SHAFT VOLTAGE AND CURRENT MONITORING

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Abstract

Grounding of shafts to prevent voltage and current damage in rotating machinery is standard practice. What is not generally known, nor fully appreciated, is why and how shaft grounding should be applied, and what are the effects of different maintenance practices. Some common procedures are illustrated and their features are compared. Methods that have been used to measure shaft voltages, currents and their power potential are described. A commentary is provided on the different features of and experiences with, shaft voltage-current monitors. Finally, the importance of recognizing the symptoms, heeding the warnings, and enacting preventative and corrective measures, is discussed. Illustrations have been taken from MPS job files covering some of the 200 installations visited in the past 15 years.

Background

The practice of applying shaft grounding brushes and current monitors to rotating machinery has evolved gradually. Even today, their application is not fully understood or appreciated. Certainly, the need was not apparent in the early 20th century when it was common to employ brushes to commutate current on armatures or to collect current on collector rings. Their use to ground the shaft and carry away electric currents most likely developed much later. Electrical current discharge damage to bearings and seals probably did not have a high priority at that time. Early 20th century literature shows such damage to have been occurring on electric machinery bearings[4, 7]. The prospect of applying shaft brushes was not mentioned, probably because at that time insulating the bearings was regarded as an adequate solution. Performance and evidence have since demonstrated that this is not the case, and that there is an important need for shaft grounding and condition monitoring. Users are becoming increasingly aware that significant benefits are gained by incorporating information from shaft monitors in predictive and planned maintenance programs, not only to enhance on-line performance, but as an aid in improving operation.

Very likely the first shaft brush was applied to steam turbines, due to high shaft voltages produced by electrostatic charge separation of saturated steam and its pitting effect on bearings. Today, all utility-type turbine generator sets and very large motors have shaft grounding brushes of various designs and applications. Yet, many still do not have monitors to measure and track brush performance and shaft voltages. Increased usage of both reliable shaft grounding brushes and functional monitors that provide critical information is expected for all types of rotating machinery, especially at this time when there is a growing interest in unit life extension and dependability.

It is the purpose of this paper to show the level, character and interpretation of shaft voltage measurements made on operating machines, most of which have experienced shaft current problems in their bearings or seals. Also covered are the benefits to be derived from applying shaft brushes and monitors.

How to Measure Shaft Voltage

Shaft voltage and current measurements can be either temporary or continuous. Temporary measurements are invaluable in identifying and analyzing shaft problems and in choosing preventative and corrective measures, such as selecting and placing shaft grounding brushes and monitors. Problem identification is based, for the most part, on the magnitude, waveshape and character of the measured voltage and current traces. On the other hand, continuous measurements made with reliable shaft monitoring equipment provides valuable information on the unit condition and operation.

Temporary shaft voltage measurements require more skill and different instrumentation than is needed for conventional electrical circuit measurements. There are often obstacles, such as inadequate access to the shaft for placing the voltage pick-up, and locating suitable ground or other reference points for making meaningful voltage measurements. Sometimes ingenuity is required to gain access to shaft areas, and in providing an acceptable brush or other shaft point of contact for conducting the measurements. It has been found that, except for fully enclosed machines of the types employed in hazardous atmospheres, pipe taps, instrumentation access holes, etc., can be used to gain the needed access. Sometimes a characteristic pattern can be established for a train by taking measurements at the outboard ends and possibly at one or more intermediate points. From these it can often be determined that it may not be necessary to take additional readings. The most meaningful measurements are usually made from the shaft locations to ground and between the ends of one or more coupled units of the train. Accurate shaft voltage to ground measurements require that the true ground reference point be determined. It may be necessary to establish the true ground. This could require electrical bonding of all casing parts, bearing enclosures, etc., producing low impedance paths to the reference point, which will preferably be the plant electrical ground grid.

Fundamental to making reliable shaft voltage measurements is dependable, low impedance shaft contact. For long-term usage, a brush that has been proven to maintain long term, low-resistance and continuous contact should be employed. Conventional carbon brushes and most alloy solid brushes are not suitable. For testing purposes, a temporary brush applied under heavy pressure may be adequate.

Practices vary considerably; however, if measurements are made at all, they are normally taken with voltmeters or oscilloscopes connected between the shaft and ground, with or without the shaft being grounded. As will be shown in the following section, careful instrument selection is necessary because of the erratic and transient nature of the voltages being measured. The preferred method for taking measurements is illustrated in Figure 1a and 1b, which depict electromagnetic and electrostatic voltage sources, respectively. These circuits show shaft-to-ground variable resistors that are representative of electrical discharge between the rotating and stationary members.

Figure 1c depicts an equivalent Thevenin generator and its electric circuit, along with a current shunt and measuring instruments. This circuit, although it may not apply to all units, conveys what is generally involved. For instance, if there is no discharge of shaft voltage, the impedance Zc is infinity and the measured shaft voltages and currents relate to the circuit source voltage and its characteristics. On the other hand, when there is shaft current discharge or drain, Zc has a value that is usually intermittent and changing. What is measured in these cases is the shaft voltages and currents of a parallel branch to the discharge path. As the resistance Rsh is reduced, this circuit branch gradually becomes the primary current drain from the shaft. Analyses based upon tests where Rsh has been lowered sequentially in value have been found to be most valuable in determining the character and power capability of shaft currents. These help determine the permanent grounding brush capabilities and their locations. The goal is to reduce the shaft voltage to levels that avert possible current discharge in bearings, seals, etc.

Shaft Voltage and Current Waveforms

Time traces shown in this section are temporary measurements that were obtained on the shafts of operating machinery in-situ using the instrumentation of Figure 1. They have been recorded on, and plotted from, a digital storage oscilloscope. Other conventional meters and oscilloscopes are useless in obtaining meaningful results. Even so, numerous trials were needed to acquire traces that were truly representative of the quantity being measured. It is also found that trace appearances vary considerably, depending upon the instant the sample is taken, oscilloscope sweep times and circuit alterations, such as by varying the value of Rsh. Only in the cases of voltages generated by electrical machinery was it possible to lock-in on a trace using conventional oscilloscope time sweeps.

Two simple waveforms illustrate recurring trace shapes found in recordings. These are shown in Figures 1d and 1e, labeled as “inductive” and “capacitive,” and relate to circuits of Figures 1a and 1b, respectively. As a general rule, confirming evidence is also found in measured traces. An inductive circuit may not only produce the trace of Figure 1d, but can have a persistent nature of very slow reduction in current levels as resistance Rsh is reduced. The capacitive circuit with the trace of Figure 1e is not persistent and, in fact, demonstrates a rapid drop in current as Rsh is applied. It has been observed that a waveform will sometimes change character, usually from that of Figure 1e to that of Figure 1d, as resistance of Rsh is reduced and the shaft voltage decreases. This is to be expected when a shaft has both magnetic or inductive conditions in addition to electrostatic or capacitive conditions.

In simplest terms, it can be said that elimination of an excessive electromagnetic type voltage requires degaussing of the machinery and/or correction of the factors causing the offending magnetism. The correction for an excessive electrostatic-type voltage requires reliable shaft grounding brushes draining shaft current to a well-established ground point, and minimizing the potential of an electrostatic current source. In some machines, both excessive magnetic and electrostatic voltages exist, and thus there is a need for multiple corrections.

Electrical Machinery

Stray currents in electrical machinery are easily understood, since by design there is very intense magnetism in the core section that serves as a means for energy transfer between the stator and the rotor. This magnetism may stray or divert from the core due to the design or construction, or because of a developing problem or defect. A resulting imbalance or asymmetry in the assembly, core or winding can generate stray voltages and/or stray currents. A notable change in measured shaft voltages can be regarded as a precursor of possible problems. The consequences can range from disastrous overall unit damage and failure to mild pitting and/or blackening of the lubricating oil. Shaft voltage traces from these causes are invariably sinusoidal in nature at the rotational or power frequency plus harmonics. This usually distinguishes them from electrostatic or residual magnetic-generated voltages.

As an example, Figure 2 shows selected traces from a total of 75 tests conducted on a wound rotor motor driving a blower. Trace 2a was taken at the outboard bearing (which is insulated) and Trace 2b was taken at the inboard bearing (not insulated). The basic shape of sinusoidal components and harmonics is apparent on the former. The latter is erratic, though sinusoidal in appearance, possibly because of intermittent bearing discharge periodically grounding the shaft. The persistent or inductive nature of the shaft voltage is demonstrated in the same shaft location of Trace 2a, as Traces 2c and 2d. The former shows that there is little reduction in the shaft voltage by setting Rsh = 1.0, while the latter, with Rsh = 0.1, shows a significant reduction in shaft voltage. Incidentally, a negative zero offset amounting to a few millimeters on all these traces is disregarded, as it was generated accidentally within the oscilloscope plotting circuitry.

The correction for magnetic problems caused exclusively by electrical machinery requires alterations in construction, windings or electrical supplies. Electrical traps or filters, and sometimes insulation or non-magnetic barriers, may be adequate to control a problem. If not, a major and costly correction is required.

Residual Magnetic

There are many possible residual magnetic sources that will produce electromagnetic current generation. These originate from residual magnetism in the rotating machinery and its components, in the structure or piping, or from another machine on the line, all of which act as permanent magnets. Retaining residual magnetism are high-retentivity materials such as high alloy steels, which have been exposed to magnetic fields through actions such as magnetic particle inspection, magnetic chucks, welding, etc. Magnetic shaft-generated voltages are more persistent than those from electrostatic sources, but are less persistent than those generated by electrical machinery. They produce microscopic craters or pits, which show as a frosted surface. Craters or pits that become continuous in a wandering pattern are known as “spark tracks.” They often erode the bearing surface, removing babbitt, sometimes erratically and completely. They also produce rotor damage, extending from scattered pits to frosting, and to major metal removal, as if by Electric Discharge Machining (EDM). They can even produce runaway similar to that of a compound-wound electrical machine, generating up to thousands of amperes with disastrous results.

An example of the persistence of residual magnetic shaft voltages is shown in Figure 3. These shaft voltage traces were taken on a utility turbine generator for values of Rsh = infinity, 1000 ohms, 100 ohms and 10 ohms, respectively. Note that when comparing the first two traces there is no reduction in the peak voltage value of 40 volts, but the waveform is changed slightly. A negative DC offset amounting to approximately 15 volts is indicative of either electrostatic or magnetic homopolar generation.

Correction of residual magnetic shaft voltage generation consists of conducting a thorough magnetic survey and degaussing of all components of the machinery before reassembly, and to verify that only low levels of magnetism exist in the machine at assembly. The assurance afforded by adding reliable shaft grounding brushes and continued accurate and consistent monitoring is highly recommended.

Electrostatic

Stray currents from electrostatic sources are common in steam turbines as charge separation in wet steam passing across the turbine blades. There are many other sources for static electricity, including high velocity lubricating oil in pipes and filters, charge separation in the process, friction-excited currents from rubs of certain materials, etc. Static electricity shows up as frosting due to current discharges at either close gaps or contact points of oil film surfaces, sometimes precipitated by dirt or other impurities in the oil. Because of its lower energy potential, it does not usually frost the shaft surfaces. The shaft voltage has the same polarity along its length, and the measured traces exhibit a saw-tooth pattern. This can be described as a gradual charge build-up to voltages reaching as high as several hundred volts, with discharges in a variably discontinuous, repeating pattern. Static current, while not requiring a closed loop in which to flow, does search out a means to equalize the charge. In doing so, it will follow a return path to a region of charge neutralization or equalization, which could be the piping, the condenser, a cooler, the oil reservoir, etc. Solid ground bonding of all units and their components minimizes errant and possibly destructive current return paths.

An example of the shaft voltage from static charging on the shaft of a turbine generator is shown in Figure 4. Trace 4a shows charge build-up, with sudden discharge from voltages of from 10 to 15 volts, and with a positive DC offset of 3 to 4 volts. When Rsh = 10,000 ohms, the charge build-up virtually collapses and the shaft voltage reaches a peak of 4 volts. It also assumes the character of an inductive circuit. Complete collapse of the shaft voltage occurs when Rsh is at the still high value of 1000 ohms.

Correction for elimination of shaft electrostatic voltage generation is twofold. First, it is important to apply reliable shaft grounding brushes with monitors to drain away static and to divert low level magnetic shaft currents from critical areas under the watchful eye of the monitor. Secondly, static current generation must be minimized through controlled operation and maintenance of such items as steam conditions, oil filters, etc.

Controlling and Monitoring Shaft Voltages

Measuring shaft voltages accurately and consistently the same way every time is necessary for reliable comparisons and trending. The difficulty in reading the oscilloscope traces shown previously gives some appreciation for the wide diversity of interpretations that may be expected from readings taken by different individuals, or even the same individual at different times. A means to obtain accurate and consistent readings of the shaft voltages and currents has been developed and is employed in the performance of the MPS VCM. Figures 5 shows what is taking place in this meter. The top trace is a typical as-read voltage or current waveform, and the lower one shows it to be normalized for evaluation of the absolute average and peak readings. An important feature of the VCM is that readings are adjusted with time to capture changes in the waveform and voltage levels during operation. The basic VCM provides local display of shaft currents and requires only one shaft brush. The full-function VCM requires two shaft brushes, the second one to provide the additional monitoring of shaft voltages. In the latter, voltage and current readings are also converted to conventional 4-20 ma signals for transmittal to the data recorders. There are local and transmitted alarms for excessive shaft voltage and minimum brush current, the latter indicating when the brush is not functioning. The VCM full function unit is shown in Figure 6.

The VCM is a passive type monitor since it measures, but does not affect or control, the shaft voltage. Active shaft monitors are available, one of which is described in Reference No 9. It responds to shaft voltage changes by injecting normalizing currents onto the shaft, clamping its voltage to below 100 mV.

Figure 6 shows a VCM installation for use on critical machines and utility generators. Obviously, proper shaft grounding requires the use of dependable shaft brushes strategically located on the train. Temporary type testing described above can be invaluable, serving as an educ-*ated guide in selecting brush and monitor locations, whether active or passive. Both the active and passive shaft grounding systems provide the operator with useful operating and maintenance information. However, the passive system, being but an observer, would seem to have a greater sensitivity to machine operating malfunction. The controlling capability of the active system could, within its capability, ensure that the shaft voltage (at least in its immediate vicinity) is maintained below the predetermined value. It should be possible to evaluate unit shaft condition and performance based upon the amount and character of the injected normalizing current.

Special tests show that the passive VCM can be depended upon to alert the operator when there is a change in shaft voltage or current, requiring attention in either unit operation or maintenance. This could indicate the presence of improper steam in the turbine, or its seal conditions. The detection of shaft rubs on bearings and seals as sudden and periodic changes in shaft voltages has been demonstrated.

Electrical machinery faults in the core and windings will also be indicated, as should the loss of bearing insulation integrity.[10] In fact, indication of these problems should show on the VCM long before their effect is made known on temperature and vibration sensors.

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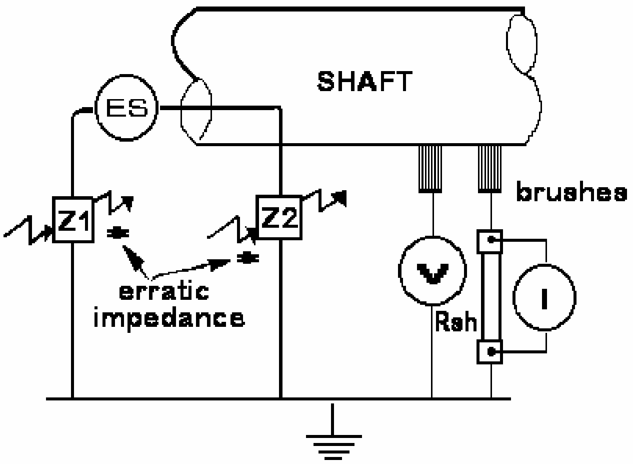
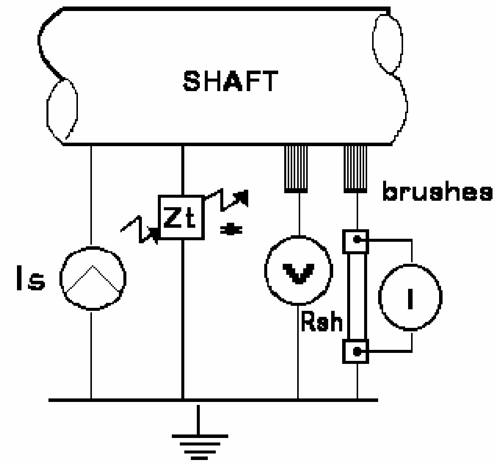
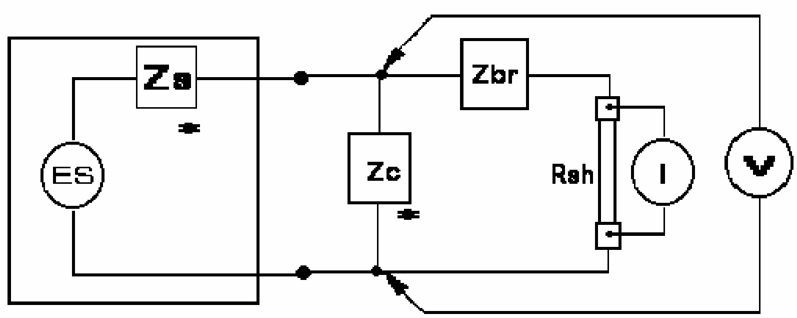


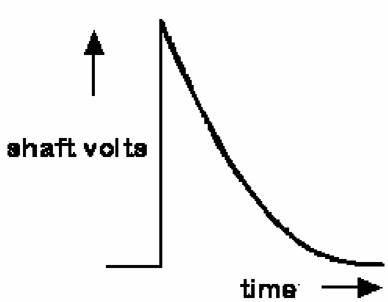
1a Electromagnetic Source



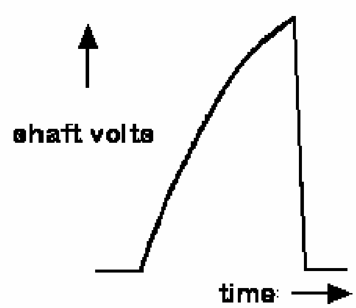
1b Electrostatic Source



1c Thevenin Equivalent Circuit

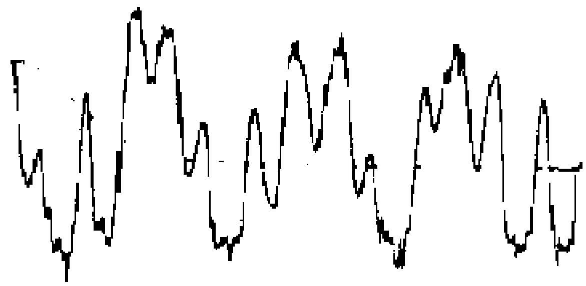


1d Inductive Circuit Suddenly Established With Transient Decay

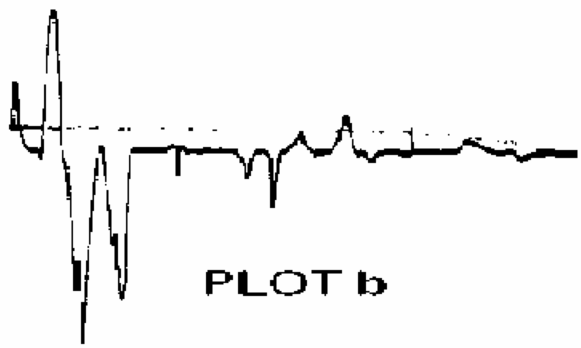


1e Capacitive Charge Buildup To Point Of Sudden Discharge

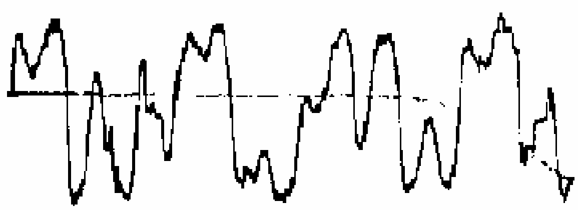
Figure 1



PLOT a



PLOT b



PLOT c

PLOT d

FIGURE 2

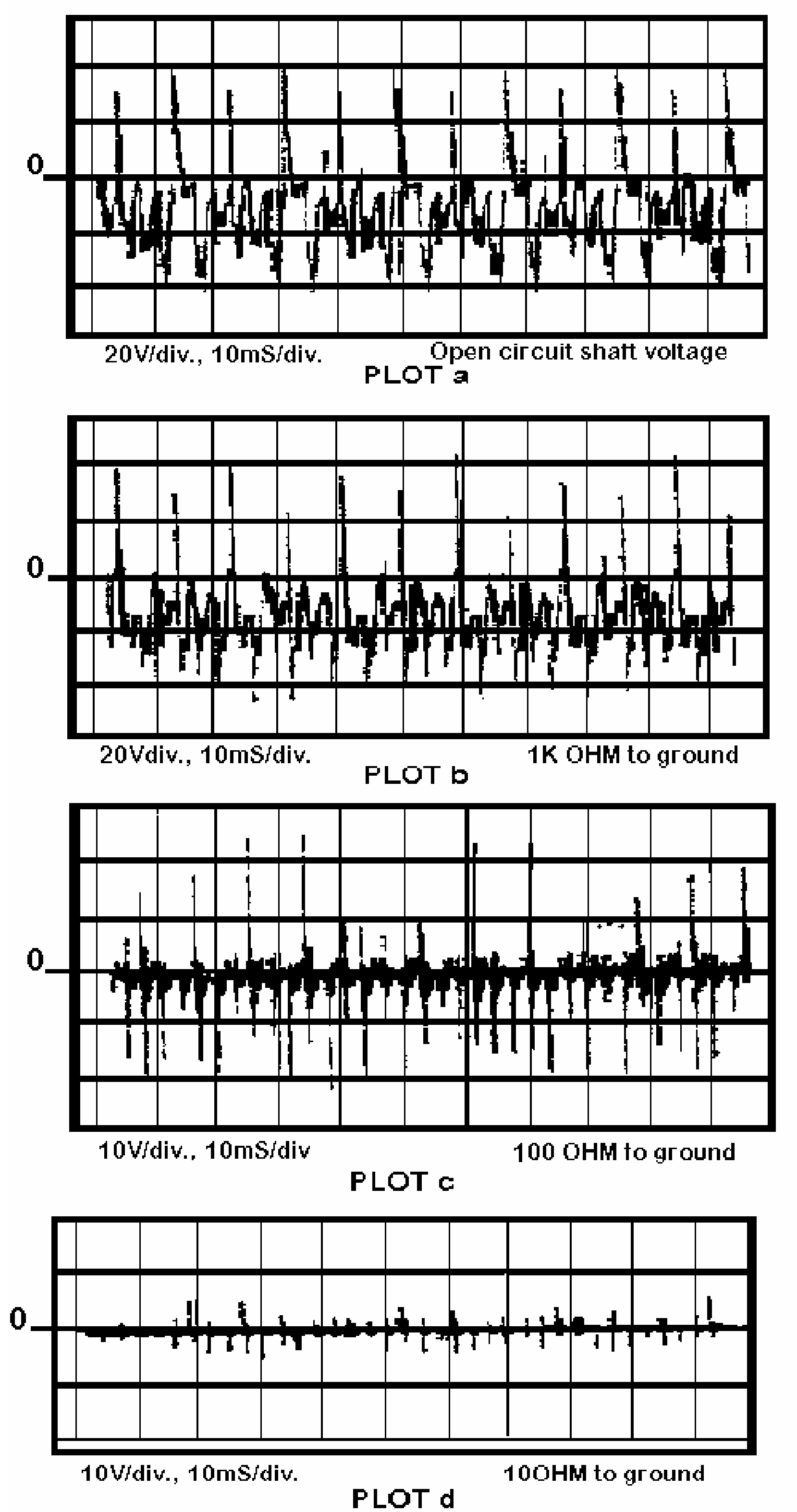
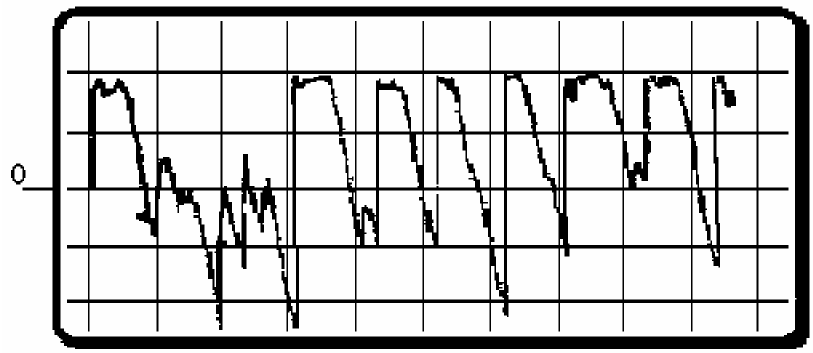
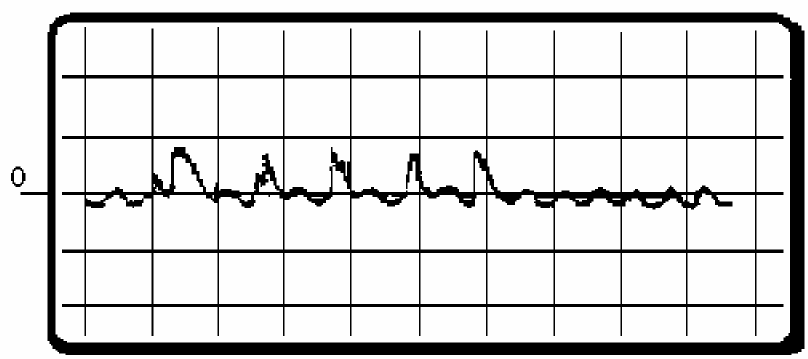

0
20V/div., 10mS/div.
Open circuit shaft voltage
PLOT a
0
20Vdiv., 10mS/div.
1K OHM to ground
PLOT b
0
10V/div., 10mS/div
100 OHM to ground
PLOT c
0
10V/div., 10mS/div.
10OHM to ground
PLOT d

FIGURE 3



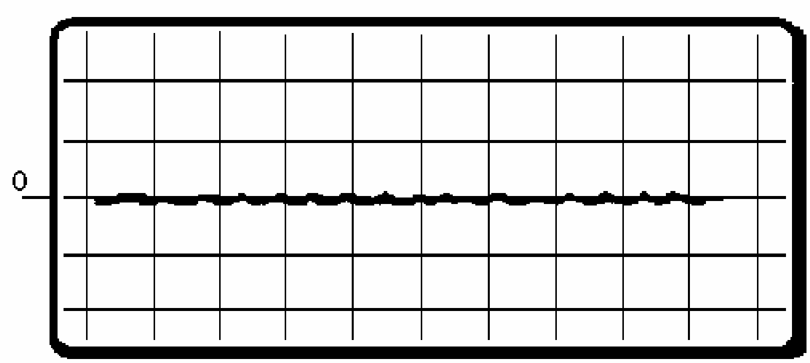
5V/div , 10mS/div Open circuit shaft voltage

PLOT a



5V/div , 10mS/div 10K OHM to ground

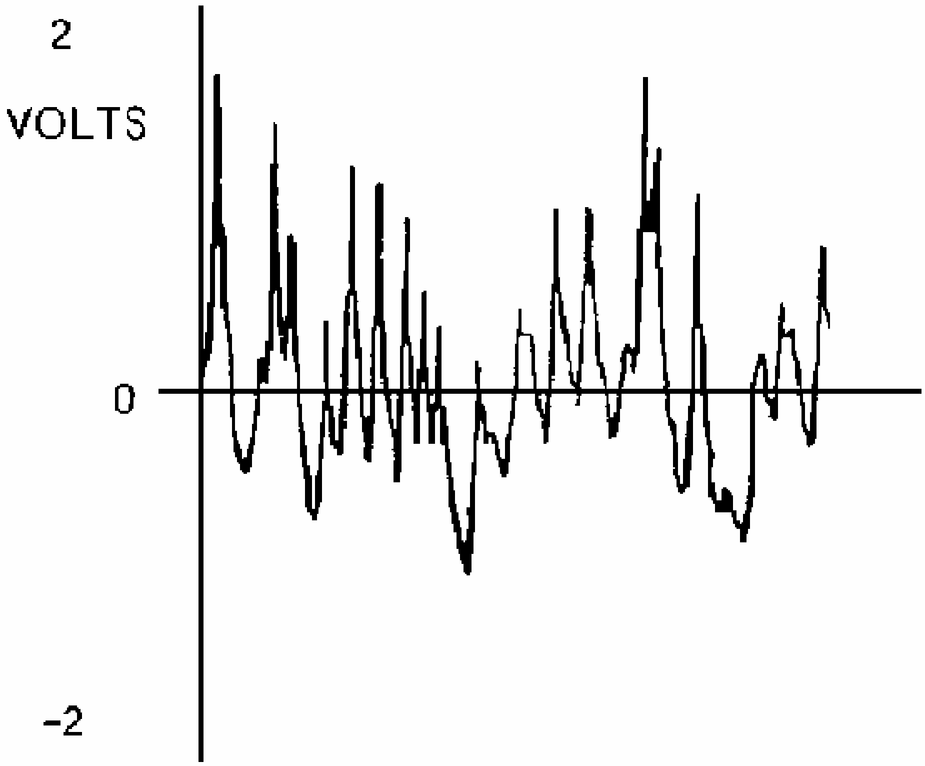
PLOT b



5V/div , 10mS/div 1K OHM to ground

PLOT c

FIGURE 4



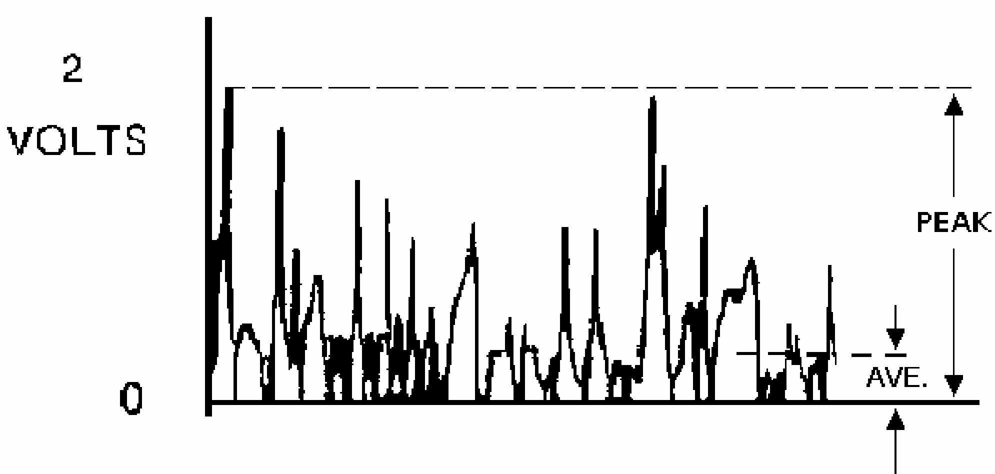


FIGURE 5

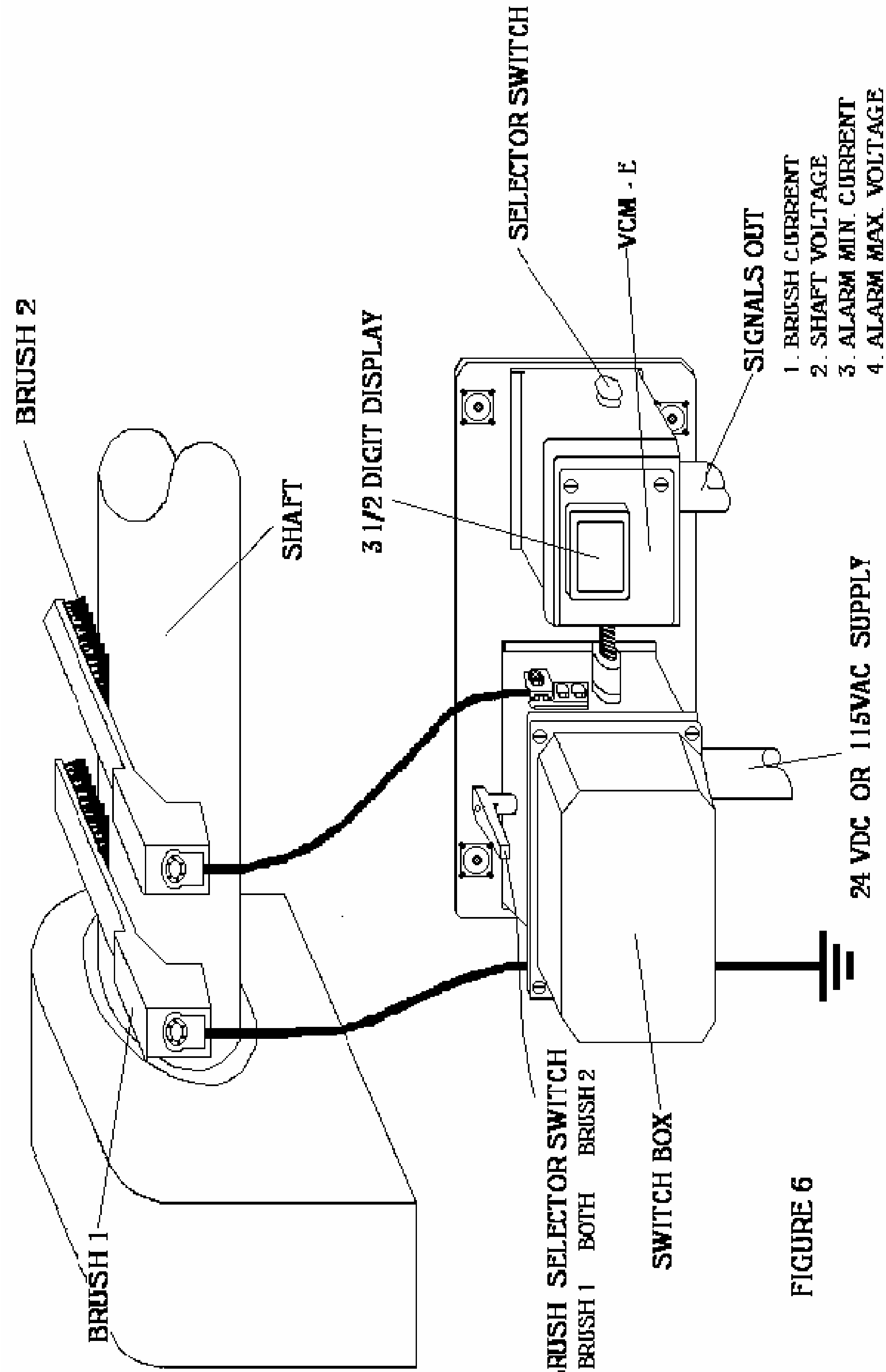


FIGURE 6

FIGURE 6