Application of EL CID to salient-pole electrical machines

by

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**Notation**

\( \Phi_m \) Magnetic flux induced in an annular stator core
\( V_1 \) Voltage applied to the EL CID excitation winding
\( I_o \) Excitation (Primary) winding current
\( E_1 \) emf induced in the excitation winding
\( E_2 \) emf induced in the equivalent secondary winding
\( I_e \) Stator core magnetisation current
\( I_w \) Current component supplying the core iron losses
\( I_2 \) Secondary winding current
\( I_1 \) Primary winding current
\( \delta \) Fault current circulating through adjacent laminations (delta)
\( I_c \) Stator winding circulating current
\( P_e \) Excitation amp: turns per stator slot
\( I_l \) Current equivalent of joint air gap leakage flux
\( I_R \) Current equivalent of leakage flux between the stator and the rotor

**Note** The symbol \( \delta \) is chosen to represent the fault current, merely on the basis that such current is small compared to other electrical current values. But typographically “**delta**” is usually preferred to \( \delta \).
Acknowledgements

Grateful thanks are expressed to Dr. David R. Bertenshaw for his interest and encouragement. Warm appreciation is also due to Mrs Rodica Zlatanovici, the widow and former close colleague of her husband, Professor Dan Zlatanovici, for permission to include the very positive Book Review by the latter, published in 2008 of the 3rd edition of the candidate's book "EL CID - Application and Analysis". The finite element analyses provided by Dr Tom Preston, and Mr Mike Tarkanyi are also readily acknowledged.

The debt owed to Professor Li Ran is acknowledged for his encouragement of the submission of this thesis, which recognises many years of contribution to Engineering Literature.

Finally, appreciation is thankfully expressed for the recognition by the candidate's mother, Clara Annie Ridley, of his potential for higher education, when none others did.

DECLARATION

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.
Abstract
Sutton introduced EL CID in the 1970's. This thesis records the development of EL CID theory, with particular reference to its application to large, salient-pole, water-turbine driven, electrical machines, known as hydrogenerators. Factors are identified and clarified which otherwise may cause misunderstanding of hydrogenerator stator core interlamination insulation condition.

Features discussed, with reference to their impact upon the detected EL CID signal, are alternative forms of excitation winding of the stator core, its constructional features, including core build bars (or key bars), core segmentation, proximity of ferrous components, plus ancillary matters such as the location of brake/jack units, the degree of machine assembly, whether in or out of the operational situation, the extent of the machine enclosure, and the presence of the stator winding and rotor-mounted salient poles.

Although satisfactory application of EL CID to turbogenerators was achieved in the 1970's, anomalies arose when applied to salient-pole machines, due to shorter stator winding end-overhang, its multi-parallel circuits, and also the disincentive of realignment of the rotor if removed, making access to the stator bore and accurate location of the excitation cable more difficult. When present, joints in very large hydrogenerator stator frames and cores, for transportation, made analysis of EL CID results particularly difficult.

The problem presented by core joints arose in the initial factory demonstration of application of EL CID to hydrogenerators. The solution recognises the interdependence of the two orthogonal EL CID signal components, which indicate EL CID as analogous to a transformer, with two short-circuited secondary windings; one for interlamination fault current (designated "\( \delta \)"), the other being the stator winding, when present. In order to draw the phasor diagram with reference to the secondary side of the analogous transformer, the direction of the excitation phasor is reversed, since the fault current is detected in a secondary circuit. Application of standard transformer theory produces an appropriate EL CID phasor diagram, in various forms, depending upon the particular test circumstance. In this context, the significant concept of a line for which interlamination fault current (\( \delta \)) is zero (i.e. a zero delta line) was introduced.

The two orthogonal EL CID signals, designated PHASE and QUAD, are plotted on equal scales; unless related appropriately by a technique described, which takes the difference into account, to ensure the highest accuracy.

Evaluation of delta indicates the effectiveness of core repairs, which supports the usefulness of the EL CID technique when applied to hydrogenerators, as well as turbogenerators. At core joints, the detected maximum fault current (\( \delta_{\text{max}} \)) is usually appreciably greater than the traditional acceptance criterion of 100 mA. This is discussed, and the conclusion drawn that the distribution of \( \delta \) along the core length provides an adequate indication of any weak region of interlamination insulation.

The practise of routinely resetting the Phase Reference for an EL CID test is examined, and found to be not acceptable, unless the results are subsequently referred back to the basic reference.

As a final demonstration of the EL CID technique usefulness, the analysis of results from a core joint, where there was an imposed artificial fault, identifies the location concerned.
Chapter 1 - Introduction

1.1 The essential need for extending experience of application of EL CID from turbogenerators to hydrogenerators.

EL CID is an acronym for the full name of “Electromagnetic Core Imperfection Detection”. The EL CID technique and associated equipment are discussed in this thesis. The full name identifies the purpose of EL CID as detecting circulating current arising from degradation of stator interlamination insulation, resulting in a short-circuit between adjacent laminations. The fault current is induced in a largely resistive electrical circuit comprising the metallic contact between adjacent laminations, the adjacent stator laminations themselves and the build bars (also sometimes called keybars) which short the laminations at their outer periphery. In some cases, there may also be water carrying cooling tubes fitted through the stator core.

This chapter introduces a) the basic EL CID technique\textsuperscript{1,p.8}, b) the effectiveness when applied to turbogenerators\textsuperscript{2,3}, and c) anomalies encountered with hydrogenerators\textsuperscript{1,p.29et seq.}. The analysis for hydrogenerators requires several discrete steps p.82 et seq.. Electromagnetic Testing (EMT) of stator cores, and particularly EL CID\textsuperscript{2}, is used worldwide, assuming that the test results can be relied upon to predict the thermal risk of stator core faults. But, despite more than 30 years' experience of EL CID with both turbogenerators and hydrogenerators, the test, when applied to the latter, remains relatively little
studied in terms of its efficacy and accuracy. Industrial confidence in the technique stems much more from experience than analysis. Bertenshaw\textsuperscript{2} researched and quantified a number of sources of error in certain circumstances relating to turbogenerators, so as to improve the reliability of result interpretation. The research is inevitably specific to the EL CID test due to its dominance in the industry. Many results can be read across to alternate EMT techniques with little difficulty. Bertenshaw has communicated privately that these are covered in his doctoral thesis.

Differences between turbogenerators and hydrogenerators\textsuperscript{p.38} are identified, e.g. the length to diameter ratio, which results in a long stator winding overhang for the former, compared to the latter. That affects the disposition of the EL CID stator core excitation winding relative to the stator core, with consequences to the EL CID trace\textsuperscript{p's 52, 53}.

Another practical factor, for some hydrogenerators, is the form of excitation which can be applied. Constraints may arise due to civil work foundations, machine steel support structure and the desirability not to remove the rotor of vertical shaft type hydrogenerators, to avoid interfering with the line-out.

When present, other physical features, which produce falsely high EL CID results, are rotor salient poles\textsuperscript{p.59} and stator core annular airgaps\textsuperscript{p.47}. This latter
feature arises when large diameter machines are factory tested.

The thesis shows that circulating fault current, arising from degraded interlamination insulation, may be identified by regarding the EL CID set-up as analogous to a transformer \(^{p.65 \text{ et seq}}\) with two secondary windings. It will be seen that several stator magnetic flux patterns may apply, depending upon the particular features present (Figure 19). For each of these, there is an equivalent electrical circuit diagram (Figure 20), and a corresponding phasor diagram, replacing the very simple phasor diagram\(^{1, p.11}\) applicable to turbogenerators.

The complexity, of the magnetic field at core joints, is recognised by identifying that a single criterion, for the fault circulating current (\textit{delta}), is not always sufficient. It is found that the relative distribution of \textit{delta}, along the length of the core, can be more applicable p.\(^{99}\). This depends upon the basic assumption that the \textit{delta} value will not be unacceptable throughout the core length.

This general research area is offered as a significant contribution to the maintenance of large power generation utilities, which is of the utmost importance for modern society, both industrially and socially. The unexpected loss of such facilities causes major distress domestically, and places high risk upon many industrial processes. Therefore, the importance of resolving anomalous EL CID results, and their interpretation is identified.
1.2 – **EL CID basic theory**
The basic theory of EL CID, illustrated by Figure 1, is well-known and understood, but for completeness a summary is provided.

![Figure 1 Basic EL CID principles](image)

AC excitation of an annular stator core produces a pulsating circumferential magnetic flux to link with a largely resistive electrical circuit as identified in Section 1.1. above. This induces circulating current. The resultant magnetic field at the stator bore (core inner periphery) is detected (Figure 2) by a Chattock Potentiometer\(^4\) (or Rowgowski coil\(^5\)). The mathematical justification of this proposition was established by Sutton\(^6\), the inventor of EL CID, basically by a simple application of Ampère's Law. Sutton also discusses further ramifications, which are not of concern here.
The purpose of this present thesis is to justify its application to large salient-pole rotating electrical machines, not to defend the basic concept of EL CID, which is already well established and well tried\textsuperscript{7}. Briefly, therefore, the output from the EL CID sensor, whether called a Chattock Potentiometer or a Rowgowski coil, is connected to an electronic package, called a Signal Processor Unit (SPU)\textsuperscript{3}.

![Figure 2 EL CID test on a hydrogenerator](image)

The SPU incorporates an electronic phase sensitive detector to produce two orthogonal current components. The one in phase with a reference signal (now
provided from the excitation current) is called PHASE, the other is named QUAD. Further details on the electronic operation of EL CID may be found in Reference 2, Ch: 3, p. 52 et seq. In particular, on page 63 of that Reference, an EL CID functional block diagram, Figure 3.11 is provided. The PHASE and QUAD components are fed to a computer (see Figure 2), which produces a graphical display, which is immediately viewed on the computer screen, and is then normally also printed. Originally, the SPU output was recorded by a graphical printer on paper. The modern SPU, based on digital technology, produces a simultaneous output of both PHASE and QUAD values. For methods of applying excitation, see Figure 5 (p. 40) below.

When EL CID was applied to turbogenerators, the phasor diagram adopted consisted simply of the PHASE signal and, orthogonal to it, the QUAD signal, as reproduced, both by the candidate\textsuperscript{1},p.11,Fig:5 and by Bertenshaw\textsuperscript{2},p.57,Fig: 3.5. It was considered that the PHASE signal would be essentially constant\textsuperscript{6}, and that the QUAD signal would indicate, therefore, the mainly in-quadrature current circulating in the fault circuit of adjacent laminations. Such fault current would be large compared to any other deviations arising from relatively minor inherent stator core permeability variations (Figure 3)\textsuperscript{1},p.29.
EL CID was first encountered by the candidate as only an observer of its application, demonstrated by John Sutton\textsuperscript{3}, to a large hydrogenerator stator core in the machine manufacturer's factory. The result was good, except where core joints (provided for shipping purposes) existed. The solution, suggested by Sutton, was simply to transfer the reference (initially provided by an air cored coil) to the core joint. Although the signal magnitude was considerably reduced, it was still much higher than the normal acceptance value of 100mA\textsuperscript{6,p.17}. When applied to salient-pole hydrogenerators, the EL CID technique came to be regarded, therefore, with considerable suspicion by operators of such machines generally, and the application was abandoned; at least by some.
1.3 - Anomalous EL CID results encountered

EL CID is still widely used, in the context of hydrogenerators, for checking core regions considered to be beyond the influence of core joints. Nevertheless disconcerting anomalies in the results, arose\(^1\), the full range being as follows:-

1. Incorrect magnetic induction level.
2. EL CID trace axis tilt.
3. EL CID trace tails.
4. EL CID trace axis curvature
5. Circumferential EL CID peaks and troughs,
6. Changes to QUAD signal values generally.
7. Increased QUAD signal values near salient poles.
8. QUAD signal ripples.
10. Significantly increased QUAD signal values near core joints.

1.4 General steps in the solution of anomalies of Section 1.3

These problems were initially referred to others, both of high academic and of high industrial standing, who were considered best qualified to deal with them. This proved negative, as none had any clarification to offer.

The candidate has endeavoured, therefore, to determine the validity\(^7\) of the EL CID technique when applied to hydrogenerators. The bulk of the work was
undertaken after retirement without support financially or technically, apart from
three valuable finite element analyses (prompted by the candidate) - two
contributed by Dr. Tom Preston\textsuperscript{8,9}, and one by Mr. Mike Tarkanyi\textsuperscript{10}.

The various problems, identified above, arose intermittently, according to
circumstances. The candidate's interest in validating the EL CID technique with
reference to hydrogenerators has persisted, nevertheless. In this activity, the
candidate has had the interest and encouragement of Dr David Bertenshaw, one
time CEO of the EL CID manufacturing company (originally Adwell Industries
Ltd., subsequently ADWEL International Ltd and finally IRIS Power LP), who,
after retirement, also pursued research into the electromagnetic field at the bore
of large stator cores\textsuperscript{2}.

This present thesis identifies the following steps in the analysis:

1. Correct excitation level. Originally it was assumed by technician staff
   that the approximate setting advised in the Instruction Book of that time,
   could be used for hydrogenerators. It has, however, to be calculated for
each particular machine (Ref: Appendix 3). It should be noted that if the
excitation is not set precisely on the value required to produce the
recommended 4\% of rated stator magnetic flux, it is permissible\textsuperscript{6,p.8} to make
a pro-rata correction to the resulting values of PHASE and QUAD.

2. Awareness of several categories of EL CID trace distortion (Section 2.6.5)
3. Association of the anomalies with particular circumstances:

   (i) excitation type

   (ii) impact of stator winding

   (iii) effect of salient-pole rotor

   (iv) proximity to stator core joint

   (v) general state of assembly

4. Recognition of various forms of EL CID set-up with appropriate analogous transformer situations (Figures 19p.69 and 20p.70).

5. Alternative solutions of the identified problems

   (i) direct comparison of the evaluated fault value (\textit{delta}) to the recognised criterion\textsuperscript{6,p.17}

   (ii) assessment of the distribution\textsuperscript{p's99,116} of fault values along the core length

\textbf{1.5 The advantages of EL CID}

The first advantage of EL CID is that it provides the means of putting the monitoring of stator core interlamination insulation on a new and more convenient basis than had been provided by the long established High Flux Ring Test (HFRT).

The HFRT procedure involves several difficulties:

1. A significantly large a.c. power is required to provide the required excitation, which is not always readily available, particularly in Hydro Power stations.
2. The cabling involved has to be heavily insulated to match the relatively high voltage required.

3. The cabling is also of considerable cross-section to meet the current rating involved.

4. Such cable is not easily handled, therefore the activity is labour intensive.

5. Adequate access is required by which to apply the excitation cable.

6. The high magnetic flux level required is likely to exacerbate the degradation already present of the interlamination insulation.

7. Appreciable time is required, both to mount an HFRT, and to execute it,

8. The results are susceptible to changing ambient conditions.

9. There is lack of a sound quantitative basis for assessing the results.

It is unsurprising, therefore, that correlation of EL CID results with those from an HFRT is difficult, and depends largely upon the experience of those involved. An attempt to correlate EL CID results from hydrogenerators with those of an HFRT was initiated by the candidate and reported to the Biennial Session of CIGRE in Paris in 2002.

Initially, it appeared that EL CID results were little better than the HFRT, as a basis for establishing an assessment of stator core interlamination insulation condition. This was due to misunderstanding of how to set the excitation level, lack of awareness of local features which could modify EL CID results,
incorrect conclusions from the results obtained, failure to take account of the
effect of the manner of applying the excitation winding, and complete ignorance
of the effect of core discontinuities produced by core joints (i.e. circumferential
gaps).

EL CID was soon established as a valuable aid for comparing locally damaged
or repaired core material, with other undamaged regions in the vicinity. It was
also soon recognised that EL CID could provide a valuable basis, or foot print,
from which to judge later tests, thus assessing the degree of degradation suffered
in the course of service operation.

Unfortunately, one major stumbling block existed, for the removal of which no-
one appeared to have an answer. That was the effect of core joints, required
when such physically large machines were specified by the customer to be tested
in the place of manufacture, and then shipped to the site where the machine
would operate.

It was widely reported (e.g. from USA, Australia, New Zealand) that, at core
joints, EL CID indicated alarming deterioration, which was not confirmed when
machines were kept in service. In fact, they continued to perform satisfactorily
for many years, and EL CID became largely discredited by hydrogenerator
operators. The candidate's research into the state of such situations was
stimulated purely by the desire to achieve a true understanding: either EL CID worked, or it didn't! Whilst Bertenshaw\textsuperscript{2} has researched this correlation, his work did not extend to core regions in the locality of core joints. This thesis records the candidate's success in resolving the problem presented by stator core joints.

1.6 The work covered by this PhD thesis

This is summarised as follows:

(i) Recognition of the need for and the consequences of different forms of excitation set-up\textsuperscript{Section 2.6.1}.

(ii) Awareness of the environmental electromagnetic field\textsuperscript{Section 2.62}.

(iii) The significance of PHASE and QUAD signal variations, both independently and mutually\textsuperscript{Section 2.6.3.1 to 4}.

(iv) The impact of stator core joints\textsuperscript{Section 2.6.4}.

(v) The cause and significance of circulating current in the stator winding\textsuperscript{Section 3.2.2}. 


Chapter 2 - Review of Previous Work

2.1 – Initial need for the development of EL CID

In the 1970's a major step upwards took place in the specific rating of steam-driven turbo-generators, due to the introduction of direct water cooling, i.e. the primary coolant (water) was put into direct contact with the high voltage stator winding copper, with the result that heat dissipation was vastly improved. Normally, intimate contact between the conductor (copper) of high voltage electrical machine windings and coolant water is unacceptable. The cooling water used for direct cooling of these highly rated turbo-generators is very pure (conductivity being 2 to 5 microSiemens per centimetre). In a thermal power station, condensate from the steam turbines provides a ready source. In hydropower stations such ready access to very low conductivity cooling water is not available, but the candidate has had excellent experience\textsuperscript{12} in designing and commissioning a purification system for the UK's first direct-water-cooled hydro-generator/motor. In practice, the system achieved 0.13 microSiemens per centimetre, or less\textsuperscript{12}. This illustrates the possibility of the specific rating of hydro electrical machines being raised equally as high as turbo-generators, with similar consequent problems.

The means of checking repairs to the interlamination insulation, in the early days of interlamination insulation failure, due to the increased specific rating, was the well established High Flux Ring Test\textsuperscript{11} (HFRT) method. That involved
exciting the stator core to near normal magnetic flux. The chosen method of
inducing this relatively high magnetic flux in turbogenerator stators was usually
of the Figure 5c (Ref: page 39) form, since the rotor was normally removed to
allow access for personnel carrying out the repair to the core.

A radical new method of checking the progress of the repair work, which would
overcome all the foregoing problems involved with the HFRT, was needed.

2.2 - Application to round rotor steam turbine driven generators

When the early increased specific rated designs of turbogenerators were
commissioned, unexpected problems began to develop, in terms of hot spots in
the stator cores, built from thin steel laminations. Figure 4\textsuperscript{1,p.3} (provided by
Adwel Industries Ltd, original manufacturer's of EL CID) shows a photograph
taken by a heat sensitive camera of a stator core undergoing a high flux test.

![Image of stator core hot spots during a High Flux Ring Test on a turbogenerator](image-url)

**Figure 4\textsuperscript{1,p.3}** Stator core hot spots during a High Flux Ring Test on a turbogenerator
When the original development of electrical machines began, it was realised that the alternating magnetic field would produce significant circulating current between the stator laminations, unless they were insulated from each other. Suitable insulation was applied, therefore, to these laminations, and the problem appeared to have been avoided.

Unfortunately some designers, of the early direct water-cooled machines with significantly increased specific rating, overlooked that the increase in output, also increased the electromagnetic field, to the extent that the interlamination voltage exceeded the ability of the insulation to withstand that applied voltage. Consequently break-down occurred and the circulating current between affected laminations led to intense hot-spots (See Figure 4p.30) above. The subsequent burning of the laminations caused unacceptable damage, and an outage of the machine. Such outages were, of course, extremely expensive\(^3\) for the operating management and also for customers, both domestic and industrial.

The first step was to assess the damage and consider the possibility of a repair. Access to the bore of such machines is not easy, usually necessitating removal of the rotor – quite a major activity. Generally, a repair strategy could be undertaken, but the question arose as to when the repair had been sufficiently achieved. The method was well known, and conveniently referred to as the High Flux Ring Test (HFRT)\(^11\), consisting of applying a high voltage excitation
cable toroidally round the stator, to induce a near normal operating magnetic flux in the stator iron. This had several associated difficulties. Primarily, a suitable power source was not always immediately available. As already identified (in Section 2.1), the cable required was necessarily of substantial diameter, and it required a team of personnel to handle it. This was also time consuming, during which the machine was absorbing huge amounts of money\textsuperscript{3,p.1} through loss of revenue, and the cost of repair work. The unplanned outage was additionally causing severe disruption of processes dependent upon a reliable source of electrical energy. In addition, this form of investigation may exacerbate the damage caused by the insulation failure. The reliability of power generation is an aspect becoming ever increasingly important throughout the world. Reference to it in the news media is almost a daily occurrence.

2.3 A brief over-view of the EL CID system providing a simpler way to test the interlamination insulation of stator cores

An easier way than the HFRT to check stator cores became a vital necessity. A physicist, John Sutton, of the CEGB’s research establishment, called CERL, found himself tasked with solving this problem. Consequently, he invented an Electromagnetic Core Imperfection Detector\textsuperscript{3}, for which the acronym EL CID was coined. The equipment involved is described basically in Reference 6. It comprises a Chattock potentiometer sensor, connected to a Signal Processor Unit, which provides simultaneous orthogonal signals, known as PHASE and
QUAD to a computer. This both displays the results on a screen for immediate inspection, and also permits a printed copy to be obtained.

Briefly the operation of the EL CID test is as follows. The interlamination circulating (fault) current (*delta*) flows in a largely resistive circuit, comprising contact between adjacent laminations, the laminations themselves, and core structure features (usually building bars – or key bars, and, if present, cooling water tubes). It was argued that the circumferential magnetic field induced in an annular stator, would be modified by a component in quadrature to it. It was only necessary, therefore, to detect such a combined field and separate the orthogonal components. John Sutton found that the Chattock Potentiometer could be applied as the required sensor. This sensor is highly sensitive, so that a much lower magnetic induction was required than that for normal operation. The signal from the sensor was then passed through an electronic Signal Processor Unit (SPU) to produce the PHASE and QUADRATURE (known simply as QUAD) components relative to the main core flux. Experience showed that the QUAD component was less than 100 mA for a healthy core, and was the main part of the circulating current. It was recognised that the path of the circulating current is not perfectly resistive, and therefore, a small component would exist in phase with the basic magnetic field, but that was considered of secondary significance.

Consequently, checking for the adequacy of a core repair became very much
simpler, and quicker$^3$. Moreover, the supply power required for the excitation winding was considerably less than for the HFRT$^3$. This meant that a suitable cable was more flexible, readily obtainable and could be handled quite easily. Instead of a team of half a dozen or so personnel, the test could be made in a relatively short time, say a day, by a couple of people.

There were one or two teething problems, but nothing serious, and the advent of EL CID was regarded as a great success. It so happened that the convenient power supply available when introducing EL CID produced about 4% of normal flux, and that was adopted as the standard, for which the corresponding QUAD value was not more than 100 mA$^6$. This became the acceptance criterion. Since it appeared that there was not a great variability in the electromagnetic parameters of turbo-generators, a standard excitation set-up (in terms of volts per unit length) was conveniently incorporated in the original Instruction Book.
2.4 Application to large diameter salient-pole water turbine driven generators (typically, hydrogenerators)\(^1\)

After the success achieved with the application of EL CID to turbogenerators, the next logical step was its application to hydrogenerators. This was demonstrated in the factory of a British manufacturer of large machines in the early 1980's. The demonstration, carried out by John Sutton, was very positive, except in the region of core joints, which had been introduced to allow shipment of such very large stator units. At that time an "air-cored coil" was used to provide the reference of the main circumferential flux. The Reference Coil was held on the stator core bore by a magnetic base, with the plane of its turns in line with the longitudinal (or axial shaft) direction. Consequently, leakage flux from the core, which is circumferential in direction, linked with the Reference Coil turns. It was suggested, therefore, that the problem, caused by the extra large leakage flux at a core joint, could be alleviated by re-siting the Reference Coil close to the joint. This changed, in effect, the PHASE Reference of the EL CID set-up, which will be shown to be undesirable, unless appropriate compensation is made (See Section 8.3.3).

This strategy proved inadequate. Even the introduction of a current transformer, fitted on the excitation cable, and the improved ability of the EL CID kit to cope with very much higher circulating current values, did not solve the core joint problem. The thesis identifies the solution later (See Chapter 5).
In the course of further use of EL CID in connection with hydrogenerators, a number of anomalies in the results arose, as identified in Section 1.3 (p.23). Clearly, for reliable use of the EL CID technique, it is essential that the evaluation of the outcome should be accurate and unambiguous. Whilst maintenance in service of large turbogenerators is important for a reliable electrical power system, good serviceability from renewable energy powered hydrogenerators contributes additional ecosystem value. The purpose of this submission is to present the considerable volume of work published by the candidate in order to provide an adequate understanding of the theory behind EL CID, and hence to facilitate comprehensive analysis of EL CID results. There is no other such study known (App: 7). For example, a theoretical study, by Müller et al\textsuperscript{14}, demonstrates a very interesting application of 3-D finite element modelling, involving advanced mathematics, but the work does not apply to the practical situations encountered in actual electrical machines. Also, Bertenshaw has completed a PhD submission\textsuperscript{2} on the competence of EL CID or any comparable electromagnetic test, compared to the HFRT thermal test, other than anecdotally. His undoubtedly valuable work, which is not yet released into the public domain, seeks to establish confidence in this correlation. The test model employed by Bertenshaw related primarily to turbogenerators. The electromagnetic field of a hydrogenerator core joint situation was not included.
2.5 – Design differences between the two basic types of rotating electrical machine in electrical power production (i.e. turbogenerators and hydrogenerators)

In view of the prior highly successful application of EL CID to turbogenerators, the need to consider separately the application to hydrogenerators is of interest. This arises from significant differences in the design of these two basic types of large rotating electrical machine employed in the electrical power production industry throughout the world. Therefore, before considering in detail the application of EL CID to hydrogenerators, these design differences are set out in Table 1 below. These features have to be determined by a pre-test survey of the machine. Their significance was only appreciated in the course of developing the work covered by this thesis.

An aspect of setting up for an EL CID test on hydrogenerators which cannot be closely predetermined, is the electrical power supply required. Whilst this is significantly less that for an HFRT\(^3\), allowance for the magnetic flux absorbed by the massive stator frame is indeterminate because it is a significantly large feature, which varies considerably for different situations. Although this affects the setting up of an EL CID test overall, it is only the resultant electric field in the stator (in terms of volts per unit length of core) which determines the level of fault current.
<table>
<thead>
<tr>
<th>Turbogenerator (TG) design features</th>
<th>Hydrogenerator (HG) design features</th>
<th>Impact on EL CID Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Large air gap between stator and rotor may permit application of motorised EL CID without rotor removal.</td>
<td>1. Space between salient poles may allow access without rotor removal, or by removal of only one or two salient-poles.</td>
<td>1. Pole proximity effect arises in HG's (Sect: 3.2.3, p.59)</td>
</tr>
<tr>
<td>2. Cylindrical rotor needs removal, if work on stator bore is required, to allow access for personnel.</td>
<td>2. Removal of the rotor is undesirable for vertical machines to avoid realignment. Removal of rotor poles, spider and rim may be possible, but leaves the shaft in-situ.</td>
<td>2. Major dismantling of TG's is needed. Excitation winding is difficult to apply for HG's, with shaft in-situ, even with poles, rim and spider removed. EL CID traces may have tails &amp; sloping axes (Sect: 2.6.1, p.43).</td>
</tr>
<tr>
<td>3. Stator core cooling usually involves longitudinal ventilation ducts</td>
<td>3. Air-cooled hydro machines normally have radial stator ventilation ducts</td>
<td>3. Stator radial vent ducts of HG's affect EL CID signals. (Sect: 2.6.3.2 (ii), p.45)</td>
</tr>
<tr>
<td>4. A pressurised hydrogen cooling system is usually provided in addition to direct-water cooling of stator winding.</td>
<td>4. Some of the larger HG's may employ direct-water cooling, but a hydrogen atmosphere would be exceptional.</td>
<td>4. In practise, preparation of either for application of EL CID is similar.</td>
</tr>
<tr>
<td>5. TG stator endwinding extention beyond the ends of the stator core is relatively long.</td>
<td>5. HG winding overhangs are relatively short, and space at the bottom of vertical machines may be limited by supporting structure.</td>
<td>5. Proximity to core ends of HG's excitation cable may affect EL CID trace. (Sect: 3.1.4 p.53)</td>
</tr>
<tr>
<td>6. The number of stator winding parallel circuits is limited to two in TG's</td>
<td>6. HG's may have a relatively large number of parallel circuits.</td>
<td>6. Disturbance of HG EL CID trace greater than for TG's (Sect: 3.2.2 p.57)</td>
</tr>
<tr>
<td>7. TG stator cores are of relatively small diameter, compared to most HG's, and have always been built as a complete annulus.</td>
<td>7. Stator cores of large HG's may be built in sections resulting in small, but significant, radial air gaps in the core.</td>
<td>7. Core joints in HG's create complexity in the electromagnetic field. (Sect: 2.4 p. 35; Sect: 4.2.4 p.77)</td>
</tr>
</tbody>
</table>

Table 1 Basic design differences between turbogenerators and hydrogenerators affecting application of EL CID.
2.6 Introduction to the detail of the work submitted

2.6.1 - Application of excitation to stator cores of salient-pole machines for the EL CID test.

EL CID was initially applied to round rotor steam-turbine-driven large electrical machines\(^{13}\). Removal of the rotor was required in order to provide access for remedial work on the stator core. It was most convenient, therefore, to apply the excitation winding in the form of a group of turns along the axis of the core (Figure 5c). The strength of excitation was given in Reference 6\(^{\text{'s}}\) 3,8,11,17, and repeated in the original Instruction Book, as a standard value, in terms of trace turn voltage, of 5Vrms/metre of stator core length, since it was considered that most turbogenerators had similar electromagnetic characteristics.

Figure 5 Alternative forms of EL CID excitation winding

The first EL CID test on a hydrogenerator in its work-site was made in order to check remedial work on the ends of the stator core in a few locations. The excitation winding was applied as a group of turns, wound close to the stator
bore, between the salient-poles local to the remedial work (Figure 5a). The strength of the excitation adopted was as given in the Instruction Book. Although this was later shown to be erroneous for salient-pole machines, it was of little consequence at that time, since the checks were of a comparative nature and made only in relatively few limited positions around the stator bore. Nevertheless, this practise demonstrates the need for EL CID tests to be made under the close supervision of an engineer qualified to check the work, rather than only a technician, with a limited understanding of the work and the situation.

Excitation of this form (Figure 5a) is theoretically acceptable, as shown by Moullin. His work, however, related to a steel annulus situated remotely from any source of magnetic leakage. In the practical situation of a machine in a hydro-electric power station, significant magnetic leakage arises from various ancillary structures, i.e. bearings, brakes, stator frame, machine enclosure, etc. If the test is in the machine maker's factory, environmental factors such as steel flooring can be significant.

When EL CID was first applied globally to a stator, the previous experience regarding excitation level was adopted by the technician appointed to the task. This immediately produced abnormally high EL CID signals. As the candidate chanced to be on site for other purposes, and being the only design engineer present, the results were referred to him. Although not previously directly
involved with EL CID tests, the candidate quickly identified that, for salient-pole hydrogenerators, it is necessary to evaluate the excitation level appropriately for the specific machine concerned, as given in Appendix 3. The candidate had been responsible for the refurbishment design\textsuperscript{16}. From memory of that design, it was possible, therefore, to calculate the required excitation volts per turn close to that required for magnetisation of the core to the standard level\textsuperscript{6,p.3} of 4% of the operational value, as had been adopted previously.

The EL CID test then proceeded appropriately. But in the region of the core joints (or splits), apparently unacceptably high signals were evident. It was recalled by the candidate, from memory of witnessing the factory demonstration of EL CID by John Sutton, that in the similar situation on that occasion, it was suggested that the reference coil should be moved to the joint region, thus resetting the Phase reference. This action was recommended, therefore, to the EL CID operator. Although the level of EL CID signal was significantly reduced, it was still abnormally high in comparison to the acceptance standard of 100mA\textsuperscript{6,p.17}, for interlamination insulation in good condition. The electromagnetic field at core joints was not, at that time, understood. The anomalous results from such situations were the last to be analysed, despite having been referred to several electrical machine experts, from both university and industry.

In this event, it was decided, by the customer, that the machine, and its five
sister machines, should have their stator cores renewed as part of the refurbishment and enhancement in hand. It is interesting to note that the major French electrical power utility (EDF) had already adopted such action as its standard policy\textsuperscript{17}.

The form of the excitation coil is decided according to the circumstances. Reference has been made already to Moullin's justification of the Figure 5a type, but only in a rather theoretical situation. Figure 5b illustrates excitation turns wound toroidally, or helically, close to the stator bore. In Figure 5c, the excitation winding comprises a group of turns wound along the axis of the stator. Appendices 1 and 2 show that both Figure 5b and 5c forms of excitation respectively establish a uniform circumferential magnetic field in an annular core. Figure 5d is only an extension of Figure 5a, but the added groups provide compensation for possible flux leakage.

When the rotor is removed, the excitation is applied most easily in the way generally adopted for EL CID testing of turbogenerators, (Figure 5c), i.e. the required number of turns are located as a group along the axial centre-line, then returned over the core ends. This was found to be very satisfactory for turbogenerators, but when applied to hydrogenerators the results contained anomalies, which were traced to subtle differences between the two types of machines, such as the greater length of winding overhang for turbogenerators. Although the hydrogenerator rotor-mounted salient-poles can be sometimes
removed as an integral unit with the laminated rotor rim, leaving the shaft in-situ, the remaining shaft influences the results. The Figure 5c form of the excitation in these circumstances may cause trace axis tilt (Section 3.1.4) and trace tails (Section 3.1.5). Removal of the shaft is undesirable, as such action introduces a significant delay during re-assembly for renewal of the line-out of the generator and turbine shafts.

Where the hydrogenerator rotor is not removed, the only alternative form of excitation winding is as a toroidal coil spread evenly around the stator (Figure 5b). This form has particular merit, if it is desired to establish EL CID results for a core, whether new or not, as a basic footprint to be compared with later EL CID results. To remove the rotor for such a purpose would probably be impractical. Use of the toroidal form of excitation winding, however, raises its own problems. Firstly, care is necessary not to work too closely to the winding turns. This requires sufficient slack in the turns at the back of the stator core to allow easy movement during the test. A restriction on this requirement sometimes arises due to the limited access available through the machine foundations and/or top structure. Of course, the circumferential location of the EL CID axial traverse of the core relative to salient poles has an impact on the EL CID results, in the form of curvature of the trace axis (See Section 3.2.3, page 60), whatever the form by which excitation is applied.
2.6.2- Environmental electromagnetic field

Although not usually a problem, the sensitivity of the EL CID sensor is such that occasions have been identified when a change to the background electromagnetic field has been detected. This arose when other machines were started-up or shut-down in the power station during the course of an EL CID test.

2.6.3 - The significance of PHASE and QUAD signal variations

2.6.3.1- Identification of perturbations arising from an interlamination insulation fault and those produced otherwise.

The fundamental concept of EL CID for a fault free core, was that the sensor would produce an approximately flat trace (i.e. to within 50 mA)\textsuperscript{6,p.13} for both PHASE and QUAD detected signals. Where a fault was detected, the QUAD trace would show a very significant excursion (See Figure 3), but the PHASE signal would be largely unaffected, and equal to the magnetic potential difference (mpd) established by the applied excitation. For turbogenerators, this was the normal experience. For hydrogenerators, however, the EL CID results were usually much different, although initially the focus was on QUAD values.
2.6.3.2 – QUAD value variations from other than defective interlamination insulation.

(i) The Effect of the form of excitation winding

Several of these have been identified in the discussion (Section 2.6.1) of the form of excitation applied to a stator core for an EL CID test, i.e. trace axis tilt, trace tails and trace axis curvature (See also Sections 3.1.4 and 3.1.5).

(ii) The impact of ventilation passages

Historically, ventilation of hydrogenerators has been mainly by means of air as the primary coolant, whether for the "open" type of machine, or the "closed" type, employing water for the latter as a secondary coolant. In each case, the heat generated by machine losses is dissipated by air circulating through the machine. For this, radial air passages along the core have usually been provided. These constitute a discontinuity in the permeability of the core, which is reflected in a reduction of the longitudinal signal of the EL CID sensor.

(iii) An additional source of QUAD signal variation

This was reported in Reference 18. At the time of the tests to which these results are mainly referred, understanding of the application of EL CID to hydrogenerators was considerably lacking, and the attempted analysis left much to be desired. There was, however, some indication of correlation with the number of slots per core plate segment, and the location of key bars (or core
building bars), which previously had not been noted. The former cause of trace variation is now considered most likely to have been a stator winding circulating current effect (See Section 3.2.2).

2.6.3.3 - PHASE variations.

Initially, little or no interest was taken in PHASE values, except to check, at locations remote from core joints, that the magnetic potential difference (i.e. mpd), given by excitation ampere turns divided by the number of teeth, or slots, was as desired.

It was found, however, that when the PHASE signal from hydrogenerators was recorded, it could have a wide variation in both the axial and circumferential directions.

(i) Negative PHASE values circumferentially

Circumferential (i.e. from slot to slot) PHASE variations were particularly notable, in so far as they sometimes became negative Fig:10,p.58. This appeared to have a very special significance, as identified later (Section 3.2.2).

(ii) Correspondence of longitudinal PHASE and QUAD values

The axial PHASE variation was found to be matched, approximately, by that of the QUAD signals, which also indicated some particularly special significance. This is taken into account later (Section 3.2.1).
2.6.3.4 - **PHASE and QUAD variations together.**

(i) Further consideration of circumferential variations will be given later.

(ii) The matching **PHASE** and **QUAD** longitudinal variations arise fundamentally from variation in permeance along the length of the core.

Dukshtau et al\(^{19}\) have noted that "The stator of a hydro-electric generator is a large, complicated structure subject to diverse loads of electromagnetic, vibration and thermal origin when in operation." In other words, stator cores of such machines are not at all homogeneous, which is reflected strongly in EL CID results. It is no surprise, therefore, that EL CID results are far from the theoretical form often assumed and expected. The matching of variations in **PHASE** and **QUAD** values along the core length is indicative of a very important connection to be discussed later (Section 3.2.1).

2.6.4 - **The impact of stator core joints**

At or close to stator core joints, the EL CID signals indicated a serious deterioration in the condition of the interlamination insulation. But experience, voiced by hydrogenerator users at international engineering forums, did not support such a conclusion, and cast doubt on the reliability and value of the EL CID technique. This erroneous perception may be dispelled by application of recent work by the candidate in successfully p. 82,90 et seq. analysing the situation.
4. **2.6.5 - Summary of problems (other than arising from fault conditions) encountered when applying EL CID to salient-pole electrical machines**

<table>
<thead>
<tr>
<th>Problem</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Higher signal values than normal</td>
<td>1. a) Incorrect excitation level.</td>
</tr>
<tr>
<td></td>
<td>b) Sensor too close to excitation cable turn.</td>
</tr>
<tr>
<td>3. Signal trace tails</td>
<td>3. a) Excitation cable too close to core end.</td>
</tr>
<tr>
<td></td>
<td>b) Magnetically sensitive component(s) in the vicinity.</td>
</tr>
<tr>
<td>4. Trace axis curvature</td>
<td>4. Salient-pole proximity to traverse of sensor.</td>
</tr>
<tr>
<td>5. Trace ripple along the core length</td>
<td>5. a) Ventilation ducts</td>
</tr>
<tr>
<td></td>
<td>b) Core construction features (e.g. core build (or key) bars, core segmentation gaps).</td>
</tr>
<tr>
<td>6. Significantly low signal values</td>
<td>6. a) Incorrect excitation level</td>
</tr>
<tr>
<td></td>
<td>b) Deeply embedded fault</td>
</tr>
<tr>
<td>7. Major cyclic signal circumferential variations</td>
<td>7. Stator winding circulating current</td>
</tr>
</tbody>
</table>
Chapter 3 - Detail of the initial phase of the work submitted

3.1 - Application of excitation to stator cores of salient-pole machines for the EL CID test.

3.1.1 - The form of excitation winding to be applied (Section 2.6.1, Figure 5)

It has been identified that there are four basic forms\(^7\) by which to apply the excitation winding for an EL CID test:

a) A single multi-turn group wound closely to the stator bore (Figure 5a).

b) A toroidal application of the excitation winding turns (Figure 5b).

c) A single multi-turn group wound along the longitudinal axis of the machine (Figure 5c).

d) Several (often four) groups of turns wound at evenly spaced locations around and close to the core (Figure 5d).

The Form 5a excitation winding is useful when it is only necessary to apply local magnetisation of the core. Although Moullin has shown\(^{15}\) that this form of excitation can theoretically produce a uniform magnetic field around an annular steel construction, this is only feasible when there are no leakage paths. But, when access is very limited, this form can be useful.

The Form 5b excitation is shown in Appendix 1 to produce a magnetic field in the annular stator which is principally circumferential, other components being negligible.
The Form 5c excitation is shown in Appendix 2 to induce a relatively high flux density in the iron annular stator compared to that produced in the air.

The Form 5d excitation is merely an extension of Form 5a). Form 5d overcomes the tendency of leakage flux to diminish the circumferential magnetic field.

### 3.1.2 – The strength of excitation to be applied

The hydraulic conditions of hydro-electric schemes are far from standardised. This is reflected in the highly variable electromagnetic characteristics of the associated large salient-pole electrical machines. Standardisation of the strength of excitation to be applied to the stator core of such machines for an EL CID test is virtually impossible. Consequently the voltage per turn of the excitation winding, as detected by a trace turn, needs to be calculated as laid out in Appendix 3. As the characteristics of the stator core steel magnetic properties are not well defined at the low intensity of magnetic field employed in an EL CID test, it is necessary to set the excitation ampere-turns by some measure of trial and error. This can be refined from experience, although some difficulty remains in pre-test assessment of the excitation supply requirements.

Although the standard 4%⁶ of normal operational stator core magnetic field strength is recommended, it is not absolutely essential to achieve this figure, as the strength of the signal obtained from the EL CID kit may be adjusted pro-rata with magnetic field within a limited range.
3.1.3 – Avoidance of being too close to excitation turns

Application of excitation forms b and d (Figure 5) requires care in the provision of adequate slack to permit moving the turns sufficiently to provide about a metre distance between the EL CID sensor and the nearest excitation turn. This is in order to avoid undue interference of the excitation current electromagnetic field with that of fault current. A metre is considered good practise, based on experience, although not an absolute rule from theory.

3.1.4 – Care required when applying the Figure 5c form of excitation winding

Before discussing the EL CID traces arising when this form of excitation was applied, it is necessary to identify the significance of variations exhibited in any case. If a stator core consisted of a truly homogeneous mass of steel, the trace of an EL CID signal would be a perfectly straight line, there being no variation in permeability, and no varying fault current. It is necessary, however, to use insulated laminations as the stator core material to inhibit inherent circulating current. This introduces two factors which impact upon the EL CID trace. First, there is a variation in permeability along the length of the core, causing a reduction in the EL CID signal. Secondly, there is imperfection of the interlamination insulation, causing a further variation in the EL CID signal. Also, as noted in Section 2.6.3.2(ii)p.45, ventilation ducts reduce the core permeability, and hence, the EL CID signal.
Thus variation in the EL CID trace indicates some measure of circulating current. Complete elimination of circulating current is, of course, impossible. For the purpose of assessing the degree of slope of the EL CID trace, it is necessary to exercise judgement regarding the general level of signal.

When the EL CID sensor was moved circumferentially, with the Figure 5c form of excitation applied, it was noted that at the end of the trace, there were sometimes exceptionally high values.

Figure 6  EL CID results, along the stator core length, exhibiting trace axis slope and significant deviations at one end of the stator core.

The significance of the trace slope is dealt with in Section 3.1.5p.55.

The high values at the end of the trace appeared indicative of interlamination
insulation degradation at the core ends. This could sometimes result from filing
the ends of the stator slots as an aid to fitting the stator winding. Examination
of the core usually eliminated such a cause. The high end trace values formed
a pattern, however, relative to the radial arm of the excitation cable crossing the
core end\textsuperscript{10}.

This provided a clue to an item by Carter\textsuperscript{20} [p.142, Sect:7.12(a)] relating to the effect
of a current carrying conductor above a magnetic surface. This was not
developed by Carter but the candidate has shown\textsuperscript{10}, as reproduced in Appendix
4, that the field intensity in the steel surface, in this situation, varies dramatically
in the region close to the conductor (Figure 7).

![Figure 7](image)

**Figure 7** Theoretical variation of Flux Density ($B$) in a magnetic surface due
to a current carrying conductor above and parallel to it.
The conclusion was reached, from this development, that for a Form 5c type of excitation winding, it is desirable to run the radial arm at least a metre away from the end of the core. Although this is not always possible, particularly at the bottom of a vertical machine, this awareness provides a warning with regard to interpretation of the results.

3.1.5 – Misalignment of the excitation Form 5c within the stator bore

A further distortion of the signal picked up by the EL CID sensor, in the form of a slope of the trace axis (Reference Figure 6), arises from misalignment of the axial leg of excitation winding Form 5c with the axis of the machine. Such misalignment may be twofold, i.e. at an angle to the machine axis, and also offset. This is readily illustrated in Figure 8 resulting from a finite element analysis. It is noted that if the shaft has been left in-situ, an offset of the excitation winding through the stator bore is inevitable.

In order to analyse the effect of misalignment of the Form 5c excitation cable through the stator bore the field intensity at the stator bore is considered for a given degree of off-set, thus representing a particular cross-section of the situation. Figure 8 is the result for one particular such off-set of 10%. Additional studies, for different values of off-sets, to simulate slope of the cable, showed that the flux density is essentially inversely proportional to the distance of the cable from the bore. Saturation effects may be neglected at the low level of magnetic induction involved.
The variation\textsuperscript{1,21} of the EL CID trace axis slope round the bore indicates the position of the excitation cable, if it has not been reported clearly. The need for attention to detail, of such as the excitation winding application, again highlights the need for an adequate understanding of the EL CID technique for application of EL CID.

![Figure 8](image.png)

**Figure 8** – Finite element analysis of cable attitude

3.2 Variations of \textit{PHASE} and \textit{QUAD} values unrelated to fault conditions

3.2.1 – Corresponding \textit{PHASE} and \textit{QUAD} variations

As has been stated earlier, initially \textit{PHASE} values (traces) were largely disregarded, as it had been the experience in relation to turbogenerators that they
were relatively constant. When, however, *PHASE* traces were recorded for hydrogenerators, it was found that variations along the core length could be quite marked. It was noted in Section 2.6.3.4 above that stator cores are far from homogeneous constructions. Moreover, it was observed that resulting variations were reflected in corresponding *QUAD* traces\(^{22}\). Figure 9 records this at a core joint, where the *QUAD* values were particularly significant.

![Graph showing EL CID Values, Phase, and Quad](image)

**Figure 9** – Corresponding *PHASE* and *QUAD* values at a core joint

Whilst the correlation of *PHASE* and *QUAD* values in Figure 9 is not immediately striking, it is evident that there is evidence of it to some degree. Moreover, it has to be recognised that these results were not obtained using the latest version of EL CID, which electronically records both *PHASE* and *QUAD* at the same time. In addition, paper traces, used earlier, suffered from some lack of precision in the recording of the values relative to their disposition along the stator core. The general trend can, however, be seen.
3.2.2 – The impact of stator winding circulating current on PHASE records

Figure 10 records a major departure from the expected uniform value of mmf circumferentially. Particularly noteworthy was the excursion into the negative region in the case the PHASE trace of one of the two machines illustrated.

The significance of these records was not immediately recognised, until it was realised, in discussion, that a negative value of PHASE, i.e. essentially mmf, pointed to a driving electrical current. This led to an examination of the possible effect by the stator winding, if present, during an EL CID test. It was found that if all the phases and parallel paths of the stator winding were shorted, the circulating current would have the same distribution pattern as the upper PHASE values in Figure 10, as seen in Figure 11. The same result was obtained for the lower PHASE values in Figure 10 by again taking account of stator winding circulating current.

A fuller discussion is given in Reference 1. An important confirmation of this aspect of the work was provided by Bertenshaw and Sutton.

As a supporting check, Dr. Preston applied a finite element analysis technique, using a SLIM package, with the result given in Figure 12.
**Figure 10** - Circumferential variation in *PHASE* value

**Figure 11** - Circulating current effect on EL CID values
3.2.3 – The proximity effect of salient poles on EL CID traces

In general, the space (air gap) between the stator bore and the surface of salient-poles is small for hydrogenerators, particularly those of early vintage, which are most likely to suffer from degradation of stator core interlamination insulation. In order to carry out a monitoring check during an in-service period (although not operationally active), it is not worth dismantling a machine to the extent of removing the rotor to provide the EL CID operator with access, nor is the air gap usually large enough to permit an EL CID remote controlled trolley (tractor) to travel through it. At best, therefore, sufficient access is usually made
available by removing only one, or maybe two, of the salient poles.

In the case of an early application of EL CID to check the stator core insulation condition, the resultant QUAD trace obtained was that identified as Curve A in Figure 13. Initially, it appeared that the insulation towards the ends of the stator core was defective. But upon turning the rotor to allow access to another part of the stator bore, it was found that the results for the same slot had become Curve B. It was recognised that the essential characteristic of the trace, which included a pronounced blip near one end, had not changed, but the axis had been flattened. This raised awareness of the possible effect of salient poles on EL CID results.

![Figure 13 – EL CID trace curvature due to Pole Proximity effect](image)

The question was also raised as to the circumstances in which a pole-proximity effect might be expected. An earlier test on another machine, for which no poles were removed, was thought (erroneously, as it was later proved p.'s61,62) to
indicate the absence of such an effect.

An in-depth study of this phenomenon was undertaken\textsuperscript{8}. It included three-dimensional Finite Element Analysis models for two machines, such as shown, for only one of them, in Figure 14. Figure 15 shows the geometry for both.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure14}
\caption{Three-dimensional finite element analysis model}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure15}
\caption{Longitudinal sections for two machines investigated for pole-proximity}
\end{figure}

Details of this study of pole proximity during an EL CID test are given in Reference 8. In the light of this, a re-examination of results, which initially appeared not to show a pole-proximity effect, found that such did exist, although of varying degree, as reported in detail in Reference 8. The conclusion was that
a pole-proximity effect will always be present where there are salient- poles.

3.2.4 Brief analysis of EL CID results from a remote site

An important point illustrated here is that application of EL CID needs to be under the control of engineers who understand all that this dissertation covers, as indicated by Sutton\textsuperscript{6,p.7}.

EL CID results reported from a distant site were received for comment. Questions raised were not referred back to the data source, although requested. Consequently, progress with analysis was deferred. The reported EL CID results were unusual, as they referred only to the end packets of laminations, rather than the length of an entire tooth (or slot).

![Figure 16 A plot of top-end core packet EL CID QUAD signal results](image)

The comprehensive suite of EL CID vector diagrams (Reference Section 4.2\textsuperscript{p.68}) had not been developed, but understanding already gained indicated the
analysis of results as shown in Figure 16. For instance, the theoretical form of
EL CID signal values identified in Figure 7, arising from too close a proximity
of the excitation cable to the core end, is seen also in Figure 16. In the
appendices of Reference 21 it is deduced that there was a tilt of the excitation
cable as it passed through the stator bore, such that the EL CID signal
distribution might be greatest to the right of the indicated location of the cable.
This is suggested by the approximate mean curve drawn. Although the
relationship to construction features is uncertain, there is clearly some
correlation.

From Figure 16 it is considered that the recorded maximum QUAD value of
280mA is falsely inflated (if an indication of core condition) as follows:-
From results elsewhere around the core, the base signal was indicated as 68mA.
The signal in this region of slots 100 to 200 affected by the excitation cable and
core joint is considered to level off to about 228 mA, i.e. an increase of 160 mA,
possibly due to stator winding circulating current. There is also the apparent
effect of proximity to the core end, estimated as 38 mA. The 4 mA difference
between results each side of the cable position is considered to be due to tilt. A
further increase of 10 mA is ascribed to the segmentation of the core
laminations. Finally, the core was judged to be over-excited by [(4.90 / 2.69) -
1] 100% = 82%. Thus, the recorded maximum QUAD value of 280 mA is
reduced to (280 - 10 - 4 - 38 - 160) (2.69/ 4.9) = 37mA, indicating a very
acceptable core condition. In fact, the machine performed good service over many further years. This was confirmed by the candidate's personal visit. The need for comprehensive reporting of the test set-up and results is nevertheless strongly indicated, for a reliable analysis.
Chapter 4 – The major development in the work submitted - based upon identification of EL CID as a transformer

4.1 The basic EL CID phasor diagram

The accumulated evidence indicated that PHASE and QUAD values were closely inter-related, and it was concluded that consideration of the EL CID set-up as a transformer, with two short-circuited secondary windings, closely represented the situation. The standard phasor diagram for this is shown in Figure 17. The identification of the symbols used is given in the Notation (p. 13).
Since the EL CID sensor detects the effect of current in the secondary circuits comprising a) the fault, and b) the stator winding, it is necessary to view the excitation circuit (i.e. the normal primary circuit) from a secondary winding point of view. The phasor diagram is re-drawn below, therefore, with reference to the secondary side of the EL CID set-up regarded as a transformer. It is to be noted also, that the Signal Processor Unit (SPU) of the EL CID equipment, reverses the Phase values\textsuperscript{26,p.3}. The result is shown in Figure 18, where only current phasors are included.
Figure 18  The basic EL CID phasor diagram, including Circulating Current ($I_c$) and PHASE axis reversal; current phasors only shown; all components referred to the secondary side)

Figure 18 is essentially as produced by Bertenshaw\textsuperscript{26} from basic electromagnetic theory of the induction of a magnetic field in the stator core, including current in a fault path (due to degradation of interlamination insulation). The diagram is extended for current in the stator winding (if present). Bertenshaw does not develop the phasor diagram to match the various different electromagnetic situations which may be encountered in practical situations. The effect of the presence of a rotor is neglected until later.
4.2 Development of a suite of EL CID phasor diagrams to match different electromagnetic conditions\textsuperscript{24}

4.2.1 Introduction

When the EL CID test is applied to the annular stator core of a salient-pole large electrical rotating machine, such as a hydrogenerator, a number of conditions may apply. These are illustrated in Figure 19. As indicated earlier\textsuperscript{p.65}, it is considered that the EL CID set-up may be regarded as a transformer. For this purpose, a comprehensive equivalent circuit is presented in Figure 20, deduced as shown in engineering literature\textsuperscript{25}. It covers all the various alternatives. Interlamination insulation degradation (i.e. a fault), with its associated fault current (\textit{delta}) is assumed to be present in each case, and is not shown in Figure 19.
This diagram is a very simplified version of the magnetic flux paths set up by the conditions identified as “a”, “b” and “c”. Stator slots and rotor salient-poles are only shown where necessary to illustrate the effect of different machine conditions.

**Figure 19. Flux paths during an EL CID test for various cases**

Three different flux conditions are identified in Figure 19, by text and by illustration, as:

a. air gap leakage flux at stator core joints (Ref: Figure 24)

b. an unbalanced excitation winding (Ref: Sect: 3.1.4 & 3.1.5; Figures 22 & 23)

c. leakage flux between the stator and rotor (Ref: Figure 25)
All three situations may arise at one time or be established separately. For clarity an example of each situation is illustrated individually. Each condition produces an imbalance to the magnetic field. If a shorted stator winding is present, with two or more parallel paths, the magnetic imbalance gives rise to circulating current in the stator winding, which is an extra item to be included in the phasor diagram (See Ch: 4, p.65 et seq).
Figure 20. Equivalent transformer circuit diagram for various cases

The objective is to evaluate \textit{delta} from the results of an EL CID test. To achieve this, it is very important that EL CID operators, and subsequent analysts, have
sufficient understanding of the physical conditions existing, and also the electromagnetic situation at the time of the test. *For any one test, therefore, the appropriate features in Figures 19 and 20 are selected, and the corresponding choice made from the suite of phasor diagrams developed below. It may be necessary to develop new ones which are most appropriate for different situations.*

It is fundamental to the analysis to accept the basic EL CID theory, as set out in the thesis, with reference to Figure 1. The immediate extension to that is awareness that the EL CID sensor (Chattock Potentiometer) detects whatever magnetic field is present at the inner periphery of the annular core for a particular case. Detailed consideration of several cases follows. In this discussion of each of the conditions identified, reference is made only to those features of Figure 19 and 20 which apply in the particular case under consideration.

Excitation of the annular stator core is applied in one of the four forms shown in Figure 5. In ideal circumstances, Moullin\textsuperscript{15} shows that Form 5a would induce a uniform magnetic field in the iron of the stator core. It is shown in Appendices 1 and 2 of this Thesis that Forms 5b and 5c, for equally ideal conditions, would also induce a uniform magnetic field. Inevitably conditions are not ideal, with the consequence that there is flux leakage, as illustrated in Figure 19 for
different circumstances of the stator core assembly and state of erection. Excitation Form 5d produces an acceptably practical uniformity of flux induction, but must clearly be associated with a significant degree of flux leakage.

4.2.2 Case 1. No stator winding fitted, no rotor in-situ, no core joints. For this case, none of the features a, b, and c, illustrated in Figures 19 and 20, are present.

*It is to be noted that, as in Sutton's original work in developing EL CID, the phasor diagram is rotated clockwise through 90 degrees from the angular position in the general diagram given in Figure 18.*

Thus the relevant phasor diagram comprises only the current ($I_o$) in the excitation winding (drawn in the reverse direction to match the view from the secondary winding), plus the fault current ($delta$, drawn orthogonally to the direction of the flux induced in the annular stator core) to give the resultant secondary current ($I_2$), as shown in Figure 21.

This is virtually the same as the original simple phasor diagram proposed by Sutton, except that it is drawn in the 4<sup>th</sup> quadrant. Due to the power loss associated with the stator iron, the magnetic flux direction is out of phase with the PHASE axis, the direction of which is identified as that of the excitation current. As generally assumed in initial EL CID tests, whilst *delta* is seen to be approximately equal to the *QUAD* value, it is evident that it also has a small *PHASE* component.
Figure 21  EL CID phasor diagram in the absence a stator winding.

It is to be recognised that the relevant version of the phasor diagram, applies strictly to the conditions encountered at a particular position at the core bore, circumferentially and longitudinally. If the stator winding is present in the stator, the associated circulating current is constant along the length of the particular slot position under examination, but the stator core permeance may vary for a variety of reasons, and hence also the apparent mpd, directly related to the effective excitation current ($I_o$). This appears as a variation in the detected PHASE value.

Consequently, if $\delta$ is zero and the PHASE value varies, the operating point moves along the PHASE axis. In this case the PHASE axis is defined as the zero $\delta$ line. Its significance will be seen more clearly in other cases.
4.2.3 Case 2. Stator winding present and its terminals short-circuited, no rotor in-situ, no core joints.

The relevant feature here in Figures 19 and 20 is b). As identified by Bertenshaw, when a stator winding, comprising parallel circuits, is in place with its terminals short-circuited, the unbalanced magnetic field of the stator core, arising from the disposition of the magnetising winding, provides flux leakage linking the stator conductors to induce current in them. Added to the phasor diagram of Figure 21, therefore, is the component of stator circulating current (Ic), in parallel with the interlamination fault, in which delta circulates, to form Figure 22.

For any one slot position the stator winding current is constant, thus if the PHASE value varies, the delta phasor moves along a line parallel to the PHASE axis passing through the tip of the stator circulating current phasor. This line is the reference line along which delta is zero, and defines the zero delta line for this case.
Figure 22  EL CID phasor diagram for a location remote from a core joint, but including a shorted stator winding

Throughout the winding the current must balance out to zero. Therefore, whilst for any one slot position the stator winding current is constant, there is variation, circumferentially (i.e. from slot to slot, including phase reversal), as illustrated in Figure 23.
Figure 23  Phasor diagram for a location remote from a core joint, including reversed stator winding circulating current (-I_c)
4.2.4 Case 3 Stator winding present (as in Case 2), rotor not in-situ (as in Case 1), core joints present (to facilitate transportation).

This very important case remained unsolved until all other EL CID phenomena had been analysed. Figure 24 applies.

The relevant features for this case in Figures 19 and 20 are a) and b).

The presence of core joints introduces a major degree of flux leakage, i.e. a relatively large phasor component \( I_l \), which is aligned to the direction of the main magnetic flux \( \Phi_m \). To \( I_l \) is added the stator winding current \( I_c \). The direction of \( I_c \) is such as to oppose the local leakage flux, but due to the winding resistance the direction of \( I_c \) is slightly out of direct phase opposition to the leakage flux's equivalent current phasor. Bertenshaw has shown that the phase difference is not far from 180 degrees. The presence of resistance tends to produce an anti-clockwise rotation relative to the leakage flux. This rotation is exaggerated in Figure 24 for clarity. Although the symbols in this figure are as defined in the Notation, it is important to observe the following:-

- \( I_e \) represents the excitation current, required to magnetise the stator core.
- \( I_o \) represents the total current required in the excitation winding, when account is taken of \( I_w \), the current drawn by the losses in the core iron.
- \( I_c \), \( I_o \) and \( I_w \) are essentially primary side values, which are reversed due to the diagram being drawn from the perspective of the secondary side, to correspond to the current values detected by the EL CID sensor. Thus -\( I_o \) is the base for the rest of the diagram.
Figure 24  The EL CID vector diagram, including leakage flux from a core joint, and stator winding circulating current.

The final phasor component contributing to the total current detected by an EL CID sensor is the fault current \((\delta)\). i.e. the current circulating in (a) the short between laminations, (b) the laminations themselves, and (c) the short effected by building bars, and/or sometimes cooling tubes. This \(\delta\) component produces heating in the defined circuit, particularly in the relatively high resistance short between laminations. As this is a loss component, it is directed in the phasor diagram at right angles to the direction of the leakage flux inducing it. This flux is from the core, and has the same phase as the main flux \((\Phi_m)\).
4.2.5 Case 4  Stator winding present, the salient-pole rotor in situ, 
no stator core joints.

The relevant features in this case in both Figures 19 and 20 are b) and c).

The phasor diagram (Figure 25) is essentially the same as Figure 22, with the addition of the current phasor $I_R$ corresponding to the leakage flux crossing the machine air gap from the stator iron to that of the rotor. The direction of this additional phasor is parallel to the main stator magnetic flux phasor, as it is leakage from the latter. With the rotor present, allowance has to be made for the phasor $I_R$. 
Figure 25 The EL CID phasor diagram for a location remote from a core joint, but including stator winding circulating current, plus the effect of a salient-pole rotor in situ.
4.3 Justification of the various forms of the EL CID phasor diagram
A check that the phasor diagrams developed are applicable to EL CID results, as obtained for defined situations, has been detailed for several cases in Section 6.6 of Reference 1 (p. 95 et seq.).

Locations considered include: -

a) Remote from a core joint, no stator winding, no rotor present\textsuperscript{1,p.94,95}.

b) Two slots away from a core joint, no stator winding, no rotor present\textsuperscript{1,p.94,96}.

c) Two slots away from a core joint, stator winding current circulating, rotor in-situ\textsuperscript{1,p.93,97}.

d) At a core joint, stator winding current circulating and rotor in-situ\textsuperscript{1,p.91,98}.

After establishing the various forms of the EL CID Phasor diagram, they were checked that they matched appropriate plots of \textit{PHASE / QUAD} values\textsuperscript{1,24}. The phasor diagrams exhibited above are not necessarily a perfect match for the EL CID results obtained in practise, but they provide a basis and pointer for what to expect. At two slots away, a core joint, perhaps in most cases, may have very little impact upon the detected EL CID results, whereas in some cases the core joint effect can be still evident\textsuperscript{1,p.28,Fig.12} at a considerable circumferential distance from such a feature.
Chapter 5 Evaluation of \textit{delta} at a core joint

This chapter sets out the procedure for evaluating \textit{delta}, thus providing the opportunity of identifying specific interlamination insulation failure locations.

5.1 - The 1\textsuperscript{st} step in the process of evaluating \textit{delta} is obtaining the EL CID traces

EL CID signal traces are first obtained, in the form as recorded in Figure 26, as output from the computer in the EL CID set-up. Only the \textit{QUAD} trace is shown here, as the \textit{PHASE} trace is of similar form, but with much higher recorded values. To allow the scale to be increased for clarity, an offset (the so-called DC offset) from zero is selected and removed by the computer for convenience (i.e. values to be measured are reduced, but the Phase Reference is not affected).

\textbf{Figure 26}\textsuperscript{32, Fig:2} \textit{QUAD} trace at a core joint, with the DC offset removed
5.2 2nd step in evaluating delta is plotting \textit{PHASE / QUAD} points

\textit{QUAD} and \textit{PHASE} values have to be read off the traces by which to plot points on a \textit{PHASE / QUAD} diagram (Figure 27). It is necessary to decide which values to read off the traces at corresponding longitudinal positions. There are four possibilities:-

a) the actual trace, b) a minimum envelope, c) a mean curve, or d) a maximum envelope.

As discussed in Section 2.6.3.2(ii), it is considered that the variations along the traces, caused by vent ducts, arise from reduced magnetic permeance. Therefore, the deviation must be an excursion towards zero and the true value would be that given if there were no such deviations. It is argued\textsuperscript{28}, therefore, that the envelope touching the maximum values are those which are to be selected for drawing the \textit{PHASE / QUAD} diagram (Figure 27). \textit{PHASE} and \textit{QUAD} scales are the same in this Figure.
**Figure 27**  *PHASE / QUAD* plot of EL CID results adjacent to a core joint with offset removed
5.3 3rd step in evaluating delta is determining the “zero delta line”

From knowledge of the phasor diagram of Figure 24, it is recognised that the line, which touches the right-hand side of the plotted points, is the “zero delta line”. Occasionally, a difficulty arises when there are too few outstanding points to provide a confident reference for the “zero delta line”. It may be necessary to try more than one position for the “zero delta line”, but this is exceptional.

The method of determining delta for any other electromagnetic condition is the same as for this case (i.e. proximity to a core joint), except that the reference phasor diagram has to be identified appropriately.

5.4 4th step in evaluating delta is final determination of the delta value

A line parallel to the “zero delta line” is drawn in Figure 27 to touch the left hand side of the points. The orthogonal distance between these two lines gives the maximum value of delta (i.e. delta_max). A value of delta_max less than the criterion of 100mA\(^6\)p.17 indicates an acceptable condition of the intersegmental insulation. If delta_max exceeds the criterion, it is desirable to identify where the insulation is degraded (i.e. delta is high) by evaluating each individual value. This requires measurement of the orthogonal distance from each plotted P,Q point to the “zero delta line”. Such measurement appears likely to be subject to error. This is addressed in Section 7.3 (p.92).
Chapter 6 Repeatability of EL CID results after a significant interlude

6.1 Comparison of EL CID results after a 12 year interval

Figure 28 is the record of \textit{delta} values obtained in 2007 for a particular large hydrogenerator, and Figure 29 is the comparable record obtained in 1995 for the same machine.

\textbf{Figure 28} \textit{delta} values from an EL CID test in 2007 for
the same machine as Figure 29
Figure 29  \textit{delta} values from an EL CID test in 1995 for the same machine as Figure 28

It is significant that the maximum \textit{delta} value occurs at the same location along the stator core length for both tests.

The general distribution of \textit{delta} values is comparable, confirming the repeatability of an EL CID test. This is significant with regard to the use of EL CID as a condition monitor.

It might have been expected that the value \textit{delta} would have increased over a 12 year period of service, whereas the indication generally is of a reduction. Some possible reasons are judged to be that a) the core had become better
consolidated, b) the modern version of EL CID equipment may have performed with greater accuracy, c) any slight off-set of the excitation coil through the stator bore from the machine centre-line originally may have been corrected.

6.2 Further discussion of the results shown in Figures 28 and 29

It is observed that the values of \( \delta \) indicated by the analysis of \( PHASE \), \( QUAD \) values recorded over a large portion of the core length in Figures 28 and 29 are greater than the normal acceptance criterion of 100mA\(^6.p.17\). The integrity of the core insulation is not doubted, since the relevant machine has had many years of good service, without remedial attention to the core. This raises yet another problem requiring a solution in connection with EL CID.

This is discussed in Reference 26. Briefly, attention is focused upon the possible effect of the cut edges which are exposed at a core joint. Various measures have been applied by different manufacturers with a view to insulating these vulnerable lamination edges. In one case, the practise has been to apply varnish insulation to cover both the main surfaces (top and bottom sides) together with the edges. Core joint faces, however, are particularly vulnerable to the relative movement which undoubtedly occurs in service. Other manufacturers have endeavoured to protect against such movement by inserting sheets of insulation material, but experience has shown that it is very difficult to maintain these in place.

Experience indicates, therefore, that, even in a sound core, detection of higher
than normal circulating current values between adjacent laminations at core joints may be expected. This may be so, because current paths between laminations are envisaged as being well distributed along the radial edge of laminations at a joint. This is understood as follows:- There are no perfect insulators. Slight circulating current must develop along the radial depth of the stator core. Without any of this becoming unacceptable, the total may add to a greater value than is usually detected. Although the bulk of the current is buried in the radial depth of the core, it is known that EL CID can detect electric current which is quite far distant from the surface of the stator bore$^{28}$.

Determination of an acceptable criterion at core joints remains to be undertaken, but it will be shown in Section 7.6 that the lack of such a criterion is not necessarily a major difficulty.
Chapter 7 Correlation of EL CID results with a deliberately imposed fault in the interlamination insulation\textsuperscript{29,30}.

This is the culmination of the candidate's work being submitted, with a view to greater general understanding of the EL CID technique, giving increased confidence in using and accepting its results.

References 29 and 30 are the published results of the analysis of EL CID test results at a core joint, where a fault had been deliberately created in the interlamination insulation. Both papers are identical except for their titles. Subsequent to the publication of Reference 29, it was regarded by the editorial staff of Dam Engineering, who claim only to publish “International papers of technical excellence”, as appropriate for them to request permission to include Reference 28 in their journal. The candidate agreed\textsuperscript{30}.

Although Chapters 5 and 6 give actual values for EL CID results, these can only be used as an indication of their validity, since the core condition was not known absolutely. The results evaluated in this section actually pinpoint where a fault had been deliberately imposed.

The opportunity for this exercise arose from the work reported by Paley et al\textsuperscript{31}. As 4 inches of the upper end laminations of the core of the machine concerned were due to be replaced, after an HFRT check, artificial faults (by screw compression of a short copper strip into the laminations\textsuperscript{31}) were imposed in
selected locations, prior to an EL CID test. The results showed good correlation between fault locations identified by EL CID, and the known locations, except at core joints. The report in Reference 31 stated that EL CID results at core joints were *useless* due to the disturbed electromagnetic conditions produced by the small air gap inherent at a core joint.

It seemed most appropriate, therefore, as a final confirmation of EL CID as a valid technique, to analyse the results, which fortunately were available in Reference 30. The several steps in this task are basically the same as those in Chapter 5, as briefly repeated below, plus an extension.

### 7.1 1st step of the analysis, i.e. obtain corresponding P & Q values

At corresponding distances along the stator core trace axis, mark off ordinates to the recorded *PHASE* and *QUAD* traces (Figure 30) to obtain corresponding *PHASE* and *QUAD* values. Tabulate these on a spreadsheet. Note: the original caption above Figure 30 labelled the *QUAD* results *incorrectly* as “unusable”.

### 7.2 2nd step of the analysis, i.e. plot PQ points

Plot the tabulated points on a *PHASE / QUAD* diagram (Figure 31). The appropriate values are determined as discussed in Sections 3.1.4. and 5.2. In view of a procedure introduced to enhance accuracy\(^3\), it is desirable to rotate the QUAD axis clockwise through 180°, and then the whole diagram through 90° clockwise\(^3\). This brings the QUAD axis to be vertical on the page.
Figure 30  PHASE and QUAD traces from EL CID test at joint slot 120 after insertion of an artificial fault (Reprinted from Reference 31, also 29 & 30)

7.3 3rd Step of the analysis - Determine the “zero delta line”

From the various alternatives of the phasor diagram, Figure 24 is identified as appropriate. The “zero delta line” is determined accordingly. The accuracy of
the determination of $\text{delta}$ depends upon two factors: i) the location of the “zero $\text{delta}$ line”, ii) the accuracy of measurement of the distance (i.e. the length of a “$\text{delta}$ line”) of the relevant P/Q point from the “zero $\text{delta}$ line”. When equal P and Q scales are used, $\text{delta}$ values are given by the orthogonal distance from a given P / Q point to the “zero $\text{delta}$ line”.

Since P values are so much greater than Q values, it can be seen that error may be introduced in determining the length of the $\text{delta}$ line, both regarding the position of the “zero $\text{delta}$ line” and the measurement of the $\text{delta}$ line itself. In order to achieve maximum accuracy, a special routine was developed as reported initially in Reference 32, and repeated substantially in References 29, 30 & 33. This involves increasing the scale for plotting $\text{QUAD}$ values, as shown in Figures 31, for which, as mentioned above (p.91), it is most convenient to have the QUAD axis vertical on the page. This is to suit computer work.

Two benefits accrue from this technique: a) The “zero $\text{delta}$ line” can be located more accurately. b) The length of the $\text{delta}$ lines can be measured more precisely.

For clarification, Figure 31 is repeated in Figure 32, with the same orientation of the axes.
Location of the “zero \textit{delta} line” is initially with reference to the plot of \(P/Q\) values (Figure 32) with the enhanced QUAD scale. It can then be readily transferred to refer to the plot of \(P/Q\) points \textit{with equal scales}, by proportioning the position of the “zero \textit{delta} line” according to the different scales. If the new “zero \textit{delta} line” does not have a good fit with the plot of \(P/Q\) values with equal scales, it is necessary to adjust the position relative to the plot of \(P/Q\) values having an enhanced QUAD scale.
7.4 4th Step of the analysis. Determining delta values

The next problem is to determine the direction of the delta lines, since it is not the simple matter of drawing lines orthogonally to the “zero delta line”. The method of compensating for unequal PHASE and QUAD scales originally set out in Reference 32, repeated in References 29, 30 & 33, involves construction of trapezoid AA'BB' (See Figure 32). Briefly, the starting point is A on the “zero delta line” for the P,Q points with the increased Q scale. The line AA' is drawn parallel to the QUAD axis to A' on the “zero delta line” for P,Q points having equal scales. The line A'B' is then drawn orthogonally between the boundary lines for the P,Q points having equal scales. From B', a further line is drawn parallel to the Q axis to cut the boundary line of the P,Q points with the increased Q scale at B. The line BA provides the required direction of the “delta lines”, i.e. the lines from which the magnitude of delta values are derived.

The required delta values are evaluated from the length of the “delta lines” drawn from each P,Q point to the “zero delta line” in the direction determined.

There are alternative ways of making this measurement:-

i) direct ruler measurement and a simple division by the increased QUAD scale factor, This is useful for achieving a quick result.

ii) use of endpoints given by the computer grid, plus application of the Pythagoras theorem, and then simple division by the QUAD scale factor, Theoretically slightly better than i) above, but no real difference in practice.

iii) as ii), except for division of the QUAD values by the scale factor before
applying Pythagoras. This is the most accurate measurement of \textit{delta}.

\textbf{Figure 32.} Plot of \textit{PHASE} and \textit{QUAD} values with delta lines added

\textbf{7.5} Identify the location of a pre-established fault at a core joint

The result of the determination, by all three methods set out above, of \textit{delta} values for this case of a pre-established interlamination insulation fault at a core joint, is plotted in Figure 33. The pronounced spike of \textit{delta} values is located
less than 2½% of the core length different from the reported 4 inches (approximately 100 mm) from the top of the stator core. But it is not known how precise the reported 4 inches was. It is noted that conversion alone from inch units to mm incurs over 1% difference. Moreover, from other EL CID traces in Reference 31, there is doubt regarding the consistency in the length of trace, which puts doubt on the exact correspondence of the length of trace with the core length. It is considered, therefore, that Figure 33 clearly identifies the position of the deliberately imposed interlamination insulation fault. This demonstrates, when the method is adequately understood, the validity of the EL CID technique in this most difficult of electromagnetic field situations,
Figure 33  Variation of \( \delta \) along the length of the core at a joint slot
7.6 Further discussion of the results shown in Figure 33

It is observed that the $\text{delta}$ values generally in Figure 33 are significantly higher than the normally acceptable criterion of 100mA$^{6, p.17}$. This feature of core joint EL CID results was discussed in Section 6.2. The important factor in the assessment of EL CID results at core joints, therefore, is the distribution of $\text{delta}$ along the core, i.e. in the longitudinal direction.

Whilst it is evident that there is significant degradation of the interlaminar insulation where the fault was deliberately imposed, the question arises regarding the integrity elsewhere as values of about 400mA are observed. But it had already been concluded that such values might be expected$^{26}$ at core joints. Also, no data is recorded regarding the condition of the interlaminar insulation other than in the upper part of the vertical core. Since, however, after the HFRT check, remedial action was only considered necessary for the top 4 inches, the indication is that the condition of the remainder was judged to be adequate.

It is concluded that EL CID is well able to identify stator core interlaminar insulation degradation in every situation for a salient-pole machine, as well as for round rotor machines.
Chapter 8 PHASE reference reset

8.1 The need for Phase reference reset

In the early days of applying EL CID, relatively high values encountered at core joints promoted the practise of resetting the PHASE reference. The motive for this is clearly illustrated by Figure 34 where the QUAD values are very much less than in Figure 31. But the magnitude of QUAD values at core joints is not a problem for the modern version of EL CID equipment. That is not to be confused with removal of the “DC” value (See Figure 31), which is a built-in feature of the modern EL CID package.

![QUAD values with 25° Phase reset for joint slot 120](image)

**Figure 34** QUAD values with the PHASE reference reset for the case analysed in Chapter 7

(Note: “Calc: QUAD with 25° Phase reset” values are calculated, assuming 25° Phase reset, from QUAD signals recorded without Phase reset. And “QUAD with 25° Phase reset published” values are as published with an unrecorded degree of reset, but deduced from other information to have 25°.)
8.2 The consequence of resetting the PHASE reference

It is immediately evident, from Figure 34, that the plotted PHASE / QUAD values do not identify the location of the artificial fault, when the PHASE reference is reset. The significance of the QUAD values has been lost. In general QUAD values in themselves are clearly insufficient for fault identification. Only in the circumstances for which Figure 21 applies (i.e. no core joint, stator winding or rotor) would the QUAD values be approximately significant themselves.

If, for some reason, it should be considered necessary to reset the PHASE reference when making an EL CID test, then the values obtained need to be referred back to the basic axes\(^1\) p.103. This can be readily achieved using the appropriate geometrical equations\(^3\) p.88.

8.3 Further examples, of “delta” evaluation, for which the PHASE reference is reset and also when not reset

It is demonstrated below that if EL CID results, obtained with PHASE reset, are not referred back to the basic axes, the result will be delta values which are inaccurate, and/or their distribution distorted along the length of the core.
8.3.1 “*delta*” evaluation at a stator core location remote from any core joint, with no stator winding in the core and no rotor in-situ.

**Figure 35** (Figure 3 of Reference 34) *PHASE/QUAD* plot of EL CID results for a slot remote from a core joint, with no stator winding in the core and no rotor in-situ

In Figure 35, as identified in Reference 34, the theoretical zero delta line is the PHASE axis. It is evident that there is an offset from the theoretical zero delta line. The reason is not known, although discussed in Reference 34, where it is not considered significant. Evaluation of \( \text{deltamax} \) is derived, for no PHASE Reset, by subtraction of the offset (i.e. the minimum *QUAD* value) from the maximum value. Evaluation of \( \text{delta} \) throughout the core length is obtained similarly by subtracting the offset value from each of the *PHASE/QUAD* points.
The result is displayed in Figure 36 by the red line.

The effect of resetting the PHASE axis is investigated by drawing a PHASE Reset axis through the estimated centroid of the group of PHASE/QUAD points produced by the EL CID test. Although results from an EL CID test with the PHASE reference reset were not obtained directly, they were simulated by taking the angle ($\theta$) by which the PHASE reference was reset, and calculating revised $\Delta_{\text{reset}}$ values from the equation derived as follows:-

$$\Delta_{\text{reset}} = LM \cos \theta$$

$$\Delta_{\text{reset}} = (KM + KL) \cos \theta$$

$$\Delta_{\text{reset}} = KM \cos \theta + (OK - OJ) \tan \theta \cos \theta$$

$$\Delta_{\text{reset}} = KM \cos \theta + (OK - [a / \sin \theta]) \tan \theta \cos \theta$$

$$\Delta_{\text{reset}} = Q \cos \theta + P \sin \theta - a$$

where $P$, $Q$ and $\theta$ are referred to the basic axes, and $a$ = the orthogonal distance between the PHASE reset axis and the parallel line enclosing the minimum $P$, $Q$ points. The result is displayed by the green line in Figure 36. This provides the results for a further example of evaluation of $\Delta$, both when the PHASE reference is reset and when not reset.
Figure 36 [Figure 4 of Reference 34] Comparison of delta values with and without PHASE reference reset

For the most part of the core length, Figure 36 shows that there is close agreement between the $P_Q$ points for which the PHASE reference is not reset and also for which it is reset. But in part of the core there is significant difference. This is undoubtedly due to the choice of reset angle ($\theta$), which indicates that there is an inherent weakness involved in resetting the PHASE reference.
8.3.2 “delta” evaluation close to a stator core joint, with both stator winding and rotor present, and no PHASE reference reset

Results for this situation are plotted in red in Figure 36.

![Figure 36](image)

**Figure 37** (Figure 5 of Reference 34) PHASE/QUAD plot of EL CID results for a slot near to a core joint, with both stator winding and rotor in-situ

Evaluation\(^{34}\) of \(\delta_{max}\), including that by application of the procedure described in Chapter 7 (i.e. introducing an increase in the QUAD scale) produces \(\delta_{max}\) values as in table 2. The several steps involved are set out below.

a) (i) The first step (before introducing unequal scales) is to establish the "zero delta line" for \(\text{PHASE}(P), \text{QUAD}(Q)\) points plotted on axes having equal P and Q...
Q scales. From this "zero delta line", the parallel line embracing the largest "delta" value can be drawn.

(ii) In many cases the plot of $P,Q$ values will readily indicate where the "zero delta line" is to be found and drawn. If this is not the case, it is necessary to consider which phasor diagram applies. Typical cases have been illustrated in various publications, particularly Reference 1. Not all cases are covered, of course, which possibly necessitates the creation of a new version by considering how the case under consideration may be expected to modify the nearest existing example. It may be necessary, however, to return to basic principles, with occasional reference to someone of greater experience.

(iii) The case in hand is not fully covered already by any published phasor diagram, but the starting point is considered to be that of Figure 25. Account is taken there of stator winding circulating current, and the presence of a salient-pole rotor, it is, however, remote from a stator core joint. The proximity of a core joint introduces further leakage flux, which is in the same direction as the flux leaking from the stator to the rotor. But the influence of core joints does not usually extend very far. Hence, Figure 25 essentially includes all the phasor components required for the case under consideration, with some change in the magnitude of the phasor $I_r$.

The phasor diagrams are not produced to scale, therefore, it is permissible to
assume a diagram essentially similar to Figure 25. That view might need reconsideration in the light of actual $P,Q$ values obtained from EL CID signal records.

(iv) In this instance it is evident from the Plot in Figure 37 of $P,Q$ values that the above view is valid. The $P,Q$ values plotted as "red" points are those obtained directly from the EL CID output, plotted with equal scales.

b) In order to check for possible error in locating the "zero delta line", the routine of increasing the Q scale is employed. The subsequent $P,Q$ points are plotted in Figure 36 as "green" points. It is evident that a line can be reasonably applied to the upper points nearest to the PHASE axis, which is the relevant "zero delta line" as already defined by Figure 25. It is identified from the plot of the "green" points for greatest clarity of its position, and is then transcribed to lie with reference to the "red" points by proportionality, taking account of the increased Q scale.

The validity of the chosen "zero delta line" is confirmed by it lying in the same proximity to the "red" points, as it did when applied to the "green" points.

c) As identified in a) above, the parallel line to embrace the largest "delta" value is drawn relative to the "zero delta line" produced by either set of $P,Q$ points.

d) By identification in the basic EL CID phasor diagram, for equal $P$ and $Q$
scales, the length of the line drawn orthogonally from the "zero delta line" to any particular P,Q point represents the relevant value of delta for that axial location along the stator bore.

e) With reference to the plot of P and Q values for which the scales are unequal, it is evident that delta lines are not orthogonal to the "zero delta line". It is necessary, therefore, to deduce the angle required. The candidate has evolved and published a routine in Reference 32, and incorporated into References 29 and 30, whereby the required direction of the delta lines can be determined.

In Figure 37, the orthogonal direction, identified by line $A'B'$, applicable when equal scales are used, is converted by the routine mentioned above to line $AB$. After establishing the direction of one delta line, those for all other P,Q points, plotted with unequal scales, are given by lines parallel to $AB$.

f) The value of $\delta_{\text{max}}$, or, in fact, delta for any P,Q point, may be determined finally by five ways, as identified below.

i) A ruler measurement of the delta line. In the case of the plot of P,Q points with equal scales, the $\delta_{\text{max}}$ line is the orthogonal line between the "zero delta line" and the parallel line embracing all points. “delta” for individual points is obtained by measuring the relevant orthogonal distance to the "zero delta line".
ii) A ruler measurement of the length of \textit{delta} lines constructed as referred to above, (Section 8.3.2e), with increased QUAD scale. This line is not orthogonal to the two parallel lines. Division of this measurement by the QUAD axis scale factor provides a value of delta, which is slightly approximate. See below in \textit{v}).

iii) Accurate ruler measurements are difficult. Therefore, it is better to use the computer grid to determine the end points of a particular \textit{delta} line for the plot of P,Q values using equal scales, and then calculate the length using the Pythagoras theorem.

iv) The same technique of measurement as in iii) above may also be applied to \textit{delta} lines obtained from the plot of P,Q values involving an increased QUAD axis scale. A value of delta is then obtained by dividing by the QUAD axis scale factor, as in ii) above, with the same caveat.

v) In later papers\textsuperscript{29,30}, it was clarified that, strictly, the \textit{QUAD} value of the end points of the delta line should be divided by the scale factor, before being combined with the corresponding PHASE values using the Pythagoras theorem.

It has been found that the values of delta obtained by the different methods are not greatly different. In a particular case the variation was only +2.4\% to -3.8\%. 

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Table 2 Summary of the evaluation of \( \delta_{\text{max}} \) by the methods identified in Section 8.3.2 without applying PHASE reference reset.

<table>
<thead>
<tr>
<th>Method</th>
<th>“( \delta_{\text{max}} )” in mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruler measurement of AB</td>
<td>164.91</td>
</tr>
<tr>
<td>Ruler measurement of A‘B’</td>
<td>174.47</td>
</tr>
<tr>
<td>Grid determination of AB</td>
<td>164.26</td>
</tr>
<tr>
<td>Grid determination of A‘B’</td>
<td>174.82</td>
</tr>
<tr>
<td>Calculation for A‘B’</td>
<td>170.68</td>
</tr>
</tbody>
</table>

8.3.3 Close to a stator core joint, with both stator winding and rotor present, and PHASE reference reset applied

The choice of the PHASE reset angle is a matter of opinion. It is normally chosen so that the revised axis passes through the region where it is thought that \( \delta \) will be least, after a preliminary scan. This is difficult to determine, and in Figure 37 it so happens that the PHASE reset axis passes through the location along the core where \( \delta \) is a maximum. Inspection of Figure 37 indicates that, without referring the PHASE reference back to the basic axis (assuming...
that it had initially been obtained with the PHASE reference reset), the value of \textit{delta} indicated by the lines parallel to the reset axis is 295.3mA, which is far different from the values in Table 2 above.

It is evident, therefore, that resetting the PHASE reference, without referring the results back to the basic axes, produces an incorrect analysis, indicating that the magnitude of fault circulating current (\textit{delta}) and its distribution along the longitudinal length of the core is distorted.
Chapter 9  Conclusions

9.1 The original need for EL CID

A major rise in the specific rating of large steam-turbine-driven round rotor generators in the 1970's due to the introduction of direct-water-cooling resulted in a severe increase in the electrical stress on the stator core interlamination insulation. Due allowance for this was not always incorporated in new generator designs, leading to failure of the insulation.

An urgent need arose for a means of checking the effectiveness of remedial work on stator cores subjected to such failures, which would be less time consuming than the traditional High Flux Ring Test (HFRT). The Central Electricity Research Laboratory (CERL), the research arm of the British Central Electricity Generating Board (CEGB), was tasked to develop such a new facility, with the result that John Sutton, a physicist on the staff of CERL, invented an Electromagnetic Core Imperfection Detector (EL CID)\textsuperscript{3}, which was a much simpler and easier means than HFRT.

9.2 Problems arising when EL CID was applied to hydrogenerators

The success of EL CID in its initial application to turbo-generators naturally promoted the idea of its application to water-turbine driven salient-pole
generators, and similar large machines. This was demonstrated, with considerable success on an appropriate machine in the manufacturer's factory. The only indication of a problem was extremely large signals arising from encounter at the core joints with a major disturbance of the electromagnetic field, although not due to fault conditions. The suggested solution at the time was to move the reference coil to the core joint, in effect resetting the Phase axis.

When EL CID was subsequently applied on site, the core joint problem was again encountered, and the resultant signals were not reduced to acceptable proportions by the recommended tactic. This remained a major stumbling block causing wide spread lack of trust in the reliability of EL CID in the hydro-electric field, and subsequent discarding of EL CID in that context.

EL CID continued to be used on hydro-electric machines as a valuable monitoring device for the major part of their stator cores. There were, however, other EL CID result phenomena encountered :-) generally higher readings than appeared justified, traces of the EL CID output exhibited a slope, sometimes a curvature of the axis, plus unexpected and initially alarmingly high values at the ends of the stator core.
9.2.1 Solution of problems due to the form of excitation winding

Since it was usually required that the rotor was removed for access when remedial work was in hand, the form of the excitation winding for EL CID applications to turbo-generators was generally a group of turns down the centre-line of the stator (i.e., Figure 5c), necessarily passing over the core ends. Although this is applicable to hydro-generators when major refurbishment is being undertaken, in general an alternative is desirable, particularly if the object is primarily to establish a “footprint” of the core condition, i.e. a reference when carrying out subsequent comparative checks.

But each method of applying the excitation winding has presented problems which require understanding in order to eliminate their impact. Appropriate solutions have been demonstrated in this record of the candidate's investigations. Briefly:-

i) the required mmf should be calculated in terms of trace turn voltage;

ii) a note should be made of environmental factors likely to cause electromagnetic disturbance (e.g., operational state of nearby machines, magnetic materials in the area, the test machine's constructional features, including its state of erection);

iii) form 5c cable in the bore should be carefully aligned to the stator axis;

iv) the distance from the core ends should be not less than 1 metre, if possible;
v) an adequate distance should be maintained for the EL CID sensor from excitation turns.

### 9.2.2 Counteracting the pole-proximity effect

If the salient-pole rotor of a hydrogenerator is in-situ, removal of one, or possibly two poles may be necessary to provide access for the EL CID operator. In some cases, adequate physical access is available without removal of poles. The presence of salient-poles always has some “pole-proximity effect”, i.e. curvature of the EL CID trace axis, although for some configurations the effect may be slight. To minimise this, an adequate distance from the side of nearby salient-poles is required. Mainly, it is important to recognise that the effect may be present.

### 9.2.3 Analysis of the electromagnetic field at the stator bore

Originally, only a very simple vector diagram, comprising two orthogonal components, was proposed for the electromagnetic field arising from establishing a circumferential magnetic field in the stator iron, and the presence of circulating current between adjacent laminations due to imperfection of the interlamination insulation. The phasor components, known as **PHASE** and **QUAD**, were understood to represent the excitation mmf and the fault current, respectively.

Whilst such a simple phasor diagram was adequate, although not perfect, for EL
CID results from turbogenerators, it was soon evident that it did not represent the situation for hydrogenerators. The original phasor conception required development to a more complex approach. This was provided by regarding the EL CID set-up as a transformer with one or more shorted secondary windings. Whilst one basic phasor diagram was identified, several versions were developed to cater for different situations. One of these very importantly covered circulating current in the stator winding, if present and short-circuited. Other versions allowed for flux leakage between the stator and rotor. Perhaps most importantly, allowance was made for the leakage flux at stator core joints. This permitted the derivation of a solution of the problem encountered at core joints in the original application of EL CID to hydrogenerators having stator cores constructed from more than one part, as required for transportation.

### 9.3 Overall conclusion

The work described in this thesis covers a wide range of situations which originally were not understood, and resulted in loss of confidence in the EL CID technique for hydrogenerators as an adequate core condition monitor, although useful for checking the adequacy of remedial work, other than at core joints.

Importantly, every known electromagnetic situation at the stator bore has been encompassed satisfactorily. The EL CID results have been reasonably correlated with those produced by the HFRT, although more work in this context would be
useful. It is considered that for absolute confidence in the core insulation condition as acceptable it should, in general, meet the 100mA criterion, except at core joints.

At core joints the circulating current evaluated is usually substantially greater than the normal acceptance criterion. Reason for this has been shown. Therefore, it is not considered essential that the actual value should meet the standard criterion. It has been demonstrated that the vital aspect of the circulating fault current, more than its absolute value, is its distribution along the length of the core. This outcome of the work by the candidate is a most important conclusion.

It is recognised that at core joints, an immediate analysis of EL CID results is not readily available, but the importance of taking time to achieve this should be seen as well worthwhile.

Finally, EL CID may be applied as a monitoring tool, not only as a check on interlamination core insulation deterioration due to normal service, but also after application of a quality control high voltage impulse test on a coil component of the stator winding. Sutton has shown\textsuperscript{35} that such a test may apply a very high electric field to the stator core laminations at the bottom of a slot. This emphasises the need for high quality insulation of stator core laminations subjected to impulse testing. The reliability of EL CID in this context is clearly
of first class importance. It should be noted that Sutton's paper has restricted access, but the candidate had approval to reproduce a version of it as Appendix 8.1 in his book\textsuperscript{1}. 
Thesis References


pp 32-37.

30. Ridley, G. K. "Correlation of EL CID results with a Stator Core Joint Interlamination Insulation Fault, Dam Engineering, October 2014, Vol: XXV, pp 3-17. [Full paper attached as Appendix 14]


Author's Bibliography (additional to Thesis References)


Appendices

Appendix 1 - The magnetic field induced by a toroidal coil around the core

![Diagram of a toroidal coil with flux paths labeled C, C', H, H', R, r]

Figure 38 Arrangement of excitation winding as in Figure 5b

A homogeneous annular steel ring of inner radius \( R_i \) and outer radius \( R_0 \) is magnetised by a closely wound toroidal coil of \( N \) turns (i.e. the successive turns are close to each other) carrying \( I \) amperes. Flux paths in the steel are identified in length by the letter \( C \), with an appropriate subscript, and in radial location by the letter \( r \), with a corresponding subscript, i.e. \( C_1, r_1 \); \( C_2, r_2 \); etc. Flux paths in air are identified in length by the letter \( C \), with an appropriate superscript, and in radial location by the letter \( r \) with a corresponding superscript, i.e. \( C', r' \); etc.

1. Considering flux paths \( C_1, C_2, C_3 \), within the steel core, which are all
linked by the excitation winding having \( NI \) ampere-turns, then

By Ampère's law, \( NI = \oint_C H \cdot ds \)

Thus \( NI = \oint_{C_1} H_1 \cdot ds = \oint_{C_2} H_2 \cdot ds = \oint_{C_3} H_3 \cdot ds \)

\[ H_1 \cdot 2 \pi \cdot r_1 = H_2 \cdot 2 \pi \cdot r_2 = H_3 \cdot 2 \pi \cdot r_3 \]

Hence, \( H_2 = H_1 \frac{r_1}{r_2} \) and \( H_3 = H_1 \frac{r_1}{r_3} \)

If \( R_1 \) and \( R_0 \) are great compared to \( (R_0 - R_1) \),

\[ H_2 \approx H_3 \approx H_1 \approx H \text{ (say)} \]

2. Considering a flux path \( C' \) internal to the annulus, it is seen that it does not link any current,

therefore \( \oint_{C'} H' \cdot ds = 0 \),

and \( H' = 0 \)

3. Considering a flux path \( C'' \) external to the annulus, it is seen that it links equal and opposite values of \( NI \),

therefore \( \oint_{C''} H'' \cdot ds = 0 \)

and \( H'' = 0 \)

4. It is shown by Carter\(^{20}\), that both \( H_4 \) and \( H_5 \) are small in comparison to \( H \).
This implies that the magnetic field is principally circumferential and other components may be neglected.
Appendix 2 - The magnetic field set up by a concentrated coil along the core Axis.

Figure 39 Arrangement of excitation winding as in Figure 5c

Application of Ampère's Law (alternatively known as the Magnetic Circuit Law) to the path \( C_1 \) in a homogeneous annular iron ring gives

\[
NI = \oint_{C} H_s \cdot ds
\]

\[
= H \cdot 2 \cdot \pi \cdot r
\]

Therefore \( H = \frac{NI}{2 \pi r} \)

The value of \( H \) is given everywhere by the above equation, whether within or outside the iron core. But the Flux Density \( B \) depends upon the permeability of the medium, which is much greater for iron than for air. Thus, a relatively high flux density is induced in the iron compared to that produced in the air.
Appendix 3 - Calculation of EL CID trace turn voltage

Let $\Phi$ = sinusoidal circumferential flux induced in an annular stator core

$$= \Phi_m \cdot \sin (2 \cdot \pi \cdot f \cdot t)$$

where

$\Phi_m$ = maximum value of the above flux in Webers

$f$ = frequency in Hz of sinusoidal variation

$t$ = time in seconds

Then, the voltage induced in a turn round the stator core, enclosing the above cyclic flux, is given by Faraday's Law as:

$$V_t = \frac{d\Phi}{dt} = -2 \cdot \pi \cdot f \cdot \Phi_m \cdot \cos (2 \cdot \pi \cdot f \cdot t)$$

The r.m.s. value is:

$$v_t = \frac{2 \cdot \pi \cdot f \cdot \Phi_m}{\sqrt{2}} = 4.44 \cdot f \cdot \Phi_m$$

since $\Phi_m$ is in Webers.

However, $\Phi_m = \Phi_a / 2$ (that is, flux per pole crossing the air gap divided by two)

therefore:

$$v_t = \frac{\pi \cdot f \cdot \Phi_a}{\sqrt{2}} = 2.22 \cdot f \cdot \Phi_a$$
Appendix 3 - Calculation of EL CID trace turn voltage (Cont:)

For 4 per cent of normal flux crossing the air gap, the EL CID trace turn voltage is equal to:

\[ 0.0888 \ f \ . \ \Phi_a \ \text{volts r.m.s.} \]
\[ 4.44 \ . \ \Phi_a \ \text{volts r.m.s. for } f = 50 \]
\[ 5.33 \ . \ \Phi_a \ \text{volts r.m.s. for } f = 60 \]

But electrical machine air gap flux (\(\Phi_a\)) in Webers is given as:

\[ \Phi_a = \frac{V_L}{\sqrt{3}} \cdot \frac{1}{4.44 \cdot K \cdot T_{ph} \cdot f} \]

where,

\(V_L\) = Rated Line Voltage (Y connected),

\(K\) = Combined spread and chording factor of the winding

\(T_{ph}\) = Series turns per phase

Therefore, at 4 per cent flux,

\[ v_T = 0.0888 \ f \cdot \frac{V_L}{\sqrt{3}} \cdot \frac{1}{4.44 \cdot K \cdot T_{ph} \cdot f} \]

\[ v_T = 0.04 \cdot \frac{V_L}{\sqrt{3} \cdot K \cdot 2 \cdot T_{ph}} \]

as given in the EL CID Handbook.
Appendix 3 - Calculation of EL CID trace turn voltage (Cont:)

Note: If $V_L$ is in kilovolts, and a typical value of $K$ of $1/1.08 = 0.926$ is adopted, then

$$v_t \approx 12.5 \left[ \frac{V_L}{T_{ph}} \right]$$
Appendix 4 - The effect of the excitation cable crossing the core end.

Figure 40 The field of an electrical current in the presence of an iron block

The problem is to determine the flux density at the surface of a steel block arising from the field of current in a straight conductor above and parallel to the steel surface.

Point A, in Figure 39 above, identifies the position of a conductor carrying current I at a distance AC = a, above the surface of a block of steel.

The solution is obtained by application of the proposal given in Reference 20, pages 141 and 142. This comprises the use of an image current. In this, the steel block is replaced by a second conductor located at Point B, at a distance BC = a, directly below Point A, and carrying current I, which produces an equipotential plane of corresponding position to the original iron surface.
Appendix 4 - The effect of the excitation cable crossing the core end. (Cont:)

Applying Ampère's law to any Point P, distant \( r \) from Point A,

\[
I = \oint_c H_s \cdot ds
\]

\[
I = \oint_{2\pi r} H_s \cdot ds
\]

\[
= H_{AP} \cdot 2\pi r
\]

Therefore, \( H_{AP} = \frac{I}{2\pi r} \)

Hence, at any Point Q on the steel surface,

from current I at Point A, \( H_{AQ} = \frac{I}{2\pi r} \)

and from current I at Point B, \( H_{BQ} = \frac{I}{2\pi r} \)

It is shown in Reference 20, that the Magnetising Force \( (H) \) is perpendicular to the radius joining the current carrying conductor to the point of observation (i.e. Q), and in accordance with a right-handed screw rule relative to the current direction.

From geometrical considerations, it is clear that both \( H_{AQ} \) and \( H_{BQ} \) are inclined at an angle \( \phi \) to the steel surface.

Thus, the resultant magnetising force at Point Q is \( H = \frac{2I\sin\phi}{2\pi r} \)

\[
= \frac{I\sqrt{r^2 - a^2}}{\pi r^2}
\]
Appendix 4 - The effect of the excitation cable crossing the core end. (Cont:)

and, the required Flux Density $(B) = \eta_0 \, H$

\[
i.e. \quad B = \frac{\eta_0 \, I \sqrt{r^2 - a^2}}{\pi} \cdot \frac{10^4}{r^2}
\]

where $\eta_0 = \text{the primary magnetic constant} = \frac{4 \pi}{10^5}$

in the rationalised MKS system.

Consequently,

\[
B = \frac{4 \, I \sqrt{r^2 - a^2}}{10^7} \cdot \frac{10^4}{r^2}
\]

where $B$ is in weber per sq: metre, $I$ is in amperes, $r$ and $a$ are in metres.

It is clear from the above formula for $B$ on the iron surface, that

1. when $r = a$, then $B = 0$, and

2. when $a = 0$, then $B = \frac{1}{10^7} \cdot \frac{4 \, I}{r}$

The above general expression for Flux Density $(B)$ is plotted for several values of “$a$” in Figure 7
Appendix 5 - An independent assessment of the candidate's work

A "Book Review" by Professor Zlatanovici and published in “Hydropower and Dams” Issue 1, 2008.

The third edition of G.K. Ridley’s book “EL CID – Application and Analysis” represents a complete revision compared with the previous two. The book deals with the very particular field of determining the magnetic stator core condition of rotating electrical machines, using the method of low flux density: about 4 per cent of the rated flux density. The author has made an important contribution to the development of this method, which is already widely known as the EL CID method.

In the first part of the book (chapters 1 to 4) the basic principles and practical application of EL CID are presented, including the factors which influence test results. Some test results and a comparison with the classical high flux ring test (HFRT) are also given. In the second part (chapters 5 to 7), the theoretical fundamentals of the method are presented, and in the third part (chapters 8 to 9), details are provided about why, where, when and how to use the EL CID method.

In this third edition of the book, starting from the theoretical basis developed in the previous editions and having an extensive experimental base consisting of...
results from tests carried out on various types of generators, the author presents in the 6th chapter a new theoretical approach. This is based on a complete vector diagram, including all the electro-magnetic phenomena accompanying the EL CID test. To develop this complete vector diagram, the author presents the analogy of the EL CID phenomena with those existing in a transformer having one or more secondary circuits. The author applies standard transformer theory, and considers the basic electromagnetic theory of the magnetic flux induced in the stator core, the flux leakage at joints built into the core, the current induced in a fault path caused by degradation of the interlaminar insulation and, if present, the current induced in the stator winding. Fault current and, when present, stator winding circulating current, are thus both seen to be induced in secondary circuits of the equivalent transformer.

The author focuses attention particularly on the phenomena in the region of the core joints. Application of the vector diagram in the core joint zones, such as presented in the 6th chapter, is now very importantly able to explain fully the results obtained from EL CID tests. The vector diagram contributes to a comprehensive understanding of all other phenomena appearing in the EL CID tests, arising from variable conditions of the core, both along its length and around its circumference, and also caused by perturbations provoked by the
measuring system itself. This full understanding of all phenomena is the necessary basis for a correct assessment of the stator core condition.

Another very important contribution of the vector diagram developed by the author is the inclusion of a component representing leakage flux between the stator and a salient-pole rotor, when the test is carried out without complete removal of the rotor, or at least of only a couple of poles.

In conclusion, by the procedures now incorporated in this third Edition, it is now possible to solve that most difficult case of stator core condition: the one encountered at a core joint. This is a most important contribution, and one for which users of EL CID have waited a long time. I consider that the book is of a high level, both scientifically and in practical application, explaining all of the phenomena and their theoretical justification, which proves the superiority of the EL CID method and contributes to its generalization. - Prof. Dan Zlatanovici, Scientific Secretary of Icemenerg, Bucharest, Romania.
Appendix 6  Extracts from References and Bibliography in IEEE


(Permission given on 12.02.17 by G. Mottershead, P1719 Working Group Chairman)

F4.7 References include:


F.4.7 Bibliography includes:


[B5] Ridley, G.K., EL CID - Application and Analysis, Ed: 2, ADWEL
International Ltd., 2004

Appendix 7 – Correspondence

A communication in 2010 in support of a nomination (unsuccessful) as Fellow of the IEEE from Prof. Dan Zlatanovici (deceased), formerly Scientific Secretary of Icemenerg, Bucharest, Romania. [Original held by Mrs Rodica Zlatanovici, Professor Zlatanovici’s widow and former professional colleague as Head of Electrical Machines in Icemenerg]. Mrs Zlatanovici is one of the two referees required by the University of Warwick for this submission.

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In 1994 I assisted at a test on a large turbo-generator (330 MW, Rovinari - Romania), performed with the instrument called EL CID, used to detect stator core defects. Then, I read some of the Mr. Ridley’s papers in international journals or conference proceedings, dealing with this subject. As a result, the EL CID method was accepted in Romania instead of the classical method.

In 2000 I met Mr. Ridley personally at a CIGRE meeting in Paris and after that and till today we had a constant change of opinions and information about this subject.

"I read almost all Mr. Ridley’s papers and the 3 editions of his book “EL CID – Application and Analysis” and I see the progress made by the author in understanding and explaining all the phenomena appearing in the EL CID tests, arising from variable conditions of the core, and also caused by perturbations provoked by the measuring system itself."
The book entitled “EL CID – Application and Analysis” 3rd Edition July 2007 is a comprehensive record of the theory and practice of the electromagnetic technique for assessing the condition of stator core inter-lamination insulation in large electrical machines, with particular reference to hydrogenerators. The book represents an extraordinary development beginning from the theoretical base and finishing with practical application in the field.

The application of EL CID for the analysis of the condition of interlamination insulation of stator cores, particularly for the more difficult case of hydrogenerators, recorded in Mr. Ridley's numerous papers & his book, entitled “EL CID - application and analysis” has been pursued entirely independently. This body of work is not known to be paralleled elsewhere, and is, therefore, a unique contribution to engineering literature. Most recently, the determination of absolute values of interlamination fault current at core joints, reported in papers published in 2008 and 2009, has been a major advance, and has solved a long standing problem. Mr. Ridley is the foremost authority on the use of this electromagnetic technique."

Dan Zlatanovici
- Ph. D. in Electrical Engineering from "Politehnica" University Bucharest in 1987
- Univ. Professor at the “Valahia” - Targoviste University in 1998 – 2005
- Scientific Secretary and senior researcher at the Energy Research and Modernizing Institute – Bucharest, Romania (www.icemenerg.ro), employed by
Icemenerg from 1969 till present time.

- Member (on behalf of Romania) of the CIGRE - Study Committee A1 – Rotating Electrical Machines in 1996 – 2006

- Member of the staff of the Study Committee A1 – CIGRE from 2006 till present

- Reviewer of the review “Electra”.

- Awarded with the CIGRE Technical Committee Award in 2005