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MEASURING FLUX AND INTERLAMINAR VOLTAGE IN TURBINE GENERATOR END REGIONS

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INTRODUCTION

In the end regions of large turbine driven generators, extraneous fluxes, which may be insignificant in small machines, cause appreciable eddy currents and interlaminar voltages which, in turn, influence loss and temperature patterns within the machine. Therefore before the designer can predict the likely effect of any particular change in design parameters upon performance, he must first appreciate how changes in operating conditions or machine geometry affect the flux distribution. Whilst this paper describes flux and interlaminar voltage measurements only, it should be seen as covering only part of a much broader spectrum of theoretical and experimental work aimed at furthering the understanding of large machines and improving them.

Finite element analysis (Phemister (1)) is widely used to model two dimensional electromagnetic fields, but three dimensional calculations can be expensive, especially when saturation is taken into account. Modelling three dimensional fields under transient conditions as yet demands too much computer power to be applicable for large scale problems. Hence the importance of experimental measurement on machines.

GENERAL APPROACH TO INSTRUMENTATION

Flux densities and interlaminar voltages have been measured in detail in the end regions (Fig. 1(a)) and in other parts of generator stators up to 800 MW rating. As changes in flux in one place tend to produce effects elsewhere, it is inadvisable to confine search coils to only the areas thought to be of immediate interest. For instance, coils may sometimes be included to measure leakage flux at the back of core and in the core frame ribs; parts often neglected, but which experience shows contribute to the machine iron losses (Abolins and Rieger (2)).

In addition to the investigations on production machines, a test rig comprising the two ends of a full size 660 MW generator has been built to aid the future designs of large machines. Almost nineteen hundred sensors of various types were installed, some in positions not acceptable in production machines.

Groups of sensors and their leads must be designed to give a high signal to noise ratio and avoid disturbing the local environment in a way that will alter the quantity being measured. They must be robust enough to withstand service conditions, fail safe, and be installed into the machine without disrupting the manufacturing programme.

A significant part of the cost of instrumentation lies in the support arrangements to accurately locate and orient the sensors, their lead runs and terminal connections, rather than in the sensors themselves. Documentation which specifies the characteristics of each sensor, their spacial positions in relation to a known frame of reference and their terminal connections, is essential. Without it no data capture and handling system can function and no meaningful analyses made.

FLUX MEASUREMENTS WITH SEARCH COILS

Search coils are the most robust, convenient and cheapest transducers to obtain complete information about alternating fluxes. Their principle of operation is expressed by:

$$e = -(AN)\ \frac{dB}{dt} \quad ....(1)$$

where e (volts) is the instantaneous value of emf induced across the terminals of a coil of N turns of average area A (m^2) embracing flux of density B (tesla). The coil constant (AN) fixes its sensitivity for a given rate of change of flux density.

Search coils range from single turns of wire wound around a packet of laminations to determine the flux distribution in the core, to those of a few thousand turns wound on formers to measure the flux entering iron from air gaps. Coil constants are chosen to give a high signal to noise ratio. An upper limit is imposed on coil constants by dimensional restrictions and by the minimum size of wire used to wind the coil (in practice 52 swg, i.e. 0.02 mm dia).

Construction of Search Coils

Coils of various sizes and sensitivities are required and techniques have been developed to wind and terminate them from fine wires. In some locations, only simple coil formers are necessary, whilst other locations demand a specific design. All coils however have either circular or rectangular sections and examples are illustrated in Fig. 2.

A typical cylindrical coil (Fig. 2(a)) used in the end region and on the back of core has several thousand turns of 48 swg enamel insulated copper wire wound on a nylon former: the coil with its terminal pins is encapsulated in epoxy putty. Sensitivities of the order of 90 V(rms) T^{-1} peak value of sinusoidal flux at 50 Hz are obtained. In places such as the end winding region, groups of three cylindrical coils are mounted mutually at right angles to measure the flux density in all three planes. Special cylindrical coils to measure axial flux density in the core have formers without flanges and comprise 5000 turns of 52 swg wire encapsulated in epoxy resin (Fig. 2(b)).

Small rectangular section coils are used to measure radial and axial flux densities

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particularly in the air gap regions (Figs. 2(c) and (d)). These are wound with 46 or 48 swg wire over epoxy glass formers to obtain appropriate sensitivities. Coils to measure flux densities in two planes using only one former arrangement (Fig. 2(e)) are used in some locations.

To measure flux over a relatively large area, such as that leaking radially from the back of core, coils of only a few turns of 30 swg wire are used. These are wound in a single layer into recesses in a rectangular 'picture frame' former (Fig.2(f)).

Calibration and phasing of search coils

The coil constants (AN) of large single layer coils are accurately calculated from the coil dimensions and the number of turns. However the constants of small multi-layer coils cannot be determined in this manner since their effective area is not accurately known and they must therefore be calibrated.

To determine the area-turns of these coils, both the unknown coil and a standard cylindrical coil of known area-turns, wound with a single layer of wire, are placed with their axes coincident inside a solenoid of considerably larger dimensions. A virtually uniform field is embraced by the coils. Both coils are connected to a potentiometer and a sensitive null detector, and calibrations are made with sinusoidal currents of 50 Hz supplying the solenoid. From the resistance on each side of the null point on the potentiometer and the area-turns of the standard coil, the area-turns of the coil undergoing calibration is calculated. This technique makes the calibration independent of variations in the supply to the solenoid, and it fixes the terminal polarity (phase) of the unknown coil. This phasing enables coils to be installed according to a convention for defined directions of flux.

Search Coil Installation

An investigation into one or more regions of a generator may require the installation of between a few and several hundred coils of different types in locations as typified in Fig. 1(a). In regions where high gradients of flux density are expected such as in the air gap near the core ends, a number of coils are installed within close proximity to one another.

The installation must comply with stringent specifications so that it does not affect the performance or reliability of the machine. Care is therefore taken in the design of the coil assemblies, the choice of materials used, the techniques adopted to secure the assemblies to the stator and the lead runs. Other precautionary measures include the use of end winding models to check the integrity of coil arrangements under high voltage stresses as exist during over voltage tests, the establishment of voltage breakdown levels of leads and insulating conduits, the temperature capabilities of the components and gas flow considerations. The final installation must be robust enough to withstand production procedures and service operating conditions.

A typical installation of individual coils behind the back of core is shown in Fig. 1(b). Where possible, groups of coils and their leads are attached or encapsulated into pre-assembled units to reduce installation time within the manufacturing programme. Examples of this are an assembly of coils for attaching to special stator slot wedges to measure axial and radial flux densities in the air gap (Fig. 1(c)), and also a comprehensive arrangement of coils for installing on the back of core (Fig. 1(d)). Cylindical coils to measure axial flux within the core are bonded with their leads into recesses in 2.4 mm thick rubberised asbestos segments normally used to accommodate the core supervisory thermocouples (Fig. 1(e)). This forms a robust unit ready for installation during core building.

Connections are made to the search coils using pairs of fine multi-strand PTFE insulated wire. These pairs are tightly twisted to avoid flux loops. The leads are run in the stator via suitable conduits to hermetic connectors on the outer casing.

LAMINATION VOLTAGE PROBES

The main flux in a 500 MW generator stator induces a voltage of less than 50 mV between axially adjacent segmental core laminations. Near the core ends however, the interlaminar voltages are greater due to the effects of axial flux perpendicular to the plane of the laminations, and also the radial flux leaking from the back of core (Jackson (3)).

To obtain a measure of these voltages and also to improve the understanding of core behaviour, lamination probes have been installed on the back of the core of a 500 MW generator. These probes have enabled interlaminar voltages within groups of laminations near the core end to be measured under various load conditions. The voltage between a lamination in each group and the adjacent keybar was also measured. This enabled the potential of each lamination in a group to be determined with respect to the keybar.

To install the lamination probes, a hand held laser microwelder was used to attach fine gold plated molybdenum wires of approximately 0.1 mm diameter to the edges of adjacent individual core laminations. These are themselves only 0.35 mm thick excluding insulation. The microwelder employs an accurate optical system developed from a laser opthalmascope. The weld melt was established as being less than the thickness of the coreplate to avoid creating interlaminar short circuits. Fine wires laser welded to laminations on the tooth of a model generator are shown as an example inset in Fig. 3(a).

Laser welding was only the first stage in a comprehensive and quite lengthy installation operation of the type already described. Each group of fine wires was joined to a more substantial measurement lead containing individually twisted pairs of multi-strand PTFE insulated wire using a connector assembly attached with adhesive to the back of core. On one twisted pair, the voltage between the first lamination in a group and the adjacent keybar was measured. On the other pairs, the interlaminar voltages were measured (Fig. 3(a)).

MEASUREMENTS AND DATA HANDLING

Continuing developments in measuring

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instruments and computers are eliminating many tedious procedures and have reduced to an entirely different order the time taken for measurements, their storage and presentation. Search coil and potential probe voltages usually have complex waveforms and they can be analysed in two ways. In one, the magnitude and phase of each harmonic of the wave is stored and the wave can be reconstituted on a computer; in the other, the wave is recorded using either analogue or digital techniques. Each method has advantages in certain situations and both are used.

For example, the magnitudes and phase angles of the components of repetitive search coil voltages are measured up to the 15th harmonic with a specially designed complex wave analyser which may be used manually or with a computer controlled data logging system. The phase reference signal used for the analyser is synchronous with the wave undergoing measurement and is derived from a source such as the line voltage. A subsequent version of the complex waveform analyser has been described by Locke (4). For non-repetitive voltage waveforms, such as those obtained from some voltage probes, a transient recorder has proved suitable. This instrument records 1000 consecutive samples over a selected time period (minimum 0.1 ms), each sample being stored as an 8 bit digital number. Thus complete cycles or selected portions of the waveform can be recorded and transferred to paper tape or micro-computer disc for subsequent analysis.

During any test programme large amounts of data are collected and preferably these are systematically stored in a computer data base for subsequent analysis. This enables characteristics particular to a machine design to be ascertained and comparisons to be made between machines. Efficient management of the data base is therefore essential.

SOME SELECTED RESULTS

The following examples of measurements taken on generators are a very small selection from data collected over several years.

Calculations indicated that were the rotor pole lengths to be less than that of the stator core, the axial flux at the core ends would be reduced. In consequence, losses and temperatures would also be reduced. To verify this prediction a 200 MW stator was tested with both a normal length rotor and a rotor with its poles shortened by an air gap length at each end. The axial flux densities measured in the stator teeth (Fig. 4) were considerably reduced with a shortened pole length at normal open circuit voltage. As a similar trend was obtained on load, rotors since then have been advantageously shortened.

The radial leakage flux densities behind the back of core in a 500 MW 60 Hz generator on open circuit are shown in Fig. 5(a). Picture frame search coils used for these measurements were located only on the main section of core between the end and central radially ventilated regions. Flux densities are highest in regions close to the radial vents, probably because the ventilated regions have less iron. In general the radial leakage flux rises sharply above 16 kV.

A sudden short circuit test on this generator from 50% of normal voltage on open circuit induced voltages in the coils at positions 1 and 7 as shown in Fig. 5(b). Near the central ventilated region the flux voltage collapses, whilst near the core end it rises to approximately fifty times its steady state value before decaying to a value greater than its pre-fault level. These waves illustrate the balance of rotor and stator magnetising forces in the air gap and their imbalance in the end region under transient conditions: they also show that leakage fluxes under transient conditions also involve part of the iron circuit as well as the end winding region. This illustrates the importance of considering the transient leakage fluxes in a machine as well as the steady state flux. The results are similar to those already reported by Anderson (5) for small a.c. series motors under start-up conditions.

To obtain the flux distribution within the core of the model generator described previously, single turn coils were wound around core sections utilising the axial and radial vents. These coils would not be acceptable on a production machine. Whilst the total flux in the back of core on open circuit is sinusoidal, the local fluxes are distorted as shown in Fig. 6 due to the reluctances of their various paths.

An example of an interlaminar voltage waveform measured under load conditions on a 500 MW generator is shown in Fig. 3(b).The waveform contains sharp peaks and varies in a random manner between two states of different amplitude. Positive and negative peaks appear and disappear independently. The magnitude of the interlaminar voltage (approximately 2.5 V peak) is of a different order to that arising from the main flux in the machine acting on its own. The investigation into this subject continues.

CONCLUSIONS

Flux and interlaminar voltage measurements in turbine generator end regions have made significant contributions to the development of larger machines. The measurements have provided information of immediate use to the designer and have complemented theoretical calculations. They have also shown phenomena which sometimes has not been entirely anticipated such as that obtained under transient conditions.

The design of the sensors, their accuracy of location, their support assemblies and the measurement procedures and data handling all require considerable attention to detail to ensure that reliable and sensible results are obtained relevant to the investigation.

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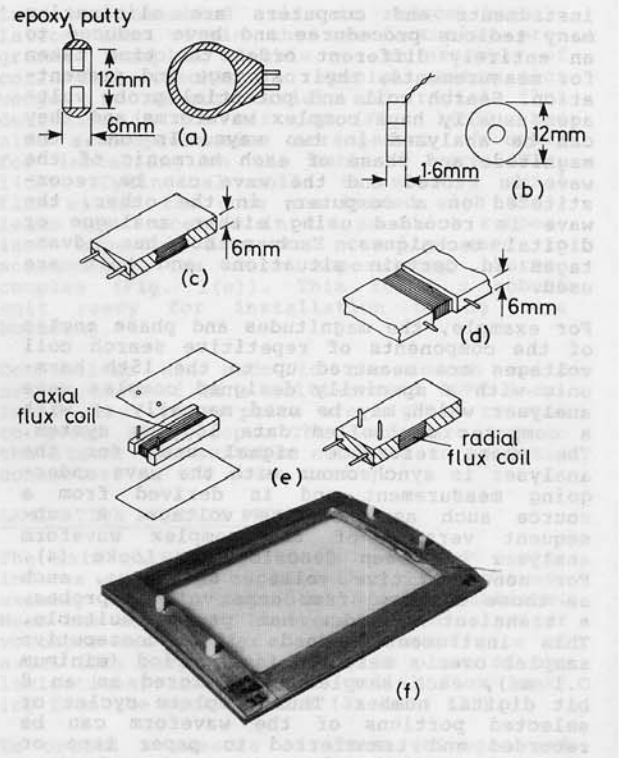

Figure 2 Examples of search coils

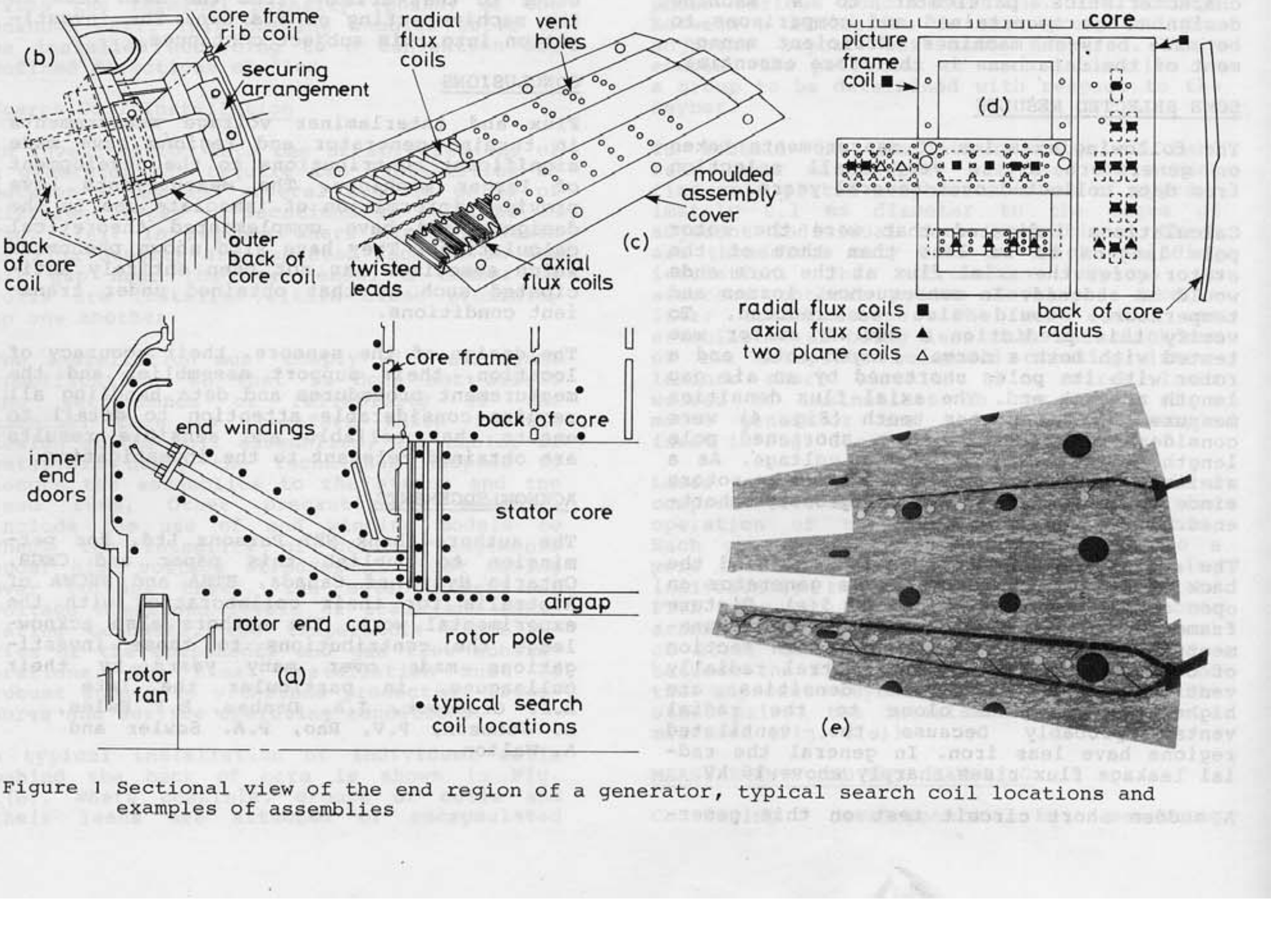

Figure 1 Sectional view of the end region of a generator, typical search coil locations and examples of assemblies

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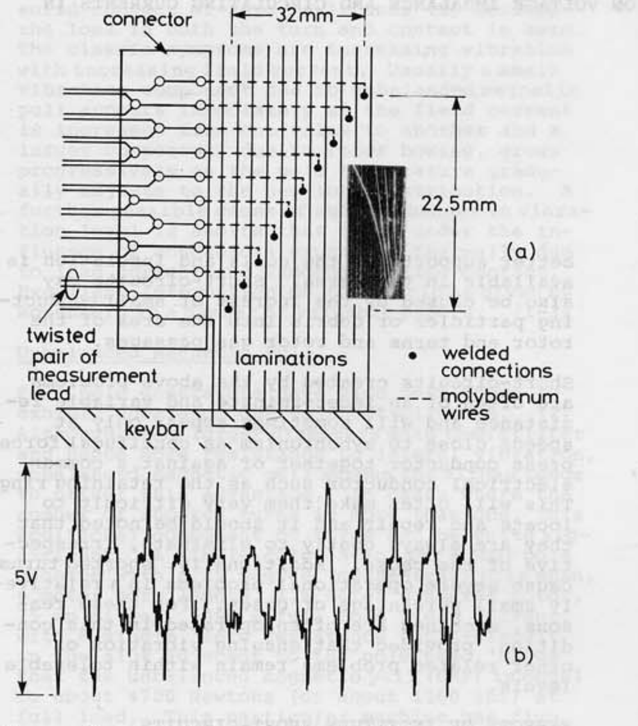

Figure 3 Connections of lamination voltage probes and an example of a 50 Hz interlaminar voltage wave

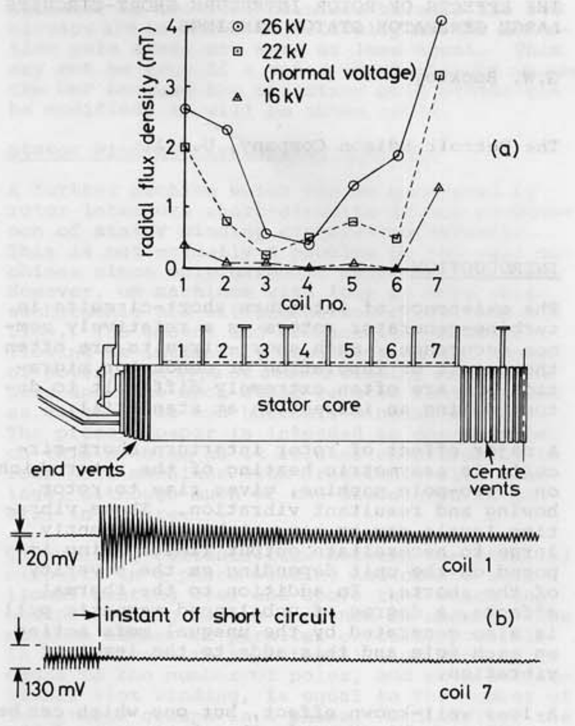

Figure 5 Flux density behind back of core on open circuit and search coil voltages during a sudden short circuit test

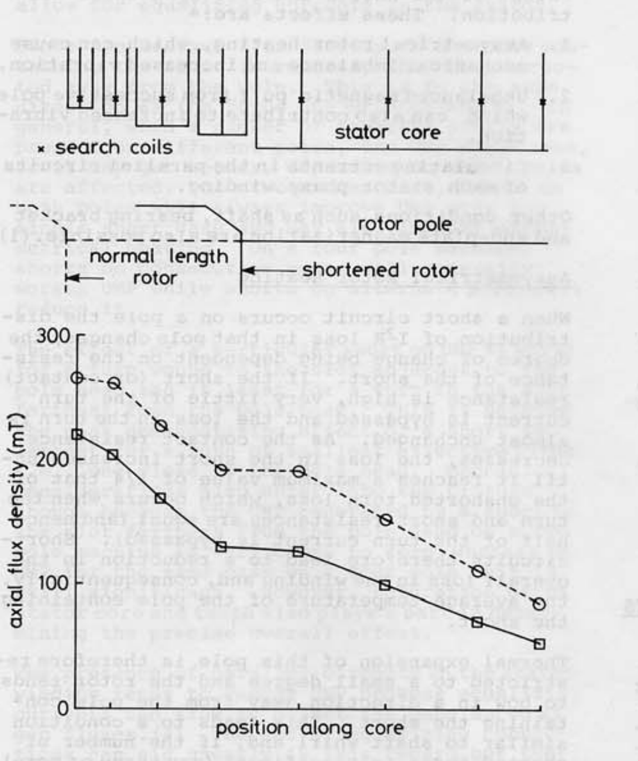

Figure 4 Axial flux density in stator teeth at normal open circuit voltage with normal and shortened rotor lengths

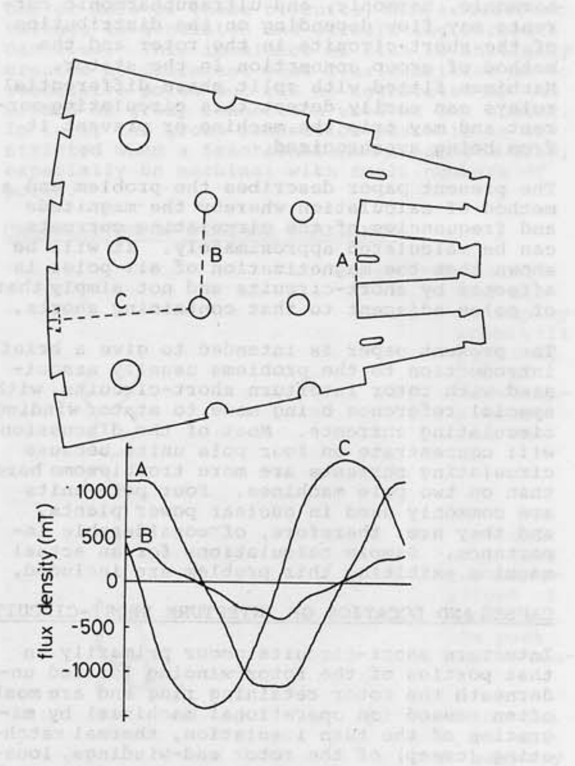

Figure 6 Radial and circumferential flux waves in a core section of a full scale model generator on open circuit