Accelerated Ageing Test Applied to the Early Detection of Insulation Failures in Low Voltage Induction Motors

M. G. Melero, M. F. Cabanas, C. Rojas, F. Pedrayes, G. A. Orcajo, J. M. Cano

Dpto. de Ingeniería Eléctrica, Electrónica, de Computadores y Sistemas
Universidad de Oviedo
Campus de Viesques, 33204 Gijón-Asturias (España)
Tel./Fax:+34 985 182453, e-mail: melero@uniovi.es

Abstract. Research has proven that several methods are able to detect shorted turns in the stator winding, even in cases involving few turns. Nevertheless, one question remains unanswered: how long does it take for shorted turns within a coil to develop into a catastrophic failure of the motor? (phase to phase or phase to earth fault). If the answer were known, it might then be applied to new diagnostic techniques in condition-based maintenance systems, particularly as one of the main drawbacks of these systems is precisely their inability to predict how far the machine is from the end of its useful life. Any information that contributes to establishing an alarm level to predict the remaining life of the motor will be very useful.

This paper shows the results obtained from a motor subjected to stator winding insulation ageing cycles. A set of measurements is taken after each cycle in order to study the variation of a turn to turn fault detector. The aim is to know how early this detector can detect the insulation damage between turns and, as a consequence, the future presence of shorted turns.

Index Terms – Diagnostics, induction motor, winding insulation ageing.

1. Introduction

It is widely accepted that turn to turn shorts are one of the most common type of stator failure [1-4], especially in random-wound motors. In most cases, this type of fault progresses to a coil to coil, phase to phase or phase to ground failure, causing the final breakdown of the motor.

In recent years, important advances in the study of the detection of insulation failures in low voltage induction motors have been made. These advances have been especially important in diagnostic techniques that detect failures without altering normal machine functioning and several techniques based on the analysis of different signals have been proposed, including spectral analysis of either axial flux [5-7] or electromagnetic torque [8], analysis of supply current [9-12] or the measurement of the *negative-sequence impedance* [13-16].

Research has proven that the above methods are able to detect shorted turns in the stator winding, even in cases involving few turns. Nevertheless, one question remains unanswered: how long does it take for shorted turns within a coil to develop into a catastrophic failure of the motor? (phase to phase or phase to earth fault). So any information that contributes to establishing an alarm level to predict the remaining life of the motor will be very useful.

This paper shows the results obtained from a motor subjected to stator winding insulation ageing cycles. A set of measurements is taken after each cycle in order to study the variation of turn to turn fault negative-sequence impedance detector. The aim is to know how early this detector can detect the insulation damage between turns and, as a consequence, the future presence of shorted turns.

2. Detection of Insulation Failures by means of the Negative-Sequence Impedance

The theory of symmetrical components provides powerful analysis techniques for simplifying calculations on unbalanced or faulted power systems. Symmetrical component quantities of three-phase systems involve the positive, negative and zero sequence components.

The positive sequence components have equal magnitudes, positive rotation (r,s,t), and are displaced 120º. The negative sequence components have equal magnitudes, negative rotation (r,t,s), and are also displaced 120º. Zero sequence components have equal magnitudes and no phase displacement. In a balanced system the negative and zero sequence components are nil. For instance, in a motor the presence of incipient failures in stator insulation, produces windings asymmetry, which causes the appearance of a negative sequence component in the stator current.

Although negative-sequence components indicate system unbalance, their presence does not always imply system failure. Small supply unbalances are often caused by single phase loading and the resulting voltage unbalance generates the flow of negative sequence current. This is not usually a problem, although the negative sequence current, even in healthy motors causes overheating which increases insulation ageing [13].

In industrial plants, the supply power system is never completely balanced. Small differences exist between the magnitudes or the phase angles of the different phases. The behaviour of an induction motor connected to such an unbalanced system can be analysed by studying its equivalent positive and negative circuits.

Since the negative sequence field rotates in the opposite direction with respect to the positive sequence field, the equivalent circuit for the negative sequence can be obtained by simply substituting slip *s* by *(2-s)* in the positive sequence circuit [13]. Figure 1 shows the new equivalent circuit.

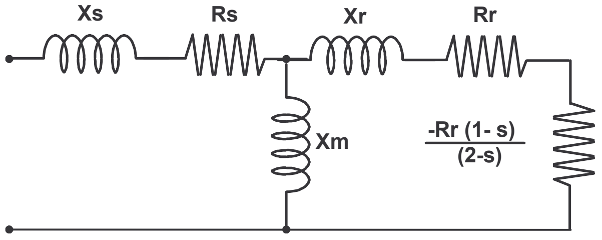

Fig. 1. Negative sequence equivalent circuit

Negative sequence impedance was calculated for different slip values corresponding to the typical operation range of an induction motor. The obtained value was almost constant, as the next figure shows:

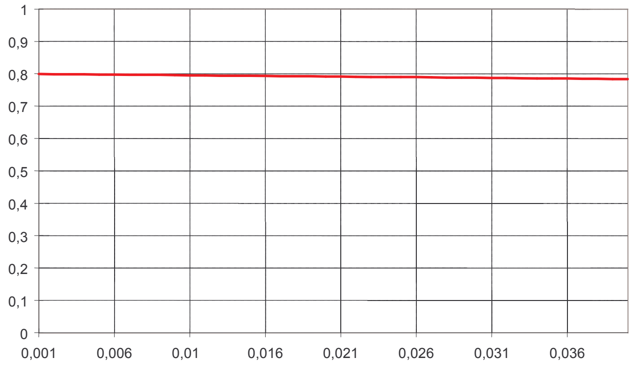

Fig. 2. Negative sequence impedance (per unit values) versus slip

The conclusion is that a healthy induction motor presents a nearly constant impedance to the negative sequence current. Such an impedance can be calculated by the quotient of the negative sequence voltage and the negative sequence current, as the next expression shows:

$$Z_{2ef} = \frac{V_{r2}}{I_{r2}} \tag{1}$$

where V_{r2} and I_{r2} are the negative-sequence components of voltages and currents respectively:

$$Vr_2 = 1/3\,(Vr + a^2 \cdot Vs + a \cdot Vt) \tag{2}$$

$$Ir_2 = 1/3\,(Ir + a^2 \cdot Is + a \cdot It) \tag{3}$$

During incipient stages of failure, symmetry is lost and the motor no longer exhibits a constant impedance to the flow of negative sequence current. The different sequence components react upon one another and voltage drops in the negative sequence can occur from the flow of any sequence component of current [13]. Because of these effects Z_{2ef} is altered during incipient failure and therefore used with monitoring purposes.

2.1 Negative sequence impedance measurement

The main problem about using Z_{2ef} for diagnosis purposes is the complexity of its measurement. The symmetrical components theory used for its calculation is only valid when both voltages and currents are perfectly sinusoidal magnitudes. However, voltages and currents in a real machine connected to a real power system always have a certain degree of distortion. For this reason, if the classical symmetrical components theory is applied for Z_{2ef} calculation it is necessary to filter both magnitudes.

This bandpass filtering considerably complicates the calculation of the Z_{2ef} since it implies the accurate filtering of the three machine voltages and currents. Moreover, all kinds of transient phenomena in the power system or the machine can also influence the calculation process. For all these reasons, as previous studies have shown [15,16], the Z_{2ef} does not exhibit a constant value with motor load as theory predicted. This abnormal behaviour implies the need to average a high number of impedance measurements to reduce its natural dispersion.

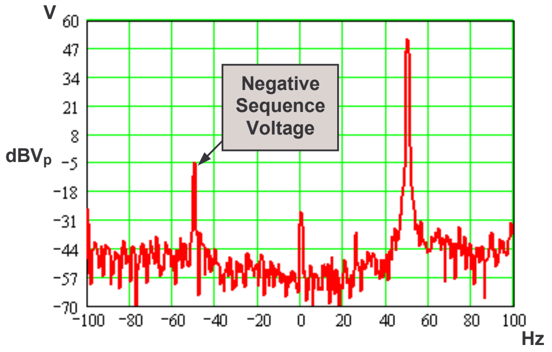

Fig. 3. Voltage spectrum

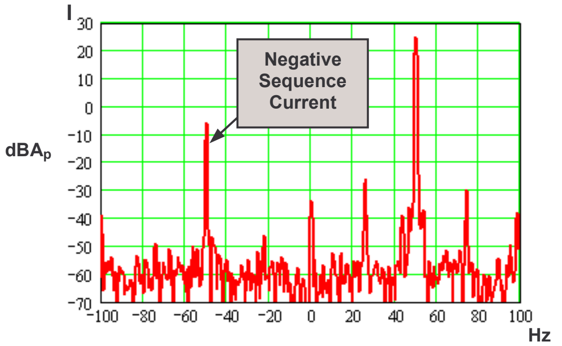

Fig. 4. Current spectrum

The application of the FFT to both the voltage and current vectors [15,16], can also be used to overcome the limitations in Z_{2ef} measurement. Park´s Vector FFT allows the direct calculation of the rotating sequence for every vector frequency component. In fact, the voltage and current negative sequence components can be calculated by directly measuring the magnitude and phase angle of the fundamental harmonic in the negative frequency scale. Since the FFT decomposes the vector into its frequency components, it is not necessary to carry out any kind of filtering prior to the Z_{2ef} calculation to use this calculation procedure.

Once the negative-sequence components of both voltage and current are obtained by the above method and expressed in decibels, Z_{2ef} is calculated simply by subtracting current component from voltage component and the result is also expressed in decibels. Fig. 3 and Fig. 4 show voltage and current spectra from which Z_{2ef} is obtained.

3. Ageing Cycles

Design of the ageing cycles is based on a previous study performed by the authors [17], in which the behaviour of a motor working under inter-turn short condition was studied. One of the conclusions was that the motor was able to perform more than 30 work cycles under such conditions, including starting up, running at full load for ten minutes and stopping. As the current flowing in the shorted turns is much higher than the rated current, overheating leads to insulation deterioration in the turns involved. This effect can be exploited in order to generate progressive damage to the turn insulation. The key is to keep the inter-turn short time enough to cause controlled damage whilst avoiding a catastrophic winding fault.

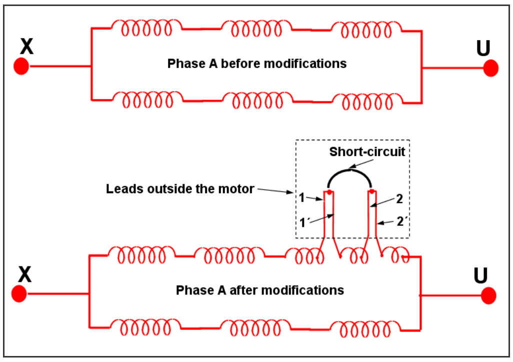

Fig. 5. Details of the modifications carried out on the winding

Based on the above considerations, in order to obtain the evolution of the turn to turn fault detector in the course of the ageing process, each ageing cycle designed consists of two phases. During the first phase, the tested motor works at full load, with an inter-turn short, until it reaches a specified temperature. This temperature is established according the results of the preliminary tests in such a way as to allow insulation damage to be progressive. During the second phase of the ageing cycle, the intern-turn short is removed and the motor works at full load until it reaches the normal operating temperature.

4. Preliminary Tests

The motor tested in this study was a squirrel cage induction motor rated 380 V, 5.5 kW, 50 Hz, 4-pole, delta connected, with two parallel paths per phase. Before starting the lab tests, the machine was dismantled in order to perform a visual inspection and to place three thermocouples in the stator winding, one per phase. A study of the thermal behaviour of the motor was thus performed before and after the shorted turns were introduced.

The inter-turn short has to be easy to remove because of the ageing cycles described above, so a part of the winding corresponding to two adjacent turns was extracted and placed outside the motor in order to facilitate the tests and, moreover, to permit the measurement of current in the faulty path. Once the motor was reassembled and energized, the voltage measurement in healthy conditions between the adjacent turns revealed that 0.85% is the percentage of stator winding to be shorted. Figures 5 and 6 show details of the modifications carried out on the winding.

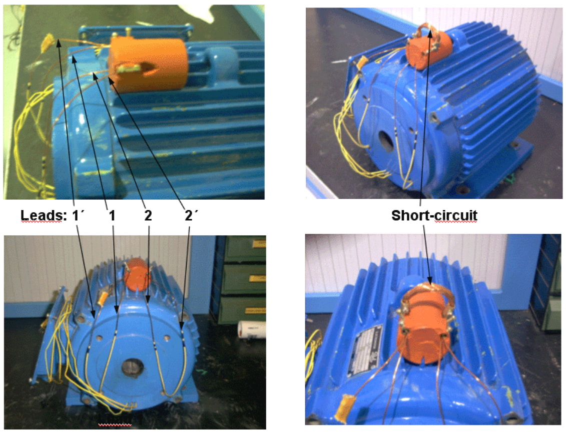

Fig. 6. Photographs showing details of the motor after modifications

Two series of preliminary tests corresponding to two different conditions of the machine were carried out on the above motor; one of them without failure and the other with the shorted turns. Each series of tests consisted of measuring supply voltages and currents and also winding temperature.

Several measurements were taken before starting the ageing cycles in order to obtain the reference level of both the winding temperature and the shorted turns detectors. Figures 7 and 8 show the temperature evolution of the motor working healthily and with shorted turns (maximum temperature established to work in the latter condition: 110 ºC).

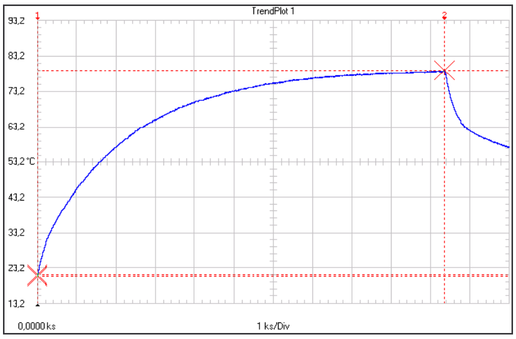

Fig. 7. Thermal behaviour of the healthy motor

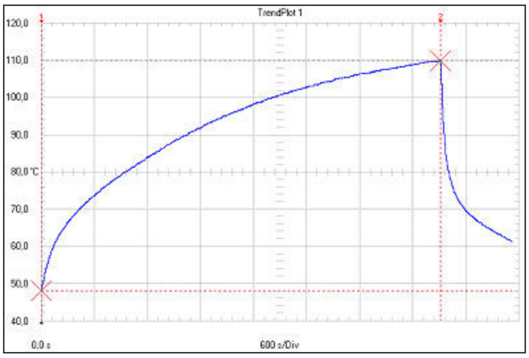

Fig. 8. Thermal behaviour of the damaged phase

5. Results of the Tests and Conclusions

As it has been shown, a healthy induction motor has a near constant impedance to the negative-sequence current. However, during incipient stages of failure, symmetry is lost and the motor no longer exhibits a constant impedance to the flow of negative sequence current. The different sequence components react upon one another and voltage drops in the negative sequence can occur as a result of the flow of any sequence component of current [13]. Because of these effects, the effective negative sequence impedance (Z_{2ef}) alters during incipient failure and can therefore be used as a detector of shorted turns. Figures 9 and 10 show spectra taken during an ageing cycle and Figures 11 and 12 show spectra taken after an ageing cycle.

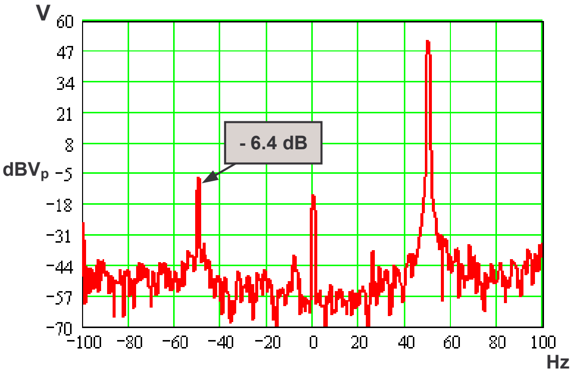

Fig. 9. Voltage spectrum during ageing cycle

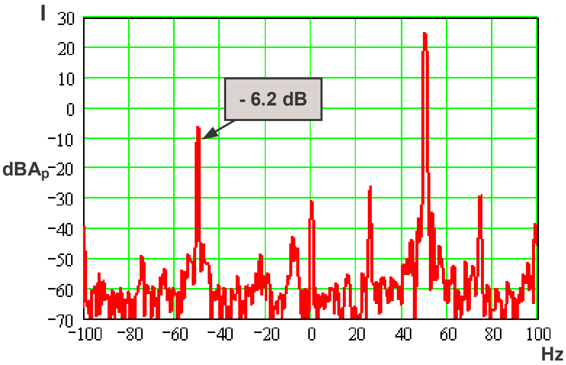

Fig. 10. Current spectrum during ageing cycle

As it can be seen in Fig. 13, the presence of a turn to turn short involving so few turns is well detected by monitoring Z_{2ef}, but it is remarkable that no large enough changes were detected after 16 ageing cycles. Z_{2ef} has so far maintained almost constant values from the beginning of the tests in each phase of the ageing cycle (healthy and with shorted turns).

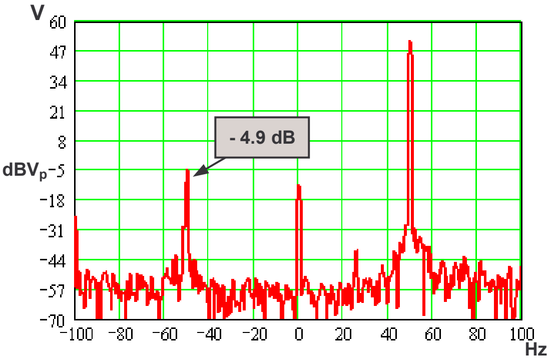

Fig. 11. Voltage spectrum after ageing cycle

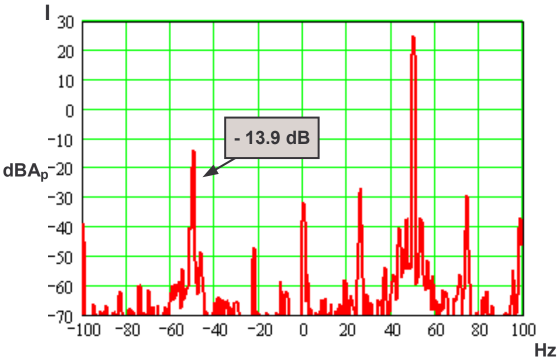

Fig. 12. Current spectrum after ageing cycle

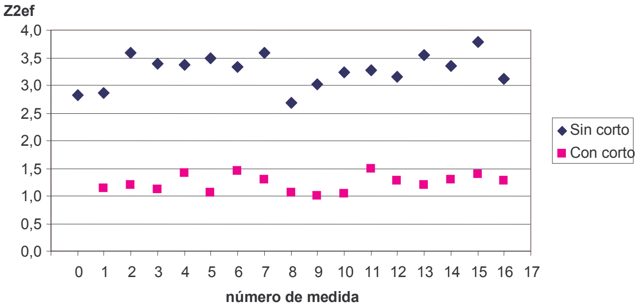

Fig. 13. Z_{2ef} values in each phase of the ageing cycles

The method based on the study of negative-sequence impedance is sensitive for detecting shorted turns when the number of turns involved is low (0.85%).

No significant changes were observed in the shorted turns detector after 16 ageing cycles. The currents flowing during the ageing phase are 13 times higher (40 A) than the rated one (3.2 A). The evident damage caused so far to the winding insulation by the high currents flowing in the shorted turns is not detected by Z_{2ef}.

The study is not yet finished, since after 16 ageing cycles the motor is still working. Valuable information about the behaviour of the shorted turn detector as the insulation ages will be obtained at the end of the useful life of the motor.

Acknowledgement

This work was supported by the Spanish Plan for Research & Development (CICYT) under Project DPI 2002-03628.

References

[1] G.C. Stone, B, K Gutpa and M. Kurtz:_*Investigation of turn insulation failure mechanism in large AC motors.*_IEEE Trans. on Power Apparatus and Systems, vol pas-103, Sept 1993.

[2] B. K. Gupta, I. M. Culbert: *Assessment of insulation condition in rotating machine stators*. IEEE Transactions on Energy Conversion, Vol 7. Nº3 Sept. 1992.

[3] O. M. Nassar: *The use of partial discharge and impulse voltage testing in the evaluation of interturn insulation failures of large ac motors,* IEEE Trans. on Energy Conversion Vol EC-2 Nº, 4 Dec. 1994.

[4] P. G. McLaren, M. H. Abdel-Rahman: *Modelling of large AC Motor Coils for steep-fronted surge studies*, IEEE Transactions on Industry applications, Vol, 24, nº 3 may/june 1988.

[5] P. J. Tavner, J. Penman: *Condition monitoring of Electrical Machines, Research Studies Press Ltd. Lecthworth, Hertfordshire England,* ISBN 0 86380 061 0.

[6] Penman, J., Sedding, H. G.; Fink, W. T.: *Detection and location of interturn short circuits in the stator windings of operating motors,* IEEE Transactions on Energy Conversion, VOL 9, NO. 4, December 1994.

[7] M. F. Cabanas et al., *Experimental Application of Axial Leakage Flux to the Detection of Rotor Asymmetries, Mechanical Anomalies and Inter-turn Short circuits in Working Induction Motors*, in Proc. Intern. Conf. on Electrical Machines ICEM´98, Istambul, Turkey.

[8] M. G. Melero, M. F. Cabanas, F. R. Faya, C. H. Rojas, J. Solares; *Electromagnetic torque harmonics for on-line interturn shortcircuits detection in squirrel cage induction motors,* in Proc. 8th European Conf. on Power Electronics and Appl. EPE´99, Lausanne, Switzerland.

[9] G. M. Joksimovic, J. Penman; *The detection of inter-turn short circuits in the stator windings of operating motors,* IEEE Trans. on Ind. Electronics, Vol 47, Nº. 5, October 2000.

[10] A. Stavrou, H.G. Sedding, J. Penman; *Current monitoring for detecting inter-turn short circuits in induction motors,* IEEE Trans. on Energy Conversion, Vol 16, Nº. 1, March 2001.

[11] A.J.M. Cardoso, S.M.A. Cruz, D.S.B. Fonseca; *Inter-turn stator winding fault diagnosis in three-phase induction motors, by Park´s vector approach,* IEEE Transactions on Energy conversion, VOL 14, September 1999.

[12] S.M.A. Cruz, A.J.M. Cardoso; *Stator winding fault diagnosis in three-phase synchronous and asynchronous motors, by the extended Park´s vector approach,* IEEE Transactions on Industry Applications, VOL 37, NO. 5, September/October 2001.

[13] J. Sottile, J.L. Kohler; *An on-line method to detect incipient failure of turn insulation in random-wound motors*. IEEE, Trans. on Energy Conversion,Vol 8, nº4 Diciembre 1993.

[14] J. L. Kohler, J. Sottile, F.C. Trutt; *Condition monitoring of stator windings in induction motors: Part I—Experimental investigation of the effective negative-sequence impedance detector*. IEEE, Transactions on Industry Applications, Vol 38, nº5 September/October 2002.

[15] M. F. Cabanas et al., *A new methodology for applying the FFT to induction motor diagnosis,* in Proc. The 1999 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives SDEMPED´99. Gijón, Spain. 1-3 Sept. 1999.

[16] M. F. Cabanas, M.G. Melero, G.A. Orcajo, J.M. Cano, F. Briz, G. Capolino, and H. Henao, *The dispersion in the calculation of effective inverse sequence impedance of induction motors: a solution based on the Complex Fourier Transform*, in Proc. International Conference on Electrical Machines – ICEM'2000, Helsinki August 2000.

[17] M. G. Melero, M. F. Cabanas, C. Rojas, G. A. Orcajo, J. M. Cano, J. Solares; *Study of an Induction Motor Working Under Stator Winding Inter-Turn Short Circuit Condition,* IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives SDEMPED 2003. Atlanta, USA. 24-26 Aug. 2003.