Early Warning of Developing Problems in Rotating Machinery as Provided by Monitoring Shaft Voltages and Grounding Currents

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***Abstract*--A unique and independent unit condition monitoring technology for rotating machinery, called Shaft Condition Monitoring (SCM) provides early warning of developing problems by monitoring and analyzing shaft voltage and grounding current profiles. The process begins with capturing and trending of critical information inherent in raw signals derived from reliable shaft-riding brushes. Through analysis of this critical information, problems in rotating machinery are detected at their inception or long before they are apparent on traditional instruments. With this data in hand, a proactive plan of monitoring and maintenance is facilitated, possibly averting the extreme costs of failure and forced shutdown.**

***Index Terms*--Alarm Systems, Compressors, Electric Machines, Generators, Motors, Monitoring, Pumps, Rotating Machines, Signal Analysis, Turbines.**

I. Introduction

Monitoring of Shaft Grounding Currents and Shaft Voltages of Rotating Machinery is hereby defined as Shaft Condition Monitoring (SCM). SCM is the culmination of early measures employed to remedy the effects of stray currents on shaft bearings. The technology was first applied using shaft Voltage-Current Monitors (VCM's) on turbine-driven compressor trains, and later on trains having electrical motors and generators. Eventually it became clear that trending of shaft grounding current and voltage is an effective tool for predictive maintenance of both mechanical and electrical rotating machinery. More recently, this technology has been in a state of continuous adaptation to meet the needs of operators, maintenance personnel and engineers in the identification and treatment of abnormalities unique to each machine, and especially to address special problems introduced with an astounding influx of machinery employing variable frequency and PWM power sources.

II. Technology

Shaft condition monitoring gives a broad and often specific picture of a train's health. Shaft-riding brushes are employed that have low resistance contact to the shaft, facilitating accurate measurement of the shaft's electrical condition. These measurements provide critical data on the magnitude and frequency of shaft grounding current and/or voltage. In mechanical trains, the source of shaft currents is typically either electrostatic charge build-up or voltage generation from residual magnetism. On trains having rotating electrical machines, there are many additional voltage sources for shaft currents. Most cause unbalance or asymmetry in magnetic fields [2], [14], such as: shorted turns in the rotor and/or stator winding, shorted rotor/stator core laminations, shorted bearing, seal and coupling insulation, uneven air gap, and/or harmonics and transients from power electronics, power supplies or loads, as well as low level stator winding faults close to the neutral star connection.

A number of papers have been written on the mechanisms of stray shaft current generation [2] - [4], [7] - [16]. The location, direction and power delivery of stray current sources are almost impossible to anticipate and track, and for this reason no attempts are made here, other than to refer to those published in the indicated references. It is possible, however, to measure shaft grounding currents and voltages, to identify and relate these to the different kinds of sources and to project the potential for damage, along with studying and listing early warning signs of the measured currents and voltages, [1]**,** [2]. Success is evaluated by collected field experience, measurements and related damage. Shaft grounding current peaks range from 20 mA to 20 A on healthy rotating machines rated above 75 kW (100 Hp) up to the largest, 1200 MW. Voltages on electrical machine shaft ends opposite from the grounding brush location are customarily insulated from ground to prevent flow of damaging shaft currents. Shaft voltages here can be very high, reaching hundreds of volts. Significant deviations from normal values of grounding currents and shaft voltages signal changes in a machine's condition and are usually initial indicators of problem development. In some well-maintained trains with proper shaft grounding and monitoring, measured peak grounding currents were in the low milli-ampere range. On some mechanical trains, without or lacking proper shaft grounding, shaft rubs occurred, resulting in severe current damage and unusually high magnetism. The cause is attributed to voltage generation from friction of the rub. Still, electrical machines have the greatest potential for generating shaft currents and voltages, as a certain amount of magnetic asymmetry is normal.

The technology of monitoring shaft grounding currents and voltages of rotating shafts is derived from the performance of

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machinery in the field. The technology is based upon the following factors. (Proven field cases are marked with an asterisk.)

1) Shaft or rotor rubs onto casing or stationary members:
   a. Shaft voltage decreases at rub occurrence [16] *.
   b. Shaft grounding current increases and increasingly compounds, heavily magnetizing the rotating and stationary members. *
   c. If no detectable shaft voltage exists initially, very likely one would be generated by the rub, depending upon the type of materials that come into contact.
2) Static charge build-up on the rotating member due to:
   a. High liquid or gas velocity.
   b. Liquid or gas flow through filters.
   c. Turbine saturated steam. *
   d. Turbine dry steam under certain conditions. *
   e. Fogging or wet compression in gas turbines. *
3) Voltage generation from residual magnetism from:
   a. Magnetic particle inspection. *
   b. Welding with improper ground return. *
   c. Improper demagnetizing. *
   d. Magnetic bases. *
   e. Lightning strike nearby. *
   f. Plant electrical faults or ground currents.
   g. Compounding of residual magnetism [13]. *
4) Electromagnetic asymmetries in electrical machines:
   a. Loss of bearing or seal insulation[12].*
   b. Loss of coupling insulation [12].*
   c. Core lamination shorting. *
   d. Unequal gap between the stator and rotor.
   e. Rotor winding turn shorting. *
   f. Rotor winding ground faulting. *
   g. Stator winding loss of a parallel circuit. *
   h. Stator winding transposition or turn shorting.
   i. Stator winding faults near wye connection.
   j. Induction motor broken rotor bars.
5) Voltage harmonics and/or transients induced into electrical machines:
   a. Variable frequency drives [9]. *
   b. Pulse-width modulated supplies [7], [8]. *
   c. Excitation system harmonics [15]. *
   d. Unbalanced phase loads on generators.
   e. Rectifier or SCR loads or power supplies [10].

III. Components Needed

Quality shaft riding brushes are essential for both shaft grounding and shaft voltage sensing [1], [2]. Experience has demonstrated that conventional carbon and babbitt brushes are unreliable for shaft grounding duty, especially in the presence of oil and dirt. Even in a clean atmosphere, carbon brush current density should be maintained above 7 A/cm^2 (40 amperes per square inch), a condition that is essentially impossible to attain. With normal brush sizes, performance is impaired by high resistance glazing of the shaft contact surface and by chipping away of the brushes. The most reliable brushes have proved to be those that have metallic bristles contacting the shaft. These maintain cleanliness of the brush track and bristles conduct current selectively, producing a low resistance and minimally sparking contact to the shaft.

Reliable shaft grounding protects bearings against damage from shaft currents and provides a means to measure shaft-grounding currents. A reliable shaft riding brush elements must be electrically insulated, with the output connected to the brush shaft-riding element(s) only. With these, quality shaft grounding and accurate measurements of the grounding current and shaft voltage are achieved, providing accurate signals of the shaft grounding current and shaft voltage. Voltage and current signals to the monitor are conditioned and compressed, maintaining critical signal aspects needed for providing early warning of impending unit problems. It is important to avoid ground loops and the monitor should be mounted as close as possible to the current shunt or tapped resistor in the brush grounding cable to avoid interference from extraneous electromagnetic signals.

IV. Typical Configurations

A. Turbine Generator Trains (Figure 1)

Dual grounding brushes are commonly employed on large and critical machines and are located between the turbine and the generator on large turbine generator sets. Small voltage sensing brushes are usually located at the generator outboard, or excitation end of the shaft and on one of the turbine shafts.

B. Mechanical and Electro-Mechanical Sets (Figure 2)

Where the train has solidly-bolted couplings, two brush locations are usually adequate for proper shaft grounding, in addition to sensing grounding current and shaft voltage.

Additional brushes for shaft grounding and voltage sensing may be necessary on trains where elements are isolated by electrically-insulated couplings and/or train shaft oil films, such as in gear-type couplings and speed-changing gears. Each such electrically-isolated shaft should have its own brushes for shaft voltage sensing and shaft grounding, along with its own VCM.

V. Analysis, Detection and Pinpointing

Changes in VCM indications of the shaft electrical profile are the first indicators of a developing problem. If this does not point to a specific problem, conventional instruments and monitoring devices should be trended very carefully, narrowing the possibilities to specific problems. For example, identification of an indicated problem and its further development can usually be obtained by investigating and/or tracking changes of the following:

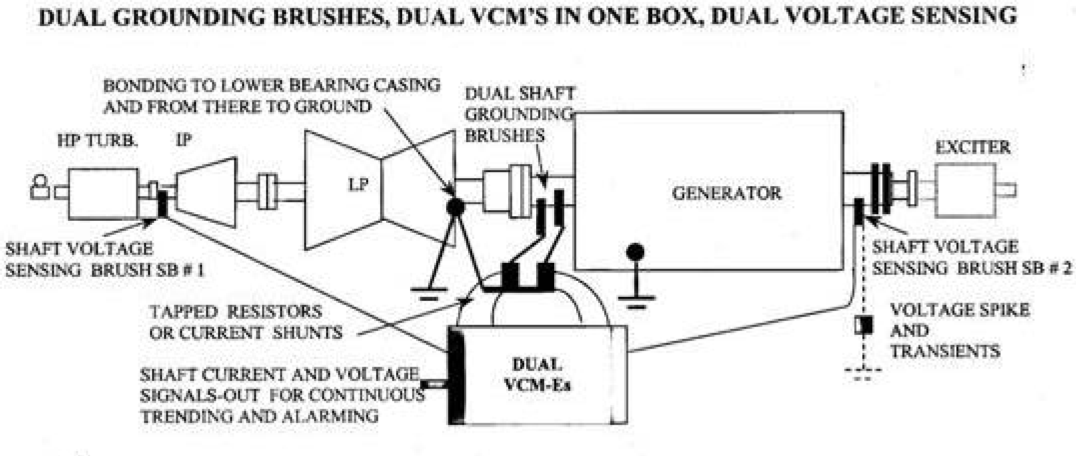

Fig. 1. Turbine Generator Shaft Grounding Current and Voltage Sensing

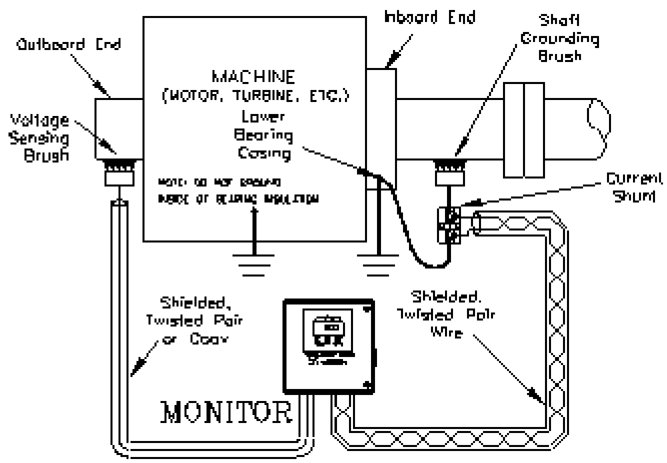

Fig. 2. Sensing Grounding Current and Voltage on an Electrically-Isolated Shaft

In all rotating shaft machines:

1) Vibration of Shaft, Bearing, Frame and/or Core [10].
2) Temperature of Bearings.
3) Oil Particle Analysis.
4) Audible Levels and Frequencies.
5) Shaft Torque.

In electrical machines and trains:

6) Temperature of Armature and/or Field Windings of Electrical Machines.
7) Electrical Current and/or Voltage Harmonic Analysis.
8) Stator Winding Partial Discharge Level and Changes.
9) Stator Winding Turn and/or Circuit Short or Open Circuits.
10) Field Winding Ground Fault Indications.
11) Current Side Band Analysis on Induction Machines.
12) Gap Flux-Probe Symmetry on Synchronous Machines.
13) Field AC Impedance Changes on Synchronous Machines.
14) Field Current for a Given Load and Power Factor on Synchronous Machines
15) Cooling Gas Particle Monitor Indications.
16) Sparking of Brushes on Commutator and/or Collector Rings.
17) Diode, Fuse or Other Component Failure in Excitation System.

Abnormal trends of shaft condition monitor signals should encourage operators to watch carefully for correlated changes in the above factors. Even gradual changes could be overlooked as a syndrome worsens without the benefit of early warning provided by effective shaft sensing and monitoring. By narrowing the possible problems, effort can then be focused on effective troubleshooting, leading to orderly planning and/or execution of maintenance or shutdowns, as appropriate.

VI. SCM Technology Case Histories

A. A Stator Coil Failure Due to Core Iron Shorting on a 750 MW Turbine-Generator:

During the month of July 1995, VCM shaft grounding current readings were recorded on a strip chart. The author inspected this chart and found that the unit operated less than half time in this normally high demand period. There were six periods of operation lasting from 10 to 20 hours. Five of the six periods showed initial normal low level current, less than three amperes, followed by bursts of high to excessive currents. Figure 3 shows the period of highest currents exceeding the scale maximum of ten amperes. For all six periods, the shaft grounding current then settled down to either a normal or a slightly higher continuous level, indicating that shorted laminations or turns either blew open, or shorted together. At that time, the author predicted (based upon experience) that these signals were either from shorted stator core laminations or shorted rotor field winding turns. Operators were questioned about other possible unit operation or instrument conditions that would explain the trace abnormalities, but none could be found. In year 2000, the unit was pulled from service because of a stator coil failure to ground located adjacent to a zone of excessive heat caused by shorted core end lamination packets. Confirmating the 1995 prediction after five years is reasonable since this generator was on peaking duty, operating only for short periods during the 1995-2000 interval.

B. Electrostatic Charges from Wet Steam [1]:

The shaft grounding peak current on a large turbine-generator changed from 3 amperes to 6 amperes, coincident with a drop in steam temperature entering the turbine, from

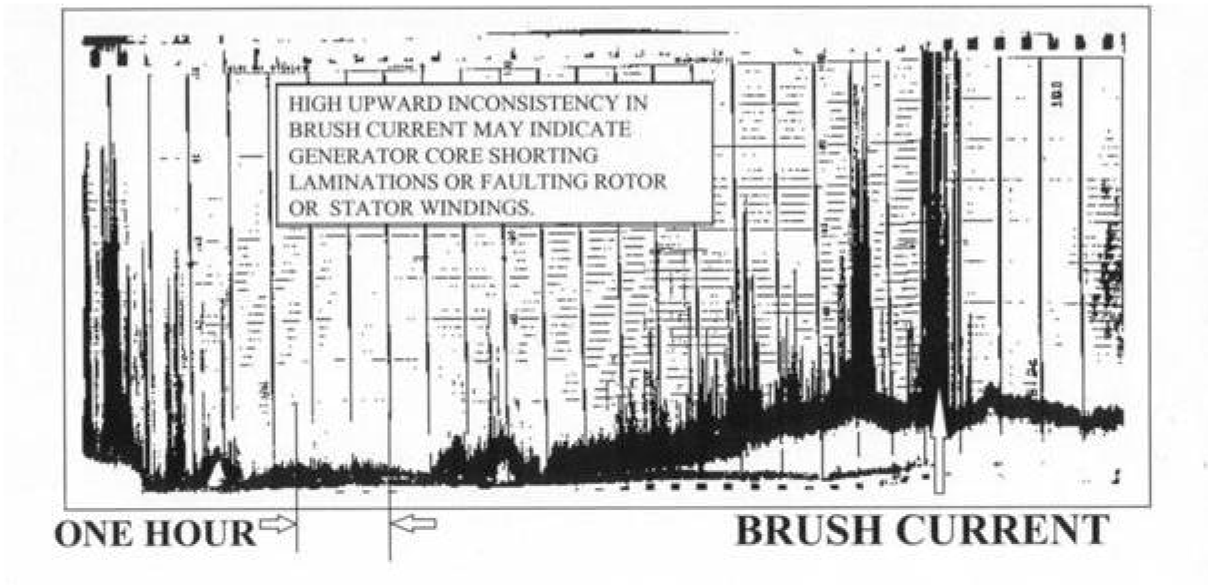

Fig.3. 750 MW Generator VCM Output Indicating a Unit or System Recurring Condition

521°C (970°F) to 510°C (950°F). The correlation was duly noted and when the steam temperature was restored to 521°C (970°F), the shaft grounding current consequently returned to 3 amperes. This is attributed to water droplets in steam due to lowered steam temperature, a frequent occurrence in steam turbine generators [12]. These droplets result from steam condensation due to low steam temperatures and are undesirable since they cause turbine blade erosion and rotor electrostatic charging, possibly damaging bearings.

C. Shaft Residual Magnetism [2], [4] - [6]:

Trains sometimes experience current attack on their bearings, seals and couplings from currents generated by residual magnetism. This occurs, even on purely mechanical trains. Thrust, anti-friction and/or journal bearings are affected and can exhibit increased temperature and vibration, shaft axial or vertical displacement, and in some instances, unit crashes. Figure 4 shows electrical current damage from residual magnetism in the turbine on a turbine-compressor train. Excessive magnetism was measured in the turbine casing and rotor.

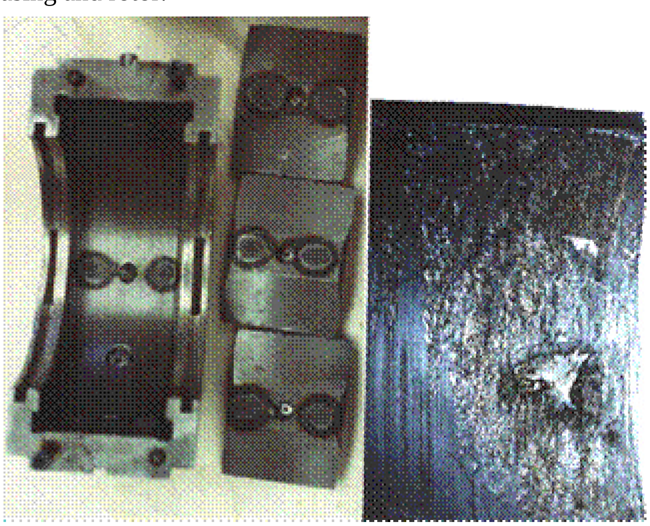

Fig. 4. Results of Electrical Current Damage from Residual Magnetism

Down-cycle demagnetizing was effective in reducing the source for stray voltage generation. Shaft grounding, in conjunction with shaft current monitoring, was instituted to protect bearings and to identify evidence of possible recurrences. For example, a steel mill furnace turbine-driven blower had experienced failure of its outboard bearing. Following complete demagnetizing, the monitor recorded a shaft peak voltage of 1.8 volts on the blower outboard end when the shaft grounding brush, located on the turbine front end was lifted, un-grounding the shaft. However, the blower outboard end peak voltage reduced to 0.5 volts when the turbine shaft grounding brush was installed onto the shaft, restoring shaft grounding.

D. Excitation Circuit Failure:

A large utility generator employing static excitation had severe current damage to its bearings even though the bearings were properly insulated. The cause was traced to a high spikes and harmonics generated by the failed diode in the excitation circuitry passing current through the high capacitance character of the bearing insulation. With the installation of reliable shaft grounding and a voltage current monitoring system calibrated to warn of excitation diode failure, the operators are now alerted at the onset of such a problem.

E. Rotor Excitation Circuit Ground Fault:

A large nuclear station generator experienced ground fault indications starting in January 1, 1999. The fault indication would clear when field current was reduced; however, there was a limit below which further reduction of the field current would be permitted. Since it was important to locate the cause, a voltage and current monitoring system (VCM) and an event recorder were installed to determine what was occurring. During the next ground fault indication, the recorded peak shaft grounding current increased suddenly from 3 to 17 amperes and the event recorder showed complete offset of the field voltage. Generator rotor dismantling in March 1999 revealed a torn shim in one of the rotor winding excitation leads coming into contact with the shaft. Correcting this and the other DC lead, which was developing a similar problem, preventing a possible disaster, if both polarities had shorted coincidentally. The VCM provided completely independent confirmation of a valid alarm, proving that the ground fault alarm was due to a rotor winding fault and not an instrument or excitation system failure or error (see Figure 5).

F. Loss of Bearing Insulation:

Numerous cases have occurred where the bearing insulation on a train has been bridged or defeated. Damage was averted by properly insulating the bearings and by monitoring the shaft voltage. It was observed that shorting of the insulated bearing caused a voltage drop by at least one half, with a proportional rise in grounding brush current.

G. Shaft Rubs:

During shop testing of a motor, its shaft voltage dropped in value by one half. It was also noted that the oscilloscope trace of this voltage became half wave rectified, rather than sinusoidal. Disassembly of the motor revealed that a rub had developed. When the rub was cleared, the full wave character of the shaft voltage was restored; half wave discharge having occurred at the initial shaft rub contact.

VII. PROBLEMS ENCOUNTERED WITH VCM INSTALLATIONS

The first VCM's were sold in 1989 and since that time, more than 600 have been sold. Very few problems with VCM’s or their installation have been reported. Users have been very forthcoming with performance information and have been very cooperative in ensuring proper VCM installation and performance. Listed below are VCM problems that have been encountered requiring correction to ensure technology reliability:

A. Installation Issues:

1) Poor performing shaft riding brushes.
2) Shaft-riding brush insulation missing or shorted.
3) Improper routing and/or connection of shaft grounding brush cable.
4) Improper VCM installation or wiring connections.

B. External Factors:

1) Shaft or cable pickup of interfering electromagnetic signals.
2) Plant ground grid has voltage or is unreliable.
3) Signal interference from stray plant voltage and/or current spikes.

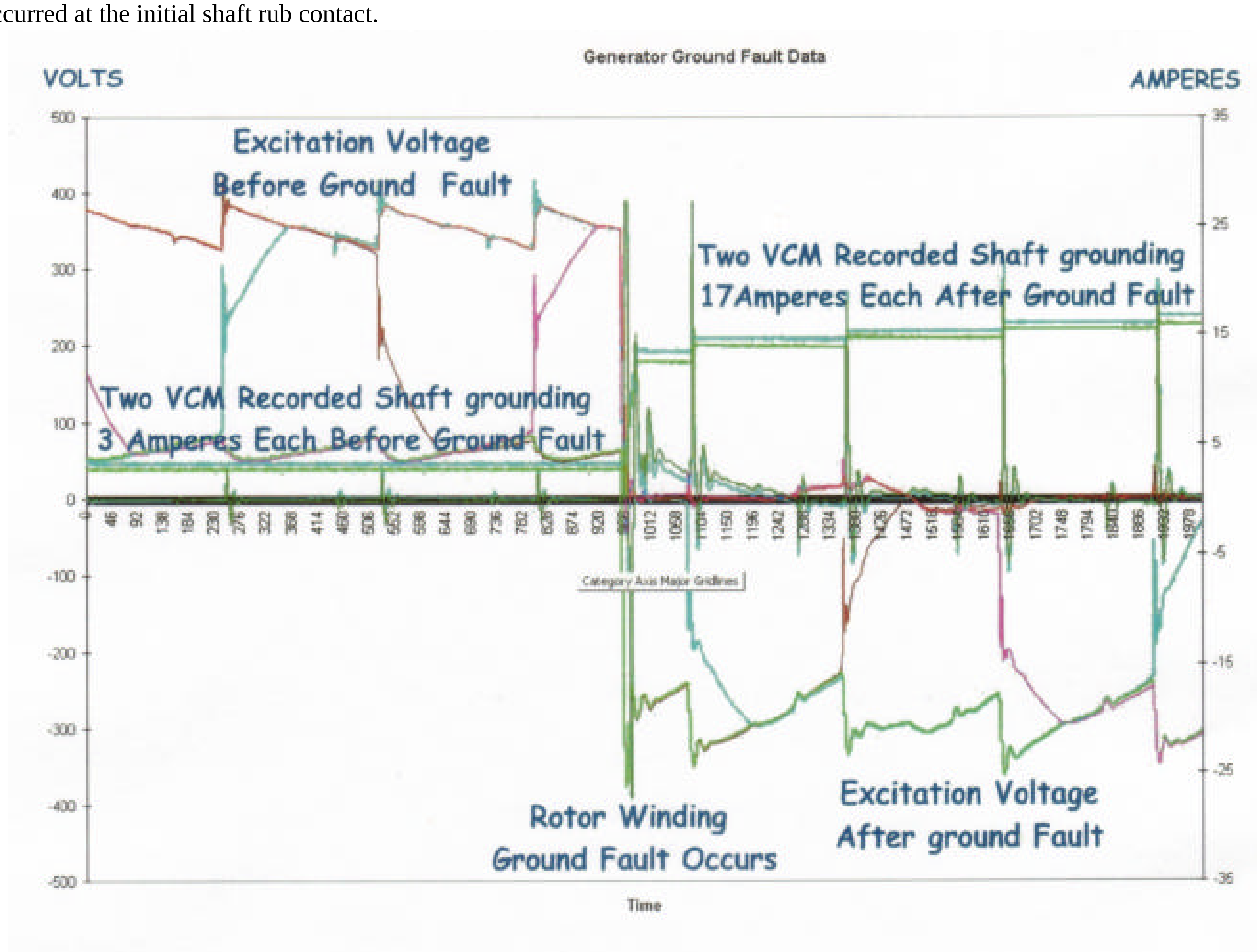

Fig. 5. Rotor Winding Ground Fault Occurrence

VIII. SUMMARY AND CONCLUSIONS

Shaft condition monitoring is an ever-expanding technology based upon in-the-field performance of rotating machinery. It is designed to warn of developing problems in rotating machinery and to pinpoint specific problems, either directly, or through confirming and predictive capabilities of normal plant system monitors and instruments. Warning of impending damage is provided in advance of normal plant alarms and monitors that indicate only after damage has already occurred. As is demonstrated in Section VI, "SCM Technology Case Histories" of this paper, considerable data has already been collected over the past 15 years and more is being gathered, leading to increased accuracy in the interpretation of shaft voltage trends [1], [2]. The economic potential in savings is enormous when taking into account the losses from forced shutdowns and the replacement of parts due to failure, which may have been averted if the electrical source had been properly diagnosed and treated in its embryonic stages. Furthering the economic appeal of this treatment is the fact that installation does not require disassembly of the machine and VCM's can be installed on operating machines with insulated shaft-riding brushes, precluding unwanted and unnecessary shutdowns. As even more advances in this innovative technology take place, applications to monitoring for specific causes of shaft current damage will be tailored to the needs of users worldwide. The trend is clearly toward the implementation of shaft condition monitoring as an industry standard in the science of preventing machine damage before or as it starts.

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Paul I. Nippes, P.E., is a pioneer in solving shaft current problems and designing corrective solutions and products. A Fellow of IEEE, Paul has served as Chairman of ANSI C50, and has been Chairman of IEC SC2G for the past 20 years. He earned a B.S.E.E. from Penn State (1950) and a MSEE from the University of Wisconsin in 1955. He was the recipient of the first Cyril Veinott Electromechanical Energy Conversion Award in 2000. For over 30 years, Mr. Nippes has served as a consultant to thousands of manufacturers and users in the industry.