CONDITION-BASED MAINTENANCE OF ELECTRICAL MACHINES

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***Abstract*-Twenty-five years ago, the former U.S. Bureau of Mines funded a research project aimed at developing the enabling technology for incipient failure prediction in electric power system components as a means of reducing the injuries and fatalities that sometimes occur when equipment malfunctions. Over the ensuing years, interest in this has waxed and waned, but recently interest has been growing for both civilian and military applications. This paper addresses the level of turn-to-turn insulation deterioration that can be resolved using an on-line monitoring technique. The detection of turn-to-turn defects is especially important because they are believed to represent the beginning stage of most motor winding failures.**

INTRODUCTION

The detection of incipient failures and the replacement of the components just prior to failure would eliminate the consequences of unexpected equipment failures. The capability to do this has long been desired by industry; however, it has been an illusive goal. Failure prediction of mechanical components, particularly bearings, is an old art form, with a history of 50 or more years. The desire to apply predictive techniques to electrical equipment has been slower to develop. The measuring and subsequent tracking of insulation resistance was an early form of predictive maintenance, providing reasonably good indications of deterioration of ground insulation systems. One of the first instances of a continuous on-line monitoring system to detect electrical deterioration was reported in [1]. That system and approach was also notable because it established a link between improved personnel safety and the application of on-line monitoring for incipient failures.

Interest in this technology has waxed and waned in the two decades since this work was started. As hardware and software technologies advanced, it became more practical to deploy powerful, yet inexpensive signal processing systems to implement a predictive monitoring function. Industry became more interested in developing a predictive maintenance capability to reduce the costs associated with downtime, as well as to avoid safety hazards associated with unexpected and catastrophic failures. Much has been reported in the literature (see [2] through [9]).

More recently, the military has recognized the potential of this technology to reduce costs and labor needed to maintain equipment. In recent years, the term condition -based maintenance (CBM) has been used to define the practice of effecting maintenance actions based on monitored information. One weakness shared by all CBM systems is an inability to predict the remaining useful life of a failing component with any degree of accuracy. This is an area of increasing research, however.

This paper addresses a part of the original failure prediction technique described in [1] and focuses on the ability of one predictor, the effective negative-sequence impedance predictor, defined as the negative-sequence voltage divided by the negative-sequence current, to detect meaningfully small levels of deterioration.

STUDY OBJECTIVES

Catastrophic electrical failure of motors is usually the result of a line-to-line or line-to-ground fault; afterwards, there is little evidence remaining to determine the origination and cause of the failure. While motor insulation may fail directly in a line-to-ground mode or even a phase-to-phase mode, the field and laboratory experience of manufacturers, plant operators, and researchers point to the turn-to-turn

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defect as the source of deterioration that ultimately evolves into a catastrophic failure. These turn-to-turn defects result from the cumulative damage from the dielectric stresses of overvoltages and other adverse conditions. Over some period of time, these defects can increase in size, i.e., fault energy level, until a catastrophic fault involving another phase or ground occurs. Thus, it would be advantageous to detect this early stage of deterioration to allow for a timely prediction of incipient failure.

The purpose of this study has been to investigate the performance of the effective negative-sequence impedance predictor for the low levels of turn-to-turn deterioration that may exist well before failure is imminent. A complicating factor in this analysis is the small unbalance in either voltage and/or machine structure that should exist in any real system. While the effects of this natural unbalance are known to be problematic, the current study was focused upon obtaining a better understanding of the physical behavior of the effective negative-sequence impedance predictor in the presence of low level turn faults. In order to see these relationships most clearly, no attempt was made to apply technologies that might be used to correct for the natural unbalance, such as those presented in [10].

EXPERIMENTAL APPARATUS

The experimental apparatus was developed to allow the study of electric motors under varying conditions of load and deterioration. This apparatus can be divided into two groups for the purposes of this description: the power equipment and the instrumentation.

Power Equipment

The power equipment facility was constructed to provide a platform for testing a three-phase motor under different load conditions and consisted of a three-phase transformer, the three-phase motor under test, a dc generator, a lamp bank, and protective devices, e.g., fuses and guards. A three-phase transformer was used to convert the three-phase voltage in the laboratory to the required nameplate voltage for the motor. The motor and generator were rail-mounted on a test fixture that allowed the motor to be changed easily. Belts were used to connect the motors to the generator, and sheave sizes were selected to achieve the desired generator speed for a given motor. The load on the generator, and therefore on the motor, was adjusted by switching lamps on a load bank. It was possible to vary the load on the motors up to their rated full load. Three single-phase variacs were used to unbalance the supply voltage for the studies in which a voltage unbalance was desired.

A variety of low-voltage squirrel-cage induction motors of different designs have been used in this research. Three motors were used for the work reported here: one manufactured by General Electric, one by Reliance, and one by Baldor[1]. All were 5-hp, 460-V, four-pole motors. This size was chosen because there is evidence that they would be representative of motors as large as several hundred horsepower [11]. Different brands were included to eliminate the possibility of a bias from the design of one manufacturer. This mix of brands was based on their availability at a local supply house. However, based on previous work, similar results would be expected with a different mix of motors.

Deterioration of the turn-to-turn insulation was simulated by placing taps on the wires of the stator winding and then shorting these taps. This process occurred as follows.

First, the motor was disassembled and the rotor removed to expose the stator windings. Five wires, located adjacent to each other, were chosen and the insulation at a point on each was carefully removed. A 36-in, 18-awg, stranded and insulated wire was attached to the stator by braiding the strands of the tap wire around the stator wire; it was then soldered. After all of the connections had been completed, electrical coating varnish was applied and allowed to dry. Two additional coats were applied, and an insulation resistance test was performed to verify that the resistance to ground was greater than 1 MΩ. The wires were placed back into their original form and lashed to the coil from which they were separated at the beginning of the procedure. The motor was then reassembled.

The five tap wires were fastened onto posts on an insulating board. The motor was then energized, and the open-circuit voltage between each combination of the five wires was recorded. This measured open-circuit voltage between the taps, divided by the line-to-neutral value of the measured voltage applied to the motor, is a measure of the fraction of the phase winding that is involved. The defects that could be simulated by shunting different tap wires for each motor are shown in Table 1. The placement of the taps to achieve a specified level of deterioration is nearly impossible, although over all of the combinations it was possible to realize a useful range. In retrospect, it would have been useful to simulate larger defects in all of the motors.

TABLE 1
SIMULATED DETERIORATION OF THE STATOR WINDING IN THE TEST MOTOR

Motor Brand	% of stator winding shorted by the turn-to-turn defect						
Baldor	0.23	0.46	0.68	0.91			
Reliance	0.14	0.20	0.41	0.61	0.82		
GE	0.44	0.88	1.31	1.74	2.18	2.61	3.05

Each motor was tested prior to disassembly, and the three-phase voltage and current phasors at different loads were recorded to establish the "normal" motor baseline. These

[1] Mention of any company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

tests were repeated with the modified motors with all taps open to verify that the modifications had not changed the motors' "normal" operating characteristics.

Instrumentation

An instrumentation system was developed to sample each of the three-phase voltage and current waveforms and to process and store the data. Absolute accuracy of the system is less important than precision because the value of the predictor at time t, as compared to time t-δ, is more significant than the true value of the predictor. In other words, repeatability was more important than absolute accuracy. Nonetheless, an effort was made to acquire the most accurate components that were commercially available and to identify and reduce variability in the instrumentation and overall data collection process. After the system was assembled, extensive studies were conducted to understand the nature of system variability; the results of this are summarized later in this paper.

Active potential transformers (PTs) and active current transformers (CTs) were used to sense each of the three-phase voltage and current waveforms, respectively. The stated accuracy of these sensors exceeded 0.1% in this application. An eight-channel data-acquisition card, with eight sample and hold circuits, had a stated accuracy of 2%. A personal computer with a 486/166 processor was used to run the data acquisition software, which was a custom - developed Windows-based program. This program controlled the sampling on the data acquisition card and the display and storage of the sampled data. The channels to be sampled, sampling parameters, and the number of samples to be collected could be specified, as could the filenames for data storage. After the experiment was completed, the raw data files were imported into MATLAB for analysis.

First, a discrete Fourier transform (DFT) was performed, and the 60-Hz component was extracted for each voltage or current channel. A data file (matrix) was constructed in which each row contained an identifier number and each of the three-phase voltage and current phasors. Other variables such as motor speed were also recorded and appended to the end of the row. Depending on the nature of the experiment, as many as several hundred samples may have been taken; as a result, those files would have several hundred rows. Next, the mean and standard deviation were computed for the 60-Hz phasors of the voltages and current for each experiment. For convenience, the mean values were then placed as one row of a new matrix that contained all of the experiments. This row was appended with other information, such as the experiment identifier number, motor number, and fault parameters. A similar matrix was created for the standard deviations. The mean values in one row, representing the three-phase voltage and current phasors were used to compute features such as complex power, impedance, and the symmetrical components. Additional analyses were then performed using MATLAB, MathCad, and other standard packages to investigate pattern recognition issues of the collected data. For the work presented in this paper, the most important subsequent calculation was the effective negative sequence impedance predictor. Over the course of the experimental study, dozens of experiments were conducted, with several trials of each. Typically, sample sizes of the computed phasors were 30, with some as large as several hundred. Many of the experiments were well behaved: the mean achieved with a five-point sample was similar to that obtained with a 30-point sample.

A series of tests was conducted to verify the correctness of the signal processing algorithms and to establish reasonable sampling parameters for the DFT. Once these were completed, performance tests focused on accuracy and precision questions. Initially, the only input to the data acquisition board was a signal generator into one channel. Then the same signal was fed simultaneously into all eight channels, and the results were compared for agreement. Next, the CTs and PTs were brought online, but all three were placed on one phase only. Again, results were compared for agreement. Afterward, the sensors were placed at the proper locations, and more samples were collected and studied. The results of these studies helped to define the optimum sample criteria (i.e., sample rates, number of samples, and etc.), to compute scale factors and to determine the resolution of the system.

The resolution is defined as the smallest difference between the means of two sets of measurements, which represents a statistically significant difference with a specified confidence level. In this application, one set of measurements with its corresponding mean would represent the "normal" or undeteriorated state for the motor and would be considered the reference value. The other set of measurements with its mean would be taken periodically and the mean compared to the reference value to determine if deterioration were underway. Of course, whether or not deterioration is underway depends on whether the difference between the two means is statistically significant. This was addressed by computing precision.

A statistical definition for the precision was obtained from the foregoing test data as follows. The computed mean for 100 samples was taken as the population (true mean). The precision of the system (S) was computed as the sample standard deviation, s_d, divided by the mean, μ [12]. These values are shown in Table 2 for each of the current (1-3) and voltage (4-6) channels. The precision is an indicator of the maximum achievable system resolution—albeit dependent on the number of sample points. If two sets of data, of $n/2$ measurements each, are taken and their means computed, then it can be shown that the smallest difference between the means that can be resolved is approximately

$4 * s_d/\mu/\sqrt{(n-2)}$ with a 95% confidence [13]. Using channel 1 as the example, with n=100, and s_d/μ =0.668, the resolution will be 0.27% with a confidence of 95%. In other words, if the mean value of the latest set of observations is at least 0.27% different than the reference mean, then the change is statistically significant with a confidence of 95%.

The first three channels were connected to CTs and the last three to PTs, which are inherently less noisy.

TABLE 2
RELATIVE ACCURACY, IN PERCENT, FOR A 95% CONFIDENCE INTERVAL

Channel					
1	2	3	4	5	6
0.668	0.670	0.668	0.030	0.031	0.030

EXPERIMENT METHODOLOGY AND FINDINGS

The first series of tests was designed to determine the relationship between small turn-to-turn defects and the effective negative-sequence impedance predictor. The same procedure was followed for each of the motors. First, the instrumentation was energized and allowed to stabilize over a 30-min period. While this was in process, the power equipment was energized, and the load on the motor was adjusted to the desired value for the test. The actual motor loading is not that significant, but it is important that sampling is done at the same motor load (speed) over time; otherwise, unnecessary error is introduced into the process. Finally, the sampling parameters were set in the software, and once initiated, a population of 30 samples was collected automatically over a time period of approximately 40 s. Once this test was completed, the next was begun.

Two taps were be shunted to create the desired deterioration level, and then another population of 30 samples were collected. This was repeated until all of the desired deterioration levels had been simulated. The final test was a repeat of the first one, with no taps shunted. The first and last tests were always compared to ensure that the previous tests had not damaged the motor or in any other way changed its characteristics. The first and last tests were always similar. Typically, it took less than 1 hr to run a complete set of tests. The complete set was repeated for a given motor several more times, that same day, weeks, and months later. The results were always nearly identical. This process was repeated for each motor, and the data were analyzed as described.

Fig. 1 illustrates a typical result. Samples were taken for the normal case, and seven levels of deterioration. The linear regression line and the R^2 value of 0.76 present a reasonably optimistic picture of the predictor's ability to detect small defects. Nonetheless, the first set of values representing the lowest level of deterioration is problematic because it causes a change in direction of the curve. This same behavior was observed at low levels of deterioration in many, but not all, of the tests. If this sample could be removed, for a justifiable cause, then the predictive curve is better and the R^2 value increases to 0.95, as shown in Fig. 2.

As shown, at the very lowest levels, the addition of a turn defect may actually improve the motor's apparent condition. However, as the deterioration increases, a steady trend becomes clear. The correlation coefficients for the three motors before and after the lowest level were eliminated from the data are shown in Table 3. The correlation is obviously stronger when those samples from the very small defects are eliminated. This would seem to present a problem for an actual application in which this information would not be known a priori. However, practically this is of no consequence because the most severe level of deterioration that was created did not damage the motor; therefore, a practical monitoring system would only need to wait until a clear trend developed, with little risk that a failure would occur before this happened.

TABLE 3
CORRELATION FACTORS BEFORE AND AFTER THE LOWEST LEVEL OF DETERIORATION IS REMOVED FROM THE DATA SET

	Motor Brand		
Condition	GE	Baldor	Reliance
Before	-0.84	-0.33	-0.81
After	-0.93	-0.76	-0.90

This anomalous behavior of the effective negative-sequence impedance predictor at very low levels of deterioration is a limitation in its application that needed to be investigated. One explanation for this behavior is presented in the next section.

THEORETICAL ANALYSIS

It is known that minor construction imperfections exist in most new motors, and most power systems have some low level of voltage unbalance. These imperfections generally do not affect the performance or life of the motor, although they will create slight current unbalances that produce a measurable negative-sequence current. As a turn insulation defect begins to develop, it can sometimes "cancel" the effect of the construction, or voltage, imperfections and make the motor currents more balanced than before the onset of deterioration. As the level of deterioration becomes more severe, however, the predictor should then continue on a predictable path. In order to demonstrate this observed phenomenon, a computer model of a deteriorating motor was used to validate this behavior.

The deteriorating motor model predicts motor currents as a function of user-defined applied voltages, motor speed, and type and location of stator winding deterioration. A description of this model is beyond the scope of this paper;

the reader is directed to [14] through [16] for a detailed description. Fig. 3 illustrates the network diagram of the armature of the induction motor being modeled. For this study, the motor is a 15-hp, six-pole induction machine for which suitable design information was available for configuring the deteriorating motor model. The deterioration being modeled was a leakage path across eight turns in one coil of an 18-coil-per-phase stator. Deterioration severity was controlled by defining the resistance of the leakage path. The magnitude of the positive sequence voltage was 440V and the magnitude of the negative sequence voltage was 1.70V. Output of the deteriorating motor model most relevant to this investigation are the six element currents shown in Fig. 3.

Fig. 4 illustrates a typical example of the type of behavior that was predicted by the motor model, and therefore, could be expected in an application for situations in which the negative-sequence current caused by an unbalanced supply and the negative-sequence current caused by the deterioration tend to cancel at low levels of deterioration. Note that the ordinate in Fig. 4 corresponds to decreasing resistance in the leakage path. The figure shows very similar behavior to that observed in the experimental effort.

CONCLUSIONS

The accuracy levels achieved in the system were unremarkable, at nearly 1.5% with a 95% confidence interval. The levels of deterioration simulated by shorting turns of the stator winding were very small. In two of the motors the worst defect resulted in less than 1% of the stator winding being shorted; in the third motor, the worst defect shorted 3% of the stator winding. Yet under the worst condition created, there was no detectable change in the sound or performance of the motors, and they were able to run for extended periods without harm. Under these conditions, the predictor was a reliable indicator of the presence of a turn-to-turn short in the stator winding. Moreover, as the severity of the defect increased, the standard deviation of the sample population decreased. Although a predictive curve was not computed, it is suggested that the correlation between the predictor and the defect severity will increase for more defects. Finally, the results of this study demonstrate the efficacy of the predictor to identify and track turn-to-turn insulation deterioration in stator windings well before such deterioration leads to a catastrophic failure. The application of procedures to correct for natural unbalance in a practical condition monitoring system should further serve to enhance the utility of this predictor.

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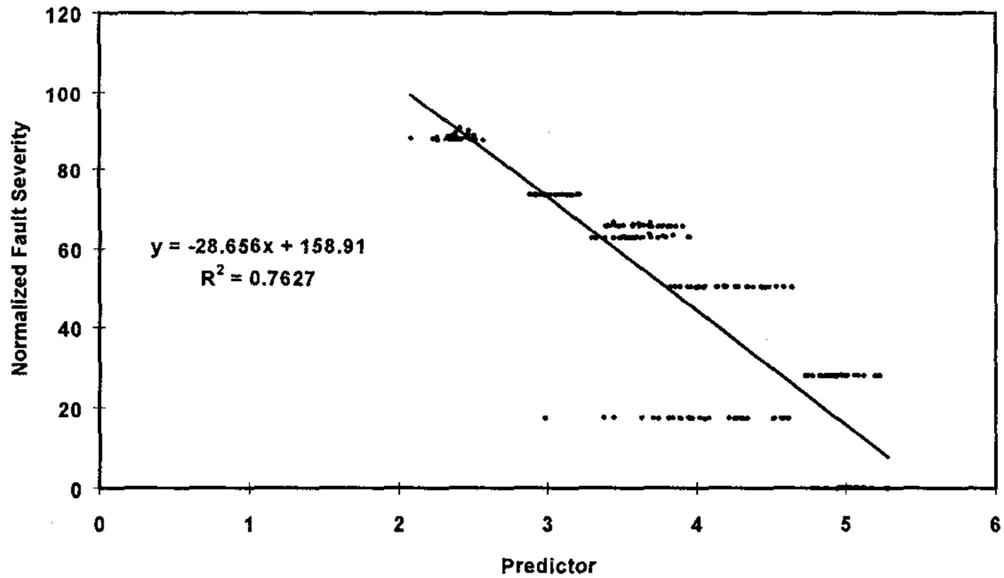

Fig. 1. Behavior of the predictor as a function of the severity of the winding defect, with all levels of deterioration included.

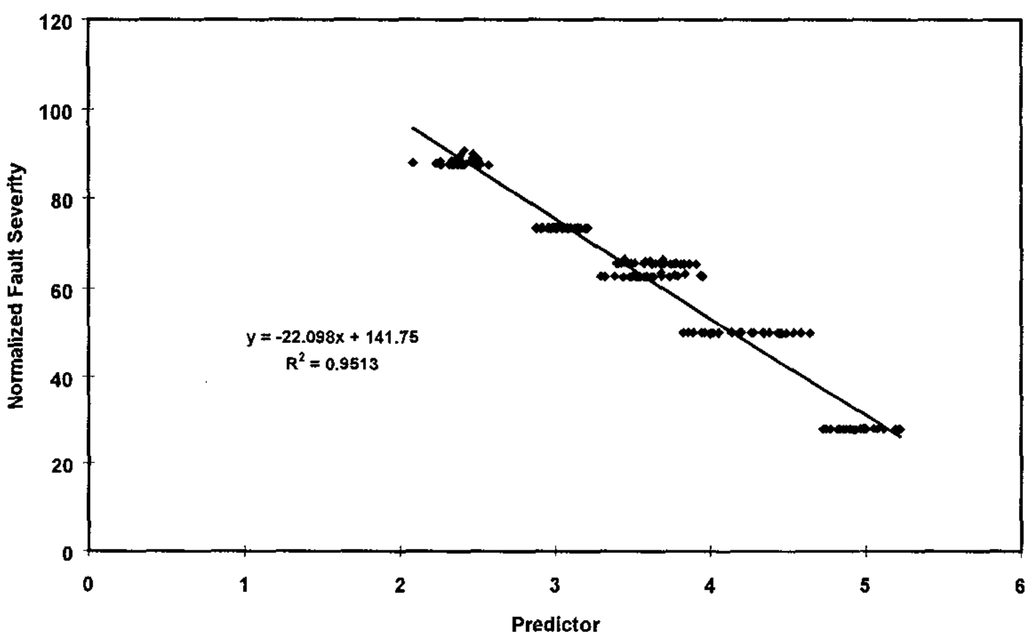

Fig. 2. Behavior of the predictor as a function of the severity of the winding defect, with the lowest level of deterioration excluded.

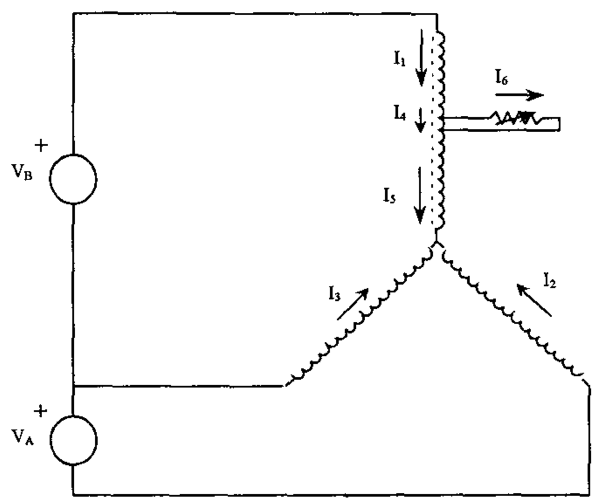

Fig. 3. Network diagram of the deteriorating motor model stator.

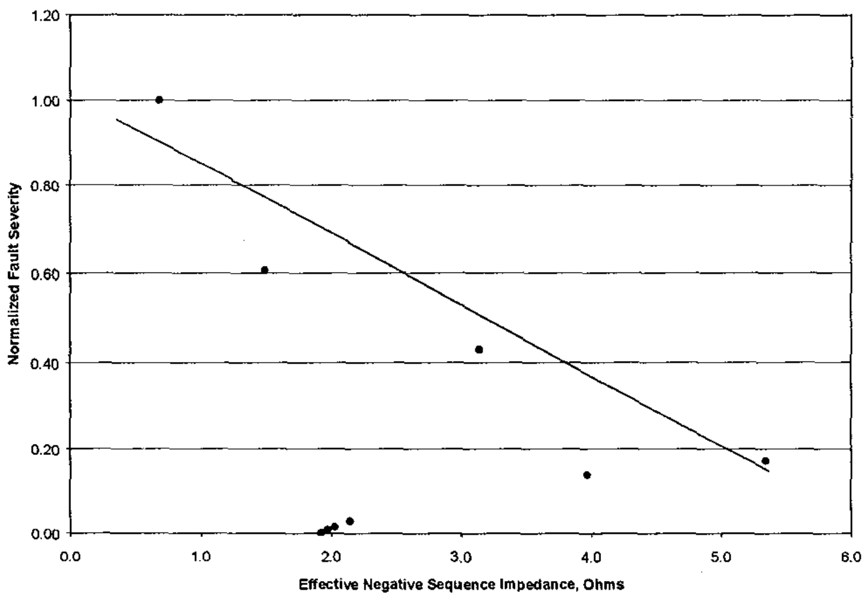

Figure 4. Effective negative-sequence impedance versus fault severity.