Application of a New Fault Detection Technology for Quality Improvement of Appliance 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.

In this paper, together with the theoretical aspects of the methodology, a case study where the contribution of this system to customer quality improvement requirements will be presented. During this case study, a test system is used at a washing machine producer warehouse for incoming quality control of the motors received to be assembled in washing machines. A Beta-Test is designed where the operation of the system is monitored continuously and decisions reached by the system about the motors are questioned. Motors that are passed or failed by the system are taken through an extensive testing procedure to assess the quality of these motors independently. In addition, service return rate of the washing machines, where the tested motors are assembled, are monitored and change in this rate due to motor malfunctioning and motor noise is observed.

REVIEW OF THE MOTOR TEST TECHNOLOGIES

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 decomposition, 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 behaviour. 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 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 [1-4]. 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.

FUNCTIONALITY OF THE 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

$$L\frac{di}{dt} + Ri + kwi = V$$

$$J\frac{dw}{dt} + fw = ki^2 - T_L$$

Where

V = input voltage
ω = 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 modelling 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.

TESTING THE PERFORMANCE OF MQM

The first application area is selected for the washing machine electric motors and the performance criteria is selected as the following:

- Detection of the motors which are “known” to be faulty
- Motors which are failed at the MQM test should be validated by other test methods
- Service return rate given to the washing machines due to motor problems should be decreased after the MQM installation

After determining the success criteria for MQM, a test procedure is designed to check all the above points. An MQM system is installed to the washing machine manufacturer’s warehouse and motors received from the motor manufacturer first tested at MQM. Then, only the ones, which are accepted by the MQM, are sent to the washing machine assembly area. Motors, which are failed at MQM test, are sent to the laboratories for extensive testing.

TEST RESULTS

Fault Detection

For several cases, MQM’s fault detection capability is examined with different types of motors. Interesting results have been achieved especially for the motors which have noise problems. It should be noted that, MQM only measures the current, voltage and speed of the motor, and none of these signals is directly related with the noise behaviour. However, with the aid of the modelling, effects of the faults that cause extensive noise can be detected from the motor parameters monitored by the MQM. Results obtained for a particular set of noisy motors is depicted in Figure 3, which is the screen plot of the MQM's Analysis Menu. As it can be seen from that figure, a clear discrepancy between the noisy and normal motors is obtained.

At different occasions, MQM also shows the unexpected variations occurred during the production of the motors. An example case is reported for the change in the quality of the sheet iron material used to manufacture laminations of the motor. This capability of MQM enables the identification of costly epidemics at an early stage.

Validation of the MQM's Decisions

Another performance criteria were the validation of the MQM's PASS and FAIL decisions. To achieve this goal, extensive tests have been performed on a set of motors tested at the MQM. Extensive tests contains:

- Performance (efficiency) measurement at the dynamometer
- Speed measurement at the washing machine without close-loop speed control
- Winding temperature measurement under a certain test load

Some examples of the results obtained from extensive tests are given in Figures 4, 5 and 6. In Figure 4, performance measurement of a motor which is PASSED at MQM test is given compared to a motor which is FAILED at MQM test. Comparison is achieved by measuring both motor efficiencies at the dynamometer. It is clear that motor which is PASSED at MQM test is providing a higher efficiency compared to the motor which is FAILED at MQM.

In Figure 5, comparison of the speed measurement of the motors is given. Motors were assembled to the same washing machine and operated at the spin speed with a standard unbalanced mass without electronic control. Result shows that the motor which is PASSED at the MQM test is reaching a higher speed compared to the motor FAILED at the MQM test.

In Figure 6, another comparison is achieved for a couple of different motors. This figure shows the recorded winding temperatures of motors tested at washing machine for a complete washing cycle with a standard test load. It is clear from the figure that the motor which is FAILED at the MQM test gives a higher temperature rise compared to the motor which is PASSED at the MQM.

Decrease in the Service Return Rate Due to Motor Problems

The final success criterion is the service return rate given to the washing machines due to motor problems. Motor problems cover the range of failures due to both functionality and noise. During the a test period of one month, the washing machine producer used only the motors which passes the MQM test for a selected washing machine model. Then, in coordination with the service department service rated given to that model of the washing machine is monitored. The service rates achieved after screening with MQM shows a dramatic drop compared to the average of previous years where motors were not tested at MQM. This finding can be seen from Figures 7 and 8 where service return rate given to the motors due to noise and functionality is plotted respectively.

RESULTS

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.

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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.

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

References

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FIGURES

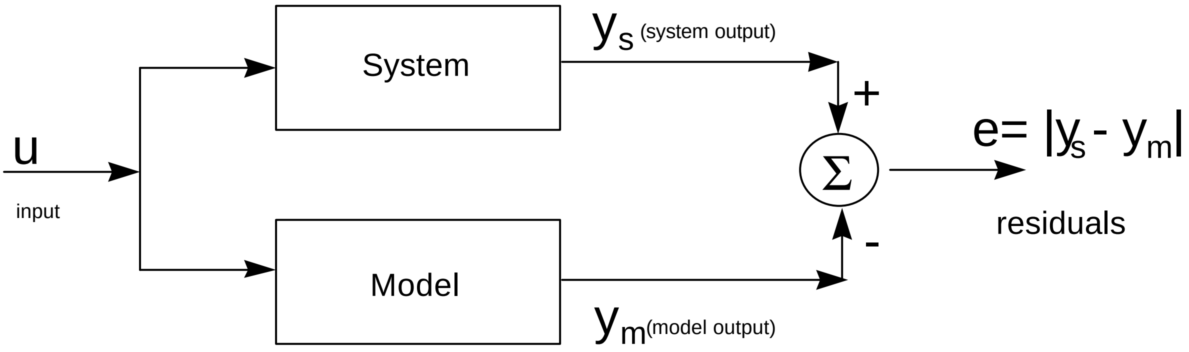


Figure 1: Model Based Fault Detection Scheme

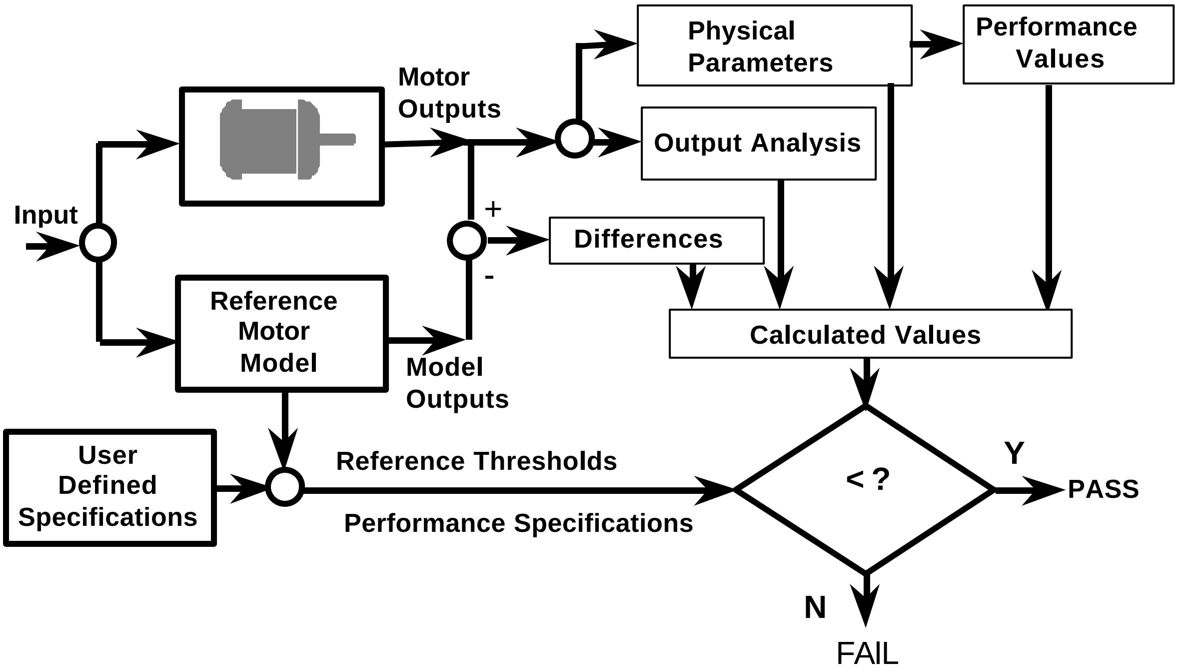
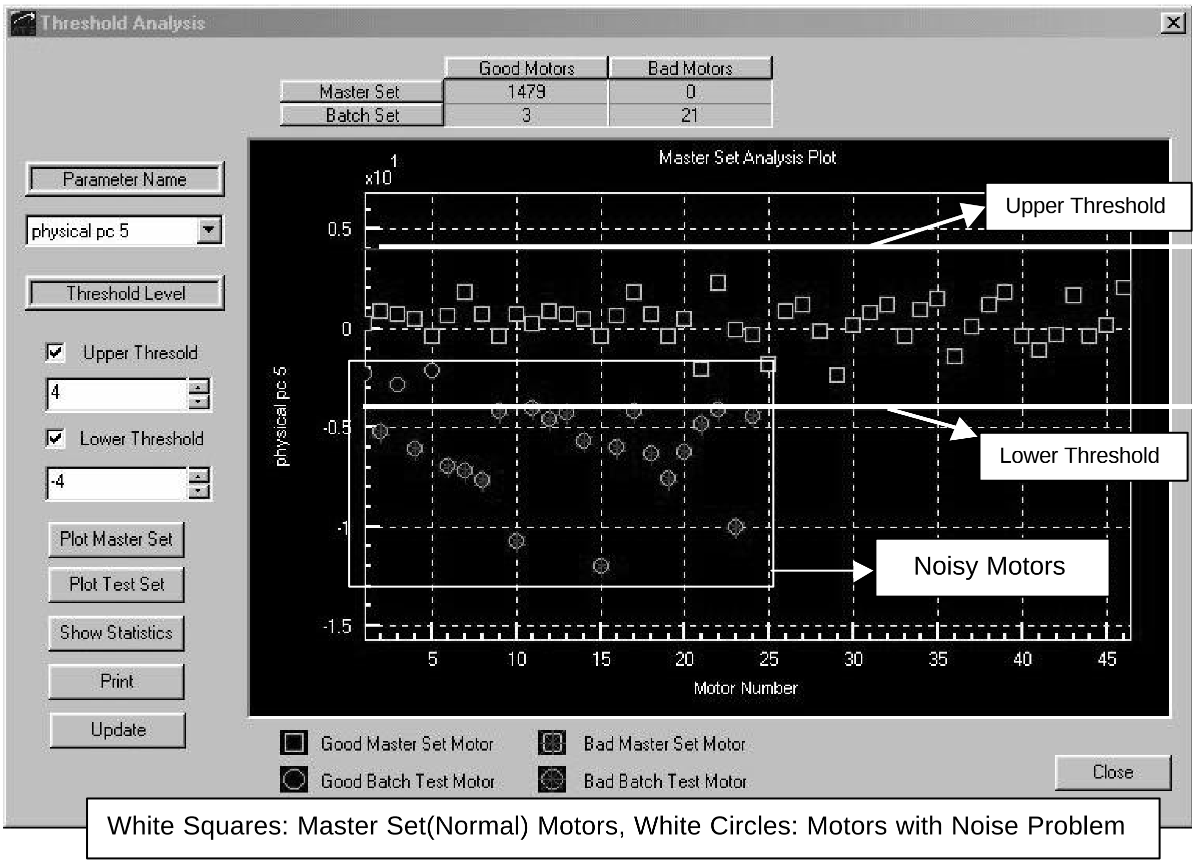


Figure 2: Flow Chart of the MQM's Operation



	Good Motors	Bad Motors
Master Set	1479	0
Batch Set	3	21

Parameter Name: physical pc 5

☑ Upper Thresold: 4

☑ Lower Threshold: -4

Upper Threshold

Lower Threshold

Noisy Motors

White Squares: Master Set(Normal) Motors, White Circles: Motors with Noise Problem

Figure 3: Separation of Noisy Motors from Normal Motors at MQM

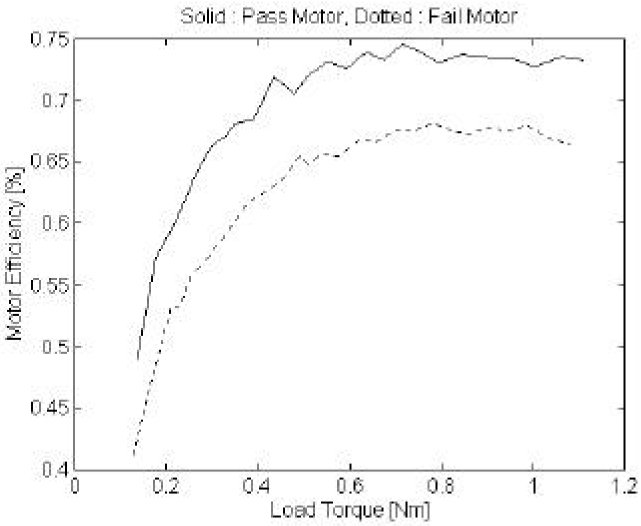


Figure 4: Measured efficiencies for a pass and a fail motor selected by MQM test

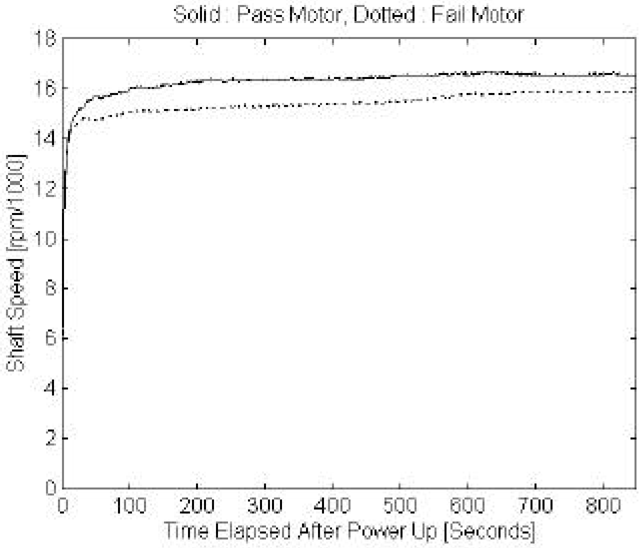


Figure 5: Measured speed for a pass and a fail motor selected by MQM test (0.5 kg-unbalanced load exists in washing machine)

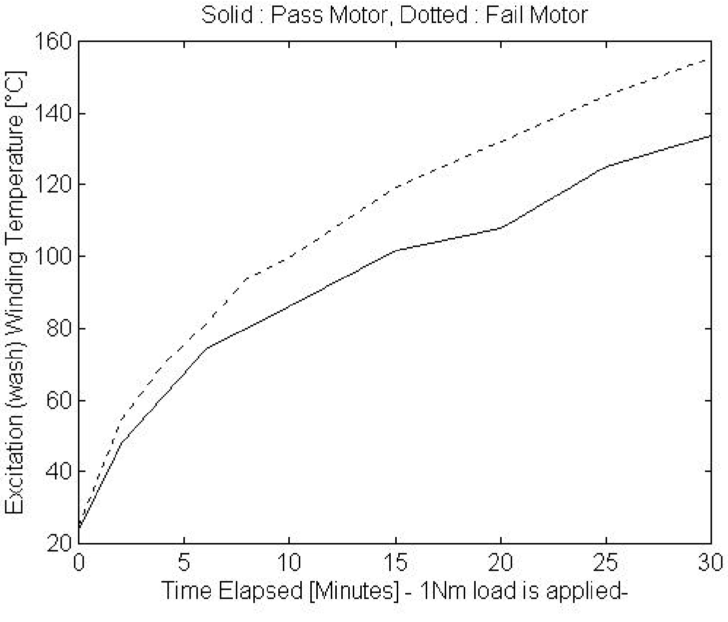


Figure 6: Measured temperature rise in excitation winding of a pass and a fail motor selected by MQM test (washing cycle)

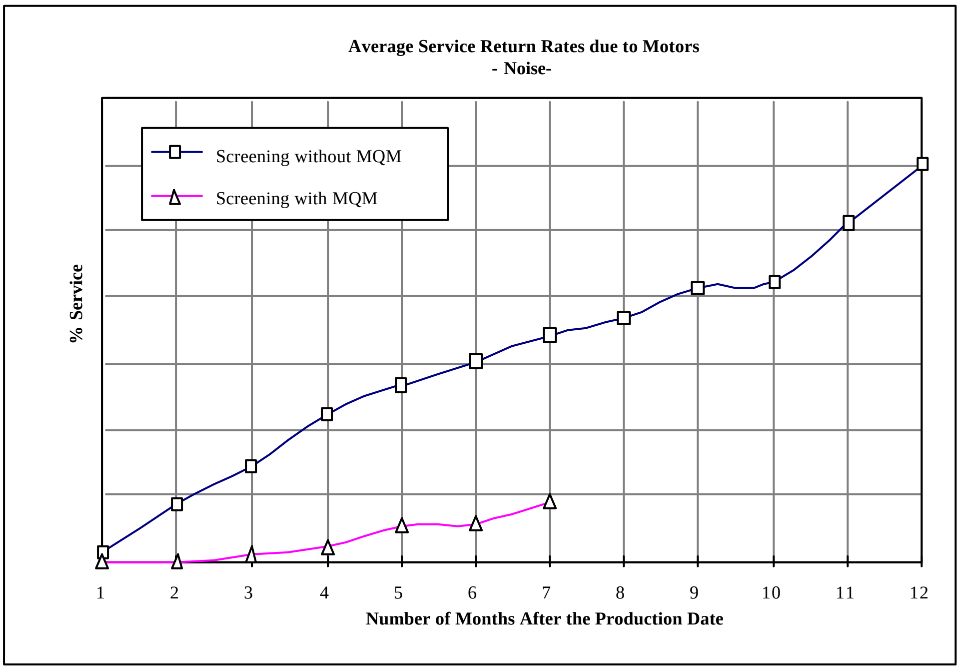


Figure 7: Service Return Rates Given to Washing Machines Due to Motor Noise

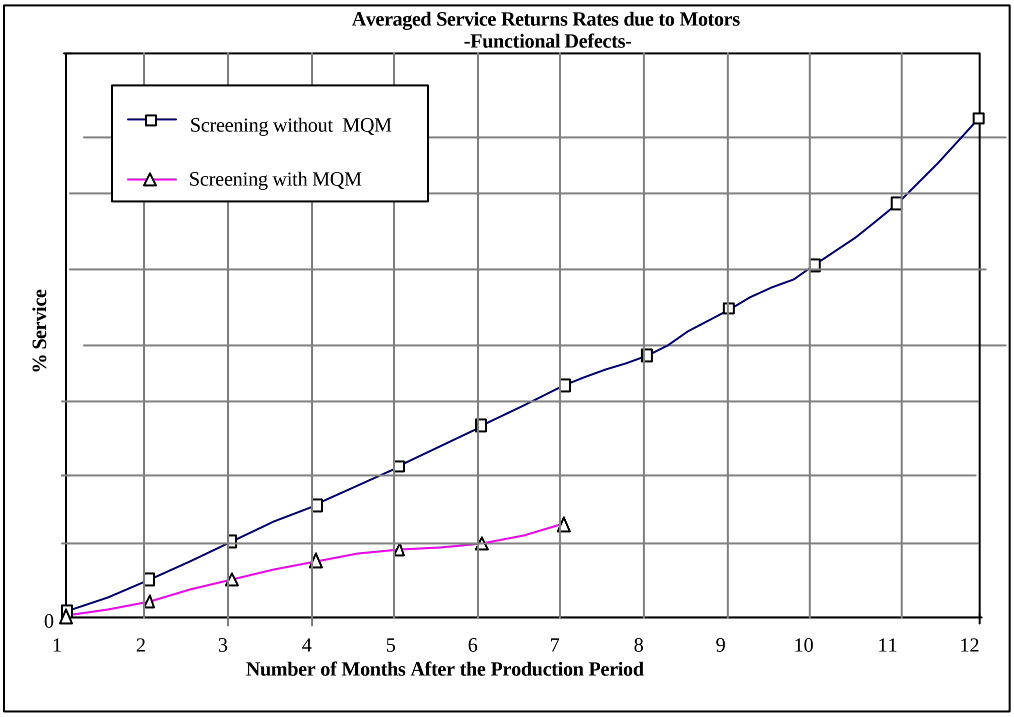


Figure 8: Service Return Rates Given to Washing Machines Due to Motor Malfunctioning