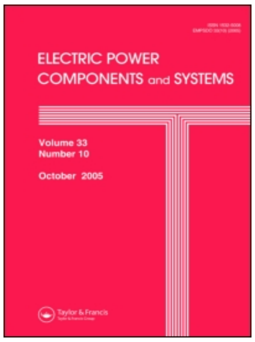

Electric Power Components and Systems

ISSN: 1532-5008 (Print) 1532-5016 (Online) Journal homepage: https://www.tandfonline.com/loi/uemp20

Detection of Electrical Winding Deterioration in Induction Motors

F. C. Trutt, J. Sottile

To cite this article: F. C. Trutt, J. Sottile (2001) Detection of Electrical Winding Deterioration in Induction Motors, Electric Power Components and Systems, 29:11, 1025-1033, DOI: 10.1080/153250001753239239

To link to this article: https://doi.org/10.1080/153250001753239239

Electric Power Components and Systems, 29:1025–1033, 2001

1532-5008/01 $12.00 + .00

Detection of Electrical Winding Deterioration in Induction Motors

F. C. TRUTT
J. SOTTILE

College of Engineering
University of Kentucky
Lexington, Kentucky 40506-0046

J. L. KOHLER

National Institute for Occupational Safety and Health
Pittsburgh Research Laboratory
Pittsburgh, Pennsylvania

Presented in this paper is the development and analysis of deterioration predictors that may be used to detect electrical winding deterioration in induction motors. One major advantage of the approach that is described is that it may be used to reliably indicate low levels of deterioration in induction machine windings even though the machine may have internal construction unbalances and may be operating under conditions of varying applied voltage magnitude and symmetry. In addition, the proposed monitoring scheme is relatively simple in concept and may be implemented in practical situations. The procedure, and its robust nature, is illustrated by application to the detection of turn-to-turn deterioration in the stator winding of a three-phase induction motor.

1 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 nonideal 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 incipient 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

Manuscript received in final form on 7 December 2000.
Address correspondence to Dr. Frederick C. Trutt.

system unbalances, such as the residual negative sequence current reported in [6] and the effective negative sequence impedance described in [7]. These methods are based upon some simplifying assumptions, and each may be shown to work well in many situations. The purpose of this paper is to demonstrate an alternative approach that may be used instead of, or as a supplement to, those given in [1–7]. This proposed approach may be used to monitor rotating machine stator winding health independent of construction imperfections and changes in the power supply. In addition, the procedure should be adaptable to real-world situations.

In the text of the paper, a theoretical justification for the use of the suggested predictors is presented along with the corresponding mathematical development. Verification of the approach is accomplished by applying the faulted induction motor model presented in [8] to a typical three-phase induction motor. A proposed step-by-step procedure for application of the process in an industrial environment is also included.

2 Theoretical Development

Consider a three-phase, wye-connected induction motor connected to a three-phase, wye-connected power source, as shown in Figure 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 [9]

$$V_{a0} = z_{00}I_{a0} + z_{01}I_{a1} + z_{02}I_{a2}, \tag{1}$$

$$V_{a1} = z_{10}I_{a0} + z_{11}I_{a1} + z_{12}I_{a2}, \tag{2}$$

$$V_{a2} = z_{20}I_{a0} + z_{21}I_{a1} + z_{22}I_{a2}, \tag{3}$$

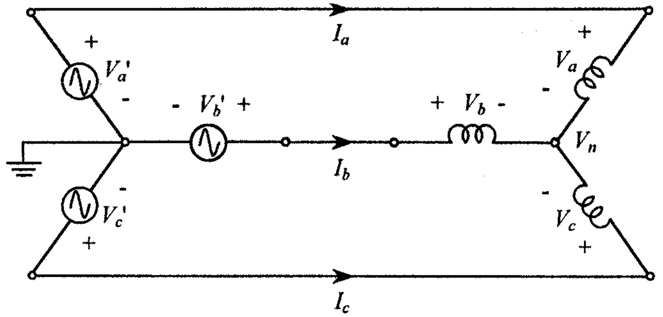

Figure 1. Wye-connected power source and induction motor.

where the z_{xy} parameters are functions of the motor design, construction, any internal deterioration, imperfections in a measurement system, and the motor's operating speed. In these equations, the zero sequence component of the line currents is equal to zero if 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 and are relatively easy to detect and correct. For the remainder of this paper, we will 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.

With this assumption, equations (2) and (3) become

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

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

and it is then possible to determine z_{11}, z_{12}, z_{21}, and z_{22} from two separate tests on the motor 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 $z_{12} = z_{21} = 0$. Note that the zero-sequence voltage required in equation (1) is no longer needed, and it is a relatively simple matter to obtain the unique positive- and negative-sequence voltages required in equations (4) and (5) from the positive- and negative-sequence components of the line voltages using standard formulae [9].

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 (4) and (5) 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 will 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 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 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. The application and robust nature of this monitoring approach will be illustrated in the following discussions.

3 Verification

In order to investigate the behavior of the positive and negative sequence voltage mismatch predictors, the induction motor model developed in [8] was modified for the analysis of a 15-hp, 440-V (254 V line-to-neutral), wye-connected, 6-pole, three-phase squirrel cage induction motor. As this model is capable of simulating

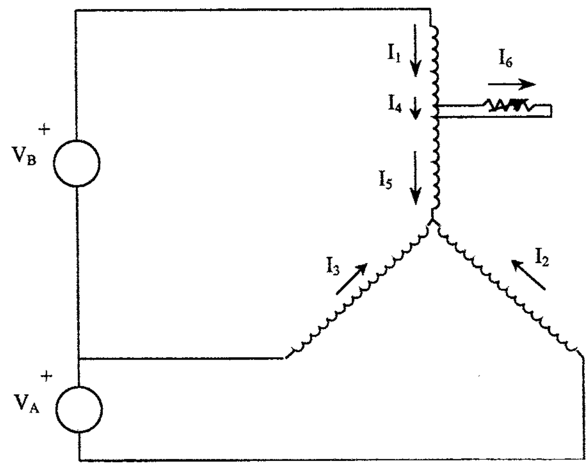

Figure 2. Simulation of coil-to-coil stator winding deterioration in one phase of an induction motor.

construction imperfections and power system supply unbalances, as well as internal winding deterioration, it is an ideal tool for demonstrating the utility and robust nature of the proposed predictors in the presence of these system variations. For the purpose of this study, coil-to-coil deterioration in one phase of a stator winding was selected as shown in Figure 2.

Before any simulated deterioration was added to the motor model ($I_6 = 0$A in Figure 2), two separate analyses were conducted using the same value of V_A, but with different values of V_B. Motor speed was maintained at 1170 rpm. Data from these analyses was then used to determine the parameters z_{11}, z_{12}, z_{21}, and z_{22} at 1170 rpm using equations (4) and (5).

The behavior of the V_{a1} and V_{a2} voltage mismatch predictors as a function of fault severity is shown in Figure 3. To obtain the data shown in Figure 3, deterioration in one coil of the 18 coil/phase perfectly balanced stator winding (no

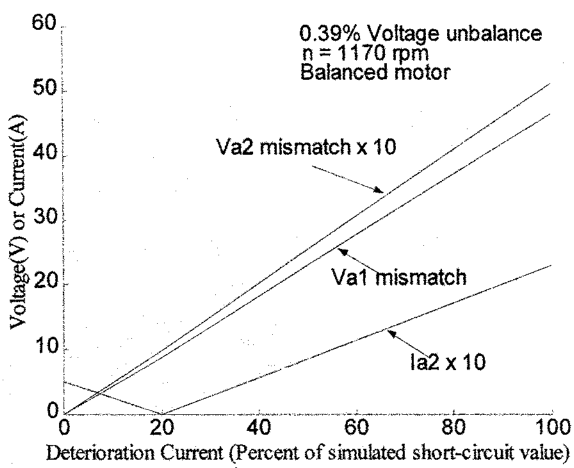

Figure 3. Actual values of predictors versus deterioration of a single stator coil.

construction imperfections) was simulated by connecting a variable resistance across the deteriorating coil. This resistance was then varied from a very large value (no deterioration) to 0.05 Ω (simulation of a short-circuit fault with a very small contact resistance), and the magnitudes of the mismatch predictors were calculated. During this analysis, the unbalance factor of the voltages applied to the motor (defined as $[V_{a2}/V_{a1}] \times 100$) was maintained at 0.39%, and the motor speed was held at 1170 rpm.

Analysis of Figure 3 shows that the positive- and negative-sequence voltage mismatch predictors exhibit a well-behaved monotonic increase as the deterioration varies from none to a short-circuit fault. It should be noted that while the positive-sequence voltage mismatch exhibits the largest change in magnitude (the V_{a2} mismatch has been multiplied by 10 as a convenience in drawing the graph), its percentage change is much smaller than that observed for the negative sequence voltage mismatch, as is shown in Figure 4. In Figure 4, the percentage changes in the mismatch predictors are obtained by dividing the actual mismatch in volts by the applied voltage magnitude of 254 V line-to-neutral for positive sequence and 1 V line-to-neutral for negative sequence. Note also that $(1/254) \times 100 = 0.39\%$ applied voltage unbalance.

For purposes of comparison, the magnitude of the negative sequence line current (also multiplied by 10 as a convenience in drawing the graph) to the motor is also included in Figure 3. As this parameter is sometimes proposed as a simple measure of deterioration, it is instructive to note the initial decrease in this predictor during the lower levels of deterioration. This occurs because the deterioration is initially acting to cancel the effect of the 0.39% applied voltage unbalance. This result emphasizes the need for a more sophisticated approach to the condition monitoring problem as presented in this discussion for the voltage mismatch predictors and in [6] for the negative-sequence current predictor. Note that the negative-sequence voltage mismatch predictor has already shown an approximate 200% increase before the magnitude of the negative sequence current begins to exceed its predeterioration value.

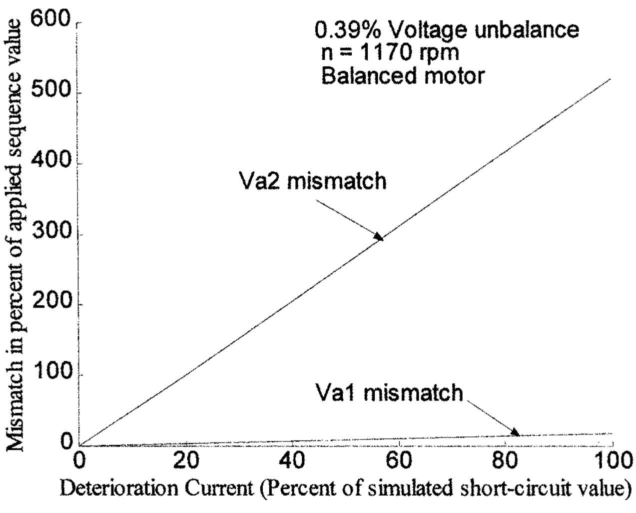

Figure 4. Percentage changes in predictors versus deterioration of a single stator coil.

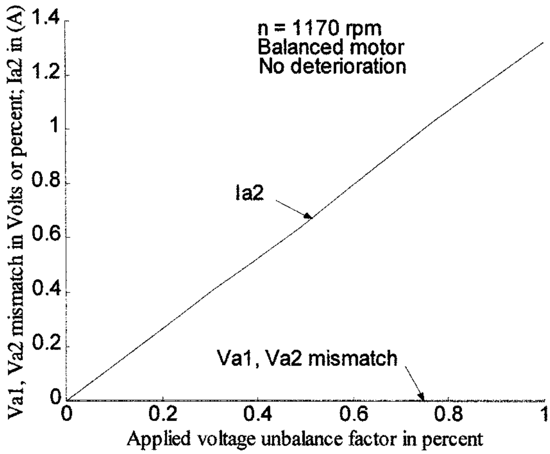

Figure 5. Predictors versus applied voltage unbalance for a motor with no deterioration.

Figures 5 and 6 demonstrate the robust nature of the proposed voltage mismatch predictors with changing supply voltages. To construct both graphs, the applied voltage unbalance factor is increased from zero to 1.0%. For Figure 5, the motor has no construction imperfections and no deterioration. For this situation, both the positive- and negative-sequence voltage mismatch predictors remain at zero (indicating no deterioration) independent of the applied voltage unbalance. Once again, the magnitude of the negative-sequence current is included for reference. Note that this predictor increases with the applied voltage unbalance even though no deterioration is present (Fig. 5).

In Figure 6, the motor has no construction imperfections, but a deterioration corresponding to approximately 20% of the short-circuit current is simulated. Note

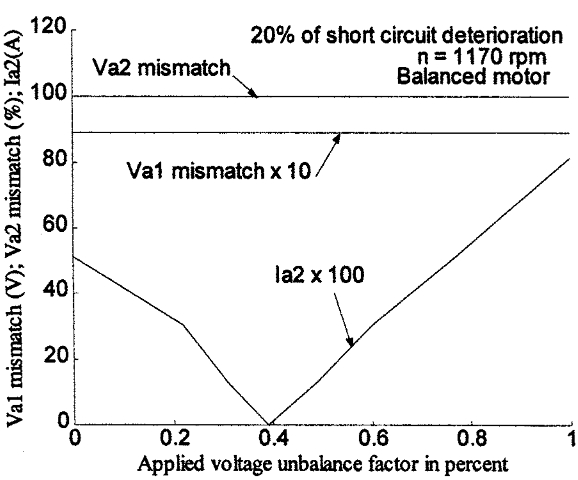

Figure 6. Predictors versus applied voltage unbalance for a motor with a fixed level of deterioration.

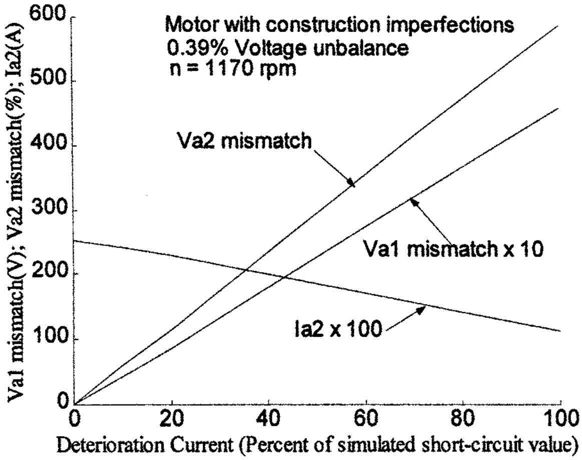

Figure 7. Predictors versus deterioration of a single coil in a motor with construction imperfections.

that both voltage mismatch parameters predict the deterioration with their reference values (see Figs. 3 and 4) independent of the applied voltage unbalance. In this case the negative-sequence voltage mismatch remains at 1 V (100%) while the positive-sequence voltage mismatch remains at 8.9 V (3.5%). Once again, the magnitude of the negative-sequence current is seen to behave in an erratic manner.

Figure 7 shows the effect of winding construction unbalance on the voltage mismatch predictors. In this case, motor construction unbalance was simulated by removing approximately 10% of the stator winding turns from the healthy phases of the motor (see Fig. 2). The appropriate z_{xy} parameters were determined for this imperfect motor at 1170 rpm, an applied voltage unbalance of 0.39% was maintained, and the deterioration current was varied from zero to the simulated short-circuit value. Once again, the positive- and negative-sequence voltage mismatch parameters are seen to be clear predictors of the deterioration while the negative- sequence current moves in a direction opposite to the deterioration. The large value of negative sequence current when no deterioration exists is due to the motor construction unbalance plus the 0.39% applied voltage unbalance. The decrease in I_{a2} as the deterioration level is increased occurs because the deterioration is acting to overcome the construction and applied voltage unbalances in order to create a more balanced overall system. The robust nature of the positive- and negative-sequence voltage mismatch predictors in this situation seems apparent. Other situations of applied voltage unbalance and construction unbalance have also been simulated with similar results.

4 Application

In order to apply the suggested monitoring procedure in an industrial situation, it would first be necessary to instrument the motor system with current transformers for the measurement of the three line currents, potential transformers for the measurement of the line-to-neutral or line-to-line voltages, and a speed measuring device, such as a d-c tachometer. No careful calibration or matching of these devices for accuracy should be required. Sensor outputs should be reproducible over time, however. These outputs may then be routed through an appropriate analog-to-digital converter and into a digital computer for analysis.

Once this is done, the sensor and processing configuration should remain fixed. Determination of the required z_{xy} parameters as a function of load (motor speed) may then be accomplished during a training period. One method of doing this might be to create an applied voltage unbalance by inserting a power resistor in one of the three-phase lines with the instrumentation located between the power resistor and the motor. The motor speed, currents, and voltages as the motor operates through its normal loading cycle may then be monitored. This resistor may then be moved to a different phase, and this process could be repeated. The recorded data may then be used to create a library of z_{xy} parameters as a function of motor speed. Each set of z_{xy} entries is calculated from equations (4) and (5) using the measured voltages and currents at a particular operating speed for the two different operating conditions. These calculations may be automated using appropriate programs in the digital computer.

At the conclusion of this training period, the in-place measurement system may then be utilized as a monitoring device for the detection of incipient deterioration in the system. The positive- and negative-sequence voltage mismatch predictors presented in this paper may automatically be calculated at periodic intervals and used as a measure of internal motor deterioration. For increased reliability, alternative predictors, such as those given in [1–7], may also be incorporated to form a more comprehensive monitoring system.

5 Conclusion

Results of the theoretical analysis presented in this paper using a linear model have clearly supported the proposed approach. Both the positive- and negative-sequence voltage mismatch predictors have been shown to be sensitive to the single-coil stator winding deterioration that was simulated, and their performance is not degraded by voltage supply unbalances or inherent machine asymmetry. Changes in these predictors also appear to be indicative 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 to increasing deterioration severity; however, the absolute changes in the positive-sequence voltage mismatch predictor are larger. 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 system. This is an important attribute for predictors that will be used to monitor low levels of deterioration.

While not reported in this paper, recent experimental testing of this concept on a universal laboratory machine with applied voltage unbalances has also served, to verify the proposed procedures [10]. However, future research must include much 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 nonlinearities. In addition, correlations between the predictors, type of deterioration, and severity should be developed as appropriate.

References

[1] M. Arkan and P. J. Unsworth, 1999, "Stator fault diagnosis in induction motors using power decomposition," Record of the 34th IEEE Industry Applications Society Conference, pp. 1908–1912.

[2] R. R. Schoen and T. G. Habetler, 1997, "A new method of current-based condition monitoring in induction machines operating under arbitrary load conditions," *Electric Machines and Power Systems*, Vol. 25, pp. 141–152.

[3] M. A. Cash and T. G. Habetler, 1998, "Insulation failure detection in the stator windings of ASD-driven induction machines using standard deviation of line currents," Record of the 33rd IEEE Industry Applications Society Conference.

[4] A. J. Marques Cardoso, S. M. A. Cruz, and D. S. D. Fonseca, 1999, "Inter-turn stator winding fault diagnosis in three-phase induction motors by Park's vector approach," *IEEE Transactions on Energy Conversion*, Vol. 14, No. 3, pp. 595–598.

[5] M. A. Cash, T. G. Habetler, and G. B. Kliman, 1997, "Insulation failure prediction in induction motors using line-neutral voltages," Record of the 32nd IEEE Industry Applications Society Conference, pp. 208–212.

[6] G. B. Kliman, W. J. Premerlani, R. A. Koegl, and D. Hoeweler, 1996, "A New Approach to On-Line Turn Fault Detection in AC Motors," Proc. 1996 IEEE Industry Applications Society Annual Meeting, pp. 686–693.

[7] J. L. Kohler, J. Sottile, and F. C. Trutt, 1999, "Condition-Based Maintenance of Electrical Machines," Proc. 1999 IEEE Industry Applications Society Annual Meeting, pp. 205–211.

[8] S. Williamson and P. Mirzoian, 1985, "Analysis of cage induction motors with stator winding faults," *IEEE Trans. on Power Apparatus and Systems*, Vol. 104, No. 7, pp. 1838–1842.

[9] S. A. Nasar and F. C. Trutt, 1999, *Electric Power Systems*, CRC Press, pp. 124–125.

[10] J. Sottile, F. C. Trutt, and J. L. Kohler, 2000, "Experimental Investigation of On-Line Methods for Incipient Fault Detection," Proc. 2000 IEEE Industry Applications Society Annual Meeting, pp. 2682–2687.