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MAGNETIC FIELD ANALYSIS FOR HEALTH MONITORING OF INDUCTION MOTOR USING SEARCH COIL : AN EMPIRICAL REVIEW AND ANALYSIS

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ABSTRACT

Health monitoring of induction motors is a process that may be used to great advantage in mining and other industrial applications. The early detection of motor winding deterioration prior to a complete failure provides an opportunity for maintenance to be performed on a scheduled routine without the loss of production time. Presented in this paper is a review of theoretical and experimental analysis of a voltage mismatch technique that may be used in operating situations to monitor the health of induction motor windings. This review concentrates on the condition based or predictive maintenance approach which entails providing assessment of machine condition based on measured data. It extends previous work in this area by demonstrating the robust nature of the monitoring process not only under conditions of power supply unbalance but also in situations where motor construction imperfections exist and mechanical loads are unpredictable. A suggested procedure for application of this condition monitoring process in industrial situations is also included.

KEYWORDS

Magnetic Field Analysis in Health, Usage of Induction Motor in Medical and Health Sciences, Search Coil, Health Monitoring

INTRODUCTION

Magnetic field analysis for health monitoring of induction motor using search coil is a review to the collection of fault related data associated with induction motor drives. The stator to rotor magnetic flux of an induction motor is monitored by a number of strategically positioned search coils, each wound around a single stator pole. The data collected is in the form of time records of the induced voltage in the coils and is subsequently used to form the data base for a fault detection and diagnosis strategy. Health Monitoring or Condition monitoring (CM) is widely employed in order to detect the onset of faults on induction motors and associated machinery. The fault condition will ideally be detected at an incipient stage which will potentially reduce those costs associated with unplanned breakdowns [1]. The types of faults being monitored by CM are often referred to as 'soft' or 'drift' faults where components drift outside their normal operating characteristics due to factors such as wear and operational stresses. Drift faults are subject to an increasing level of severity until they reach an unacceptable level, at which point the system no longer operates within satisfactory performance limits. The role of CM is to detect and diagnose these faults before they reach an unacceptable level. In general CM can either be applied to condition checking which results in an alarm activation if a pre-set limit is reached, or trend monitoring where the machine condition is continuously monitored and recorded. It is preferable to perform CM under normal operating conditions and with normal operational inputs rather than applying special test signals to the system. This saves the expense and complexity of injecting special test signals such as low-levels of pseudo-noise added to the normal operational input signals. In all cases a systems 'healthy' response is established when the monitored system is known to be performing correctly [2]. It is possible to perform CM under both transient and steady state conditions, since these two conditions are invoked under normal switch on and run conditions respectively. 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 low levels of 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. In the text of the paper, a theoretical justification for the use of the suggested predictors is presented. Initial verification of the approach is accomplished with laboratory experiments conducted on a universal laboratory machine operating as an induction motor. Results of these experimental observations are then compared with a corresponding theoretical investigation using a general induction motor model similar to that developed in. The general motor model is then utilized to supplement the experimental verification process and a proposed step-by-step procedure for application of the process in a mining environment is provided.

LITERATURE REVIEW

This research employs coils to monitor the magnetic flux in the stator of a 4 kW, 415 V, 50 Hz, 4-pole, 1425 r.p.m. squirrel cage induction motor. Researchers, including Voitto Kokko [2], state that measurement of flux by magnetometers and Hall effect sensors are not reliable enough for condition monitoring purposes. Hall effect devices have a high temperature dependency and also require an external power supply. In addition the reliable lifetime of these sensors is probably lower than that of induction motors. It is stated [3], however, that flux coil, or search coil, sensors can reach adequate reliability for useful condition monitoring of induction motor drives. The useful frequency range of a flux coil sensor is stated as approximately 0.2 Hz to 15 kHz, a range that is more than adequate for this research. This research is based upon the author's hypothesis that the condition, healthy or otherwise, of the induction motor driven system, described in this thesis, can be determined by using a number of strategically positioned search coils, each sensitive to the state of the induction motor stator to rotor air-gap flux. The starts and finishes of the three search coils were identified, labeled, and brought out via the motor terminal box to a terminal block. It has already been well reported that electromechanical faults on the motor can be detected and diagnosed by MCSA [3]. The stator flux can be used to detect not only electromechanical faults which develop on the motor itself but also a range of mechanical faults present on the immediate mechanical system connected to the motor. This basic idea is supported by a number of researchers including Daily and in particular Korde and Thomson which states; "When MCSA was initially applied in industry in the early1980s to diagnose broken rotor bars it was observed that current components could also be induced due to the mechanical load or drive train characteristics". This seems reasonable since faults on the connected load which are mechanical in nature will be exhibited as vibration, rubbing etc, the energy for which must be provided by the supply. It is therefore reasonable to assume that mechanical load faults will have the measurable effect of modulating both the supply current and the resulting stator flux.

MONITORING AND ANALYSIS

Thermographic analysis uses the heat generated, transmitted, or reflected by a machine to determine the condition of the machine. An infra red camera can be employed to detect infra red radiation from the surface of an object. Typical monitoring points would include areas around rotating machine bearing housings, supply cables and connections, control gear fuse holders etc. Infra-red monitoring is non-intrusive and can be performed under normal machine operating conditions. Infrared scanning can be used effectively for almost any system in which surface heat distribution is representative of operating condition. During a survey an infra red image of a machine's heat distribution is stored and a digitized photographic-like heat contour image can be produced for reporting purposes. The color map given in the image ranges from dark blue representing cooler areas through red, orange, yellow and finally to white which represents the hottest areas. The actual temperature range which these colors represent can be selected using the camera ranging functions provided. Crosses can be placed at appropriate locations on the image, each cross location is labeled and the temperature at the position of each cross can be displayed for reporting and analysis purposes. This method can be employed with equal effect to monitor both the condition of the induction motor and the plant being driven. Infrared Thermography (IRT) inspections are identified as either qualitative or quantitative. The quantitative inspection attempts the accurate measurement of the temperature of the item under test. This requires detailed knowledge and understanding of the relationship of temperature and radiant power, reflection, emittance, and environmental factors, as well as the limitations of the detection instrument. Qualitative measurements are time-consuming, and are not normally required for condition monitoring purposes. The qualitative inspection is interested in relative differences, hot and cold spots, and deviations from normal or expected temperature ranges. Qualitative inspections are significantly less time-consuming since the thermographer is not concerned with highly accurate temperature measurement. Instruments that perform infrared detection detect electromagnetic energy in the short wave (3 to 5 microns) and long wave (8 to 15 microns) bands of the spectrum. A short wave instrument is best for inspections of electrical and mechanical equipment, although when taking readings in situations subject to solar reflections shiny surfaces may appear to be hotter than they really are. IRT instruments are normally portable, are sensitive to within ±0.2 ºC over a -100 to +3000 ºC, and accurate to within ±3%. In addition, the instrument must be capable of storing thermographic images for later analysis. Thermography is limited to line of sight and care must be taken to account for material color, material geometry, and environmental factors such as solar heating and wind effects.

INDUCTION MOTOR FAULTS

Induction motors are susceptible to many electrical and mechanical faults. Commonly occurring major types of faults in the induction motors [4] electrical faults— Poor power quality of the input supply to the motor/supply unbalance, single phasing, unbalanced phase currents, poor and faulty capacitor(s), etc.; stator faults—shorting and opening of a portion of stator phase winding, stator insulation weakening, etc; broken rotor bar(s) or broken end rings mechanical faults: bearing failure and fatigue-–inner and outer race defect, ball defect, train defect, abnormal displacement in bearing races, etc; bent rotor shaft; static and dynamic air gap eccentricity. Among all the faults mentioned earlier, the bearing faults. Different types of air gap eccentricity. (a) Static Eccentricity.

(b) Dynamic Eccentricity. stator faults, broken rotor bar faults or/and end ring failures, and the eccentricity related faults are the most happening ones and their occurrence probability decreases in the order they have been mentioned earlier. The motor faults are instigated due to various stresses that affect the working of machine components. Various types of stresses that are instrumental in initiating machine faults are [5]: Thermal stresses due to ageing, overloading, cycling, etc., electrical stresses, such as transients, corona, etc. magnetic stresses, such as unbalanced magnetic pull (UMP), etc., mechanical stresses, such as coil movement, rotor rub, etc., dynamic stresses, such as shaft torques, centrifugal forces, etc. and environmental stresses due to moisture, presence of acidic and basic chemicals, etc. These faults result in unbalanced air gap voltages, unbalanced line currents, increased torque pulsations, decreased average torque, increased losses, poor efficiency, and excessive heating. These motor faults affect the stator current profile/spectrum in a definite way.

ROOT CAUSE ANALYSIS OF FAULT EFFECTS

The faults applied to the system for the purpose of this research will have two predominant effects upon the outputs obtained from the search coils. The applied faults will require fault related modulations to the energy taken from the supply and hence the current and stator to rotor flux pattern. In addition any fault related radial or axial movement or vibrational activity in the load will be reflected back to the rotor and will result in fault related rotor positional perturbations. The fault induced rotor positional perturbations will have an effect on the reluctance of the motor magnetic circuit and hence will produce fault related perturbations in the magnetic flux linking the search coils. This stator to rotor flux perturbations will be reflected in the induced emfs produced in the search coils.

MOTOR ROTOR DYNAMIC ECCENTRICITY

Rotor eccentricity in induction motors takes two forms, static eccentricity and dynamic eccentricity. Static eccentricity is where the rotor is displaced from the stator bore centre but is still turning upon its own axis. Dynamic eccentricity is where the rotor is turning upon the stator bore centre but not on its own centre. The causes of either type of rotor eccentricity include incorrect bearing positioning during assembly, worn bearings, bent rotor shaft etc. Eccentricity causes a force [6] on the rotor which tries to pull the rotor even further from the stator bore centre. The magnetic pull is the result of Maxwellian pulls which affect elements of the surface of stators and rotors of electrical machines. In the case of static eccentricity this is a steady pull in one direction. In the case of dynamic eccentricity, the form of eccentricity considered in this research, eccentricity produces an unbalanced magnetic pull (UMP) which acts on the rotor and which rotates at rotor speed. The air gap eccentricity refers to the condition of unequal air gap between stator and rotor. The eccentricity, if substantial, may result in UMP forces (UMPF), and this can result in the damage of the stator and/or rotor due to stator to rotor rub. Some of the possible causes of the air gap eccentricity are shaft deflection, inaccurate positioning of the rotor with respect to the stator, bearing wear, and stator core movement. There are two types of air gap eccentricity: static eccentricity and dynamic eccentricity. Static eccentricity is

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space dependent and refers to the condition of asymmetrically placed motor shaft in the air gap region. The probable causes for the static eccentricity are oval stator cores and the incorrect positioning of the stator or rotor. In the case of stator air gap eccentricity, the position of the minimal radial air gap length is fixed in space. Dynamic eccentricity is space and time dependent and refers to the condition when center of rotation and the center of the rotor are not the same. The probable causes for the dynamic eccentricity are misalignment of bearings, bent rotor shaft, wear-out bearings, and mechanical resonance at critical speed. An air gap eccentricity of up to 10% is generally permissible. However, the air gap eccentricity is kept lower to minimize UMPF, vibration, and noise. The static and dynamic eccentricities exist even in newly manufactured motors. The machine eccentricity can be estimated by monitoring the air gap flux density in the air gap region.

ROTOR IMBALANCE SEVERITY

Machine vibration analysis becomes one of the most important tools for machine health diagnostic. There are two types of analysis: time domain and frequency domain. In most research, the frequency domain analysis is more attractive because it is provide more detailed information about the status of the machine whereas the time domain analysis can give qualitative information about the machine condition. In general, machine vibration signal is composed of three parts, stationary vibration, random vibration, and noise [6]. Traditionally, Fourier transform (FT) was used to perform such analysis. If the level of vibrations and the noise are high, inaccurate information about the machine condition may be obtained. In this paper, Fast Fourier Transform (FFT) is used to extract some useful features of the vibration signal i.e. root mean square (RMS) value, the crest factor.

MOTOR FAULTY DRIVE-END BEARING

The motor drive bearing fault was applied damaged inner surface of the outer raceway. Ball bearings pass across the defect on the outer race and produce impacts of ball pass frequency due to outer race defect (BPFO). The bearing used during this research contained 9 balls and therefore the expected frequencies would lie in the range between 1 times BPFO and 9 times BPFO. The contact angle β referred to in figure 1.6 is relevant to an 'angular contact bearing', for this research a plain bearing was employed therefore β = 0 and cos β is equal to 1 in the given formulae. The bearing data sheet provided the pitch diameter of 52.1 mm and the ball diameter was measured as 8.6 mm. These impact frequencies would produce both modulations in supplied energy and field perturbations as previously proposed. Reference [7] also states that vibrations occur at higher frequencies, up to a few kHz or so, often related to radial resonances in bearings.

MECHANICAL FAULTS

Mechanical faults typically refer to bearing failure and eccentricity in most machines. Bearing is a mechanical component which consists of two rings and a set of balls rolling between them and it has been recorded as one of the dominant causes for electric machine failure. It could be caused by

1) Metal fatigue

2) Unbalanced stress

3) Improper installation

4) Corrosion/Contamination

These problems could result in vibrations and noise during machine operation, which are usually measured and processed as diagnosis indicators. Since bearing fault manifest itself as a vibration of rotor and unbalance air gap length, it is sometimes also classified in the eccentricity category. However, it has its own frequency signatures related to its number of balls, ball diameter and ball pitch, which is not the same as eccentricity. This is a common issue to all machines with similar effects on performance.

INDUSTRIAL APPLICATIONS

Applications of this monitoring procedure in a mining or other industrial situation would require an initial training period with the normal motor in order to build a library of *zxy* parameters as a function of motor speed. Prior to the training period, the motor system could be instrumented with three

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current transformers to continuously measure the line currents, two potential transformers for measuring the line voltages, and a speed-sensing device that would provide an electrical signal proportional to the motor shaft speed. The signal outputs from these devices could then be passed through a six-channel analog to digital converter capable of sampling each channel at a rate of about 5000 samples/s. The digital output of the converter could be fed into a laptop or other computing system that would be programmed to initiate a sampling sequence every few seconds [8]. Depending upon the dynamic nature of the system loading, the sampling interval could be adjusted to perhaps 0.2 to 0.5 s. Software within the computer could then be used to check for a reasonably constant speed range during the sample time in order to validate the sample. Assuming that the speed variation over the sample time is within an acceptable limit, symmetrical components of the phase voltages and line currents would be computed and the values of *Va1* and *Va2* would be compared with previous samples gathered at that speed. For those samples showing the largest differences, the inversion matrix for computing the *zxy* parameters should be well conditioned and a new calculation of these parameters at the measured speed may be added to the library for each previous sample that was selected. This process could then be continued over a number of complete loading cycles. At the end of this training period, the *zxy* parameters for each speed could be averaged and the library of these parameters as a function of motor speed would be available.

CONCLUSION

Both the positive and negative sequence voltage mismatch predictors have been shown to be sensitive to the inter-turn stator winding deterioration that was simulated and their performance is not degraded by voltage supply unbalances or inherent machine or sensor asymmetry. Changes in these predictors also appear to be a measure 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 (on a percentage basis) to increasing deterioration severity at the lower motor speeds that correspond to heavy loading. However, the absolute changes in the positive sequence voltage mismatch predictor are larger, particularly at high motor speeds consistent with light loading. 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 motor. This is an important attribute for predictors that will be used to monitor low levels of deterioration. Future research should include 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 non-linearities. In addition, correlations between the predictors, type of deterioration, and severity should be developed as appropriate. Finally, the application of this approach to the monitoring of machine windings in an industrial situation is needed in order to demonstrate the true applicability of this process.

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