A Novel Method for Fault Detection in Electrical Motors

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A model-based approach to fault detection is described. Its practical application has resulted in a breakthrough technology for the evaluation of electrical motors. The Motor Quality Monitor (MQM) is a system for the detection of faults of motors at the production line or at an incoming quality control station. The technique can detect a wide range of electrical and mechanical problems, including noise and vibration. In addition, the physical model allows rapid estimation of motor performance characteristics.

Traditional methods for fault-detection and condition monitoring are mainly based on inspection of several measurable quantities after suitable signal processing. The well-known methods applied to electrical motors include analysis techniques such as the power spectrum, principal component, and wavelet decompositions, applied to records of current, vibration, noise, temperature and similar measurements. The main shortcoming of these methods is that they are based only on the external manifestations, disregarding any internal dynamics that are responsible for the particular behavior. Consequently, they offer little insight into the actual dynamics of motor operation. It is thus not surprising that a particular technique may detect certain types of faults but fail on others. Furthermore, the traditional methods are not always applicable in arbitrary settings since they may require controlled environment conditions.

An alternative to traditional methods is provided by a model-based approach. The underlying principle, summarized in Figure 1, is to compare a mathematical model of the motor to a reference model which represents a fault-free system. The usual outputs such as current and rotor speed are still measured, but now the data are used for identifying the unknown parameters of the motor model, and the main comparison is made between the parameters themselves. If a realistic model is used in the process then the identified parameters have physical significance, which makes it possible to trace any discrepancy between the system and the reference model to specific physical causes. In this way, model-based comparison provides a direct clue to the internal dynamics of the motor.

In what follows, we introduce an advanced technology which makes use of the model-based approach to rapidly test motors for electrical and mechanical faults. Underlying this patented technology is a proprietary algorithm that was originally used in the field of aviation and was applied to propulsion systems [**Error! Reference source not found.**-4]. The mathematical basis for the original applications was developed in [5]. The application to fault detection in electrical motors progressed rapidly [6] and has now reached a state of maturity, enabling rapid and reliable testing of different types of motors for a wide variety of faults. In addition to fault detection, the technology makes it possible to estimate the steady-state performance characteristics of the motor in a matter of seconds.

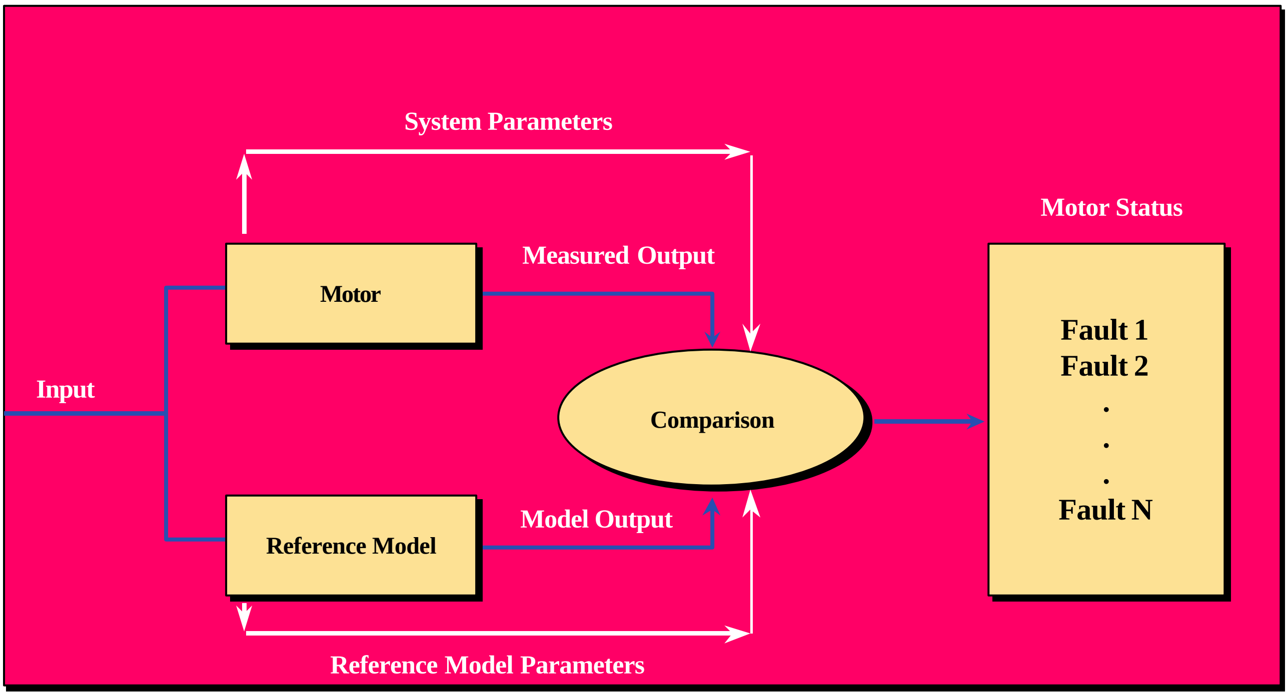

Figure 1

Motor Quality Monitor (MQM)

MQM is an application of model-based methodology to fault-detection of electrical motors. The principle underlying its operation is that the faults in a motor are traceable to the appropriate elements in its physical model. The model used has the form of a set of differential equations, with voltages as input variables, and currents and motor speed as outputs. For instance, for the universal motors used in household appliances, the model is derived from the circuit equivalent equations as

$$\begin{aligned} L\frac{di}{dt} + Ri + kwi &= V \\ J\frac{dw}{dt} + fw &= ki^2 - T_L \end{aligned} \tag{1}$$

where

V = input voltage
w = rotor speed
i = field current
L = self-inductance
R = resistance
k = mutual-inductance
J = moment of inertia
f = friction coefficient
T_L = load torque.

The model can be improved as necessary to take additional nonlinearities into account, such as the saturation of the iron in the magnetic circuit [7].

Once a model is available, the motors are treated as systems with known dynamical equations but unknown parameters. MQM's analysis consists of the determination of what the parameters of a fault-free motor (reference model) would be, as well as the parameters of the motor being tested, followed by a sophisticated algorithm to compare the two sets. Any discrepancy beyond what is attributable to measurement noise and modeling errors is an indication that the tested motor is different from the reference model.

Determining the parameters of the motor being tested is rather straightforward: A rich input signal, designed to stimulate all the dynamical modes of the system, is applied to the motor for a duration of about 2 seconds, while current and speed measurements from the motor are recorded. A parameter identification algorithm, such as linear least-squares method, is then used to complete the dynamical model of the motor. The determination of a reference model, on the other hand, requires some care since it is not obvious what the parameters of a fault-free motor model would be. For this purpose, a statistical method is used based on the premise that under normal production conditions, the majority of the motors will be fault-free. A large group of motors (several hundred, or preferably, thousand) are measured by the above procedure and their model parameters are calculated. Following this, the statistical distribution of each parameter is determined from a calculation of the means, variances, and related quantities, resulting in a comprehensive picture of the production variations. Based on this information, the data for motors whose parameters lie outside of user-selectable thresholds (expressed in units of standard deviations) are discarded. The thresholds are usually chosen so as to exclude the outliers in the distribution, or to exclude a predetermined percentage of motors based on past knowledge of field returns. After an iterative process, there remains a set of motor parameters which are taken to be the parameters of the reference model. The whole procedure is schematically depicted in Figure 2.

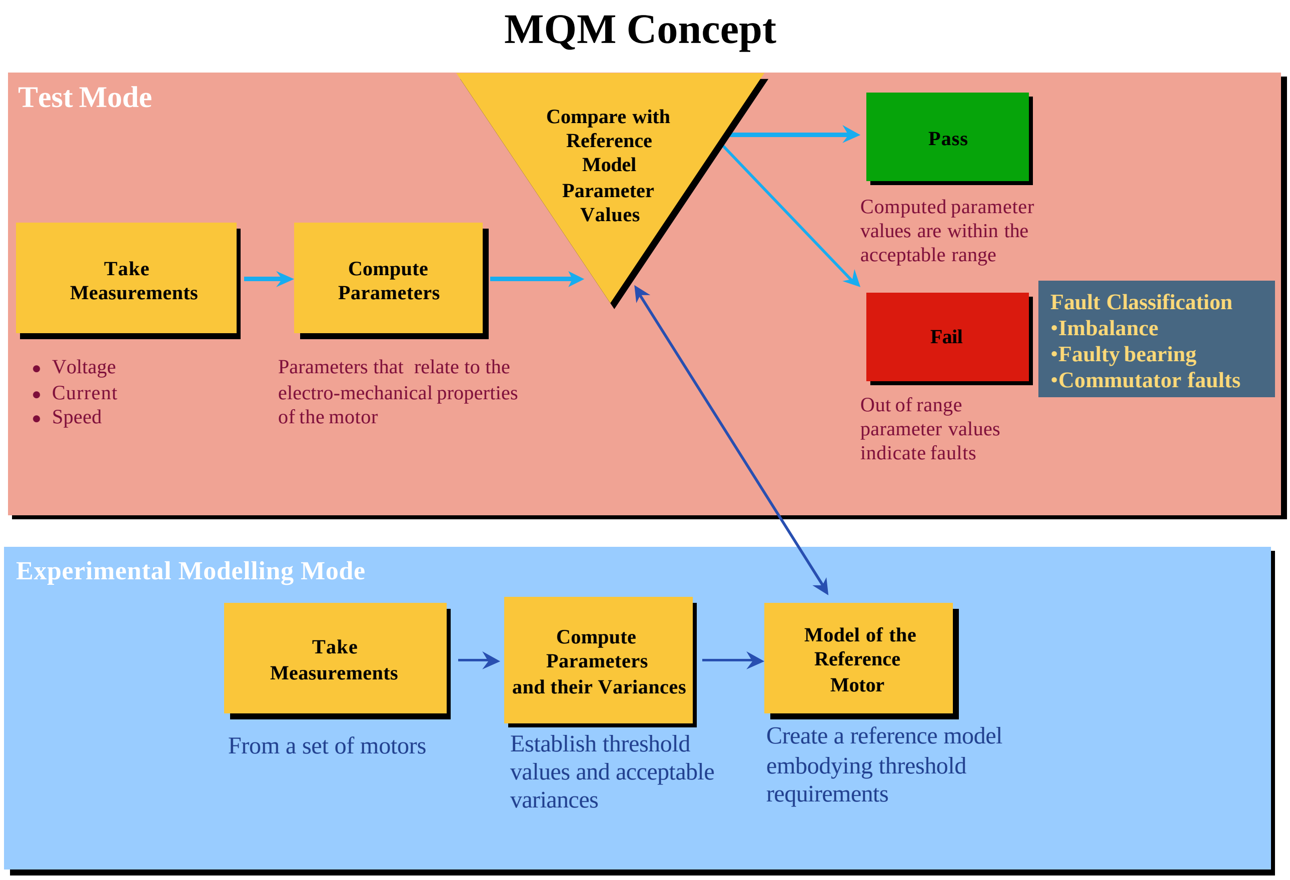

Figure 2

The creation of a reference model is done once for a particular type of motor, and also whenever a change in the production process deems it necessary. After that, the testing of an individual motor can be done under 10 seconds floor to floor. This makes it possible to test every motor coming off the production line, avoiding any disadvantages associated with statistical sampling.

Fault Detection and Classification with MQM

Most of the electrical and mechanical faults in an electrical motor can be traced to particular parameters in its mathematical model. Since MQM's evaluation of the motors is based on the comparison of their parameters with a fault-free reference model, the faults can be identified in a natural way. Furthermore, detailed information on the physical causes of a fault can often be obtained, something that is not always possible with alternative methods.

MQM's capabilities based on the comparison of the set of parameters that appear in Equation (1) are further augmented by its ability to perform sophisticated analysis in the abstract parameter space. Using such mathematical techniques as the Principal Component Analysis (PCA) [8], it is possible to determine those parameter combinations that contribute the most to the particular observed behavior. This greatly enhances the capability to detect a wide range of motor faults, since some faults show themselves only in certain parameters while not affecting others. This is particularly true with noise and vibration problems, which are among the major reasons for the service returns of household appliances. Figure 3 shows the success of one of the estimated parameters in distinguishing motors with noise problems. The squares in the graph denote the motors comprising the reference set, and the circles denote motors coming from a batch with noise problems. These parameters have proved highly capable of detecting motors suffering from excessive noise. As a result, the implementation of MQM as an incoming quality-control technology at an appliance manufacturer's plant in Istanbul has dramatically reduced the service return rates due to noise, as shown in Figure 4.

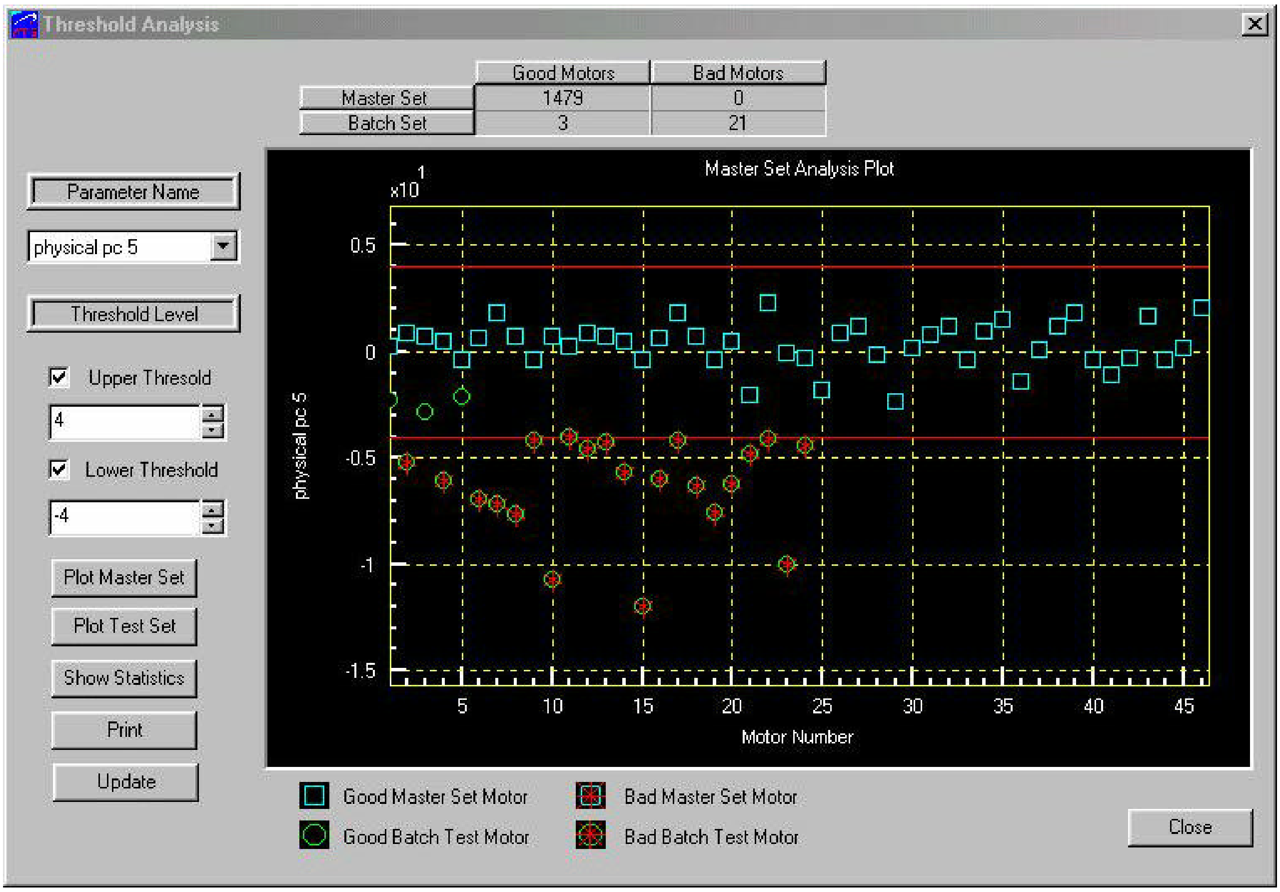

Figure 3

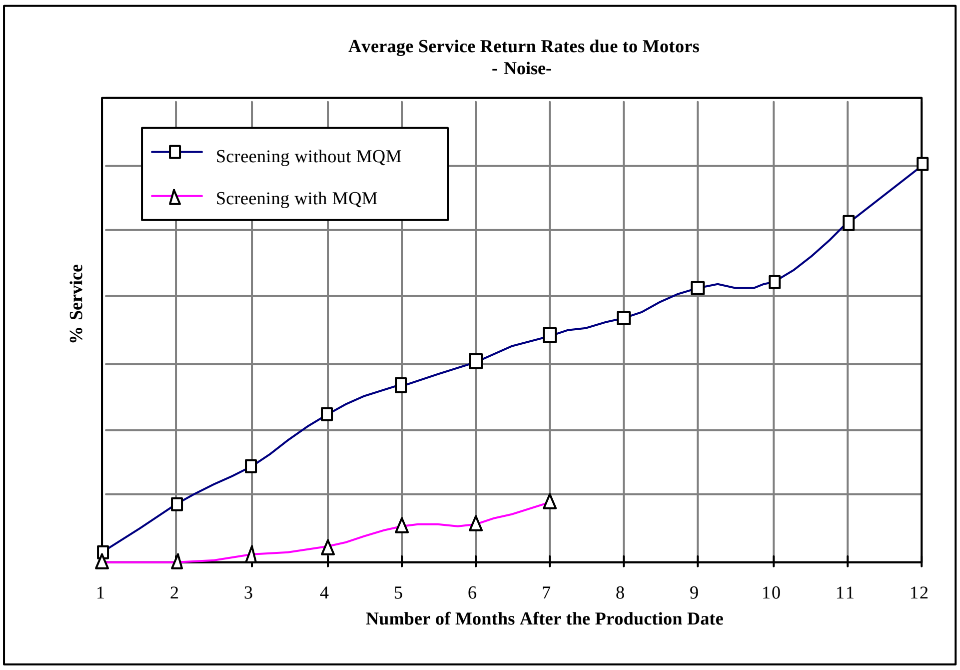

Figure 4

In addition to noise, the type of faults that can be detected by these techniques covers a whole range of common problems encountered in motors, such as sparking, broken or short-circuited windings, vibration, bearing faults, and the like. Figure 5 shows the decrease in the service return rate due to general functional defects of motors after MQM was implemented at the plant.

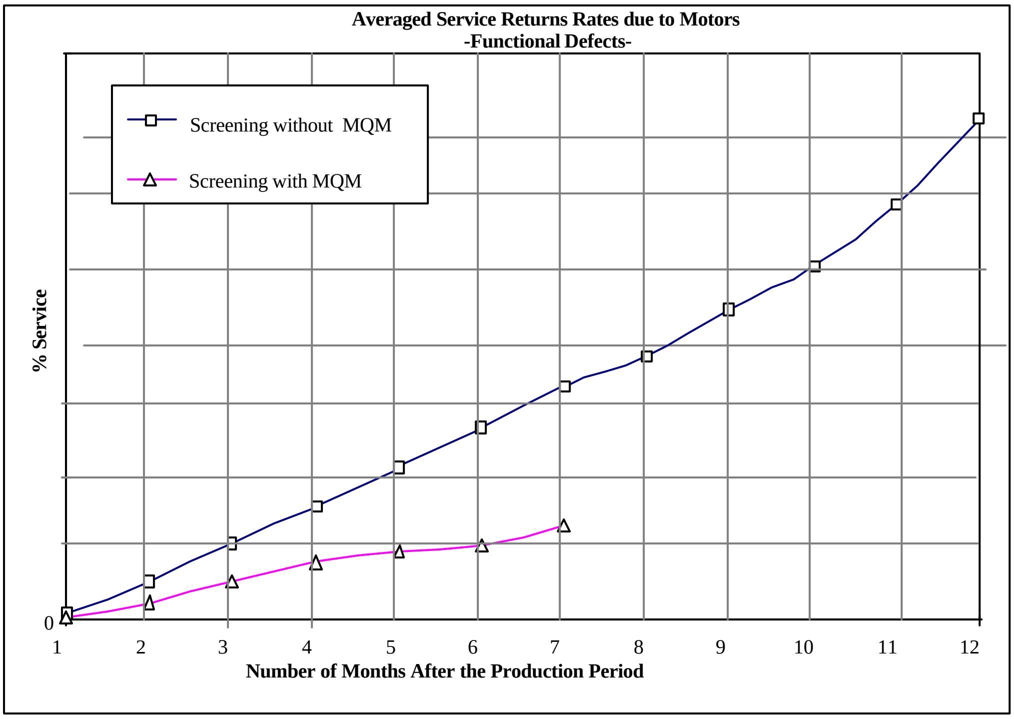

Figure 5

Estimation of Motor Performance

MQM's model-based approach actually has farther-reaching implications than mere fault detection. For instance, the steady-state performance of the motor can be estimated once a dynamical model of the motor is available. This follows from the fact that the dynamical behavior of the motor is completely determined by its equations of motion, such as those given in Equation (1). For instance, the torque produced by the motor at steady-state is given by

$$T_L = ki^2 - fw\,,$$

which can be calculated once the constants k and w are estimated. This in turn leads to a sequence of further quantities that are of interest, such as the mechanical power output of the motor:

$$P_{out} = \omega T_L\,.$$

If the motor drives a fan, as in a vacuum cleaner, then the rate of air flow through a given orifice and the pressure generated can be calculated from the knowledge of output power. Indeed, if the diameter of the orifice is denoted d, then the motor generates a pressure H of

$$H = \text{const.} \times \left(\frac{P_{out}}{d^2}\right)^{2/3},$$

and the air flow rate Q is given by

$$Q = \text{const.} \times d^2\sqrt{H}\,.$$

Here, the term "const." denotes proportionality constants that depend on the units used. It is thus seen that the dynamical model of the motor entails, among other things, detailed information about the motor performance at steady-state.

In this way MQM can reproduce the results of detailed dynamometer tests, since it works directly with the dynamical model of the measured motor. Whereas a dynamometer test typically takes more than half an hour, MQM estimates within a matter of seconds a complete set of performance indicators such as the input power or the mechanical efficiency. The results show good agreement with the dynamometer tests, the relative error being less than 5-10% in general. An example of the comparison between dynamometer and MQM estimates is shown in Figure 6, for a particular type of motor used in vacuum cleaners.

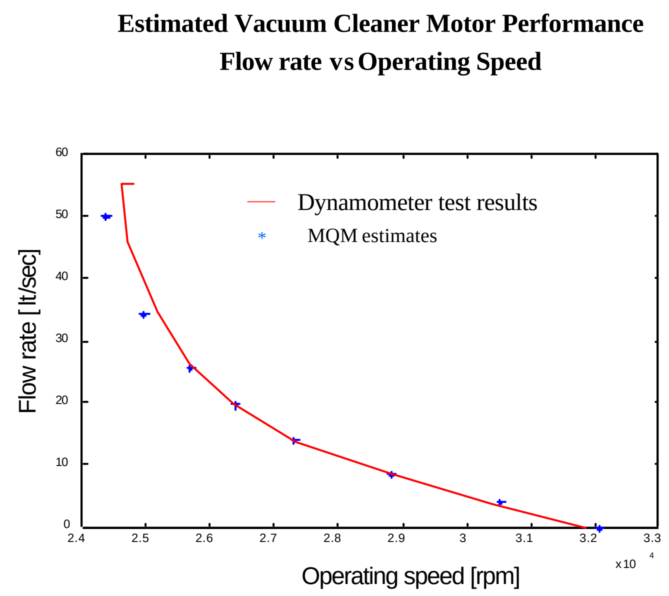

Figure 6

Following Production Variations

Since the reference model created by MQM embodies statistical information about the production, testing motors against the reference model provides a way to follow the variations in the production process. Figure 7 shows the distribution of an estimated parameter among two batches of motors produced in two consecutive months. The shift in the distributions is unmistakable, and the user-adjustable thresholds (seen as red horizontal lines in the figure) makes it easy for MQM to identify and warn about such variations. This capability of MQM enables the identification of costly epidemics at an early stage.

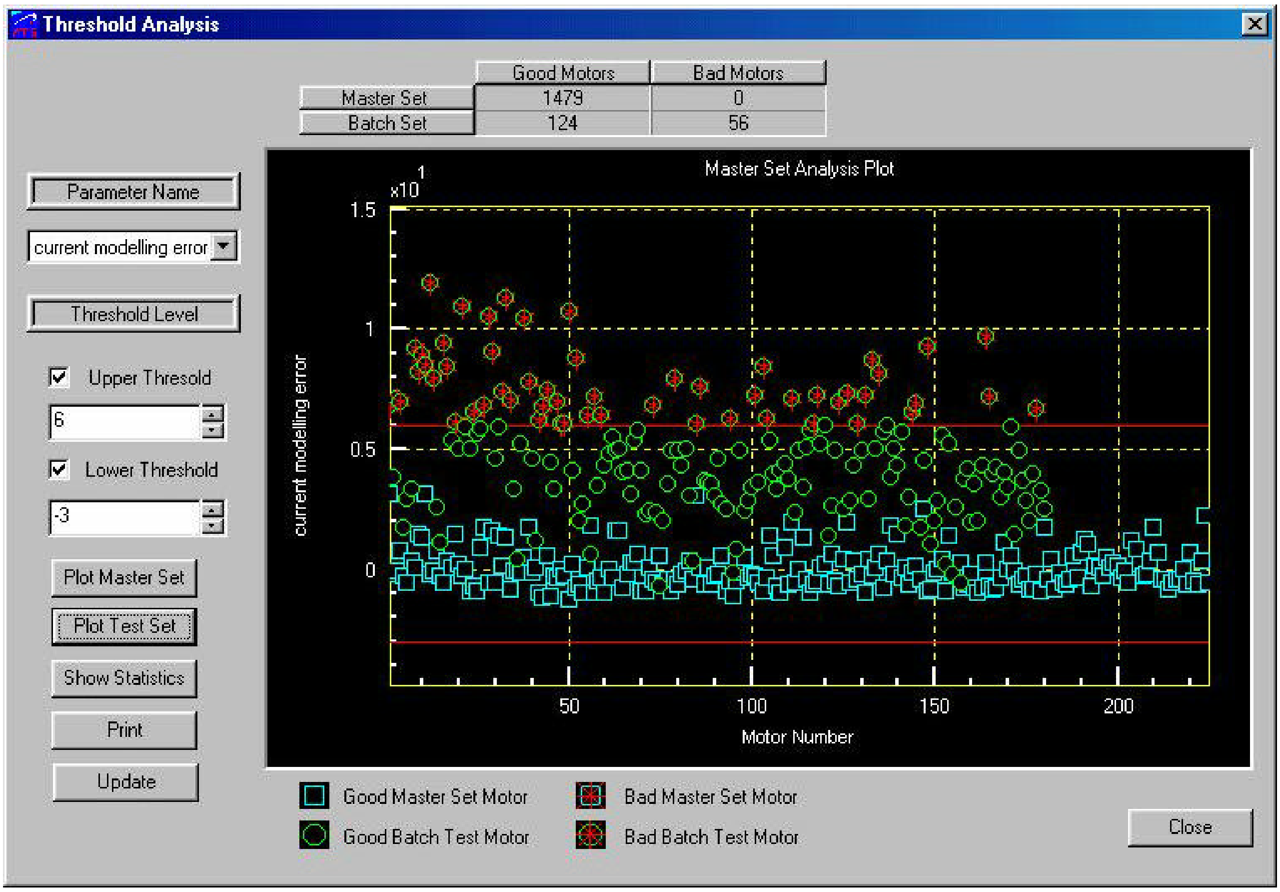

Figure 7

Conclusion

The model-based approach to fault detection has distinct advantages over traditional methods. MQM is a patented technology making use of these advantages in industrial settings. It identifies a number of parameters that are sensitive to changes in motor quality and performance, thereby making it possible to detect a wide range of motor faults. Furthermore, the creation of the reference model by MQM provides a detailed analysis of production variations. Consequently, MQM can automatically detect changes at the epidemic level.

The success of the MQM approach depends on having appropriate mathematical models for the dynamics of the motor as well as the relevant environmental and operating conditions. This is particularly true for compound systems such as a motor-fan combination. The technology has so far been implemented for both direct and alternating current machines, including universal, permanent magnet, single-phase and three-phase induction motors, and for compound systems utilizing these motors. The applications include washing machines, vacuum cleaners, pumps, compressors, fans, and so on, in industries ranging from household appliances to automotive components.

MQM results have proved to be robust and highly repeatable. Equipped with a graphical front-end which makes it easy to create reference sets, evaluate motors, plot and print motor performance characteristics, and provide statistical information, MQM is a flexible and reliable tool for fault detection of electrical motors and for end-of-line quality assurance.

Acknowledgments

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