On-Line Condition Monitoring of Induction Motors

F. C. Trutt
University of Kentucky
Lexington, KY 40506 USA

J. Sottile
University of Kentucky
Lexington, KY 40506 USA

J. L. Kohler
National Institute for Occupational Safety and Health
Pittsburgh, PA 15236 USA

Abstract - Condition monitoring of induction motors is a process that may be used to great advantage in mining and other industrial applications. The early detection of motor winding deterioration prior to a complete failure provides an opportunity for maintenance to be performed on a scheduled routine without the loss of production time. Presented in this paper is a theoretical and experimental analysis of a voltage mismatch technique that may be used in operating situations to monitor the health of induction motor windings. It extends previous work in this area by demonstrating the robust nature of the monitoring process not only under conditions of power supply unbalance but also in situations where motor construction imperfections exist and mechanical loads are unpredictable. A suggested procedure for application of this condition monitoring process in industrial situations is also included.

I. INTRODUCTION

The detection of low-level electrical winding faults in induction machines is a technology that has been limited by the natural unbalances that are normally present in an operating power system. These unbalances are related not only to construction imperfections within the rotating machine itself but also to the non-ideal nature of the supply system. To make matters even worse, continuous changes in the power system, such as the introduction and removal of single-phase loads, may also cause voltage fluctuations and imbalance resulting in significant problems for a monitoring system intended to detect low levels of deterioration. If small faults cannot be detected at an early stage before the situation progresses to catastrophic failure, little has been gained in an attempt to avoid expensive repairs and lost production time.

A number of investigators have considered approaches that may be used to detect winding deterioration in induction motors [1] – [5]. Included in this research have been methods utilizing predictors designed to address the problem of natural system unbalances such as the residual negative sequence current reported in [6], the effective negative sequence impedance described in [7] and a voltage mismatch procedure introduced in [8]. These methods are based upon some simplifying assumptions and each may be shown to work in many situations. The purpose of this paper is to expand on the concepts introduced in [8], to demonstrate the robust nature of this approach in the presence of inherent machine, power supply and sensor system unbalances, and to provide a suggested approach to the application of this process in mining and other industrial situations.

In the text of the paper, a theoretical justification for the use of the suggested predictors is presented. Initial verification of the approach is accomplished with laboratory experiments conducted on a universal laboratory machine operating as an induction motor. Results of these experimental observations are then compared with a corresponding theoretical investigation using a general induction motor model similar to that developed in [9]. The general motor model is then utilized to supplement the experimental verification process and a proposed step-by-step procedure for application of the process in a mining environment is provided.

II. THEORETICAL APPROACH

A schematic representation of the universal laboratory machine operating as a wye-connected induction motor is shown in Fig. 1. Line voltages V_A and V_B are applied to this motor resulting in the line currents I_a , I_b and I_c . Each phase of the motor consists of four coils that are connected in series with terminals that are accessible on the machine panel. As a result, construction imperfections in the motor may be simulated by connecting a resistance R_c as shown in phase b and low level faults may be simulated by connecting a resistance R_f as shown in phase a. Varying degrees of voltage unbalance may also be introduced into the motor phase voltages V_a , V_b and V_c . The machine shaft is connected to a d-c generator that provides a means to vary the mechanical loading of the motor. While the situation depicted in Fig. 1 is somewhat specific to the laboratory machine, it should be evident that this diagram applies in the more general case to any induction motor.

Referring to a typical text on symmetrical components [10], let V_{a1} and V_{a2} represent the positive and negative

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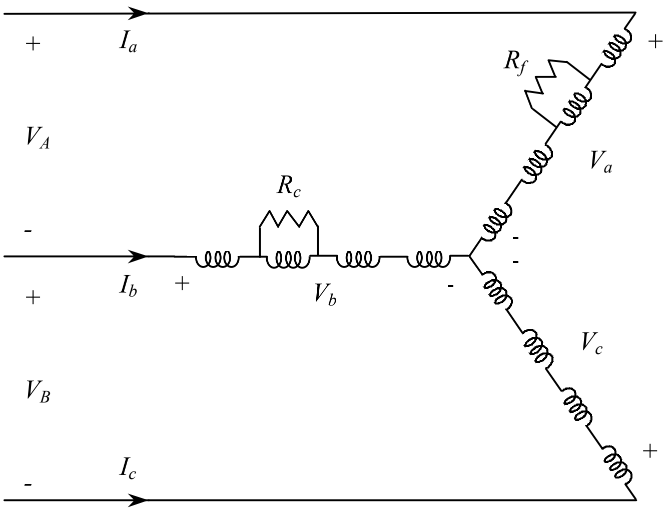

Fig. 1. Schematic diagram of the universal laboratory machine.

sequence symmetrical components of the motor phase voltages and let I_{a0}, I_{a1}, and I_{a2} represent the symmetrical components of the line currents. V_{a1} and V_{a2} may be derived directly from the motor phase voltages or they may be derived from the line voltages. In any case, potential transformers or voltage dividers may be used to obtain voltage measurements that may be used to calculate V_{a1} and V_{a2}. In a similar manner, current transformers may be used to measure the line currents in order to derive I_{a0}, I_{a1}, and I_{a2}. Since the junction point of a wye-connected induction motor is normally not grounded (or the motor is delta connected and is being represented by its equivalent wye), $I_{a0} = 0$ and the relationship between the symmetrical components becomes

$$V_{a1} = z_{11} I_{a1} + z_{12} I_{a2} \tag{1}$$

$$V_{a2} = z_{21} I_{a1} + z_{22} I_{a2} \tag{2}$$

where the z_{xy} parameters are functions of the motor design, construction, any internal deterioration, imperfections in the measurement system, and the motor's operating speed. Saturation has been neglected such that these parameters are assumed to be independent of the motor currents. It has been further assumed that there are no ground faults in the system. Such faults or deterioration involving ground may be observed by standard techniques that monitor the zero-sequence component of the line currents. Such ground faults are relatively easy to detect and hopefully correct. For the remainder of this paper, we will therefore assume that $I_{a0} = 0$ (no significant ground leakage exists) and concentrate on the more difficult problem of detecting deterioration that does not involve ground such as coil-to-coil faults within one motor phase or phase-to-phase deterioration.

Referring to (1) and (2), it is possible to determine z_{11}, z_{12}, z_{21} and z_{22} from two independent sets of voltage and current measurements conducted at the same motor speed. In this way, a library of z_{xy} parameters may be constructed for the range of motor operating speeds. Should the motor and sensor system be perfectly balanced (no motor construction imperfections and perfect instrumentation), then $z_{12} = z_{21} = 0$.

After a library of z_{xy} parameters as a function of motor speed has been constructed, motor condition may be monitored by continuously measuring the line voltages and the line currents from which the actual values of V_{a1}, V_{a2}, I_{a1}, and I_{a2} may be determined. Equations (1) and (2) may then be used to calculate the expected values of V_{a1} and V_{a2} at the measured motor operating speed. If no internal deterioration has occurred, the calculated values should match the measured values. If internal deterioration such as a coil interturn fault or phase-to-phase leakage has developed, the z_{xy} parameters will have changed from their library values at that speed (note that the library values for the normal motor are still being used in this calculation as the modified values for the deteriorated motor are unknown) and there should therefore be a mismatch between the measured positive and negative sequence voltages and the corresponding calculated values. These mismatches may then be used as a measure of internal motor deterioration. They are calculated as

$$V_{1m} = V_{a1} - (z_{11} I_{a1} + z_{12} I_{a2}) \tag{3}$$

$$V_{2m} = V_{a2} - (z_{21} I_{a1} + z_{22} I_{a2}) \tag{4}$$

where V_{a1} , V_{a2} , I_{a1} and I_{a2} are derived from a measurement at any given time and the z_{xy} are parameters that have been previously determined for the normal motor/sensor system.

An important advantage of this approach is that the voltage mismatch predictors should be independent of initial construction imperfections and unbalances within the motor itself as well as any changes or unbalance that may develop in the motor power supply system. In addition, the performance of the predictors should not be affected by mismatched sensors. Therefore, no careful sensor calibration is necessary.

III. RESULTS

Experimental portions of this investigation were carried out on a 208-V 2.0-kVA two-pole universal laboratory machine connected as an induction motor. Voltage signals were acquired by connecting high resistance voltage dividers between the motor terminals and ground. Current signals were obtained using current transformers connected to resistors for conversion of the current transformer output to a voltage signal. No special efforts were made to balance the sensor output signals. The analog signals from the voltage dividers and the current transformers were digitized with a 16-bit analog to digital converter that collected 1024 points/channel at a sample rate of 5,128 samples/s. The digitized signals were then transferred into a laptop computer for analysis. The motor was loaded with a d-c generator connected to a bank of resistors. An external rheostat connected to the generator field winding was utilized to adjust the loading on the motor such that the speed was 3303 rpm for all experiments.

The first step in the experimental procedure was to run tests on the motor/sensor system that were sufficient to determine the z_{xy} parameters defined in (1) and (2) at 3303 rpm. Two methods were utilized. First a three-phase autotransformer, modified to allow each phase voltage to be controlled separately, was used to create the two levels of unbalanced applied voltage needed to determine these parameters. The second approach was to insert a small value of resistance in one phase of the motor in order to obtain the required voltage unbalance at the motor terminals. Both approaches were found to give satisfactory results and the z_{xy} parameters were determined for two situations, one for the motor/sensor system with no intentionally introduced construction unbalance and the other with a simulated construction unbalance of $R_c = 21.5\ \Omega$ as shown in Fig. 1.

The theoretical portion of this work involved adapting a motor model similar to that given in [9] to the analysis of the universal laboratory machine operating as an induction motor. For this investigation, design and dimensional data of the laboratory machine were used to create a working analytical model of the motor without consideration of the sensor system. A comparison of calculated and experimental parameters for a typical observation is given in Table 1 for a case involving both simulated construction unbalance (21.5 Ω) and simulated deterioration (5.29 Ω).

Table 1. Comparison of calculated and experimental parameters (rms values) at 3303 rpm. Universal laboratory machine with simulated deterioration and construction unbalance.

Quantity	Calculated	Experimental
V_{line}	204.6V	202.1V
I_a	6.36A	6.48A
I_b	5.93A	5.87A
I_c	5.83A	5.67A
I_{a1}	6.03A	6.01A
I_{a2}	0.34A	0.33A
I_{const}	1.45A	1.42A
I_f	5.17A	5.2A

Table 2 shows a comparison of theoretical and experimental calculations of the z_{xy} parameters for the universal laboratory machine with simulated construction unbalance only. The larger values of z_{12} and z_{21} in the experimental column are attributable not only to inherent motor unbalance in the universal laboratory machine that is not present in the theoretical analysis but also to sensor unbalance. To illustrate this latter point, the current to voltage conversion ratios for the three current transformers used to measure the line currents were determined to be 1.13V/A, 1.06V/A and 1.02V/A for phases a, b and c respectively. Once again, this unbalance should not influence voltage mismatch determinations as long as no changes are introduced into the measurement system.

Table 2. Calculated and experimental impedance parameters at 3303 rpm for the universal laboratory machine with simulated construction unbalance.

Quantity	Calculated	Experimental
z_{11}	$21.14/\underline{18.37}^\circ\Omega$	$20.9/\underline{18.21}^\circ\Omega$
z_{12}	$0.0784/\underline{139}^\circ\Omega$	$0.4563/\underline{149.8}^\circ\Omega$
z_{21}	$0.0654/\underline{-10.2}^\circ\Omega$	$0.1207/\underline{-22.74}^\circ\Omega$
z_{22}	$3.203/\underline{48.58}^\circ\Omega$	$3.215/\underline{53.05}^\circ\Omega$

An example of the experimental and predicted behavior of the positive and negative sequence voltage mismatch predictors in the presence of an unbalanced supply voltage is given in Fig. 2. Here the power supply voltage unbalance was maintained at 5.2% (the ratio of the negative sequence applied voltage to the corresponding positive sequence value x 100) and deterioration was simulated by introducing a resistance R_f (see Fig. 1) in phase a. No intentional construction unbalance was simulated (R_c open). The deterioration current was varied between 0 and 15% of the simulated short circuit deterioration current which is 48A when $R_f = 0\ \Omega$. The mismatches that are plotted in this figure are the magnitudes of V_{1m} and V_{2m} as determined using (3) and (4). In constructing these graphs, the maximum values of the sinusoidal voltages and currents are used in their phasor representations.

From Fig. 2, it is seen that both the positive and negative sequence voltage mismatch predictors increase significantly with the level of the deterioration current and that there is good agreement between the experimental and theoretical results. Note that the natural variability of the experimental predictors for the condition of zero deterioration is quickly overcome at very low levels of deterioration current. It should also be evident that the increase in the magnitude of the positive sequence voltage mismatch with increasing levels of deterioration current is greater than that of the corresponding negative sequence voltage mismatch. (This latter quantity has been multiplied by 10 as a convenience in drawing the graph.) However, if these mismatch increases are considered as a percentage of the applied positive or negative sequence voltage values, the negative sequence indicator shows a significantly greater percentage increase.

The magnitudes of the experimental and calculated negative sequence currents (again multiplied by 10 as a convenience in drawing the graph) have also been included in Fig. 2 in order

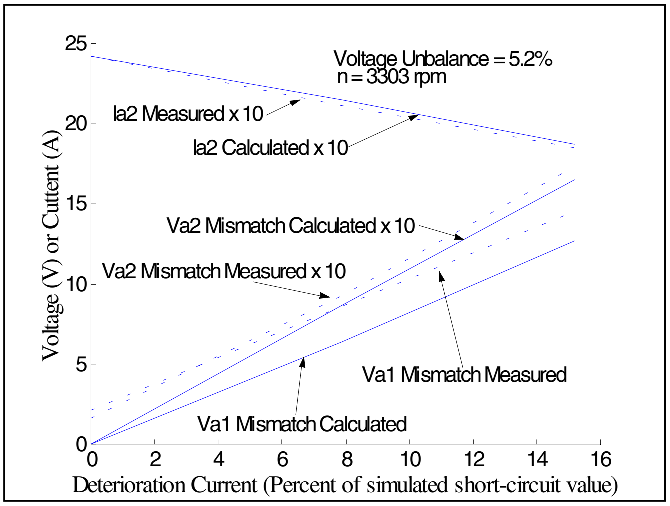

Fig. 2. Experimental and theoretical voltage mismatches with a large supply voltage unbalance.

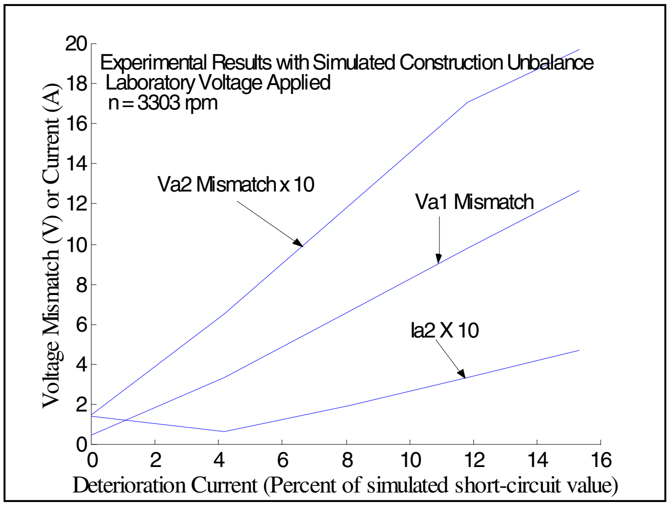

Fig. 3. Experimental results with simulated construction unbalance.

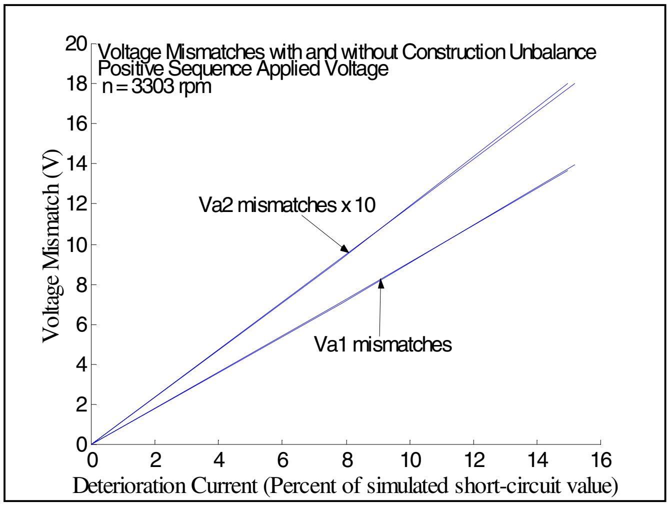

Fig. 4. Calculated voltage mismatches with and without simulated construction unbalance.

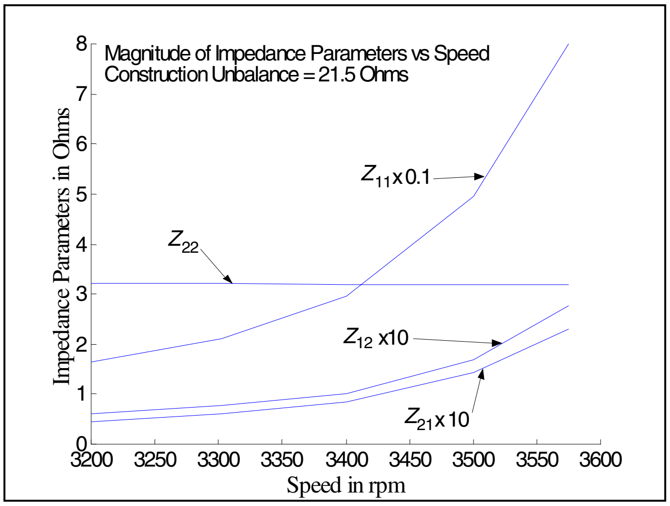

Fig. 5. Magnitudes of impedance parameters.

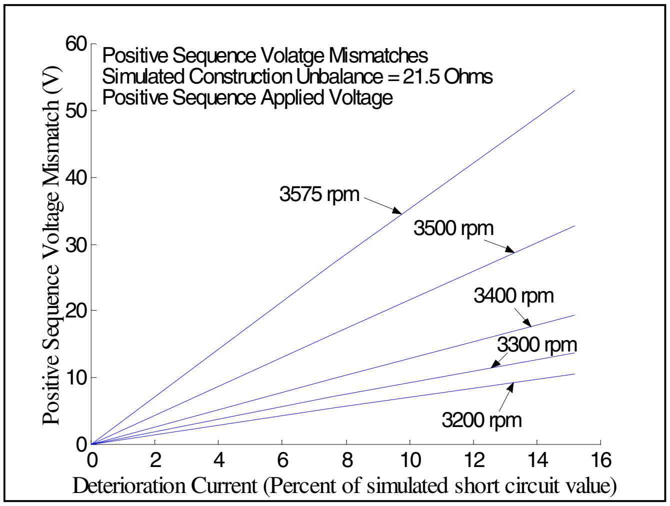

Fig. 6. Positive sequence voltage mismatches.

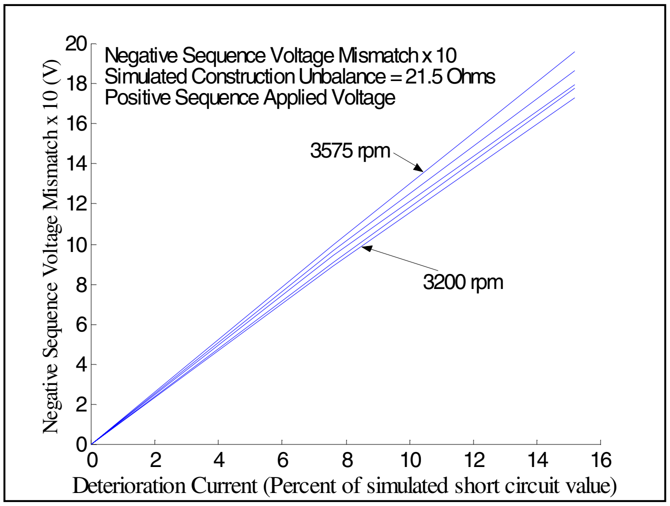

Fig. 7. Negative sequence voltage mismatches.

to illustrate the difficulty associated with the use of this simple deterioration indicator as is sometimes suggested. In this case, the deterioration is acting to decrease the negative sequence current that is due to the power supply unbalance and the use of this simple measure of deterioration would produce erroneous results. This emphasizes the need to use more sophisticated approaches such as presented in this discussion of the voltage mismatch predictors and in [6] for the negative sequence current indicator.

Experimental results in the presence of construction unbalance are illustrated in Fig. 3. In this case, construction unbalance is simulated with a resistance $R_c = 21.5\ \Omega$ and the deterioration is simulated as was done in creating Fig. 2. However, the z_{xy} parameters associated with this simulated construction unbalance (see Table 2) are used in (3) and (4). No intentional power supply unbalance was introduced but there was a natural unbalance in the laboratory supply of approximately 0.3%. An examination of Fig. 3 shows that the positive and negative sequence voltage mismatch predictors are clear indicators of the deterioration and they behave in a similar manner to that illustrated in Fig. 2. The measured negative sequence current to the motor is also included in Fig. 3. The initial decrease in this indicator is similar to that reported in [7] and is attributed to the fault initially acting to reduce the unbalance due to the simulated construction imperfection.

Fig. 4 shows the theoretical behavior of the positive and negative sequence voltage mismatch predictors under simulated conditions of construction unbalance and deterioration identical to those of Fig. 3 except that the small laboratory power supply unbalance of 0.3% was not included. Comparison of Figs. 3 and 4 once again shows good agreement between the experimental results and theoretical predictions. An addition to Fig. 4 is the theoretical behavior of the positive and negative sequence voltage mismatch predictors without the simulated construction unbalance. The behavior of the voltage mismatch predictors with and without the simulated construction unbalance is essentially identical.

The results presented in Fig. 2 – Fig. 4 show the robust nature of the proposed positive and negative sequence voltage mismatch deterioration predictors in the presence of power supply and/or motor construction unbalance. Good agreement between experimental results and theoretical predictions has also been demonstrated. Based upon these observations, the theoretical investigation was continued in order to investigate the effects of motor speed on the z_{xy} parameters and the voltage mismatch predictors.

Figs. 5 – 7 show the results of this investigation with a simulated construction unbalance of 21.5 Ω. Fig. 5 is a plot of the magnitudes of the impedance parameters as a function of speed from 3200 rpm to 3575 rpm for this 2-pole machine. As can be seen, there is little change in z_{22} as the motor speed increases while there is a definite increase in the off-diagonal terms z_{12} and z_{21}. The increase in z_{11} is even more significant. Note that the values of the off-diagonal terms are multiplied by 10 as a convenience in drawing these graphs while z_{11} has been divided by 10. Inspection of Fig. 5 clearly shows the need to categorize the impedance parameters as a function of speed.

Fig. 6 depicts the behavior of the positive sequence voltage mismatch predictor at speeds from 3200 rpm to 3575 rpm with the simulated deterioration ranging from zero to approximately 15% of the simulated short circuit value of 48 A. Fig. 7 shows similar results for the negative sequence voltage mismatch predictor. Comparison of Figs. 6 and 7 with Fig. 4 shows that there is a significant increase in the sensitivity of the positive sequence voltage mismatch predictor as the motor becomes more lightly loaded and its speed increases. The corresponding increase in the sensitivity of the negative sequence voltage mismatch predictor is much smaller and should not be a major factor.

IV. INDUSTRY APPLICATION

Application of this on-line monitoring procedure in a mining or other industrial situation would require an initial training period with the normal motor in order to build a library of z_{xy} parameters as a function of motor speed. Prior to the training period, the motor system could be instrumented with three current transformers to continuously measure the line currents, two potential transformers for measuring the line voltages, and a speed-sensing device that would provide an electrical signal proportional to the motor shaft speed. The signal outputs from these devices could then be passed through a six-channel analog to digital converter capable of sampling each channel at a rate of about 5000 samples/s. The digital output of the converter could be fed into a laptop or other computing system that would be programmed to initiate a sampling sequence every few seconds. Depending upon the dynamic nature of the system loading, the sampling interval could be adjusted to perhaps 0.2 to 0.5 s.

Software within the computer could then be used to check for a reasonably constant speed range during the sample time in order to validate the sample. Assuming that the speed variation over the sample time is within an acceptable limit, symmetrical components of the phase voltages and line currents would be computed and the values of V_{a1} and V_{a2} would be compared with previous samples gathered at that speed. For those samples showing the largest differences, the inversion matrix for computing the z_{xy} parameters should be well conditioned and a new calculation of these parameters at the measured speed may be added to the library for each previous sample that was selected. This process could then be continued over a number of complete loading cycles. At the end of this training period, the z_{xy} parameters for each speed could be averaged and the library of these parameters as a function of motor speed would be available.

In the preceding discussion, it has been assumed that there will be enough natural variability in a typical mining power supply system to obtain the required differences in the positive and negative sequence voltages at the motor terminals. If this is not the case, a small resistance rated to carry the line current could be inserted in series with one phase of the motor after a database without the resistance has been established. The training period could then be continued through the normal loading cycles in order to generate the required library. In situations where the supply voltage is very well balanced, it may be necessary to repeat this process with the resistance inserted in another phase.

Once the library of z_{xy} parameters has been established for the unfaulted motor, the system may then be converted to the monitoring mode. All instrumentation used during the training period should remain exactly in place. The only change would be to switch programs in the digital computer from z_{xy} determination to calculation of the voltage mismatches. The establishment of deterioration warning thresholds would also be required.

During the course of both the training and monitoring phases of this application, the output of the three current transformers should be checked on a regular basis for the presence of zero-sequence line currents. If the phasor sum of these currents is not equal to zero within an acceptable tolerance level at any time, the motor system should be checked for ground faults or excessive ground current leakage. This situation should then be corrected before the training or monitoring is continued.

V. CONCLUSION

Results of the experimental and theoretical analyses presented in this paper using linear models have clearly supported the proposed approach to the detection of stator winding deterioration in induction motors. Both the positive and negative sequence voltage mismatch predictors have been shown to be sensitive to the interturn stator winding deterioration that was simulated and their performance is not degraded by voltage supply unbalances or inherent machine or sensor asymmetry. Changes in these predictors also appear to be a measure of the level of deterioration severity. In addition, no special sensors or sensor calibration procedures are required to obtain these results. The negative-sequence voltage mismatch predictor appears to be more sensitive (on a percentage basis) to increasing deterioration severity at the lower motor speeds that correspond to heavy loading. However, the absolute changes in the positive-sequence voltage mismatch predictor are larger, particularly at high motor speeds consistent with light loading. Both voltage mismatch parameters are seen to predict deterioration independent of whether this deterioration acts to create more balance or to create more unbalance in the motor. This is an important attribute for predictors that will be used to monitor low levels of deterioration [7].

Future research should include more extensive experimental testing on a variety of induction motor systems in order to provide additional verification of the proposed monitoring scheme as well as to provide a better understanding of the physical behavior of each mismatch predictor in the presence of machine non-linearities. In addition, correlations between the predictors, type of deterioration, and severity should be developed as appropriate. Finally, the application of this approach to the on-line monitoring of machine windings in an industrial situation is needed in order to demonstrate the true applicability of this process.

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