An inexpensive, simple to use condition monitoring system

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This paper presents an innovative and cost effective new tool, 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 enhances maintenance planning by detecting impending mechanical and electrical failures at the early stages of fault development through continuous monitoring. It also provides the user with the diagnostic information. Its primary function is to provide early warning of progressively deteriorating machine and process conditions to prevent unplanned downtime, and improve productivity. MCM’s core technology stems from a decade-long research effort, which has been applied to the space shuttle main engine, helicopter engines and gas turbines. It 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.

Manufacturers are faced with growing production demands while cutting the cost of manufacturing. One pervasive cost is caused by unplanned equipment and manufacturing process downtime [1]. Unexpected failure of processes and machinery in industrial environments is always undesirable. 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 and predictive maintenance capabilities to factory automation systems.

A major concern of condition monitoring is for electric motors and motor driven systems such as pumps, compressors, fans, presses etc. Such equipment is common throughout industry with a wide range of motor power ranging from a few watts up to 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 (from a few weeks to a year or more) would be plotted to observe any trends indicative of possible failure. Vibration based condition monitoring can be expensive, difficult to use and the results difficult to interpret.

The sensors and their associated electronics are expensive. 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. Data gathering (portable systems) and analysis is time consuming and the interpretation of the data requires skill and training. Data obtained from portable vibration analysis may end up not repeatable due to machine loading conditions and the person collecting the data. Background vibration can also interfere with the measured signal. Vibration analysis is effective in the detection of mechanical faults and some electrical faults, but not all.

In summary, Vibration analysis has been the traditional technique that is used in industry over the last 30 years. However, it is expensive, difficult to use, requires expertise both in acquiring the data and interpreting its results. Therefore, manufacturers increasingly demand inexpensive, simple to use condition monitoring techniques and products that can be integrated into factory automation systems.

A new method has been developed to overcome some of the shortcomings of vibration-based systems. It is “current signature analysis”. In this method information is extracted from the line current supplied to a motor. 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 that 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 traditional vibration and 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. Changes in the parameters of the system indicate 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 is therefore immune to the surrounding noise or noise on inputs. Also the difference between expected and actual behavior filters out and enhances only abnormalities generated by the system. This allows for
earlier and more accurate warnings. The expert system approach eliminates the need for a database 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 on 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:**

**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. The MCM unit does not need to be in close proximity to the monitored system

**Ease 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.

A comparison of MCM with vibration and current signature analysis is shown in Table 1.

In addition to maintenance planning, MCM also provides diagnostic information. The information provided can be used to find the cause of the problems in most cases. However, with multiple faults or a variety of drive schemes, different types of fault may generate similar signatures. In these cases other signals (speed, torque, vibration etc.) should also be explored together with different techniques such as thermal measurement, chemical analysis, etc.

**How does MCM work?**

The technology used for the detection of impending mechanical and electrical faults is a proven technology that has been previously employed in space and aviation applications [3,4,5,6]. The operation of MCM is described below using an electric motor based system to represent three phase driven systems.

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

In Fig. 1, \( u(n) \) is the measured input voltage to both the mathematical model and the actual motor-based system. \( y(n) \) corresponds to the measured current of the motor-based system. \( i(n) \), on the other hand is the current calculated by the model. \( y(n) - i(n) \) 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. System identification algorithms for the calculation of model parameters process the real-time data acquired from the system. 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.

Using the measured three phase voltage and current signals, MCM also calculates a set of physical parameters such as rms-values of these 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 in one device.

MCM is built into a small box-shaped device that is suitable for installation in motor control panels (Fig. 2). The condition of the motor based system as well as selected physical quantities can be displayed on the LCD screen of the device.

Graphical user interface
The device can be integrated to factory automation and maintenance management systems using the Modbus communication protocol. Fig. 3 shows an example of integration of MCM units to a SCADA system.

Here, several pumps (400 V, 140 kW) are located in 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 continuously on-line. 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.

It is also possible to use MCM with its own desktop application, MCMSCADA for trending and diagnostics. MCMSCADA 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 shown in Fig. 4. 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 example of MCM**

An example of MCM in practical use is for a generator, (720 A, 380 V, 1500 RPM) shown in Fig. 5, used on 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 was installed for trial and testing purposes. Here shortly after the learn stage was completed MCM gave an alarm, first at the second level (load change) and later at the fourth level (examine). Fig. 6 and 7 show that both mechanical and electrical parameters changed. During this time, the existing monitoring system did not give any warning. Therefore, the users continued to operate the generator. The continued operation caused the generator to fail. An examination using MCMSCADA diagnostic report indicated a fault due to eccentricity/imbalance of the coupling/gearbox. An examination showed that imbalance caused the alarms. The imbalance eventually caused the rotor to touch the stator which caused multiple faults, both imbalance and electrical failure.

**References**


