A model-based high-frequency matched filter arcing diagnostic system based on principal component analysis (PCA) clustering

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ABSTRACT

Arcing in high-energy systems can have a detrimental effect on the operational performance, energy efficiency, life cycle and operating and support costs of a facility. It can occur in motors, switching networks, and transformers and can pose a serious threat to humans who operate or work around the systems. To reduce this risk and increase operational efficiency, it is necessary to develop a capability to diagnose single and multiple arcing events in order to provide an effective measure (or grading) of system performance. This calculated parameter can then be used to provide an effective measure of system health as it relates to arcing and its deleterious effects. This paper details the development of a model-based matched filter for an antenna that recognizes single and/or multiple arcing events in a direct current (DC) motor and calculates a functional measure of activity and a confidence factor based on a estimate of how well the data fit the matched filter model parameters. A principal component analysis is then performed on the descriptive statistics calculated from the model's output data stream to develop cluster centers for classifying non-arcing and arcing events that are invariant to system operating set point. This approach also has a deployment benefit in that the PCA decreases the computational load on the classifier system by reducing the order of the system.

A similar model was developed for a magnetic field probe. This paper details the work and results for the antenna only.

Keywords: DC motor diagnostics, incipient/entrained arc detection, matched filter model, prognostics and health assessment, principal component analysis

1. INTRODUCTION AND BACKGROUND

There are many failure modes associated with a direct current (DC) motor. Examples include

- mechanical joint failure of bus bars,
- failure of riser connections,
- brush spring failures,
- shorted brushes (copper touching copper),
- degradation of commutator surface,
- mechanical seating of brushes,
- shorted commutator bars, and
- open circuit in the riser connection due to tungsten inert gas weld failure.

Any one of these can cause arcing in a DC motor with varying degrees of damage. A major contributor not listed is poor commutation between the brushes and the commutator bar. When this occurs it leads to pitting or burning of

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the commutator and increases operating and support and life cycle costs. There is also a safety issue associated with operating these machines in these conditions. Based on these observations there is a need to develop a diagnostic capability to detect incipient and entrained arcs in power systems, such as DC motors. By doing so, plant personnel and operators would have an effective means of quantifying the level of arcing in a machine and determining system health through a graded response and confidence estimate indicative of the machine's operational state. Based on this need, the University of Tennessee's Maintenance and Reliability Center, Oak Ridge National Laboratory (ORNL), and the Aluminum Company of America (Alcoa) conducted a series of tests to develop a prognostic capability for detecting arcs (level and extent) in a DC motor. The sensors of choice were an antenna and magnetic field probe.

The project included laboratory tests to experimentally confirm the theoretical antenna and magnetic field probe models and field tests conducted on a motor-generator (M-G) set to simulate varying degrees of arcing. Three sets of tests were conducted on the M-G set. The first captured and analyzed armature voltage and current and a demodulated radio frequency (rf) signal from an amplitude modulation (AM) radio. The second and third tests focused on capturing and analyzing rf signals from an antenna and a magnetic field probe. The following provides a description of the motor test system.

2. DESCRIPTION OF THE DC MOTOR TEST SYSTEM

In order to test the feasibility of detecting incipient and entrained arcing in a DC motor, a set of controlled experiments (arcing between commutator and brushes) were conducted on a 100-horsepower (HP) DC motor. The test protocol required moving the brush arm with respect to its neutral position. The intensity of arcing depended on the position offset and the load on the motor, which was facilitated using a DC generator and accompanying load resistor. The test motor is rated at 100-HP and the generator load capacity around 45 kVA. The following are the specifications on the M-G set and the load resistor.

DC Motor:
- Rating: 100-HP
- Number of commutator bars: 182
- Number of brush pairs: 6
- Number of poles: 6
- Each brush covers three commutator bars
- Motor full field: 3.1 amps
- Motor speed at 200 V: 300 rpm

DC Generator (Load):
- Generator full field: 23 amps

Load Resistors:
- Two 0.75 ohm (0.25+0.25+0.25) in parallel: 0.375 ohm
- Load current at 100 volt DC: 266 amps

3. EXPERIMENTAL PROTOCOL

Three tests were conducted on the 100-HP test motor. During each, varying degrees of arcing (subjected evaluation by facility manager) were recorded while changing the motor's operating set point and load. The following is a summary of the test specifics.

- Signals recorded: Armature voltage
Armature current
AM radio signal
rf antenna signal
Magnetic field probe
- Sampling rates: 200 kHz (1st Test) and 2 MHz (2nd and 3rd Tests)
- Motor speed: Approximately at 300 rpm

- Maximum load current: 250 amps
- Brush positions: Neutral; 1.5/3.0 bars relative to neutral

Varying degrees of arcing, from pin-fire to continuous arcing, were generated and recorded as a function of the brush position relative to neutral. At each position, the load current was increased from approximately 25 amps to around 300 amps. The degree of arcing generally trended with increasing load current at a given brush position. Table 1 shows a summary of the test protocols.

Table 1. Summary of test conditions for the 100-HP DC motor.

Load Current (amps)	Neutral Bar Position	1.5 Bars From Neutral	2.5 Bars From Neutral
30	X	X	X
60	X	X	X
120	X	X	X
200	X	X	X
250	X	X	X
300	X	X	X

4. A DESCRIPTIVE ANALYSIS OF THE MOTOR SIGNAL

In order to develop the matched filter response model, consideration had to be given to the base line signal and what it might look like. This understanding of underlying components had to be developed through a process of intuitive reasoning and simple analytic investigation. From this effort, a basic descriptive equation was developed defined by Eq. (1).

$$\underset{\text{overall}}{G(t)} = \underset{\text{rf function}}{Work(t)} + \underset{\text{rf signal}}{Motor(t)} + \underset{\text{rf noise}}{Environ(t)} + \underset{\text{rf signal}}{Arc(t)} \qquad (1)$$

where,

G(t) overall	=	Composite rf antenna signal
Work(t) rf function	=	rf function resulting from set point changes
Motor(t) rf signal	=	Motor rf signal resulting from brushes making contacts
Environ(t) rf noise	=	Extraneous rf signals from environment
Arc(t) rf signal	=	Arcing signal <sporadic, light, medium, heavy>

This equation captures the fundamental elements that could be expected in the overall (G(t)) rf signal. The elements include a rf work function (Work(t)) representing changes in motor set point and the resulting rf signal generated by such; a motor rf signal resulting from the brushes making/breaking contacts with the commutator; an environmental (Environ(t)) rf signal representing ambient noise (which could include switching systems, ubiquitous rf signals, etc.); and the arcing signal radiating (Arc(t)) from the brushes, themselves. This system metaphor raised several questions that needed to be investigated. These questions were:

1. As we move the operating set point, are we introducing artifacts into the system that could change or bias our observations?
2. Can we resolve 'true arcing' (transients) or only the heavy, constant fire arcing that results from an additive current density (energy) being dumped into the system?
3. Are there any anomalous transients present? If so, is it necessary to characterize them?
4. Are multiple system parameters needed to quantify arcing?

The answers to questions (1) and (3) can be found by visually inspecting Figure 1. The answers to questions (2) and (4) required additional thought and analysis and are presented in the following sections. In Figure 1, plots of two waveforms are shown. The upper figure is the motor running at 28 amps load current and brushes at 3.0 bars relative to neutral. The lower figure is the motor running at 28 amps load current and brushes at 1.5 position relative to neutral. Both are in a non-arcing state but show marked differences in signal strength and noise. This supports a hypothesis that changing motor set point does introduce artifacts that need to be considered when developing the algorithm. There are also transients present in the base line signal indicating some form of arcing or switching that also need to be considered.

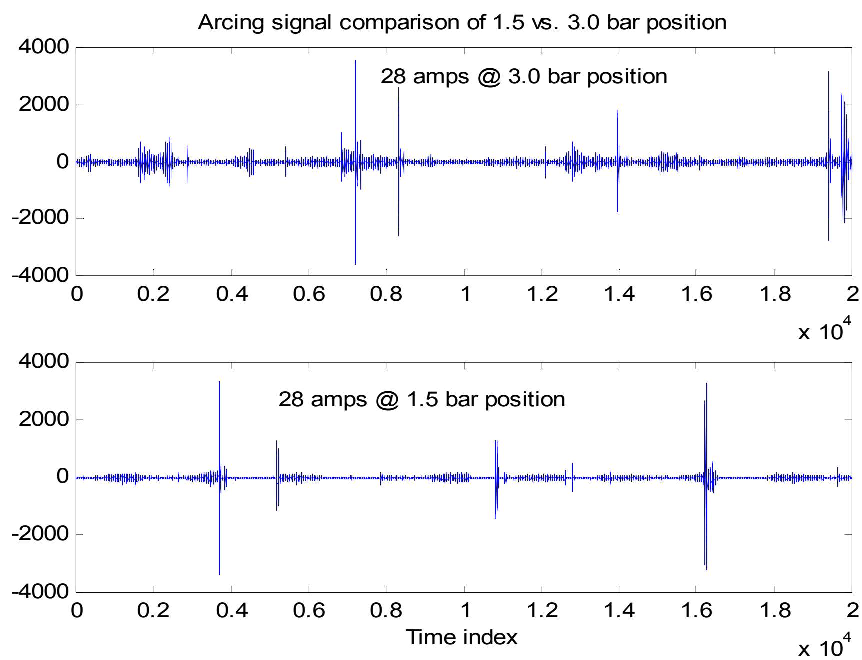

Figure 1. Antenna signal for 28 amp load current at 1.5 and 3.0 bars relative to neutral. A comparison shows there is anomalous arcing events in the base line signal and that power and noise increase as set point changes.

5. MODEL DEVELOPMENT AND ANALYSIS

1.1. Preliminary results of motor test no. 1 - initial sensitivity test

Three tests were conducted at Alcoa's Tennessee Hot Line Facility. The first acquired armature voltage, armature current, brush to ground voltage, and a demodulated AM radio signal. Two sets of data were collected for each test condition, one with a low-pass filter set at a cut-off of 100 kHz and one without.

The analysis on these data consisted of identifying time series metrics, histograms, and power spectral densities (PSDs) coinciding with the motor test configurations, i.e. constant voltage and motor rpm, 190 and 300, respectively, and changing load currents and brush position relative to neutral. In each, the AM receiver was held outside of the motor housing to establish a base line and then inside to capture operational characteristics.

The results from this analysis uncovered three important facts. The first was that the armature current and the AM radio signal had the greatest sensitivity to brush position and armature current variations. The second was that even though the armature current and AM radio signal had the most sensitivity they could not characterize, in sufficient detail, different levels of arcing in the motor. The third was that further testing was needed to characterize the arcing phenomena itself.[1.]

1.2. Development of the arcing-response matched filter model - tests 2 and 3

The second and third tests were in response to the findings of the initial study. In these, the focus was on enhancing the detection capability for single and entrained arcing events. Two sensors, new to the test matrix, were employed for the test (see Figure 2). The first was an in-house designed E-field antenna (single-loop) co-located with the brush. The second was a magnetic field probe that contained a single turn, shorted loop inside a balanced E-field shield.

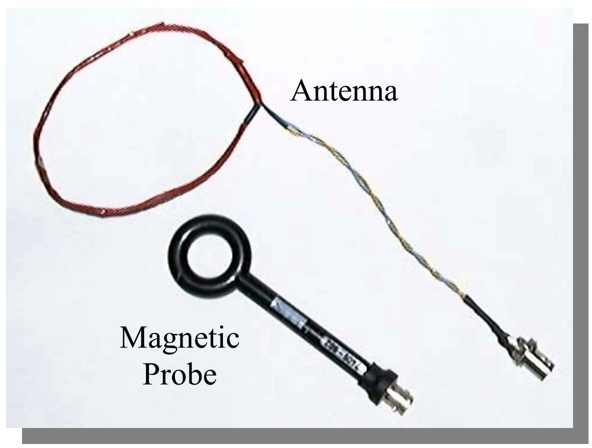

Figure 2. Simple design antenna and commercial-off-the-shelf magnetic field probe used in the 2nd and 3rd tests. Emphasis was on the experimental validating of arcing model developed from theory and laboratory tests.

The experiment was conducted in two phases. Phase I validated the theoretical arcing model for the antenna and magnetic field probe. This involved setting up the loop antenna/magnetic field probe and arc generator in an electromagnetic interference (EMI) protected chamber and acquiring multiple data sets. Additional sets of tests were conducted outside the chamber to characterize the ambient noise floor and to validate the model in an operational setting. Figure 3 shows a time waveform of an arc as seen by the antenna in the ambient environment. From these data, the final matched filter arcing model (both antenna and magnetic field probe) was developed and coded for testing at Alcoa's Tennessee Hot Line Facility. Figure 4 is a spectral comparison of the arc signal and matched filter model.

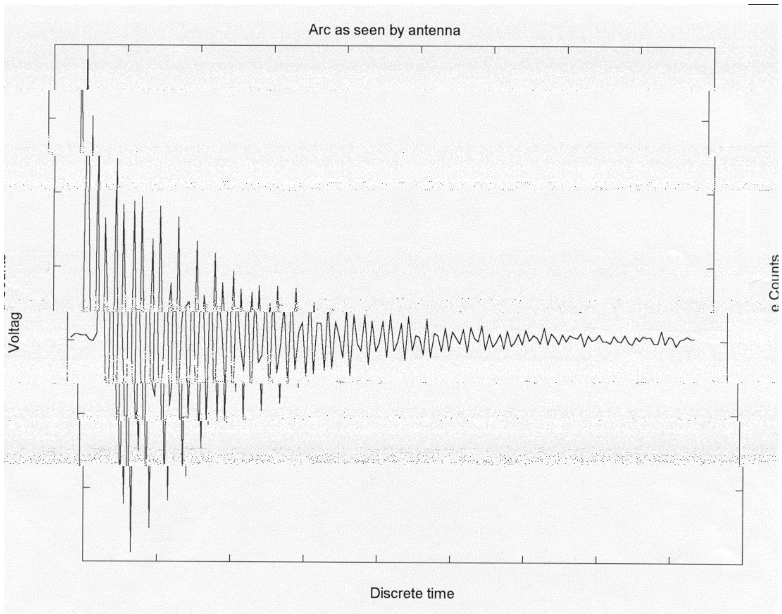

Figure 3. Time waveform of an arc as seen by the in-house designed antenna.
The data was acquired outside the EMI chamber to see ambient noise.

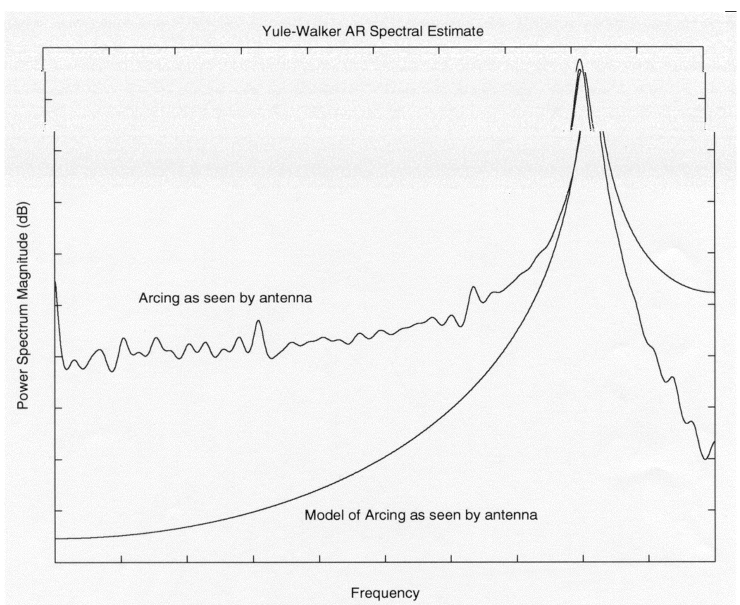

Figure 4. Comparison of matched filter arcing model with arc acquired
in laboratory tests.

Phase II testing involved moving the antenna and magnetic field probe to Alcoa's Tennessee Hot Line Facility and conducting a series of field tests with the same protocols used in the initial tests (see Table 1). This data was used to qualify the capability of the antenna/magnetic field probe matched filter models to detect and characterize single and multiple arcing events in a DC motor under normal operating conditions.

Figure 5 is the data and algorithm block flow diagram implemented for the Alcoa field tests. As shown, the acquired antenna (magnetic) signal is high pass filtered and then passed through the matched filter (arcing) model (H(t)). Its output is then sent to three independent processing channels for further analysis.

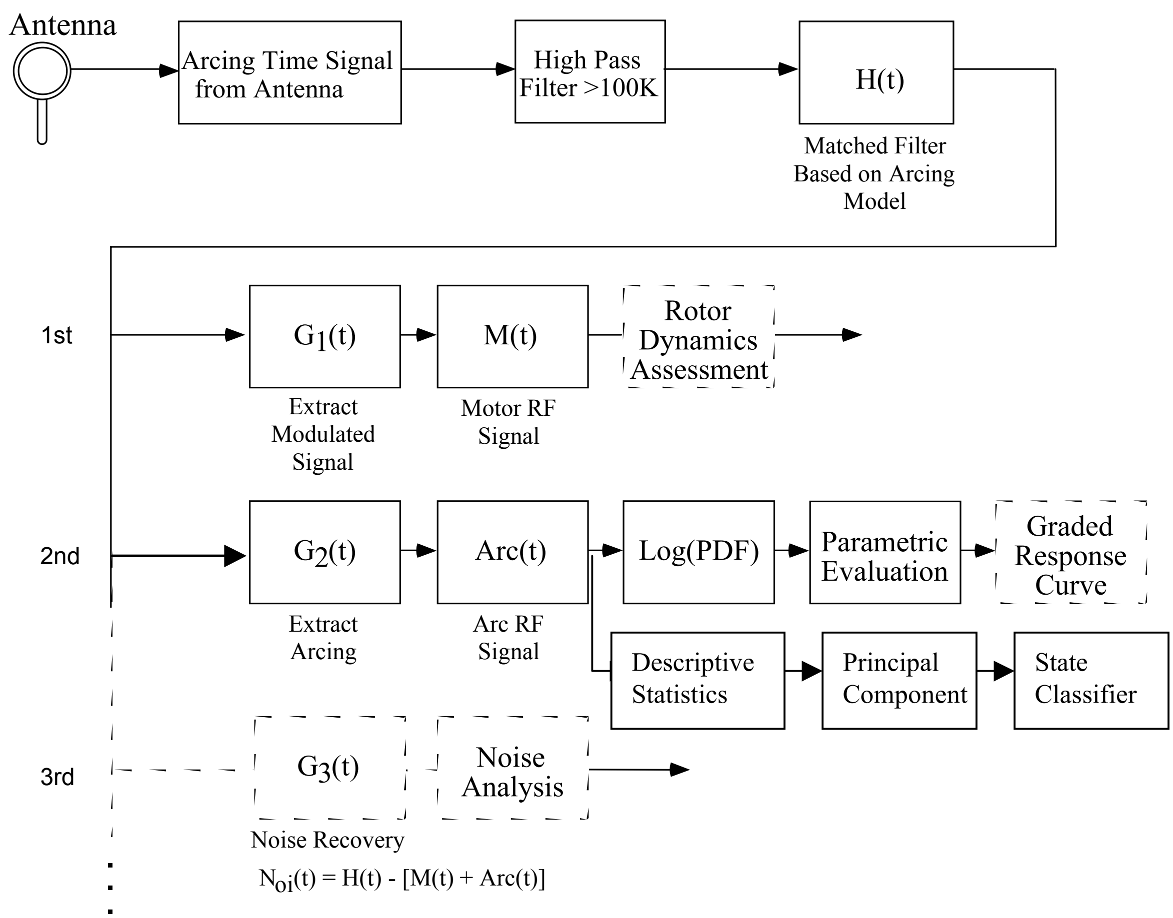

Figure 5. Data and algorithm block flow diagram implemented prior to the Alcoa field tests. Three processing branches will exist in the final form. Only two exist to date (Motor rf Signal and Arc rf Signal).

In the first channel, the algorithm $G_1(t)$ extracts rotor dynamics as a function of arcing and inputs this to a second algorithm, M(t), to provide statistics and other measures of performance. The output from this block can then be fed to a rotor dynamics assessment algorithm that could provide information about the health and status of the rotor. As of this writing, the rotor dynamics assessment block has not been implemented.

The second channel sifts information related solely to the brush arcing event. Here, $G_2(t)$ extracts the event from the matched filter output data stream, which can contain other arcing signals (events) that have been picked up by the antenna. This data is further processed, Arc(t), and used in a parametric evaluation to provide the graded response curve needed to characterize the state of the motor. Figure 6 shows the output from Log(PDF) for the motor running at 25, 200, and 300 amps and at the 1.5 bars and 3.0 bars position from neutral, respectively. The parametric evaluation and graded response algorithms are being completed at this time. (It should be noted that in process channels 1 and 2, a confidence estimate is calculated based on how well the data fit the parameters of the matched filter model.

There is a second diverging data stream on the second branch. Its purpose is to perform a descriptive statistical analysis on the output of Arc(t), map these descriptors onto a new set of variables (principal components), and then classify the state of the machine in terms of arcing or non-arcing and provide an estimate of extent. The descriptive statistics include harmonic mean, geometric mean, median value, skewness, sample variance, and kurtosis and form the descriptive metaphor for the state (health) of the motor. This process is described in more detail in the next section.

The third branch, which is currently under construction, will extract the arcing signals (G_1*M + G_2*Arc) associated with the brushes and the rotor dynamics from the matched filter module's (H(t)) output stream to provide a signal that isolates ambient noise only. An analysis of this data could potentially provide additional information about the process and other events that may be occurring in the plant.

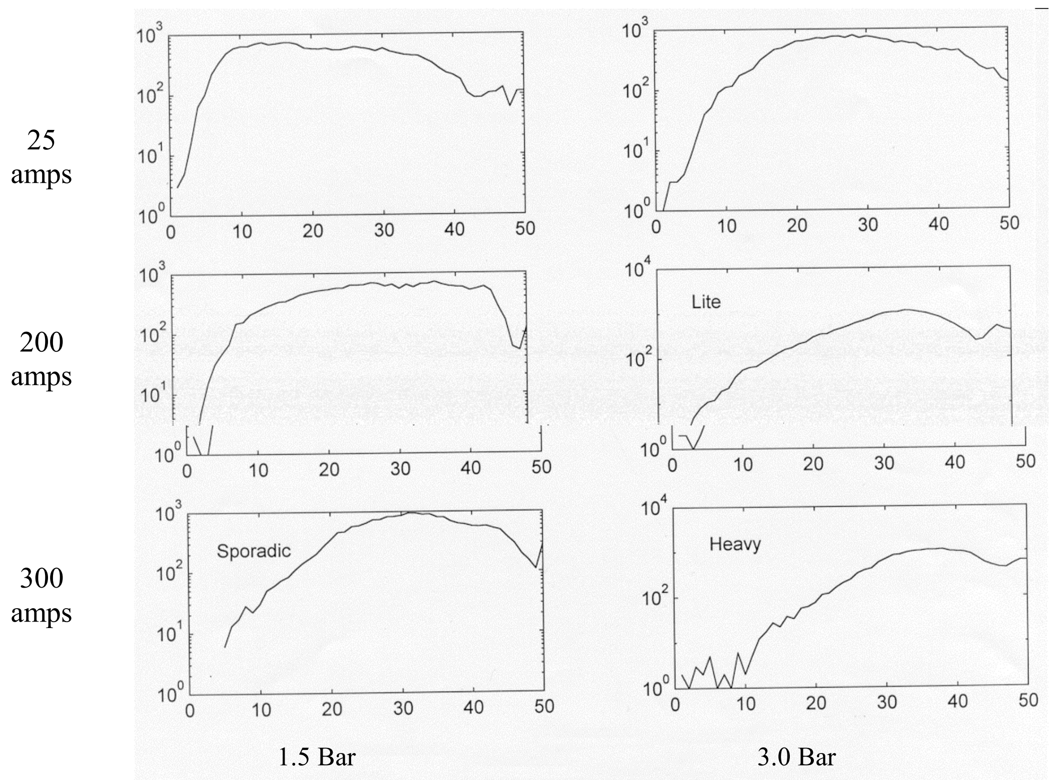

Figure 6. Processed data stream from Arc(t) for motor running at 25 amps, 200 amps, and 300 amps and 1.5 bar and 3.0 bar position relative to neutral, respectively.

6. PRINCIPAL COMPONENT ANALYSIS AND CLASSIFIER

A data set was extracted from the test sets that represented the operational states of the motor under normal operating conditions. The set consisted of data acquired at brush positions 1.5 and 3.0 bars moved relative to neutral and load currents of 25, 200, and 300 amps. These data formed the exemplar that would be used to develop the PCA arcing classifier. Figure 6, above, is a plot of the exemplar data set.

Table 2 shows the descriptive statistics for the exemplar data set after it has been normalized. Test conditions NoArc and Sporad are representative of a no-arcing condition and sporadic arcing, respectively. The analysis shows that the harmonic mean has the largest data set value with the geometric mean, second. The rest seem to have comparably low values. One of the major observations from this analysis is that no natural segmentation or clustering of data with respect to operating point and arcing condition seems to exist.

Table 2. Descriptive statistics for exemplar data set.

Test	Harmonic	Geometric	Median	Skewness	Variance	Kurtosis
$NoArc_1$	1.2552	0.9130	0.8375	2.8500	0.0569	2.0467
$NoArc_2$	2.0462	1.5697	1.4670	3.5569	0.5255	2.7338
Sporad	2.1450	1.7713	1.5917	1.8501	1.5041	0.7174
$NoArc_3$	2.5470	2.1417	1.8862	1.6851	2.8082	0.5779
Lite	4.2034	3.8664	3.7866	0.6813	0.8110	0.1592
Heavy	2.9682	2.3836	2.1044	1.8337	1.8556	0.7120

These data were then used in a principal component analysis. The results from this are shown in Table 3 and Figure 7. Table 3 identifies the total variability associated with each principal component. As seen, principal components 1 and 2 constitute over 95% of the total.

Table 3. Summary of total variability assigned to each principal component for exemplar data set.

Principal Component No.1	66.6665
Principal Component No.2	28.7590
Principal Component No.3	4.4086
Principal Component No.4	0.1220
Principal Component No.5	0.0439
Principal Component No.6	0.0000

Figure 7 is a plot of Table 2 exemplar data projected onto the new transform domain and segmented into two sub-domains that characterize non-arcing and arcing states of the motor. The boundary separating these two states is defined by the equation.

$$Y = 1.1667 * m + 0.8333. \qquad (2)$$

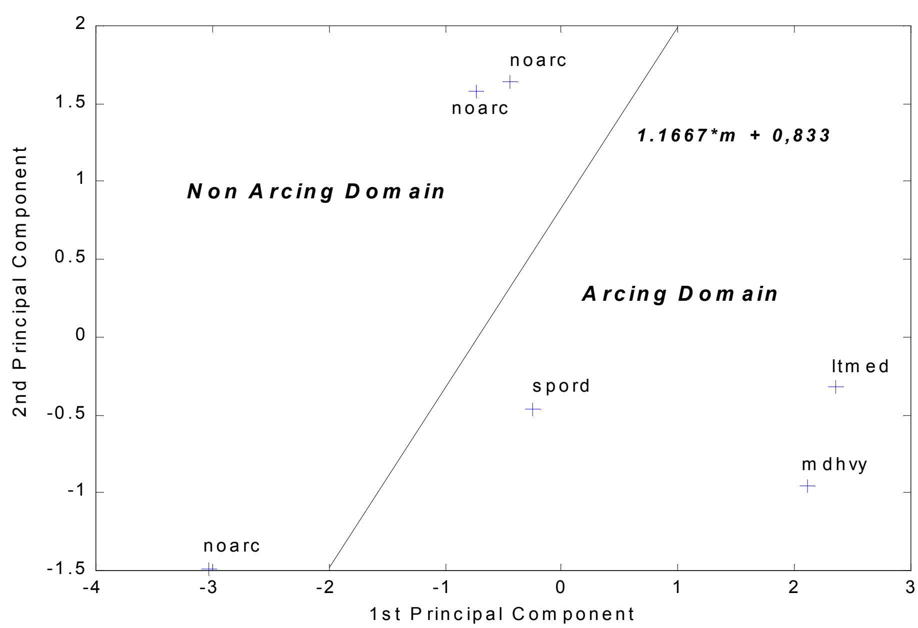

Figure 7. Table 2 exemplar data projected onto the new transform domain defined by the principal components analysis.

Figure 8 is a plot of an operational data set selected from the tests and run through the filter / classifier algorithm suite. These data were selected based on the motor's operational set point, i.e. brush position and load current. The separation boundary defined in the exemplar data has been superimposed on the plot. As seen, the model-based matched filter / principal components classifier algorithm has an ability to project (map) arcing and non-arcing motor states onto the 2-D transform defined by the exemplar data set.

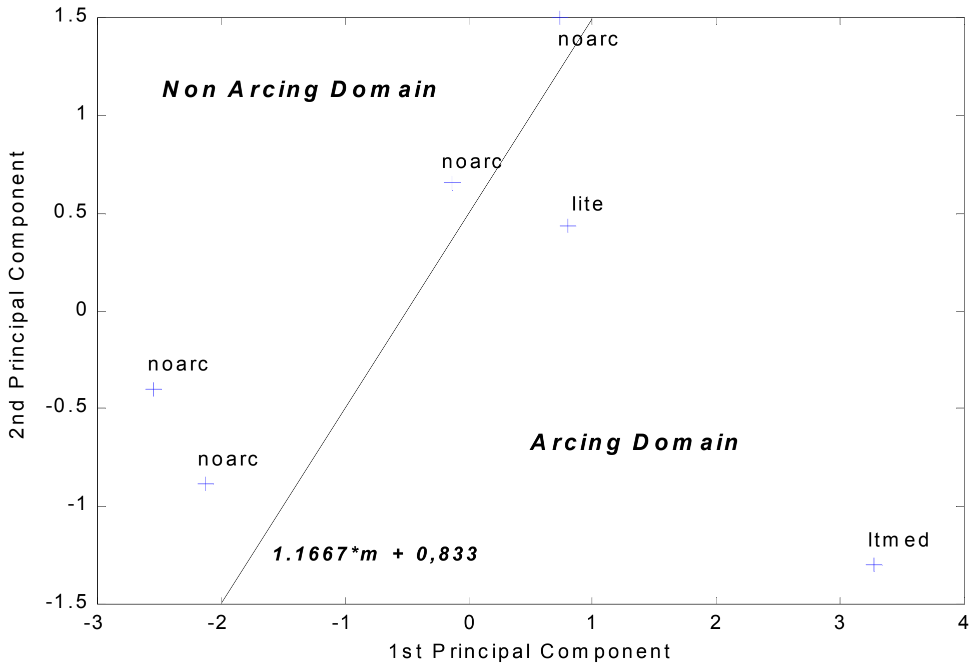

Figure 8. Operational data set projected onto the new transform domain defined by the exemplar principal components analysis.

7. GENERAL OBSERVATIONS

This segmentation and separation of motor arcing from non-arcing states provided by the matched-filter model / principal component classifier seems to be invariant to operating set point. Another observation is that a consistent mapping exists, i.e., similar arcing (non-arcing) states projected onto similar regions in the new transform domain. Preliminary analysis seems to confirm this hypothesis. The magnitude of orthogonal vector projections from the boundary to the classification points seems to scale with level and extent. Further investigation will confirm this conjecture.

8. CONCLUDING REMARKS

A new technique for the detection of incipient and entrained arcing in a DC motor has been developed and demonstrated through an extensive experimental study. The following are the major conclusions drawn from the study.

- Very low levels of arcing can be detected by high frequency analysis of a wide band antenna signal (and magnetic field probe) using a matched filter model.
- The derived arcing (matched-filter) model provides sufficient sensitivity to extract single or multiple arcing events.
- Performing a principal component analysis on an exemplar set of descriptive statistics generated from the matched-filter model provides a classification scheme for characterizing non-arcing states and arcing states in the motor.

- This invariant approach would be well suited for deployment in an agile manufacturing environment.
- A single measured variable (rf signal) is sufficient to characterize the degrees of arcing in the DC motor.

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REFERENCES

1. G.O. Allgood, B.R. Upadhyaya, N. Kerkez, J.D. Kueck, R.D. Haynes, G.B. Brown, and E.O. King, "Incipient Fault Detection of Large DC Motors," MARCON 99, Gatlinburg, TN, May 10-12, 1999.