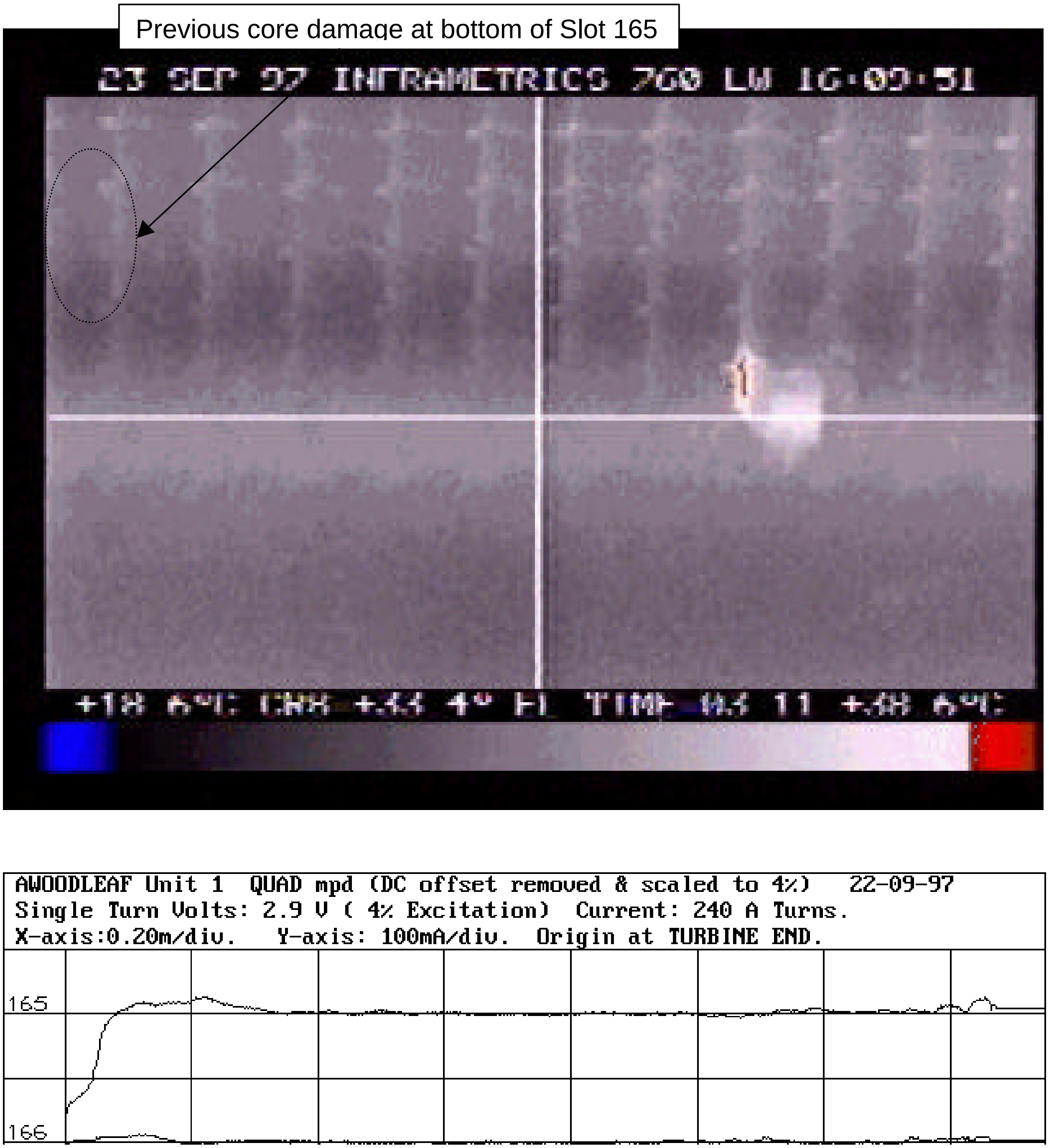
Setup of the loop test coils was time consuming, three different loop arrangements were attempted, 6, 5, and 5.5 turns. The 6 turn setup did not provide enough excitation and the 5 turn setup overloaded the diesel set. Each setup required many man hours to re-loop the coil and many cuts and reconnections in the 500 mcm cable. The diesel generator was a trailer mounted self contained power plant rented for the duration of the loop testing.

A second loop test was performed on September 27, 1997 after core repairs and a partial restack.

Correlation Between Test Results

The correlation obtained from the artificial faults between the two test methods is shown in Table C. Severity of faults indicated from the EL CID tests is in most cases sufficiently high to provide positive indication, including that from the existing damaged area at the base of slot 165. Figures 8 and 9 illustrate the comparative indications of both tests for artificial and non-artificial faults respectively.

Figure 8: Correlation of Artificial Fault C1 at Tooth Tip 51/52


Previous core damage at bottom of Slot 165

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AWOODLEAF Unit 1  QUAD mpd (DC offset removed & scaled to 4%)   22-09-97
Single Turn Volts: 2.9 V ( 4% Excitation)  Current: 240 A Turns.
X-axis:0.20m/div.   Y-axis: 100mA/div.  Origin at TURBINE END.
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Figure 9: Correlation of Non Artificial Fault C1 at Slot 165

Summary and Conclusions

The EL CID test technique has been demonstrated to be able to detect a variety of fault types of previously unevaluated severity on the core of a hydrogenerator machine, and also to detect a previously damaged area. When compared to the Ring Flux Test method the ELCID method was better able to detect deeper seated faults.

Techniques have also been used to demonstrate the effectiveness of reducing the spurious effects of phase distortion in the region of core splits to a level which should enable serious faults to be detected. Further reduction in background variations should be possible using more elaborate phase resetting techniques, including multiple resetting along a single slot, which although more arduous would be limited to a number of slots in the core split region. With regards to splits, however, further work is required to provide more specific guideline routines in order to demonstrate the ability to detect more positively fault signals around the fault threshold level.

Acknowledgements

The authors gratefully acknowledge the opportunity to carry out the study presented by the machine owner and the contractor and also the facilities and assistance provided in the course of the practical work involved.

References

1. J.Sutton: Theory of electromagnetic testing of laminated stator cores
INSIGHT, April 1994

2. J.Shelton,B.Reichman: A comparative Analysis of Turbo-Generator Core Inspection Techniques
AMERICAN POWER CONFERENCE, April 1985

3. G.K.Ridley: EL CID Test Evaluation, 1984 – 96
POWER ENGINEERING JOURNAL, IEE February 1997

4. G.K.Ridley: Why, when and how to apply EL CID to hydrogenerators
MODELLING, TESTING & MONITORING FOR HYDRO POWER PLANTS II, Lausanne 1996

Authors

Derek Paley obtained an electrical engineering degree at London University and subsequently spent many years in R&D in electronic, computer and engineering industries in the UK before entering more general engineering industry management. Before assuming his current role of Technical Director in ADWEL International , he was Technical and Operations Director of the previous UK Adwel Industries Ltd. company, which specialised in the EL CID stator core test products. Derek is a Fellow of the IEE.

Brad McNamara (P.Eng.) received a Bachelor of Electrical Engineering degree from the Technical University of Nova Scotia (TUNS) in 1990. Prior to joining ADWEL International in 1995 he worked with Litton Systems Ltd as a test and development engineer in the design of military automated test instrumentation systems. He is presently the Sales and Support Engineer for North America with ADWEL International's corporate headquarters in Toronto, Canada.

Glenn Mottershead (P.Eng.) received his Electrical Engineering degree from the University of Waterloo in 1978. He joined Westinghouse after graduation working with the installation, commissioning, test and design of turbo an hydro generators. He is currently an Electrical Design Engineer with Westinghouse Hydro Generation Services where he designs high voltage stator coils and bars. Glenn is a member of IEEE PES and is active on working groups creating and revising IEEE standards.

Steven C. Onken (P.E.) received a Bachelor of Science Degree in Civil Engineering from California University Polytechnical College at Pomona in 1970. He served eleven years as a Hydro Engineer in maintenance and operations for Pacific Gas and Electric Company's hydro generation department. For the past seventeen years Steven has been the Power Division Manager for Oroville-Wyandotte Irrigation District's South Fork Hydroelectric Project. He is responsible for the maintenance and operations of four powerhouses, eight dams and water conveyance systems.