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Predicting the Failure of Electric Motors

By Gerald T. Homce



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CONTENTS

	<i>Page</i>
Abstract	1
Introduction	2
Background	2
Recent failure prediction research	2
Data collection	3
Failure prediction research results	3
General	3
Methodology	3
Theoretical analysis of algorithm	4
System specification	4
System structure	4
System operation	5
System utility	5
Model development	6
Cable-connected motor models	6
Induction motor deterioration model	6
Computer analysis	7
Cable deterioration	7
Motor deterioration	9
Experimental program	9
Deteriorating-motor experiments	10
Destructive testing	11
Electrically excited vibration	11
Theoretical study	11
Laboratory experiments	11
Practical applications of research results	12
Computer model use	12
Off-line failure prediction techniques	13
Summary	13
U.S. Navy submarine power system monitoring	14
General	14
Submarine data acquisition	14
Summary	15
Conclusions	15

ILLUSTRATIONS

	<i>Page</i>
1. Cable-connected motor system for Bureau of Mines laboratory test program	3
2. Laboratory equipment for data collection from cable-connected motor system	3
3. Functional diagram of condition and performance monitoring system	5
4. Information flow in failure prediction algorithm	6
5. Effect of line-to-line cable insulation deterioration on feature complex power	8
6. Effect of line-to-line cable insulation deterioration on kappa transform values for complex power	8
7. Illustration of a nonlinear response as deterioration approaches fault level	8
8. Effect of winding-to-winding insulation deterioration within a motor, on feature current	9
9. Effect of winding-to-winding insulation deterioration within a motor, on kappa transform values for current	9
10. Effect of winding-to-winding insulation deterioration within a motor, on motor efficiency	10
11. Effect of motor load on feature current, for a constant level of winding-to-winding insulation deterioration	10
12. Line current values, I_L , I_b , and I_o for sudden failure during destructive testing of motor	11
13. Equipment connections for submarine power system data acquisition	15

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	mA	milliampere
hp	horsepower	pct	percent
Hz	hertz	rpm	revolution per minute
kW	kilowatt		

PREDICTING THE FAILURE OF ELECTRIC MOTORS

By Gerald T. Homce¹

ABSTRACT

A system capable of monitoring a mine electrical power system to detect incipient electrical component failure could significantly improve power system safety and availability. The U.S. Bureau of Mines funded a contract with The Pennsylvania State University (Penn State) to establish the theoretical and technical framework for such a system. This report briefly outlines the contract, reviewing related Bureau and Penn State work prior to its award, and describes support work carried out by the Bureau. The main focus of the report is on research efforts by Penn State and subsequent results. An existing algorithm for incipient-failure detection and classification was studied, and recommendations are made to improve its performance. In addition, mathematical models of cable-connected motor systems and deteriorating motors were developed and implemented on computers. These models and laboratory tests were used to study and document relationships between component deterioration and electrical terminal effects. The project was supported by the U.S. Navy and the nature of its interest in the application of failure prediction techniques is also included.

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INTRODUCTION

Monitoring and control technology is currently being applied to many aspects of mining operations. Computer-based systems can now aid mine operators in the management of production, health and safety monitoring, process and equipment control, and other activities. Another area in which such systems can be applied is the monitoring of mine electrical power systems for maintenance purposes. U.S. Bureau of Mines research, through contract JO338028 with The Pennsylvania State University (Penn State), focused on the development of a system to monitor the performance of mine power systems and to allow detection of component deterioration in very early stages.

A system capable of detecting incipient electrical component failure would impact mining operations in two areas. One benefit would be the implementation of predictive maintenance programs to increase equipment

availability and thereby improve productivity. In addition, such a system would enhance personnel safety.² Electrical system deterioration, detected early, could often be corrected before a substantial shock or fire hazard developed. Furthermore, the need for emergency power system maintenance, which tends to be rushed and substandard, could often be avoided.

This report details the progress of Bureau research in the detection of incipient electrical component failure and results to date. A brief review of past failure prediction research and its contribution as a foundation for present work is given. A description of contract JO338028 and an overview of laboratory support work by the Bureau are presented. The majority of the report covers research efforts and results by Penn State. A section is included that describes U.S. Navy involvement in this program.

BACKGROUND

Research in the detection of incipient electrical component failure, conducted from 1974 to 1983, formed the foundation for the development of an electrical power system monitoring-failure prediction system. The Bureau funded a research program at Penn State in 1974 (grant GO155003), to develop a continuous monitoring system that could predict electrical safety hazards on mine electrical power systems. Ultimately, the program failed to produce an operational monitoring system; it did, however, yield valuable information for subsequent failure prediction research.³ Work continued at Penn State with university research funds, and efforts focused on areas that were unresolved at the close of the grant.⁴ Early progress included more clearly defining the problem, creation of a system concept, identifying relationships between

terminal electrical characteristics and failure modes, and development of a failure prediction algorithm to serve as a basis for the proposed system. The primary results were a working algorithm and identification of monitoring system requirements. A number of points remained to be addressed, however, such as algorithm performance problems, further study of failure modes and their electrical signatures, and internal failure of induction motors.

At this stage, the Bureau examined the research performed since 1974, and a decision was made to establish a new program to further study the application of failure prediction to mining electrical power systems. Consequently, contract JO338028 was awarded to Penn State in August 1983.

RECENT FAILURE PREDICTION RESEARCH

This contract specified research that would further develop the basis for a power system performance monitoring-failure prediction system. The primary original objective was the collection and analysis of power system deterioration characteristics, to improve the existing failure

prediction algorithm. Contract modifications extended research efforts to include mathematical modeling of cable-connected motor systems and induction motors, examination of electrically excited stator vibration effects, and specification of the proposed monitoring system.

²Morley, L. A., F. C. Trutt, and J. L. Kohler. Final Report—Evaluation of Coal-Mine Electrical-System Safety (grant GO155003, PA State Univ.). BuMines OFR 160-81, 1981, 202 pp.; NTIS PB 82-139338.

³Work cited in footnote 2.

⁴Kohler, J. L. A Decision-Theoretic Method for the Classification of Incipient-Failure Patterns Which Are Characteristics of Deteriorating Mine Power-System Components. Unpublished Ph.D. Thesis, PA State Univ., Mar. 1983, 141 pp.; available upon request from J. L. Kohler, PA State Univ., University Park, PA.

DATA COLLECTION

Under the provisions of contract JO338028, a laboratory power system and a data acquisition system were established at the Bureau's Pittsburgh (PA) Research Center, as per specifications from Penn State. The arrangement was designed to generate data to support analytical work for the contract, by sampling voltage and current phasors from an operating three-phase cable-connected motor system. More specifically, the collected information covered areas such as—

Laboratory motor parameters,

Data acquisition system characteristics,

Validation of mathematical power system models, and

Various modes of power system deterioration for evaluation of the prediction algorithm.

Specified experiments called for a squirrel-cage induction motor with deterioration simulated on the incoming cable. The motor was directly coupled to a single-phase alternator that in turn powered a variable load bank to create motor load cycles. Faults external to the motor (on the cable) were simulated by a variable load placed across various phase and ground combinations. The overall layout of the cable-motor system is shown in figure 1. The Bureau's data acquisition equipment included signal conditioning interfaces, a fiber optic signal transmission system, and a data collection computer system. Information was digitized, processed, and organized using Bureau developed software. Figure 2 shows the general arrangement of the Bureau's experimental apparatus for failure prediction research.

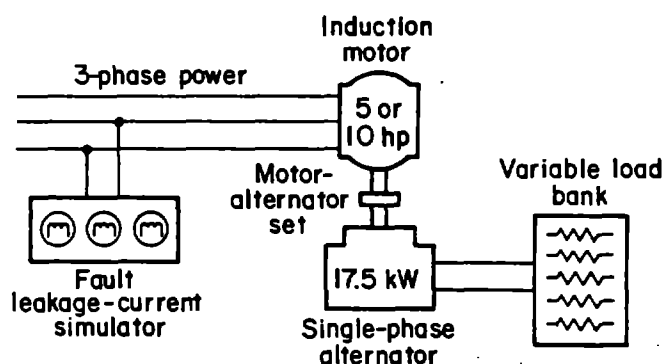


Figure 1.—Cable-connected motor system for Bureau of Mines laboratory test program.

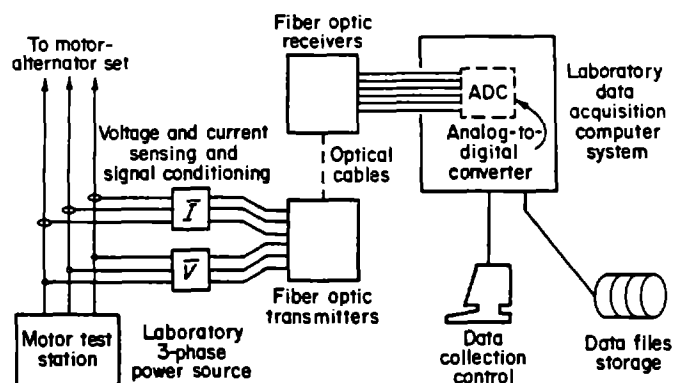


Figure 2.—Laboratory equipment for data collection from cable-connected motor system.

FAILURE PREDICTION RESEARCH RESULTS

GENERAL

The original objective of the contract, was refinement of the existing failure prediction algorithm through analysis of laboratory generated data. Subsequent modifications broadened the program scope to include efforts that would support this refinement, including extensive computer modeling of power systems and motors undergoing deterioration, examination of electrically excited vibration in motors, and application of failure prediction techniques to

Navy submarine power system maintenance. This section will describe the results of contractor work in all these areas, with the exception of Navy applications, which are discussed in a separate section.

METHODOLOGY

Initial work focused on identifying performance anomalies in the existing algorithm and determining the cause of these anomalies. Project researchers have determined,

however, that nearly all anomalies are related to hardware sampling and monitoring system sensitivity problems.⁵

A revised sampling scheme eliminated most of the hardware-related problems, but difficulties associated with monitoring sensitivity required more extensive investigation. This investigation called for more and different power system data, and in response, additional laboratory experimentation was carried out. Such an approach, however, proved too expensive and time-consuming for the volume of data needed; therefore, computer modeling of deteriorating power system components was undertaken to generate terminal values needed for the work. The development of appropriate models not only freed researchers from the limitations of available laboratory equipment, but decoupled the analysis from the hardware characteristics of any particular measurement system.

In addition to mathematical modeling of deteriorating power systems, other areas added to the original contract scope of work were specification of a proposed performance and condition monitoring system and examination of electrically excited motor vibration with respect to failure prediction techniques. These modifications not only further refined existing failure prediction theory, but also generated independent and more immediately useful results. Details of results for each area are presented in the balance of this section.

THEORETICAL ANALYSIS OF ALGORITHM

A significant performance anomaly from past tests of the failure prediction algorithm was a large standard deviation among samples for identical cases of component deterioration. A firm correlation was established between this problem and the method used for sampling voltage and current phasors. The sampling technique used prior to this contract was unable to accurately trigger at a predetermined target current level. The associated deviation in sampling points resulted in unacceptable variations in voltage and current values. Without a series of accurately reproduced points from motor load cycles, the algorithm had difficulty identifying changes in features (values derived from voltage and current values) that were due only to power system deterioration. A modified triggering system rectified this situation by sampling a range of values, up to nine cycles in duration. The data acquisition software could then extract from this range the best match to the desired target level.

Sampling trigger techniques are also a probable source for another anomaly, asymmetry of algorithm performance among different phases. Past results have indicated decreasing prediction accuracy for phases A, B, and C, respectively, and this may be attributable to sampling schemes that monitor phase A for triggering. A solution to this is the use of a sampling method that triggers from

some characteristic of motor loading, such as speed, that does not rely on one particular phase. A suitable triggering technique should also be independent of system deterioration.

Early testing of the algorithm also revealed erratic results for conductor degradation on a power system. Tests using data representing this mode of deterioration randomly exhibited either extremely good or extremely poor classification accuracy. The electrical characteristics of physical conductor degradation were, therefore, addressed in a series of tests. These tests proved very difficult to complete because of temperature effects, which often had more influence on cable resistance than reduction in conductor cross-sectional area. Test results, however, along with computer simulation of conductor degradation, sufficiently defined the deterioration to permit decisions regarding further examination of the problem.

Analysis indicated that in No. 8 AWG cable and larger, the incremental resistance change for severing of individual strands was beyond the sensitivity of the existing monitoring system. In addition, cable resistance change reacts exponentially to point reduction in conductor cross-sectional area, with an eventual sharp increase in heating effect influence and ultimate burn through of the cable. These factors give conductor degradation a somewhat all or nothing characteristic, and thus it was determined that monitoring for such deterioration was beyond the capabilities of the present failure prediction system.

SYSTEM SPECIFICATION

The on-line incipient failure prediction system proposed by the contractor is based on a software approach that utilizes simple, rugged sensors and microcomputers.⁶ With one microcomputer servicing multiple motors, and relatively low hardware costs, motors as small as 5 hp could be monitored economically. The difficulties and expense of such an approach are primarily in the development of software, which requires research into degradation mechanisms for electrical components.

System Structure

The proposed system monitors power system bus voltage, using simple voltage division circuits. While present work monitors all three phases, future implementations may only require one phase voltage value, depending on sensitivity requirements. Line currents for each power system component in question are monitored using current transformers shunted with resistors to produce an output voltage proportional to the primary current. Voltage and current signals then undergo analog-to-digital conversion for input to a microcomputer. Given the comparative techniques employed by the failure prediction algorithm software, the resolution of the monitoring system hardware is more important than its absolute accuracy. Thus, relative accuracy and long-term stability are important factors

⁵Pennsylvania State University. Prediction of Incipient Electrical Component Failure. Ongoing BuMines contract J0338028; for inf., contact J. C. Cawley, TPO, Pittsburgh Research Center, BuMines, Pittsburgh, PA.

⁶Work cited in footnote 5.

in instrumentation selection. Based on results thus far, the proposed monitoring system will be capable of detecting deterioration levels approximately two orders of magnitude lower than those that will typically affect power system performance or safety. Figure 3 is a functional diagram of the proposed system.

System Operation

The current state of the failure prediction algorithm requires that voltage and current phasors be sampled from a reproducible point during motor operation. Most of the data generated for this program have used a specific current level (from phase A) during motor loading for this reproducible point. The 60-Hz components of these phasors are then used to calculate a number of features for the power system, including system impedance (real and imaginary components), complex power, and power factor. These, along with the original voltage and current phasors, form patterns that are used to evaluate system condition.

The first step is a yes-no check for deterioration based on the presence of negative sequence current. If deterioration is detected, feature values are preprocessed, which involves comparing features from the sample under evaluation to a reference feature set that represents normal operation (no deterioration).

The initial preprocessing step is the use of interphase distance (kappa) transforms. Earlier research has demonstrated that the actual values of pattern features are too variable within the patterns to be useful for classification of system deterioration. Use of the kappa transform, however, reduces the variability while retaining characteristics unique to the pattern and the type of deterioration it represents. The kappa transform is, by definition, the change over time of the difference between feature values for two particular phases.⁸ If X_a , X_b , and X_c are feature values for phases a, b, and c for some class of deterioration, and $X'a$, $X'b$, and $X'c$ are the reference feature values for the same power system, the kappa transforms are

$$K(1) = (X_a - X_b) - (X'a - X'b),$$

$$K(2) = (X_b - X_c) - (X'b - X'c),$$

$$\text{and } K(3) = (X_c - X_a) - (X'c - X'a).$$

These values then undergo a statistical level of significance test based on feature standard deviations, wherein each feature is assigned a +1 (significant increase), 0 (no change), or -1 (significant decrease). The significance test reduces the effects of power system noise when attempting to classify mode and location of deterioration, particularly at low levels. The resulting collection of mathematically modified features forms a

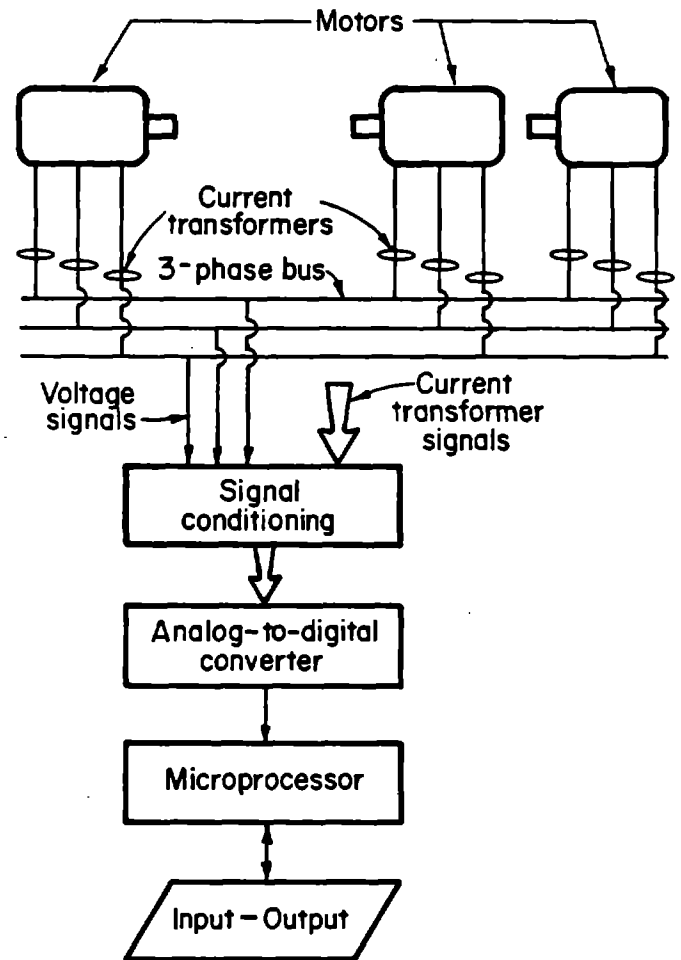


Figure 3.—Functional diagram of condition and performance monitoring system.

pattern in N-dimensional space (where N is the number of features). The pattern is mapped into a partitioned decision space that can determine the type and location of deterioration. Such a partitioned decision space is trained using data from motor systems operating under known deterioration conditions.

This has been only a brief description of the failure prediction algorithm, but more detail, as well as the FORTRAN source code, can be found in the work cited in footnote 4. Figure 4 is an information flow diagram for the algorithm.⁹

System Utility

The hardware and software, installed as an on-line failure prediction system, would be capable of monitoring both power system condition and performance.¹⁰ Performance monitoring focuses on operational characteristics of system components and, using the electrical features listed earlier in this section, could be used to study system

⁷Work cited in footnote 5.

⁸Work cited in footnote 5.

⁹Work cited in footnote 5.

¹⁰Work cited in footnote 5.

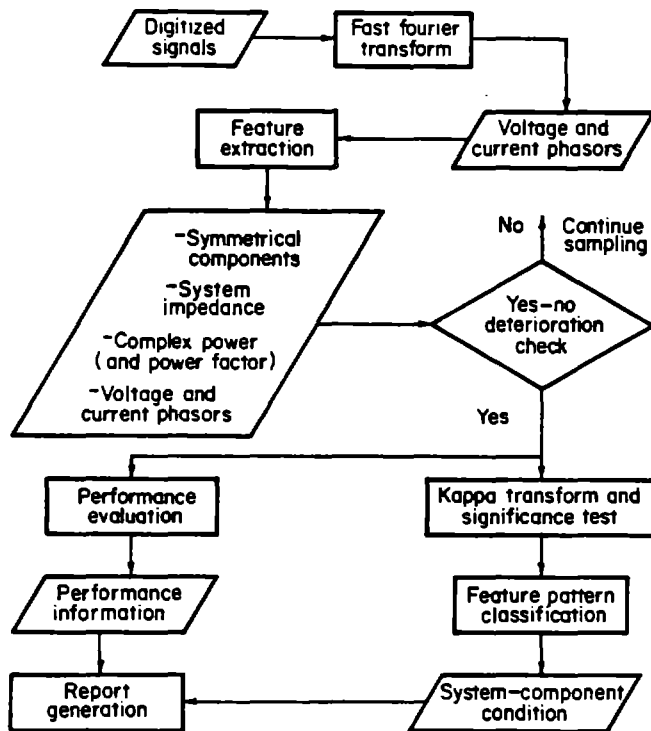


Figure 4.—Information flow in failure prediction algorithm.

application problems, load characteristics, and efficiency. Performance evaluation can in some cases reveal power system component problems, but condition monitoring, by definition, attempts to accurately detect incipient component deterioration as early as possible and determine its type and location. The failure prediction system proposed, used as an on-line monitoring system, would be capable of detecting—

Cable insulation deterioration (line-to-line or line-to-ground),

Motor stator turn-to-turn leakage (wye or delta),

Motor stator to ground leakage,

Uniform insulation leakage, and

Shorted connections.

Although much of the basic research for a failure prediction system is complete, information from recent work must still be incorporated into existing techniques and further research conducted before such a system is ready for implementation. Areas that will further refine failure prediction monitoring include improvement of sensing and signal processing hardware, a better understanding of the relationships between motor deterioration and electrical signatures, modification of detection and classification

software, and inclusion of mechanical parameters such as electrically excited vibration in motors.

MODEL DEVELOPMENT

Efforts to refine the failure prediction algorithm created a need for an economical method to generate terminal values (voltage and current phasors) for deteriorating electrical components. This led to the theoretical development and computer implementation of mathematical models for cable-connected motor systems undergoing cable deterioration and for squirrel-cage induction motors experiencing stator insulation failure.¹¹ With these models, researchers created a data base of electrical features with which to evaluate patterns associated with incipient failures.

Cable-Connected Motor Models

Mathematical modeling of a cable-motor system must include the positive and negative sequence impedance presented by the induction motor. This information is obtained using a per-phase equivalent circuit for an induction motor, with parameters taken from manufacturer's data or laboratory tests. In addition to motor circuit equivalent impedances, other important information for a cable-motor system includes cable impedance, fault type, fault location, and fault impedance. Applied voltage is assumed to be known, and motor speed can be assumed or determined by an iterative solution for a given line current level. With this information, symmetrical component techniques can be employed to determine voltage and current values for specific phases.

The three general cases modeled using this approach were conductor degradation (increased impedance), line-to-ground cable leakage, and line-to-line cable leakage. The simulation of conductor degradation has had only limited use, since early in the program the failure prediction algorithm was found to be unsuitable for detecting this type of deterioration. Line-to-ground and line-to-line fault modeling, however, were implemented in computer programs and used to evaluate failure conditions. Results of their use are discussed in the "Computer Analysis" section, and a more detailed description of their theory and use can be obtained from the work cited in footnote 5.

Induction Motor Deterioration Model

Initial attempts to model the effects of internal deterioration on an induction motor used a symmetrical component solution of the motor system equivalent circuit. In this circuit analysis, turn-to-turn leakage is represented by a reduction in the number of turns in a faulty phase. The solution also requires that stator phase windings be represented by concentrated full-pitched coils, that deterioration of insulation has progressed to a zero-resistance state, and that the motor is a two-pole machine. These assumptions, however, severely limit the utility and

¹¹Work cited in footnote 5.

accuracy for evaluation of deterioration involving turn-to-turn leakage.

Given these limitations, a more general analysis approach was pursued, resulting in a mathematical model able to predict terminal values for an induction motor experiencing a wide variety of internal stator faults. The overall approach for construction of this model involved the following seven steps.

1. The airgap magnetic flux (including space harmonics) produced by a single stator coil is theoretically evaluated.

2. The portion of this flux that links a second stator coil is then determined.

3. Using the results of steps 1 and 2, an expression for the mutual impedance between an arbitrary pair of stator coils is determined.

4. Considering a winding to be a series connected set of coils (these series sets are defined by the specific fault situation), the results of step 3 may be summed to give expressions for the mutual impedance between stator windings.

5. Similar approaches to steps 1 through 4 are then utilized to obtain expressions for self and mutual impedances relating to stator-rotor, rotor-rotor, and rotor-stator interactions.

6. The effects of leakage impedances are then added to the model, and Kirchhoff's voltage law is utilized to obtain a set of N-equations having the N-winding currents as unknown quantities.

7. The equations of step 6 are then solved to give the winding and line currents, symmetrical components current, input power, and effective power factor. Efficiency is also estimated.

A detailed theoretical development of this model is available from the work cited in footnote 5.

COMPUTER ANALYSIS

Models for cable-connected motor systems and deteriorating motors were implemented in FORTRAN programs and validated using experimental laboratory data. In general, model predictions and laboratory data agreed well, with differences remaining below a few percent. The validated models were then applied to the analysis of relationships between power system conditions-characteristics and calculated terminal features.¹²

Cable Deterioration

The application of the cable-connected motor models addressed the following three general topics:

Feature patterns resulting from cable deterioration in a cable-motor system.

Level of sensitivity required (from a failure prediction monitoring system) to detect given levels of deterioration.

Effect of different component types and sizes on feature patterns.

The results from an analysis of cable leakage and its effects on specific electrical features are presented in graphical form in the work cited in footnote 5, where the reaction of numerous features and their respective kappa values are graphed for line-to-line and line-to-ground cable leakage of varying severity. Figures 5 and 6 are examples of these plots, which represent the change in feature values and kappa values, respectively, for complex power as line-to-line deterioration level increases. Although this information is not directly applicable to failure prediction in the form presented, it serves to give a general feel for deterioration effects on a power system. More importantly though, the sum of all such feature reactions is the key to the pattern recognition process used in the failure prediction algorithm. As described earlier in the report, the kappa values are more useful for pattern recognition than the actual feature values.

The cable-connected motor system models were also used to evaluate system sensitivity; that is, to determine the best possible performance from specific monitoring hardware or select hardware for a desired level of sensitivity.

In order to study sensitivity, deterioration levels and their relation to power systems needed to be better defined. Deterioration levels of interest are those that would normally go undetected. Practical limits for these are levels above which protective devices will operate or levels that cause changes noticeable to human operators. In the first case, this would commonly be above 125 pct normal line current; in the second case, an estimate based on practical experience is a negative sequence current 25 pct or more of normal line current. Past results indicated that deterioration could be detected well below these values, and in the sensitivity analysis they were used as upper limits of deterioration. This definition of deterioration level limits is further supported by a tendency for features to be linear at low levels of deterioration, and nonlinear as fault levels are approached. Figure 7 is an example of this tendency for a feature value and the third kappa value of current.¹³

¹²Work cited in footnote 5.

¹³Work cited in footnote 5.

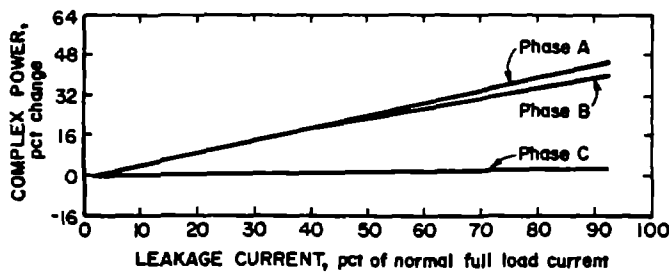


Figure 5.—Effect of line-to-line cable insulation deterioration on feature complex power.

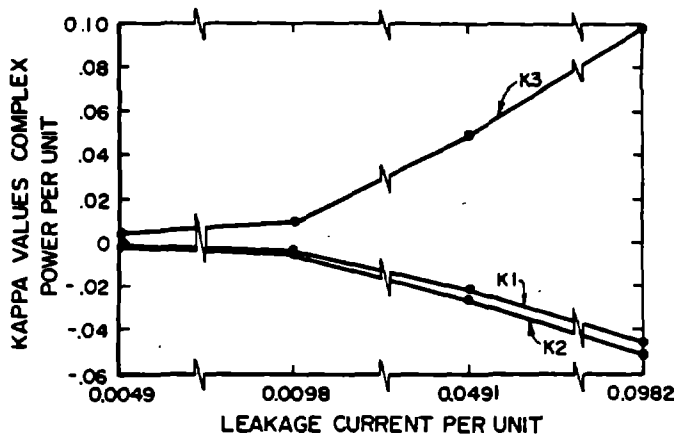


Figure 6.—Effect of line-to-line cable insulation deterioration on kappa transform values for complex power.

In actual sensitivity analyses, kappa values for various levels of cable deterioration were examined. Sensitivity required to detect a given leakage impedance was determined by the resulting change in the kappa value of a measured feature. For example, if a 1,250-ohm line-to-line leakage impedance causes a line current kappa value of 100 mA, then the monitoring system used must have resolution capable of detecting 100-mA change. In addition, random (uncontrollable) fluctuations in measurements due to sampling errors, temperature changes, etc., must be well below 100 mA. Another consideration when dealing with deterioration involving ground is the influence of any power system grounding impedance. Since a grounding impedance is in series with any line-to-ground leakage impedance, it influences the leakage current. The influence is minimal when the leakage impedance is one or two orders of magnitude larger than the grounding impedance; when the grounding impedance is high (ground flow current limited to <1 A, for example), it acts to mask changes in measured features. In the latter situation, monitoring resolution must, therefore, be better than would be necessary on a system with a lower grounding impedance, to detect comparable deterioration levels.

Random fluctuations in a power system and monitoring system cause measurement changes that do not relate to

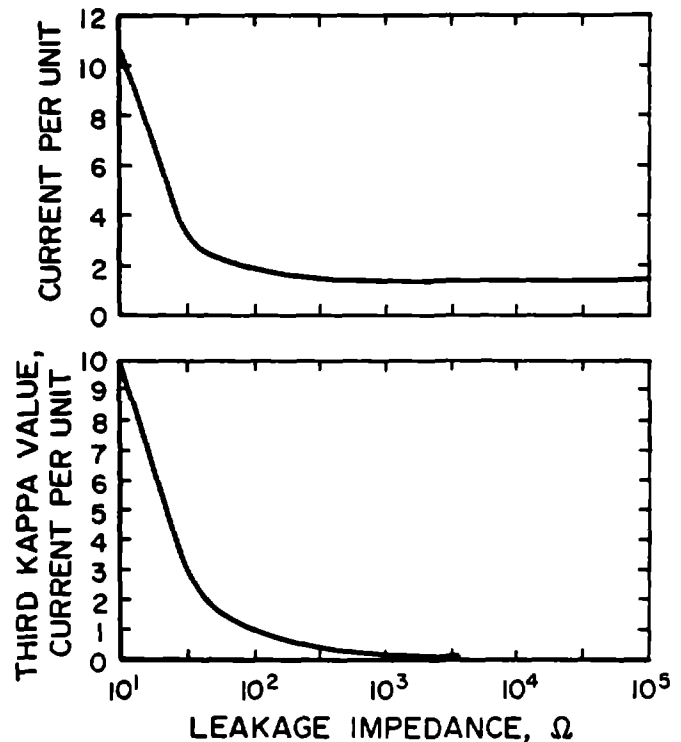


Figure 7.—Illustration of a nonlinear response as deterioration approaches fault level.

load changes or deterioration. These factors, which include conductor temperature, air temperature and humidity, sampling errors, and supply voltage fluctuations, have an increasing influence on failure prediction accuracy as changes due to deterioration become smaller. Although they are not controllable, most effects can be predicted and accounted for, if necessary. A 5-pct supply voltage imbalance, for example, causes a small but significant change in kappa values. The effects of this imbalance, however, can be subtracted from total system imbalances to improve detection accuracy, if necessary.

The third topic analyzed using the cable-connected motor models was the effect of different types and sizes of power system components on feature kappa values. The type and size of cable (assuming correct sizing for load) does not affect feature values, since cable impedances are typically small compared to leakage impedances. Thus the performance of the failure prediction algorithm is unaffected by cable type or size.

The effect of motor type and size, however, is not so easily identified or defined. Motor parameters can vary drastically, even for machines with identical horsepower ratings; consequently, their impedances will also vary widely. Since a leakage path is essentially in parallel with motor impedance, motor characteristics affect the accuracy

and sensitivity of failure prediction techniques. Although use of per-unit values in analysis reduces the apparent variation for dissimilar motors, the effects are still significant and become more pronounced as deterioration levels increase. Analysis of these variations presented an additional problem, since identical leakage paths cannot be created on systems with different components. The evaluation, therefore, was carried out using several different criteria for deterioration levels, and results for each were compared.

The analysis involved producing several feature kappa values for three different cable-motor systems with similar leakage paths. For the systems examined, sensitivity to similar deterioration was different for different motors by as much as 36 pct, but the overall feature patterns remained the same in almost all cases. This suggests that while sensitivity criteria may have to be situation specific, the incipient failure classification process is independent of motor type and size. Additionally, the criteria used for defining the level of deterioration had little effect on feature variation among the different motor types.

Motor Deterioration

Analysis of computer-generated deteriorating motor data was less extensive than that for cable-motor systems, since the motor model had been available for a shorter time and input data were not as readily available. Terminal values and the resulting features were produced, however, for a motor undergoing turn-to-turn stator deterioration, both within one winding and between two windings (phase to phase). The runs made were not comprehensive and the analysis was not exhaustive, but feature reactions to various parameter changes can be shown by selected graphs from the work cited in footnote 5.

Figures 8 and 9 are the feature values and kappa values, respectively, of line current for a motor at 75 pct full load, and various levels of winding to winding leakage. Figure 10 shows motor efficiency for the same situation, as deterioration increases. Line current for the same motor and leakage path are shown in figure 11, but for a constant deterioration level and varying motor load. Additional cases examined were the effect on features of changing leakage path location (winding to winding) while holding load and deterioration level constant, and the behavior exhibited by features during turn-to-turn leakage within the same winding.

The information derived from analyses using the cable-connected motor models and deteriorating motor model is essential to application of the failure prediction algorithm. The results better define the effects of numerous power system and deterioration parameters on terminal electrical features, and will allow more effective

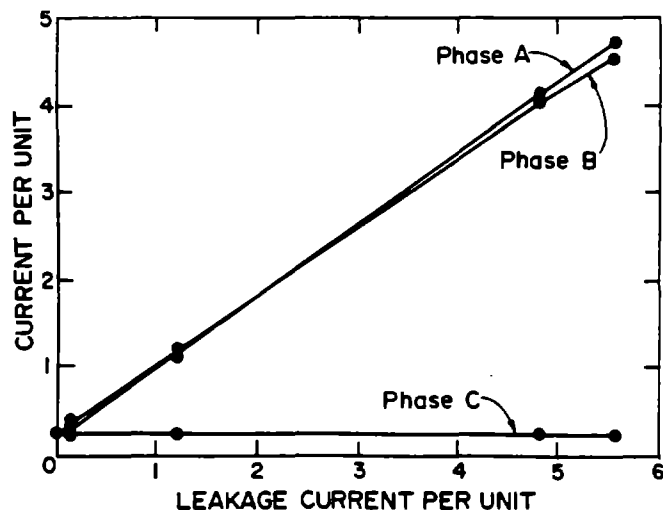


Figure 8.—Effect of winding-to-winding insulation deterioration within a motor, on feature current.

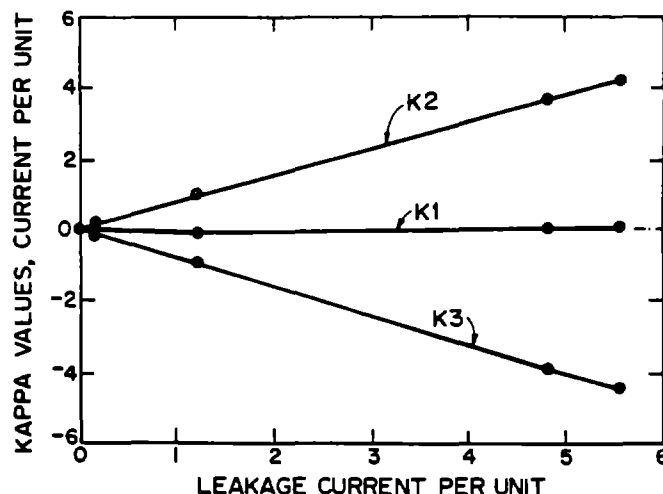


Figure 9.—Effect of winding-to-winding insulation deterioration within a motor, on kappa transform values for current.

use of these features for incipient failure detection and classification.

EXPERIMENTAL PROGRAM

The experimental program at Penn State supported analytical work by aiding in the development of mathematical deterioration models, validating the completed models, and investigating various application issues. Most

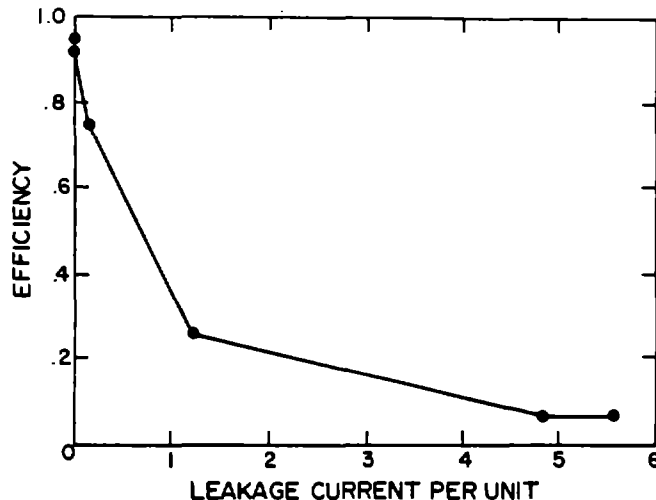


Figure 10.—Effect of winding-to-winding insulation deterioration within a motor, on motor efficiency.

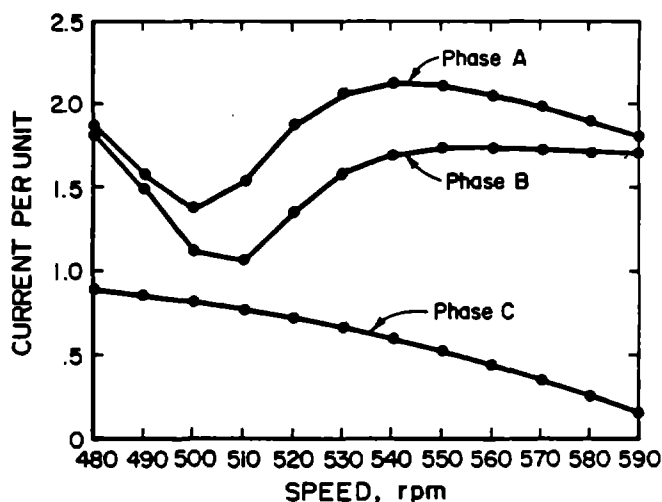


Figure 11.—Effect of motor load on feature current, for a constant level of winding-to-winding insulation deterioration.

work involved laboratory simulation of a deteriorating induction motor and destructive testing of motors.¹⁴

Deteriorating-Motor Experiments

An extensive data collection program was carried out to document feature patterns associated with motor deterioration and to develop a data base of patterns for use in development of pattern classification functions. A nondestructive laboratory-simulation approach was used, utilizing a Hampden Universal Machine, a deterioration simulator, and a data acquisition system. Testing was organized to simulate several different fault types at different stator

locations, in delta- and wye-connected motors. Researchers had direct control over test conditions relating to motor-winding connections, deterioration simulation, and motor loading. Research requirements were arranged into logical test procedures defined by the following system parameters:

Winding connection (delta or wye).

Deterioration type (phase-to-phase, phase-to-ground, or within a single phase).

Deterioration location (within windings).

Motor load.

Deterioration level.

The resulting experimental procedure had a total of 322 test cases. The primary result of the tests was a large collection of electrical feature patterns, but a number of general comments can be made regarding the behavior exhibited by the deteriorating motor.

Features that were more sensitive than others to change in winding insulation degradation included the following:

Power factor at no-load conditions.

Line impedance.

Magnitude of line currents.

Zero and negative sequence currents.

Rotor double-frequency component.

Power factor exhibits a marked change with leakage level increase, but the effect diminishes quickly when the motor is loaded. The line currents also display increasing imbalance as deterioration increases, but unlike power factor, their relative positions remain constant for motor load changes. Similarly, zero and negative sequence current increase proportionally to deterioration, while remaining independent of motor load.

Although the connection between deterioration level and negative sequence current was evident from test results, the relationship was not consistent. Additional analysis indicated that leakage current and negative sequence current are directly related for constant leakage path potential. This was then extended to suggest that a direct relationship exists between negative sequence current level and power consumed by a leakage path, for currents limited only by leakage impedance. Verification of this is only preliminary, but such a correlation would allow negative sequence information to be used as an indication of deterioration severity. Double-frequency rotor currents are related to negative sequence stator currents, and are also extremely sensitive to system imbalance. They, however, can only be monitored on wound-rotor machines.

¹⁴Work cited in footnote 5.

Destructive Testing

Accelerated life cycle testing of induction motors was conducted to verify model predictions and laboratory deterioration simulations. Test results are terminal value feature patterns from actual motor failures for comparison to simulated or modeled values. The acceleration processes, however, were not quantified, and so no insulation life predictions are intended.

The method chosen for accelerated aging was a combination of electrical stressing, thermal stressing, and moisture exposure. High dc voltage was placed across stator windings for electrical stress; thermal stresses were created by overloading the motor while restricting ventilation. Moisture was introduced by a humidifier and by direct spraying.

Three-phase voltage and current values were monitored during testing, with phasors measured and digitized for storage at regular intervals, and continuous magnetic taping used to ensure recording of unexpected failures. In addition, insulation resistance tests were conducted at regular intervals for comparison to terminal value feature patterns.

One specific test resulted in a motor failure on the 208th day of operation. This was a sudden failure which produced feature patterns that closely match those for a winding-to-winding leakage path simulated on the Hampden Universal Machine. Although line currents exhibited a sharp increase at the point of failure, the test motor continued to run after the failure occurred. Line current changes at failure are shown in figure 12.¹⁵

In addition to the correlation between actual and simulated failure, the destructive testing program helped identify several monitoring implementation problems. The foremost of these was random fluctuations in terminal values when measured over a long period of time. The factors that were most notable during testing were bus voltage imbalances and temperature changes, which caused impedances to vary.

Overall, the experimental program successfully supported failure prediction theory development and mathematical modeling of motor deterioration. Additional benefits included verification of laboratory simulations and examination of monitoring implementation problems.

ELECTRICALLY EXCITED VIBRATION

One aspect of the failure prediction program was a preliminary investigation of electrically excited vibration in deteriorating motors. A theoretical study of electrically excited vibration was made to determine the feasibility of modeling its relationship to stator deterioration. Such a model could be used to develop vibration monitoring techniques as part of a failure prediction system. Limited laboratory experiments were also carried out to observe electrical-mechanical interactions for a deteriorating motor.

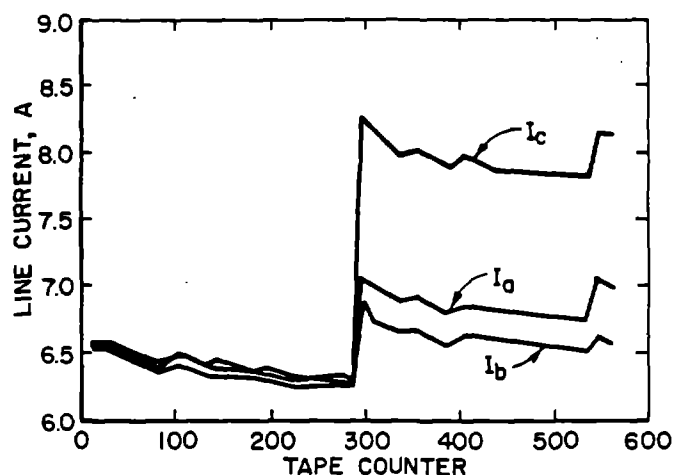


Figure 12.—Line current values, I_a , I_b , and I_c , for sudden failure during destructive testing of motor.

Theoretical Study

This part of the investigation involved a literature search and subsequent review of pertinent information on electrically excited stator vibration. Researchers concluded that it is feasible to construct an electrically excited stator vibration model, and a general theoretical approach for such modeling was outlined. An approximate analysis, using the general approach outlined, was used to compare a normal motor and one undergoing phase-to-phase stator deterioration. The differences in the resulting frequency spectra were significant and indicated that vibration monitoring may prove useful for incipient failure detection.

Laboratory Experiments

Experiments were conducted to differentiate between electrically and mechanically induced motor vibration, and to identify the electrically induced vibration due specifically to motor deterioration. Several motors were fitted with vibration transducers, with the outputs monitored on a waveform analyzer. Vibration spectra were recorded for the motor running with no deterioration, the motor rotating immediately after removing power, and the motor running under single-phasing conditions. Subtracting the vibration present after removing motor power from total vibration leaves only electrically excited vibration, which can then be used in comparison of deteriorated and non-deteriorated cases. For the tests run, two important results were noted. The change in vibration spectra due solely to electrical imbalance during motor deterioration is significant, but this change can be entirely different for different motors.

¹⁵Work cited in footnote 5.

In summary, this investigation has determined that modeling of electrically excited vibration in deteriorating induction motors is feasible. Furthermore, results from laboratory experiments indicate that to continue research in this area, such modeling will likely be necessary because of the complex and machine specific relationships between electrical deterioration and mechanical vibration. Further investigation of this topic could enhance the capabilities of incipient failure detection techniques by adding an additional parameter with which to recognize motor deterioration.

PRACTICAL APPLICATIONS OF RESEARCH RESULTS

The theoretical and experimental work under this program have thus far been described only as applied to development of an on-line automated failure prediction system. The concepts and tools resulting from these efforts, however, have independent value and may be immediately useful to maintenance engineers. The utility of these items can be described under two categories: (1) use of computer models for evaluation of power system component behavior and (2) use of simplified feature pattern analysis for manual incipient failure detection.

Computer Model Use

Analysis of power system components or branches can be augmented by computer simulation of system conditions. Examples of situations to which models could be applied include

Examination of terminal feature patterns for frequently encountered component failures,

Determining possible causes for observed component problems, and

Analysis of effects on performance, for changes in component characteristics or application.

The following are brief descriptions of the computer models developed under this program to support failure prediction research.

Cable-connected motor modeling first requires the use of a program to determine positive and negative sequence impedances. A program named SPEED is used if motor line currents are available, and another called MOTOR Z is employed if motor speed is known. The balance of required input for either program is

Stator resistance,

Stator reactance,

Magnetizing branch resistance,

Magnetizing branch reactance,

Rotor resistance,

Rotor reactance,

Motor synchronous speed, and

Phase A to ground voltage.

Outputs in either case are positive and negative sequence motor impedances, which are required input for the cable-connected motor system modeling programs.

The modeling programs and the conditions they simulate are

CASE 1—conductor degradation.

CASE 2—line-to-ground deterioration.

CASE 3—line-to-line deterioration.

Input parameters for the programs are

Phase A to ground voltage.

Motor horsepower rating.

Motor positive sequence impedance.

Motor negative sequence impedance.

Cable impedance.

Leakage (fault) impedance.

Leakage (fault) position.

Voltage base.

Impedance to ground (CASE 2 program only).

The models compute the voltage and current phasors that would exist at the line side of the cable-connected motor system in question. From these values, the programs derive and output a number of features including current (echo), complex power and its components, power factor, complex impedance and its components, current symmetrical components, and kappa values for all of these features (requires reference data set). Instructions for use of these programs as well as their FORTRAN source code are found in the work cited in footnote 5.

The deteriorating motor model developed under this program, MTRMDL, simulates internal stator deterioration, and so requires extensive motor design and deterioration description data for input. Input information

selection requires a basic understanding of electric machinery as well as the modeling techniques used, and includes data describing

Network connections and impedances for the motor and deterioration condition in question,

Complete physical and electrical characteristics of the motor, and

Motor operating conditions.

The output of MTRMDL is voltage and current phasors at the subject motor's terminals. The work cited in footnote 5 contains the FORTRAN source code for MTRMDL and instructions for program use, including selection of input information.

Off-Line Failure Prediction Techniques

Failure prediction theory has not yet reached a point at which it can support an on-line fully automated system for incipient failure detection. Several aspects of this research, however, are sufficiently developed to have some utility for manual implementation. Although when considering a nonautomated approach, definite guidelines are not available to allow quick detection or classification of power system deterioration, application of these manual evaluation techniques can still provide more information on component operating performance and condition than is normally possible. To allow use of such performance and condition monitoring on an interim basis, a program called THREE-PHASE ANALYZER was derived from the formal incipient failure detection algorithm.

The first step of off-line monitoring would be to measure and record the necessary values from the system under test. Any method used must accurately record the voltage and current values while maintaining all phase relationships. Selection of a data acquisition system, however, raises many of the questions brought forth earlier in this report, such as required accuracy and resolution of hardware, method of analog-to-digital conversion, sampling point reproducibility, sample length, sampling method, sampling speed, and random fluctuations in the power and monitoring system. Although these factors are important for acquisition of accurate and appropriate data, they are situation specific and will not be covered here.

Input to the THREE-PHASE ANALYZER program consists of the line-to-neutral voltage and line-current phasors monitored at the terminals of the electrical component in question. The program requires input of phasors for a reference condition (no deterioration) as well, in order to calculate feature value differences (between reference and present case) and kappa values. Reference data should come from samples at some known

condition, such as when a motor is new or recently rebuilt. Output from the program consists of

Voltage phasors (echo),

Current phasors (echo),

Complex power and its components,

Power factor,

Complex impedance and its components,

Symmetrical components for all the above, and

Kappa values for all the above.

Further directions for use and the FORTRAN source code listing of THREE-PHASE ANALYZER are in the work cited in footnote 5.

Output from the THREE-PHASE ANALYZER contains information (raw feature values for the test data) useful for power system component performance evaluation. Items such as voltage balance and phase relationship can be used to check power supply quality, while current levels, power consumed, and power factor describe motor load level and general efficiency for the application. The raw feature values are then subtracted from the reference set to yield feature change values; interphase distance transforms are applied to create kappa values. Using this information, changes in system-component condition can be detected. A notable rise in negative sequence current for instance (not due to supply voltage imbalance), indicates some sort of deterioration, and examination of other feature changes can better define likely locations and modes for the incipient failure. This sort of analysis would be most productive if progressive deterioration can be identified and documented, from point of first detection to actual failure. Such trending information will be essential for the eventual extension of incipient failure detection to accurate failure prediction.

Computer modeling and manual failure prediction are direct results of efforts to create an automated failure prediction system. Although their practical applications are limited, in appropriate situations they can be useful tools for maintenance engineers in the evaluation of power system component performance and condition.

SUMMARY

Research by Penn State under the failure prediction program has focused on establishing a theoretical framework for a feasible incipient failure prediction system. Work to refine an existing failure prediction algorithm exposed many aspects of electrical deterioration theory

that required more development. The necessary additional analysis involved mathematical modeling of deteriorating cable-connected motor systems and induction motors with internal deterioration, and the computer implementation of the models. Extensive laboratory testing was also conducted to simulate deterioration conditions. In addition, a theoretical and experimental examination of electrically excited vibration determined its utility for deterioration detection, and the feasibility of mathematically modeling its effects.

Through these activities, researchers identified areas on which to focus analysis, implemented computer models and experimental programs to carry out the analysis and, as a result, defined many relationships between terminal electrical features and system component deterioration. Additionally, they specified the proposed incipient failure detection system, established the significance of electrically excited vibration effects, and described immediate applications for the interim results of this program.

U.S. NAVY SUBMARINE POWER SYSTEM MONITORING

GENERAL

The Submarine Monitoring Maintenance Systems Office of the U.S. Navy partially funded the failure prediction program, under agreement N002485RAAZ001 with the Bureau. The U.S. Navy is interested in the application of failure prediction techniques to existing submarine power system maintenance programs, and specifically requested—

An examination of electrically excited vibration in induction motors, the feasibility of modeling its effects, and evaluation of its utility for deterioration detection;

General specifications for an on-line monitoring system, including a definition of its capabilities; and

Delivery of data collection hardware, analysis software, and procedures documentation, for use as an off-line performance-condition monitoring system.

Electrically excited vibration and on-line monitoring system specifications were covered in the previous section. The last item listed, however, is a deliverable that involves measuring voltage and current phasors from a power system component, processing these phasors using the THREE-PHASE ANALYZER program, and manually analyzing the results to evaluate performance and possibly detect incipient deterioration. The purpose of such a monitoring system is to give Navy engineers an interim failure prediction method with which to judge the merits and feasibility of expanding their monitoring techniques.

SUBMARINE DATA ACQUISITION

Use of the THREE-PHASE ANALYZER and manual analysis of terminal feature values have been previously discussed, but off-line monitoring also requires some method of collecting information from a power system on-board a nuclear-powered submarine. Voltage and current values must be obtained in such a manner that identification, time base, and sequence relationships remain intact. In addition, original power system magnitude values must be available from reproduction signals. Bureau personnel, therefore, researched, designed, and constructed a portable data collection system to meet these criteria.

Bureau engineers visited a nuclear-powered submarine in order to attempt data collection from the power system, and assess the requirements for an on-board data acquisition system. It was determined that beyond functional requirements, any system devised must be reasonably simple and safe to operate, small and light because of physical constraints on-board a submarine, and self-contained for convenience.

Basic components for the system are a data collection-storage device, sensors and leads for connection to the power system, and an interface unit to link the sensors and leads to the recording device. The first two categories were filled by commercially available items, while the interface required custom design and construction to address the unique characteristics and environment of a submarine power system. A portable seven-channel FM instrumentation tape recorder-reproducer was selected for signal recording and storage. Clamp-on-type current

transformers are used to sense line currents, while direct connections monitor line-to-line voltages. An interface unit was designed to connect sensors and the recorder, which isolates and reduces voltage inputs, monitors correct phase rotation, shunts current transformer outputs to create voltage signals, and amplifies these line current signals as required for input to the recorder. Figure 13 illustrates the on-board data collection arrangement.

The complete system was tested by the Bureau, using a power system that simulated distributed capacitance grounding as would be the case for a submarine distribution system. Use of the system and data collection procedures were completely documented, and the system was demonstrated for Navy personnel.

SUMMARY

Results for the failure prediction program, including monitoring system specifications, failure prediction concepts-theories, and mathematical models for power system component deterioration, have been delivered to the U.S. Navy. In addition, procedures and hardware for off-line power system performance-condition monitoring have been demonstrated and delivered.

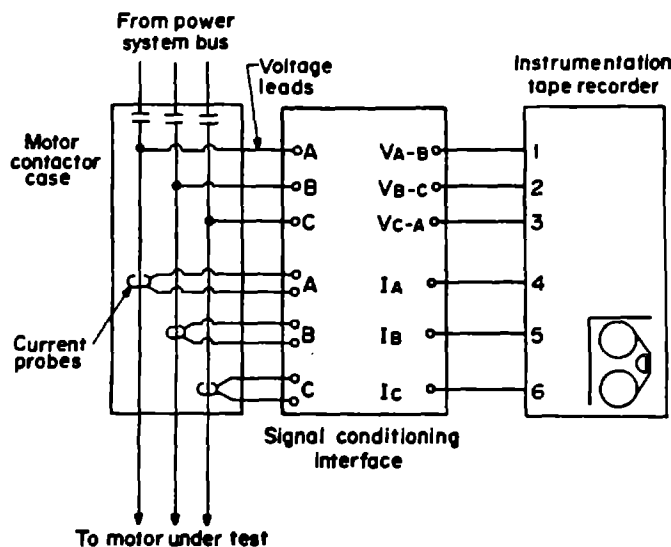


Figure 13.—Equipment connections for submarine power system data acquisition.

CONCLUSIONS

The original goal of this program was improvement of the electrical component failure prediction algorithm developed by Penn State. Research scope was expanded, however, to further study the relationships between component deterioration and electrical terminal effects. The documentation of these relationships is the most important result of this research, since it forms much of the basis necessary for automated on-line failure prediction. An example from this theoretical basis is the predictable relationship between negative sequence current level and the power consumed in a deterioration leakage path.

The analysis techniques and tools developed to study deteriorating electrical components are another significant result of this program. Mathematical models of cable-connected motor systems and deteriorating motors were developed to examine the effects of various deterioration conditions; but such models also have utility for electrical system design and maintenance and, as such, are valuable engineering tools independent of failure prediction research.

With respect to the original program goal, results indicate that the existing failure prediction algorithm does not require modification, but the techniques used for implementation must be revised to improve its performance. Monitoring sensitivity requirements should be thoroughly addressed in the application of the algorithm, in order to provide resolution adequate for low levels of deterioration. Any factor that introduces random fluctuations into measured values will adversely affect failure prediction accuracy. In addition, data acquisition techniques must provide reproducible sample points during motor operation, to ensure valid comparisons between reference and test cases. A suitable method would trigger sampling based on motor load, but not be influenced by system deterioration.

Beyond these accomplishments, research into electrically excited vibration in motor stators has confirmed the feasibility of modeling the connection between internal motor deterioration and stator vibration, and established the value of vibration as a parameter for use in detecting deterioration.

