RECLAMATION

Managing Water in the West

Generator Rotor Rim to Spider Arm Attachment Data Collection

Research and Development Office
Science and Technology Program
Final Report ST-2019-7140-01

U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

September 2019

Mission Statements

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14. ABSTRACT The U. S. Bureau of Reclamation, Technical Service Center conducted tests designed to measure generator rotor rim movement on two, seventy-five megawatt hydroelectric generators. Tests focused on evaluating the generator rotor rim to spider arm attachments and the measurement of movement of the rotor rim as a result of centrifugal and torque loading and thermal expansion. On one unit, tests were conducted prior to and after repairs were made on the rotor to 'reshrink' the rotor rim. Minute measurements of radial and tangential movement and changes in rotor shape relative to increased generator speed were recorded as the rim lost pre-tensioning with the rotor spider.		
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Generator Rotor Rim to Spider Arm Attachment Data Collection

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Primary research was performed by the Technical Service Center, Electrical and Mechanical Engineering Division (86-68400); Hydropower Diagnostics and SCADA Group (86-68450) and Mechanical Equipment Group (86-68410).

Reclamation's Principal Investigators were Mr. John Germann, Mechanical Engineer and Mr. James DeHaan, PE, Electrical Engineer. Other team members were Electrical Engineers, Mr. Jacob Lapenna, PE, Mr. Patrick Council, and mechanical engineer, Mr. Michael Rauh.

Field research was conducted at the following Reclamation Powerplants: Yellowtail Powerplant, Montana Area Office, Fort Smith, Montana with the cooperation and assistance of Mr. Brandon Hilliard, Power Manager, Montana Area Office, and the late Mr. Thomas Tauscher, Facility Manager, Yellowtail Field Division, and others.

Executive Summary

On certain hydro-generators, the rotor rim laminations often relax with age and the tight shrink fit between the rotor rim and rotor spider loosens. This relaxing is often accelerated by the forces created during load rejections, overspeed events, and thermal cycling. When the rim keys, that align and keep the rim preloaded, loosen to the point that the rim ‘floats’ during normal operating speed or below, the accelerated cyclic loading and unloading can lead to damaging consequences to the rotor. Detrimental issues that can occur include irregular air-gap, rotor arm fatigue leading to rotor cracks, loss of rotor center, irregular magnetic forces between the rotor poles and stator winding, poor balance and damage to the rotor spider rim ledge.

In recent years, hydroelectric generator manufacturer’s and utilities have expressed increased concerns with rotor pole and rotor rim attachments cracking due to cyclic fatigue. This has generated the need for better insight into better methodology that can be used for stress analysis, fracture mechanics and material degradation so that the remaining life of the rim and attachments can be predicted. By using actual data, assessments of stresses and cyclic loading of components can be more accurate. This successful research focused on the ability to measure within the rotor and in real time, generator rotor spider arm to rotor rim movement on an operating hydroelectric generator. Reclamation research engineers instrumented and developed test methods and techniques that were used in testing a generator with a suspected loose rotor rim. This report includes a travel report that details the methodology and findings from the test effort. The knowledge gained from the research will help to better assess rotor spider arm to rim fixation conditions in Reclamation’s aging generators.

Real-time measurements were taken on two hydroelectric generators. Research tests demonstrated the ability to obtain high precision measurements of rotor rim movement from the rotating rotor platform. When applied across Reclamation, data collected from this new test method allows for improved operation and maintenance that will help extend the life of these critical assets. This research was conducted on two hydroelectric generators at one of Reclamation powerplants and funded through Reclamation’s Science and Technology program.

Contents

Figures

Main Report

The U. S. Bureau of Reclamation's (Reclamation) aging hydroelectric power plant infrastructure presents some unique problems with mechanical components associated with its large hydro-generators and pump motors. These include fatigue related cracks in the rotor spider arm to rim and rotor pole to rim connections, loss of rim shrink where the rotor rim attaches to the rotor spider arms, and occasionally a loose fit at the rotor to shaft hub. This research examines dynamic testing that was conducted in an attempt to accurately measure the amount of looseness and rim 'float' on a hydro generator where a loose rotor rim was identified.

Most hydroelectric generators in the Bureau of Reclamation fleet are designed such that the generator rotor rim will expand and can lose the tight shrink fit between the end of the rotor spider arms and the rim. This is normally designed by the manufacturer to occur in an overspeed condition. As generators age, inherent stresses within the laminated rotor rim often relax, and the rotor rim becomes loose at synchronous operating speed or below. With repeated start-stops, load rejections and thermal cycling, this condition worsens and the rotor rim deviates from its design diameter and original circular shape (National Electric Coil, 2017). When this happens, several major problems can occur. For example, torsional loads produce higher than normal tangential forces on certain individual rotor arms as the loss of rotor stiffness creates higher than designed cyclic loading on these arms. This can eventually cause fatigue cracking issues in the rotor arms. Second, rim deformation, created from the rim not returning to the same position after it floats, creates a narrowing and irregular air gap between the generator rotor and the stator. This can produce greater fluctuations in magnetic forces between the rotor poles and stator. Rotor imbalance can also be effected as the rotor center deviates.

Yellowtail Power Plant (Yellowtail) is a four-unit, 280,000 KW hydroelectric powerplant located in south central Montana. The plant's generators are over fifty years old. The four units at Yellowtail are in the process of receiving an extensive generator refurbishment. Work includes a new stator core and winding, rotor pole removal and refurbishment, and various turbine work and recoating.

Recently, the rotor rim to spider arm attachment on each of the generators was determined to be loose resulting in an irregular and changing rotor shape. In 2017, during start-up and balancing of Unit 1, the second unit to have completed the generator and pole refurbishment, excessive shaft runout was measured. The contractor was unable to fully balance the unit and unit start-up was postponed. Subsequent hard measurements of the rotor spring keys determined that the generator rotor rim was not adequately pretensioned to the rotor spider arms and had lost almost all of its rim shrink. It was hypothesized that this condition was allowing the rotor rim to 'float' at operation below synchronous operating speed.

Reclamation recognized that Unit 1 at Yellowtail presented a unique research platform to perform dynamic tests and collect data on rotor rim movement. This research project allowed for dynamic rotor rim movement measurements to be taken and helped to verify the rim condition. Reclamation used this opportunity to test the unit prior to and after completion of the rim repairs allowing measurement of both post- and pre-repair conditions.

Reclamation has developed within its Technical Service Center, Hydropower Diagnostics and SCADA Group, specialized instrumentation to dynamically measure the amount of movement and the corresponding speed condition where a hydroelectric generator rotor rim separates from the rotor arms. This instrumentation was attached inside the rotor structure and through the use of advanced wireless technology, transmitted rotor spider arm to rim movement, to data acquisition equipment outside the generator where measurements were stored for analysis. Rotor/stator air gap shape and tolerance and other critical measurements from stationary sensors were also recorded. Reclamation is the only known entity within the hydroelectric community that performs this particular type of dynamic test that measure the amount of rotor spider arm to rim movement from inside the spinning rotor.

Initial field measurements on Unit 1 were conducted in April 2017. The findings helped lead to a contract modification to 're-shrink' the generator rotor rim onto the rotor spider arms. This work was conducted by the primary contractor through a contract modification. The rotor rim reshrink work was substantially completed in late April 2018. Dynamic rotor rim measurements, similar to the initial measurements, were again repeated on Unit 1 in June 2018. Measurements were also conducted in July 2018 on Unit 4, the next unit to be refurbished, prior to its rotor being reshrunk. Funding did not allow for post rotor rim measurements of this machine. Additional inspections and findings have indicated that sister Yellowtail Units 2 and 3 may also be experiencing rotor rim to spider arm attachment issues.

Generator Rotor Design

Hydroelectric generator rotors rims are generally assembled to the rotor spider using one of three typical designs (Westinghouse Electric Corporation, 1984).

One method is where generator rim lamination punching's have dovetails at the inside diameter which are inserted in a similar dovetail slot machined into each spider arms outside diameter. In this case the rotor spider is subject to the centrifugal forces of the rim, poles, coils and other rotating appurtenances. This method is typically no longer used in the industry due to the massive size required of the spider structure to offset these centrifugal forces.

Another method used by some manufacturers is to allow the rim to be loose, or 'float' from the spider at all conditions of operation. This method does not force the rim to stay centered on the spider and can be very detrimental to the operating balance of the unit as well as creating other problems.

A more typical method is where the generator rim lamination punching's have keyways at the inside diameter and the rotor spider has similar keyways machined into its outside diameter. The rim is then built around the spider with a gap between the structures. When the rim is completely assembled, it is expanded by heating, and keys that are larger than the gap plus the keyway depths are inserted into the keyways. The rim is than allowed to cool and contract. The keys then apply a compressive load on the spider and a radial outward load on the spider rim. The keys are generally sized so that the rim retains a small radial outward load on it during normal operating speed. If the generator goes to runaway speed, the rim is allowed to expand beyond any imposed radial forces. When the generator returns to normal speed, a radial force is again present to force the rim to stay centered on the spider.

This is the most common method used to attach the rotor rim to the spider. The rotor laminated rim sustains its own centrifugal force and that of the poles and coils. The spider is subjected to only its own centrifugal forces and that of the brake ring, if the brake ring is attached to the spider. In this way, the spider can be less massive in size and weight.

Investigation into the Yellowtail Westinghouse generator rotor rim attachment design determined that the original rotor rim designed was similar to this design, but in lieu of using straight or tapered wedges, used a unique ‘spring’ type wedge. In the case of the Yellowtail rotors, measurements indicated that this spring type wedge had lost its original spring constant force, allowing the rim to ‘float’ even during normal speeds, such as described in the second example. It was because of this that Unit 1 could not be adequately balanced. The loss of radial forces of the spring type wedges was not forcing the rim to stay centered on the spider resulting in irregular rotor shape that changed during cyclical start/stop, thermal, and overspeed operations.

Original manufacturer’s documents from the original installation also indicated that “After the rotor rim was assembled, it was secured to the spider by driving double tapered keys at each arm of the spider until a specified deflection of the spring key was obtained. The use of the spring key eliminates the need for heating the rim prior to tightening and allows for expansion or contraction of it during operation without either overstressing or loosening” (Figure 1 through Figure 4).

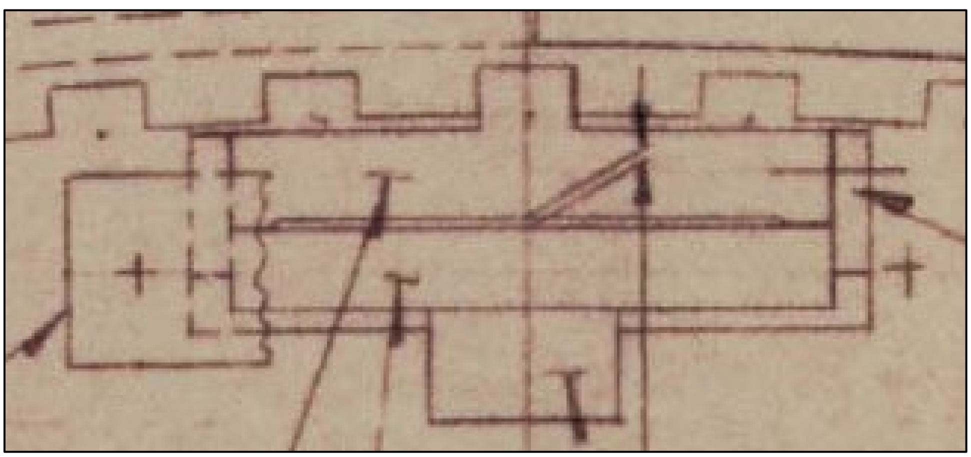

Figure 1.—Original Westinghouse Rotor Spring Key Design.

Figure 2.—Original Westinghouse Rotor Spring Key Deflection measured using a feeler gauge.

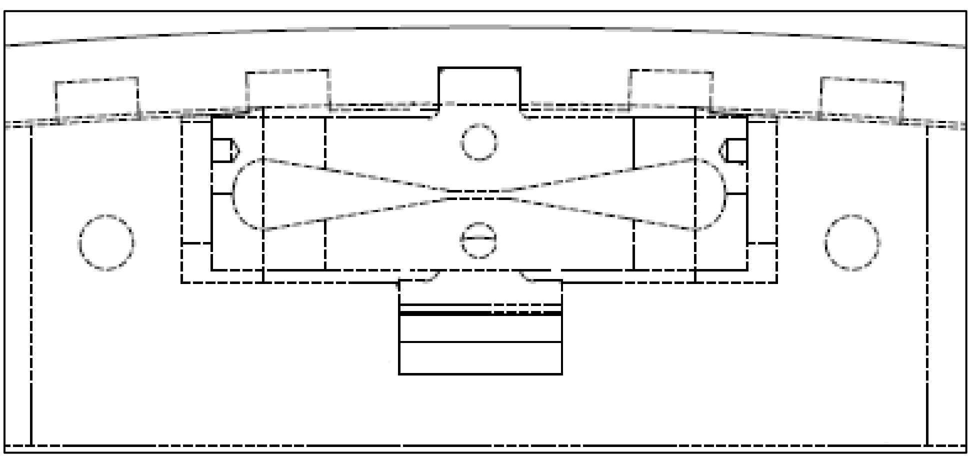

Figure 3.—New National Electric Coil Rotor Spring Key Design.

Figure 4.—New National Electric Coil Rotor Spring Key Pictured while driving the double tapered keys into position.

It is speculated that the drive keys described on each spider arm were never fully engaged to the degree necessary to achieve the required deflection, or that over time, the rim 'seasoned' and the prestress that was originally designed for the tapered wedges was lost. Hard measurements taken of the spring key gap, which indicates key deflection, measured far less than the original manufacturer's design gap. The current contractor elected to use a new spring key design for the rotor rim to spider arm attachment. A finite element analysis of the joint was conducted to assure a proper design. On installation, the contractor could not achieve the required deflection by driving the tapered wedges in cold. Heating of the rotor rim was necessary when installing the wedges to achieve the required design deflection.

Rotor Rim Tests

Taking measurements from a rotating platform such as a generator rotor rim, present several unique and difficult issues. There are two obvious challenges that must be reconciled when taking measurements from a rotating component. The first is providing power to the sensor(s). Because a direct power connection to a spinning rotor is difficult, indirect methods must be used. Batteries are the simplest source and most often used, but batteries have the drawback of having a limited power life which is strongly influenced by the amount of power consumed by the sensor(s) and instrumentation. The use of slip rings or inductive power are two other options that have been successfully used to power sensors. These systems have the benefit of being able to provide long term power, but are more difficult to design, and usually requires the fabrication of special components and modifications to the generator. With the Yellowtail rotor rim movement study, batteries were used to power the sensors.

The batteries, wireless data acquisition system and sensors were attached to the rotor. The batteries had to be large enough to provide power to the sensors for the duration of tests and yet light in weight. Weight and size need to be a minimized due to attachment issues created by the large torsional and centrifugal forces that occur on the rotor when operating and the possibility of the test instrumentation coming loose or unbalancing the rotor.

Also, the generator air housing is designated by Reclamation as a confined space. For personnel to access the rotor area, the unit must be removed from service, a clearance put in place and the unit penstock un-watered. The unit penstock must then be refilled, and the clearance removed once the task on the rotor in completed. This time sequence can take several hours, so this significant time can deplete a large portion of the available battery life once the measurement instruments on the rotor are turned on. To avoid power drain on the battery, a wireless on/off switch was designed into the instrumentation system so that personnel could remotely turn the rotor instrumentation on or off.

Similar to the method to provide power, the second issue that must be addressed when taking measurements from a rotating platform is how to extract the measured data from the sensor. A data acquisition system with a built-in wireless transmitter was used for the Yellowtail tests. When using this type of system, time synchronization of the wireless signal transmitted with other stationary signals being taken, signal strength and noise are problems that must be recognized.

Finally, any measurements taken from the generator rotor or other rotating component comes with a certain degree of risk of the mounted instrumentation becoming unattached. If this were to occur, major damage to the generator could occur. The centrifugal force applied to the instrumentation equipment is compounded as speed increases, the force applied increases by the square of the speed and can be quite substantial. To avoid any possibility of a mounted component becoming detached, the equipment must be securely attached to the rotor. The attachment must be robust and properly designed. To help minimize these forces the battery and wireless data acquisition instrumentation were attached at the rotor hub and a large factor of safety incorporated into the design.

Rotor spider arm to rotor rim movement was measured using proximity probes. Iron brackets were welded to the edge of the spider arm allowing the proximity probes to be mounted facing the rotor rim laminations. Probes were wired back to the centrally located wireless data acquisition equipment using multi-conductor cables. Cables were securely attached to multiple locations to insure that they remained attached during unit operation.

Measurements

Rotor rim measurements on Yellowtail Unit 1 were conducted in April 2017, prior to the unit being disassembled for refurbishment of the rotor rim connections. Similar tests on Yellowtail Unit 1 were conducted on June 2018, after the refurbishment was completed. Finally, the same series of tests were also conducted on Yellowtail Unit 4 in July 2018, prior to its disassembly for similar contract work. The purpose of the research was to develop rotor measurement techniques, including the measurement of rotor rim movement, that could be used to better assess rotor spider to rim fixation issues. Dynamic rotor shape, rotor pole flux, equalizing circuit CT secondary currents, and generator electrical and mechanical parameters were also measured on the stator as part of these tests. Static rotor and stator shape were also recorded.

Reclamation engineers designed and built custom instrumentation that was used to conduct a series of tests on a generator with a rotor that was suspected of having lost its initial rotor rim to rotor spider pretensioning. Measurements were taken inside the rotor frame to determine the minute amount of movement of the rotor rim. Each test consisted of the following operational series of measurements:

1. Baseline measurements from a stopped position in which all sensors were zeroed
2. Unit slow roll to speed-no-load measurements
3. Measurement when the electrical field is applied
4. No load to full power load measurements
5. Offline overspeed measurements
6. Load rejection measurements (Unit 4 only)

Certain tests were conducted with a cold rotor and reconducted after the unit was in operation at full load for long enough to fully heat the rotor.

The following sensors were mounted to the generator rotor to measure spider arm to rim movement:

1. Rim back iron movement – Eight to twelve proximity probes were mounted on brackets attached to leading and/or lagging edge of spider arms measuring radial movement of the rim back iron (Figures 5 and 6).

The following measurements were taken from stationary sensors on the generator on each test:

1. Airgap distance - Two airgap capacitive probes were mounted on the stator to measure rotor shape and air gap distance.

2. Generator equalizing circuit secondary currents - All nine equalizing circuits were monitored using clamp-on CT's (Current Transducers).

3. Speed - Generator speed was measured by a once per revolution optical laser sensor and from the governor's speed signal.

4. Airgap flux – Flux was measured by a Reclamation designed-and-built flux probe.

Figure 5.—Proximity Transducer Monitoring Generator Rotor Rim Back Iron.

Figure 6.—Three Proximity Transducer Located Vertically on the Rotor Arm Used to Measure Generator Rim Back Iron Movement.

With each test, the following generator parameters were recorded from existing generator signals:

1. Megawatts
2. Megavars
3. Terminal Voltage
4. Terminal Current
5. Frequency

Separate mechanical parameters were also measured and recorded during each test. This included:

1. Upper guide bearing runout
2. Lower guide bearing runout
3. Turbine guide bearing runout
4. Wicket gate opening
5. Scroll case pressure
6. Draft tube pressure

The data from the rotating rotor transducers was processed by an analog-to-digital data acquisition system (DAQ) prior to being transmitted wirelessly for analysis. Signals from stationary transducers were also digitized on a separate DAQ and data analyzed and stored.

Test Findings

This research work demonstrates the capabilities that Reclamation has developed to remotely study unique rotor and stator issues that may be occurring on a hydroelectric generator rotor. The results of real-time measurements of generator rotor rim position prior to and after the rotor rim was reset were very encouraging. Travel reports were written after each series of field tests. These reports, found in Appendix A, provides further details of measurement points, tests conducted, instrumentation used, results and conclusions from the individual tests conducted on the two generators tested at Yellowtail. It is suggested that the reader refer to the document that is included in the addendum for further specific information related to the rotor rim measurements and additional test results and conclusions.

The goal of this research was to measure with high resolution and in real-time, small radial and tangential movements of the rotor rim on an actual hydroelectric generator. In addition, it was hoped that it could be identified from these measurements when a rotor rim with inadequate rim shrink starts to float or loses contact with the rotor arms. With this regard, the research was highly successful.

The generator rotors tested have a spring type designed connection as previously described. The objective of the spring key design is to provide a constant linear spring force to the rotor rim to counter and balance the compressive forces of the thermal shrink and the opposing radial outward growth as a result of thermal and centrifugal forces that occur during operation. This type of design is thought to make it more difficult to gage, compared to the more conventional tapered key design, when actual contact between the rotor rim and arm is lost and the rim fully separates.

Prior to reshrinking the rotor rim on Unit 1 and Unit 4, hard micrometer measurements of spring deflection measurements by plant personnel (Figure 2), indicated that the spring keys had lost all spring tension and preload and thus the rims were probably floating when operated at some speed below rated speed. The following examples provide some notable observations from this research that help indicate the accuracy of measurements and present evidence of the separation at below normal operating speed are given:

1. Figure 7 displays the rotor rim movement from generator start to synchronous operating speed of Generator Unit 1 prior to rim reshrink. In this test, conducted prior to the rim being retensioned, the distance between the arm and rim decreased at start up before moving outward as speed increased. This movement is likely due to the tangential deflection of the spider arms as tangential load is applied by centrifugal force. Since the sensor is not mounted on the centerline axis of the rotor arm, the distance measured, increases or decreases depending on the side of the arm it is located on, due to tangential forces slightly bending the arm. Later tests confirmed this hypothesis when sensors were also installed on the opposite side of the arm and recorded opposite deflection motion. All the proximity probes were located on the leading edge of the spider arms in this initial test, and the sensor deflects closer to the rim as the arm bends. The example shown occurred with a rapid start. On slower starts, less deflection was observed. Figure 8 illustrates the same test conducted on the rotor after retensioning the rim and over a slower start period. As can be seen, the negative deflection on start-up is not as pronounced. This may also partially be due to the retensioned rim applying additional stiffness to the rotor which was not there with the rim being loose.

   The figures also display an offset that occurs between some probes as speed increases. Radial movement of the rotor arm is higher in some probes than other. Those probes measuring higher movement were located higher on the rotor. This shows that the top and middle of the rim moved outward more than the bottom of the rim.

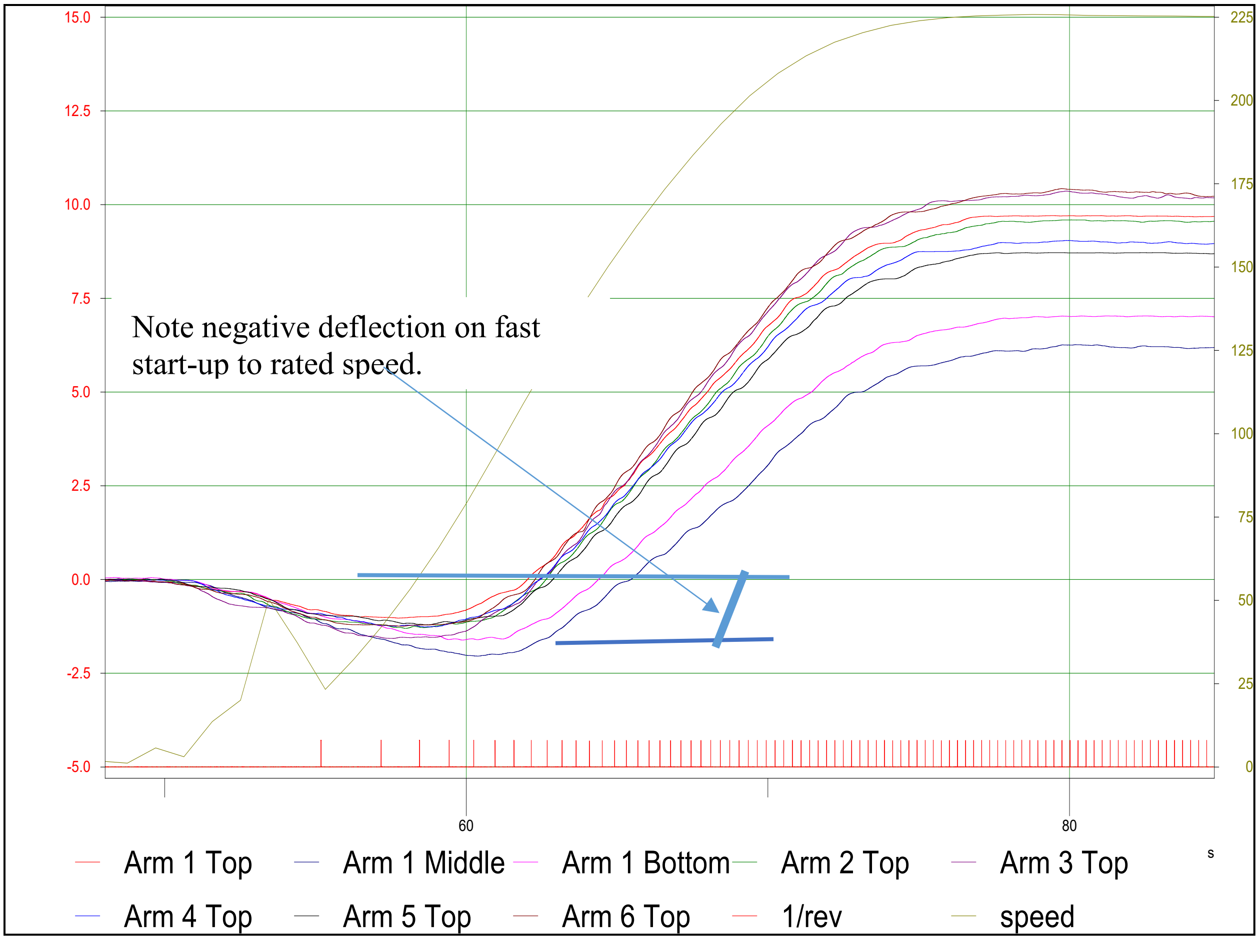

Figure 7.—Unit 1 Rotor Spider Arm to Rim Movement During Start Prior to Reshrink (Ignore non-linearity in initial rotation speed signal).

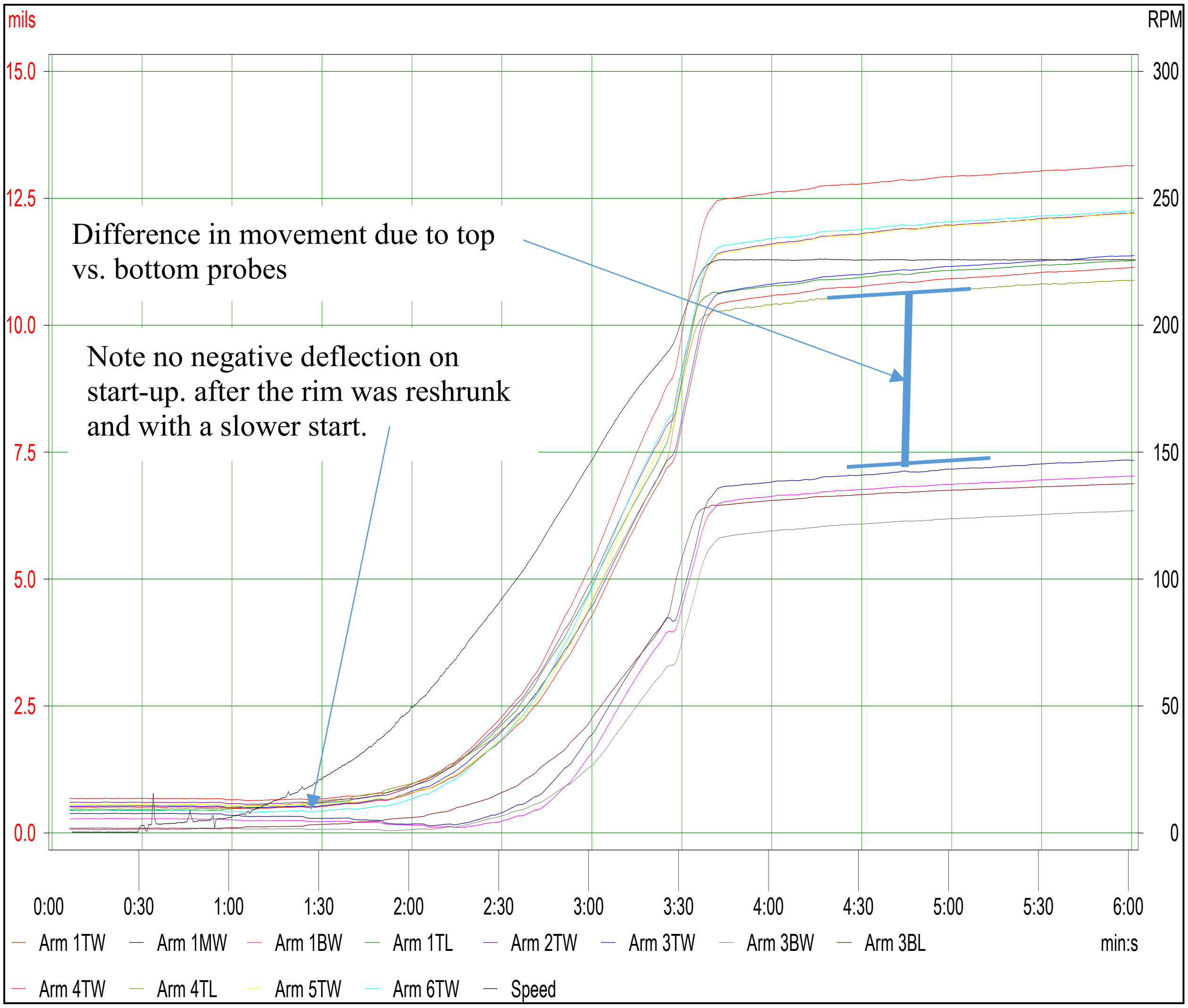

Figure 8.—Unit 1 Rotor Spider Arm to Rim Movement During Ramped Start after Rim Reshrink (Proximity sensors nomenclature- [Arm# - Top, Middle, Bottom – Windward, Leeward]).

2. Figures 9 and 10 are interesting illustrations of rotor rim movement as the unit increasing in speed above synchronous speed into an overspeed condition. As can be seen in Figure 9, the movement of Unit 4 rotor arm 4 becomes non-linear at approximately 290 RPM with the rotor prior to reshrink. This condition was not seen on Unit 1 either prior to or after the rim was retensioned, as seen in Figure 10. The Unit 1 overspeed test was limited to 290 RPMs.

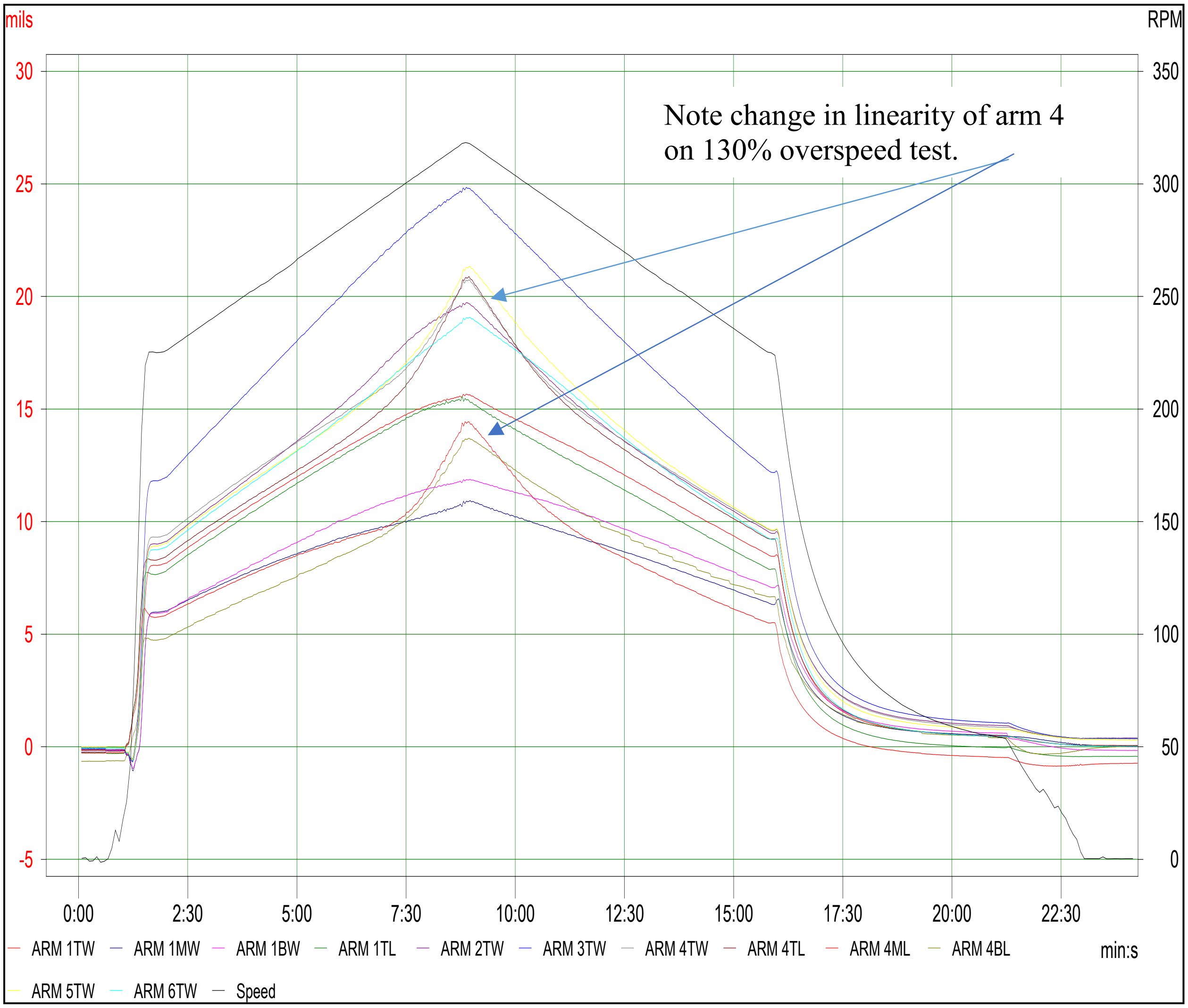

Figure 9.—Unit 4 Rotor Spider Arm to Rim Movement During Over Speed, Test 3 – Rim cold Arm 4 probes display non-linear movement above 130% rated speed.

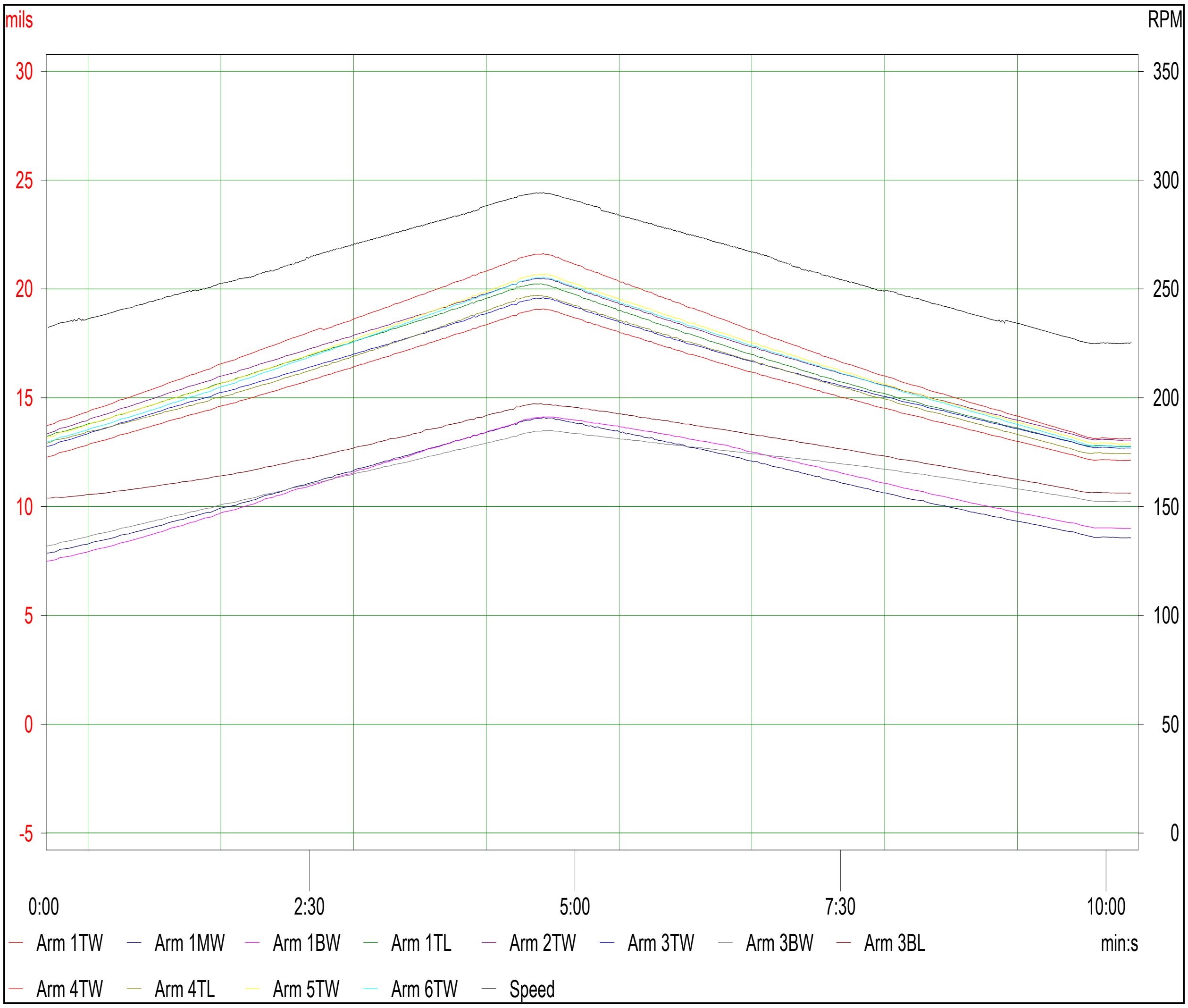

Figure 10.—Unit 1 Rotor Spider Arm to Rim Movement During Overspeed Test of Unit 1 After Reshrink Rotor Rim in a Warm State. Similar results were recorded prior to reshrink.

3. Figure 11 illustrates individual rotor arm deflection as the generator load is increased to full load and torsional load is applied to the rotor arms. Increasing distance is shown on windward arm probes while decreasing distance is measured on leeward side probes on this counter-clockwise rotating rotor.

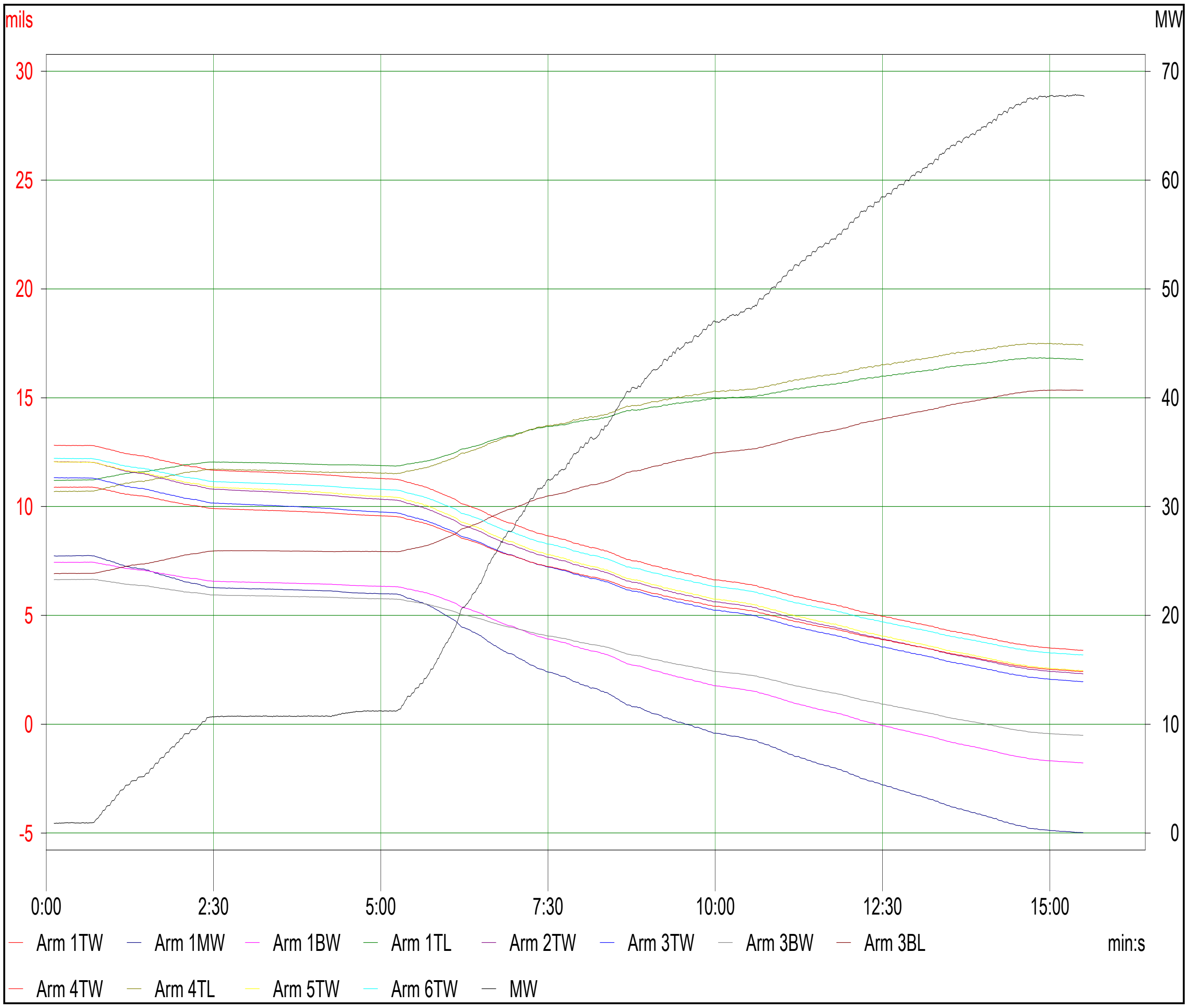

Figure 11.—Rotor Spider Arm to Rim Movement During Stepped Unit Loading.

4. Figure 12 is an example of the high precision of the rotor rim movement measurements. This plot of Generator Unit 1 after the rotor has been retensioned shows a minute 0.17 mil., once per revolution movement when the rotor field is applied. This once per revolution movement is a result of stator shape and unequal current flow resulting in a slight magnetic imbalance.

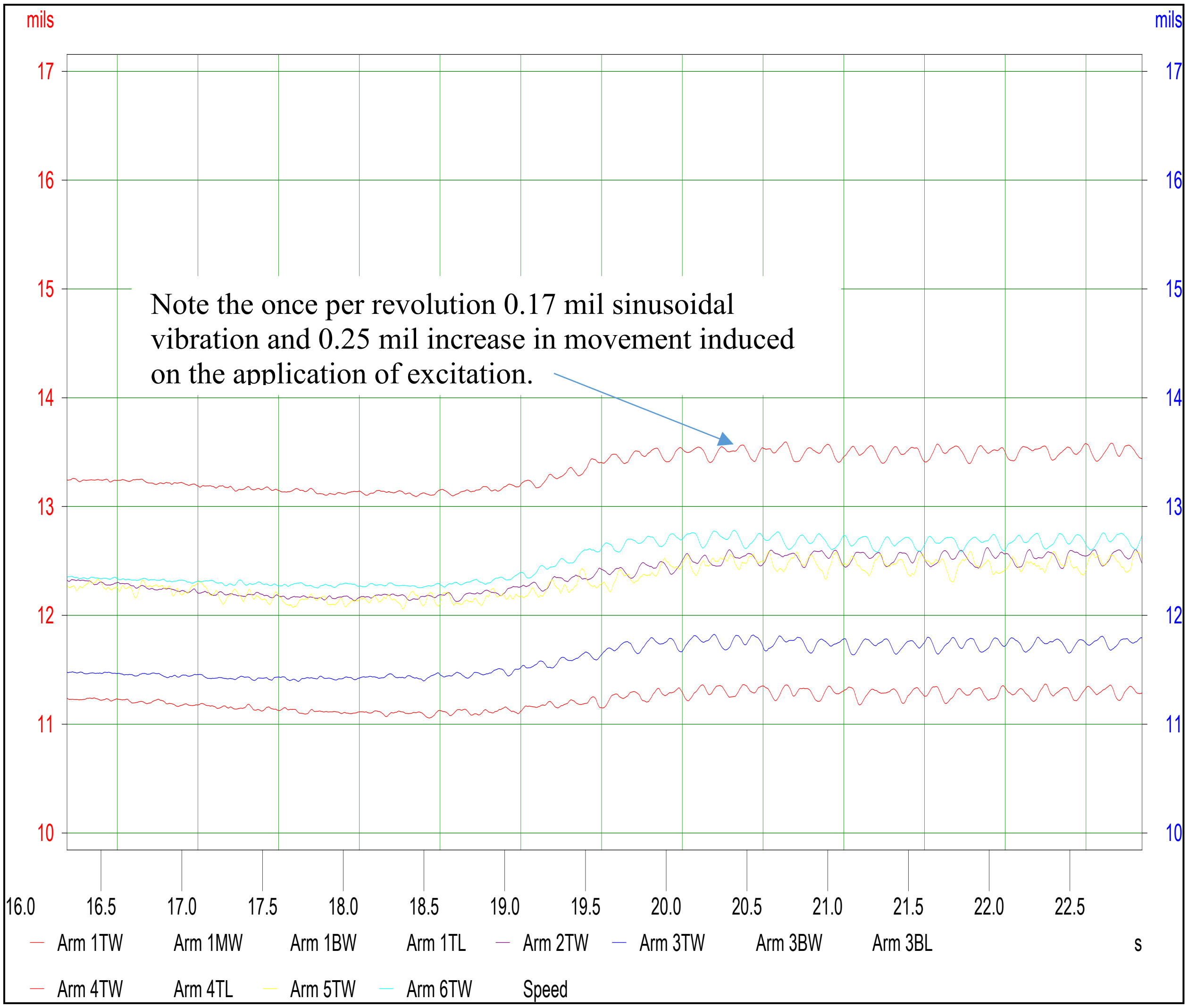

Figure 12.—Rotor Spider Arm to Rim Movement During Excitation - Test 2. DC offset between excited and unexcited =0.25 mils. Excited ripple is 0.17mils peak to peak with a period of 0.267 sec (225 RPM). Phase shift between arms is 60 deg.

Conclusions

Rotor rim movement tests were successfully completed on three different occasions on two different generator units at Yellowtail Powerplant in south central Montana. Rotor rim movement could accurately be measured within a thousandth of an inch; a far higher precision than can be achieved from other types of sensors such as air gap sensors. Various tests demonstrated Reclamation's abilities in carrying out these difficult measurements with a high degree of accuracy. These tests also demonstrated the capability of the instrumentation used by measuring simultaneously multiple channels through a wireless communication link. The tests conclusively displayed certain aspects such as radial and tangential movement of the spider rim and the spider arms as higher speed was obtained. The proximity probes used were capable of measuring non-linear rim movement, minute cyclic movements of the rotor rim and differencing amounts of movement of individual spider arms. Other measurements determined accurate rotor and stator shape. The measurements of rotor arm and rotor rim movements illustrate that rotor and rotor rim are very dynamic components when in operation which change in shape and size as changing forces are applied. These include start-stop forces, increasing load torque, and even once-per-revolution cyclic forces due to magnetic imbalance. While further research in this methodology is recommended, these tests show that precision measurement techniques such as those demonstrated can help fulfill an important opportunity and need that can be applied to many suspect generators with similar rotor rim issues and help provide needed data for end of life rotor and rotor rim attachment assessments. Future tests may include experimenting with different sensor locations on the arm, torque and strain measurements, or making other changes which could possibly better define results. The research conducted under this project will explicitly benefit future intended research in this area and aid in Reclamation's future research in developing a permanent rotor scanning instrument.

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Westinghouse Electric Corporation. (1984). *Glen Canyon Stress Calculations - 55A5m001-1*.

Appendix A – Yellowtail Generator 1 and Generator 4 Rotor Measurements Travel Report

BUREAU OF RECLAMATION
Technical Service Center
Denver, Colorado

TRAVEL REPORT

86-68450
PRJ-20.00

Date: Sept 7, 2018

ELECTRONIC MAIL ONLY

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Hydropower Diagnostics and SCADA Group

From: James DeHaan, P.E., Electrical Engineer

Jacob Lapenna, Electrical Engineer

Patrick Council, Electrical Engineer

Subject: Yellowtail Generator 1 and Generator 4 Rotor Measurements

1. Travel period: June 18-22 and July 8-13 2018.

2. Places or offices visited: Yellowtail Powerplant, Fort Smith, MT.

3. Purpose of trip: Perform Tests on Generator 1, June 18-22 and Generator 4, July 8-13.

4. Synopsis of trip: The rotor measurement tests are summarized as follows:

Overview:

Prior to the subject testing, Generator 1 (G1) and Generator 3 (G3) at Yellowtail were refurbished. This included a new stator core, new armature winding, and the field poles were removed and re-insulated. G3 was returned to service with little balancing issues. When attempting to balance G1 to return it to service during the spring of 2017, it was discovered that there was a significant balance difference between running the unit excited or un-excited. It also was noted that when G1 was subject to an overspeed event the balance would get much worse and not always return to pre-overspeed values until unit rotation was stopped. In addition, when G1 was loaded for a long period of time it was noted that the unit balance would vary over time. Various unit conditions were discussed that could lead to these undesirable issues including rotor rim float.

The rotor rim is connected to the spider arms via a spring system. Previous measurement made by the rewind contractor and Great Plains regional personnel showed that the spring deflection had relaxed and was not per original specifications. Thus, it was suspected that the rotor rim was floating (springs no longer active) when operated at rated speed. On April 20, 2017, rotor tests were performed at the request of Great Plains Region to determine if G1 rotor rim was floating (springs not compressed) and investigate any potential issues related to the re-insulated field poles. Travel Report *Yellowtail Generator 1 Rotor Measurements* dated May 31, 2017 details these measurements and is included as Attachment C to this report.

Following these 2017 tests Great Plains Region decided it would be best to re-shrink the rim. This involved pulling the rotor and having the contractor re-tension the spring system. This ended up being a fairly complex process that required redesigning the spring shape to reduce spring fatigue stresses, heating the rotor rim to remove the springs, designing individual custom new springs to fit into the existing warped rotor rim slots, heating the rim to re-tension the new springs and installing the rotor into the generator. Following this work G1 was returned to service with little balancing issues. Tests on G1 were performed in June 2018 to gather new rotor rim movement data to compare to pretest results.

Generator 4 (G4) is the next unit schedule to be re-furbished. Testing of G4 was performed in July 2018 to gather pre-teardown data on rim movement and to record rotor and stator shape.

Measurements:

On June 21, 2018, rotor tests were performed to record G1 rotor rim movement during various operating conditions. To measure rim movement relative to the spider arms, 12 proximity probes were affixed to each spider with proximity to the rotor rim recorded. A battery powered data acquisition system (DAQ) was used to record and transmit the proximity probe data. Details of these measurements are included in Attachment A. Prior to testing, the reading of all proximity probes were zeroed. Three series of tests were conducted. These tests included measurements while ramping G1 from stand still to rated speed, at speed-no-load-no-excitation, at speed-no-load-excited, while ramping megawatt load from zero to rated load, and while ramping the unit to an overspeed condition. Test results are contained in the attachment.

On July 11, 2018, rotor tests were performed to record G4 rotor rim movement during various operating conditions. Rotor rim movement was measured using the same method as described for G1. Details of these measurements are included in Attachment B. Prior to testing, the reading of all proximity probes were zeroed. Four series of tests were conducted. These tests included measurements while ramping G4 from stand still to rated speed, at speed-no-load-no-excitation, at speed-no-load-excited, while ramping megawatt load from zero to rated load, while ramping the unit to an overspeed condition, and during a load rejection. Test results are contained in the attachment.

In addition, the rotor and stator shape was measured on G4 in a cold, static condition. To measure the shape of the rotor, 2 capacitive probes were mounted to the bottom and top of the stator. The rotor was spun slowly and the shape of the rotor was recorded. To measure the shape of the stator, 2 capacitive probes were mounted to the bottom and top of a rotor pole. The rotor was spun slowly and the shape of the stator was recorded. Details of this measurement are included in Attachment B.

G1 Observations:

Movement of rim relative to spider arm:

As G1 was accelerated from zero to rated speed, the distance between the arm and rim increased by about 11 mils at the top of the rim (figure A1) with a maximum spread of about 2.5 mils. Given the spring deflections of 48 mils average measured by Great Plain regional personnel, the springs remain engaged with the rim at rated speed.

> Compared to previous measurements (prior to rim re-shrink): The distance between the arm and rim increased by about 10 mils at the top of the rim with a maximum spread of about 2 mils. Given the spring deflections of 9 mils average, there was little to no spring tension left in the spring at rated speed.

Very little rim to spider arm movement was measured when G1 was excited. An average displacement of 0.25 mils was recorded. After G1 is excited a once per revolution (1/rev) periodic movement of the rim with respect to the spider arm is seen. The movement is 0.17 mils peak to peak (see figures A6 and A7).

> Compared to previous measurement: No additional rim to arm movement was measured and no periodic movement was observed when the unit was excited. However, an older wireless DAQ system was used to record this data and its minimum digital resolution was about 0.25 mils. Thus, small movement of 0.25 mils or less were at or below the noise level of the recorded signal and were not observable.

When G1 was loaded, the distance between the spider arm and rim either increased or decreased about 10 mils on average (figure A2) dependent on whether the probe was located on the windward or leeward side of the spider arm. The largest movement was recorded on Arm 1MW (Middle, Windward) probe of 12.7 mils. The windward mounted probes all moved closer to the rim while the leeward probes moved further from the rim. This is due to the spider arm deflection under load. Three windward probes actually moved closer to the rim at full load than at standstill when the probes were zeroed.

> Compared to previous measurement: The distance between the arm and rim decreased about 6.5 mils on average. All the proximity probes were located on the windward side of the spider arms. The largest movement was recorded on Arm 1MW (Middle, Windward) probe of 9.8 mils.

When G1 was loaded at 68 MW for 1:45 hour, the stator and rotor both expand due to heat. Rotor expansion was noted as all the proximity probe signals increase of 2 to 3 mils during this time period (figure A3).

> Compared to previous measurement: When G1 was loaded at 63 MW for 1 hour, rotor expansion was noted as the proximity probe signals showed an increase of 2 to 3 mils.

During unit shutdown, the arm to rim proximity probe signal decreases as G1 speed decreases (figure A4). When the unit comes to a complete stop, the distance between the arm and rim was about 2 mils greater than when the unit was initially started. This is most likely due to the rim being warm from running for 1:45 hours at 68 MW.

> Compared to previous measurement: When the unit comes to a complete stop, the distance between the arm and rim was about 2.5 mils greater than when the unit was initially started due to rotor rim heating.

G1 was accelerated to about 130% of rated speed. During this ramp in speed the distance between the arm and rim increased somewhat linearly with respect to speed (figure A5 and A6). The movement at each arm is fairly consistent as their change in distance during the ramp were within 1 mil of each other. Two overspeed tests were performed. One with the rotor at room temperature (figure A5) and one after the unit had run at full load for 1:45 hours and the rotor rim was warm (figure A6). For the cool rotor rim the maximum reading was 19 mils. For the warm rotor rim the maximum distance was 21.6 mils. Movement at the middle and bottom of the arm was about 4 mils less than the movement at the top. Given the spring deflections of 48 mils average, the springs remain engaged for both these overspeed events.

> Compared to previous measurement: G1 was accelerated to 130% of rated speed. Overspeed test was performed following 1 hour of operating the unit at 62MW and the rotor rim was warm. The distance between the arm and rim increased somewhat linearly with respect to speed. For the warm rotor rim the maximum movement was 20.5 mils. The movement of 5 of the 6 arms were fairly consistent, with the exception that the movement at arm 6 was about 2 mils greater than the average movement at the remaining arms. Given the spring deflections of 9 mils, there is no spring tension left at over speed. Movement at the middle and bottom of the arm was about 2 mils less than movement at the top.

G4 Observations:

Movement of rim relative to spider arm:

As G4 was accelerated from zero to rated speed, the distance between the arm and rim increased between 9-11 mils at the top of the rim (figure B1) except Arm 3TW (Top, Windward), which moved 13.8 mils. Given the spring deflection measurements of 8 mils average by Great Plain personnel, there is little to no spring tension left in the spring at rated speed. It is interesting to note that Arm 3 measured spring deflection was 0 mils and it moved the most during this test.

> Compared to G1 measurements: Similar measurements to G1 that showed a movement of around 10-11 mils during startup.

Very little rim to arm movement was measured when G1 was excited. An average displacement of 0.25 mils was recorded. After G1 is excited a 1/rev periodic movement of the rim can be seen. The movement is 0.17 mils peak to peak. (see figures B7 and B8)

> Compared to G1 measurement: Similar results were observed.

When G4 was loaded, the distance between the arm and rim either increased or decreases about 10 mils on average (figure B2) dependent on probe location. The largest movement was recorded on the Arm 4ML (Middle, Leeward) probe of 13 mils. The windward mounted probes all moved closer to the rim while the leeward probes moved further from the rim. This is due to the spider arm deflection under load. Two windward probes moved closer to the rim at full load than at standstill when the probes were zeroed.

> Compared to G1 measurement: Similar results were observed with one of the middle probes showing the largest movement.

When G4 was loaded at 62 MW for 1 hour, the stator and rotor did not show any additional movement. This most likely is due to the fact that the unit was ramped from zero to 74 MW over a 90 minute period and the rotor rim heating and expansion occurred during the slow load ramp. When G4 was shutdown (next paragraph) the distance between the arm and rim was about 3 mils greater than when the unit was initially started. This movement is most likely due to the rim being warm.

> Compared to G1 measurement: Although movement was not recorded on G4 during the steady state load, it appears that there was similar movement between G4 and G1 of around 2 to 3 mils due to rotor heating.

During unit shutdown, the arm to rim proximity probe signal decreases as G4 speed decreases (figure B3). When the unit comes to a complete stop, the distance between the arm and rim was about 3 mils greater than when the unit was initially started. This is most likely due to the rim being warm from running for 1 hours at 62 MW.

> Compared to G1 measurement: Similar results were observed.

G4 was accelerated to about 140% of rated speed. The distance between the arm and rim increased somewhat linearly with speed (figures B4 and B5) to 130% over speed. From 130% to 140% of rated speed, an exponential increase in rim movement was recorded on all Arm 4 measurements (Arm 4TW, Arm 4TL, Arm 4ML and Arm 4BL). Two overspeed tests were performed. One with the rotor at room temperature (figure B4) and one after the unit had run at full load for 1 hour and the rotor rim was warm (figure B5). For the cool rotor rim the maximum movement was 25 mils on Arm3TW (Top, Windward), for the warm rotor rim the maximum movement was 24 mils. Movement at the middle and bottom of the arm was about 4 mils less than the movement at the top. Given the spring deflections of an 8 mils average, there is no spring tension left in the spring at over speed.

> Compared to G1 measurement: G1 had similar results to 130% of rated speed. Measurements between 130% - 140% were not conducted on G1 so it's behavior above 130% cannot be compared to the non-linear movement noted on G4.

G4 load rejection test was performed. The load rejection was from a load of 50MW. The maximum speed reached during the load rejection was 122% (274 RPMs). The movement of the rim was a bit higher than the ramped over speed test. For example, the rim movement measured at the unit maximum speed of 122% is about 3 mils greater than the 122% speed value measured during the slow ramped test. Spider arm deflection during the overspeed event would be a probable reason for this discrepancy.

Compared to G1 measurement: No load rejection tests were performed on G1.

Rotor and stator shape:

Rotor shape is shown in Figures B14. From this figure it can be seen that the rotor shape varies by up to 30 mils between the rotor top vs the rotor bottom. Pole 23 is also about 10 mils closer to the stator than surrounding poles.

To help evaluate how round the rotor is, the rotor concentricity and circularity were calculated per CEATI guidelines.[1] Concentricity is defined as the deviation between the best center and the axis of rotation. It also may be referred to as eccentricity in other documents. Circularity is defined as the deviation between maximum and minimum radii, as measured from the best center. The slow roll rotor shape data was evaluated to determine these parameters. Rotor circularity is 1.95% at the top of the rotor and 2.97% at the bottom of the rotor in percent of measured average airgap of 582 mils, and is within the CEATI guidelines tolerance of 6% or less. Rotor concentricity is 1.32% at the top of the rotor and 1.03% at the bottom of the rotor in percent of the measured average airgap. The concentricity at the top location is slightly greater than CEATI guideline tolerance of 1.2% or less. Figure B12 shows the best center data used to determine these quantities.

Stator shape is shown in Figures B13. From this figure it can be seen that the stator shape is nearly identical between the top and bottom of the stator with a maximum variance of up to 15 mils between the stator top vs the stator bottom. It is interesting to note that the stator shape shown in figure B9 is similar to the once per revolution wave shape of the rim movement when it is excited shown in figure B6.

The slow roll stator shape data was evaluated to determine stator circularity and concentricity. Stator circularity is 6.01% at the top of the stator and 6.04% at the bottom of the stator in percent of measured average airgap of 582 mils and is within the CEATI guidelines tolerance of 8% or less. Stator concentricity is 4.15% at the top of the stator and 3.09% at the bottom of the stator in percent of the measured average airgap and is within the CEATI guideline tolerance of 8% or less. Figure B11 shows the best center data used to determine these quantities.

5. Conclusions: This report documents the rotor rim movement measurements performed on G1 and G4. In-depth analysis of this data and specific conclusions will be contained in a subsequent research report. In general the following was observed:

G1 test results.

- Rotor rim movement before and after the installation of the new springs and re-shrinking the rim were very similar. After the rim was re-shrunk the reported spring

[1] Hydroelectric Turbine-Generator Unit Guide for Erection Tolerances and Shaft System Alignment, CEATI International, June 2015.

compression dimensions was determined to be 48 mils. G1 rim movement measured after spring replacement and rim shrink indicates the springs are remaining in contact with the rim at rated speed as well as overspeed of at least 130% of rated, while the old springs did not remain in contact with rim under this same movement.

- During rated speed and over speed conditions, the rotor rim movement is fairly consistent at each spider arm, but some discrepancies remain. This indicates the rotor rim shape is being slightly distorted during operation.

G4 tests results.

- G4 rim movement measured during testing indicates the current spring deflection of 8 mils is not adequate for them to remain in contact with the rim with the unit at rated speed.
- From zero to rated speed the movement at Arm 3 is substantially greater than the movement monitored on the other arms.
- During overspeed the movement or the rim was fairly linear with respect to speed up to 130% of rated speed. Above 130% rated speed the movement of the rim near Arm 4 became exponential with respect to the change in speed.
- During rated speed and over speed conditions, the rotor rim movement is greater than the movement recorded on G1. This indicates the rotor rim shape is slightly distorted during operations.

There is no large variations in the rim movement data that was recorded for G1 prior to re-shrink, G1 after re-shrink, and G4 that would be a good indicator to use to determine if a re-shrink is necessary or demonstrates the advantage of re-shrinking the rim. Additional evaluation and analysis of the rim movement is necessary to identify if any additional systematic observations can be made.

If you have questions or comments, please contact Jim DeHaan at (303) 445-2305.

6. Suggestions: None.

7. PRIS Recommendations: None.

8. Client feedback received: None.

9. Action correspondence initiated or required: None.

cc: 86-68400 (McStraw), 86-68410 (Germann), 86-68430 (Mauer), 86-68450 (DeHaan, Myers),
MT-300 (Tauscher), MT-600 (Hilliard), GP-2600 (Anderson), GP-2200 (Skinner)
(w/att to each)

SIGNATURES AND SURNAMES FOR:

Travel to: Yellowtail Powerplant

Dates of Travel: June 18-22 and July 8-13, 2018

Names and Codes of Traveler: James DeHaan, Jacob Lapenna, Patrick Council 86-68450

James M DeHaan
Digitally signed by James M DeHaan
Date: 2018.09.07 16:19:30 -06'00'

Traveler

JACOB LAPENNA
Digitally signed by JACOB LAPENNA
Date: 2018.09.11 17:00:56 -06'00'

Traveler

PATRICK COUNCIL
Digitally signed by PATRICK COUNCIL
Date: 2018.09.12 09:06:50 -06'00'

Traveler

Noted and Dated By:

NATHAN MYERS
Digitally signed by NATHAN MYERS
Date: 2018.09.17 13:17:08 -06'00'

Peer Reviewer

NATHAN MYERS
Digitally signed by NATHAN MYERS
Date: 2018.09.17 13:17:31 -06'00'

Manager,
Hydropower Diagnostics and SCADA Group

Attachment A-
Yellowtail Tests, Generator 1
Technical Addendum

1. Test Measurements

The following measurement points were instrumented during these tests:

1. Rim lamination movement with respect to rotor spider arms
    a. Proximity Probes
        i. Mounted on brackets attached to windward and leeward edge of spider arms
            1. Arm 1 is located adjacent to rotor pole 1
            2. Successive poles located clockwise around rim
        ii. 12 probes
            1. 1 probe attached near top windward side of each arm (6 total)
            2. 1 probe attached near top leeward side of arm 1 and 4 (2 total)
            3. 1 probe attached near middle and bottom of windward side of arm 1 (2 total)
            4. 1 probe attached near bottom of windward and leeward side of arm 3 (2 total)
        iii. Measure spider arm to rim movement
        iv. Automation Direct, Model: AM9-05-1A
    b. Wireless Link
        i. 16-differntial channel transmitters mounted on shaft
        ii. Adaptation of a National Instruments Compact DAQ-9191 Wi-Fi chassis with NI9205 analog input card.
2. Generator speed
    a. Shaft rotation
        i. 1/rev shaft pickup location approximately aligned with pole 1 (may be off by ±1 pole) and stationary sensor located directly downstream.
        ii. 1/rev via remote optical laser system
        iii. Speed via remote optical laser system plus frequency to analog converter
3. Generator parameter
    a. PT/CT transducer board
        i. MW
        ii. MVar
        iii. Terminal Voltage
        iv. Terminal Current

        v. Frequency
    b. Gate Position
        i. Governor transducer
4. Data Acquisition Equipment
    a. I/O Tech Wavebook
        i. Gate position
        ii. 1/rev and speed
    b. NI 9181 Ethernet chassis with NI 9205 analog input card
        i. Generator electrical parameters

2. Test Sequence

Three series of tests were performed on June 21, 2018 as follows:

- Test 1 – The unit was started on a slow-roll and then slowly accelerated to rated speed. The unit was then stopped. For this test, the remote functionality of the wireless transmitter was not functioning correctly and some data was lost. The wireless transmitter power was switched from remote to always on.
- Test 2 – The unit was slowly ramped from stand still to rated RPMs. It was then excited and un-excited. An over-speed test to 292 RPM (130% speed) was then performed with the unit un-excited. Following the over-speed test, the unit was ramped back to rated speed and then shut down normally.
- Test 3 – The unit was slowly ramped from stand still to rated RPMs. It was then excited, synchronized, and ramped to a load of 68 MW. After about 2 hours, it was ramped back down to no load. An over-speed test to 292 RPM (130% speed) was then performed with the unit un-excited. Following the over-speed test, the unit was ramped back to rated speed and then shut down normally.

3. Test Results

Movement of Rim Relative to Spider Arms

Generator Startup

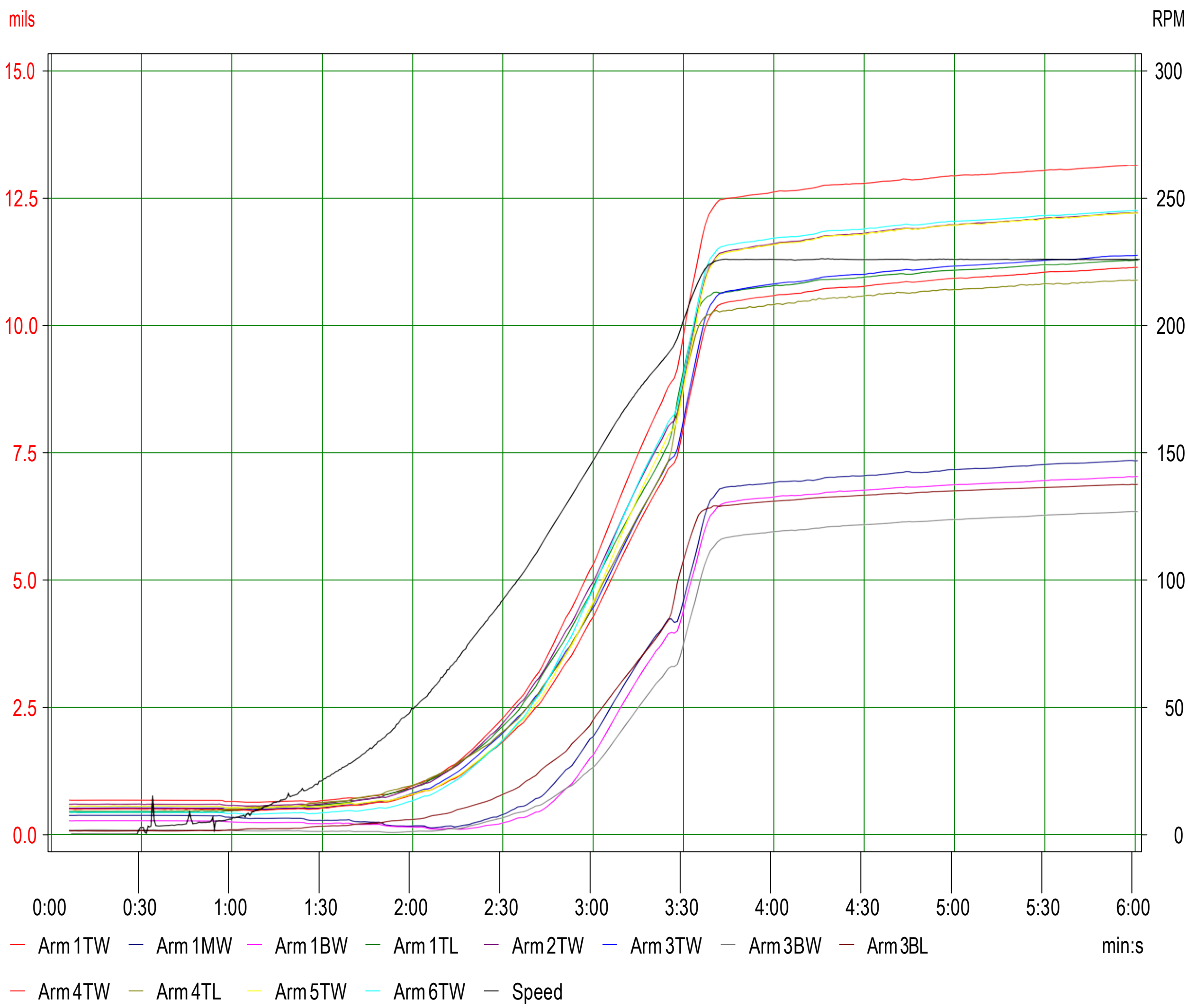

Figure A1 - Spider Arm to Rotor Rim Movement during Ramped Start, Test 2

(Proximity sensors nomenclature - [Arm# - Top (T), Middle (M), Bottom (B) - Windward (W), Leeward (L))

Unit Loading

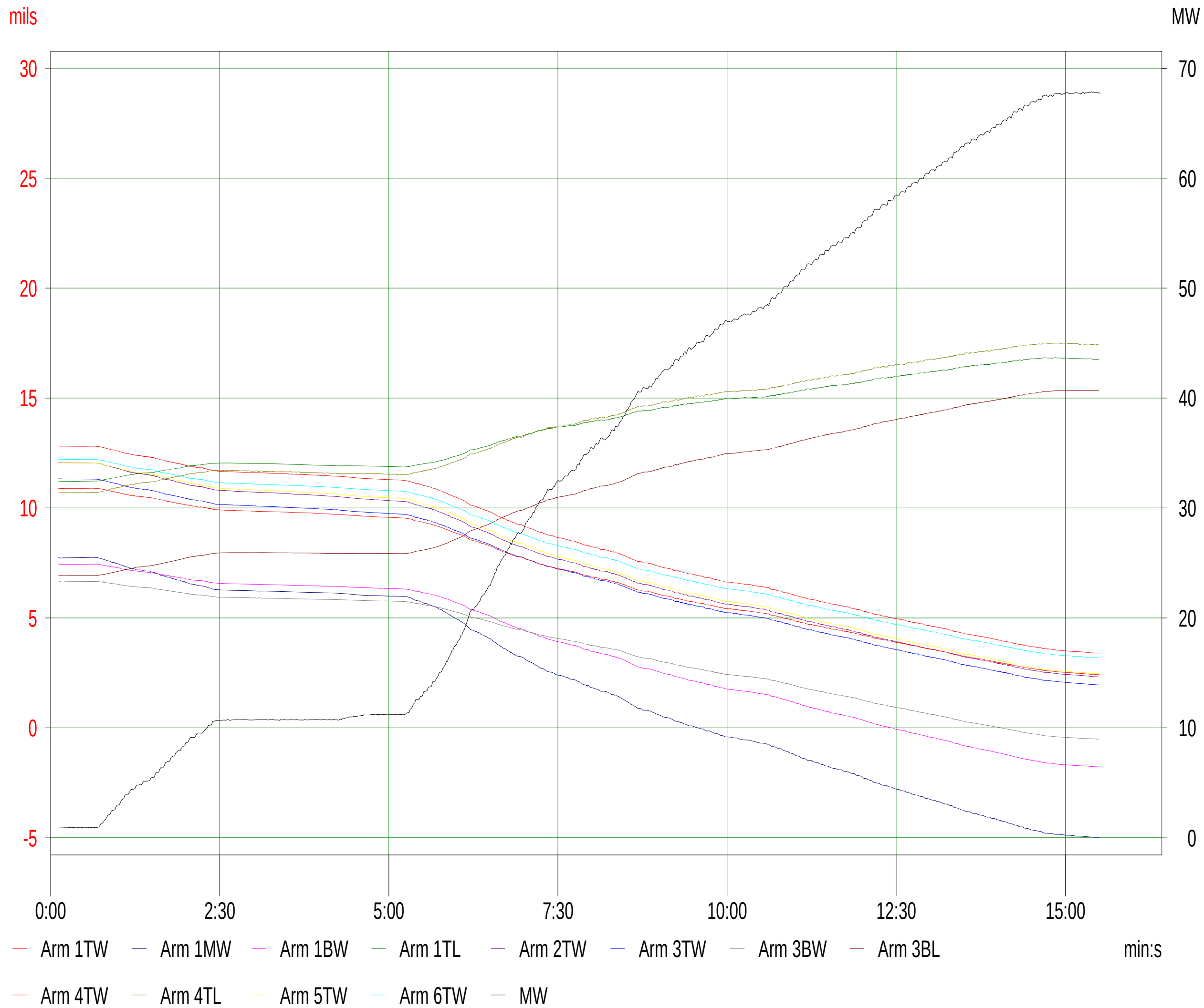

Figure A2 - Spider Arm to Rotor Rim Movement during Unit Loading, Test 3

Generator Heating

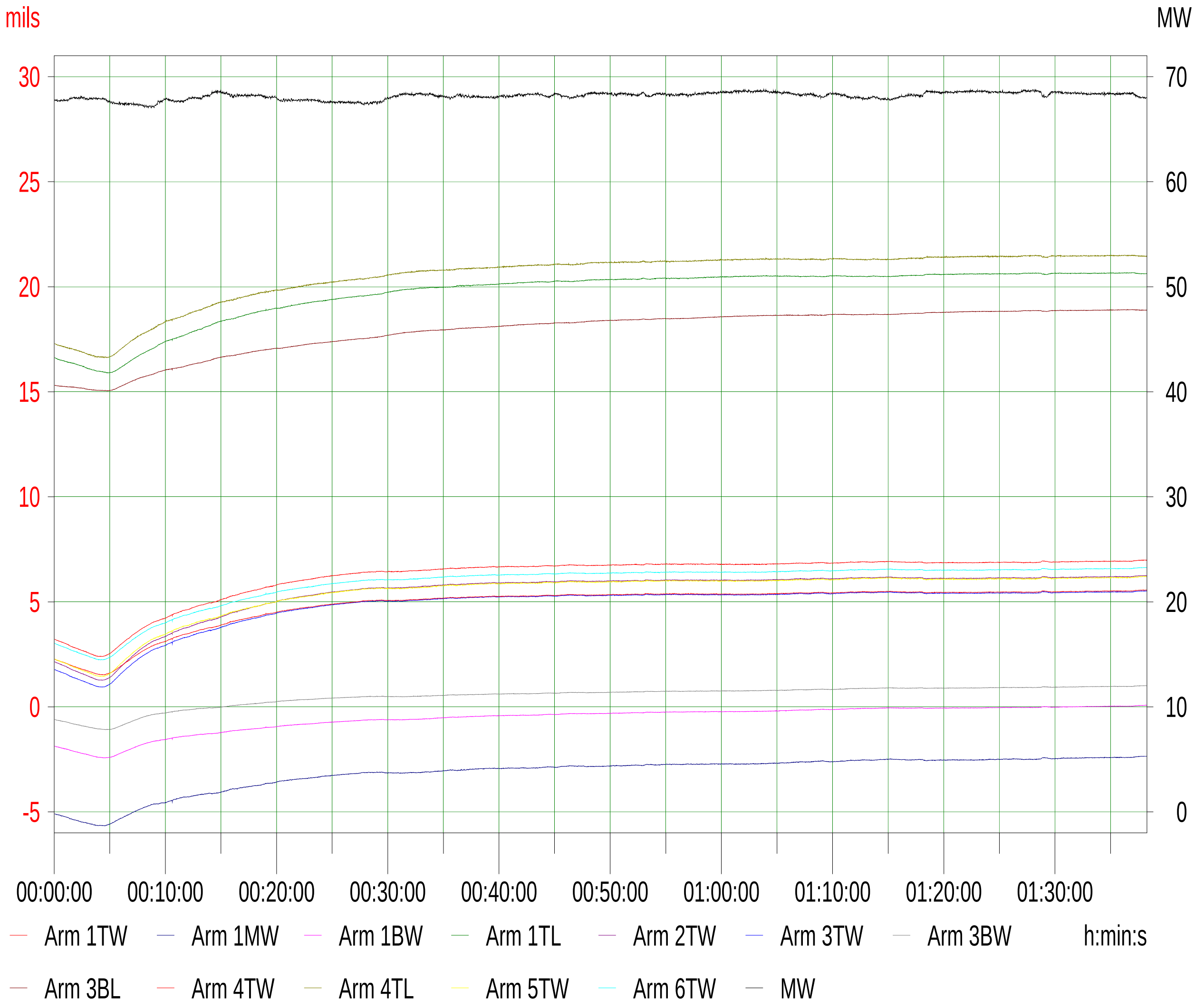

Figure A3 - Spider Arm to Rotor Rim Movement during Heatrun, Test 3

Generator Shutdown

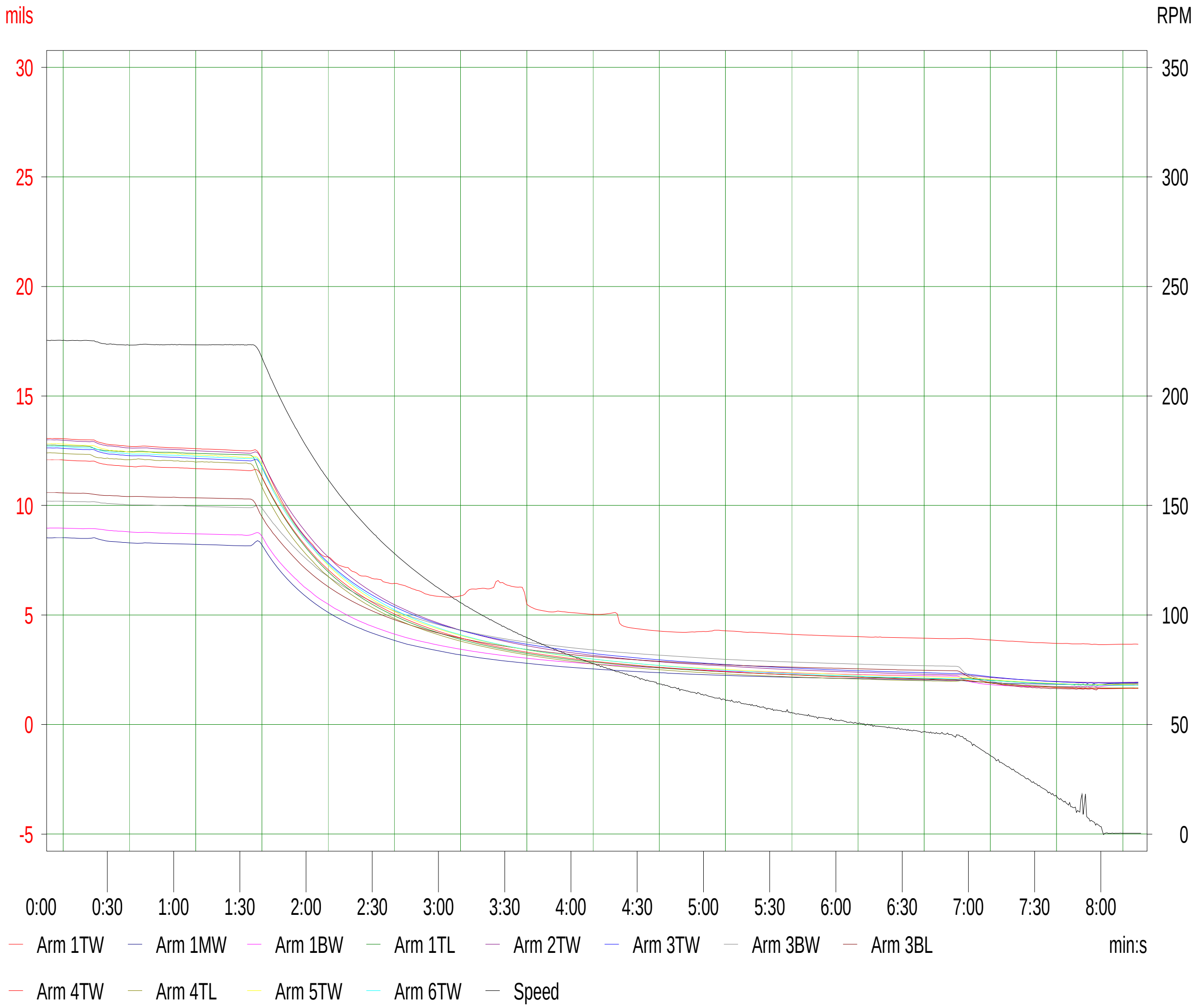

Figure A4 - Spider Arm to Rotor Rim Movement During Shutdown, Test 3

(Unit ran at full load for about 2 hour prior to shutdown.)
(Ignore non-typical movement in Arm4TW data.)

Overspeed

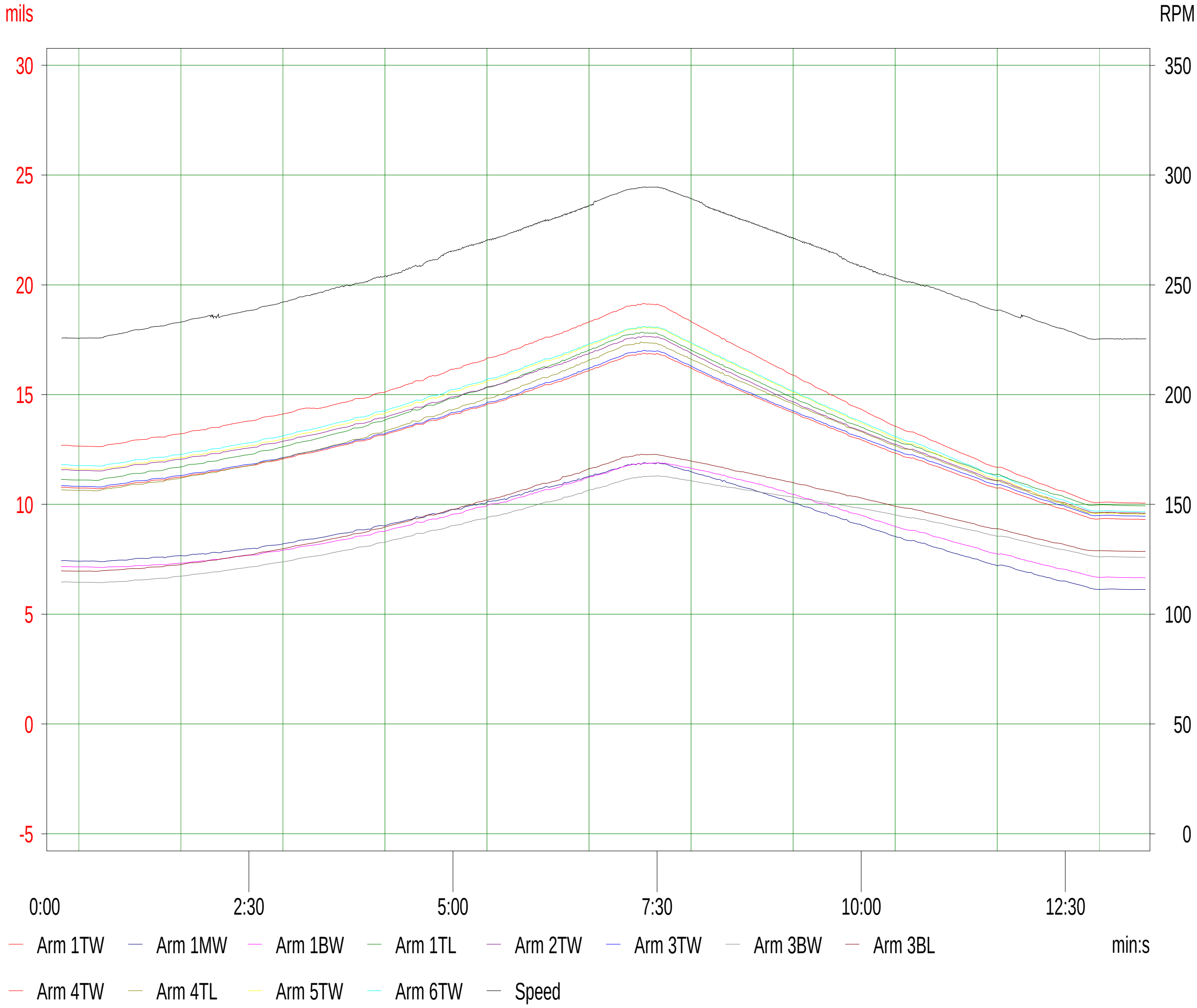

Figure A5 - Spider Arm to Rotor Rim Movement during Over Speed, Test 2 - Rim Cool

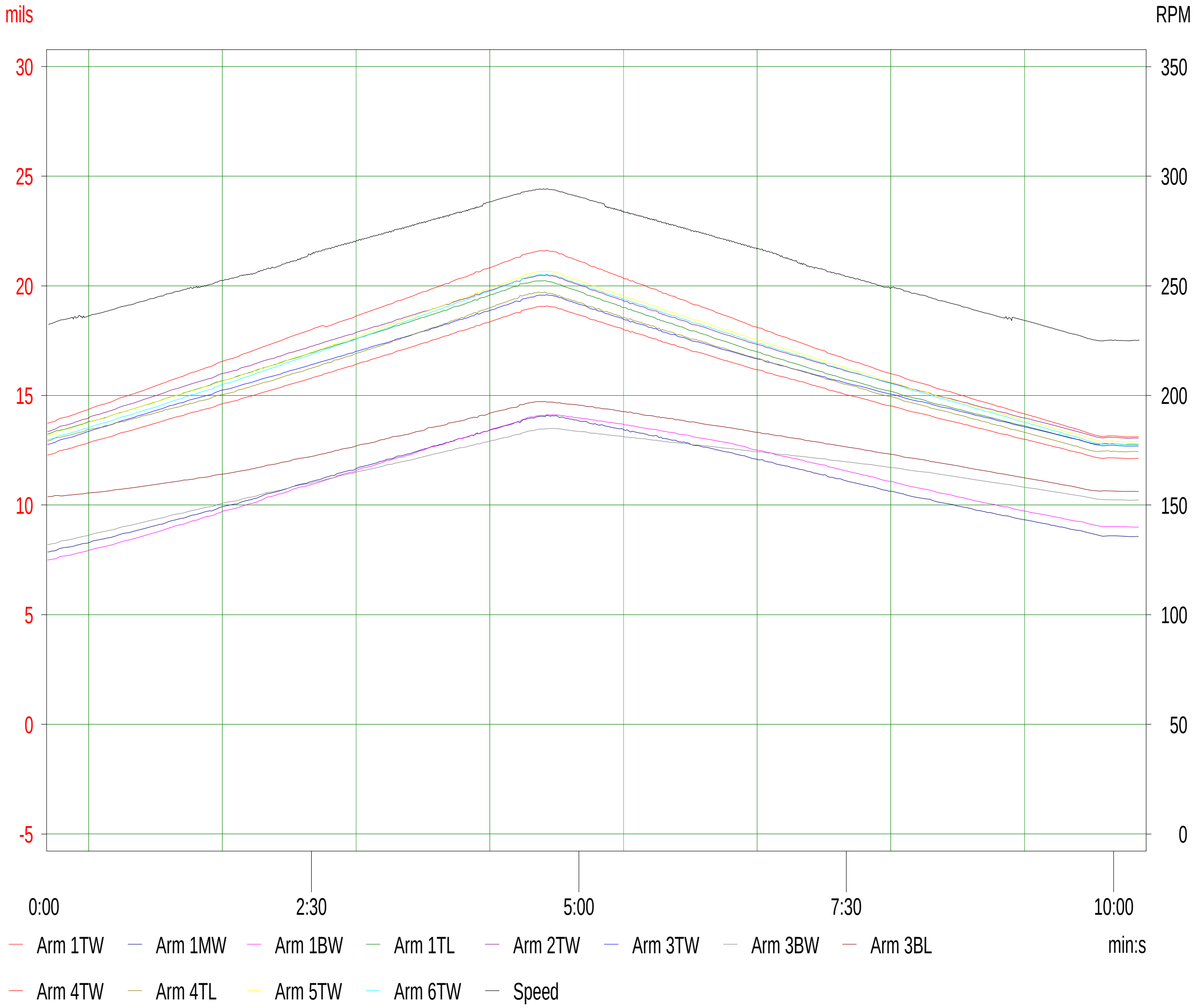

Figure A6 - Spider Arm to Rotor Rim Movement during Over Speed, Test 3 - Rim Warm

Generator Excitation

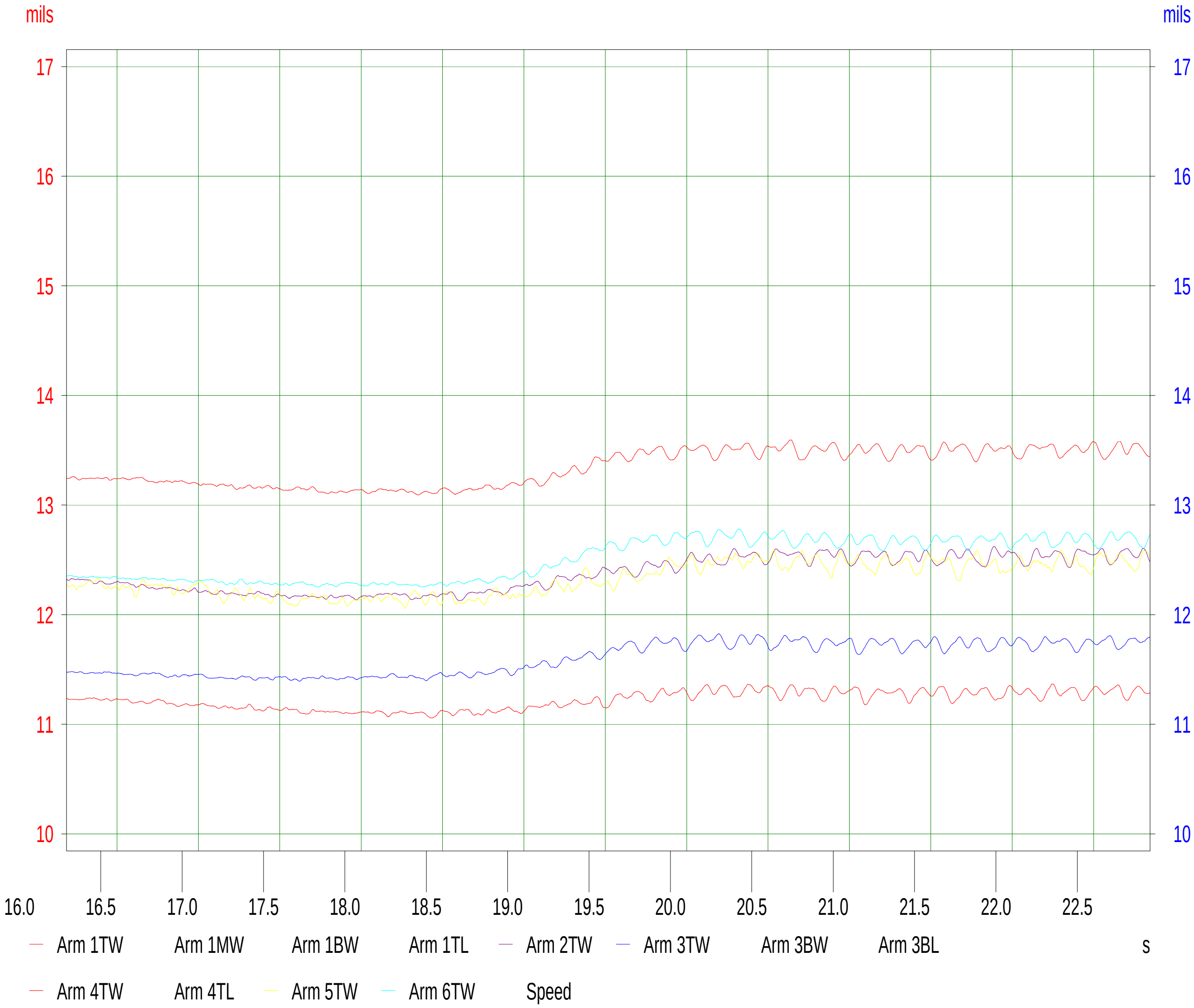

Figure A7 - Spider Arm to Rotor Rim Movement during Excitation - Test 2.

Only Top, Windward signals displayed.

DC offset between excited and unexcited = 0.25 mils.

Excited ripple is 0.17mils peak-to-peak with a period of 0.267 sec (225 RPM).

Phase shift between arms is 60 deg.

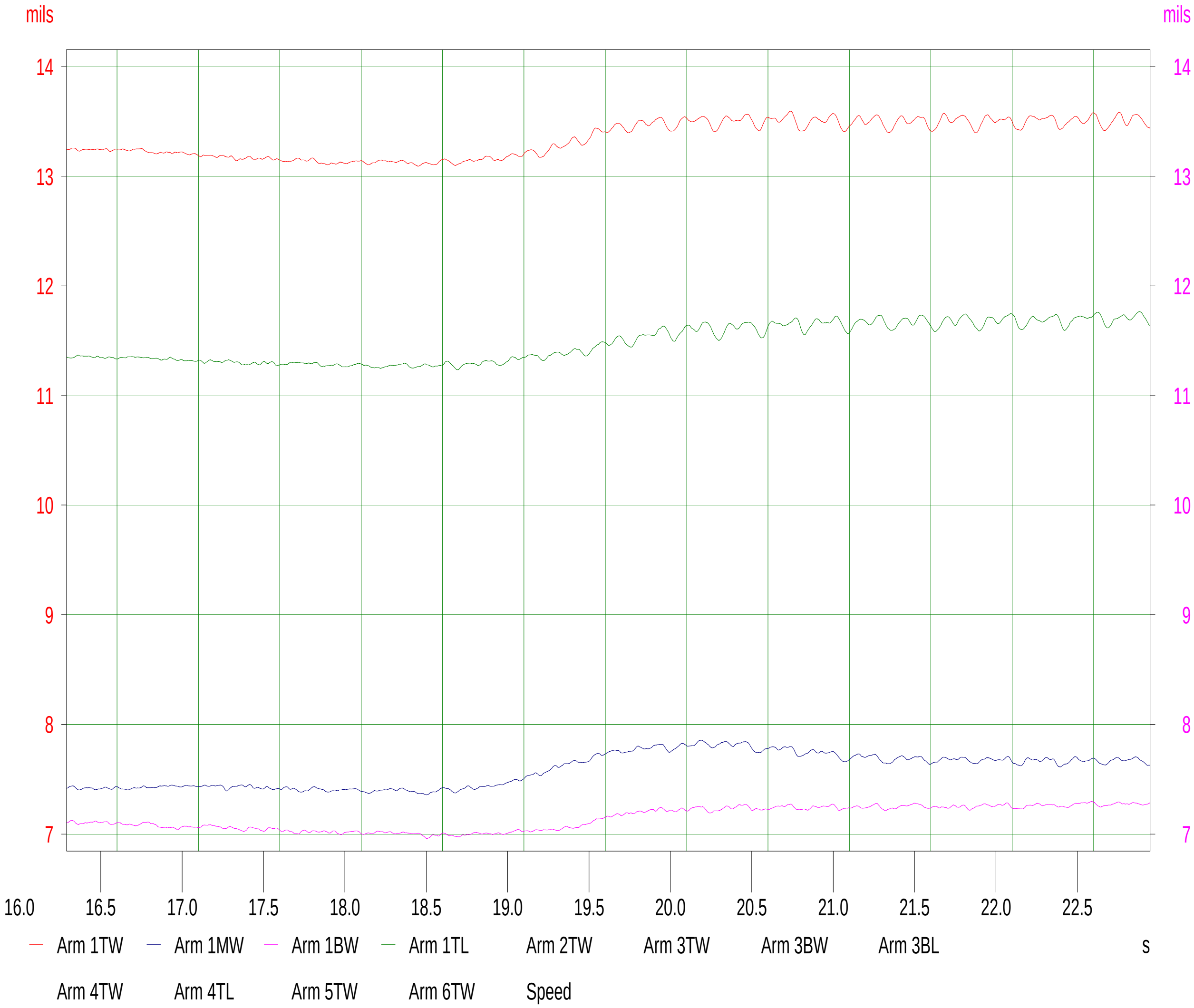

Figure A8 - Spider Arm to Rotor Rim Movement during excitation - Test 2.

Middle and Bottom signals show less peak to peak movement than top signals

4.Test Equipment

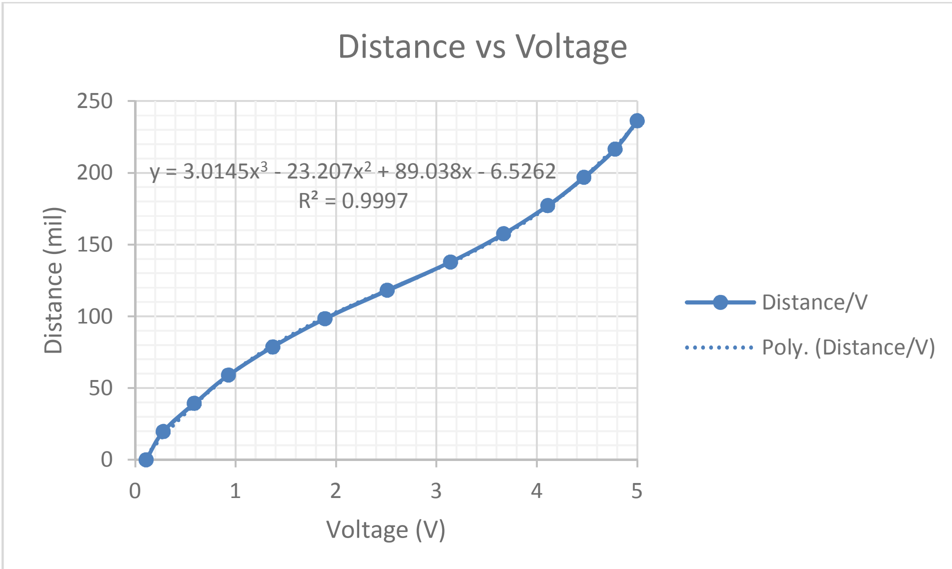

Figure A9 - Non-linear Response of Proximity Probe AM9-05-1A and Resultant Equation

Figure A10 - Proximity Probe Attachment to Spider Arm (initial gap set between 130 to 150 mils)

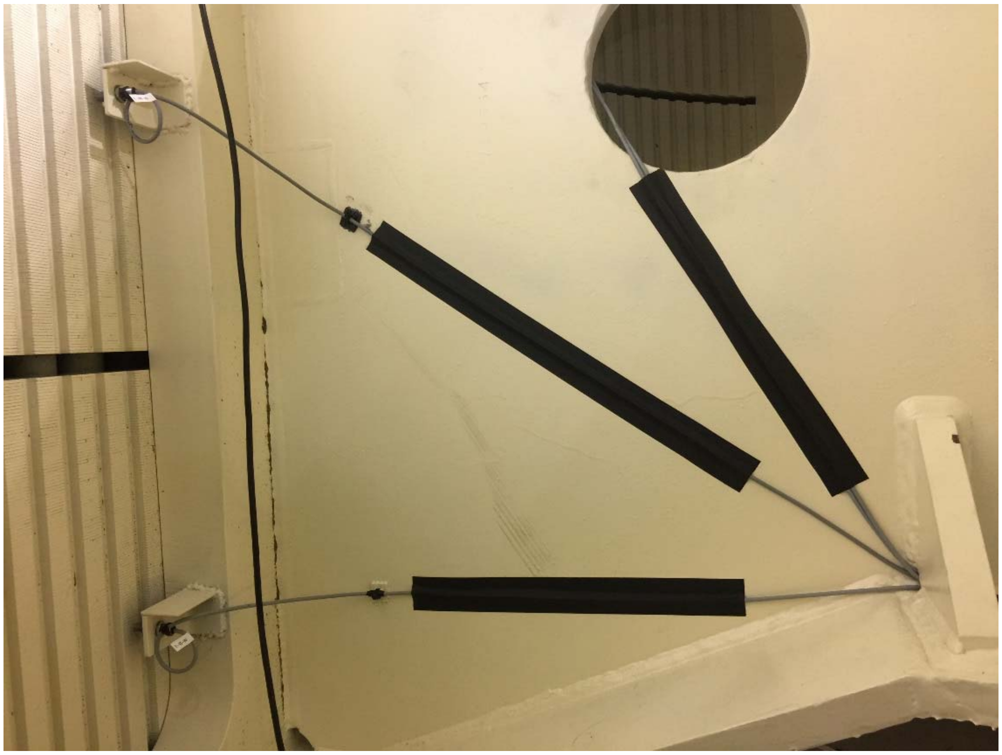

Figure A11 - Arm 1 showing Middle, and Bottom Proximity Probe Attachment on windward side of arm

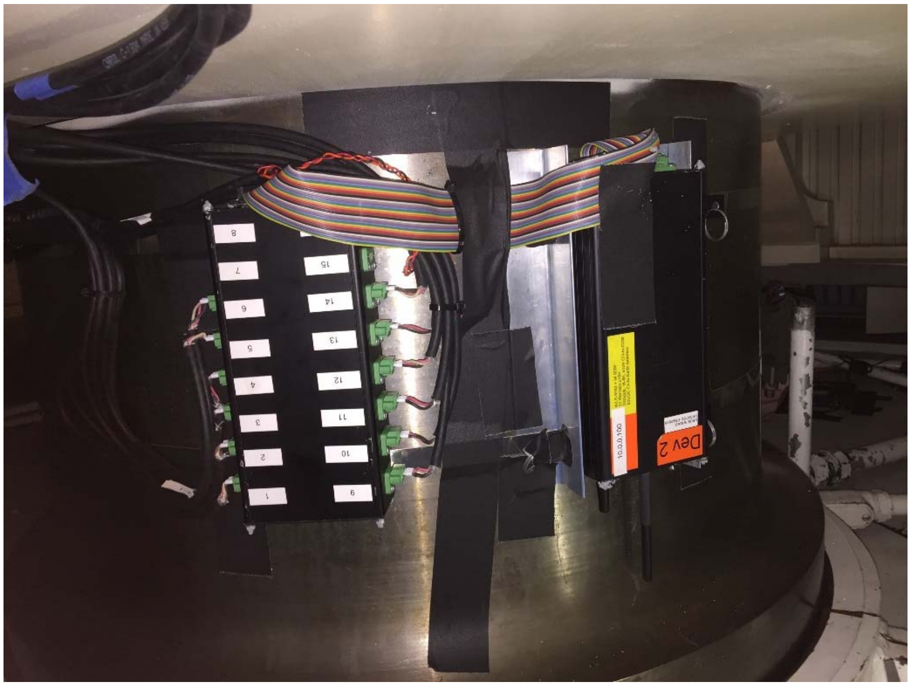

Figure A12 - Wireless Link Transmitter Attachment to Shaft just below Hub (wires connected to proximity probes)

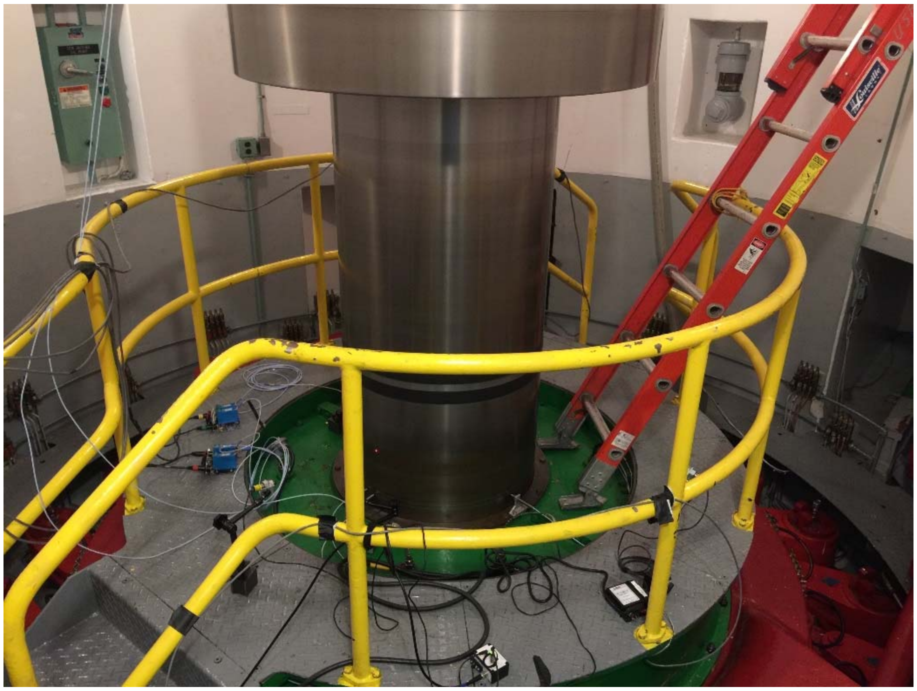

Figure A13 - 1/rev and Speed Sensor Location (1/rev shaft pickup tape approximately aligned with rotor pole 1)

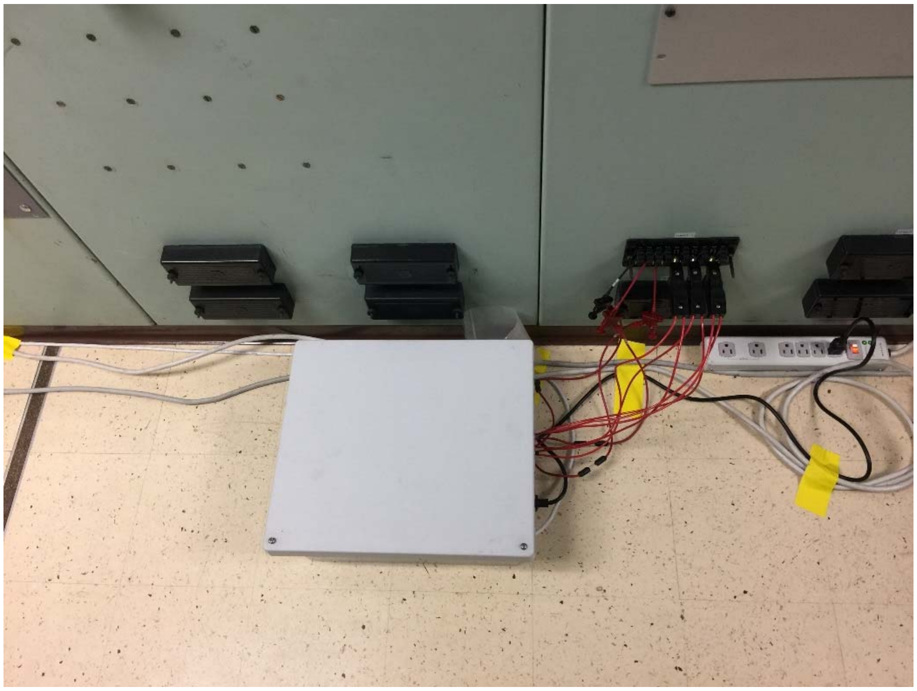

Figure A14 - PT/CT transducer board connected to unit 1 test block

Attachment B-
Yellowtail Tests, Generator 4
Technical Addendum

1. Test Measurements

The following measurement points were instrumented during these tests:

5. Rim lamination movement with respect to rotor spider arms
    a. Proximity Probes
        i. Mounted on brackets attached to windward and leeward edge of spider arms
            1. Arm 1 is located adjacent to rotor pole 1
            2. Successive poles located clockwise around rim
        ii. 12 probes
            1. 1 probe attached near top windward side of each arm (6 total)
            2. 1 probe attached near top leeward side of arm 1 and 4 (2 total)
            3. 1 probe attached near middle and bottom of windward side of arm 1 (2 total)
            4. 1 probe attached near middle and bottom of leeward side of arm 4 (2 total)
        iii. Measure spider arm to rim movement
        iv. Automation Direct, Model: AM9-05-1A
    b. Wireless Link
        i. 16-differntial channel transmitters mounted on shaft
        ii. Adaptation of a National Instruments Compact DAQ-9191 Wi-Fi chassis with NI9205 analog input card
6. Generator speed
    a. Shaft rotation
        i. 1/rev shaft pickup location approximately aligned with pole 1 (may be off by ±1 pole) and stationary sensor located 90 deg. east of downstream
        ii. 1/rev via remote optical laser system
        iii. Speed via remote optical laser system plus frequency to analog converter
7. Generator parameter
    a. PT/CT transducer board
        i. MW
        ii. MVar
        iii. Terminal Voltage
        iv. Terminal Current
        v. Frequency

    b. Gate Position
        i. Governor transducer
8. Data Acquisition Equipment
    a. I/O Tech Wavebook
        i. Gate position
        ii. 1/rev and speed
    b. NI 9181 Ethernet chassis with NI 9205 analog input card
        i. Generator electrical parameters
9. Airgap distance (slow roll test)
    a. Airgap Capacitive Probes
        i. Mounted on stator to measure rotor shape
            1. Mounted on top and bottom of stator on core tooth between slots 175 and 176
        ii. Mounted on rotor to measure stator shape
            1. Mounted on top and bottom of rotor pole 28
        iii. General Electric 4000 Series Airgap 20 mm Sensor System

2. Test Sequence

Four series of tests were performed on June 21, 2018 as follows:

- Test 1 – The unit was started and slowly accelerated in steps to rated speed. The unit was then excited and un-excited. The unit was then stopped.
- Test 2 – The unit was started normally and excited. An over-speed test to 315 RPM (140% speed) was then performed with the unit un-excited. Following the over-speed test, the unit was ramped back to rated speed and then shut down normally.
- Test 3 – The unit was started normally, excited and synchronized. It was then ramped to a load of 74 MW. The load was then reduced to 62 MW. After about 1 hour, it was ramped back down to no load. An over-speed test to 315 RPM (140% speed) was then performed with the unit un-excited. Following the over-speed test, the unit was ramped back to rated speed. It was then loaded for several hours as an issue that tripped Unit 3 off line was being addressed.
- Test 4 – The unit load was adjusted to 50MW and then the unit breaker was opened. The resulting load rejection was recorded. The unit remained excited and return to normal speed. The unit then was shut down normally.

3. Test Results

Movement of Rim Relative to Spider Arms

Generator Startup

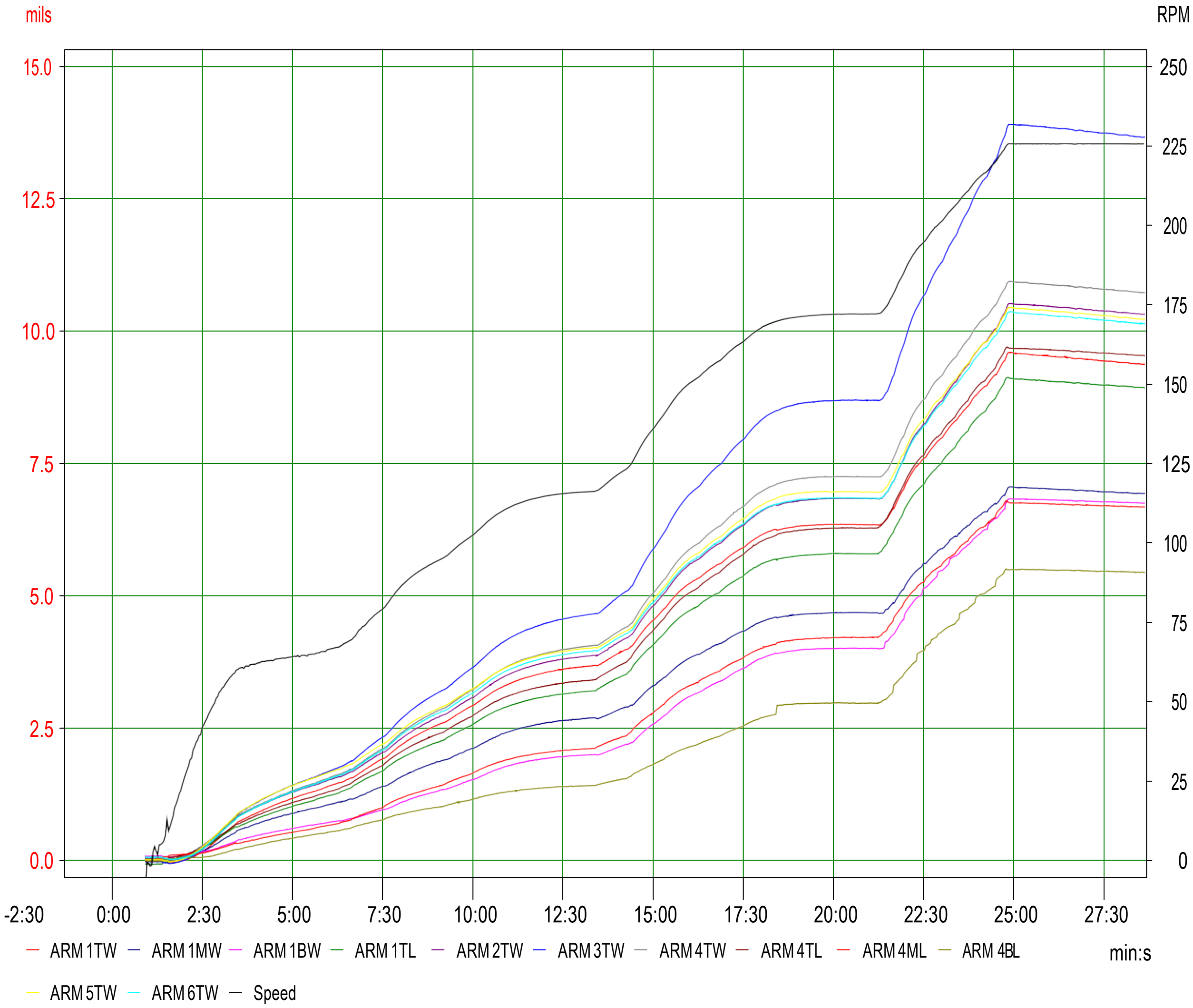

Figure B1 - Spider Arm to Rotor Rim Movement during Stepped Start, Test 1

(Proximity sensors nomenclature - [Arm# - Top (T), Middle (M), Bottom (B) - Windward (W), Leeward (L))

Unit Loading

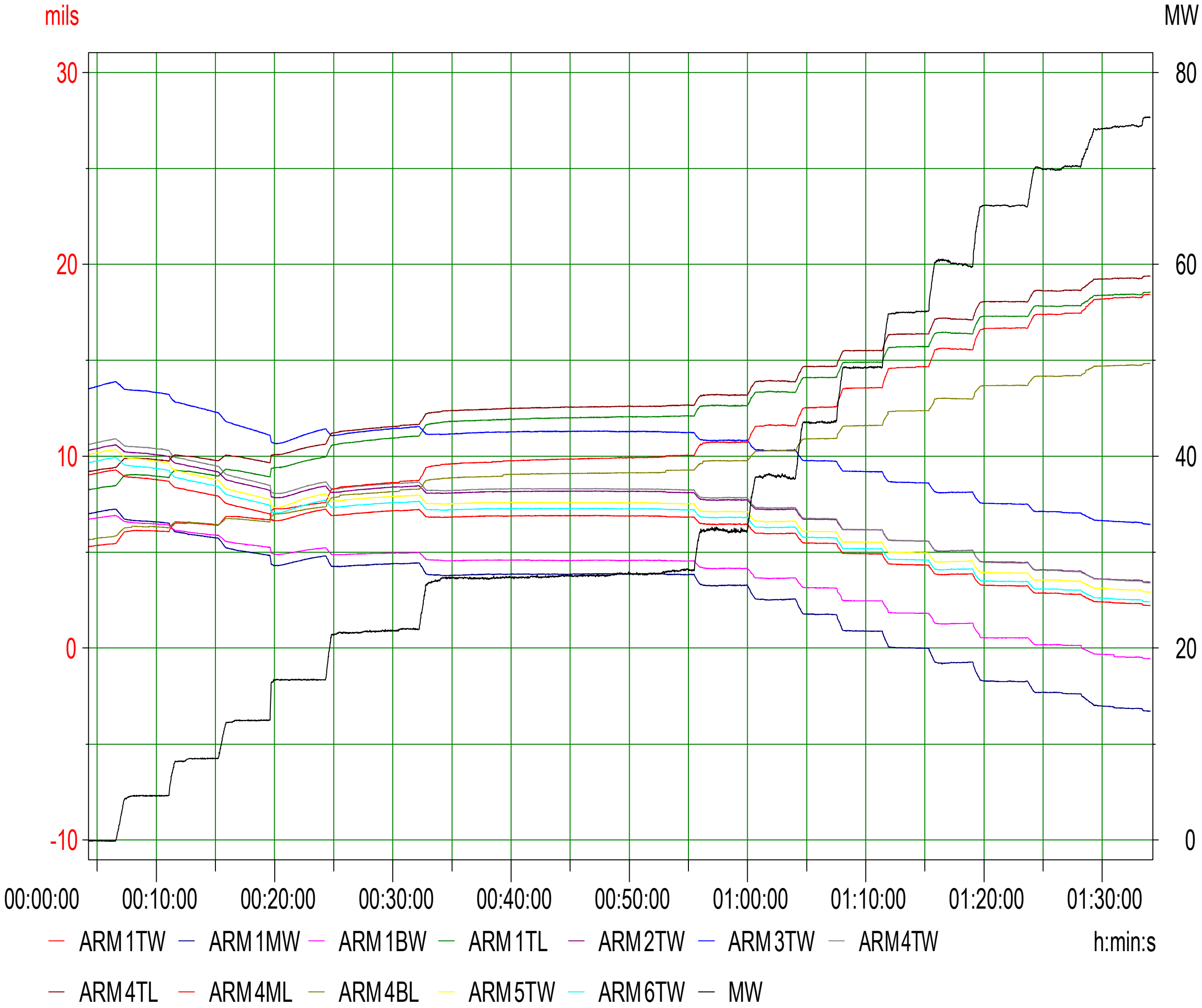

Figure B15 - Spider Arm to Rotor Rim Movement during Stepped Unit Loading, Test 3

Generator Heating

As the unit was slowly ramped to 74 MW over a 90 minute period and then the load was reduced to 62 MW for 1 hour, no additional rim movement was monitored during the constant load period.

Generator Shutdown

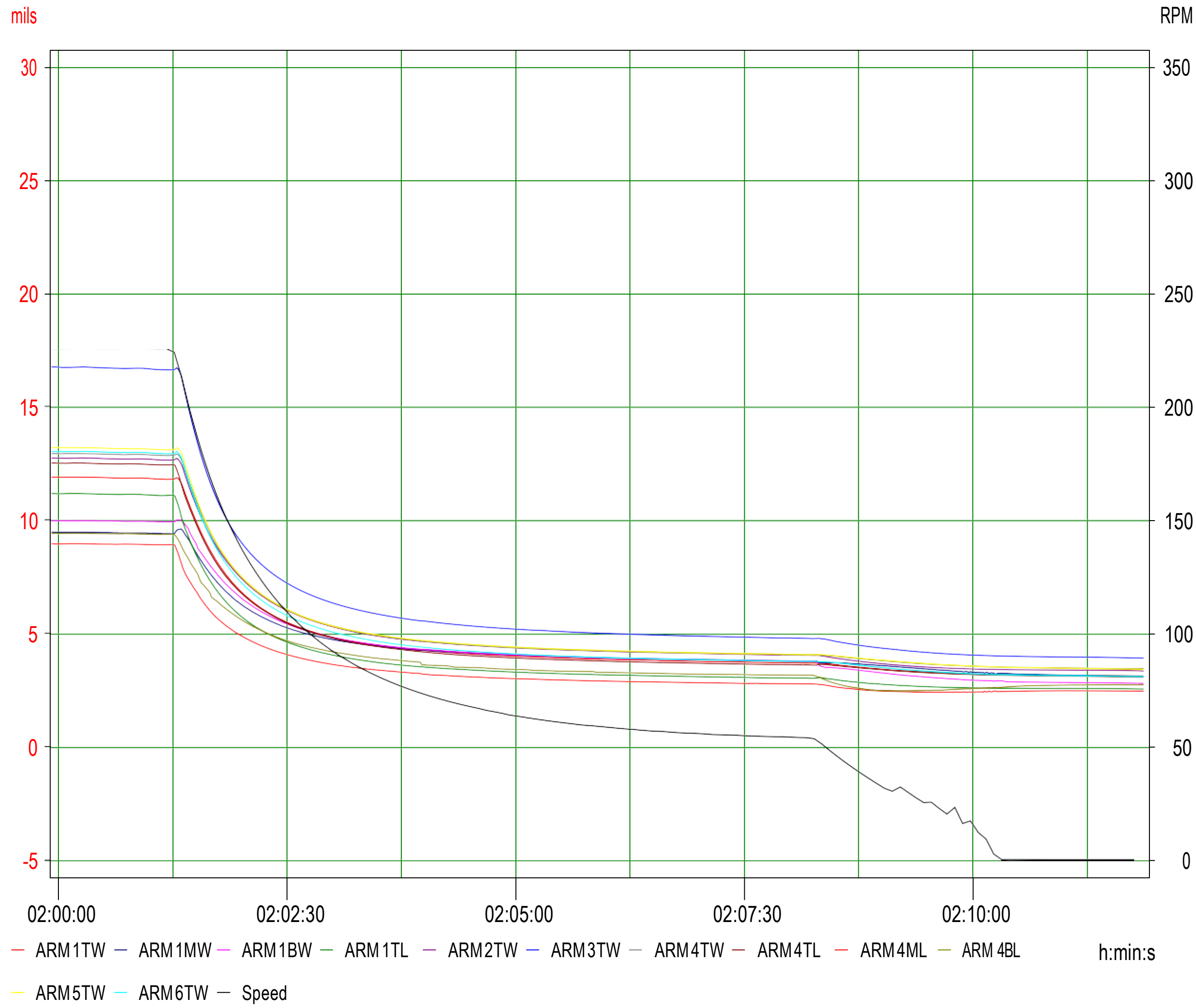

Figure B16 - Spider Arm to Rotor Rim Movement during Shutdown, Test 4

Overspeed

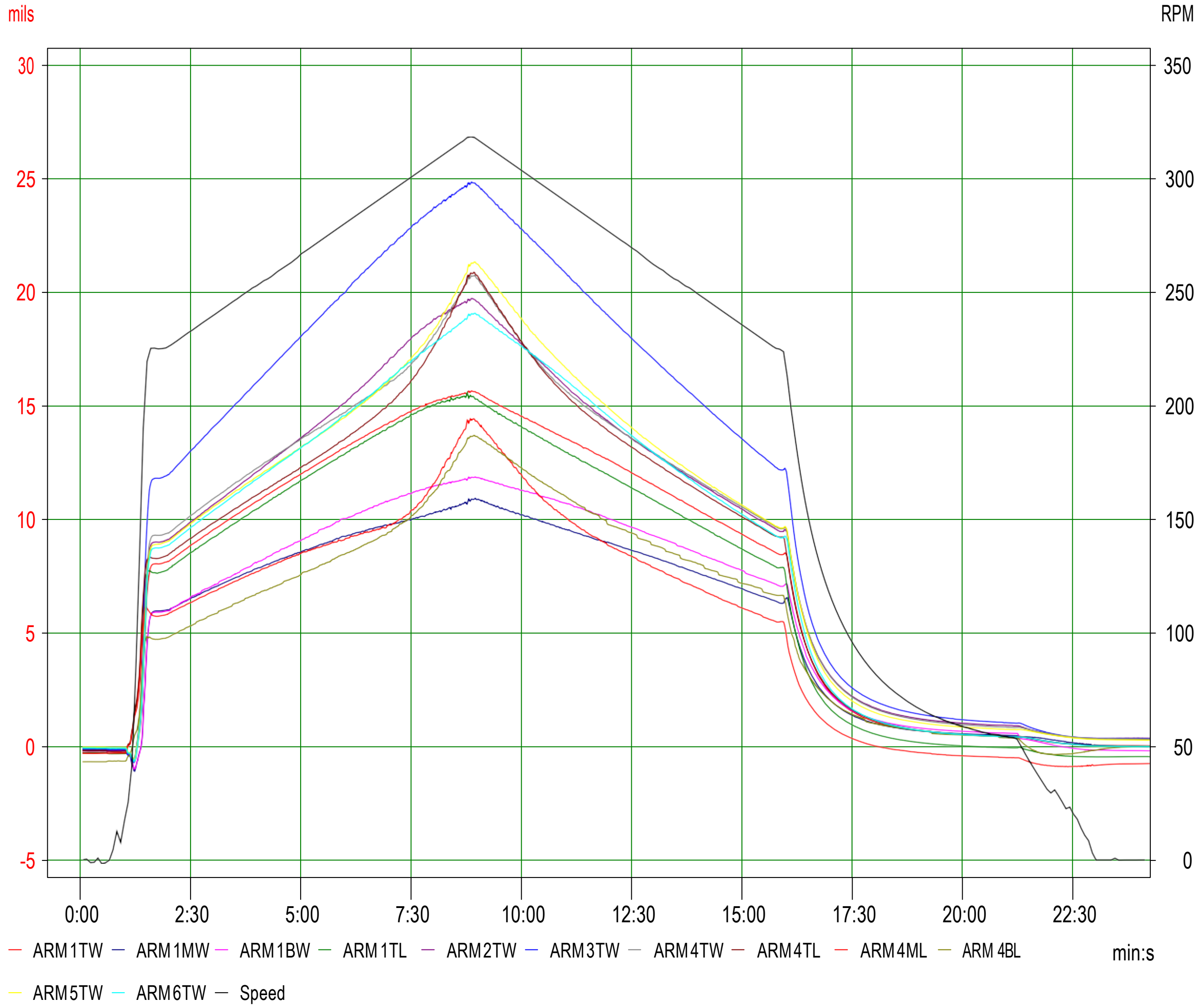

Figure B17 - Spider Arm to Rotor Rim Movement during Over Speed, Test 2 - Rim Cool

Arm 4 probes display non-linear movement above 130% rated speed

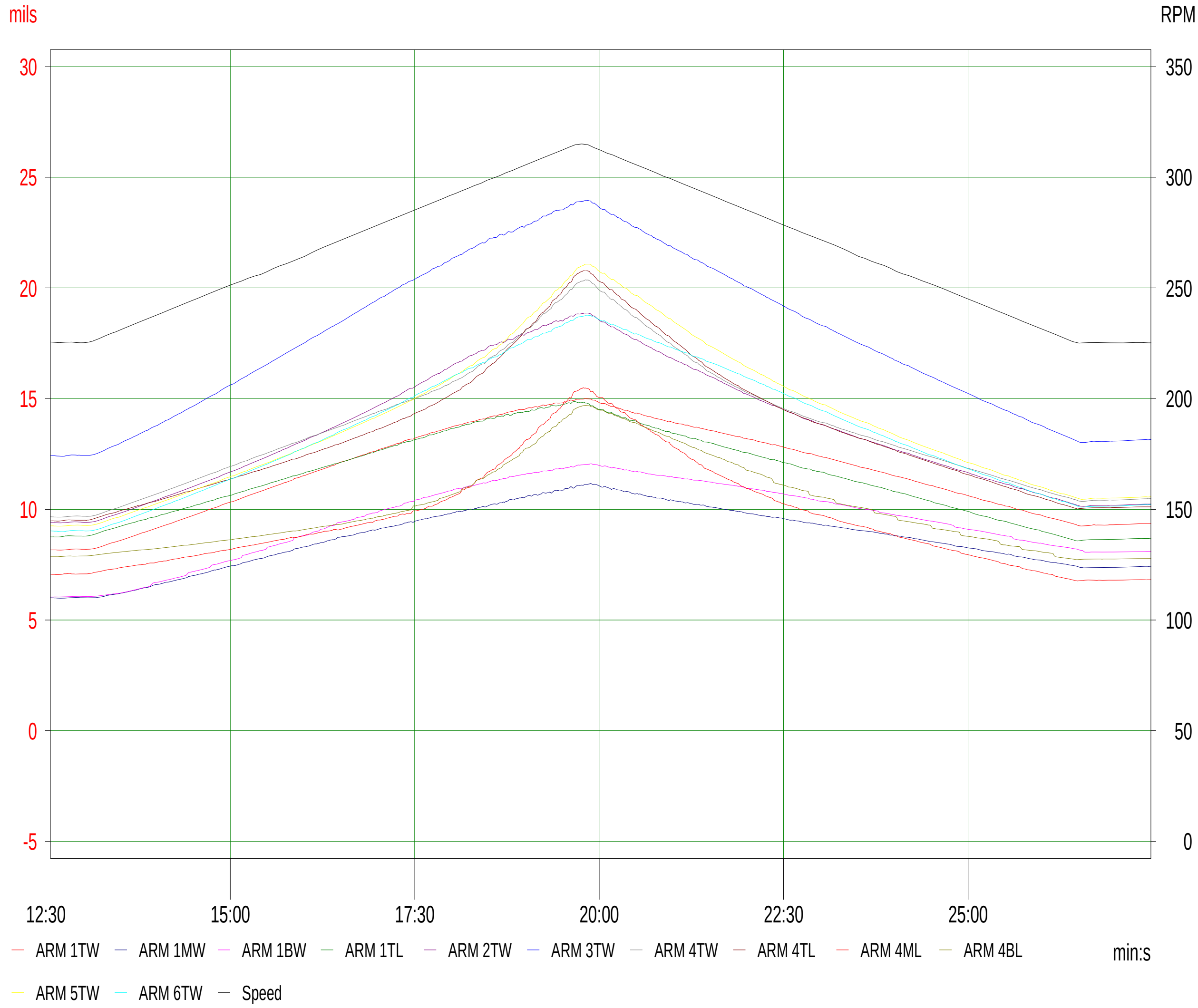

Figure B18 - Spider Arm to Rotor Rim Movement during Over Speed, Test 3 - Rim Warm

Arm 4 probes display non-linear movement above 130% rated speed

Generator Excitation

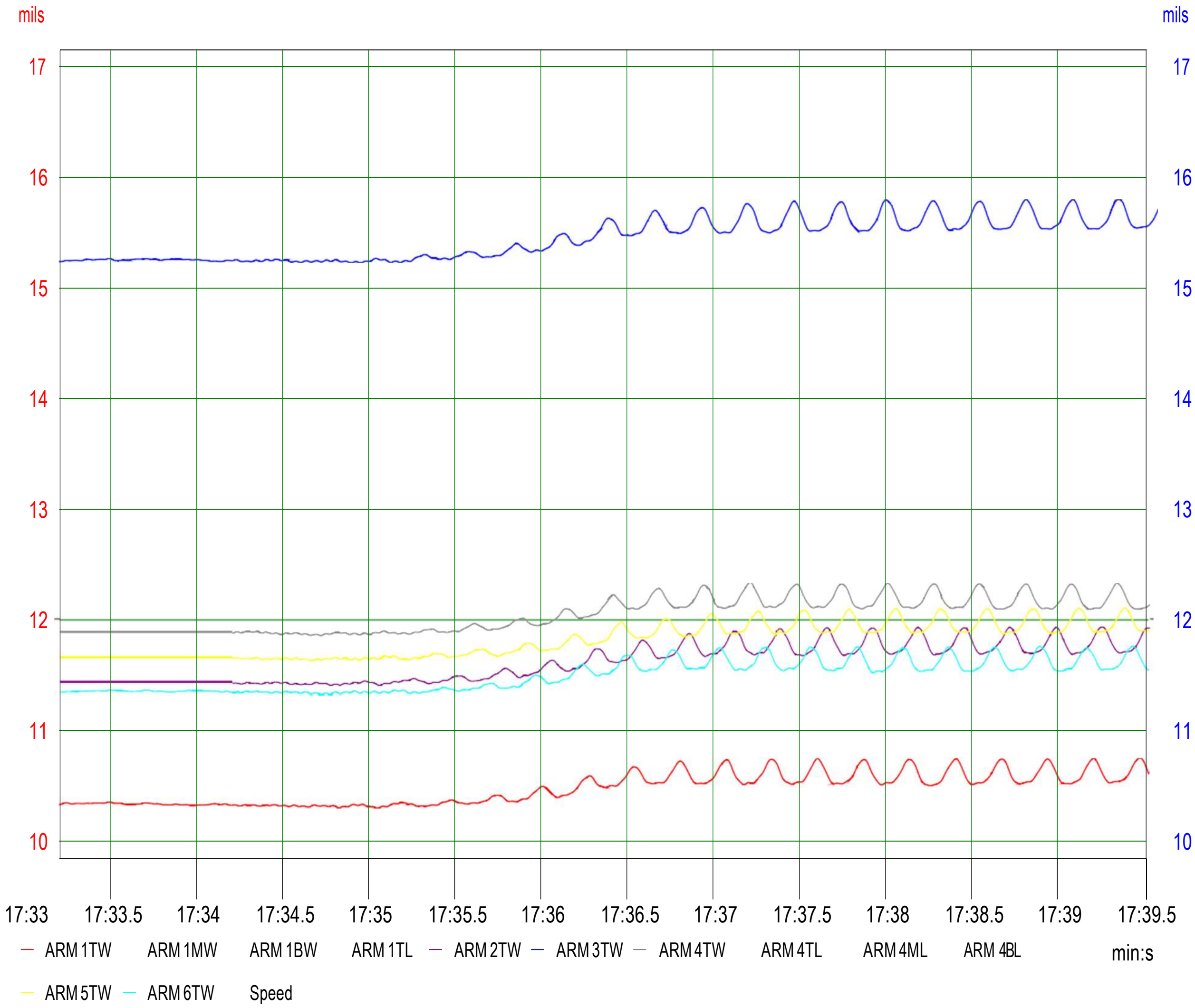

Figure B19 - Spider Arm to Rotor Rim Movement during excitation - Test 1

Only Top, Windward signals displayed.

DC offset between excited and unexcited = 0.3 mils.

Excited ripple rim to spider arm movement is 0.2 mils peak-to-peak with a period of 0.267 sec or 225 RPM.

Phase shift between arms is 60 deg.

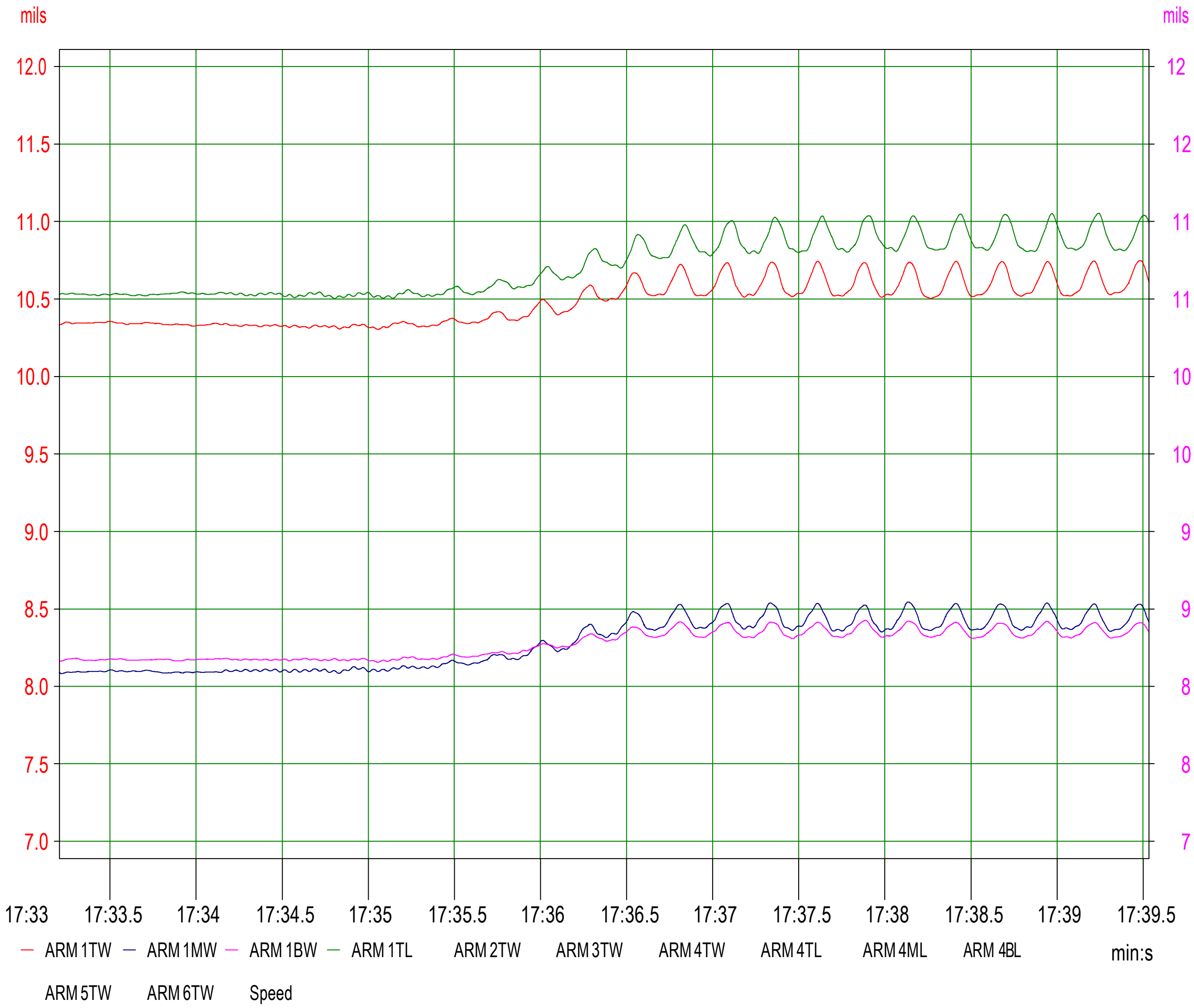

Figure B20 - Spider Arm to Rotor Rim Movement during excitation - Test 1.

Middle and Bottom signals show less peak-to-peak movement than Top signals

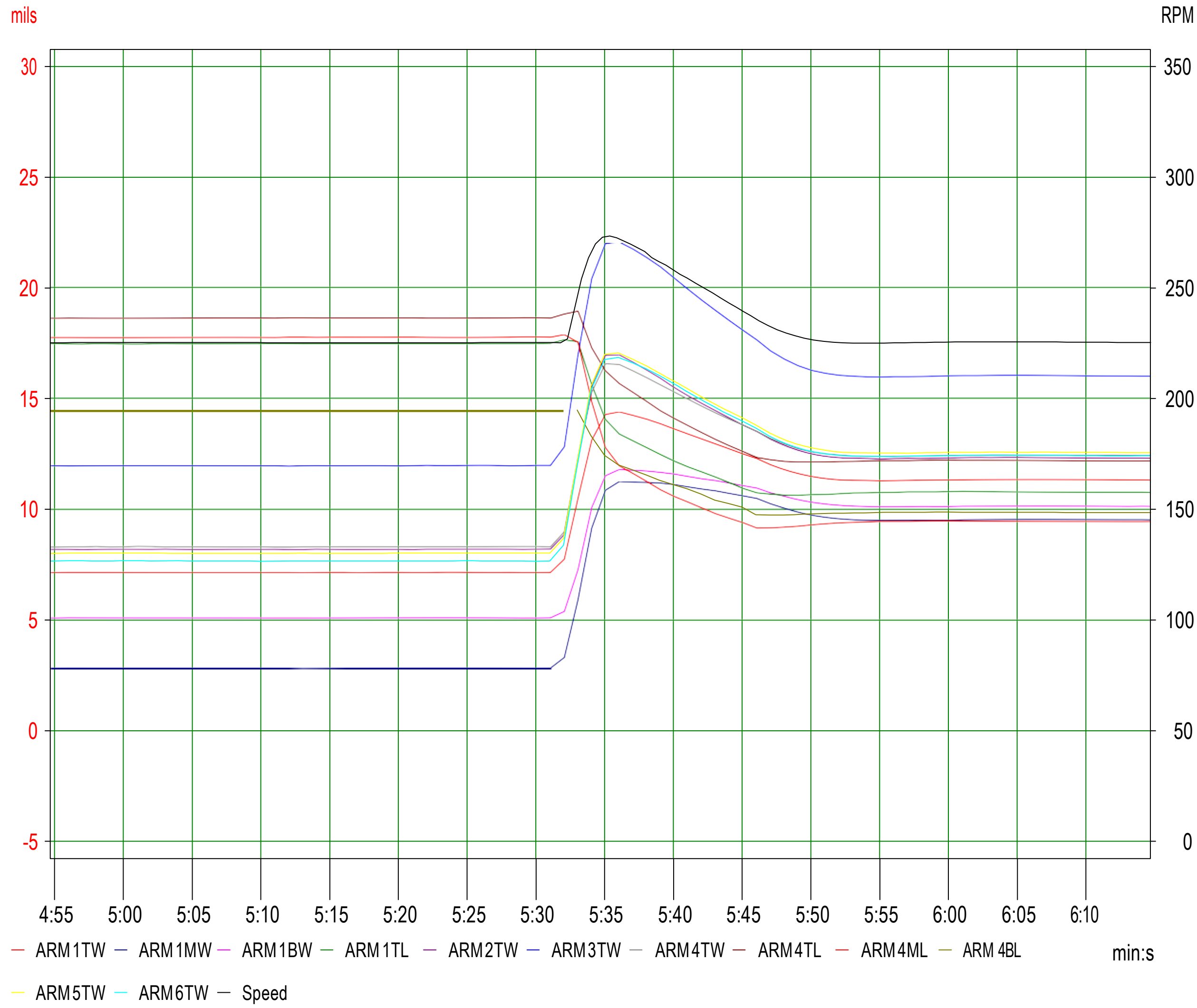

Figure B21 - 50 MW Load Rejection, Excitation remained on, Speed return to nominal

Rotor and Stator Shape Measurements

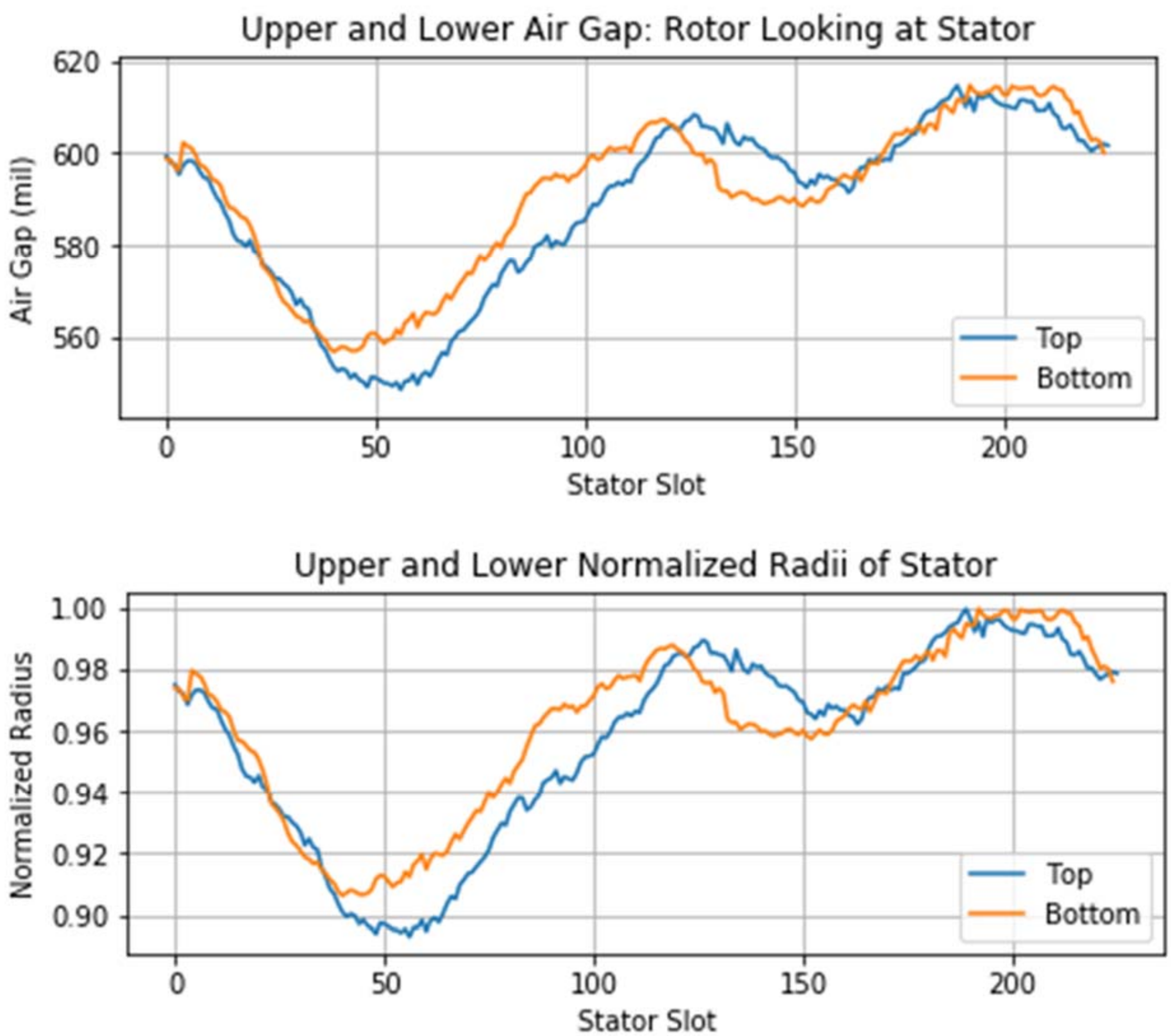

Figure B22 - Stator Shape Data - Rotor mounted probe minimum measured distance to stator.

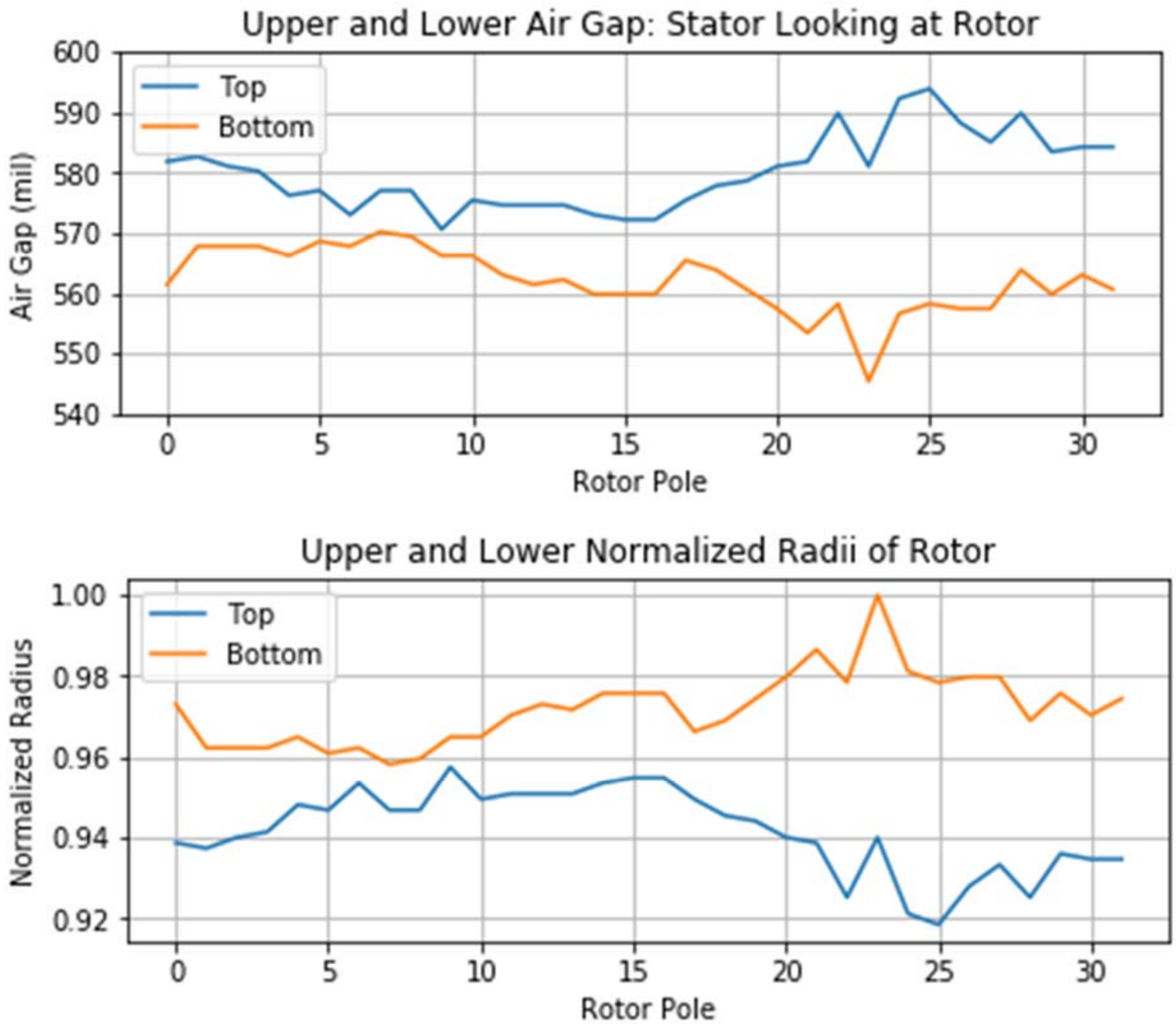

Figure B23 - Rotor Shape Data. Stator mounted probe minimum measured distance to rotor.

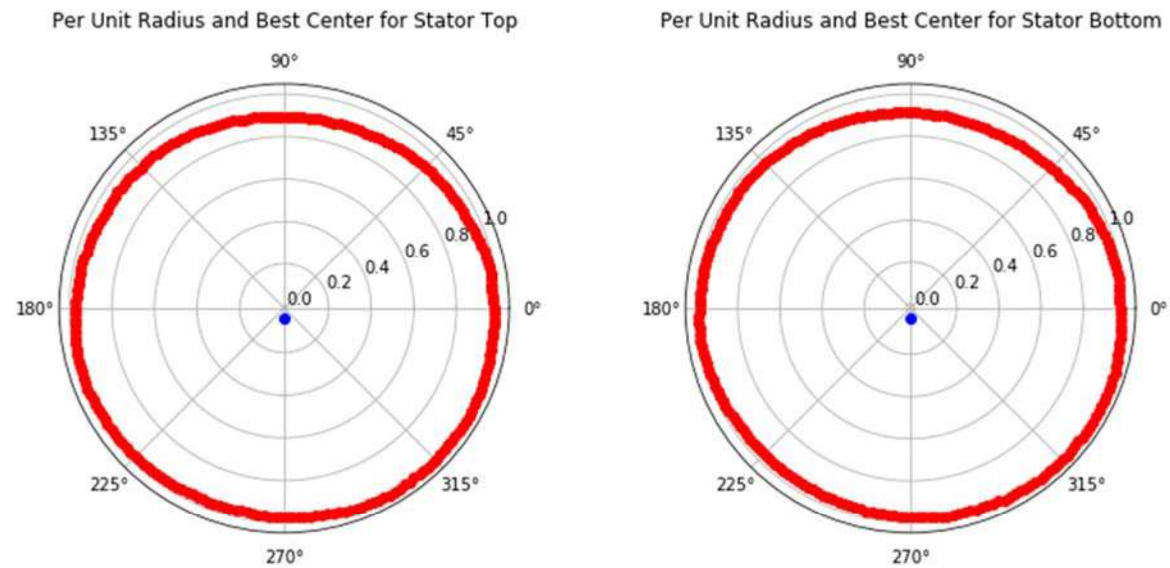

Figure B24 - Stator "Best Center" Polar Plots

Slot 1 = 0 deg.

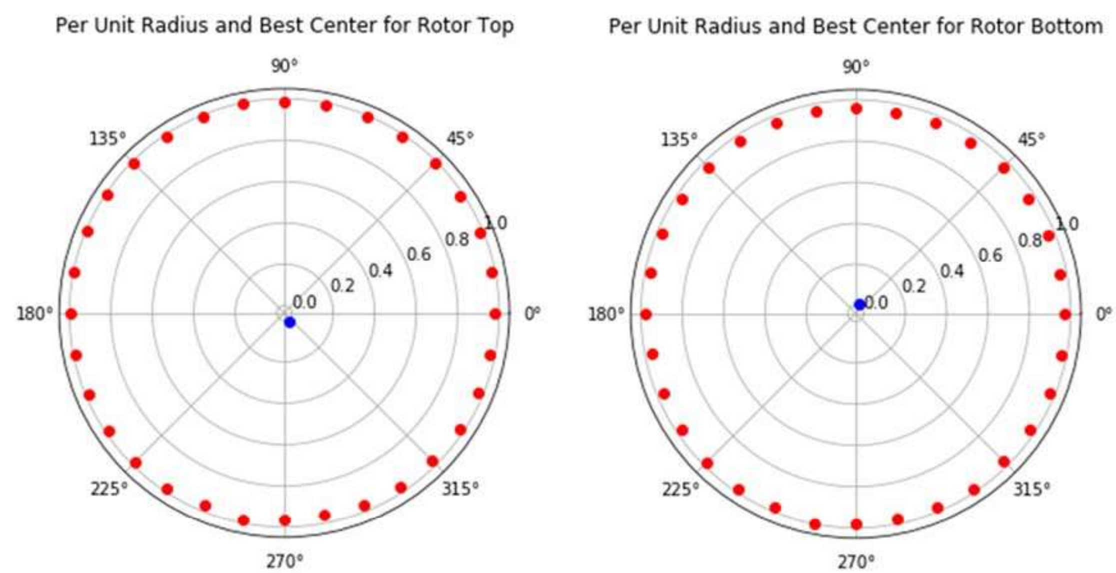

Figure B25 - Rotor "Best Center" Rotor Plot

Pole 1 = 0 deg.

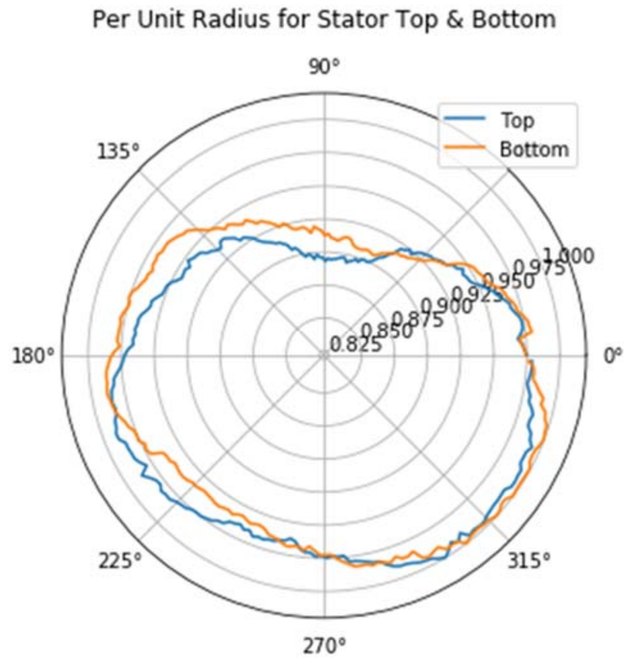

Figure B26 - Stator Orbit Plot - Zoomed to show irregularities

Slot 1 = 0 deg.

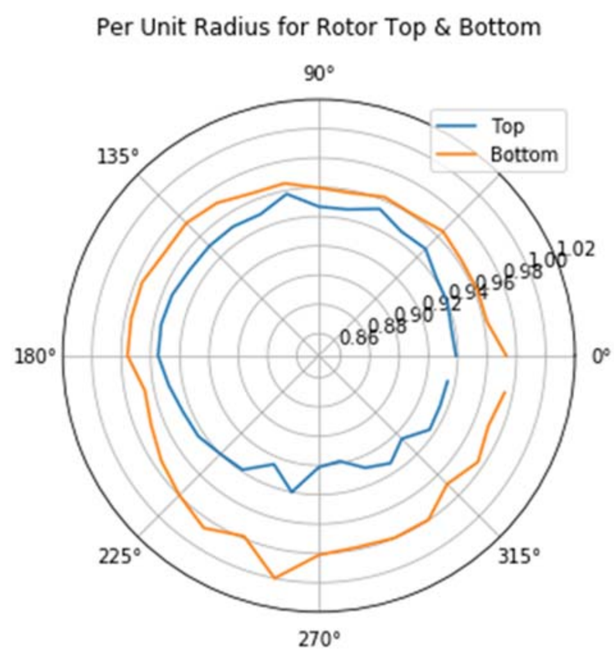

Figure B27 - Rotor Orbit Plot - Zoomed to show irregularities

Pole 1 = 0 deg.

4. Test Equipment

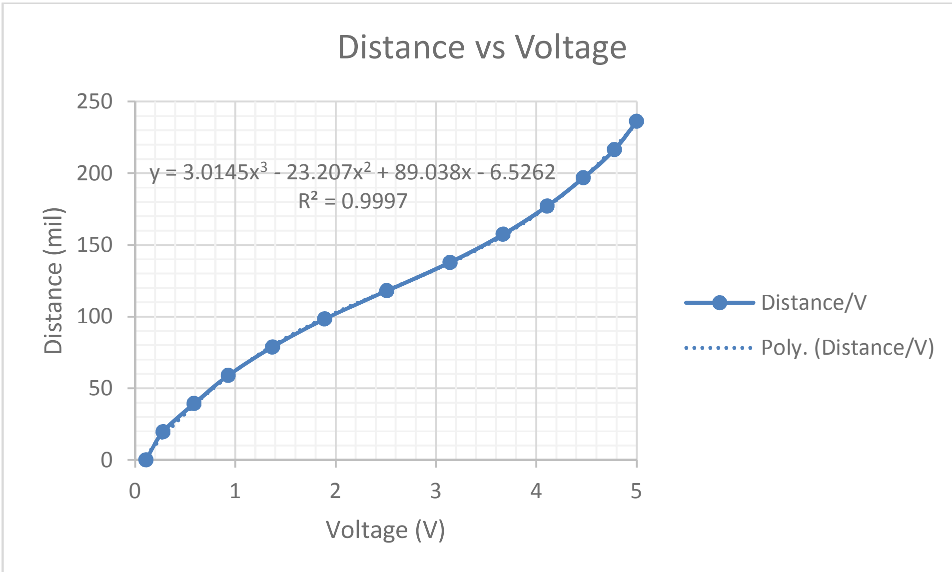

Figure B15 - Non-linear Response of Proximity Probe AM9-05-1A and Resultant Equation

Figure B16 - Proximity Probe Attachment to Spider Arm (initial gap set between 115 to 120 mils)

Figure B17 - Arm 1 showing Top, Middle, and Bottom Proximity Probe Attachment on Windward Side of Arm

Figure B18 - Wireless Link Transmitter Attachment to Shaft just below Hub (wires connected to proximity probes)

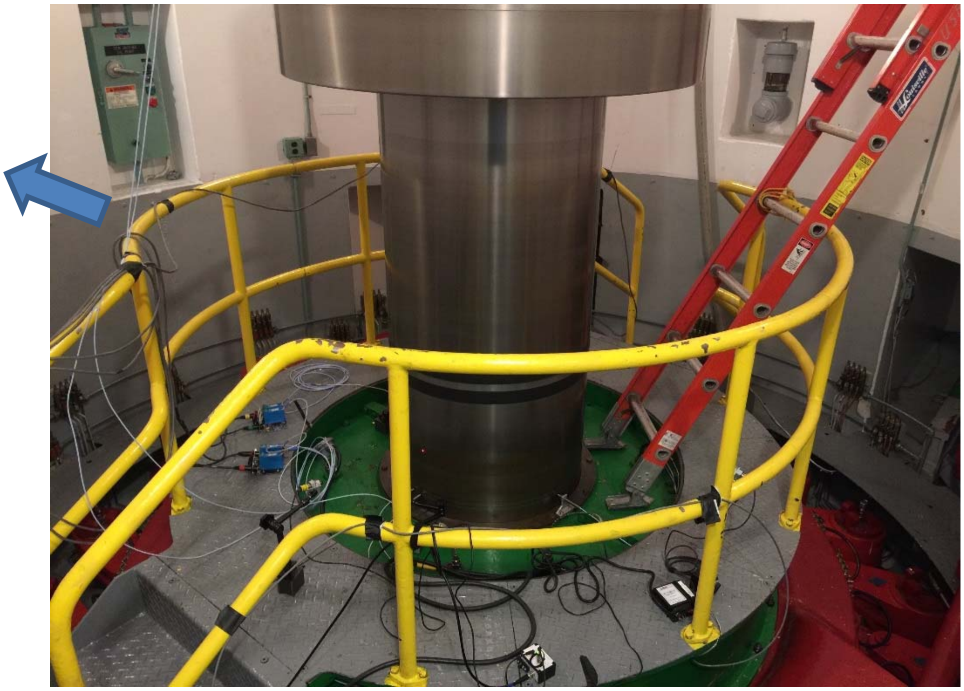

Figure B19 - 1/rev and Speed Sensor Location (1/rev shaft pickup tape approximately aligned with rotor pole 1)

Note: Unit 1 picture shown, unit 4 identical except 1/rev pickup located 90 deg. east of downstream (See blue arrow).

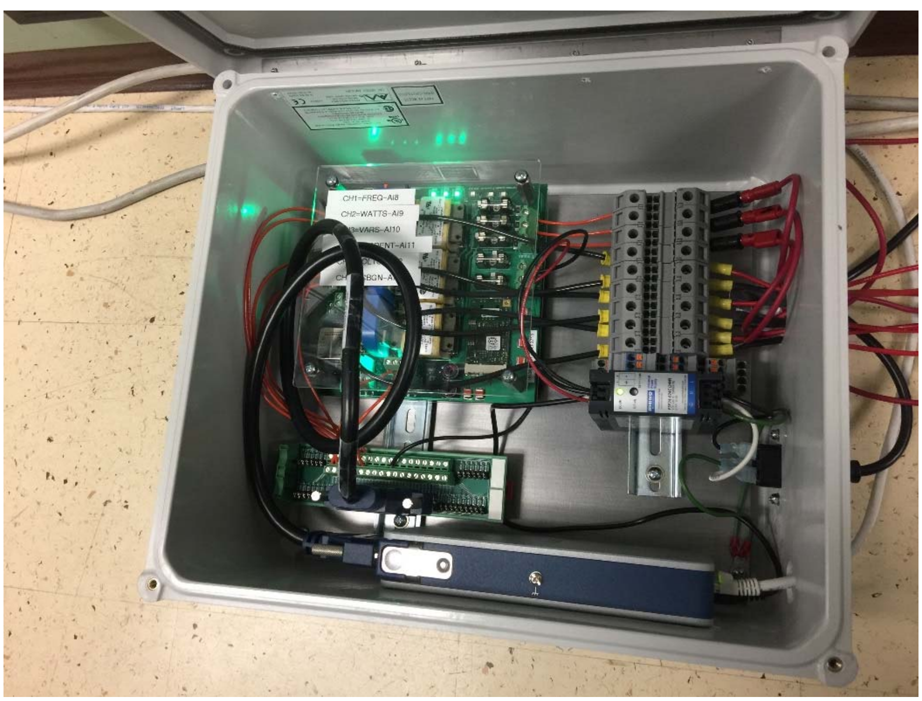

Figure B20 - PT/CT transducer board and DAQ connected to unit 4 test block

Figure B21 - Air gap probe installation on rotor

Battery powered wireless transmitter used to record and transmit probe data.

Attachment C – Generator 1, 2017 Report

BUREAU OF RECLAMATION
Technical Service Center
Denver, Colorado

TRAVEL REPORT

86-68450 Date: May 31, 2017
PRJ-20.00

To: Nathan E. Myers, Manager
Hydropower Diagnostics and SCADA Group

From: James DeHaan, P.E., Electrical Engineer
Jacob Lapenna, Electrical Engineer

Subject: Yellowtail Generator 1 Rotor Measurements

1. Travel period: April 17-21, 2017.

2. Places or offices visited: Yellowtail Powerplant, Fort Smith, MT.

3. Purpose of trip: Perform Tests on Generator 1.

4. Synopsis of trip: The rotor measurement tests are summarized as follows.

Overview:

Prior to the subject testing, Generator 1 (G1) at Yellowtail was refurbished. This included a new stator core, new armature winding, and the field poles were removed and re-insulated. When attempting to balance G1 to return it to service, it was discovered that there was a significant balance difference between running the unit excited or un-excited. It also was noted that when G1 was subject to an overspeed event the balance would get much worse and not always return to pre overspeed values until unit rotation was stopped. In addition, when G1 was loaded for a long period of time it was noted that the unit balance would vary over time. Various unit conditions were discussed that could lead to these undesirable issues including: rotor rim float, loose rotor poles, or rotor pole winding short circuits.

The rotor rim is connected to the spider arms via a spring system. Previous measurement made by the rewind contractor showed that the spring deflection was not per original specifications. Thus, it was suspected that the rotor rim is floating when operated at rated speed. In addition, issues were encountered when pole 30 was being installed on the rim. The rim lamination within the rim dovetail section needed to be shaved slightly to allow the rotor pole body dovetail to be inserted. An issue with the rim near pole 30 or within the pole 30 dovetail connection was suspected. Moreover, when the rotor poles were received after new insulation was applied, the weight of the poles was slightly higher than the original poles (up to 24 lbs), and the pole weights varied by as much as 10 lbs. from the average pole weight.

Measurements:

On April 20, 2017, rotor tests were performed at the request of Great Plains' region personnel to determine if G1 rotor rim was floating, if there was an issue with pole 30, and to check for rotor shorted turns.

To measure if the rim was floating, 8 proximity probes were installed to measure movement between the spider arms to rotor rim back iron. A battery power transmitter was used to transmit the proximity probe data to a stationary data acquisition system. Details of this measurement are included in the attachment.

To measure if there was an issue with pole 30, the shape of the rotor was monitored using 2 capacitive probes. The probes were mounted to the stator core and measured the distance to each pole as it passes the probe. The minimum distance between the probe and rotor pole face can then be measured. Details of this measurement are included in the attachment.

Finally to measure if a rotor shorted turn was occurring a flux probe was installed on the stator to measure the magnetic flux density produced by each rotor pole. A significant change in flux density between rotor poles would indicate the rotor pole has a shorted turn.

Four series of tests were conducted. These tests included running G1 at a slow-roll, at speed-no-load-no-excitation, speed-no-load-excited, at various megawatt loads, and at overspeed conditions. Test results are contained in the attachments.

Observations:

Pole flux measurements:
The flux density is nearly identical for each rotor pole. This condition was consistent throughout the tests and was independent of unit loading. This would indicate that no rotor turn short exists.

Movement of rim relative to spider arm:
As G1 was accelerated from zero to rated speed, the distance between the arm and rim increased by about 10 mils at the top of the rim (figure 3). Given the spring deflections measured by the contractor, there is little to no spring tension left in the spring at rated speed. The top of the rim is floating at speed-no-load. Movement at the middle and bottom of the arm was about 7 mils. Again, there is little spring tension left at these location.

No additional rim to arm movement was measured when G1 was excited.

When G1 was loaded, the distance between the arm and rim decreases to about 3.5 mils at the top of the rim, 0 mils at the bottom of the arm, and compressed to -4 mils at the middle of the arm (figure 4). It is hypothesized that this is most likely due to spider arm deflection under load. All the proximity probes were located on the leading edge of the spider arms. Under load, the arm may deflect slightly, which would theoretically move the proximity probe bracket closer to the rotor rim. The proximity probe is located 8.5 inch from the center of the spider arm. A 6.5 mil movement would equate to an angular displacement of the spider arm of roughly 0.04°. This deflection could also explain the initial negative movement of the proximity probes when the unit is started (figure 3), as well as when unit brakes are applied (figure 5).

When G1 was loaded at 63 MW for 1 hour, the stator and rotor both expand due to heat. Rotor expansion was noted as the proximity probe signals showing an increase of 2 to 3 mils separation between the arm and rim during this time period.

During unit shutdown, the arm to rim proximity probe signal decreases as G1 speed decreases (figure 5). When the unit comes to a complete stop, the distance between the arm and rim was about 2.5 mils greater than when the unit was initially started. This is most likely due to the rim being warm from running for 1 hour at 63 MW.

As G1 was accelerated above rated speed, the distance between the arm and rim increased somewhat linearly with speed (figure 6). However, the movement at each arm is not consistent. For example, the movement at arm 6 is about 2 mils greater than the average movement at the remaining arms. Given the spring deflections measured by the contractor, there is little to no spring tension left at over speed. Movement at the middle and bottom of the arm was about the same as the top.

Rotor shape:

Rotor shape is shown in Figures 7 and 8. From these figures it can be seen that the rotor shape is the same for both airgap probes but that airgap 1 is about 30 mils closer to the rotor than airgap 2. Either the stator is not round, resulting in this offset; or the rotor is not centered within the stator.

To help evaluate how round the rotor is, the rotor concentricity and circularity were calculated per CEATI guidelines.[2] Concentricity is defined as the deviation between the best center and the axis of rotation. It also may be referred to as eccentricity in other documents. Circularity is defined as the deviation between maximum and minimum radii, as measured from the best center. The slow roll (8 RPM, test 2) rotor shape data was evaluated to determine these parameters. Rotor circularity is 1.7% of the measured average airgap, and is within the CEATI guidelines tolerance of 6% or less. Rotor concentricity is 1.2% of the measured average airgap, and is equal to the CEATI guideline tolerance of 1.2% or less. Figure 9 shows the best center data used to determine these quantities.

The airgap comparison between various operating points (figure 9) demonstrates that the airgap decreases about 30 mils from a slow roll to speed-no-load. This movement is also shown in figure 12. When excited, the rotor center point changes slightly, shown by a shift of the center point within the rotor wave shape of roughly 3 mils towards rotor pole 25. When G1 was operating at 63 MW the airgap increased an additional 10 mils. This is likely due to stator

[2] Hydroelectric Turbine-Generator Unit Guide for Erection Tolerances and Shaft System Alignment, CEATI International, June 2015.

heating, as figure 11 shows that as G1 was initially loaded from zero to 63 MW no change in airgap was recorded.

A close comparison of the slow-roll rotor shape to the speed-no-load rotor shape also shows that pole 30 moves about 7 mils more than the other poles. This observation is highlighted in Figure 10. This plot shows how far each pole varies from the average pole position during each test condition. For most of the poles, the slow-roll, speed-no-load, and full load curves closely follow each other. However, pole 30 data points vary between the slow-roll and the two rated speed test conditions. This suggests the rim at pole 30 has more flexibility and/or rotor pole 30 may be moving within the dovetail connection.

Variation of pole weights from average are plotted in Figure 10. Pole weights vary from the average weight by about ± 9 lbs. However, there does not appear to be any correlation between pole weights and pole movement.

Equalize currents:
The wave shape pattern of the secondary currents within the equalizing circuits remain fairly constant for all operating points. A typical wave form is shown in figure 13. There is a once per revolution change in amplitude in the waveforms that persists under all observed operating points. This pattern would be typical of a rotor that is not round, and is not centered within the stator bore. The value of G1 equalizing currents is roughly the same as for G3. The once per revolution pattern is also similar between units (see figure 14).

5. Conclusions: G1 tests were successfully performed and the data successfully collected. Test results are attached. None of the test results indicate a clear reason for the vibration issues as summarized above. However, the following issues were observed:

- Rotor is not round.
- Rotor may not be centered in stator bore and/or the stator core is not round.
- Pole 30 or the rim at this location is moving more from standstill to rated speed than the remaining unit poles.
- Rotor rim movement is greater than the reported spring compression dimensions, indicating the rim is floating.
- During over speed, the rotor rim movement is not consistent at each spider arm, indicating the rotor rim shape is being slightly distorted.
- Rotor pole weights are not consistent, and not evenly distributed around the rotor.

6. Suggestions: All the issues noted above could lead to unit vibration and correction of these issues may help to correct the vibration issues.

To correct these issues, the following general suggestions could be pursued:

- Remove all rotor poles and reposition poles to evenly distribute rotor pole weights.
- Remove arm to rim springs and measure if rotor rim is circular. If not circular, reposition rim lamination to obtain a circular rim.
- Drive new spider arm-to-rim spring wedges to establish manufacturer recommended spring deflections.

- When driving new spring wedges, verify rotor rim circularity and concentricity is maintained.
- When installing pole 30, verify proper fit.
- Install rotor in center of stator bore during re-assembly.
- Ensure the stator core circularity.

If you have questions or comments, please contact Jim DeHaan at (303) 445-2305.

7. PRIS Recommendations: None.

8. Client feedback received: None.

9. Action correspondence initiated or required: None.

cc: 86-68400 (Girgis), 86-68410 (Germann), 86-68430 (Mauer), 86-68450 (DeHaan, Myers),
MT-300 (Tauscher), MT-600 (Manni), GP-2600 (Anderson), GP-2200 (Skinner)
(w/att to each)

Yellowtail Tests, Generator 1 - 2017

Technical Addendum

1.Test Measurements

The following measurement points were instrumented during these tests:

10. Rim back iron movement
    a. Proximity Probes
        i. Mounted on brackets attached to leading edge of spider arms
            1. Arm 1 is located adjacent to rotor pole 1
            2. Successive poles located clockwise around rim
        ii. 8 probes
            1. 1 probe attached near top of each arm (6 total)
            2. 1 probe attached at middle and 1 at bottom of arm 1
        iii. Measure spider arm to rim movement
        iv. Automation Direct, Model: AM9-05-1A
    b. Wireless Link
        i. Two 4-channel transmitters mounted on shaft
        ii. Summation Research, Model 500e
11. Airgap distance
    a. Airgap Capacitive Probes
        i. Mounter on stator to measure rotor to stator airgap
        ii. 2 Probes mounted near top of core
            1. Probe 1 was mounted on core tooth between slots 39 and 40
            2. Probe 2 was mounted on core tooth between slots 201 and 202
        iii. General Electric 4000 Series Airgap 20 mm Sensor System
12. Airgap flux
    a. Reclamation designed and built flux probe
        i. Probe constructed with 30 turns
        ii. Mounted on core tooth between slots 19 and 20
13. Equalizing circuit currents
    a. Clamp on CTs
        i. Measure equalizing circuit CT secondary currents
        ii. All 9 equalizing circuits monitored
        iii. Fluke, Model I30
14. Generator speed
    a. Shaft rotation
        i. 1/rev shaft pickup location approximately aligned with pole 1 (may be off by ±1 pole) and stationary sensor located directly downstream.
        ii. 1/rev via remote optical laser system

        iii. Speed via remote optical laser system plus frequency to analog converter

15. Generator parameter
    a. Plant transducers
        i. Gate Position
        ii. MW
        iii. MVar
        iv. Terminal Voltage
        v. Terminal Current
        vi. Frequency
16. Data Acquisition Equipment
    a. I/O Tech Wavebook
        i. Proximity probes
        ii. Capacitive probes
        iii. Flux probes
        iv. Gate position
        v. 1/rev and speed
    b. I/O Tech Personal DAQ
        i. Equalizing currents
        ii. Generator electrical parameters
        iii. 1/rev

2.Test Sequence

Four series of tests were performed on April 20, 2017 as follows:

- Test 1 – The unit was started on a slow-roll and then slowly accelerated in steps to rated speed. It was then excited, un-excited, and ramped back down to standstill. For this test, the wireless transmitter for proximity probes on Arms 3-6 was not functioning.
- Test 2 – The unit was started on a slow-roll and then ramped to full load. It was then excited, synchronized, and ramped to a load of 63 MW. After about 1 hour, it was ramped back down to no load and taken offline. Excitation was then reduced to about 10kV, and an overspeed test was performed. At 275 RPM (122% speed) the unit tripped on a miscalibrated overspeed pickup. For this test, the wireless transmitter for proximity probes on Arms 3-6 was not functioning.
- Test 3 – Prior to test 3, the wireless transmitter for Arms 3-6 was fixed and functioned correctly for the remaining tests. The unit was started normally. It was then excited and un-excited. An over-speed test to 292 RPM (130% speed) was then performed with the unit un-excited. Following the over-speed test, the unit was ramped back to rated speed and then shut down normally.
- Test 4 – The unit was started normally, excited, synchronized, and then ramped to 63 MW. After about 1 hour, it was ramped back down to no load and a normal shutdown was performed.

3.Test Results

Online pole flux measurements

Flux wave shape at speed-no-load and full load measurement points. The voltage produced by the flux probe, which is basically a coil of wire, is the derivative of the flux. Thus, the flux probe signal was integrated to get a true shape of the airgap flux.

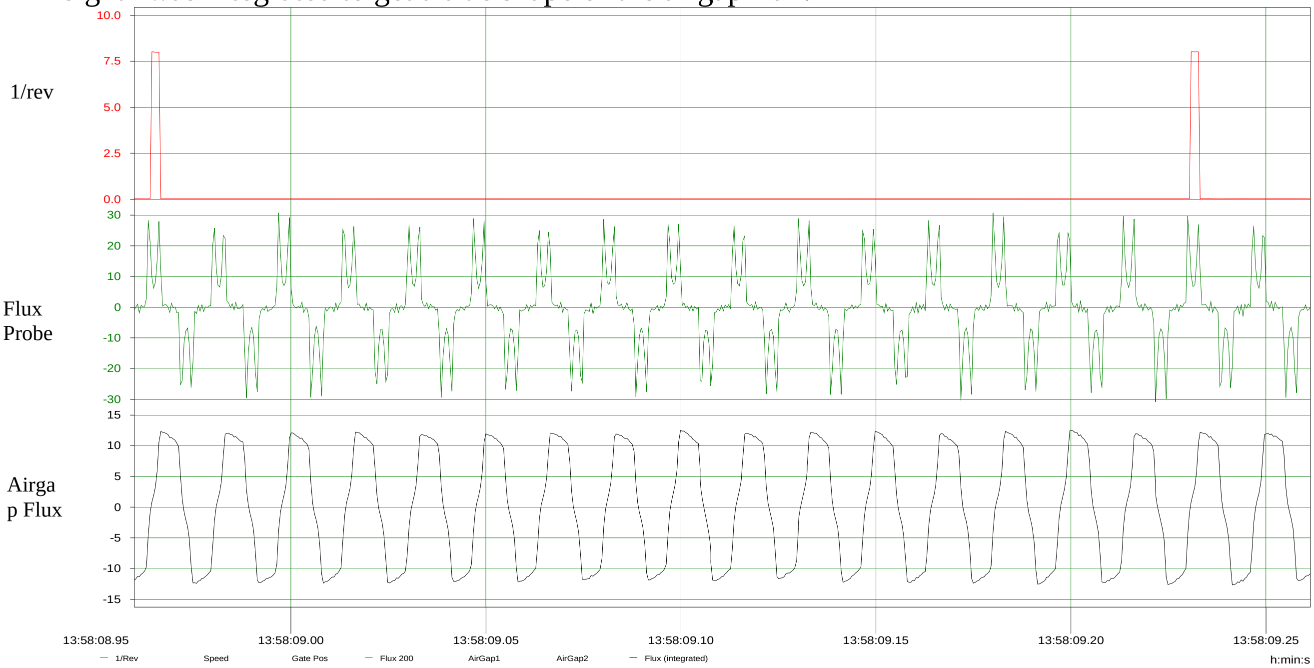

Figure 1 - Flux Signal at No Load

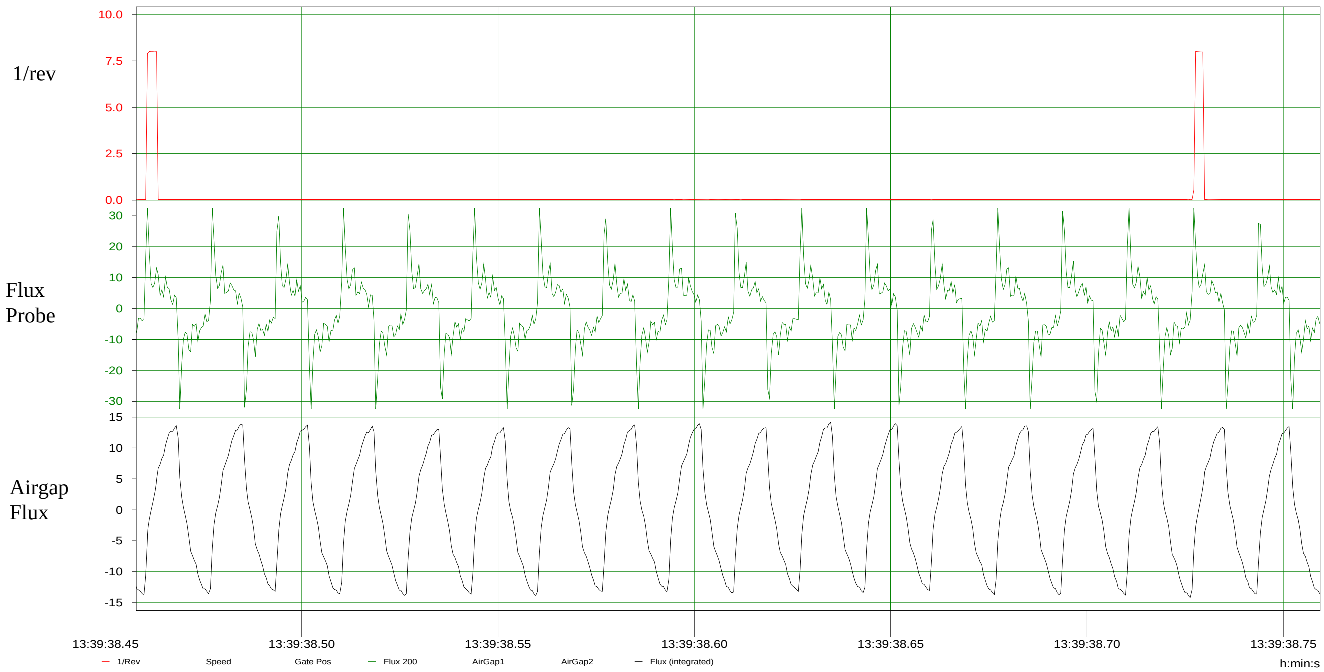

Figure 2 - Flux Signal at 63 MW, 0 MVars

4. Movement of Rim Relative to Spider Arms

Generator Startup

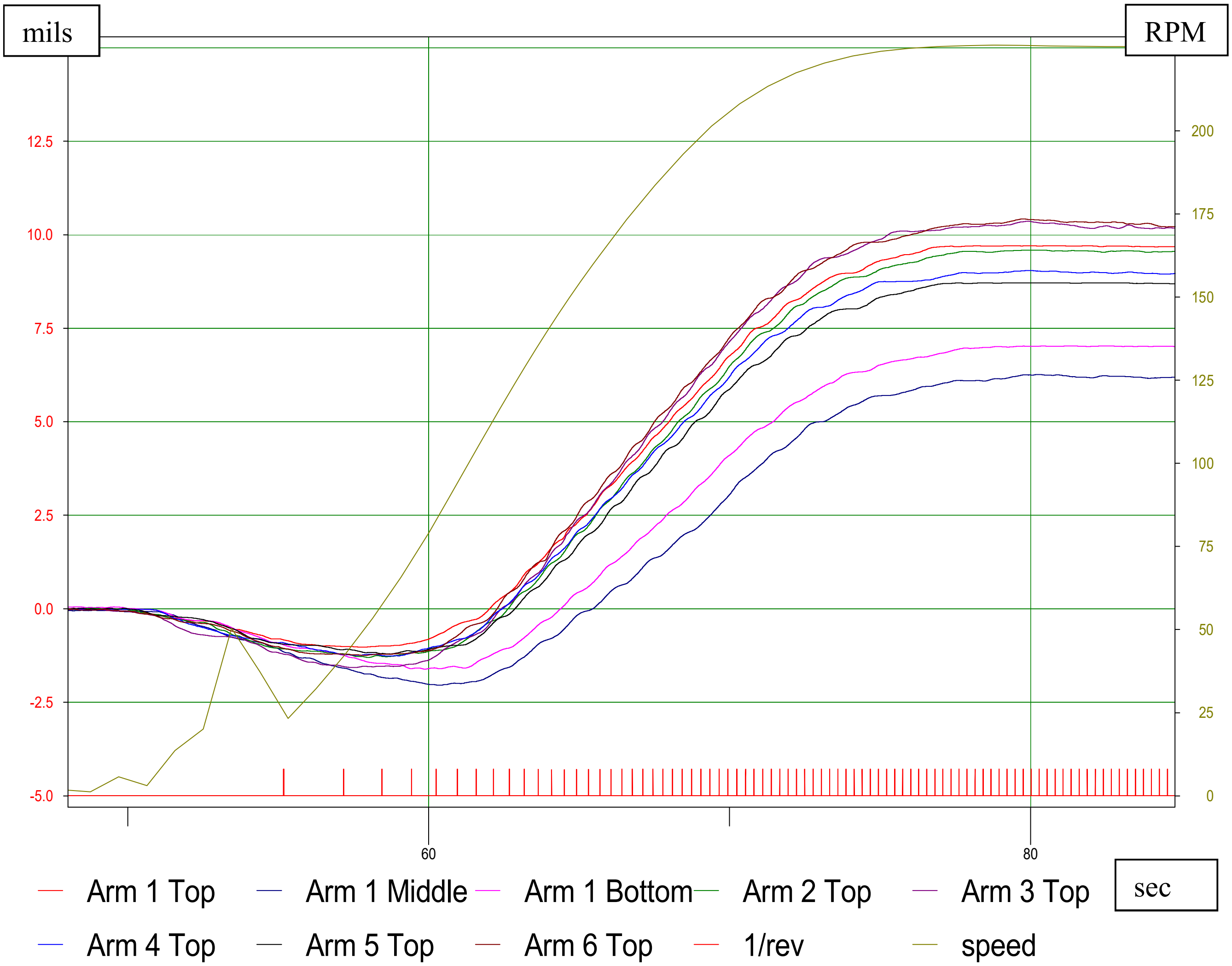

Figure 3 - Spider Arm to Rotor Rim Movement during Start, test 4

(Ignore non-linearity in initial rotation speed signal)

Excitation

No spider to rim movement was observed when field was applied.

Unit Loading

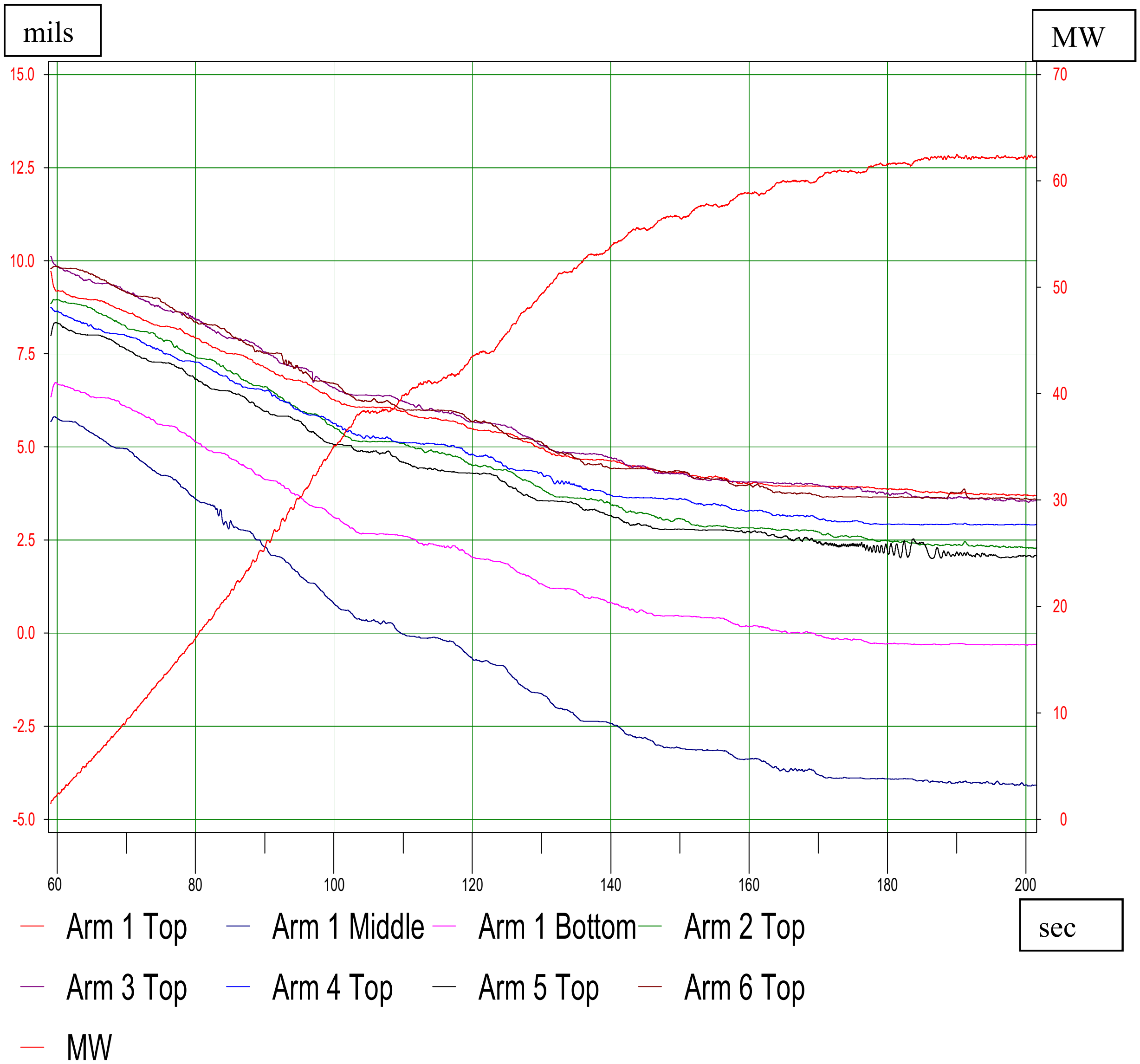

Figure 4 - Spider Arm to Rotor Rim Movement during Unit Loading, Test 4

(Proximity sensors are located on leading edge of arm rotation)

Generator Heating

Unit loaded to 63 MW at unity PF and ran for about 1 hour. Gap between spider arms and rim increased about 3 mils at top, 2 mils at middle, and 2 mils at bottom.

Generator Shutdown

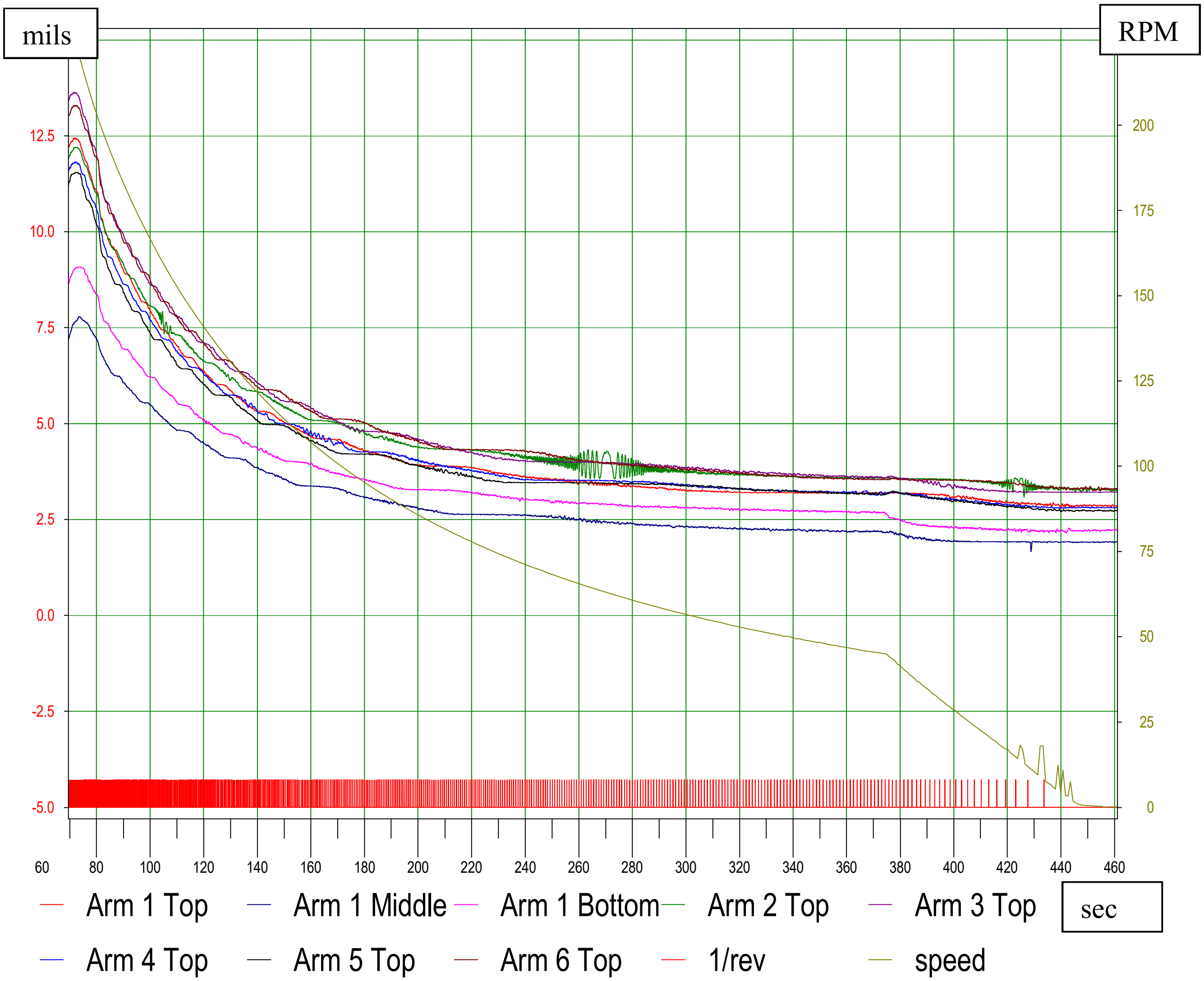

Figure 5 - Spider Arm to Rotor Rim Movement During Shutdown, Test 4
(Unit ran for over 1 hour prior to shutdown.)
(Ignore non-linearity of final rotation speed signal, ignore osculation in arm 3 data.)

Overspeed

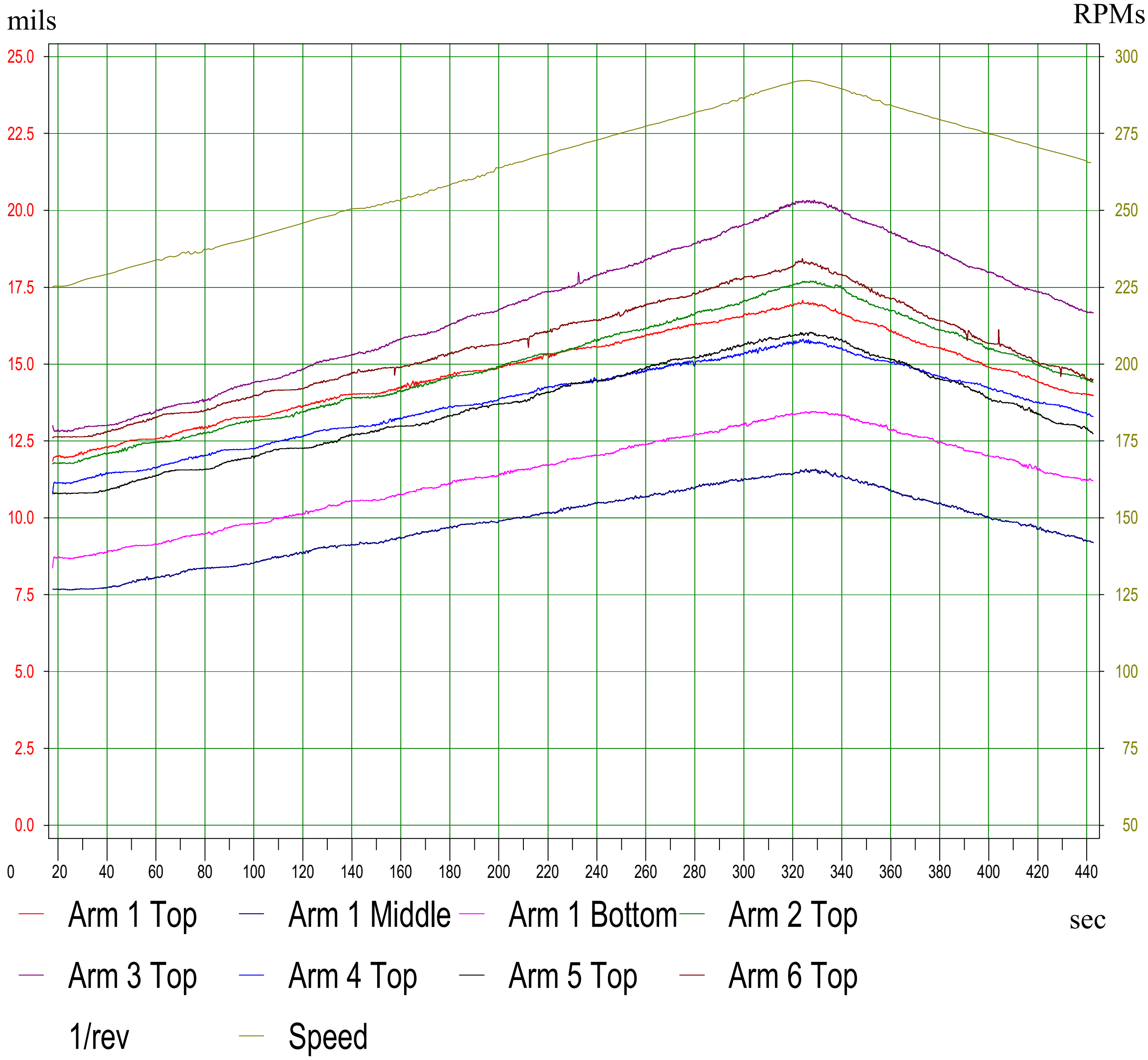

Figure 6 - Spider Arm to Rotor Rim Movement during Over Speed, Test 3

5. Rotor Shape

Airgap was recorded near the top of the rotor at two locations 180° apart. Airgap 1 is located approximately 4 rotor poles counter clockwise from downstream on the stator core, and airgap 2 is located approximately 4 rotor poles counter clockwise from upstream on the stator core. Airgap was measured using the GE capacitive probes.
Note: Probe thickness offset is approximately 150 mils, and should be added to the following plots to obtain true airgap distance.

*The following values were calculated from the rotor shape data, as recorded during the slow-roll (*8 RPM*) measurement during test 2.*

Calculated values:
Best Center was derived and is shown in Figure 9.
Concentricity (deviation between best center and axis of rotation)
=7.5 mils or 1.2% of measured average airgap, towards pole 9.

Circularity (difference between minimum and maximum radii to best center)
= 10 mils or 1.7% of measured average airgap

This data was only collected on the top of the rotor. Bottom readings would be required to more accurately model the rotor shape.
Data does not exclude the movement of the shaft at each bearing elevation. This may have an impact on the actual rotor shape results.

Slow-Roll Data

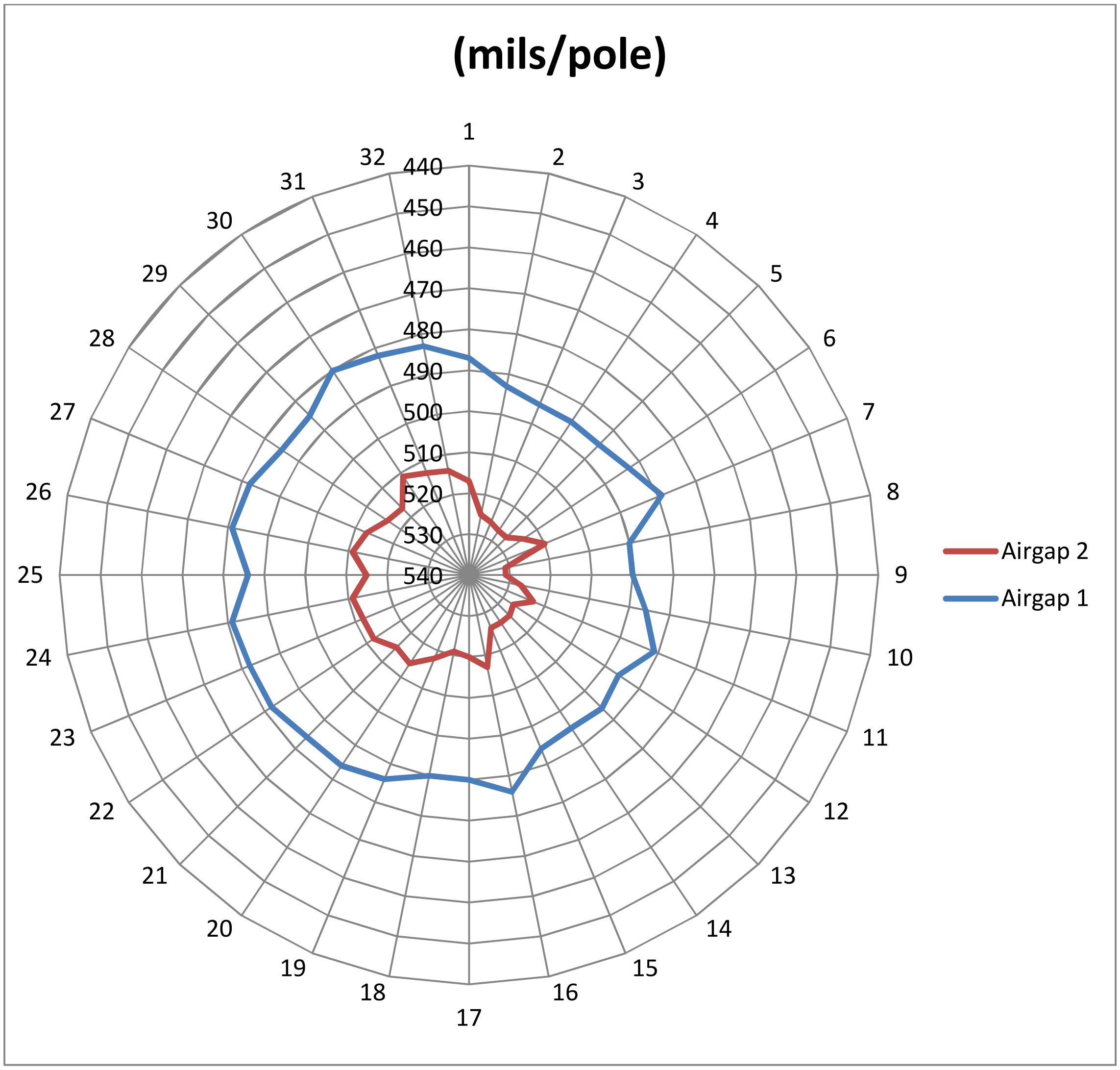

Figure 7 - Rotor Shape at 80 RPM, Test 1
(Pole numbers may be off by ±1 pole)

Rated Speed and Rated Load

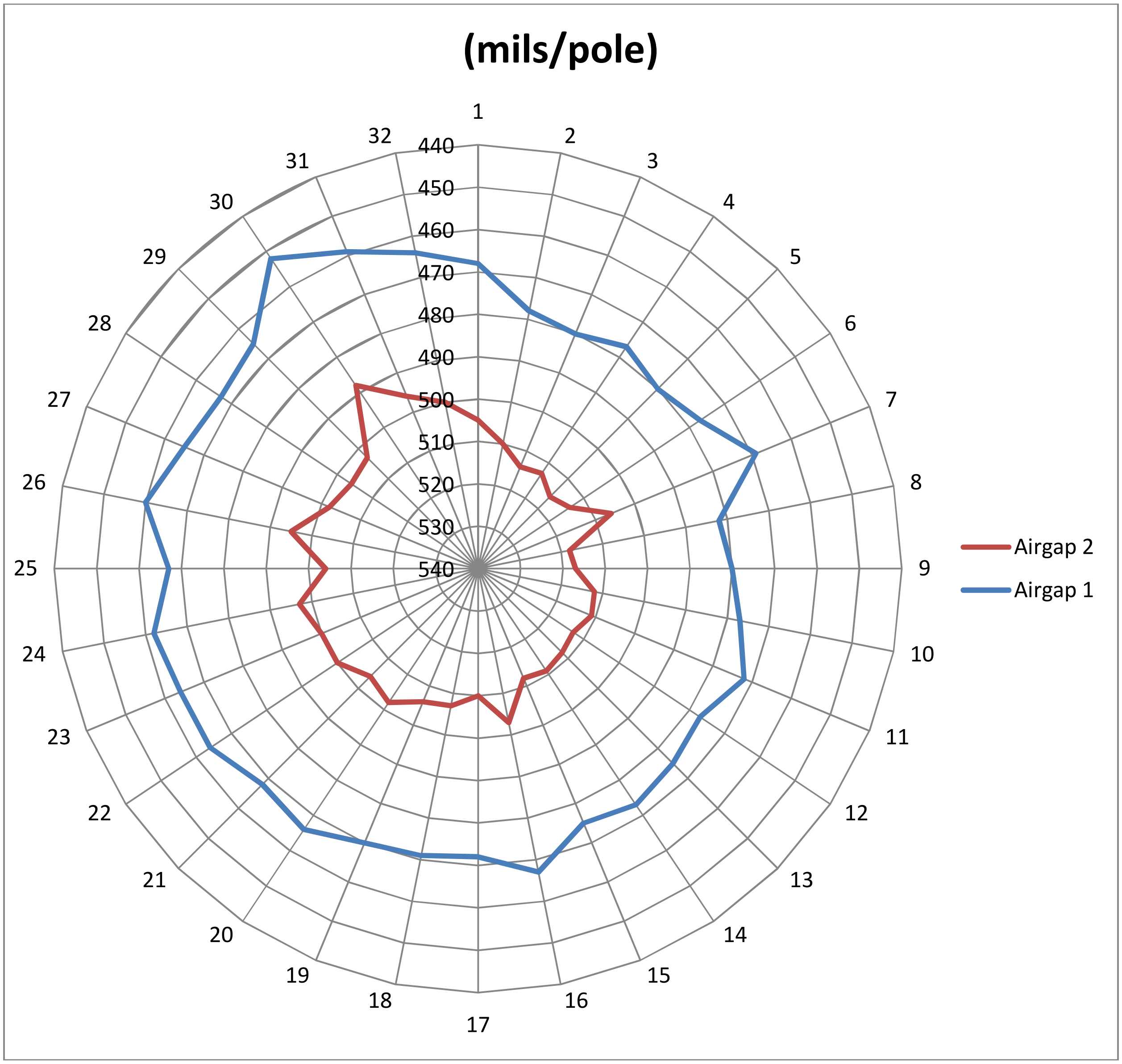

Figure 8 - Rotor Shape at Rated Speed (225RPM) and Load (62 MW), Test 2
(Pole numbers may be off by ±1 pole)

Comparison of Airgap 1 data between various tests

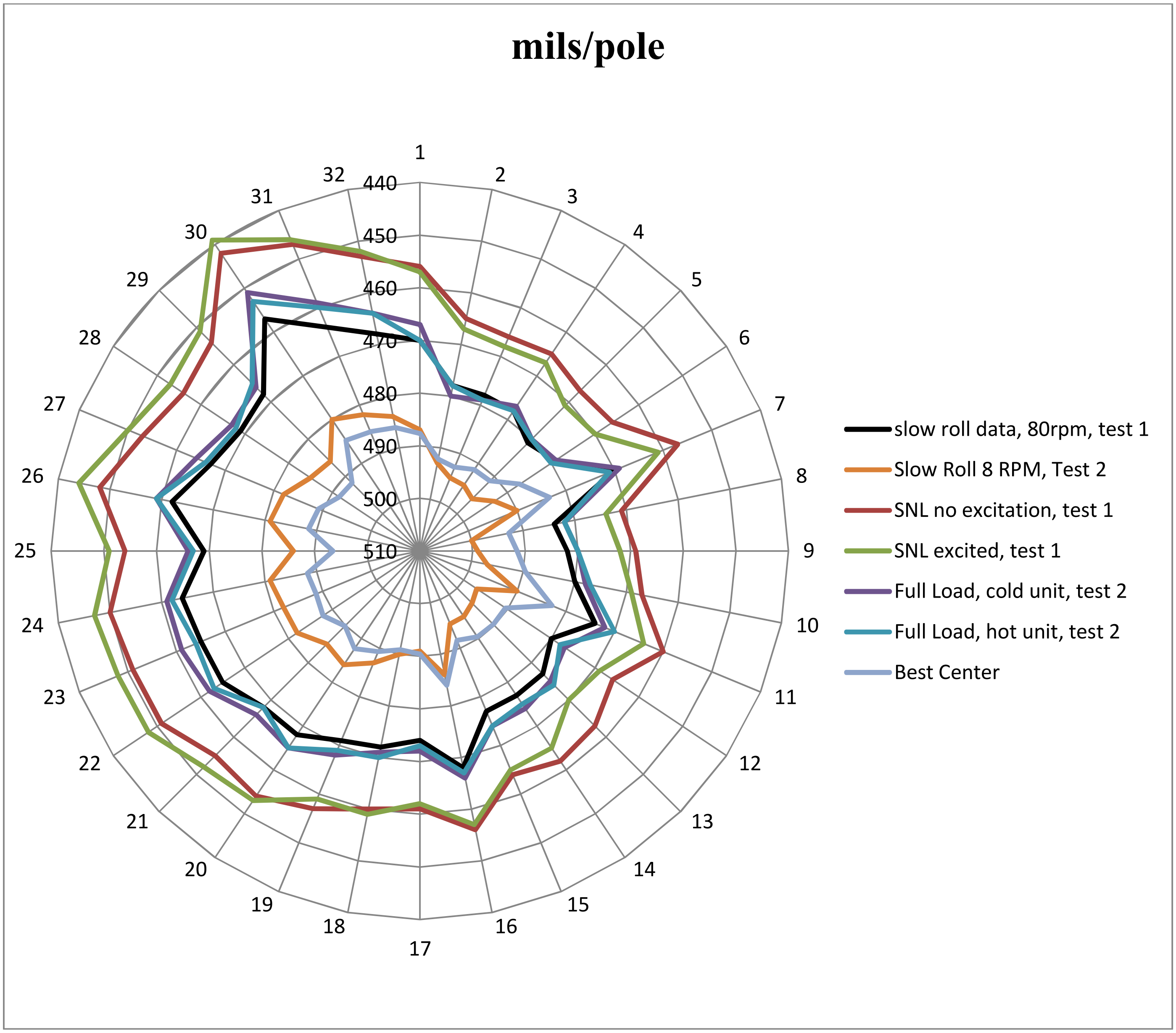

Figure 9 - Comparison of Airgap 1 data between various test conditions, tests 1 and 2. (Pole numbers may be off by ±1 pole)

Pole variation from average airgap and pole weight variation from average

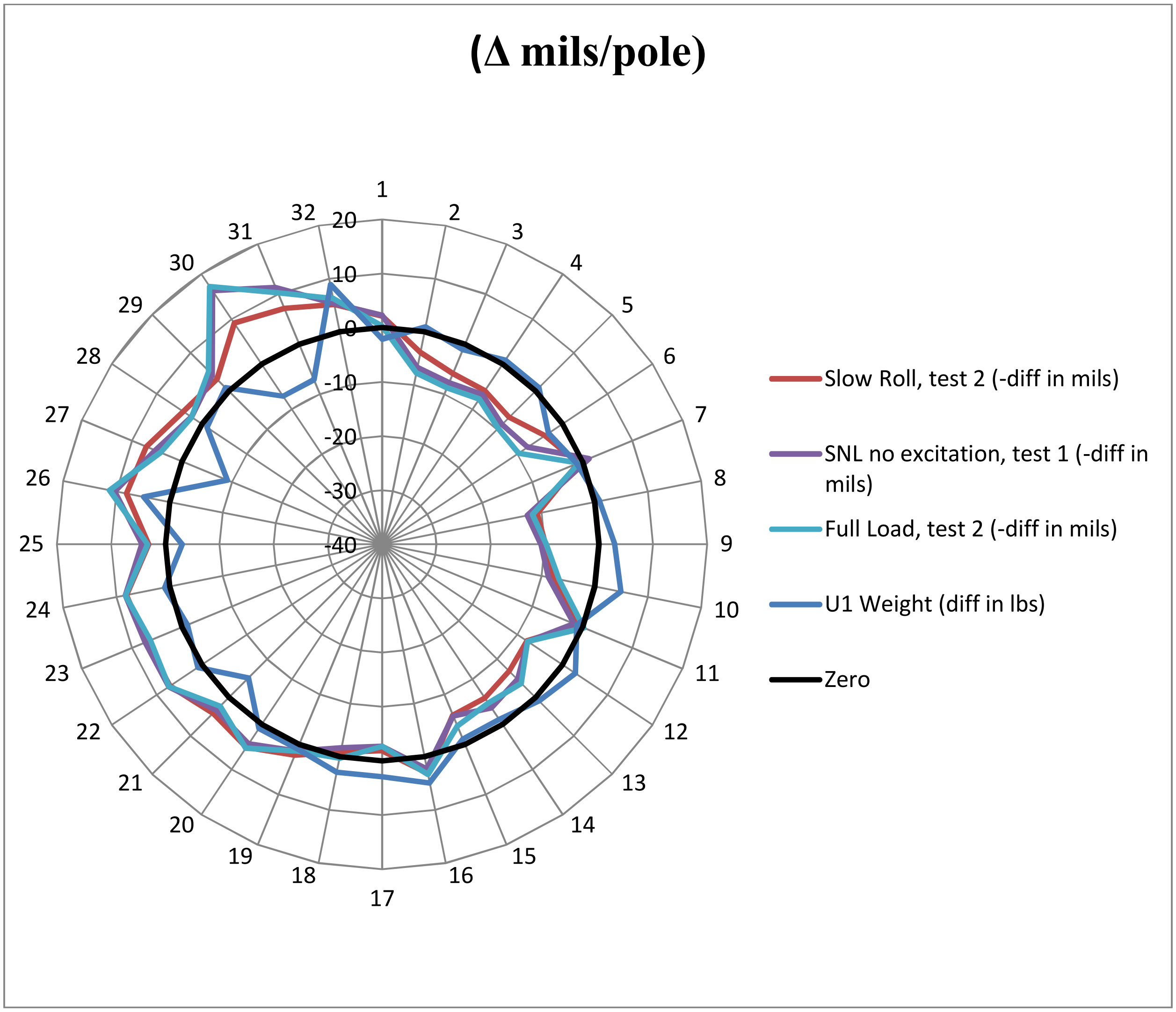

Figure 10 - Pole variation from average airgap and pole weight variation from average, Tests 1 and 2 (Pole numbers may be off by ±1 pole) (Positive variation is a reduced airgap or heavier pole weight)

Comparison of airgap data to change in load, Test 4

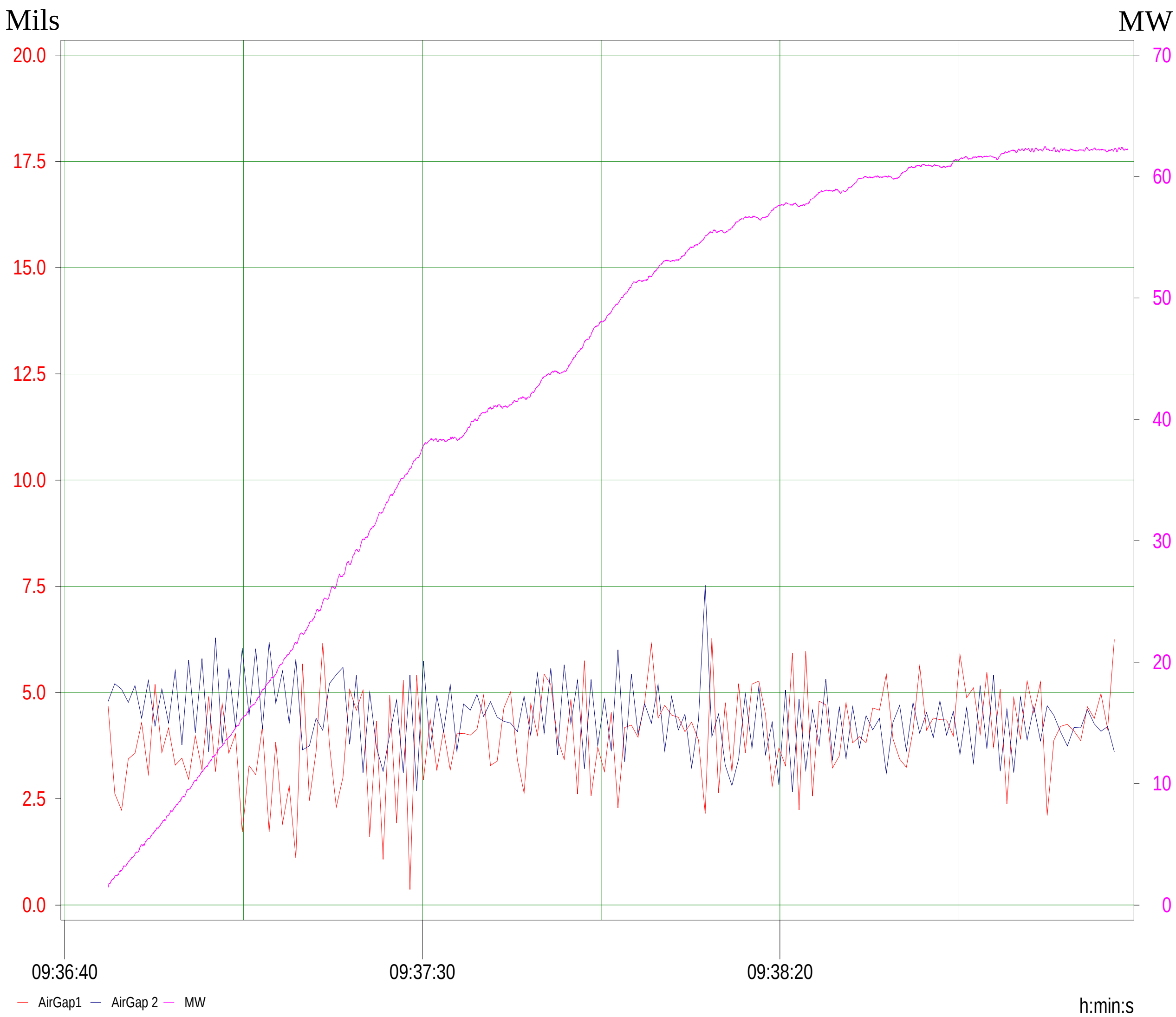

Figure 11 - Comparison of average relative airgap movement to change in load, Test 4
(Ramp Load 0 to Full, test 4)
(Airgap offset adjusted to ~4 mils for each airgap signal)

Comparison of airgap data to change in speed, Test 4

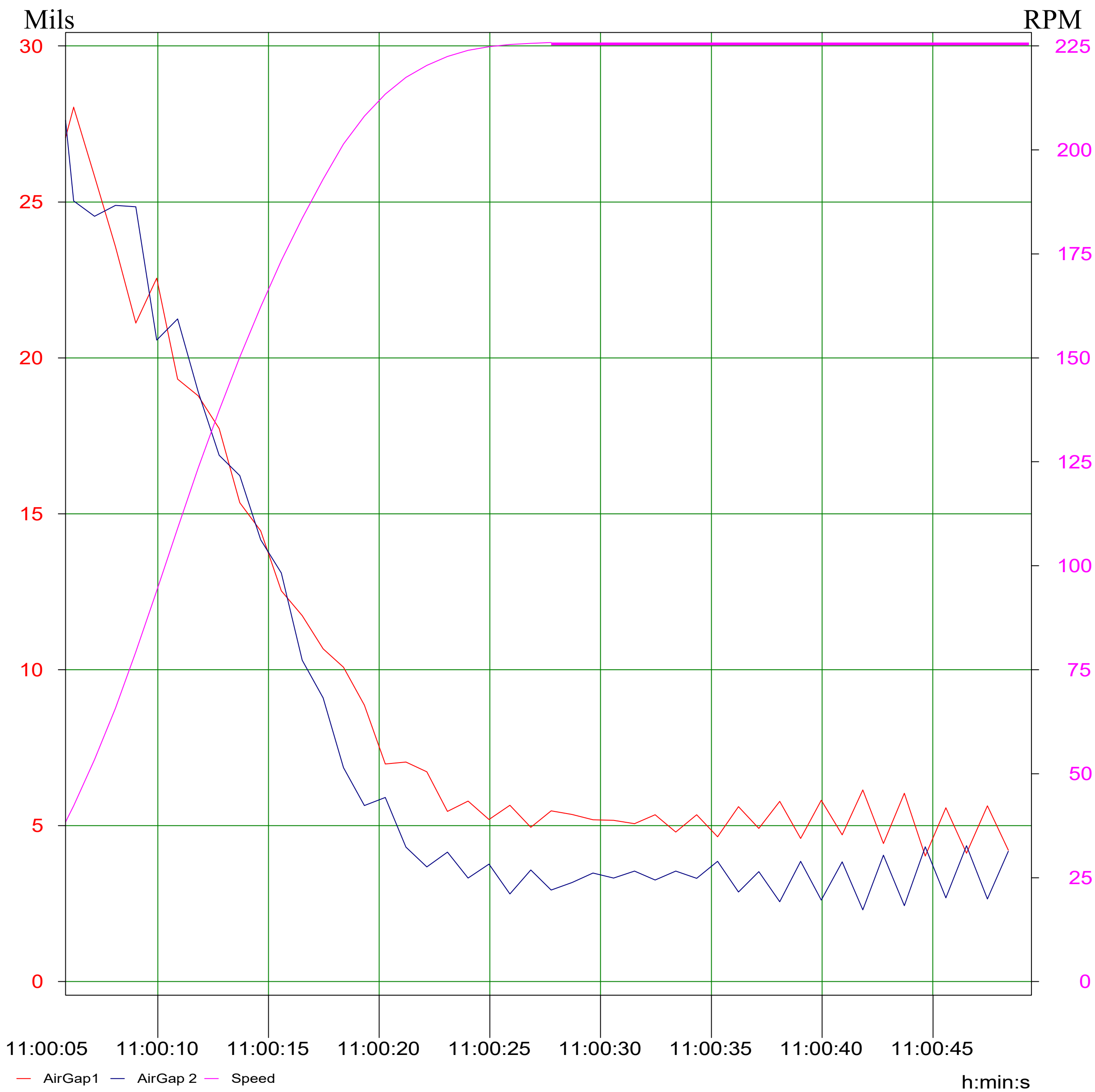

Figure 12 - Comparison of average relative airgap movement to change in speed, Test 4

(Airgap offset adjusted to ~4 mils for each airgap signal)

6. Equalize currents

Largest value on all three phases (9 circuits) is ~1 A peak on secondary circuit. Equalizer currents remain fairly constant for all loading conditions.

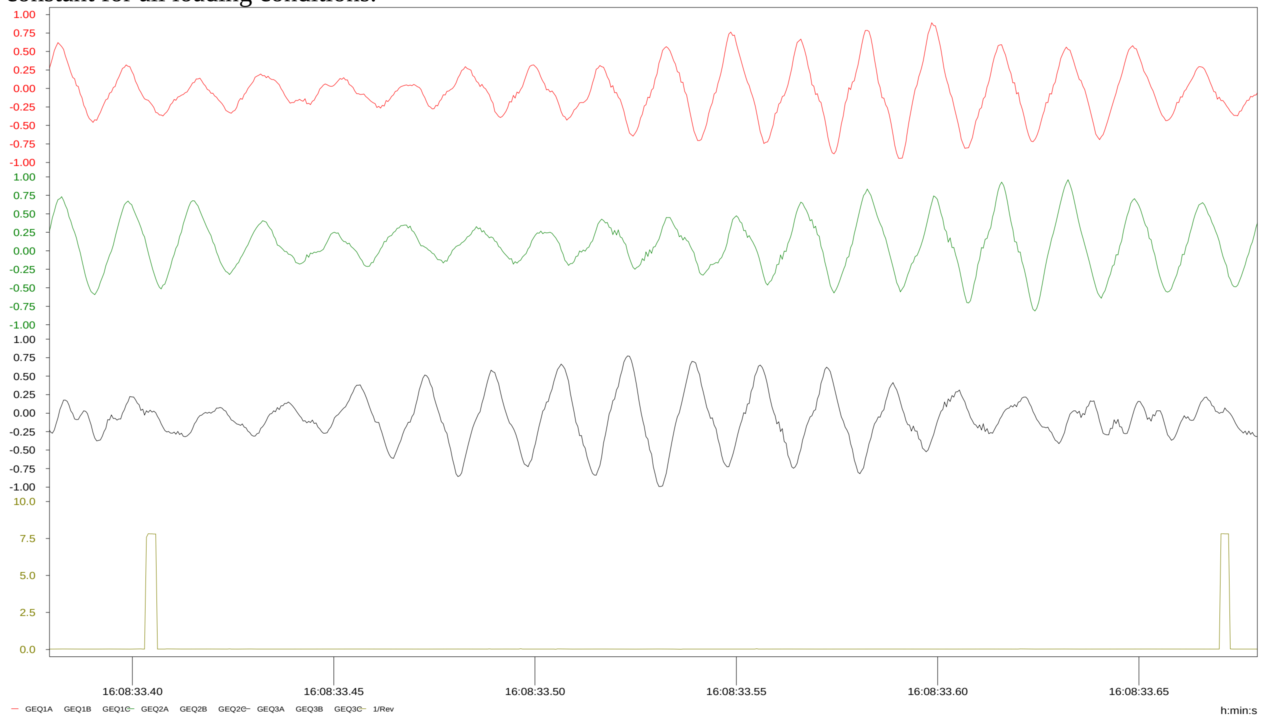

Figure 13 - Equalizer CT Secondary Currents on Phase A

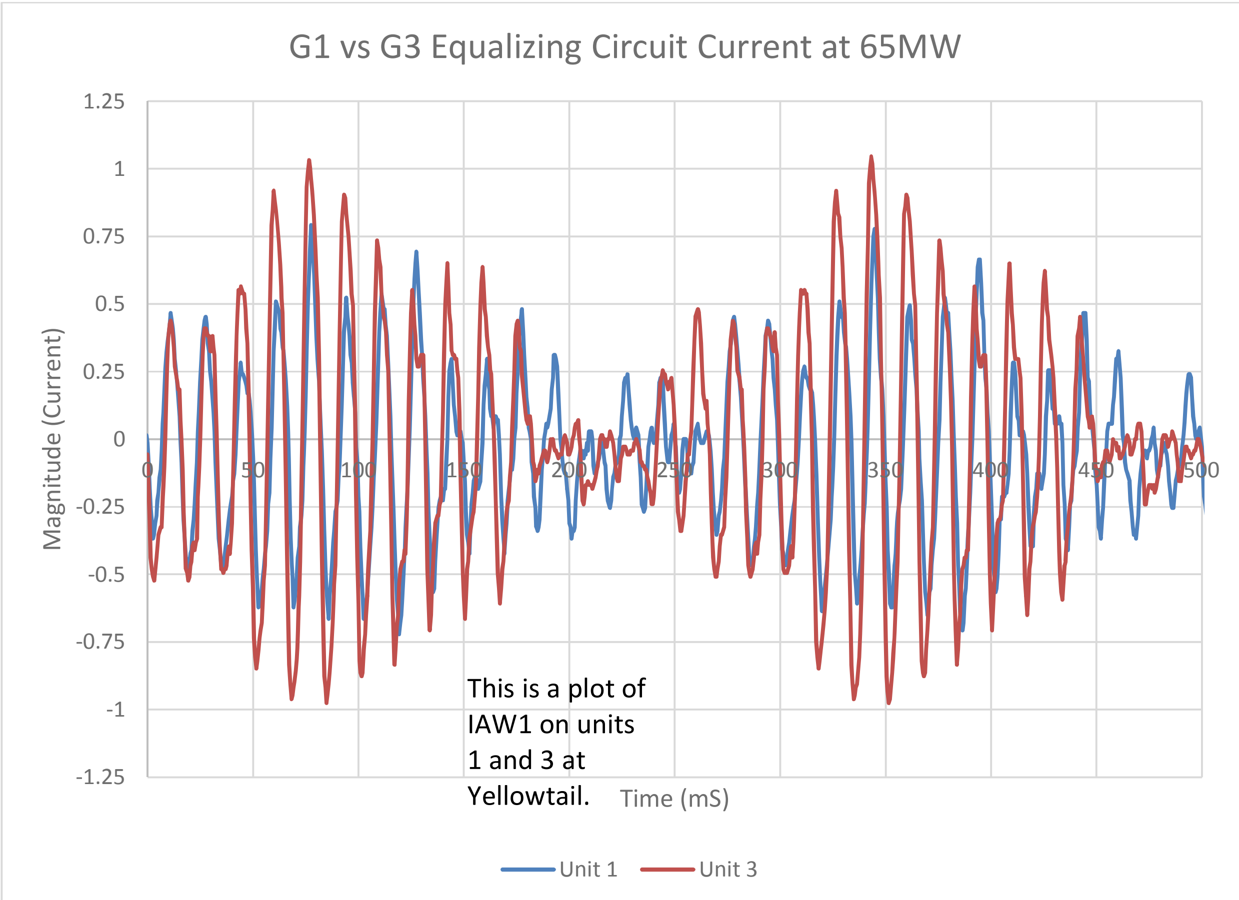

Figure 14 - Comparison of Generator 1 and 3 Equalizing Currents

7.Test Equipment

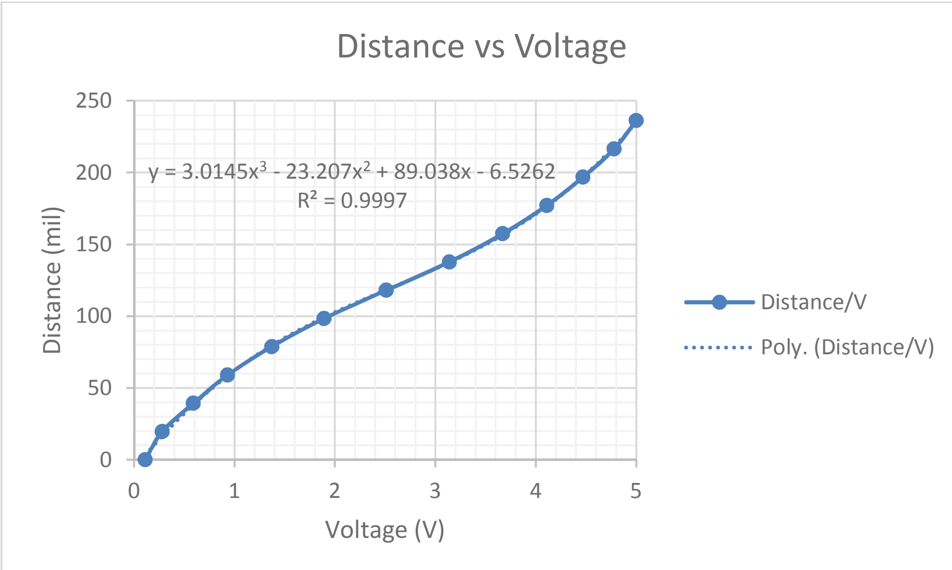

Figure 15 - AM9-05-1A Non-linear Response of Proximity Probe and Resultant Equation

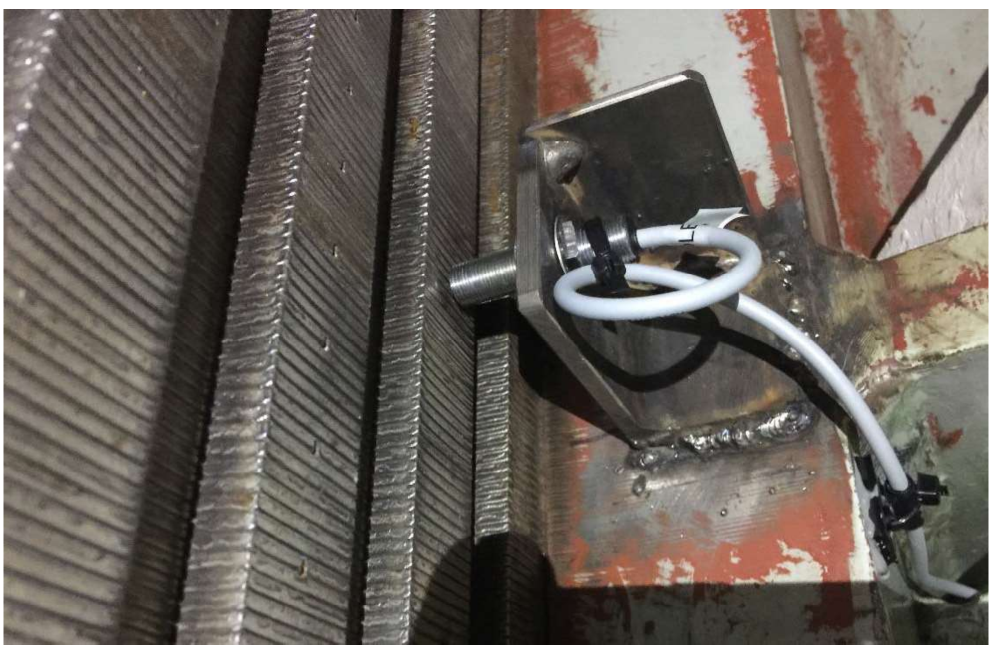

Figure 16 - Proximity Probe Attachment to Spider Arm (initial gap set between 100 to 120 mils)

Figure 17 - Arm 1 showing Top, Middle, and Bottom Proximity Probe Attachment

Figure 18 - Wireless Link Transmitter Attachment to Shaft just below Hub (wires connected to proximity probes)

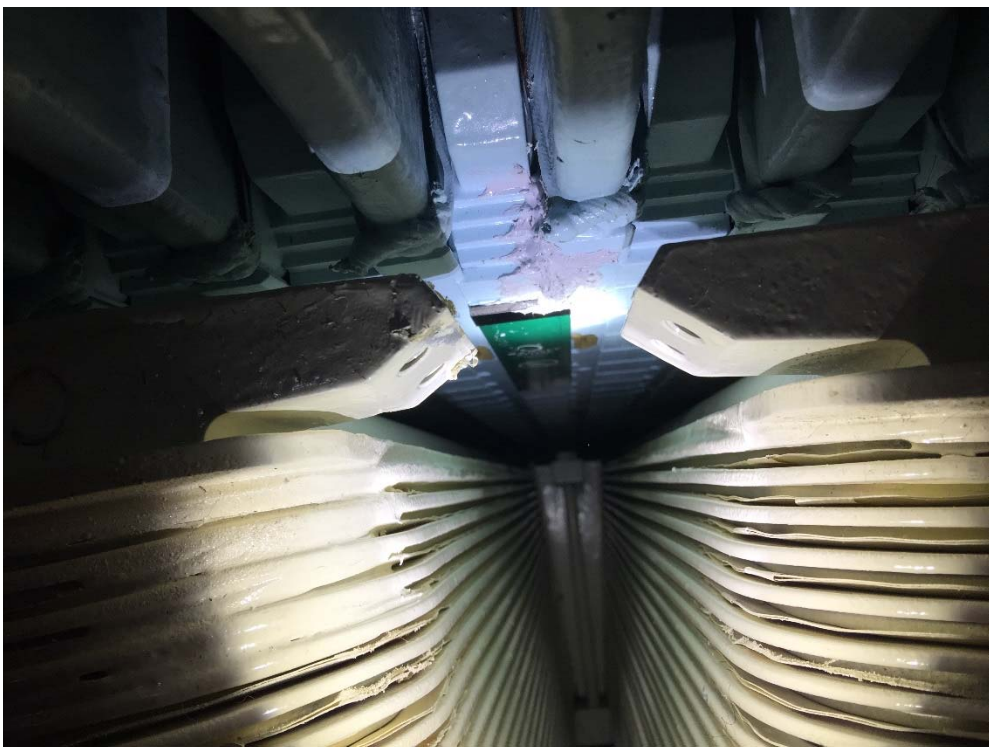
Figure 19 - Capacitive Airgap Probe Attachment


Figure 20 - 1/rev and Speed Sensor Location (1/rev shaft pickup tape approximately aligned with rotor pole 1)

Data Sets that Support the Final Report

Data sets for this project can be found by contacting the Reclamation's Technical Service Center, Hydropower Diagnostic and SCADA Group, James DeHaan, jdehaan@usbr.gov, 303-445-2305.

Information includes, DasyLab test files and worksheets, spreadsheets, word documents, and reference reports.

- Principal Investigator Point of Contact: John Germann, jgermann@usbr.gov, 303-445-2295

- Keywords: rotor rim, rotor spider, rim shrink, rotor rim float, hydroelectric generator