IN-PROCESS MOTOR TESTING RESULTS USING MODEL BASED FAULT DETECTION APPROACH

E. Albas, T. Arikan, C. Kuzkaya
Artesis A.S., 81719 Tuzla Istanbul Turkey, email: artesis@arcelik.com.tr, URL: artesis.com

Abstract: Rapid progress in process automation and tightening quality standards result in a growing demand being placed on fault detection and diagnostics (FDD) methods to provide both speed and reliability of motor quality testing. This paper presents the findings of a decade-long research and development efforts in the field of experimental modeling technique and its practical applications for the fault detection purposes, first in the fields of aerospace and defense, and now in the context of high-volume electric motor manufacturing. Underlying this patented technology is a set of proprietary algorithms that enable precise tracking of the parameters pertaining to the physical structure of the motor. The derivation of condition information from changes in the physical structure, rather than from symptoms of faults such as noise and vibration, allows detecting a wide variety of faults and drastically simplifies the assessment of fault types.

Key words: Quality control, fault detection

I. INTRODUCTION

In the last decade of the 20th Century, the field of Fault Detection and Diagnosis (FDD) has shown a very rapid development due to safety demands in aircraft and aerospace industry. Besides its importance to the aircraft and aerospace industry, FDD has become a "must" for many other industries due to productivity and quality considerations ('zero defects' manufacturing). In the electric motor manufacturing industry, where competition is keen and quality standards are high, FDD processes are becoming more and more important.

Conventional motor quality control equipment utilizes easily measured magnitudes, like steady state current, speed, and input power. With the help of advances in vibro-acoustic measurement devices and computers, use of noise and vibration data also becomes a popular tool for motor fault detection. Since all of these methods utilize indirect information about motor quality, they cannot offer in-depth information about motor faults, which is essential to provide feedback to production process. In addition, noise and vibration measurements require special handling for sensor replacement and measurement environment must be isolated against background noise and vibration, which increases the systems' cost and complexity.

On the other hand, model-based fault detection approach [1, 2] relies on the knowledge of electric motor dynamics to identify both the symptoms and the causes of faults, irrespective of environmental conditions. Its first applications were realized and verified on highly sophisticated systems such as space shuttle main engine [3, 4] and T-700 helicopter engine [5, 6]. Existing commercial applications of this patented technology (Motor Quality Monitor- MQM) were successfully applied to test final assembly quality of series universal motors (washing machine and vacuum cleaner motors), single-phase asynchronous motors (hermetic compressor motor) [7, 8, 9, 10], as well as DC motors with brush (automotive electric motors), and single-phase synchronous motors (pump and fan motors). With the help of this new technology, it becomes possible to perform fast and reliable testing of different electric motor types, and a wide spectrum of motor faults can be detected.

This paper summarizes the basics behind the development of this FDD technology. In addition, several case studies obtained from field tests at electric motor manufacturing plants are presented.

II. FAULT DETECTION APPROACH

Model based fault detection and diagnosis (MBFDD) methods utilize an explicit mathematical model of the system under test [1]. In general, the model of the system is composed of differential equations or equivalent transformed representations. For fault detection purposes, the model of the system can be used to calculate model (fault-free) outputs for the measured inputs. Alternatively, the parameters of the system can be identified using measured inputs and outputs. Use of identified system parameters for fault detection is called as parameter estimation approach, depicted in Figure 1. Parameter estimation is a natural approach for the detection and isolation of parametric faults. A reference model is obtained by first identifying the system in a fault-free situation. Then the parameters are repeatedly identified. Deviations from the reference model parameters serve as a basis for fault detection.

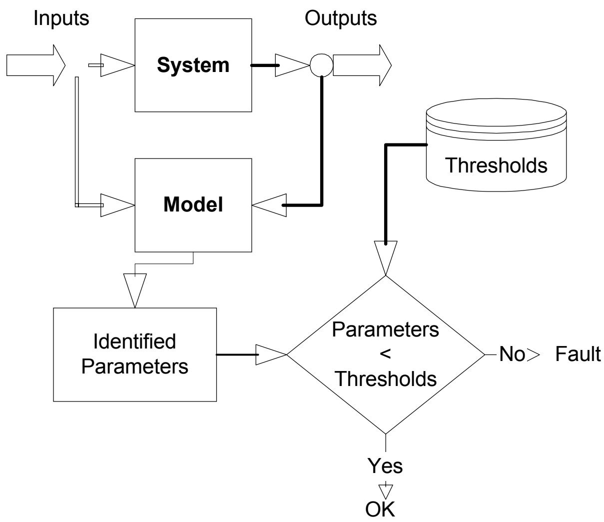

Figure 1: Scheme of model based fault detection using parameter estimation approach

The model of the fault-free system is assumed to be a discrete time linear system described by the following state equations:

$$x(k+1) = Ax(k) + Bu(k) \quad (1)$$

$$y(k) = Cx(k) \quad (2)$$

where x, u and y are the kx1 state, the px1 input and the qx1 output vectors. A, B, C are the nominal parameter matrices of the system with appropriate dimensions.

Parameters of the A, B and C matrices are considered as baseline process parameters. It is assumed that if a fault exists in the system, values of the system parameters are deviated from the nominal values. Any changes of these parameters observed away from pre-selected threshold values are used to detect the faults. Therefore, faulty system is assumed to be represented by the following equations:

$$x_f(k+1) = A_f x(k) + B_f u(k) \quad (3)$$

$$y_f(k) = C_f x(k) \quad (4)$$

For the application of this new technology, identification of A, B and C matrix is performed using a multivariable system identification algorithm whose mathematical background can be seen in the literature [11].

III. IN-PROCESS MOTOR TESTING USING MODEL BASED FAULT DETECTION

The motor test system developed using this new technology based on model based fault detection is industrialized for the quality assurance of electric motors. The basic assumption behind the operation of this system is that the faults change the parameters of electric motors and these changes can be observed through identification of motor parameters using input and output signals measured during the test period.

The model of a motor is taken as a set of differential equations, where voltages are input variables, and currents and motor speed are output variables. In general, circuit equivalent equations are used to have a physical model, which allows identification of motor physical parameters. A typical set of such parameters contains inductances, resistances, motor constant, inertia and friction coefficient, which describes the operational status of the motor under consideration. In order to minimize modeling errors, models are improved by taking non-linear effects into account, or semi-physical models can be used if a physical model cannot be constructed [8, 9, 10].

Identification of motor physical parameters also implies calculation of motor's steady state performance, which is generally represented using performance curves plotted against load applied to the motor [13]. In this way, this motor test system can reproduce the results of lengthy dynamometer tests for all motors under production cycle time, which means assured motor performance.

During the testing, motors are considered as systems with known dynamic equations but their parameters are unknown. Identification of the system parameters is achieved using the measured input and output signals and feeding them to an experimental modeling algorithm [12].

In order to enhance fault detection capability, motor physical parameters are also subjected to a principal component analysis [14]. The set of principal component parameters is also used for fault detection together with motor and performance parameters. Signature analysis of current signal is also performed which is known to be an effective fault detection method for electric motors [15].

During motor testing, parameters calculated for the motor under test is compared to the values of the reference (master) set. Master set is a statistical representation for distribution of all parameters used in motor testing. It is created after measuring enough number of motors to introduce all production variation information to the calculations. An iterative approach is applied to reject the outliers while calculating mean and standard deviation information for test parameters, which will be saved as master set values.

Allowable motor quality range is determined by using the threshold values supplied by the user in terms of standard deviation values. Parametric distribution plots provided by the system after master set creation helps the user in selecting thresholds for test parameters. Based on the mean and standard deviation values saved in the master set, the motors whose parameters are outside of the thresholds are deemed as faulty. Typical test cycle time, recorded in factories where the test systems are operational, is less than 10 seconds including the handling (floor to floor).

IV. RESULTS

The motor quality control systems developed for various motors using this new motor fault detection technology are now operational at different motor manufacturing plants. Performance of these systems is monitored using the field tests conducted by the customers.

A. Epidemic Detection

Using the parameters calculated by the motor test system, it is possible to monitor overall quality of the production. If a sudden change occurs due to degradation in product quality, system starts to reject excessive number of motors which is a sign of an epidemic change. By analyzing the motors, manufacturers identify the source of the problem and take corrective action before the motors leave the plant.

Such warnings were received at several occasions. An example epidemic detection was experienced at a synchronous motor production line. As shown in Figure 2, a sudden change was observed in parameters calculated by the test system which yields an increase in percent rejection. Analysis of the motors showed that, the latest magnets used to manufacture the rotors had a lower magnetization quality. During the extensive tests, motors with lower grade magnets failed at start-up tests under load. Using this result, manufacturer rejected the latest magnet shipment back to the supplier, and motors with low magnet quality problem were re-manufactured.

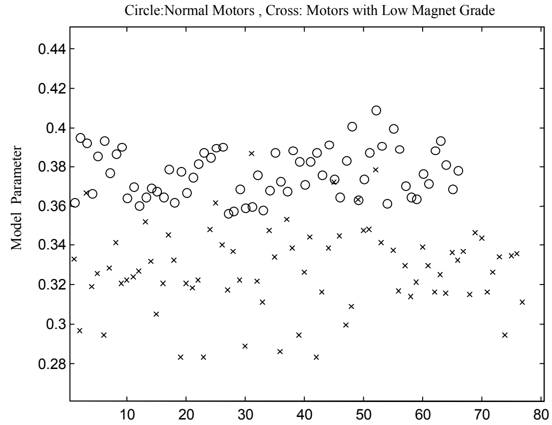

Figure 2: Separation of motors with magnet grade problem from the normal motors

Another example epidemic detection was practiced for a universal motor test application. After a sudden increase in the rejected motors by the test system, manufacturer conducted an analysis study. Source of the problem was identified as wrong positioned brushes due to a fault in assembly operation. The effect of this fault was clearly observed as high noise and low performance in the laboratory measurements as well. Figure 3 shows the separation of these motors from normal production using one of the parameters calculated by motor test system.

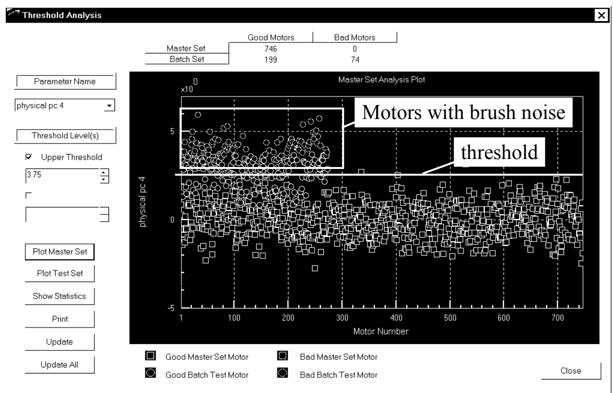

Figure 3: Detection of universal motors with brush problem by MQM

B. Fault Detection

Fault detection results obtained using this new motor test technology were reported previously [9,11]. The system found to be very effective in detecting a wide variety of electrical and mechanical faults. A table of selected faults detected by the system can be seen in Table 1. The fault types tabulated here are selected by the customers based on their importance in decreasing field return rates.

Table 1: Detected motor fault types by MQM

Motor Type	Selected Fault Types Detected by the System
Single Phase Asynchronous	Air-Gap Main & Auxiliary Winding Faults Stator Iron Core Faults Friction Faults Low Voltage Start-Up
Single Phase Synchronous	Magnet Quality Winding Faults Friction Faults
Universal Motor	Commutation Faults (Brush Noise, Spark, Wrong Brush Contact Angle…) Bearing Faults Performance Faults (low efficiency, high current, low speed…) Electrical Faults (Winding faults, isolation, grounding…) Stator Iron Core Faults
Permanent Magnet DC	Performance Faults (low efficiency, high current, low speed…) Winding Faults Magnet Quality Friction Faults Commutation faults

C. Performance Estimation

Reasonably accurate performance estimations can be obtained using this new motor test system. As an example, comparison of estimated and measured (dynamometer) torque-speed curves is given in Figure 4 for a permanent magnet DC motor. This function allows the user to control the quality of motors using motor performance parameters under load.

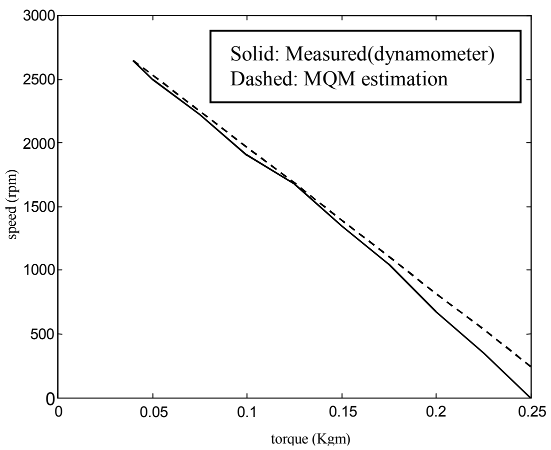

Figure 4. Measured and Estimated torque-speed curve

D. Reduction in Service Return Rate

Return rate of motors from the field is a very important quality indication. Use of this new motor test system is also beneficial to decrease service returns. An example measurement of this property of the test system is depicted in Figure 5. This figure shows average service return rates of a customer before and after the use of MQM. It is clear from the figure that a significant drop occurs after the MQM system becomes operational at the end of the motor production line.

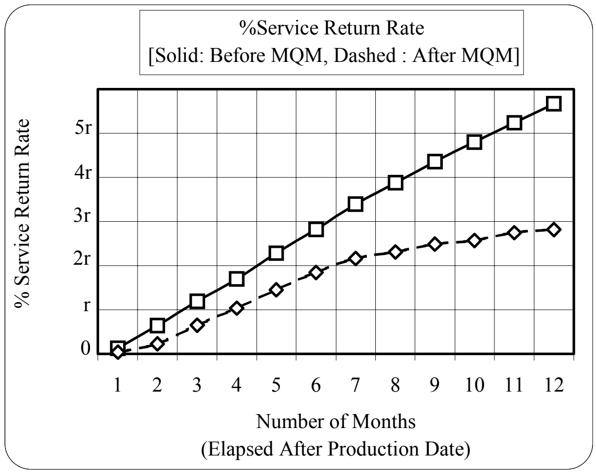

Figure 6: Reduction in service return rate before and after MQM

V. CONCLUSIONS

Model based fault detection technology is successfully industrialized for electric motor quality control purposes. The motor test systems rely on this new-patented technology are commercialized and implemented to several motor manufacturing plants. Developments are continuing for different motor types and motor based applications.

It has been showed that these new motor test systems are very effective in detecting a wide variety of electrical and mechanical faults. The customers using these systems are obtaining satisfactory results in terms of

- Epidemic Prevention
- Comprehensive Fault Detection and
- Field Return Rate Reduction

Performance estimation (without attaching a load) capability also provides the ability of using motor performance parameters under load for quality control purposes.

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