MCM; An Inexpensive, Simple to Use Model Based Condition Monitoring Technology

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Abstract

This paper presents an award-winning product, Motor Condition Monitor (MCM), for predictive maintenance of three phase systems, including electric motors, generators, transformers, and the equipment or process driven by them. MCM measures only voltages and currents. It has the ability of maintenance planning by detecting impending mechanical and electrical failures at the early stages of fault development through continuous monitoring. MCM also provides the user with the diagnostic information. The primary function of MCM is to provide early warning of progressively deteriorating machine and process conditions to prevent unplanned downtime, and improve productivity. The patented MCM core technology stems from a decade-long research effort, which previously has been applied in the U.S. to the Space Shuttle Main Engine, helicopter engines and gas turbines. MCM is an inexpensive device yielding accurate maintenance decision information that can be used by low or semi-skilled personnel. Therefore, it eliminates the shortcomings of both vibration and current signature analysis systems.

Introduction

In today's competetive business environment and low profit margins, manufacturers are faced with the growing production demands while cutting the cost of manufacturing. One pervasive cost that drags down productivity is the unplanned equipment and manufacturing process downtime [1]. Unexpected failure of processes and machinery in industrial environments is always undesirable. When these processes are critical they may lead to lost production and costly repairs. Condition monitoring is used to obtain early warning of impending equipment failure to prevent costly downtime and damage to process equipment. The basic idea behind condition monitoring is to analyze data gathered on the equipment characteristics in sufficient time so as to minimize failures as well as unscheduled interruptions in production. An increasingly widespread trend is the integration of continuous condition monitoring with predictive maintenance capabilities to factory automation systems.

There are two major areas of condition monitoring – vibration and corrosion. Vibration analysis is the larger (85%) segment of the two by a wide margin. Other technologies include infrared (IR) thermographs to detect temperature changes in bearings and shafts; tribology or analysis of the lubricating oil in a machine; ultrasonic analysis of bearing wear, to name a few.

A major application of condition monitoring is that of electric motor and motor driven systems such as pumps, compressors, fans, presses etc. Such equipment is ubiquitous throughout industry with a wide range of motor power ranging from a few watts up to a few mega watts. Vibration analysis consists of mounting sensors on the motor and measuring the vibration energy spectrum using an external data acquisition and analysis unit, typically a pc or hand-held device. Acceleration, velocity, and displacement are some of the most commonly measured quantities in vibration analysis. The basic idea is that a mechanical fault developing within the system will be exhibited as a change in the vibration energy in specific frequency ranges. A trained engineer can detect these changes by monitoring the output from the unit. In a typical case, the data obtained periodically over an extended time period (usually a year or more) would be plotted to observe any trends indicative of possible failure. The vibration based condition monitoring can be expensive, difficult to use and the results difficult to interpret for the following reasons:

- Cost; both the sensors and their associated electronics are expensive.
- Ease of installation; the mounting position of the accelerometers on the motor has to be carefully chosen for maximum sensitivity. Also mounting sensors can be a problem in inaccessible places.

- Ease of use; data gathering and analysis is time consuming and the interpretation of the data requires skill and training
- Repeatability; data obtained for vibration analysis is not repeatable. Also background vibration can interfere with the measured signal
- Comprehensive coverage; vibration analysis is effective in the detection of mechanical faults, but are not applicable for the majority of electrical faults
- Advanced warning; the threshold values used are affected by the operating conditions of the equipment. Therefore, continuous vibration monitoring systems use higher threshold values which may reduce warning time.
- Integration to factory automation systems; a significant majority of vibration systems are portable and cannot be integrated to factory automation systems.

Vibration analysis is the traditional technique that is used in industry. However, it is expensive, notoriously difficult to use, requires expertise both in acquiring the data and interpreting its results. Therefore, manufacturers increasingly demand inexpensive, simple to use condition monitoring technologies and products that can be integrated to factory automation systems with maintenance planning capabilities.

A newly developed method is introduced to overcome some of the shortcomings of vibration based systems, named as “current signature analysis”. In this method the information is extracted from the line current supplied to a motor. The variances in the stator-rotor air gap are reflected back in the motor’s current through the air gap flux affecting the counter electromotive force. Therefore current carries information related to both mechanical and electrical faults. Hence faults will exhibit a change in the frequency spectrum of the current in specific frequencies. A review of faults of an induction motor and specific frequencies at which they occur are given in [2].

Data acquisition is simple in current signature analysis since only electrical signals are measured. It also provides comprehensive coverage; both mechanical as well as electrical faults are detected. However, the interpretation of the data requires expert personnel and it is time consuming as is the case for vibration analysis. Like vibration analysis, Current signature analysis is also an output assessment. It analyzes current data which is affected by the voltage. Therefore it is difficult to separate if an abnormal signature is due to a problem in the motor or due to unexpected harmonics in the voltage.

MCM was developed to eliminate the shortcomings of both the vibration and the current signature analysis systems. The principles underlying the operation of MCM are radically different from those of vibration and current signature analysis systems. MCM uses a model based fault detection and diagnostics technique. In this technique, the expected dynamic behavior (model) of the three phase system under varying conditions, such as load, is determined and compared with the measured dynamic behavior to monitor abnormalities. MCM first learns the system for a period of time through acquiring and processing the real-time data from the system. The data is processed using system identification algorithms for the calculation of expected dynamic behavior and the model parameters. The changes in the parameters of the system indicate to abnormalities developing in the system. Further processing of these parameters is used for diagnosis.

As opposed to traditional vibration and current signature analysis, this approach uses a cause-effect (input-output) relationship and therefore immune to the surrounding noise or noise in inputs. Also the difference between expected and actual behavior filters out and enhances ONLY abnormalities generated by the system which allows to earlier and accurate warnings. The expert system approach eliminates the needs for data base or record keeping, expert personnel, time consuming data gathering and analysis. It provides comprehensive (mechanical and electrical as well as driven system) fault coverage though it measures only voltages and currents.

MCM uses the electric motor of the equipment as a sensor. Therefore, any fault of the equipment that affects the motor or the three phase system is also observed by MCM.

MCM addresses many of the objections raised by the use of vibration based and current signature analysis systems:

- Cost; MCM and its accessories are inexpensive
- Ease of installation; Industry standard current and voltage transformers can be used as sensors. These sensors are inexpensive, easily installed and familiar to all electrical maintenance personnel. MCM can be used anywhere an electric motor driven systems can be operated. Since the sensors and main unit are usually mounted in control cabinets. MCM unit does not need to be in close proximity to the monitored system
- Easy of use; the expert system approach makes it possible for MCM to automatically establish a database and monitor changes in these parameters. The degree of fault is presented on a simple and intuitive sliding scale by the device itself. Therefore, it eliminates the need for expertise of trained and skilled engineers
- Repeatability; MCM data are highly repeatable. There are no external or background effects that can interfere with the capability of MCM to monitor systems
- Comprehensive fault coverage; both electrical and mechanical faults can be detected using a single device
- Advanced warning; the thresholds are not effected by the operating conditions of the system due to expert system approach. Hence, MCM provides early and accurate alarms.
- Integration to factory automation systems; MCM units are easily connected to an external acquisition system for continuous monitoring via industry standard network cabling. This together with its simple method of fault indication makes MCM an ideal device for use with factory automation systems

In light of the above, MCM would appear to be the ideal choice for continuous electric motor and three phase driven system condition monitoring. A comparison of MCM with vibration and current signature analysis is given in Table 1.

FEATURES	MCM	Current Signature Analysis	Portable Vibration Analysis System	Continous Vibration Analysis Systems
İnexpensive ?	Yes	No	Yes	No
Simple to install/ acquire data ?	Yes	Yes	No	No
Simple to use?	Yes	No	No	Yes
Can be used by untrained Personel?	Yes	No	No	Yes
Comprehensive fault coverage, both mechanical and electrical?	Yes	Yes	No	No
Lower thresholds/ Advanced Warning?	Yes	Yes	Yes	No
Maintenance planing capability?	Yes	No	No	Yes
Integration to factory automation systems?	Yes	No	No	Yes

Table 1. Comparision of MCM with Vibration and Current Signature Analysis

In addition to maintenance planning, MCM also provides diagnostic information. The information provided by MCM can be used to remedy the problems in most cases. However, with multiple faults or different variety of drive schemes different type of faults may end up generating similar signatures. In those cases other signals (speed, torque, vibration etc., should also be explored as well as different techniques such as thermal measurement, chemical analysis, etc.

Electric Motor AND Three phase system Driven Equipment and Process Monitoring

MCM is developed to meet manufacturers' need for a condition-monitoring product that can provide simple and accurate maintenance scheduling information, without the need for interpretation by highly trained personnel. The technology used for the detection of impending mechanical and electrical faults is a proven patented technology that has been previously employed in space and aviation applications [3,4,5,6]. It was rewarded as one of the 40 best products of year 2000 by Control Engineering Magazine [7]. The operation of MCM is described below using an electric motor based system to represent thre phase driven systems.

MCM uses model-based fault detection and diagnosis techniques. The principle of this approach, as illustrated in Figure 1, is to compare the dynamic behaviour of the mathematical model of the machinery or process with the measured dynamic behaviour.

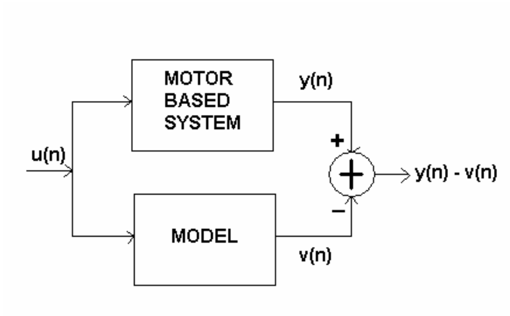

Figure 1The Comparison of the Mathematical model with the actual system

In Figure 1, u(n) is the input voltages to both the mathematical model and the actual motor-based system, it is the measured voltages. y(n) corresponds to the output of the motor-based system, it corresponds to the measured currents. v(n), on the other hand, is the currents calculated by the model. y(n)-v(n) is the difference between the measured and calculated currents. The model consists of a set of differential equations, which describe the electromechanical behavior of the motor. The real-time data acquired from the system is processed by system identification algorithms for the calculation of model parameters. The motor driving the machinery or process is being used as a sensor. Faults developing in the motor as well as the motor-based system or unexpected conditions that affect the operation of the system also affect the model parameters.

MCM first learns the motor-based system for a period of time by acquiring and processing the motor data. The results of the processed data are stored in its internal database and a reference model is established. This reference model basically consists of model parameters, their mean values and their standard deviations. While monitoring, MCM processes the acquired motor data and compares the results to the data stored in its internal database. If the results obtained from the acquired data are significantly different from the reference model, MCM indicates a fault level. The level is determined by taking into account the magnitude and the time duration of the difference.

In total, MCM monitors and compares 22 different parameters (model parameters). These parameters are classified into three groups. There are 8 parameters in the first group which are called electrical parameters. These are the network equivalent parameters and are correlated to the physical parameter of the motor, like inductances, resistances, etc. They are sensitive to electrical faults developing in the motor. MCM evaluates and analyzes the differences between the model parameters at any instant and the average value of the same parameters that are obtained during the learn stage. These differences are normalized with respect to their standard deviations obtained during the learn stage. Hence the values indicate the number of standard deviations they are away from the average values obtained during the learn stage. If they exceed threshold values, than an alarm is given. The changes in their values are associated with the faults that are developing in the system. As an example an isolation problem in winding will affect the parameters associated with resistances. Their change will allow MCM to detect the isolation problem at an early stage. Though they are primarily used to detect electrical problems, they also can indicate mechanical problems as well. As an example an imbalance or gear problem would cause dynamic eccentricity in the air gap. This eccentricity will cause a change in the induction parameters and therefore in the model parameters. By monitoring the changes in these model parameters imbalance can be detected at an early stage. This eccentricity eventually affects bearing and it will also eventually damage the bearing. Therefore its detection at an early stage can prevent further damages

The electrical parameters are further classified in two groups. Electrical parameters 1-4 indicate problems associated with rotor, stator, winding etc. while 5-8 indicate electrical supply problems such as voltage imbalance, isolation problem of cabling, capacitor, motor connector, terminal slackness, defective contactors etc.

The parameters in the second group are sensitive to mechanical faults such as load imbalance, misalignment, coupling and bearing problems. They are called Mechanical Parameters 1-12. These parameters are obtained from the frequency spectrum of the electrical signals similar to the current signature analysis. However, MCM uses the spectrum obtained from the differences between the expected current obtained from the model and the actual current. These differences include only abnormalities generated by the motor. Therefore, they are immune to the noise or harmonics present in the supply voltages.

The mechanical parameters correspond to the 12 maximum values obtained in the frequency spectrum. These parameters are also used for diagnostic purposes. Similar to the vibration as well as current signature analysis techniques, the frequencies they occur indicate the type of fault, i.e., an imbalance, loose foundation, oil whip, fan blades, inner or outer race of bearing etc. These parameters as well as their frequency intervals are provided to the user for trending and diagnostic purposes.

The parameters in the third group are sensitive to changes in the behavior of the system. These are called fit parameters (or residuals). There are 2 fit parameters. These are deviations between the actual currents (d phase and q phase) and the currents calculated from the model. If these parameters increase above their threshold values the system is considered to behave differently than it did during the learn stage which indicates that a fault is developing in the system.

In addition to the above parameters MCM also monitors the supply voltage as well as the load conditions. If the supply voltage changes abnormally, has imbalance or very high harmonic content then it issues a Watch Line alarm. Similarly if the load conditions do not match with the conditions observed during the learn stage then it issues a Watch Load alarm. Watch load alarm means that either the load conditions changed or there is a fault developing in the system. If the user determines that there is a change in the process, then the user can add this new load condition into the conditions observed during the learn period by giving the UPDATE command to MCM.

Using the measured three phase voltage and current signals, MCM also calculates a set of physical parameters such as rms-values of three phase voltage and current, powerfactor, etc. This set also includes parameters such as total harmonic distortion, harmonic content of the incoming signal and voltage imbalance which give an idea about the quality of supply power. Active and reactive power parameters in this set might be used for energy consumption estimations. Therefore, it combines many physical quantities that are of interest to both production and maintenance operators just in one device.

Figure 2 MCM; Motor Condition Monitor

MCM is manufactured as a small, box-shaped device, that is suitable for installation on motor control panels (Figure 2). Selected physical quantities can be displayed on the LCD screen of the device as well as the condition of the motor-based system both by LCD as well as the LEDs on the front panel of the device.

MCMSoC; MCM System on a Card

The MCM technology is also available as MCM software embedded system on a card, MCMSoC. Original equipment manufacturers (OEM) are currently using MCMSoC for direct integration into their own products to provide on-line condition monitoring and early fault detection capabilities. MCMSoC integrated intelligent products (energy analyzers, motor protection relays, digital multimeter, control panels, electronic thermal relays, etc.) inform the users about the status of the three phase system that it is connected to, besides its main functionalities.

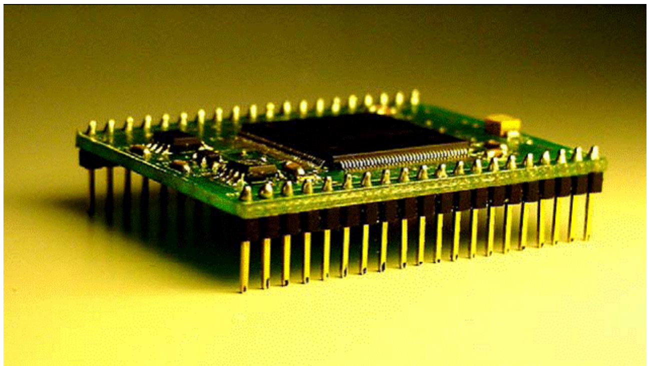

Figure 3 MCMSoC; MCM Software Embedded System on a Card

MCMSCADA and MCMDiagnostics: The Graphical User Interface of MCM

The device can be integrated to factory automation and maintenance management systems using the Modbus communication protocol. Fig. 4 shows an example of integration of MCM units to a SCADA system in an industrial park by the water supply department.

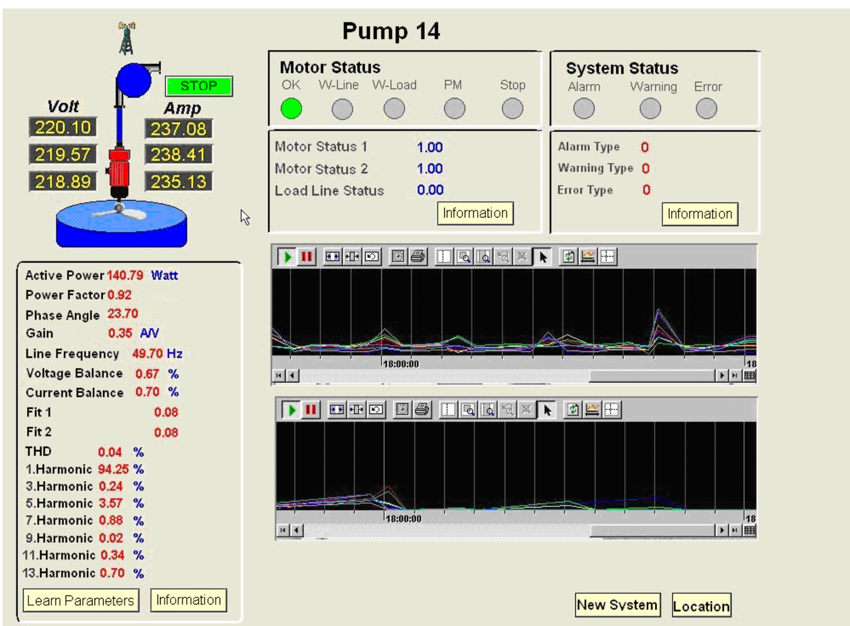

Figure 4 An example of integration of MCM to a SCADA system

Here, several pumps (400 V, 140 kW) are located in the deep wells at remote locations while their control panels are located at the surface. These pumps are monitored with a SCADA system using RF communication. MCM units are located at the control panel. The user configured their monitoring software for trending fault parameters on-line and continuously. Pertinent parameters such as energy usage (voltages, currents, active power, reactive power and power factor) as well as supply voltage quality (voltage and current imbalances, harmonic distortions) are also displayed.

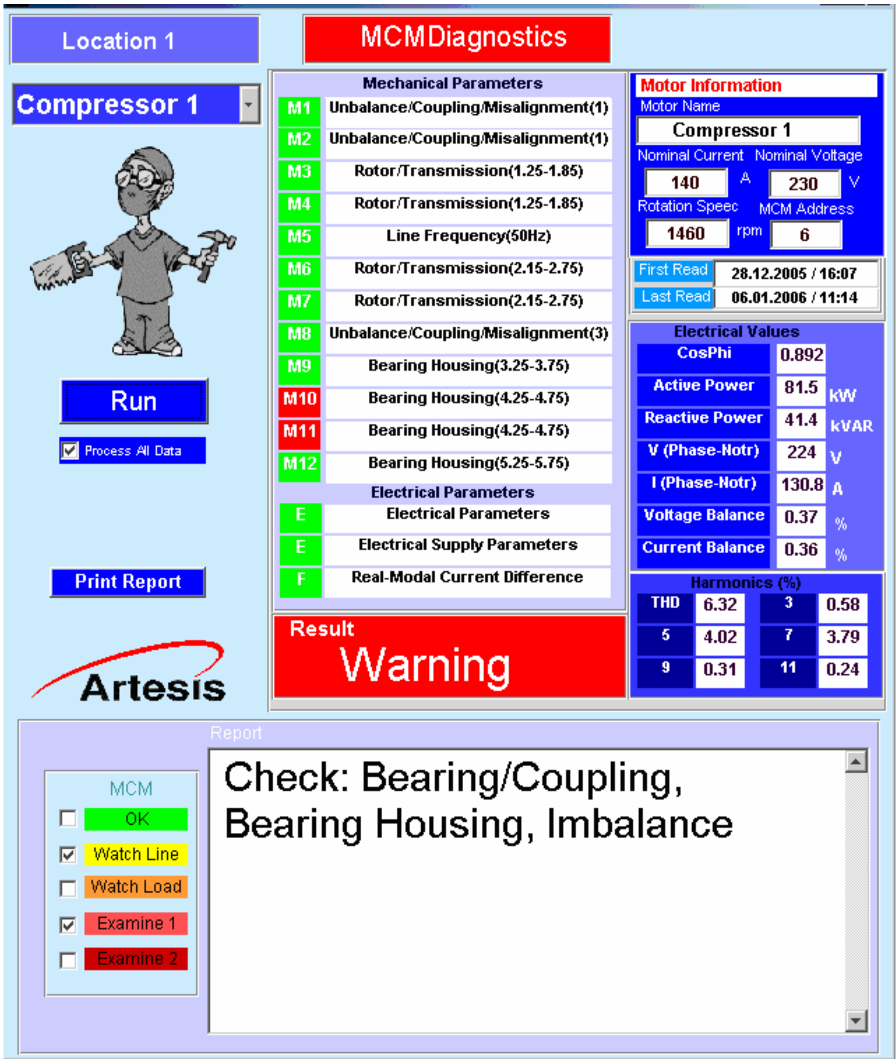

Figure 5 MCMSCADA Diagnostics and Reporting

It is also possible to use MCM with its own desktop application, MCMSCADA for trending and diagnostics. MCMSCADA also provides the user with reports outlining fault status, diagnostics as well as pertinent parameters about the operation during a selected period. In addition to trending, MCMSCADA also obtains the frequency intervals of mechanical parameters and determines the corresponding faults, such as bearing, imbalance, looseness, etc. which is presented to the user. Average values obtained for energy consumption (voltage, current, active power, reactive power and power factor) as well as the power supply quality (THD, harmonics, voltage imbalance and current imbalance) are also provided as show in Fig. 5. MCM can automatically send this report upon the existence of an alarm and at selected periods through e-mail. Using, the status, parameters of several electric motor-based machinery, equipment and processes in a plant can be monitored from several different computers at remote locations.

Application Examples of MCM

MCM has many successful applications in different areas of industry. In this section, four applications of MCM in industry will be presented.

The first case is for a compressor used in the facilities of a battery manufacturer. Here MCM started giving intermittent alarms on Sept. 13, 2005. The alarms continued with increasing frequency and duration until January 2005 as shown in Fig. 6. Mechanical parameters 10 and 11 continuously and gradually increased over months. The diagnostic report of MCMSCADA which is shown previously in Fig. 5, covering the period Dec. 12, 2005 and Jan. 6, 2006 shows that these mechanical parameters correspond to frequencies at which bearing housing faults are expected to present themselves. Later the maintenance and repair verified the diagnostic assessment of MCM.

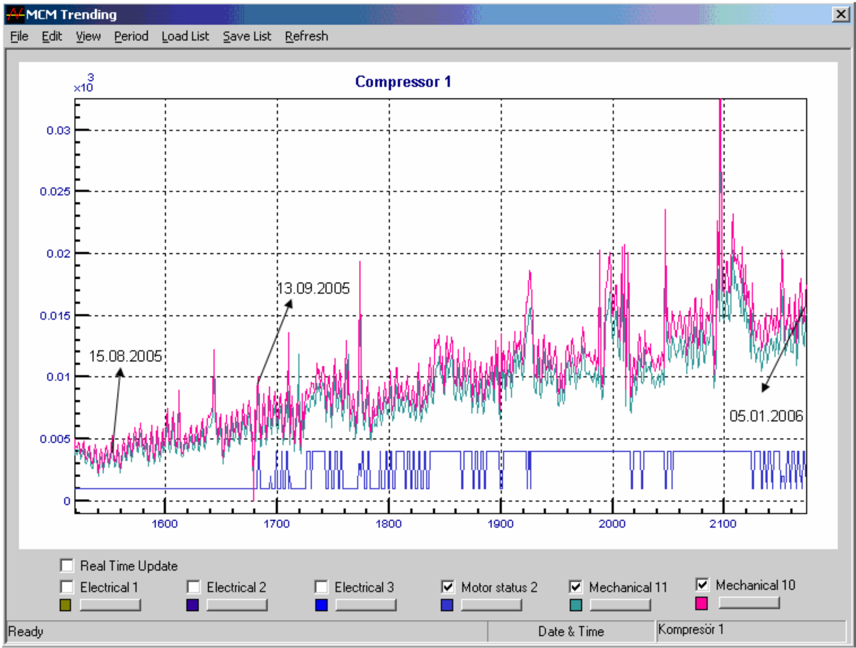

Figure 6 The Trend Plots of Mechanical Parameters 10, 11 and Motor Fault Status

The trend in Fig.6 shows that the parameters started to increase even earlier but did not reach the threshold levels until Sept. 13. This also demonstrates the capability of MCM to indicate developing faults at a very early stage. Therefore, using continuous monitoring and trending capability of MCMSCADA, faults can be detected very early and the maintenance scheduling can be done at a convenient time to prevent further damage to equipment and unplanned down time.

Next is a case study which demonstrates the capability of MCM in detecting a coupling fault of a spray pump in an automotive manufacturing plant. Here MCM monitoring the spray pump gave an alarm at a level of ''Perform Maintenance''. MCMSCADA parameters were checked and it was noticed that the mechanical parameters 2, 5 which correspond to imbalance/coupling were increasing as displayed Fig. 7, indicating that a mechanical problem has been developing. The MCM that monitored the spray pump motor gave Perform Maintenance alarm, which is not related to the motor, but to the coupling between the motor and driven equipment. It should be noted that there are no observable changes in the currents as seen in Fig.7 while the MCM detects developing mechanical faults, not only in the motor, but also with the coupling and motor driven equipment, using only current and voltage measurements.

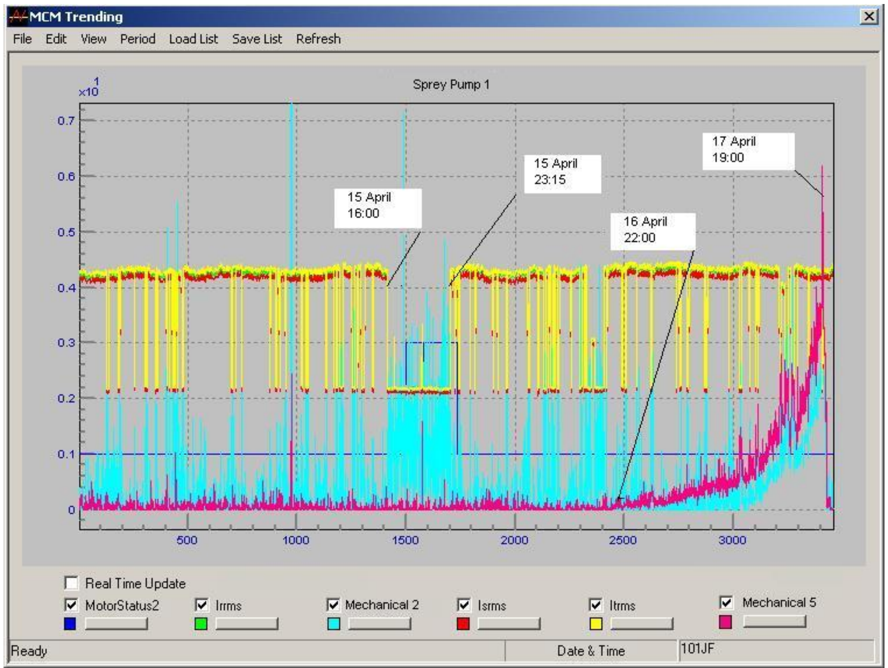

Figure 7 The Trend Plots of Mechanical Parameters 2, 5 for the Spay Pump

The third example is for a generator (720 A, 380 V, 1500 RPM) shown in Fig. 8, used in a farm in Germany. The generator already had a monitoring system for early warning of pending faults. In addition to its existing monitoring system, MCM is also installed for trial and testing purposes. Here shortly after the learn stage is completed MCM gave an alarm, first at the second level (load change) and later at the fourth level (examine). Figures 9 and 10 shows that both mechanical and electrical parameters changed. During this time, the existing monitoring system of the generator did not give any warning. Therefore, the users continued to operate the generator. The continued operation caused the generator to a fail. An examination using MCMSCADA diagnostic report indicated that a fault due to one of the possible faults of eccentricity/imbalance/coupling/gearbox. An examination showed that imbalance caused the alarms. The imbalance eventually caused the rotor touching the stator which caused multiple faults, both imbalance and electrical failure. The owners now replacing the generators wit a cost of 1.5 Million Euros.

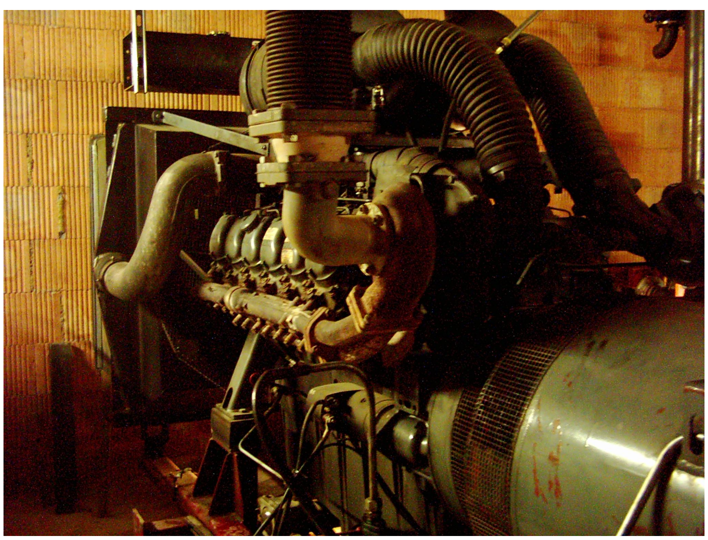

Figure 8 The 350 kW Generator

Figure 9 The Trend Plots of Mechanical parameters for the Generator

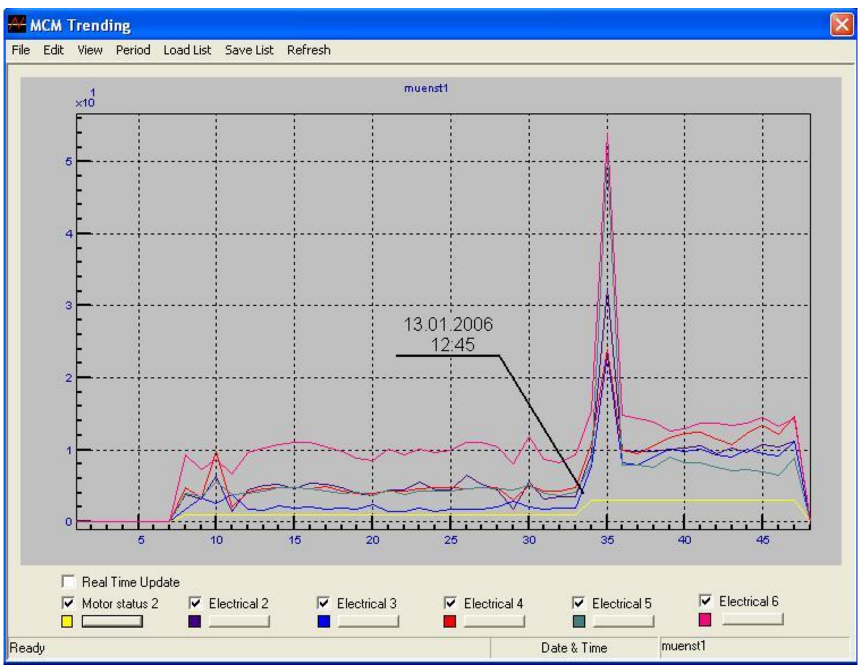

Figure 10 The Trend Plots of Electrical Parameters for the Generator

The fourth case illustrates an isolation fault. MCM device was monitoring a sand cooling filter motor. Starting from October 7, 2004 electrical parameters began to increase gradually as a result of the decrease in currents and power as seen in Fig. 11. The device started to give intermittent 'Load Change' warning. As electrical parameters increased, the 'Load Change' warnings became more frequent in November. The increase in one of the three phase currents with respect to the others was an indication of an isolation problem. On December, 5 the motor was repaired.

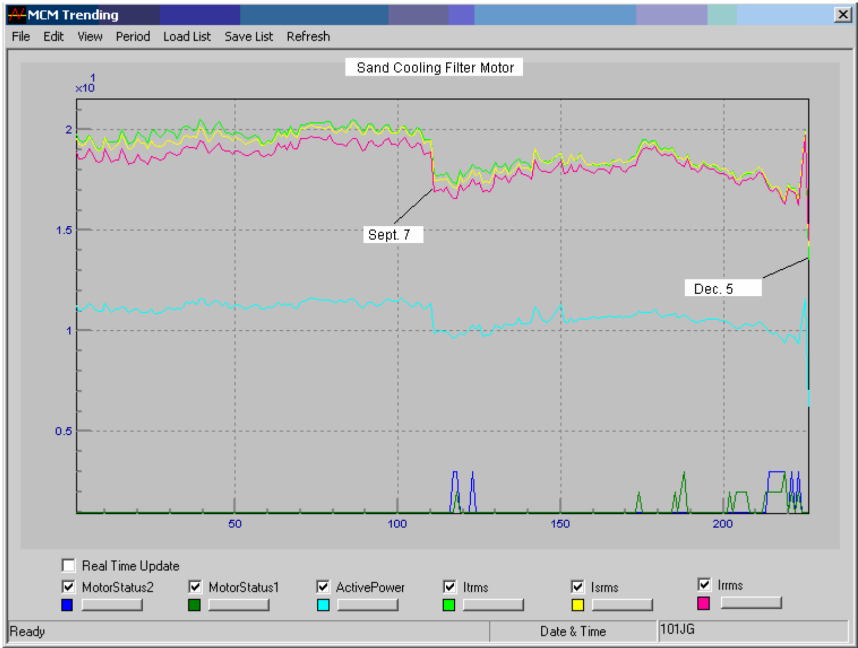

Figure 11 The Trend plots of Current, Power and Motor Status

Figure 12 illustrates the increases in the electrical and fit parameters during the development of fault. This case demonstrates the early warning capability of MCM. The device could indicate the deterioration of isolation approximately two months ahead of the actual maintenance activity.

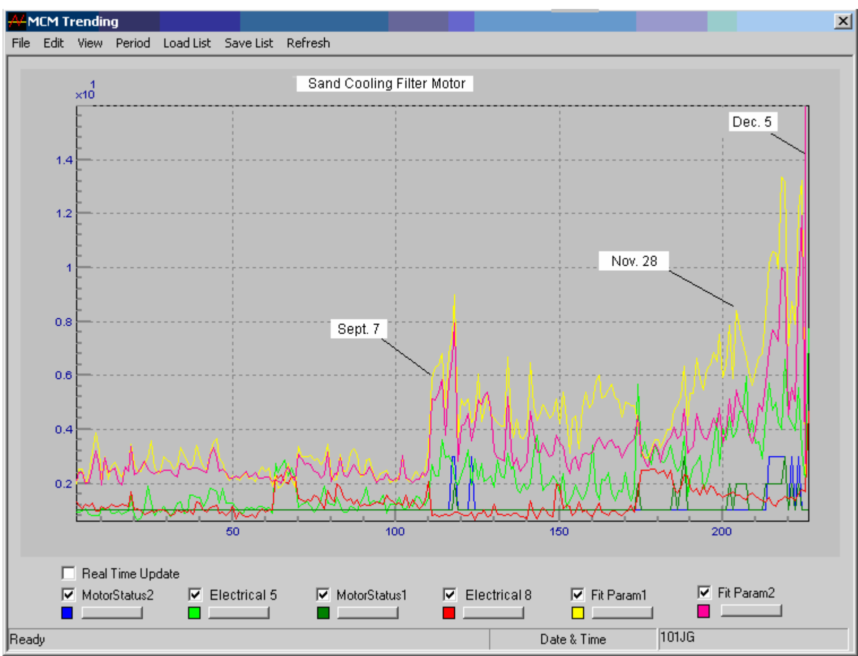

Figure 12 The Trend Plots of Electrical and Fit Parameters

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