INTERTURN SHORT-CIRCUIT DETECTOR FOR TURBINE-GENERATOR ROTOR WINDINGS

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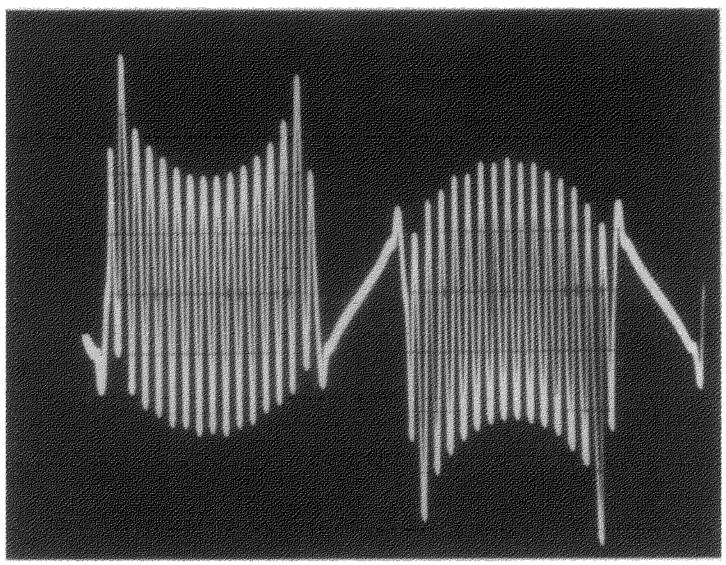

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ABSTRACT

An effective new method of detecting interturn short circuits on round rotor windings is described. The approach used is to measure the rate of change of the air-gap flux density wave when the rotor is at operating speed and excitation is applied to the field winding. The measurements are obtained by the use of a small stationary search coil positioned near the rotor surface. The voltage outputs are recorded by Polaroid pictures from an oscilloscope screen and can be analyzed based on the information presented. The sensitivity obtained from these methods is far superior to previous methods. The data obtained at operating speed identify the coils and slots which have shorted turns, and provide a good indication of the number of turns shorted in a coil if more than one short exists.

The availability of this new maintenance tool will provide valuable information for understanding the causes and effects during the investigation of rotors that exhibit operating difficulties which could be caused by shorted turns.

INTRODUCTION

Interturn short circuits on steam turbine-generator round rotor windings have rarely caused operating difficulties. However, investigations and repairs on some rare cases in the past have shown the previously accepted practices of detecting and locating shorted turns to be deficient in sensitivity. This is especially true when attempting to establish the number and locations of shorted turns at operating speed when centrifugal coil loads are applied to the turn insulation. A review of the previous detector techniques is given under "History."

The purpose of this paper is to describe the design and operation of a sensitive new shorted turn detector. This detector provides data at operating speed to locate the coil or coils which have shorted turns and give indications as to the number of turns shorted in the affected coils. The method used to obtain the improved sensitivity is to measure the rate of change in the air-gap flux density wave near the rotor surface. This measurement is obtained from a stationary search coil positioned in the air-gap. The rate of change (or differential) wave obtained from this search coil amplifies the variations of the flux density wave at each rotor slot. The analysis of these wave shapes, obtained from an oscilloscope display recorded on Polaroid pictures, provides sensitive comparative measurements of the active turns in each coil.

Measurements taken on actual machines are used to describe the results of this method. These results, along with data obtained by older accepted trouble-shooting techniques, will help Operating and Maintenance Engineers analyze rotor unbalance difficulties and/or the cause for excessive excitation current requirements due to shorted turns. With this additional information, sound decisions on corrective action can be made in much less time. Thus, over-all maintenance and operational costs can be reduced.

It is not the purpose of this paper to suggest that Operating Engineers should become overly concerned about the possibilities of fields having shorted turns. In the "Operational Experience" section of this paper, it is pointed out that shorts which exist at speed but not at standstill can be very difficult and costly to locate and repair. Considering all factors, it is suggested that repairs be made only when significant improvements can be anticipated in the performance and reliability of the generator.

HISTORY

The problem of detecting and locating shorted turns in round rotor windings has always been difficult. Figure 1 is a cross section of a typical 2-pole rotor showing the slots and buildup of the winding within the rotor shaft. As the winding is completely embedded in the steel and the turn insulation is not physically loaded until it is subjected to the centrifugal forces produced at speed, the problem of detecting shorted turns appears to be practically insolvable. However, the results of efforts by many people in the Power Industry have produced systems for detecting and analyzing rotor problems which could possibly be caused by shorted turns.

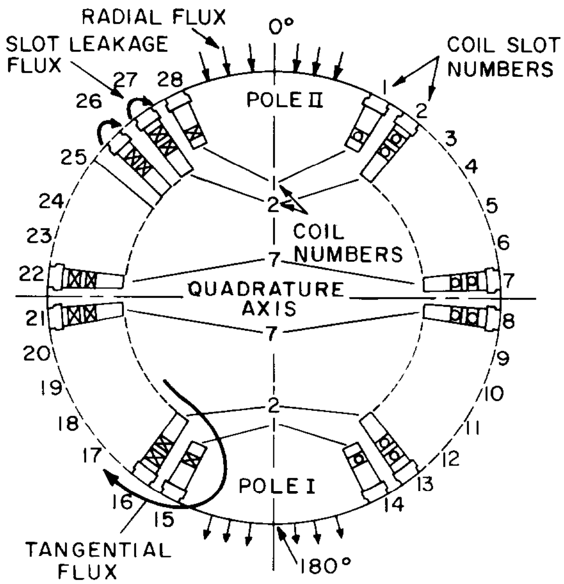


Fig. 1. Cross section of rotor

A 1963 IEEE Transaction paper[1] with its discussion covers the Industry's practices for attacking shorted turn problems. The techniques required can be classified into three categories:

1. Analysis of impedance or reactance data during a speed traverse from standstill to rated speed.

2. Analysis of search coil data traversing the rotor surface while alternating voltage is imposed on the field winding. These data are taken at standstill with the retaining rings assembled.

3. Analysis of various types of measurements at standstill with the retaining rings removed.

The test results obtained at standstill are normally quite sensitive. That is, tests performed at standstill with the retaining rings removed can identify both the coils and the turns which have shorts. Tests performed with the retaining rings assembled will identify a coil which has a shorted turn. These data, however, can be difficult to analyze, especially if more than one coil has a shorted turn and the affected coils are in close proximity. Also, fields which use retaining rings shrunk on the rotor body do not provide as sensitive a response as fields with retaining rings not shrunk on the body.

Although the data obtained at standstill are generally quite sensitive, they may have little relationship to the conditions existing at speed when the centrifugal coil load is experienced by the turn insulation. To establish an indication as to whether shorted turns develop during acceleration to operating speed, field winding impedances or reactances are sometimes measured as a function of speed. These types of data, in the past, have provided indications of the number of turns shorted. However, the sensitivity is poor unless a good base impedance or reactance value at speed is known. For example, impedance changes from standstill to speed have been observed to vary from plus 5% to minus 30% on different fields which have had no shorted turns. Considering this wide divergence in impedance disassociated with shorted turns, it is almost impossible to develop relationships between percent shorted turns and impedance changes on all the various field designs now being used.

Another major deficiency with the impedance or reactance methods of estimating the number of shorted turns at speed is that the data will not provide an indication as to the location of the shorts. To make rational decisions as to the corrective action required on a field if shorted turns are causing the operating difficulties, it is necessary to know at least the coils which are involved and it is highly desirable to know the number of turns shorted within the affected coils. For example, thermal bowing of the rotor caused by unequal coil heating will be greater if turn shorts exist in the small coils 1, 2, and 3 of one pole than if they exist in the larger coils near the quadrature axis. Also, if repair work is indicated to improve the operating characteristics, it is necessary to know the pole and coil numbers which must be reworked.

AIR-GAP FLUX MEASURING DEVICES

During the investigation of an operational problem on an old 2-pole field which had recently been rewound, it was found that the output voltage of a relatively small coil[1] held stationary in the air-gap of the generator when excitation was applied at speed produced significant signals at each rotor slot. Figure 2 shows the results as recorded on a Polaroid picture of an oscilloscope screen. The data were taken at speed with rated open-circuit excitation applied. To

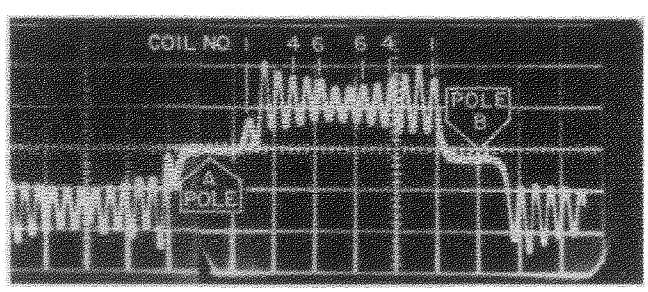


Fig. 2. Open-circuit radial flux coil voltage wave of a rotor which had a major short in coil number 1 Pole "A"

obtain such a picture, the oscilloscope's horizontal trace is synchronized with the search coil voltage wave. The two straight horizontal lines on this picture correspond to the two poles and the voltage spikes correspond to each slot. From these data it was obvious that the voltage spikes corresponding to the number 1 coil on Pole "A" were significantly smaller than for coil number 1 Pole "B." Based on this, it was apparent that the number 1 coil Pole "A" was not producing the same magnetic effect as the other number 1 coil. After disassembly of the rotor, a short which completely isolated the number 1 coil was found and a routine repair was made.

Based on the successful experience of analyzing the unit discussed above, it appeared that the technique of measuring the rate of change of the air-gap flux density could provide a means for detecting shorted turns on all types of fields at speed. To explore this possibility, tests using various types of coils and positions of coils in the air-gap were performed on generators in the factory during open circuit and short-circuit tests. Some tests were also performed at power stations with load applied. It is impractical to describe in this paper the results in detail of all the various trials, but below are listed the types of coils and measuring devices evaluated with brief descriptions of the results.

1. Coils mounted such that they measured the rate of change of the radial flux density wave.

a. Mounted on the stator wedge.

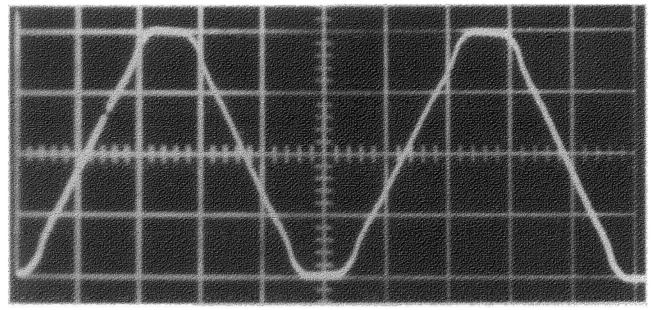
b. Mounted in the end of a 0.25-inch (.635 cm) diameter rod. This probe could be assembled through the wrapper plate and the core, and be positioned to any desired distance from the rotor. A description of this arrangement is given in Appendix I.

2. Coils mounted in a probe such that they measured the rate of change of the tangential flux wave in the air-gap. (See Appendix I.)

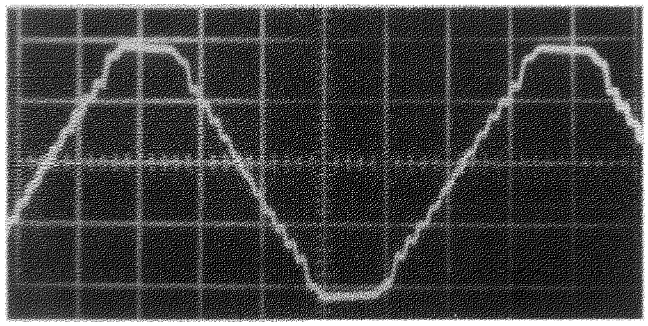
3. Hall-Effect devices,[2] mounted in a probe, which measured flux density.

4. Wave shape single turn coils which enclosed one or two stator packages were also re-evaluated.

Typical output voltage from either a Hall-Effect device (Item 3) or a wave shape coil (Item 4) are shown in Fig. 3. Figure 3 (a) shows the results when the measuring device was two inches (5.08 cm) from the rotor surface. Figure 3 (b) shows the results when the measurements were taken within 0.5 inch (1.27 cm) of the rotor surface. The data shown were taken during a 100% open-circuit heat run. Although the data measured near the rotor surface provided a distinct ripple at each tooth, it was not sufficiently sensitive to detect one shorted turn out of, for example,



(a)



(b)

Fig. 3. Open-circuit wave shapes obtained by integrating radial flux coil voltages. Also, typical wave shapes from Hall-Effect devices and Wave coils. (a) Positioned two inches (5.08 cm) from the rotor surface. (b) 0.5 inch (1.27 cm) from rotor

20 turns in a coil. These methods of measurement were, therefore, dropped from our program. However, the wave shapes using these coils measured near the rotor surface did provide a visual aid for understanding why a small stationary search coil positioned in the air-gap might provide the desired sensitivity.

In the magnetic field produced by a distributed winding, the change in flux density from one rotor tooth to the next is primarily a direct function of the ampere turns in the slot between the two teeth. Consequently, the output of a small stationary coil, which responds to the change in flux density, will give a direct and highly sensitive indication of the relative ampere turns in each slot. The results discussed later will show that this is the case. However, the sensitivity obtainable and the analysis of the results depends on the operating conditions during the test, the design of the field, and the search coil location.

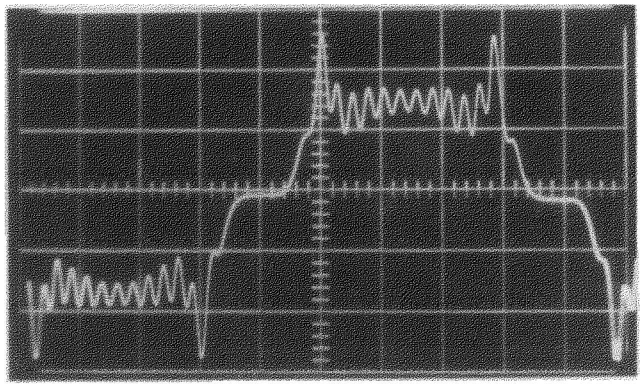
Measurements of the flux density rate of change can be obtained by coils positioned to sense either radial flux (Item 1) or tangential flux (Item 2)[3]. Both types of coils were investigated in our program. Tangential flux coils provided the greatest sensitivity during the open-circuit tests. During the short-circuit tests the sensitivity of both coils was comparable. In this paper the author has used the data obtained from radial flux coils to show typical results because the relationship of voltage spikes to each coil slot and the field fundamental flux wave is easier to interpret.

RADIAL FLUX COIL— OPEN-CIRCUIT CONDITIONS

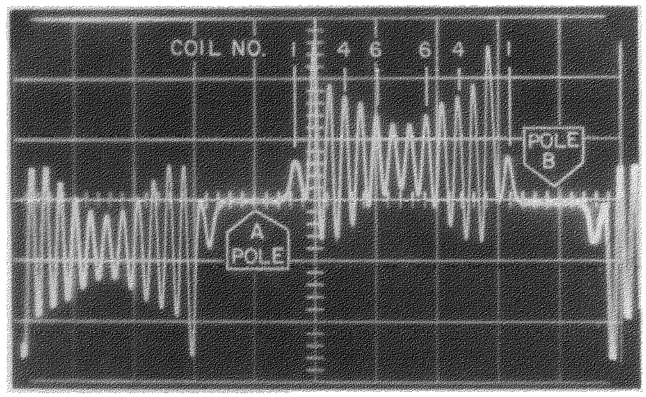
From an operational viewpoint it would be desirable to obtain shorted turn indications during open-circuit conditions just prior to synchronizing the generator. In order to determine whether or not open-circuit search coil data would provide sufficient sensitivity for detecting shorted turns, many tests were performed on different types of rotors under various conditions of coil locations and excitation levels. Although these tests showed the sensitivity to be far superior to previous practices, the tests also showed that some shorted turns may not be detected, especially in the smaller coils.

The sensitivity which can be obtained on open-circuit test is shown in the series of pictures in Fig. 4. These pictures were obtained from a 281.6 MVA 2-pole generator which had a rotor design using seven coils per pole and 11 turns per slot. The number one coil had nine turns. The data were taken with 100% field excitation applied. Figure 4 (a) and (b) shows the output of a coil positioned two inches (5.08 cm) and 0.5 inch (1.27 cm) respectively from the rotor surface. A number of interesting observations can be made from these pictures which relate directly to the flux density waves in Fig. 3. The data definitely show that the stationary search coil voltage produces a true differential of the flux density wave. Electronically integrated search coil voltages, in fact, produced the wave shapes shown in Fig. 3. The symmetry about each pole is evident, showing that data from one pole can be compared to data obtained on the other pole for establishing whether or not dissymmetry exists. The amplification of the voltage spikes, especially Fig. 4 (b), due to the differentiation indicates a significant increase in sensitivity.

Although these observations were encouraging, two other observations show that a minor number of shorted turns in the small coils may not be detected. The very small voltage spikes at the number one coil result from the use of magnetic wedges in these slots. Where magnetic wedges shunt a large portion of the slot leakage flux, a much smaller effect is seen in the air-gap. The final observation which relates to sensitivity is the gradual, but significant, increase in the magnitude of the voltage spikes starting at the quadrature axis slots and reaching a peak at the number 2 slot. This variation in voltages shows the differential wave is not providing a true indication of the active turns in each slot as previously explained in the "Air-gap Flux Measuring Devices" section of this paper. Test data obtained on different rotors with shorted turns and flux plots of the air-gap have shown the voltage spikes reflect a combination of the active turns in each slot



(a)



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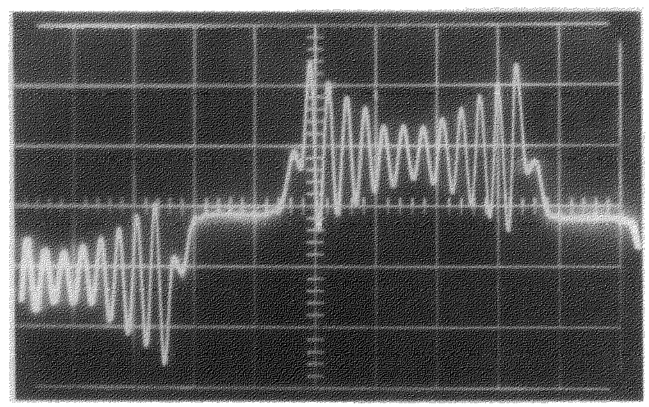


(c)

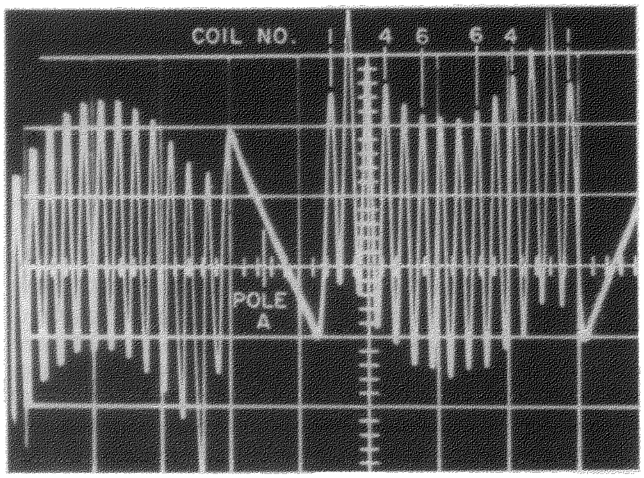
Fig. 4. Open-circuit radial flux coil voltage waves. (a) Coil two inches (5.08 cm) from the rotor surface. (b) Coil 0.5 inch (1.27 cm) from the rotor. (c) Coil one inch (2.54 cm) from the rotor—one turn shorted in the coil number 6 Pole "A"

plus a distortion factor. It has been shown that the distortion is negligible at the coils near the quadrature axis, but progressively increases toward the number one coil. Methods of analyzing these data, taking into account distortion, have been developed. However, based on the accuracy of the data which can be obtained from the Polaroid pictures, the resultant analysis is questionable unless a significant difference in symmetry exists.

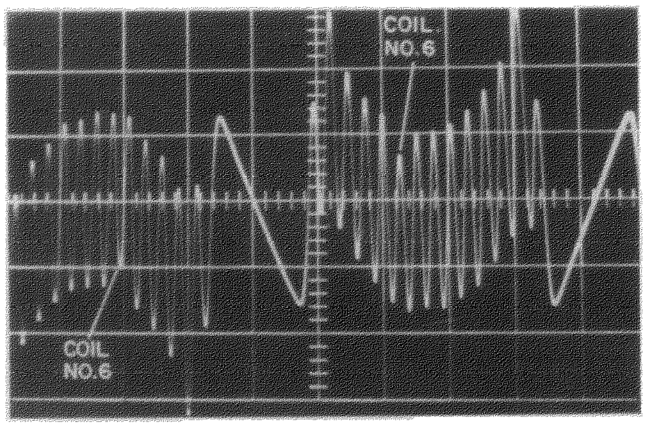
Improved sensitivity can be obtained by comparing data from an identical field which has no shorted turns. This suggests that periodic monitoring of a field under open-circuit conditions would help establish if significant changes are developing over the lifetime of the generator.

To show the type of results which can be expected if a shorted turn exists, Fig. 4 (c) has been included. These data were taken on the same generator under similar conditions, but an artificial short had been placed in the bottom turn of coil number 6 Pole "A." A cursory observation of Fig. 4 (c) will not show the shorted turn, but careful measurements will definitely pick out the coil with the shorted turn.

In summary, the open-circuit test data will clearly indicate any major shorted turn condition. For minor irregularities – for example, a single shorted turn – the sensitivity is greater near the quadrature axis. The sensitivity decreases toward the number 1 coil, but even at the number 1 coil a significant short can be detected.



(a)



(b)

Fig. 5. Short-circuit radial flux coil voltage waves. (a) Coil 0.5 inch (1.27 cm) from rotor surface—no shorted turns. (b) Coil 1.0 inch (2.54 cm) from rotor surface—one turn shorted in coil number 6 Pole "A"

RADIAL FLUX COIL—SHORT-CIRCUIT CONDITIONS

The data obtained during open-circuit tests provided sensitivities far greater than past practice. However, data obtained during armature short-circuit conditions provide even greater sensitivity approaching the ultimate. Normally, only cursory observations of the short-circuit data will establish whether or not a field has shorted turns.

Short-circuit results for the same 281.6 MVA generator are shown in Fig. 5(a) and (b). Field excitation to produce 50% of rated armature current was used during these tests. The radial flux coil was positioned 0.5 inch (1.27 cm) and 1.0 inch (2.54 cm) respectively from the rotor surface. Figure 5(a) displays the results when no shorted turn existed. Figure 5(b) shows the results when the same number 6 coil had an artificial shorted turn. Observations of these pictures dramatically show the significant increase in sensitivity which can be achieved under short-circuit conditions. The nine-percent smaller voltage spikes for the number 6 coil, when compared to its identical coil on the other pole, corresponds to one turn shorted out of 11 turns. This observation and the fact that each coil voltage spike has essentially the same magnitude show that the voltage spikes represent nearly a direct relationship to the active turns in each slot. The larger voltage spike at the number 1 coil also indicates the sensitivity for detecting shorted turns in the number 1 coils has been significantly improved.

The significant increase in sensitivity results from the fact that during short-circuit tests the field's fundamental flux is essentially cancelled by the armature reaction. Therefore, the remaining variation in flux density, as seen by the stationary coil, is predominantly the slot leakage flux. Thus, the distortion observed during the open circuit conditions has been virtually eliminated.

From the information above, it is obvious that data obtained from a short-circuit test will provide much more reliable and sensitive data to analyze a particular field. When a unit is tested in a manufacturer's shop, obtaining short-circuit data is no problem. To perform this test in a power station may pose some difficulties. However, the author's company has worked with two power companies to perform this short-circuit test and the time required has been negligible. It has been shown that short circuits made on the high-voltage side of the transformer will provide the same type of sensitivity. Using the high-voltage side of the transformer requires only light cables to make the short circuit. When preparing the conditions for running the short-circuit test, care must be taken to insure that a sudden short circuit is not applied, that interconnecting protective relays wired to sister generators are isolated, and that excitation is built up gradually after the short circuit has been made. Experience has shown that only nominal values of excitation are required to produce acceptable data. Therefore, heating of the generator and transformer windings poses no problem during this test.

OPERATIONAL EXPERIENCE

The author's company has used this detector on several units during generator factory tests, and it has proved a valuable tool for analyzing suspected rotor winding problems. In one instance, it immediately pointed out that special test connections had been improperly made. Valuable test time was saved as a result of this rapid analysis.

This detector was used on four generators where thermal balance problems were considered excessive. In all cases, the results indicated shorted turns could be the major reason for the thermal sensitive conditions as the shorted turns were located asymmetrically within the rotor. Figure 6 shows the results obtained before and after the repair on one unit. In two of the cases, where corrective action was taken, significant improvements in performance were observed. In one case, where only one shorted turn existed before taking corrective action, an improvement was observed, but conditions other than the shorted turns proved to be causing part of the thermal sensitive condition. In the fourth case, no corrective action was taken as the estimated cost to make the repair was considered too high for the anticipated gain in performance.

If, during the investigation of a field, it is found necessary to take corrective action, the following operations are required.

1. During the short-circuit test a once-per-revolution electrical signal at a known angle must be obtained. This signal, super-imposed on the search coil wave picture, will identify the pole numbers and the slot numbers. A dual trace oscilloscope is particularly adaptable for this application (see Fig. 6(a)).

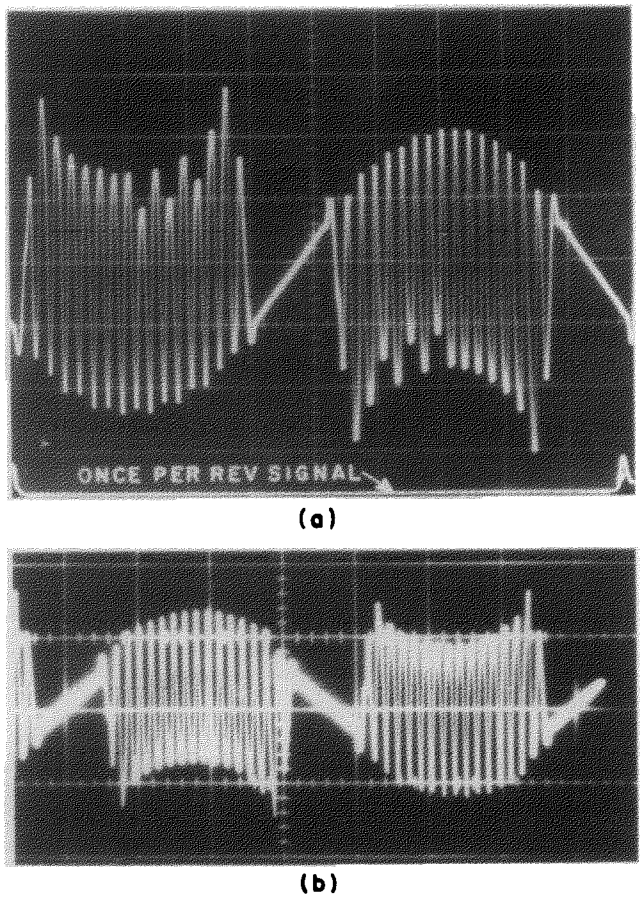


Fig. 6. Short-circuit radial flux coil wave shapes obtained during a rotor vibration problem investigation. (a) Data obtained before the repair. (b) Data obtained after the repair

2. It may be worthwhile to continue observing the search coil picture as speed is reduced to establish if the short or shorts disappear. Speed sensitive shorts are extremely difficult to locate at standstill as there is normally little or no sign of heating associated with the shorts. Field temperatures must be monitored during this operation to prevent local overheating.

3. When the retaining rings have been removed, the work to find and repair the shorts can be directed to only the known coils which have shorted turns. If the shorts continue to exist at standstill, there are many different techniques[1] available to pinpoint the exact location of the short. If the shorts were speed sensitive, and do not exist at standstill, it may be necessary to remove the affected coils

and reinsulate them to be assured the shorts have been corrected. Visual observations and clamping the end turns to simulate the centrifugal loads may not be 100% successful in locating speed sensitive shorts.

Because this paper describes a very sensitive and reliable shorted-turn detector, the author may have possibly overemphasized the problems which could result from shorted turns. Shorted turns in a rotor are not necessarily a condition to be conerned about, particularly if the required excitation and the mechanical vibration of the rotor are not excessive under load conditions. Experience has shown that operational difficulties rarely occur due to shorted turns. The author is unaware of any forced outages as a result of a minor number of shorted turns. However, if a field exhibits symptoms which could be caused by shorted turns, experience has shown that the use of this detector will significantly reduce the time required to establish whether or not shorted turns are involved.

If shorted turns appear to be causing the operational difficulties, a decision must then be made as to whether or not corrective action should be taken. Each case will usually be different; therefore, a strict guideline cannot be stated. However, considering the possible costs to make the repairs and the risk of developing additional shorts during the repair operation, it would appear that corrective action should be taken only if significant improvements can be anticipated in the performance and reliability of the generator.

CONCLUSIONS

Analysis of a stationary air-gap search coil output voltage wave obtained at speed with excitation applied can detect the coil and slot locations which have shorted turns. Indications of the number of turns shorted in a coil are also provided.

Data obtained during armature short-circuit conditions provide the most sensitive results. Therefore, if corrective action is indicated, short-circuit data should be obtained to locate all the coils which must be repaired. Fairly sensitive data can be obtained during open-circuit conditions to establish significant dissimilarities in electrical stimulus between poles. Data obtained under load conditions have not provided the sensitivity required to detect shorted turns. The sensitivity under load conditions is affected by the same high flux densities observed during open-circuit conditions and the interaction of the armature reaction flux with the field fundamental flux.

Experience during the investigation of fields with shorted turns has shown that a nominal number of shorted turns does not necessarily indicate a major failure is imminent. Considering that speed-sensitive shorts can be very difficult to locate and costly to repair, economic considerations may dictate operating fields with known shorts as long as the rotor operating qualities are within acceptable limits.

The author's company has developed a 0.25-inch (.635 cm) diameter or smaller probe assembly which will allow the temporary positioning of a search coil in the air-gap of most generators without removing the field or degassing the machine. The use of this device will allow immediate investigations of troublesome fields without expensive disassembly operations.

The use of flux coils which measure tangential flux variations rather than radial flux will provide improved sensitivity during open-circuit tests. More work is required using these tangential flux coils to establish their ultimate sensitivity and application.

APPENDIX I

Figure 7 shows a number of the different measuring devices used during the evaluation stages. One of the main problems which had to be solved to make this detector practical was to find an economical and safe design which would position the coil to within 0.5 inch (1.27 cm) to 1.5 inch (3.81 cm) of the rotor. Since the air-gap lengths on most large steam-turbine generators exceed these dimensions, the

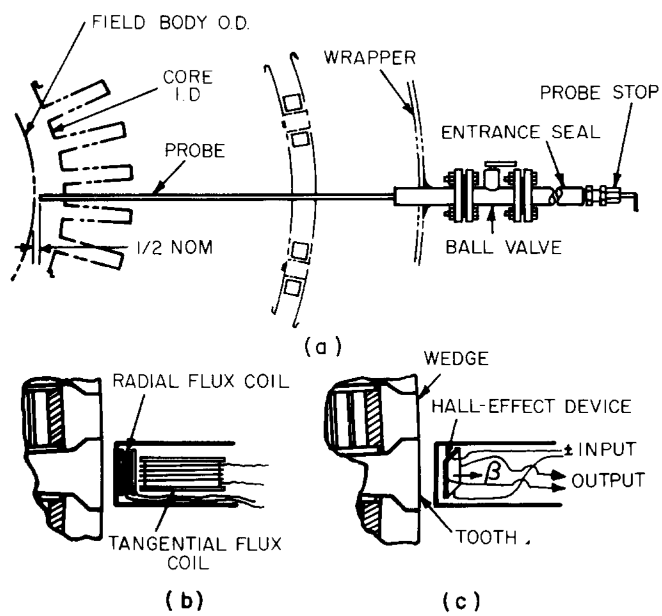


Fig. 7. Air-gap in position to record test data. (b) Radial and tangential flux coils in end of probe. (c) Hall-Effect device in end of probe

solution appeared to require a projected wedge or some other means to attach the coil in the air-gap before the rotor was assembled. However, consideration of these designs posed the problem of damage occurring to this projecting assembly during the rotor assembly or disassembly operations. To provide the desired results, the probe shown in Fig. 7 (a) is presently being used.

The nonmagnetic probe design is such that the frame wrapper plate gland, Teflon seal ball valve, and entrance seal gland can be assembled during a short outage with the hydrogen removed from the frame. The wrapper plate gland could also be assembled in the factory on new generators. The major considerations for locating this assembly are to align the gland with a core tooth vent duct and to position the probe axially such that the fewest magnetic wedges are observed. One of the advantages of this approach is that when data are not being taken, there are no parts in the generator which can vibrate, fatigue, or cause operating difficulties.

The exact design of the coils does not appear critical as long as there is a sufficient number of turns and area to provide a recordable output. Typical radial and tangential coil construction has been 100 turns of .005 insulated wire. These coils produce sufficient voltage to obtain acceptable results from almost any sensitive oscilloscope. The probe itself is made of a nonmagnetic tube material. The coils are connected to coaxial wires which are brought out the end of the probe. The coils and wires are potted in the probe with thermosetting resins such that no hydrogen leakage occurs when operating in hydrogen. Figure 7 (b) describes the radial and tangential coils positioned in the end of a probe. Figure 7 (c) describes the Hall-Effect device, used to measure flux densities, positioned in the end of a probe.

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ACKNOWLEDGMENT

The author wishes to thank Mr. D. P. Donovan for providing us with the first opportunity to try different air-gap search coils on a problem field. Messrs. D. B. Harrington, W. B. Jackson and R. Pagano's assistance to understand the air-gap flux density wave shapes proved very helpful.

The author also wishes to thank the power plant personnel who provided the time and, in one case, financed the trial use of this detector (Mr. E. C. Jones of the Sao Paulo Light Co., Brazil). This type of Industry cooperation has shown that this detector will provide the necessary information to solve shorted-turn problems. Mr. W. H. Wilson's guidance based on these field trials was particularly helpful.

DISCUSSION

L. T. Rosenberg, *Allis-Chalmers Mfg. Company*

The ability to insert a probe into the air gap without need for removing hydrogen is of great value in determining the location of suspected shorted rotor turns. The paper is a worthy contribution since, in addition to presenting test oscillograms, it also treats the merits of continued operation with a few shorted rotor turns, and suggests a criterion for deciding whether corrective action is advisable.

If abnormal vibration is present, careful measurements at various load conditions can often determine whether mechanical balance adjustment will be likely to prove adequate. In some rare cases, thermal balance techniques have been successfully applied to restore smooth operation at all loads, whether the roughness was due to shorted rotor turns or any other cause.

It is of interest that the search coil photos are more reliable when taken under short-circuit conditions rather than open circuit. The author also states that measurements under load conditions have not been successful in locating shorted rotor turns.

We have been able to locate a shorted rotor turn under actual load conditions using a 20-turn rectangular coil inserted under a stator slot stick. Not only was the turn located, but the fraction of the field current being bypassed by the contact was repeatedly checked and found to be constant within 15 percent at several load conditions and at different speeds. When the rotor was opened up, this same percentage of the battery current used to pinpoint the exact spot was bypassed by the contact which proved to be a tiny braze metal extrusion which had pierced the turn insulation and welded itself to the next turn.

This degree of accuracy was obtained with an oscilloscope beam having sharply defined edges for both the signal and the zero trace. A ruler graduated in .01 inch divisions, a magnifying glass and adequate illumination of the photos were also found helpful. The distortion due to the stator mmf was compensated for by adding the peaks of both coil sides together before comparing with the sum of the peaks of the opposite coil sides in each case.

The slot stick type search coil can usually be installed without removing the rotor, through an inspection cover at one end of the generator. Once installed, the leads are brought out to a permanent terminal board for use at any future time. Several of our largest generators were equipped with permanent search coils of this type in the initial factory assembly.

A. Lehrkind, *Allis-Chalmers Mfg. Company*

The refinements in design and application of search coils for detecting and locating rotor shorts, as presented in Mr. Albright's paper, should be of considerable help to anyone concerned with a rotor exhibiting operating difficulties. However, as he says, the risks of developing additional shorts should be considered before attempting repairs. The tests can serve in good measure to determine if repairs are really necessary.

In our own experience, the most critical item in application of the search coil test is care in measurement of the wave amplitudes. The lower limit of accuracy has been found to be equal to that indicating one-half turn shorted.

AUTHOR'S CLOSURE

The author wishes to thank Messrs. Rosenberg and Lehrkind for their discussions. The earlier work performed by these gentlemen using a similar type shorted turn detector confirms the potential value of the method described in this paper.

These discussions have also emphasized the importance of obtaining accurate data at or near operating conditions. This type of data is essential for making a rational decision as to the corrective action required. For example, one of the fields described in the "Operational Experience" section of this paper had over five percent shorted turns. The detector located the shorted turns and confirmed the cause for the excessive excitation required. The turn short locations also indicated that some thermally sensitive unbalance could be expected. However, as the shorted turns were nearly symmetrical about each pole, the thermal sensitivity could be controlled by a mechanical balance program. With the shorted turn information, the operating requirements of the unit, the cost of making a repair, and the estimated risk of a forced outage, the operating engineer was in a good position to make a rational decision. As pointed out in the paper, the decision was to take no corrective action. To the author's knowledge, no additional problems have developed on this rotor due to shorted turns.

We were interested in Mr. Rosenberg's disclosure of measuring and detecting partially shorted turns during load conditions. We have also observed data during open-circuit and load conditions which indicated partially shorted turns. However, during short-circuit tests on these same units, the shorts have proven to be full turn shorts. This is dramatically shown by comparing the results of the wave shape in Fig. 8 and Fig. 6 (a). Figure 8 is the open-circuit wave shape of the same unit as in Fig. 6. The Fig. 8 wave shape was obtained during the condition when the three shorted turns still existed. Careful measurements of the voltage spikes in Fig. 8 definitely picked out a shorted turn in one of the number 8 coils. However, the shorted turns in coils number 6 and number 4 appeared as only partial shorted turns. It was this type of data which prompted us to recommend obtaining short-circuit data before making a final decision as to the proper corrective action.

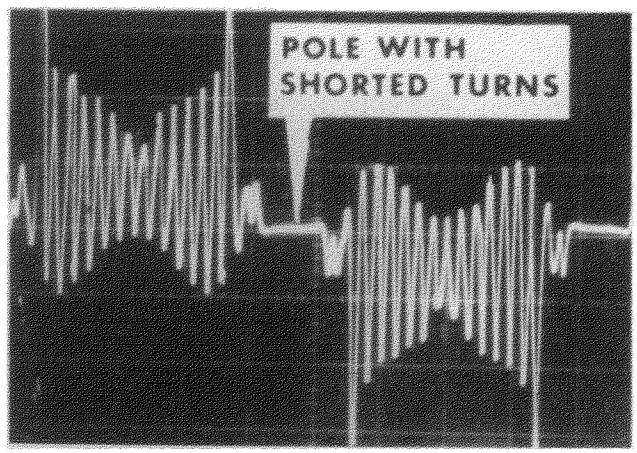

Fig. 8. Open-circuit radial flux coil wave shape. Rotor and rotor condition identical to rotor shown in Fig. 6(a)

One possible reason for the variation in sensitivity observed by Mr. Rosenberg and the author is the difference in the physical designs of the rotors observed. The author's experience is with seven or eight coils per pole rotor designs. Mr. Rosenberg's experience could have been mostly on fewer coils per pole designs. As the distortion factor appears to be also a function of the number of slots between the quadrature axis and the poles, we would expect that a rotor with fewer slots will produce less distortion during open-circuit and load conditions. The important point, however, is that each field design has its own signature. Additional work and experience will be required to understand all the variables and their effect on sensitivity during the different operating conditions.

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