Sensorless, Online Motor Diagnostics

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Electric motors play a very important role in the safe and efficient running of any industrial plant. Early detection of abnormalities in the motors will help avoid expensive failures. Motor current signature analysis (MCSA) implemented in a computer-based motor monitor can contribute to such condition-based maintenance functions. Such a system may also detect an abnormality in the process as well as the motor. Extensive online monitoring of the motors can lead to greater plant availability, extended plant life, higher quality product, and smoother plant operation. With advances in digital technology over the last several years, adequate data processing capability is now available on cost-effective, microprocessor-based, protective-relay platforms to monitor motors for a variety of abnormalities in addition to the normal protection functions. Such multifunction monitors, first introduced by Multilin, are displacing the multiplicity of electromechanical devices commonly applied for many years.

Following some background information on motor monitoring, this article features recent developments in providing tools for the diagnosis of faults or incipient faults in electric motor drives:

- Sensorless torque measurement
- Direct detection of turn-to-turn short circuits
- Detection of cracked or broken rotor bars
- Detection of bearing deterioration.

Motor Monitoring and Protection

Motor protective relaying has had a long history. In recent years, a set of techniques has been developed for diagnosing motor problems before they reach the point of tripping a circuit breaker or other major protective device. In other words, incipient failure is being detected. Of course, something has to change in order to detect an impending failure. The trick is to discover that effect well before the change grows into a catastrophic failure. This allows for several corrective actions to be taken. The motor may be taken offline before a total failure occurs, minimizing damage and rework costs. The cause of the impending failure may be remedied before permanent damage occurs. Or, a decision may be made to keep the motor online to maintain the process and arrangements made for a backup motor at the next shutdown.

When motors are large enough, various temperature sensors, accelerometers, and even flux sensors have been added into or onto them for this purpose. Perhaps only ten or fifteen percent of industrial motors are large enough to justify such measures, but the desire for incipient failure detection is strong for all motors above 100 HP or so. The analysis of the motor current to perform this function is particularly attractive, as the current (and voltage) sensors are usually installed in the motor control center for other control or protection functions. Thus, only intelligence, in the form of a microcomputer, need be added to the existing power apparatus so that it becomes economical to provide such features on a much larger proportion of the installed base.

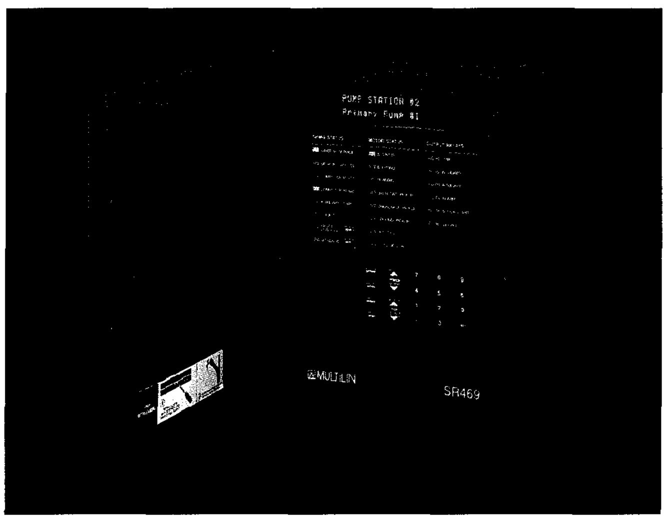

Figure 1. Multifunction monitor

As digital protection is now becoming standard, existing types of monitors may be utilized for this purpose. It then becomes desirable to provide an integrated package incorporating conventional protection plus wide-

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band load torque sensing, detection of turn-to-turn faults, rotor-cage faults, and bearing faults. Currently, several of the algorithms discussed here are being implemented in a modern computer-based electronic motor protection relay platform, such as one shown in Figure 1, for beta-site testing to gauge commercial practicality.

A review of publications on MCSA, or diagnostics based on the passive analysis of motor currents, reveals the ironic fact that there is an inverse relationship between the ease of detection of a fault (or incipient fault) and the importance to the user of the detection of that fault. For example there are dozens of papers and research theses published on the detection of cracked or broken rotor bars in induction motors and only two or three on the use of MCSA to detect bearing faults in induction motors, in spite of several studies that show bearing faults to account for almost 50 percent of motor failures as opposed to around 10 percent for rotor cage problems. These studies also noted that almost 35 percent of motor failures were attributable to insulation faults. For medium voltage motors, there is extensive literature on insulation test techniques, but only a few papers deal with the detection of turn-to-turn faults, which often precede phase-to-phase or phase-to-ground faults.

Sensorless Torque Measurement

Very few motor installations of any size incorporate torque sensors even though it is often useful to be able to monitor the magnitude of the torque being delivered to the driven process. The reason for this is not hard to see, as it is difficult to justify the considerable expense and mechanical complications of direct torque sensing for most applications. As a result, most motor users rely on monitoring the magnitude of the motor line current or, in more elaborate installations, the motor input power as a measure of the load torque in spite of the obvious deficiencies. Sensorless torque measurement is not of itself a fault detection technique, but may be used indirectly to monitor the status or condition of the driven process and aid in the detection of motor faults

Recently, however, a well known theorem has been exploited to improve on this situation by providing a means of computing air gap torque directly from the motor voltages and currents without the need to know speed or other details of the motor beyond the nameplate data. The theorem may be written explicitly in terms of the direct and quadrature axis components of stator current and flux linkages. What is being done is essentially to multiply the perpendicular components of flux and current to obtain the force on the stator windings. The direct and quadrature components of the current are obtained from at least two of the phase currents. The flux linkages are obtained by first finding the direct and quadrature components of voltage in a similar manner and then integrating them in time. The number of phases, pole pairs, and the line frequency are also required to complete the calculations.

The theorem relies on certain symmetries and assumptions in the motor analysis for its derivation. Since accuracy and precision of a few percent are desirable, a test was run on a motor using a personal computer (PC) with plug-in data acquisition cards to assess how well the theorem would meet our requirements. A small, commodity type, 3/4 HP, three-phase motor was used for convenience; its small motor characteristics (asymmetry, saturations, and typical parameters) provide a severe test of the accuracy and precision of the theorem. The result of a comparison against a high-quality, laboratory-grade torque meter, in the steady state, is shown in Figure 2. Agreement was well within ±1.5 percent except for the slight jog near zero torque. This anomaly was traced to the analog output of the torque meter that fed the data acquisition computer. Equally good results were obtained during laboratory tests when the software was ported to a commercial protective relay platform. This method of airgap torque measurement is not limited to the steady state and has a useful bandwidth up to half the sampling frequency in the usual manner.

Turn-To-Turn Fault Detection

Motors are routinely tested for turn-to-turn faults before leaving the factory and occasionally tested in the field. The usual methods require the motor to be shut down and a special high-voltage surge generator to be applied to the windings. There has, however, been no reliable

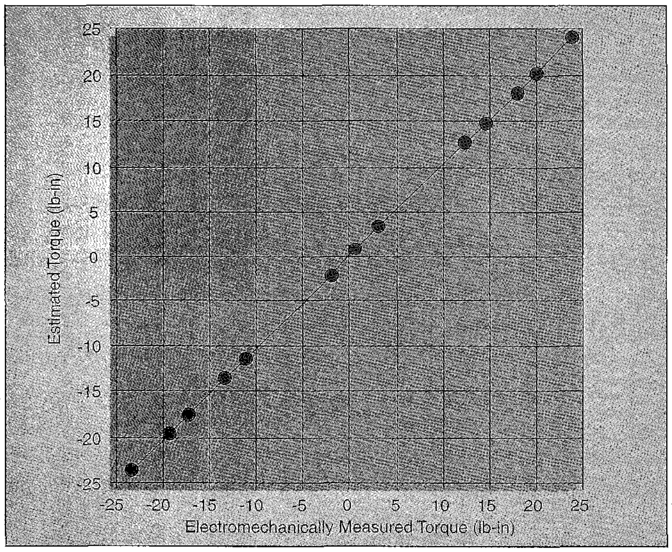

Figure 2. Calibration of the sensorless torque meter

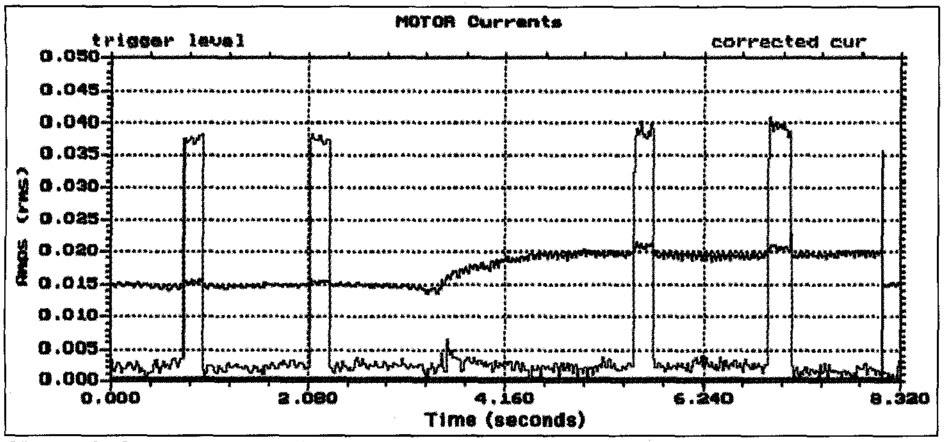

Figure 3. Corrected negative sequence current with varying load and switched turn-to-turn faults

method of detecting turn-to-turn faults online with high sensitivity and high speed using conventional motor control center instrumentation. Since it is important to catch such faults as early as possible, the highest feasible sensitivity is required. Additionally, there is often not much time from the occurrence of the fault to consequential damage of the motor (especially in random wound motors). Therefore, detection must be accomplished in a few cycles.

The basis for turn-to-turn fault detection was first set out in an analysis showing that, when a fault occurs in the windings of an otherwise symmetrical, symmetrically excited motor, the positive sequence currents do not change very much. However, a negative sequence current did appear where there should have been none. The first attempts to utilize this phenomenon as a detector recognized that negative sequence currents could also arise from an unbalanced line. The apparent negative sequence impedance was used as an indicator. The negative sequence impedance should be relatively insensitive to slip (or load). It was found, however, that the apparent negative sequence impedance behaved in ways that could not be explained readily. In addition, there was considerable variability and noise requiring averaging and trending. Thus, the method required considerable time for detection and had poor sensitivity that required high trigger thresholds.

More recent research in our laboratory has shown that the effect of a turn-to-turn fault is quite different from that previously assumed. It was found that the true negative sequence impedance of the motor is essentially constant for small faults with only small variations with speed as expected. The effect of the fault is to inject a negative sequence current into the system. That is, when there is no fault and the line is balanced, there will be no negative sequence current. When the line is unbalanced and the motor is healthy, the negative sequence current is accounted for by the negative sequence impedance. Hence, by subtracting the current in the characteristic negative sequence impedance, the injected current, which is the fault indicator, may be found. This procedure also solves a major problem of the apparent negative sequence impedance calculation when the line is close to being balanced where the result is essentially indeterminate.

The symmetrical components of a three-phase set of currents or voltages are obtained from the familiar transformation, once the line voltage and current phasors are known. Identification of the phasors in a reliable manner with good signal to noise ratio can be a problem, especially if a rapid response is needed. The method we chose was a 32-point algorithm to compute the fundamental component, on a cycle-by-cycle basis, including a corrector for frequency deviation. In this way, a filtered output was obtained, within two cycles of the line frequency, for input to the symmetrical component transform matrix. In the software implementation, a measure of the error and noise in the phasor identification is derived and used, adaptively, to set the trigger threshold in order to have maximum sensitivity under all conditions.

The procedure was implemented on a PC and exercised with a 3/4 HP, three-phase motor that was wye connected (single circuit, single strand) with 648 turns per phase. One portion of the winding was tapped so that one or more turns could be temporarily shorted by means of a mercury wetted relay. The result of one such test is shown in Figure 3 where 5 turns (0.77 percent of the 648 turn winding) were temporarily shorted. The injected negative sequence current at the motor terminals is small compared to the load or positive sequence current, but the difference between faulted and unfaulted cases is unmistakable with good signal to noise ratio. The large signal to noise ratio achieved is, in part, due to a recognition that nonfault negative sequence current is also caused by inherent asymmetries in the motor and instrumentation. Modifications to the algorithm to learn these asymmetries during normal operation and subtract out their effect were implemented in the most recent version of the software. In Figure 3, the load is at half rated for about 3 seconds and then raised to full as the fault is being turned on and off. Note also that the response (on the time scale shown) is essentially instantaneous. An expansion of the negative sequence current shows that the response is complete within two cycles. The adaptive trigger level, set at a multiple of the phasor identification error, is also shown. Note how it changes as the load and fault condition of the motor varies.

Broken or Cracked Rotor Bar Detection

Considerable effort has been put into developing broken bar detectors and several vendors offer their own versions. All of them are based on measuring the amplitude of a particular spectral component of the motor current. When there is a rotor fault, the flux distribution in the air gap is disturbed resulting in a quite predictable set of frequencies in the line current. The most prominent of them appears at twice slip frequency below the power line frequency. It is the amplitude of this sideband that is, in most broken bar detectors, used as a measure of the severity or number of broken bars. A typical motor current spectrum in the vicinity of 60 Hz for a 50 HP motor with a severely broken bar is shown in Figure 4. The method works on all induction motors from small to large, however only motors larger than about 100 HP warrant such monitoring.

Since in this case the speed was being measured simultaneously with the current, the exact frequency of the sideband has been calculated and is noted in Figure 4. There is a symmetrically placed upper sideband due

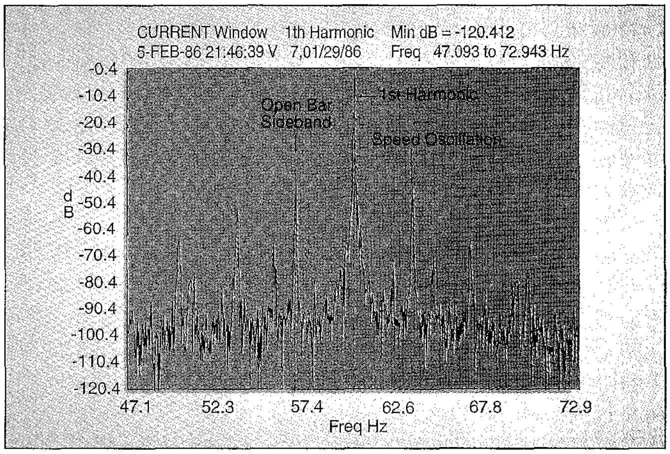

Figure 4. Current spectrum in the vicinity of 60 Hz for a 50 HP, three-phase, 460V induction motor with a fully broken rotor bar

to the speed variation resulting from the lower sideband current. Note, also, that there are numerous other features of the spectrum. Since it is usually the case that there is no reliable speed measurement available, the presence of the additional spectral components complicates the determination of the rotor condition and may, in fact, lead to a mistaken identification. Each of the broken bar detector vendors has its own means for helping to resolve this problem. More recently, the detection of cracked or broken bars has been developed within the context of the statistical techniques described in the next section. Initial results show that greater sensitivity and accuracy may be achieved while also resolving many of the ambiguities of the prior methods.

Bearing Fault Detection

A bad bearing in a motor will allow the shaft to move radially a small amount. For example, if there is a pit in one of the bearing races, the balls encountering it will "fall in" and move radially. The air gap geometry will be slightly disturbed leading to a modulation of the current. There may also be small torque perturbations associated with such faults. While some kinds of faults, such as a pit in the race, may result in predictable frequencies, others, such as a dented cage or damaged balls usually will not. The system must be able to resolve very small components of the spectrum, even when their frequencies are not definitely known, and must recognize when they differ from the nominal or healthy motor case. Recent studies have utilized neural network techniques to characterize the current spectra associated with the normal state of a motor and load. The neural network is again used to determine when the spectra have changed significantly from the nominal to indicate a fault or significant deterioration.

In examining the spectra of faulted and unfaulted bearings, however, it becomes clear that the spectra are time varying to some extent even for normal motors with nominally steady loads. When there is a bearing fault, the time variation of spectra becomes even more pronounced. This is illustrated in Figure 5 where a series of spectra for a motor with a faulted bearing are computed at intervals and displayed next to one another. The data is taken from the 3/4 HP test motor in which one bearing has two small scratches on the outer race. The spectra were computed from the total (unfiltered) current in one phase. The horizontal axis is frequency in arbitrary units but showing the band from about 146 to 154 Hz in order to include the outer race ball passing frequency. The amplitude of the spectral components is indicated by their color. The vertical axis represents several successive time intervals. In this case, the textbook calculation of the outer race ball pass frequency predicts the observed main spectrum component approximately. It should be noted that there are also significant other components. Other characteristic frequency bands are also examined. Of course, the process being driven by the motor will introduce time varying spectral components as well which are characterized by the method along with those due to the motor .

The bearing fault detector is a novel computer based algorithm to detect ball and roller bearing defects using only the stator current and the name plate information of the motor to be protected. The detector adapts itself to the operating conditions, the physical nature of the motor and utilizes statistical techniques in data processing, interpretation and decision making, resulting in high accuracy .

Detection is based on monitoring the changes in the bearing frequencies as reflected in the current spectrum. The power of the method is its simplicity in decision making, and its adaptive nature. The method consists of four stages: preprocessing, learning, monitoring, and postprocessing. In the preprocessing stage, the time fre-

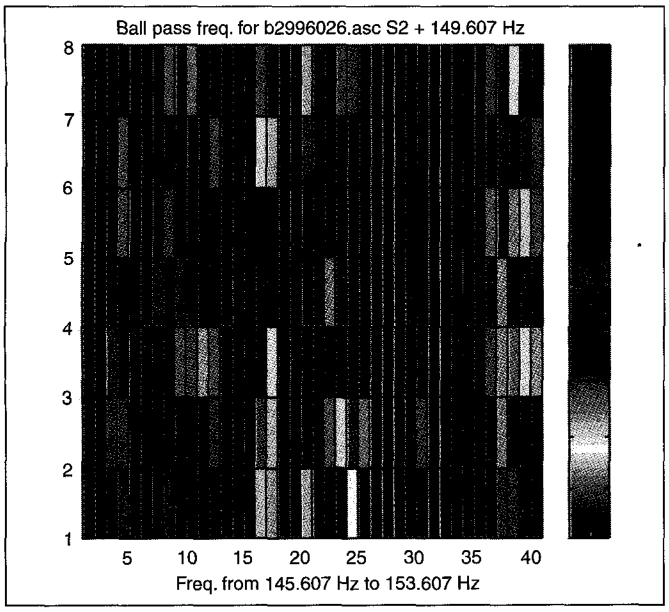

Figure 5. Time varying current spectra for a motor with a faulty bearing (horizontal axis is proportional to frequency, vertical axis is proportional to time and amplitude is indicated by color)

quency spectrum of the stator current is computed and bearing frequencies are estimated using the name plate data of the motor. In the learning stage, the algorithm is exposed to all possible normal operationg modes of the motor. Distinct operating modes are automatically identified and a reference for the bearing frequency components is extracted for each good operating mode. In the monitoring and protection stage, current data is periodically acquired and the current spectrum is computed. The bearing frequency components of the spectrum are compared with the references obtained from the normal operating modes. In the post processing stage, the trend of the potential fault signals is analyzed and a final decision is made to trigger an alarm.

Beta Sites and Practical Applications

The feasibility of measuring electromagnetic torque, the detection of turn-to-turn faults, rotor bar cracks, and bearing deterioration has been demonstrated in the laboratory and, to some extent, in the field for broken rotor bars. Several of the algorithms are being implemented in an electronic motor protection relay platform, and the devices will be upgraded with new software as it becomes available. Beta sites will be established in the power and process industry to gain the real-life operating experience needed to gauge the commercial practicality of such techniques and to indicate where further development is required.

For Further Reading

G.B. Kliman, J. Stein, "Methods of Motor Current Signature Analysis," *Electric Machines and Power Systems*, Hemisphere Publishing, New York, NY, Volume 20, 1982.

G.B. Kliman, et al, "Noninvasive Detection of Broken Bars in Operating Induction Motors," *IEEE Transactions on Energy Conversion*, Volume 3, Number 4, December 1988.

S. Williamson, K. Mirzoian, "Analysis of Cage Induction Motors with Stator Winding Faults," *IEEE Transactions on Power Apparatus and Systems.*, Volume 104, July 1985.

R.R. Schoen, T. Habetler, "Motor Bearing Damage Detection Using Stator Current Monitoring," *1994 IEEE Industry Applications Society Annual Meeting Conference Proceedings.*

G.B. Kliman, W.J. Premerlani, R.A. Koegl, D. Hoeweler, "A New Approach to Online Turn Fault Detection in AC Motors," *1996 IEEE Industry Applications Society Annual Meeting Conference Proceedings.*

Biographies

Gerald B. Kliman received his SB, SM, and ScD degrees from the Massachusetts Institute of Technology in 1955, 1959, and 1965, respectively. From 1965 to 1971 he was assistant professor of electrical engineering at Rensselaer Polytechnic Institute, Troy, New York. Since 1971, he has been with the General Electric Company. At GE Corporate Research and Development, Schenectady, New York, he has worked on linear induction and synchronous motor research, advanced drive systems, electric propulsion, advanced magnetic materials applications, vibratory motors, induction motor harmonic behavior, and incipient fault detection. He holds 27 patents. He has served on the Land Transportation, Rotating Machinery Theory, and Industrial Drives committees. He is an associate editor of *Electromechanics and Power Systems Journal* and has served on the organizing committee of the International Conference on Electrical Machines and on the Scientific Committee of the International Conference on Reliability of Electrical Machinery and Apparatus (Budapest). He is a member of Sigma Xi, Tau Beta Pi, Eta Kappa Nu, the American Physical Society, and a Fellow of the IEEE.

William J. Premerlani obtained his DEng degree in electric power engineering from Rensselaer Polytechnic Institute in 1974, and has more than 20 years experience as a computer scientist and electrical engineer at GE's Corporate Research and Development Center. He has a wide range of research interests, including medical imaging, digital signal processing, distributed power system protection and control, and software engineering. He is a coauthor of a textbook on object-oriented technology, *Object-Oriented Modeling and Design*, from Prentice-Hall. His current research interests include motor diagnostics and advanced power system protection algorithms.

Birsen Yazici received her BS degree in 1988 in electrical engineering and mathematics from Bogazici University, Istanbul, Turkey, her MS degree in 1990 in mathematics, and her PhD in 1994 in electrical engineering, both from Purdue University, West Lafayette, Indiana. She is currently with the GE Corporate Research and Development Center. Her research interests include applied mathematics, time series analysis, pattern recognition, digital image processing, and condition monitoring and fault diagnosis. She is a senior member of the IEEE.

Rudolph Koegl is an electrical engineer in the Control Systems and Electronic Technology Laboratory of GE's Corporate Research and Development Center. He is a member of Eta Kappa Nu and holds the degrees of MSCS from Union College, Schenectady, New York, and BEEE from Pratt Institute, Brooklyn, New York. His work has included development of the software systems architecture of the XINI (X-ray Inspection Module), a system designed to inspect aircraft engine turbine blades; the GE DATAQ Radial Crack Detection System, a system designed to detect radial cracks in steam turbine rotors; the development of the EPRI Broken Bar Detection system, a system designed to detect broken bars in large horsepower induction motors; development of the GE cosponsored Hybrid Electric Bus real-time communication system; and most recently, turn-to-turn fault detection. He has coauthored 10 papers and holds 7 patents in a variety of areas.

Jeff Mazereeuw is a project engineer at GE Multilin located in Markham, Ontario, Canada. He is the designer of the SR469 Motor Management Relay.