Experimental Investigation of On-Line Methods for Incipient Fault Detection

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***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 does not change in a predicable manner under certain motor operating conditions. This paper presents an experimental investigation of an improved technique for on-line detection of induction motor stator winding degradation. The paper begins with a brief description of the detectors, followed by a detailed description of the experimental setup, the experiments conducted, and results.**

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].

Methods that use voltage and current measurements offer several advantages over test procedures that require the machine to be taken off-line or techniques that require special sensors to be mounted on the motor. Hardware requirements are easily met; there is no need to modify the motor or to supply external signals to motor windings. In addition, insulation is not subjected to any unnecessary stress during the evaluation process. Finally, condition monitoring can be conducted nearly continuously if voltage and current sensors can be mounted permanently and if processing requirements are not demanding. A continuous monitoring system is particularly advantageous when we consider the speed at which deterioration can progress.

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 produces very small changes in I_{a2} makes the negative-sequence current alone an unreliable predictor of incipient failure. There is however, one group of researchers that has developed techniques that overcome the shortcomings of simple negative-sequence current monitoring for incipient stator-winding fault detection. As would be expected with a more advanced procedure, the technique requires additional information and a brief training period prior to implementation [7].

One 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:

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

where,

z_0 = zero-sequence impedance,
z_1 = positive-sequence impedance, and
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,

$$Z_{a2eff} = \frac{V_{a2}}{I_{a2}} \tag{2}$$

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_{a2eff}. Second, for a symmetrical induction motor, the effective negative-sequence impedance is not very dependent on operating speed [13]; therefore, Z_{a2eff} needs to be determined at only a few different motor speeds and motor speed need not be accurately measured in an application. Third, Z_{a2eff} 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_{a2eff} caused by deterioration are unpredictable and they are not generally related to deterioration severity. (Note that the relationship expressed in (1) does not account for the interaction of different sequence components that occurs in an unsymmetrical system such as a deteriorating motor.) This limitation was originally recognized [1, 2], but it was believed that the ease of use compensated for the lack of predictable behavior. Second, minor construction asymmetries mimic motor deterioration and reduce the ability of Z_{a2eff} 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. (Note that the calibration process only requires that the sensors in each phase match one another; absolute accuracy is not necessary.) In the next section, the theoretical development of the mismatch predictors will be presented. As will be seen, these predictors overcome the deficiencies of 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

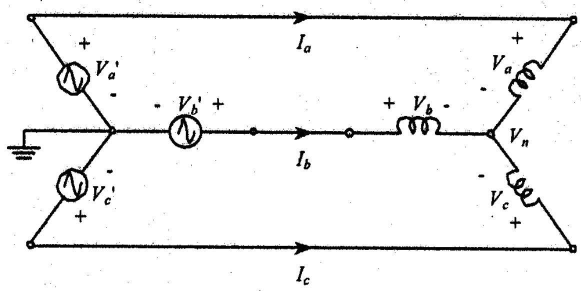

Figure 1. Wye-connected power source and induction motor.

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]

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

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

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

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 coil-to-coil faults within one motor phase or phase-to-phase deterioration.

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

$$V_{a1} = z_{11} I_{a1} + z_{12} I_{a2} \tag{6}$$

$$V_{a2} = z_{21} I_{a1} + z_{22} I_{a2} \tag{7}$$

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 constructed 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 determined. 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 predictors 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 predictors should not be affected by mismatched sensors; therefore, no 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 predictors 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 (CT) 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 predictors 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 predictors to detect simulated deterioration in the ULM. Tests were conducted at a wide range of supply unbalances with the ULM operating under several 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 would 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 predictors. The first was to determine if the predictors 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 predictors 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 predictors could be associated with level of deterioration severity. This is one of the limitations of Z_{a2eff}. Although Z_{a2eff} 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 predictors. They include a voltage unbalance factor (VUF) of approximately 0.5%, 2.1%, 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 0.45pu (per unit), and a leakage current of approximately 0.90pu.

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

$$z=\begin{bmatrix} 22.1\underline{/18.39^\circ} & 1.01\underline{/-162.47^\circ} \\ 0.0493\underline{/-28.64^\circ} & 3.31\underline{/51.60^\circ} \end{bmatrix} \tag{8}$$

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 predictors that we wanted to evaluate.

The first aspect of the mismatch predictors 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 predictors. Ideally, the mismatch for this type of situation would be zero because the changes in voltage and current are not related to motor deterioration. Figure 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 predictor is plotted.) These results indicate that the mismatch

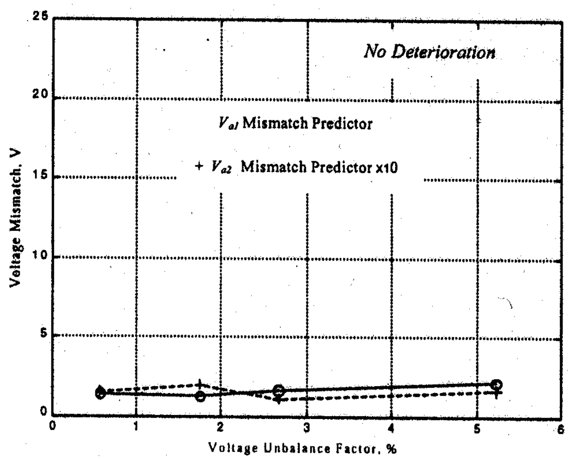

Figure 2. Illustration of the insensitivity of the voltage mismatch predictors to different levels supply unbalances for a nondeteriorated induction motor.

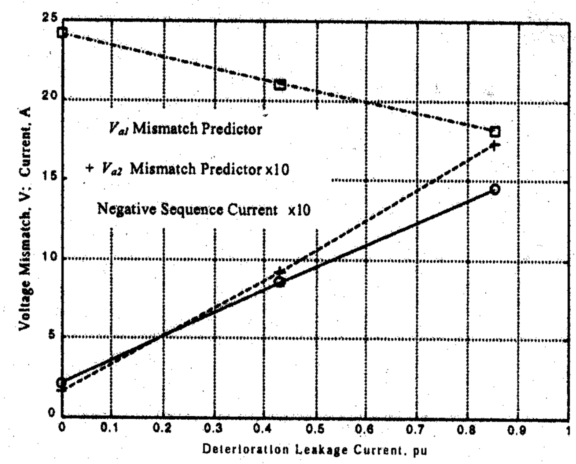

Figure 4. Illustration of changes in the voltage mismatch predictors and negative-sequence current with increasing motor deterioration for an induction motor operating at a large voltage supply unbalance.

in each predictor is very small and there is no trend or large variability in the predictors due to different levels of voltage supply unbalance.

The next aspect of the mismatch predictors to be investigated was their sensitivity to simulated winding deterioration. Figures 3 and 4 illustrate two typical results. (Note in these figures, and all figures where the mismatch

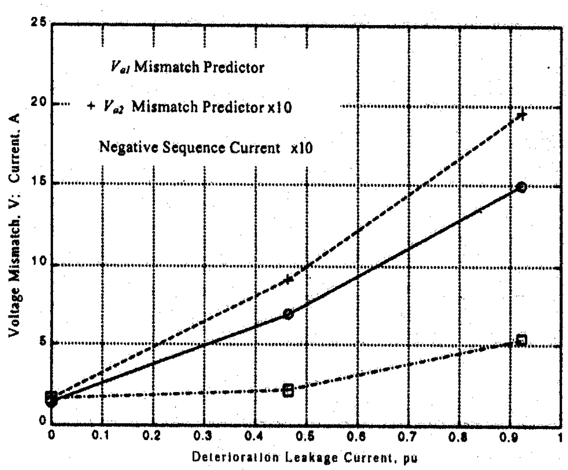

Figure 3. Illustration of changes in the voltage mismatch predictors and negative-sequence current with increasing motor deterioration for an induction motor operating at a small voltage supply unbalance.

predictors are plotted, the same scale is used for accurate comparison of the results.) Figure 3 shows results for the ULM operating at the 0.5% VUF, and we observe that both mismatch predictors increase significantly with the level of leakage current. Figure 4 illustrates the results for the ULM operating with the 5.2% VUF. We observe that the changes in the predictors are almost identical to those presented in Figure 3, in spite of the large difference in the level of negative-sequence current. In addition, closer inspection of Figure 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 predictors are not affected by the unbalance caused by the voltage supply or the inherent motor asymmetry. The predictors change only in response to the increasing deterioration.

The final aspect of the mismatch predictors 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 Figure 5 show that the predictors 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

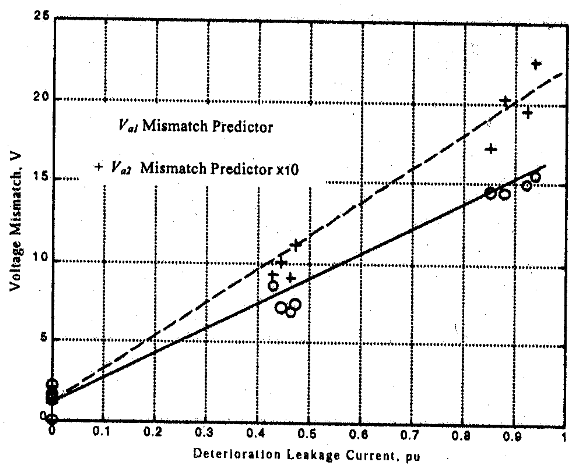

Figure 5. Changes in the voltage mismatch predictors with increasing motor deterioration for an induction motor operating under a wide range of voltage supply unbalances.

the system exhibited a significant asymmetry in the nondeteriorated state.

Inspection of Figure 5 shows that the V_{a1} mismatch is approximately 7.5V for a 0.45pu leakage current and 15Vfor a leakage current of 0.90pu; the corresponding mismatch in V_{a2} is approximately 1.0V and 2.0V and both are independent of the changing voltage unbalance.

V. CONCLUSIONS

Results from the experiments are very encouraging. Both of the mismatch predictors are sensitive to the stator deterioration that was simulated, their performance is 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 predictor appears to be slightly more sensitive to increasing deterioration severity; however, the absolute changes in the positive-sequence voltage mismatch predictor are larger.

Future research will include more exhaustive tests on numerous induction motors to better define the ability of each mismatch predictor to indicate deterioration. In addition, correlation between the predictor and deterioration severity will be developed as appropriate.

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