Monitoring for Rotor Shorted Turns

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Abstract

The paper describes the Siemens’ (formerly Parsons’) Rotor Shorted Turn Monitor (RSTM). The monitor was developed in the early 1990’s for application to large steam turbine driven generator rotors. At the heart of the RSTM is a mathematical algorithm which processes the signal from a search coil located in the air-gap. This Analysis Program is called in sequence for 1 to 4 generators by a Supervisory Program which records the results and presents them, in a variety of forms, to a PC screen.

Many results were collected from one of the first RSTMs to be placed in service at a UK power station having rotors with a history of shorted turn indications. From these it was possible to assess the effectiveness on the Analysis Program in coping with the influence of magnetic saturation in the rotor teeth over a wide range of load.

The paper also outlines alternative methods for detecting shorted turns, their causes and the case for continuous monitoring.

Introduction

One of the problems which came soon after the introduction in the UK (and elsewhere) of large, 2 pole generator rotors for base load stations was an increased vibration sensitivity to unit load, due to unequal heating from one side of the rotor to the other, and also due to unequal, or restricted expansion of the field winding. Diagnosis of the cause of thermally sensitive rotors is not the topic of this paper, but shorted-turns was one of the mechanisms identified as causing unequal heating.

The rotor windings of large utility generators may develop inter- turn short circuits, which can increase in severity over a period of time. Rotor shorts produce damage to the main wall and inter-turn insulation at the site of the short due to overheating, and thermal unbalance due to unsymmetrical heating around the rotor. This cause of increased vibration may be difficult to distinguish from that due to other causes such as ventilation blockages and end winding packing misalignment, as well as potentially disastrous mechanical problems such as crack development.

Unbalanced magnetic pull may also add to shaft line lateral vibration, and the imbalance in field end winding currents causes axial shaft flux and a risk of potentially hazardous shaft currents. All these effects increase the risk of unplanned outages and costly repair work.

Methods for Detecting Shorted Turns

The method of detecting shorted turns which is most widely used was first described by Albright (reference 1). A search coil was placed in the air-gap and a recording made of the voltage signal when the rotor field winding was excited for open-circuited and short-circuited stator windings. The recording was examined to compare one pole with the next, looking for differences between the signals corresponding to the passage of the wound portion, taking into account the reversal of polarity. Albright concluded that the greatest sensitivity was obtained with the short-circuit test. Subsequently, Albright and others have developed the test so that shorted turns may be detected with the generator on load. However, the method depends on elimination of the ’distortion factor due to the air-gap flux density wave form’ (reference 2). This is achieved by adjustment of the generator load to align the zero flux axis with the centre-line of the winding slot for each coil in turn.

Reference 3 describes an analogue electronic scheme for taking the search coil signal and adding to it the same signal delayed by 10mS, or half a revolution. Here it was possible to deduce the position of a shorted turn on load by examination of the combined signal on an oscilloscope. Difficulties arising from magnetic anomalies, usually balance weights/holes, and speed variations are described.

On-load detection is is also considered in reference 4. A monitor which detects even harmonics in the search coil wave form is described. A derivative of this scheme was subsequently put into commercial production. It may be set to raise an alarm when the even harmonics exceed an alarm level, but neither the number nor position of shorted-turns are indicated.

The authors of reference 5 provide a valuable summary of alternative methods which have been used for checking field windings for shorted turns. In addition to those requiring an air-gap search coil, these include the measurement of 100 Hz (for 50 Hz generators) and higher even harmonic components of current which may circulate between the parallel paths in each phase of the stator winding. Other methods described are suitable for off-load testing. These include the Recurrent Surge Oscillograph (RSO) test. In this test, a fast-fronted step pulse is injected (through a source resistance) between each slip ring and earth, in turn, and a comparison made between the two resulting traces. A shorted turn is indicted by a deviation between the two pulses, which also gives the approximate location of the short by measurement of the position along the pulse where the deviation starts. The method is very sensitive in that it can detect a ’short’ with a resistance of as much as 10 Ohms but its application appears to be limited to off-load operation with no field current.

Monitoring for Shorted Turns

All the methods for detecting shorted turns can be used for periodic checks. The RSO test is used for checks on new and refurbished rotors in Works over speed test pits. It is also used during planned maintenance outages in power stations. It cannot be applied to loaded units, and in any case, it is, on the one hand, too sensitive, and on the other, not sensitive enough. The resistance of a single turn is of the order of 1 mOhm. The RSO test, which can give an indication at the level of several Ohms, cannot distinguish between ’short’ resistances as low as 1 mOhm.

For monitoring, a means of detecting shorted turns on load which is able to resolve a ’short’ which diverts a significant fraction of the excitation current is needed. All the methods which use an air-gap search coil are capable of this resolution. As a result of the CEGB’s experience (reference 3 & 4) all large generator units had search coils fitted, whether or not shorted turns were suspected. Continental manufacturers, such as Siemens KWU, have also fitted search coils to large generators, often at the request of utility customers.

Thus, search coil signals are used for periodic checks for evidence of shorted turns. But when do ’periodic’ checks become monitoring - once a month - once an hour? The answer is based on how quickly the effect of shorted turn development may become apparent from the thermal response of the rotor. The time constant of a field winding is of the order of 1 minute. The corresponding change in vibration level (if any) is of the same order of magnitude. Checking a rotor with suspected shorted turns every few minutes, or less, is necessary.

Causes of Shorted Turns

The two main causes of shorted turns in turbo-type rotors are conducting debris, which has been attributed to copper 'dusting' and pick-up, and localised degradation of insulation due to overheating. In the first copper particles are produced by abrasion between half conductors ('dusting') when on barring gear, or by friction between conductor and main wall insulation at normal running speed (copper 'pick-up'). Both mechanisms for producing conducting debris may be present, but 'dusting' has been the main cause in those rotors with half conductors (see reference 6). Shorted turns and earth faults located over the body length of rotors have been attributed to this mechanism.

Localised and rapid degradation of insulation can be the result of shorts due to conducting debris, as explained later, but overheating of insulation because of inadequate ventilation can also cause shorts if there is space to allow adjacent turns to come together by distortion. These are more likely to occur in the end winding region.

Siemens RSTM Development History

The original development of the current Siemens product was carried out in two stages. The development of an improved method for the interpretation of signals from air-gap search coils followed the work of Byars and other CEGB engineers, and the many opportunies for analysis presented by the availability of coils fitted to most large UK generators. The work started in the mid 1980's and was completed in 1990, by two engineers in the Parsons' Mathematical Services R & D Group. The Analysis Program has not changed since its first release in 1990.

The second stage was the implementation of a hardware interface to plant signals and the development of the Supervisory Program, which provides the MMI (Man Machine Interface). The first order was despatched to a Canadian utility in 1992, but prior testing of the equipment was facilitated by signals collected from air-gap search coils in CEGB generators. National Power plc (NP) continued this collaboration through the purchase of hardware based on an IBM compatible PC - the Canadian equipment used an Apollo work station - and trials on a prototype RSTM were carried out at selected NP power stations. During this period, the MMI was enhanced, with the benefit of advice from potential operators.

One of the first orders from NP was for a 1000 MW PS where shorted-turns were suspected on both 500 MW generators. Data collected by the prototype RSTM from this station provided a valuable resource for detailed assessment of the performance of the RSTM over a wide range of loads. In 1996/7 a revision was made to the Supervisory Program relating to the system for reporting shorted turns for unit loads which give highly saturated rotor teeth.

Plant Signals and Conditioning

A schematic layout for a Siemens RSTM installed at a two generator power station is shown in figure 1. Plant signals required are:

i) Air-gap search coil voltage
ii) MW and MVAR loads (4-20mA).
iii) Once per rev. 'shaft marker'

The shaft marker is usually available from the shaft vibration measurement system, but a signal derived from the generator terminal voltage may be used instead.The alarm output and acknowledge signals are optional; alarms may be acknowledged at the PC. The MW and MVAR signals are converted to + 5 V and the search coil voltage scaled in the terminal connection box (TCB) to suit the PC cards After scaling/conversion in the TCB signals are passed via ribbon cable to the PC cards mounted within the PC. The signal from the search coil is passed through an anti-aliasing filter (AAF) before converting to digital form. A relay board, under software control, switches the signals from one unit to the next in sequence for the analysis and the presentation of results.

The Analysis Program

This program is run by the Supervisory Program for each scan of the plant signals. Data are presented to it in two files. One file contains the captured search coil signal; the other holds data on the geometry of the generator, the type of coil (radial or circumferential orientated) and the sampling frequency, resolution and the number of samples in the digitised wave form. Usually, 30,000 samples of 12 bit numbers, collected at the rate of 100 KHz are captured to the file of wave form data in each scan. Thus, data from 15 revolutions of a 2 pole, 3000 rpm unit are used in the analysis.

Much of the Analysis Program run time is spent in removing spurious data from the wave form (reference 7). Firstly, the variation in the time for a single revolution of the rotor is computed. Next, a non-linear, least squares fit is made to determine speed, acceleration, and rate of change of acceleration. From the results of this part of the analysis, asynchronous torsional and flexural vibration components are identified and removed. A new wave form is interpolated for equal intervals around the rotor, in place of equal time intervals. This interpolated wave form is then used to find, as accurately as possible, the position of the centre-line of the teeth in the middle of wound regions.

At this stage, overlapping of the wave form on itself, one pole pitch away, would give results similar to the analogue technique described by Byers, if there were no asynchronous components of vibration.

Any perturbation in the overlapped wave form is assumed to be a combination of shorted turns and synchronous vibration. As the flexural component in the latter may or may not be caused by shorted turns it is important to remove its effect before computing the effect of possible shorted turns. This is achieved by computing wave forms due to unit vibrations and unit turns in each wound slot, and applying least square fits. The identified synchronous vibration components are then removed.

The Analysis Program includes two measures to mitigate the effects of saturation:

i) a bias towards the search coil voltage wave form corresponding to rotor slots/teeth on the leading (in the direction of rotation) sides of the poles, the regions where the air-gap flux is least.
ii) scaling of calculated voltage wave forms by comparison with actual measured) wave forms.

The success of these measures is discussed later, by reference to data collected from an RSTM on two 500 MW generators.

The Supervisory Program

The features of the MMI can be illustrated by the screens of information which are presented to the operator. Figure 2 shows the main screen, from which all other displays may be accessed by using the function keys, F1-F12. The lower third of the screen summarises what further information or tasks may be called up by the function keys. The number keys shown under "GENERATOR SELECTION" are used to select a generator. Each pop-up window may be switched from one generator to another by pressing the appropriate number key.

The upper region of the display gives a summary of the current status for all generators. Each generator is scanned in turn. A digitised version of the air-gap search coil voltage is captured, and an analysis carried out. The results are then filed before starting a scan for the next generator.

Examples of some of the pop-up screens called up using the function keys are given in figures 3 to 8. The F1 key (figure 3) displays the present shorted turns for the selected generator. The F3 key (figure 4) provides a display of the rotor mimic diagram for the selected unit number. Any shorted turn indications from the latest scan are shown on this display.

Usually there is a difference between the present shorted turns (F1 key) and those from the latest scan (F3 key). The difference arises from the concept of alarm bands, which is designed to progressively alert an operator to increasing levels of shorted turns. Figure 5 shows a pop-up window, which is obtained via the Utility Menu (shift-F1 key). It allows changes to be made to the alarm levels. The alarm levels are defined by a threshold - the value below which no alarm is raised - and an increment value. These two values define a set of alarm bands. For the settings shown in figure 5, the bands are:- 0.00-0.30 (no alarm), 0.30-0.50, 0.50-0.70, etc. When an alarm is acknowledged, the alarm level is increased by the increment value. Entries to the present value table (F1 key) are made only if the latest scan gives a value which crosses from one alarm band to another; otherwise the present value remains the same.

The F2 key (figure 6) displays an archive of shorted turns for the selected generator. Entries are made to the archive whenever a shorted turn value crosses from one alarm band to another (changes within an alarm band are not recorded). Each entry includes the unit load, the date and the time, and an indicator if an alarm has been raised, but not acknowledged.

The F4 key provides a display of the search coil wave form for the selected generator. This screen is useful for checking that the signal looks reasonable, that its amplitude is not too high, such that the wave form is clipped, and that it is regularly triggered by the shaft marker signal.

Figure 8 shows the Utility Menu (shift-F1 key), after entering a password. From this screen the operator may change a variety of settings and back-up or print archive files. The latest search coil wave forms may be copied to floppy discs for detailed, off-line examination.

Item 9 on the Utility Menu list was introduced in the Supervisory Program revision of 1996/7, referred to earlier. The default setting is ’ON’. This is to avoid misleading indications that shorted turns have reduced under conditions of very high levels of magnetic saturation in the rotor teeth. The effect of saturation is to cause an apparent reduction in shorted turns in a particular slot, as the flux in the adjacent teeth increases. This effect is accommodated by the Analysis Program for lower levels of saturation, over a range of angles which the air-gap flux makes with the pole axis. The apparent reduction in shorted turns due to high levels of saturation outside this range of angles is not reported when the saturation correction feature is 'ON'.

One other feature that was introduced in the 1996/7 revision is that two files of archive data relating to the development of shorted turns are now kept. The first contains the data which may be recalled by the use of the F2 key, as before. The second records the results produced by the Analysis Program before correction, if any, by the Supervisory Program. The additional data recorded in the second archive allows a detailed, off-line assessment of the effectiveness of the treatment of saturation and its improvement.

Fractional Shorted Turns

Following the presentation of a paper on the Parsons' RSTM (reference 8) at the 1993 EPRI Conference the author of reference 1 disputed the existence of fractional, or partial, shorted turns. He argued that the heating of the short invariably causes a resistance weld, and therefore, shorted turns only occur in whole numbers. This belief still persists as is evident from published material on the GeneratorTech Inc. internet site (reference 2).

All our experience in detecting shorted turns is on turbo-type generators with direct, hydrogen cooled, rotor field windings. We have never seen evidence of conductors which have been welded together. There is a good reason for this. The local losses in the shorting resistance are not enough to raise the temperature high enough to melt the copper of direct hydrogen cooled conductors. Figure 9 shows how the losses vary with the ratio of short-circuit resistance to the resistance of one turn, and the field current, for a typical 500 MW unit. Overheating at the short can be sufficient to cause rapid and severe degradation of the electrical and mechanical properties of the inter-turn and ground wall insulation. For any given field current the losses are a maximum when the shorting resistance equals the turn resistance. At this value, 50 % of the field current is diverted through the shorting path. There is a 50 % shorted turn. Figure 10 shows the relationship between the ratio of shorting resistance to turn resistance, and the percentage shorted turn. In counting the number of shorted turns in a particular coil, it is possible that the reported number is the sum of several, partially shorted turns.

The Influence of Magnetic Saturation

The rotor teeth of large, turbo-type generators are worked at very high flux densities. such that, at the highest levels, the incremental value of relative permeability approaches that of air. The effect of saturation is to cause an apparent reduction in shorted turns in a particular slot as the flux through the adjacent teeth increases. With high saturation the rotor tooth tip leakage flux picked up by the air-gap search coil becomes dependent upon the position(s) of the shorted turns within the slot depth. Another effect of high saturation relates to lack of (perfect) homogeneity of the magnetic properties of rotor iron . At low flux densities and therefore, high incremental, relative permeabilities the variation in magnetic properties from one pole to the next does not matter because the magnetic field in the air-gap is dominated by the air path. At high flux densities differences in incremental (and chordal) permeabilities around the rotor could be a source of false shorted turn indications, if the alarm threshold level was set too low. Figure 11 shows some results of measurements of the magnetisation characteristics of samples taken from a rotor forging, for a typical steel specification. It is impractical to measure much beyond levels of 2.2 T.

The results of finite element calculations for 500 MW load are illustrated in figures 12, 13 and 14 for one rotor design. The highest flux densities reach 2.6 T in the rotor teeth necks and some tooth tips. Figure 15 is an example of a search coil voltage (from a radial coil) for a 500 MW unit on which are superimposed the integrated wave, and its fundamental. The vertical line marks the position where the radial flux is zero - the zero flux axis. GeneratorTech Inc. (reference 2) provide an excellent description of how the zero flux axis varies with unit load and advocates that generator load be increased step by step to place the zero flux axis at the centre-line of each slot, in turn, for each measurement. The calculation method in the Analysis Program avoids the need to adjust load to achieve this alignment, but its results are effected by saturation.

Archive data collected by the RSTM has revealed how effective, in practice, the Analysis Program algorithm copes with tooth magnetisation. The simplest indicator of the level of saturation we have found is the air-gap flux angle - that is - the angle between the axis of the fundamental, air-gap flux density and the pole axis. Contours of the air-gap flux angle, derived from measured wave forms, are shown on figure 16 for a particular 500 MW generator. Figure 17 shows the range of flux angles, for each of the 8 coils in the same 500 MW unit, within which a consistent value of shorted turns may be expected, given that the actual shorted turns have not changed. We refer to the coil as being 'in-zone' if the flux angle falls within the favourable range for that coil. Outside this zone magnetic saturation causes an apparent reduction in the Analysis Program result for that coil. The result is that, on light load, saturation tends to hide the shorted turns in the shorted pitch coils (A, B, C, D) - on high load shorted turns in the larger pitch coils (E,F,G,H) can be obscured. If the air-gap flux angle is outside the favourable range of values ("out-of-zone") for a particular coil, the Supervisory Program ensures that a reduced level in shorted turns returned by the Analysis Program is not reported.

Archive Data from Two 500 MW Units.

One of the first RSTMs was installed at a 1000 MW power station with two 500 MW units, both with suspected shorted turns. With the cooperation of the unit operators and National Power engineers, the monitor was set up to gather additional data to files on the PC’s hard disc drive. The alarm increment was set lower than usual to obtain more entries to the archive history files. A software routine was also added to automatically capture search coil wave forms, without the need for operator action. The operating chart for each unit was divided into a 25 X 25 grid, defining 625 zones (figure 18). Whenever the unit load entered any zone for the first time, a sampled search coil wave form was copied to a file on the hard disc, with a file header containing the load, date and time.

Both units were often operated in two shift mode and therefore provided data over a wide range of loads in a short period of time. Figures 19 and 20 indicate a subset of the load points for which data was recorded from unit 1, and from unit 2, over a period of 20 hours after the original unit 2 rotor had been replaced with spare of the same design. All three rotors had shorted turns. The data collected on shorted turns covered the range from a shorter pitch coil (’C’) to the largest pitch coil (’H’).

The data taken from archives in figures 21 and 22 have been selected to illustrate the effects of high magnetic saturation for the worst case found - reducing indicated shorted turns by 1/2 for each 10 degrees increment of flux angle, outside of the favourable (’in-zone’) range.

The monitor enabled both units to be operated up to rated MW load for several months, with MVAR export generally limited to below 200. The rotor in unit 2 was replaced during a planned outage with a spare. In a very short period the spare rotor developed shorted turns too. When the rotors were later removed to the original manufacturers Works and the end retaining rings removed, the cause of the shorts was found to be overheating of the end winding insulation, allowing electrical contact between adjacent conductors.

Future Development

Following the purchase of Parsons PGS in 1997 by Siemens the engineering support of C and I products and related services is being transferred to Siemens KWU in Germany. The RSTM hardware is to be developed into a single rack mounted unit which combines the PC, data acquisition cards and terminal connection box. The software will be converted from 16 bit to fully 32 bit executables to exploit the features of the Windows NT operating system.

The current Siemens DIGEST (Diagnostic Expert System for Turbomachinery) system is particularly suited for application to new plant. It allows several modular condition monitoring systems to be run together under supervision of a control room work station. Data gather from each module and other instruments in the field via a network may be combined for presentation and more intelligent diagnosis, and then integrated into the station management information system. Available modules include plant thermodynamics (heat rate), shaft vibration, RF analysis and stator coolant flow. The RSTM will be added to these.

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