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RELATIONSHIP BETWEEN ALTERNATIVE METHODS OF MONITORING THE CONDITION OF ELECTRICAL MACHINES

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1. INTRODUCTION

A recent estimate of the total annual maintenance bill for manufacturing industries in the UK has been put at £15Bn., and it is suggested that potential savings of £1.3Bn could be achieved by the application of condition monitoring, ([1] The March Report). Up to 10% of the saving will be as a result of action on rotating machines.

The principal means of assessing the condition of rotating electrical machines is through the use of vibration sensing, and analysis. Appropriate techniques have been developed to a high level of sophistication, and this has enabled large data bases to be established, which has in turn led to the founding of international standards of tolerable limits, for example VDI 2056 and BS 4675. Vibration monitoring has a long history of use, and this is a major factor in its success.

More recently however, other routes to the detection of atypical operation have been developed by examination of the machine supply currents, and leakage magnetic fields, [2 - 7]. These techniques have not yet built up a practical background to compare with vibration monitoring, and must therefore rely more heavily on their predictive capacity. Since the production of force, (and hence vibration), in an electromagnetic machine results from the interaction between currents and magnetic fluxes, there is an obvious link between all three parameters.

In this contribution we will examine some of the relationships between vibration, line current, and leakage flux. It will be demonstrated that different fault conditions may be identified more readily by one method, in preference to another, but the use of more than one monitoring parameter can often increase the confidence in the diagnosis of a faulty condition.

In the following sections we consider the effects of; electrical supply imbalance, inter-turn short circuits on the stator winding, rotor bar problems in induction machines, and mechanical imbalance and looseness of rotating elements.

2. OVERVIEW OF THE MONITORING TECHNIQUES

2.1 Vibration

Vibration measurement has a vast literature associated with it, of which a representative sample is provided in [7]. Also, the suppliers of vibration measuring systems often provide the user with good guidance to the frequency components that are indicative of the more common mechanical problems of rotating machines.

The main sources of vibration in electrical machines are;

i) the stator and frame response to the force between and stator,

ii) the response of the end windings to the forces on the conductors,

iii) the dynamical behaviour of the rotor,

iv) the bearing response to transmitted vibration.

Under (i), above, components identifiable with the sums and differences of the components present in the rotor and stator currents must be expected. It is here, therefore that similarities between current and flux spectral components must be anticipated.

The response of the end windings should be measured directly, and will not be considered here. The remaining two categories relate to the dynamics of the machine and, in general, excite responses that can be separated from the electromagnetically induced components referred to above. The dynamics of the machine, on the other hand, can induce changes in the supply current drawn, and the leakage flux resulting. The results shown below will illustrate these points.

2.2 Current Harmonics

The rationale behind the use of line current monitoring is relatively straight forward. Under normal conditions the current drawn by an induction machine should contain but a single component at supply frequency. Changes in load will modulate the amplitude of this current to produce sidebands. Any defect in the electrical circuits of the rotor will result in an effective variation in torque production, (which can be thought of as a change in load), as the defect slips past the airgap field. Hargis [2] has shown that this produces a twice slip frequency modulation of the line current, and because the rotor does not have infinite inertia, there is an associated small speed variation which leads to sidebands of line current at $f_1(1 \pm 2s)$, where f_1 is the supply frequency. The ratio of the lower sideband to the fundamental provides an indication of the number of damaged rotor bars, Juffer [8], and commercially available instruments have been developed using this principle.

Clearly the changes in line current will have an associated effect on the composition of the leakage magnetic field, and the speed variations will produce changes in the frame vibration.

Because of the presence of rotor slotting sidebands at $\pm 2sf_1$ will also be produced around the slot harmonic frequencies, [9], given as,

$$f_s = f_1\{ N(1 - s)/p \pm k\}........(1)$$

Where N is the number of rotor slots, p is the number of pole pairs, and k is a low integer number.
This leads to vibration components at twice these frequencies, and at the sum and difference frequencies of these components taken with the fundamental

2.3 Leakage Flux Harmonics
A search coil, or other form of flux sensing device placed on the longitudinal axis of an electrical machine will detect the leakage flux exiting the machine in the axial direction. Because an electrical machine has an infinite number of axes of symmetry in the plane normal to the axis, there should, in theory be no net axial field produced by a machine running under normal conditions. In practice, however there are always electrical and magnetic circuit asymmetries due to building tolerances and material imperfections. This being the case the axial field will contain harmonic fluxes corresponding to the harmonic currents flowing in both the rotor and the stator. In the same way in which current sensing effectively employs the whole of the stator winding as a search coil to examine the condition of the rotor, flux sensing does this too but it also employs the rotor winding as a search coil to examine the stator.

The above argument shows that there will always be a rich spectrum of flux harmonics to be found in the axial leakage field. Furthermore, should any fault occur that disturbs the inherent electric or magnetic symmetry of the machine then this will be detectable as a change in the pattern of axial flux. This is best appreciated by considering an example.

It is well known that a balanced 3-phase winding produces a rotating set of space flux harmonics of order $6n \pm 1$, which can be simplified to the form,

$$B_s = B_1\cos(wt-p\theta) + B_5\cos(wt+5p\theta) - B_7\cos(wt-7p\theta) + B_{11}\cos(wt+p11\theta) \quad ...(2)$$

where θ is the instantaneous angular position of an arbitrary point on the rotor with respect to a stator datum position. These space harmonics are due to the fundamental time harmonic of the supply, other time harmonics are easily added.

To find the harmonic currents induced in the rotor the components of (2) can be expressed in the rotor frame of reference, by letting,

$$\theta = w_r t, \text{ and } w_r = (1-s)/p$$

Substituting these expressions in (2) gives the frequencies of the currents induced in the rotor due to the space harmonics of the balanced winding. They are, in terms of fluxes,

$$B_s = B_1\cos(swt) + B_5\cos[(6-5s)wt] - B_7\cos[(7s-6)wt] \quad ...(3)$$

These harmonics, plus the fundamental of the supply will appear in the axial flux spectrum. Now suppose an inter-turn short circuit occurs in the stator winding. Clearly, for a 2p-pole machine the short circuit currents will produce a pulse of mmf with a mark : space ratio of 1 : (2p-1). Simple Fourier analysis of this pulse provides the space harmonics, from which the corresponding time harmonics are calculable. If we include the 3^{rd} time harmonic of the supply the harmonics due to the fault can be shown to have a general term,

$$B_s = B_n\cos[\{k \pm n(1-s)/p\}wt] \quad ....(4)$$

for $k = 1,3$ and $n = 1,2,...(2p-1),(2p+1),....(4p-1)$,

This suggests that changes in these components should be looked for in the spectrum of axial flux, as evidence of a shorted turn, but the $2p^{th}$ harmonics will remain unaffected.

The above expression represents a large number of harmonics, but in practice only the lower orders will be of significance. Following a similar line of reasoning series of harmonics that are sensitive to a variety of faults can be generated. These are summarised for some common faults, below in Table 1.

RELATIONSHIP BETWEEN METHODS OF MONITORING

Table 1.

Fault Type	Harmonics
Negative phase sequence, or loss of phase	$[k \pm n(1-s)]f_1$
Short on stator winding	f_1, $[k \pm n(1-s)/p]f_1$
Slip ring fault	$[ks \pm n(1-s)]f_1$
Broken rotor bar, or short on rotor winding	$(1-2s)f_1$, $(1+2s)f_1$, $[ks \pm n(1-s)/p]f_1$

3. TEST RESULTS

A series of test were conducted on a laboratory test rig, comprising a 4KW, 4-pole, 3-phase cage induction machine, driving a 6-pole synchronous machine. The induction machine had a rotor bar disconnected, and it was also possible to initiate an inter-turn short circuit on the stator winding. The mechanical security of the machine and the load motor could be adjusted, and the supply could be unbalanced, or single phased.

The following selection of results confirm the expected relationships.

3.1 Broken Rotor Bar

The development of the arguments of section 2, above suggest that a lower sideband should appear around the supply frequency component in both the axial leakage field and the line current. Also, from Table 1, components around 25Hz and 75Hz should be identifiable in the leakage field. More precisely these will appear as sidebands displaced by $\pm sf_1$ around the centre frequencies.

For machines with rotors of all but the most massive inertia the speed modulation effect should also produce sidebands in the force wave around the supply frequency. The sidebands in the current, flux, and radial vibration spectra are shown in figures 1 - 3, whilst the wider band spectrum of flux is given in figure 4. In each case the machine was loaded to half full load, with a running speed of 1480 rpm.

For comparison, and reference the wider band spectra of both current and flux, under no load conditions, are given in figures 5 and 6.

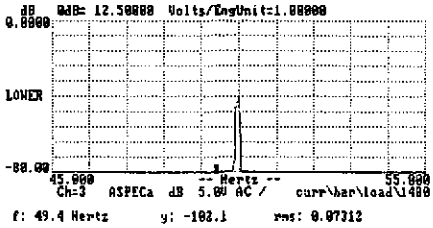

Figure 1

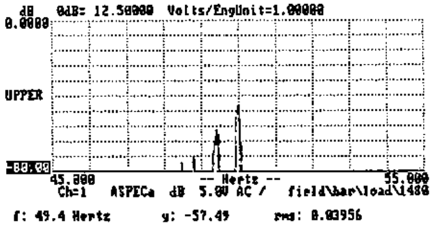

Figure 2

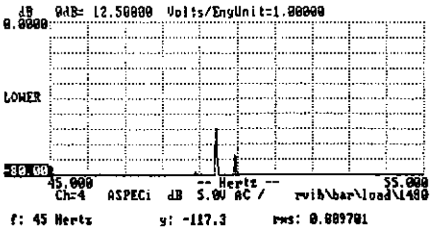

Figure 3

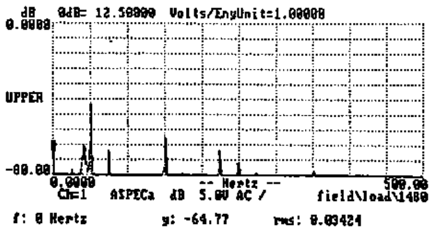

Figure 4

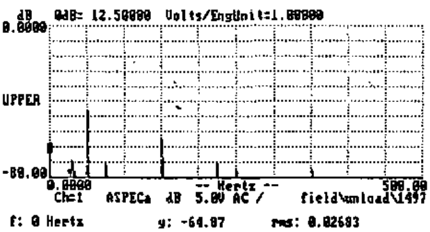

Figure 5

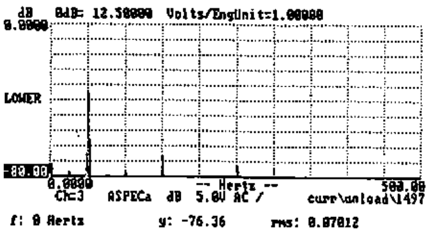

Figure 6

3.2 Loss of Phase

In this test one of the supply lines to the machine was simply disconnected whilst the machine was operating under the same load conditions that were described in the previous test. Under such conditions Table 1 predicts that there will be an increase in the components close to the even multiples of the supply frequency in the spectrum of the leakage flux. This is clearly seen by comparing figure 7 with figure 5. The line current, under these conditions is given in figure 8, but as expected there is little difference between this response and that of figure 6, although some growth in 3rd harmonic is apparent. This is due to an increased level of current in the remaining two phases.

The increased even order flux harmonics will interact with the current to excite vibration multiples of the supply frequency. There will also be an interaction between these components and the dynamically induced components of vibration at running speed, and it's multiples. This results in a rich production of sidebands, as illustrated in figures 9 and 10, which represent the axial vibration of the frame without and with the phase removed,respectively.

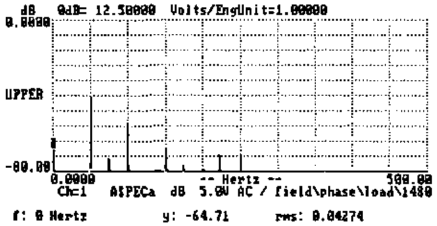

Figure 7

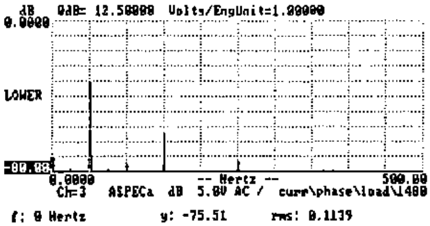

Figure 8

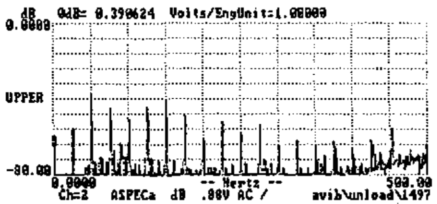

Figure 9

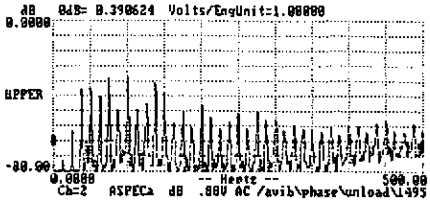

Figure 10

3.3 Stator Winding Short Circuit

With the induction machine running on no load, an inter-turn short circuit was introduced, with the fault current limited to twice the normal full load value of the machine. The spectral responses of flux, current, and axial frame vibration are shown in figures 11, 12, and 13, respectively.

Several things emerge. Comparison between figures 5 and 11 show the expected increase in the f_1 component, plus the other changes predicted by the appropriate expression in Table 1. There are, however no substantive changes in the current and vibration signals, (compare figures 12 and 13 with figures 6 and 9). This may be explained by realizing that the leakage field provides an indication of the change in the net unbalanced flux in the axial direction. In absolute terms the flux produced by the current limited fault may be very small compared to the main airgap field. Consequently it may have little impact on vibration.

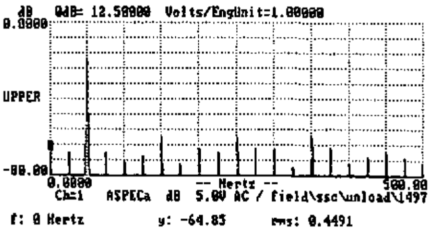

Figure 11

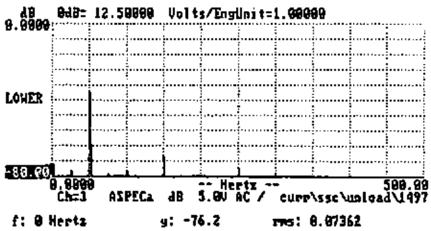

Figure 12

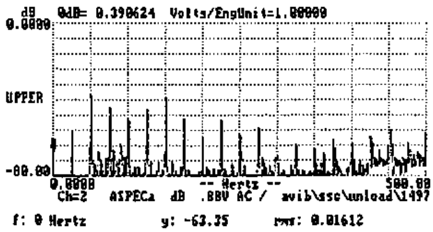

Figure 13

3.4 Mechanical Imbalance and Looseness

Throughout the test procedures the machine was operated with the frame mounting bolts slackened on one side of the machine. Also, the drive end bearing was observed to have a larger amount of play than one would expect in a properly proportioned assembly.

The machine was run, on no load but, connected to the driven machine. The looseness of the mountings can be identified clearly by the extensive number of higher orders of the running speed in the wide band spectrum of radial vibration, given in figure 14.

According to equation (1), the sloppiness of the drive-end bearing, which will induce a small degree of dynamic eccentricity, should result in the appearance of high order harmonics related to the number of rotor bars in the induction machine. The machine has 32 bars, which predicts components of line current, and leakage flux around 750Hz and 850Hz. The corresponding vibrational components will be at twice these frequencies. Their occurrence is confirmed in figures 15, 16 and 17, respectively.

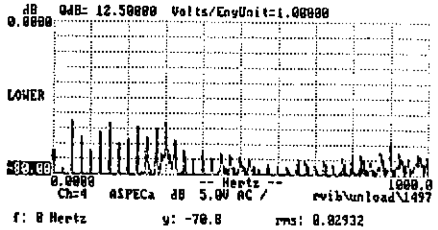

Figure 14

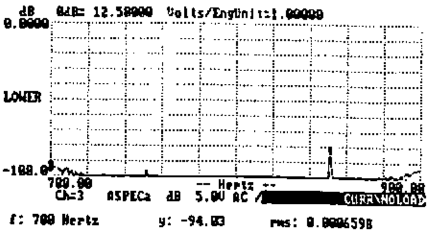

Figure 15

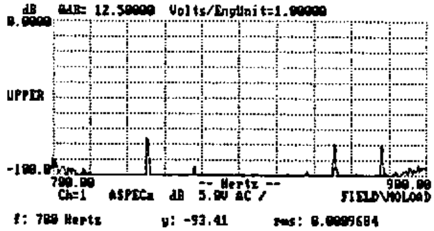

Figure 16

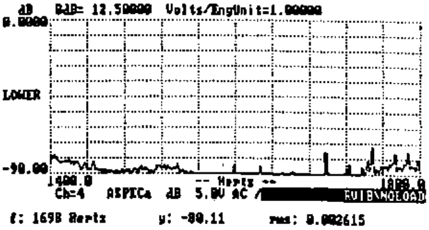

Figure 17

4. CONCLUDING REMARKS

The results presented above confirm the relationships between the different forms of condition monitoring that we have discussed. It has also been illustrated that certain fault conditions are often more readily identifiable by one method, in preference to the others.

Where diagnosis is difficult, additional confidence in a decision can be gained through the use of more than one monitoring technique. This may be of great importance if the resulting action can have significant consequences for the production process under surveillance.

5. REFERENCES

[1] The March Report, HMSO, 1986
[2] C Hargis, B G Gaydon, K Kamash, "The Detection of Rotor Defects in Induction Machines" Proc EMDA Conf, IEE, London, Publ 213, 1982, pp216-220
[3] F Notelet, G Ravilitera, "Assessment of Induction Motor Eccentricity Deduced from Fluctuations of the Feeding Currents" Proc ICEM Conf, Lausanne, 1984, pp1177-1179
[4] J R Cameron, W T Thompson, A B Dow, "Vibration and Current Monitoring for Detecting Eccentricity in Large Induction Machines" Proc EMDA Conf, IEE, London, Publ 254, 1985, pp173-179
[5] J Penman, M N Dey, A J Tait, W E Bryan, "Condition Monitoring of Electrical Drives" Proc IEE, Vol 133, pt B, No 3, 1986, pp142-146
[6] S Fruchtenicht, E Pittius, H O Seinsch, "A Diagnostic System for 3-phase Asynchronous Machines" Proc EMD Conf, IEE, London, Publ 310, 1989, pp163-171
[7] P J Tavner, J Penman, "Condition Monitoring of Electrical Machines" Pub RSP Ltd, England, 1987, pp286
[8] M Juffer, M Abdulaziz, "Influence d'une Rupture de Barre ou d'un Anneau sur les Characteristiques Externes d'un Moteur Asynchrone a Cage" Bull SEV/VSE (Switz), Vol 69, No 17, 1978
[9] W T Thompson, R A Leonard, A J Milne, J Penman "Failure Identification of Off-shore Induction Machines using On-condition Monitoring" Rel Eng, Vol 9, 1984, pp49-64