

# Condition Monitoring of Stator Windings in Induction Motors: Part II—Experimental Investigation of Voltage Mismatch Detectors

Joseph Sottile, *Senior Member, IEEE*, Frederick C. Trutt, *Fellow, IEEE*, and Jeffery L. Kohler, *Senior Member, IEEE*

**Abstract**—Condition-based maintenance (CBM) of industrial equipment is generally recognized as being the most cost-effective means for improving equipment availability. However, prerequisite to successful implementation of CBM is a reliable detector of failing components. One such detector, termed the effective negative-sequence impedance, had previously been identified as an indicator of induction motor stator winding degradation. However, a limitation of this detector is that it may not change in a predictable manner for extremely low levels of deterioration. Presented in this paper is an experimental investigation of a technique for on-line detection of induction motor stator winding degradation that addresses this difficulty. It begins with a brief description of the detectors, followed by a detailed description of the experimental setup, the experiments conducted, and results.

**Index Terms**—Conditioning monitoring, induction motors, stator winding fault.

## I. INTRODUCTION

CONDITION-BASED maintenance of induction motors is accepted as being the most effective method for scheduling motor repairs and replacements provided that deteriorating components can be detected in a timely manner. Reasonably reliable techniques now exist for detecting bearing deterioration and, more recently, cracked and broken rotor bars and improvements continue to be made in both of these areas. One component that is more problematic to monitor and detect incipient failure is the stator winding. Early stages of deterioration are difficult to detect and certain types of stator faults can progress rapidly, causing motor failure with very little warning. In spite of these difficulties, a great deal of progress is being made in incipient stator-winding fault detection. The approaches generally involve monitoring and analysis of voltage, current, and magnetic flux [1]–[11] and electrically excited vibrations [12].

A technique that has long been applied to various types of failure detection is negative-sequence current monitoring. The

approach is easy to apply; all that is required is measurement of the three line currents. Unfortunately, supply voltages and the motor itself are frequently unbalanced and induction motors exhibit a low impedance to negative-sequence current. Therefore, most power systems will always have a measurable negative-sequence current ( $I_{a2}$ ) present ranging from a fraction of a percent to several percent. In addition, the level of  $I_{a2}$  will change as the supply unbalance changes due to switching of single-phase loads or for other reasons unrelated to incipient failure. This condition, coupled with the fact that motor deterioration may initially produce very small changes in  $I_{a2}$ , makes the simple measurement of the negative-sequence current alone an unreliable indicator of extremely low levels of deterioration. This limitation has been recognized, however, and techniques have been developed that overcome the shortcomings of simple negative-sequence current monitoring for incipient stator-winding fault detection [7]. As would be expected with a more advanced procedure, the technique requires additional information and a brief training period prior to implementation.

Another concept that was developed in an attempt to satisfy the implementation issues mentioned above is the detection of the loss of motor construction symmetry due to deterioration [1], [2]. The rationale for this approach can be understood by examining the sequence voltage and current relationships for a general symmetrical, nonstatic network

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} z_0 & 0 & 0 \\ 0 & z_1 & 0 \\ 0 & 0 & z_2 \end{bmatrix} \times \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} \quad (1)$$

where

- $z_0$  zero-sequence impedance;
- $z_1$  positive-sequence impedance;
- $z_2$  negative-sequence impedance.

The concept of detecting loss of motor symmetry was implemented by considering (1) and recognizing that the ratio of  $V_{a2}$  to  $I_{a2}$  is nearly constant for a symmetrical induction motor. Based on this relationship, the detector was defined,

$$Z_{a2\text{eff}} = \frac{V_{a2}}{I_{a2}} \quad (2)$$

and was termed the effective negative-sequence impedance. This detector has several advantages in a monitoring application. First, the method is very easy to implement which is a very important requirement for the mining industry. The only motor parameter that needs to be determined is  $Z_{a2\text{eff}}$ .

Paper PID 02–34, presented at the 2000 Industry Applications Society Annual Meeting, Rome, Italy, October 8–12, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Mining Industry Committee of the IEEE Industry Applications Society. Manuscript submitted for review October 15, 2000 and released for publication July 15, 2002.

J. Sottile is with the Department of Mining Engineering, University of Kentucky, Lexington, KY 40506-0107 USA (e-mail: jsottile@engr.uky.edu).

F. C. Trutt is with the Department of Electrical Engineering, University of Kentucky, Lexington, KY 40506-0046 USA (e-mail: ftrutt@engr.uky.edu).

J. L. Kohler is with the Pittsburgh Research Laboratory, National Institute for Occupational Safety and Health, Pittsburgh, PA 15236 USA (e-mail: jtk4@cdc.gov).

Publisher Item Identifier 10.1109/TIA.2002.802921.

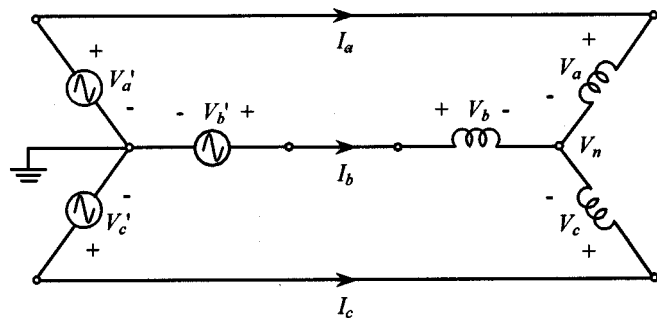


Fig. 1. Wye-connected power source and induction motor.

Second, for a balanced and unfaulted motor, changes in the voltage unbalance will not produce changes in the effective negative-sequence impedance as they would in the negative sequence current. Third, for a symmetrical induction motor, the effective negative-sequence impedance is not very dependent on operating speed [13]; therefore,  $Z_{a2\text{eff}}$  needs to be determined at only a few different motor speeds and motor speed need not be accurately measured in an application. Finally,  $Z_{a2\text{eff}}$  was shown to be sensitive to early stages of stator winding deterioration.

However, the effective negative-sequence impedance has several limitations. First, the relationship expressed in (1) applies only to a symmetrical rotating machine; therefore, the changes in  $Z_{a2\text{eff}}$  caused by deterioration can be unpredictable at extremely low levels of deterioration because of natural system unbalances. This limitation was originally recognized [1], [2], but it was believed that the ease of use compensated for the lack of predictable behavior at extremely low levels of deterioration. Second, minor construction asymmetries mimic motor deterioration and reduce the ability of  $Z_{a2\text{eff}}$  to be used to detect the inception of deterioration. Finally, mismatched sensors also tend to mimic or mask deterioration; therefore, sensors need to be calibrated to eliminate this effect. In the next section, the theoretical development of voltage mismatch detectors will be presented. As will be seen, these detectors are not based upon a balanced system concept and they may be used to overcome the deficiencies associated with the effective negative-sequence impedance.

## II. THEORETICAL DEVELOPMENT

Consider a three-phase wye-connected induction motor connected to a three-phase wye-connected power source as shown in Fig. 1. If the power source or motor is in a delta configuration, it is assumed that this component is represented by its equivalent wye.

Let  $V'_{a0}$ ,  $V_{a1}$  and  $V_{a2}$  be the zero-, positive-, and negative-sequence symmetrical components of the power source voltages measured with respect to the ground reference. Similarly, we will define  $I_{a0}$ ,  $I_{a1}$  and  $I_{a2}$  as the symmetrical components of the line currents and  $V_{a0}$ ,  $V_{a1}$  and  $V_{a2}$  as the symmetrical components of the motor phase voltages measured with respect to the junction point of its wye connection. Note that the zero-sequence voltages  $V'_{a0}$  and  $V_{a0}$  differ by the voltage at the junction point of the motor wye connection measured with

respect to the ground reference ( $V_n$ ) while the corresponding positive and negative sequence power source and motor phase voltages are equal.

It may be shown that [14]

$$V_{a0} = z_{00}I_{a0} + z_{01}I_{a1} + z_{02}I_{a2} \quad (3)$$

$$V_{a1} = z_{10}I_{a0} + z_{11}I_{a1} + z_{12}I_{a2} \quad (4)$$

$$V_{a2} = z_{20}I_{a0} + z_{21}I_{a1} + z_{22}I_{a2} \quad (5)$$

where the  $z_{xy}$  parameters are functions of the motor design, construction, any internal deterioration and the operating speed. In these equations, the zero-sequence component of the line currents is equal to zero if there is no ground fault 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 and are relatively easy to detect. For the remainder of this paper, we will assume that  $I_{a0} = 0$  (either no significant ground leakage exists or it has been corrected) and concentrate on the more difficult problem of detecting incipient deterioration that does not involve ground such as turn or coil faults within one motor phase or phase-to-phase deterioration.

With this assumption, (4) and (5) become

$$V_{a1} = z_{11}I_{a1} + z_{12}I_{a2} \quad (6)$$

$$V_{a2} = z_{21}I_{a1} + z_{22}I_{a2} \quad (7)$$

and it is then possible to determine  $z_{11}$ ,  $z_{12}$ ,  $z_{21}$ , and  $z_{22}$  from two separate tests on a motor conducted at any given motor speed. In this way, a library of  $z_{xy}$  parameters may be determined for the range of motor operating speeds. Once these parameters are known, it is then possible to monitor the three-phase motor voltages and line currents from which  $V_{a1}$ ,  $V_{a2}$ ,  $I_{a1}$ , and  $I_{a2}$  may be calculated. Equations (6) and (7) may then be used to calculate  $V_{a1}$  and  $V_{a2}$  at the measured motor operating speed and if no internal deterioration has occurred, the calculated values will match the measured values. If internal deterioration such as an interturn coil fault or phase-to-phase leakage has developed, the  $z_{xy}$  parameters will have changed from their normal values at that speed and there will be a mismatch between the measured positive and negative sequence voltages and the corresponding calculated values. This mismatch may then be used as a measure of internal motor deterioration.

An important advantage of this approach is that the mismatch detectors should be independent of initial construction imperfections and unbalances within the motor itself as well as changes or unbalance that may develop in the motor power supply system due to single phase loading or other factors. In addition, the performance of the mismatch detectors should not be affected by mismatched sensors; therefore, no careful sensor calibration is necessary. The application and robust nature of this monitoring approach will be illustrated in the experimental study.

## III. EXPERIMENTAL STUDY

The first step in the experimental study consisted of determining the elements of the impedance matrix defined by (6) and (7) from two runs on a healthy induction motor. After the impedance matrix was determined, additional runs were

conducted with the motor operating under various levels of voltage supply unbalance and deterioration. Next, the mismatch detectors were computed from the measured currents and the impedance matrix for each run. These values were compared with the positive- and negative-sequence voltages that were computed from the measured line voltages. Finally, the results were analyzed. The remainder of this paper will describe the experimental study and the results of that study.

#### A. Experimental Machine and Data Collection

The experimental machine is a two-pole uniform-air-gap universal laboratory machine (ULM) coupled to a dc generator. The output of the generator is connected to a bank of ten resistors that can be individually controlled to provide a wide range of loads for the ULM. An external rheostat is connected in series with the generator field winding, allowing very precise control of the generator output voltage. The ULM has a rating of 2.0 kVA at 208 V. The stator is composed of 24 slots, wound with 12, 26-turn coils. The terminals of each stator coil are brought out to a large panel at the front console of the machine. By making the appropriate coil-to-coil connections at this terminal panel, the user can connect the stator in either a delta or wye configuration. The user can also connect the stator coils in either a series or parallel circuit. Most important for this research is that the user also has access to the terminals of each stator coil, which provides a means for simulating internal deterioration (as will be described later). The rotor of the ULM is a wound rotor with brushes and slip rings that can be set to connect external resistors to the rotor circuit or, alternatively, the brushes can be set to short the rotor coils, thereby simulating a squirrel-cage rotor. In the experiments conducted for this research, the ULM stator was wye connected, with the stator coils connected in series.

Voltage signals were acquired by using voltage dividers connected between motor terminals and ground. Current signals were obtained by using current transformers (CTs) in conjunction with resistors. (The resistors were used to convert each CT output to an appropriate voltage signal.) The analog signals from the voltage dividers and CTs were digitized with a 16-bit analog-to-digital converter (ADC).

Each experiment consisted of collecting 1024 points per channel at a sample rate of 5128 points per second (for a combined sample rate of 30 768 points per second for all six channels). A fast Fourier transform (FFT) was used to compute frequency-domain information; subsequent calculations used the 60-Hz component of each signal.

#### B. Experimental Procedures

The first step of the experimental procedure consisted of running two tests on the ULM that were sufficient to determine the elements of the impedance matrix defined by (6) and (7). In order to accurately determine these terms, specific operating parameters had to be observed. First, because terms of the impedance matrix are speed dependent, it was necessary to run the ULM at the same speed for both tests and for all subsequent tests. Second, it was necessary to conduct the tests at two different levels of voltage supply unbalance in order to obtain four independent equations.

Control of the supply unbalance was achieved by using a three-phase variable-voltage transformer modified to allow each phase voltage to be controlled independently of the other two. Because near-zero values of  $I_{a2}$  and  $V_{a2}$  are problematic for determining the  $z$  matrix, the transformer was used to create a measurable level of unbalance in each of these two runs. The procedure we used consisted of increasing the phase  $a$  voltage to approximately 10% above the nominal for the first run and decreasing the phase  $a$  voltage to approximately 10% below the nominal for the second run. Note that such unbalances are only necessary for determining the  $z$  matrix. Once the  $z$ -matrix is determined, the mismatch detectors can be computed for any level of voltage unbalance, including a perfectly balanced system. ULM speed control was achieved by setting the appropriate resistance load on the generator and adjusting the output voltage of the generator using the field rheostat. Speed was measured with a digital tachometer.

After the two runs used to determine the  $z$  matrix were completed, a series of runs was conducted to evaluate the ability of the mismatch detectors to detect simulated deterioration in the ULM. Tests were conducted at a wide range of supply unbalances with the ULM operating under different levels of deterioration.

Stator winding deterioration was simulated by connecting a conductive path between the terminals of one stator coil (the smallest portion of the stator winding accessible on the ULM). Various levels of deterioration severity were simulated by inserting different values of resistance in this leakage path. Effort was taken to simulate small levels of deterioration during the experiments; however, because each phase of the stator is composed of only four coils, the smallest portion of the winding accessible is 25% of one phase winding. Therefore, the leakage current was limited to very low values. In the most severe level of deterioration simulated the leakage current was less than the rated input current of the ULM.

During the tests, there was no effort made to calibrate the sensors or other components of the data acquisition system. It was recognized that any bias error in the sensors should be accounted for in the  $z$ -matrix determination, provided that the sensors were not switched to different phases in subsequent experiments.

## IV. RESULTS

The tests were conducted to address three specific aspects of the mismatch detectors. The first was to determine if the detectors are well behaved (i.e., unaffected) in situations where the motor is supplied by a variable, unbalanced voltage supply and/or the motor itself has minor construction asymmetries that are unrelated to deterioration. Both of these unbalanced conditions are very common and can create the appearance of winding deterioration even though neither is actually related to deterioration. The second area to be evaluated was whether or not the detectors are sensitive to low levels of deterioration. Although it is difficult to quantify exactly what is meant by low level, the deterioration that was simulated had no perceptible affect on motor operation and the motor could be run indefinitely with the deterioration in place. The third aspect to be evaluated was whether changes in the detectors

could be associated with level of deterioration severity. This is one of the limitations of  $Z_{a2\text{eff}}$ . Although  $Z_{a2\text{eff}}$  does change with deterioration, it does not change in a predictable manner under certain operating conditions [1], [10].

A total of 14 experiments were conducted for the results presented in this paper. Six different levels of voltage unbalance were used during the experiments. Two were used to determine the  $z$  matrix, the other four were used in the evaluation of the mismatch detectors. They include a voltage unbalance factor (VUF) of approximately 0.5%, 1.7%, 2.7%, and 5.2%. (Here, voltage unbalance factor is defined as the absolute value of the ratio of the negative-sequence voltage to positive-sequence voltage, expressed in percent.) Note that the 0.5% VUF was as close to balanced as could be conveniently attained with the experimental setup. Three different states of motor condition were simulated: no deterioration, a leakage current of approximately 0.45 per unit (pu) and a leakage current of approximately 0.90 pu.

The values obtained for the  $z$  matrix are given in (8)

$$z = \begin{bmatrix} 22.1/18.39^\circ & 1.01/-162.47^\circ \\ 0.0493/-28.64^\circ & 3.31/51.60^\circ \end{bmatrix}. \quad (8)$$

In general, the off-diagonal terms of the  $z$  matrix should be very close to zero; and they would, of course, be equal to zero for a perfectly symmetrical motor/sensor system. Inspection of (8), however, reveals that the  $z$ -matrix obtained in our experiments contains fairly large off-diagonal terms, indicating a relatively large level of system asymmetry in the nondeteriorated state. Note that this inherent asymmetry includes effects that are caused by mismatched sensors as well as motor construction asymmetry. There was no attempt made to determine how much of this asymmetry was due to sensors and how much was due to motor construction. In fact, it is fortunate that this high level of inherent asymmetry existed because it represented a potentially problematic condition for the detectors that we wanted to evaluate.

The first aspect of the mismatch detectors to be evaluated was whether inherent motor asymmetry and/or changes in supply unbalance would mimic deterioration. This was accomplished by running the ULM in the nondeteriorated state under a wide range of supply unbalances and calculating the mismatch detectors. Ideally, the mismatch for this type of situation would be zero because the changes in voltage and current are not related to motor deterioration. Fig. 2 presents the results obtained from our experiments with a plot of the voltage mismatch versus level of supply unbalance at the four different levels of voltage unbalance factor previously described. (Note that because the magnitude of the negative-sequence voltage is much smaller than the positive-sequence voltage, ten times the  $V_{a2}$  mismatch detector is plotted.) These results indicate that the mismatch in each detector is very small and there is no trend or large variability in the detectors due to different levels of voltage supply unbalance.

The next aspect of the mismatch detectors to be investigated was their sensitivity to simulated winding deterioration. Figs. 3 and 4 illustrate two typical results. (Note in these figures and all figures where the mismatch detectors are plotted, the same scale is used for accurate comparison of the results.) Fig. 3 shows

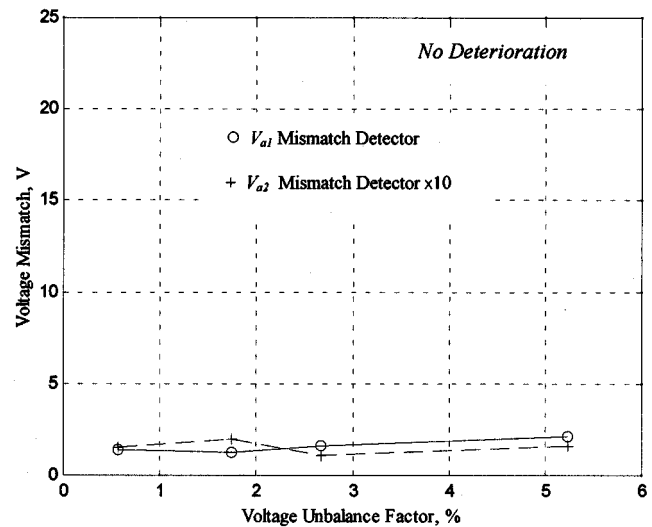


Fig. 2. Illustration of the insensitivity of the voltage mismatch detectors to different levels of supply unbalance for a nondeteriorated induction motor.

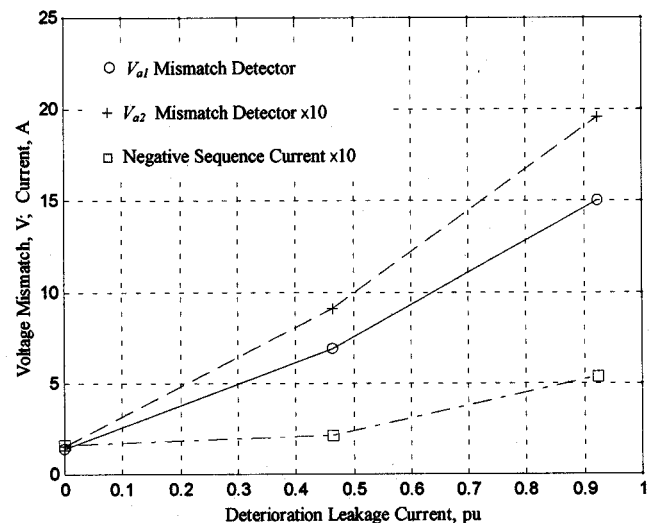


Fig. 3. Illustration of changes in the voltage mismatch detectors and negative-sequence current with increasing motor deterioration for an induction motor operating at a small voltage supply unbalance.

results for the ULM operating at the 0.5% VUF and we observe that both mismatch detectors increase significantly with the level of leakage current. Fig. 4 illustrates the results for the ULM operating with the 5.2% VUF. We observe that the changes in the detectors are almost identical to those presented in Fig. 3, in spite of the large difference in the level of negative-sequence current. In addition, closer inspection of Fig. 4 reveals that the level of negative-sequence current actually decreases with increasing deterioration severity for that series of tests. In other words, the combination of supply unbalance, inherent motor asymmetry, and the deterioration tend to balance the motor currents. This is the type of situation where the effective negative-sequence impedance may initially increase at very low levels of deterioration and decrease at higher levels of deterioration [10]. However, we observe that the mismatch detectors are not affected by the unbalance caused by the voltage supply

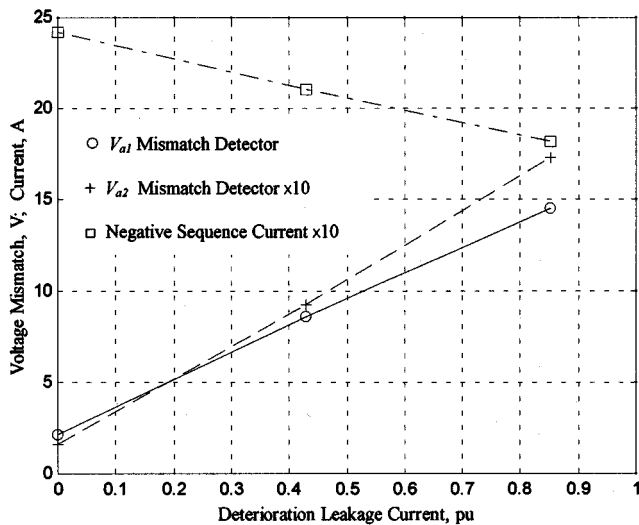


Fig. 4. Illustration of changes in the voltage mismatch detectors and negative-sequence current with increasing motor deterioration for an induction motor operating at a large voltage supply unbalance.

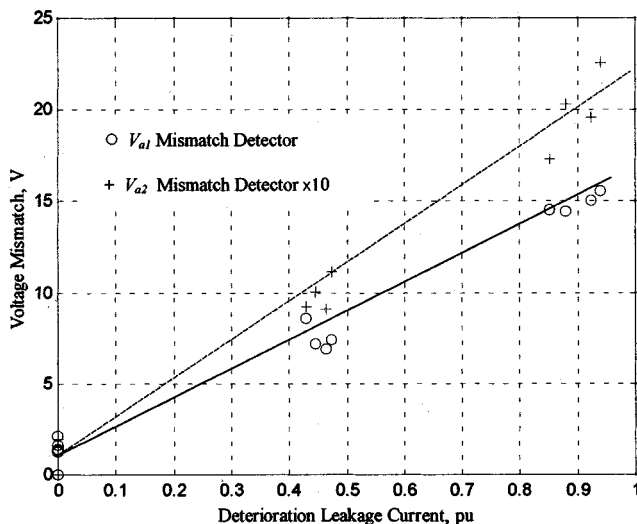


Fig. 5. Changes in the voltage mismatch detectors with increasing motor deterioration for an induction motor operating under a wide range of voltage supply unbalances.

or the inherent motor asymmetry. The detectors change only in response to the increasing deterioration.

The final aspect of the mismatch detectors to be investigated was whether or not changes in them provide any indication of the level of deterioration severity, especially in situations where the voltage supply unbalance changes. This was evaluated by combining all of the test results and plotting the voltage mismatch versus leakage current. The results presented in Fig. 5 show that the detectors increase in proportion to the leakage current despite the large variability in the voltage supply unbalance present during the different tests. This is particularly encouraging when we consider that the system exhibited a significant asymmetry in the nondeteriorated state.

Inspection of Fig. 5 shows that the  $V_{a1}$  mismatch is approximately 7.5 V for a 0.45-pu leakage current and 15 V for a leakage current of 0.90 pu; the corresponding mismatch in  $V_{a2}$

is approximately 1.0 and 2.0 V and both are independent of the changing voltage unbalance.

## V. CONCLUSION

Results from the experiments are very encouraging. Both of the voltage mismatch detectors are sensitive to the stator deterioration that was simulated, their performance was not affected by supply unbalances or inherent machine/monitoring system asymmetry and changes in them appear to be indicative of level of deterioration severity. In addition, no special sensors or calibration procedures were required to obtain these results. The negative-sequence voltage mismatch detector appears to be slightly more sensitive to increasing deterioration severity; however, the absolute changes in the positive-sequence voltage mismatch detector are larger.

This series of papers has addressed experimental results of techniques aimed at improving the ability to detect stator winding deterioration in three-phase induction motors. In [15], a summary of the performance of the effective negative-sequence impedance detector was given. As reported, this deterioration detector is very easy to implement. However, because its performance is based on the assumption of deviations from perfect symmetry, it exhibits unpredictable changes during the extremely early stages of deterioration because of natural system unbalances. In this paper, the voltage mismatch detectors were introduced as a means of overcoming this shortcoming. Because these detectors are based on a more complete model of the physical situation, performance is better, especially at low levels of deterioration. However, the voltage mismatch detectors are more difficult to apply as a training period is needed in order to develop the impedance parameters. More accurate measurement of motor speed would also be required during both the training and the condition monitoring phases.

## REFERENCES

- [1] J. Sottile and J. L. Kohler, "An on-line method to detect incipient failure of turn insulation in random-wound motors," *IEEE Trans. Energy Conversion*, vol. 8, pp. 762–768, Dec. 1993.
- [2] J. Sottile, "An analysis of induction motor incipient-failure prediction and the development of systems concepts for electrical diagnostics in mining industry applications," Ph.D. dissertation, Dept. Mining Eng., The Pennsylvania State Univ., University Park, 1991.
- [3] M. Arkan and P. J. Unsworth, "Stator fault diagnosis in induction motors using power decomposition," in *Conf. Rec. IEEE-IAS Annu. Meeting*, 1999, pp. 1908–1912.
- [4] R. R. Schoen and T. G. Habetler, "A new method of current-based condition monitoring in induction machines operating under arbitrary load conditions," *Elect. Mach. Power Syst.*, vol. 25, pp. 141–152, 1997.
- [5] M. A. Cash and T. G. Habetler, "Insulation failure detection in the stator windings of ASD-driven induction machines using standard deviation of line currents," in *Conf. Rec. IEEE-IAS Annu. Meeting*, 1998, pp. 299–303.
- [6] A. J. M. Cardoso, S. M. A. Cruz, and D. S. D. Fonseca, "Inter-turn stator winding fault diagnosis in three-phase induction motors by Park's vector approach," *IEEE Trans. Energy Conversion*, vol. 14, pp. 595–598, Sept. 1999.
- [7] G. B. Kliman, W. J. Premerlani, R. A. Koegl, and D. Hoeweler, "A new approach to on-line turn fault detection in ac motors," in *Conf. Rec. IEEE-IAS Annu. Meeting*, 1996, pp. 687–693.
- [8] M. A. Cash, T. G. Habetler, and G. B. Kliman, "Insulation failure prediction in induction motors using line-neutral voltages," in *Conf. Rec. IEEE-IAS Annu. Meeting*, 1997, pp. 208–212.

- [9] J. L. Kohler, J. Sottile, and F. C. Trutt, "Alternatives for assessing the electrical integrity of induction motors," *IEEE Trans. Ind. Applicat.*, vol. 28, pp. 1109–1117, Sept./Oct. 1992.
- [10] —, "Condition-based maintenance of electrical machines," in *Conf. Rec. IEEE-IAS Annu. Meeting*, 1999, pp. 205–211.
- [11] J. Penmen, H. G. Sedding, B. A. Lloyd, and W. T. Fink, "Detection and location of interturn short circuits in the stator windings of operating motors," *IEEE Trans. Energy Conversion*, vol. 9, pp. 652–658, Dec. 1994.
- [12] F. Ding and F. C. Trutt, "Calculation of frequency spectra of electromagnetic vibration for wound-rotor induction machines with winding faults," *Elect. Mach. Power Syst.*, vol. 14, pp. 137–150, 1988.
- [13] C. F. Wagner and R. D. Evans, *Symmetrical Components*. Melbourne, FL: Krieger, 1982, pp. 345–349.
- [14] S. A. Nasar and F. C. Trutt, *Electric Power Systems*. Boca Raton, FL: CRC, 1999, pp. 124–125.
- [15] J. L. Kohler, J. Sottile, and F. C. Trutt, "Condition monitoring of stator windings in induction motors: Part I—Experimental investigation of the effective negative-sequence impedance detector," *IEEE Trans. Ind. Applicat.*, vol. 38, pp. 1447–1453, Sept./Oct. 2002.



**Joseph Sottile** (S'87–M'89–SM'01) received the B.S., M.S., and Ph.D. degrees in mining engineering from The Pennsylvania State University, University Park, in 1984, 1987, and 1991, respectively.

He has worked in production and engineering for the Barnes and Tucker Company from 1977 to 1983 and for Consol, Inc., in 1987. He is currently an Associate Professor of Mining Engineering at the University of Kentucky, Lexington. His teaching and research interests include electrical applications in the mining industry.

Dr. Sottile is a Past Chairman of the Mining Industry Committee of the IEEE Industry Applications Society (IAS) and is currently serving on the IAS Executive Board.



**Frederick C. Trutt** (M'63–SM'78–F'91) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Delaware, Newark.

He has held several positions as a Research Engineer in industry and began his academic career as a faculty member at The Pennsylvania State University, University Park, in 1972. He is presently a Professor of Electrical Engineering at the University of Kentucky, Lexington, where he has also served as the Associate Dean for Academic Affairs in the College of Engineering, Chair of the Department of Electrical Engineering, and Acting Chair of the Department of Chemical Engineering. He has authored or coauthored more than 75 papers on electrical engineering and has been involved in teaching, research, and consulting in the areas of power systems and electric machines for more than 30 years.

Dr. Trutt is a Past President of the IEEE Industry Applications Society.



**Jeffery L. Kohler** (S'74–M'76–SM'88) received the B.S. degree in engineering science and the M.S. and Ph.D. degrees in mining engineering from The Pennsylvania State University, University Park, in 1974, 1977, and 1983, respectively.

He has held both electrical and mining engineering positions in the industry and, prior to joining the National Institute for Occupational Safety and Health (NIOSH) in 1998, he was an Associate Professor of Mining Engineering at The Pennsylvania State University. He is currently Director of NIOSH's Pittsburgh Research Laboratory, Pittsburgh, PA. His research interests include occupational safety and health, with a special interest in electrical safety. Over the past 25 years, he has investigated a number of topics related to condition-based monitoring and has published extensively in this field.

Dr. Kohler is a Past Chairman of the Mining Industry Committee of the IEEE Industry Applications Society.