2000

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Albas, E.; Eldem, V.; and Atay, M., "Identification of Compressor Faults Through Model Based Fault Detection Approach" (2000). *International Compressor Engineering Conference.* Paper 1432.
https://docs.lib.purdue.edu/icec/1432

IDENTIFICATION of COMPRESSOR FAULTS THROUGH MODEL BASED FAULT DETECTION APPROACH

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Development of a fault detection system for compressors is described. The system is designed as an "end of the line" test station and feasibility of the methodology has been proved in detecting air-gap faults. Creation of a mathematical model from the experimental data to represent "fault-free" compressor dynamics forms the basis of the method. Once the model is obtained, outputs of the tested compressors are compared with the model outputs. In the absence of a fault, outputs of the tested compressors should give a good agreement with model outputs for the same inputs. If the discrepancy between the model and measured outputs exceeds a pre-determined threshold obtained using a statistical procedure, compressor under test is classified as a "Faulty" unit. The superior capability of the system in detecting air-gap related faults are presented in this study. According to the results of the previous applications of this methodology to different types of electric motors, the system has been proved to be very successful in detecting a wide variety of mechanical and electrical faults. The system is well suited for implementation at production lines with its very short evaluation period. This property of the system was tested for a month duration at a compressor manufacturing plant where the integration of the test system to the available production flow is achieved without a significant problem.

NOMENCLATURE

i_s	: Stator current vector
i_r'	: Rotor current vector referred to stator
V_s	: Stator voltage vector
ω_r	: Rotor speed (electrical rad/sec)
R_s	: Stator resistance matrix
R_r'	: Rotor resistance matrix referred to stator
L_s	: Stator inductance matrix
L_r'	: Rotor inductance matrix referred to stator
L_m'	: Mutual inductance matrix referred to stator
L_{qs}	: Stator inductance in q phase
L_{ds}	: Stator inductance in d phase
L_{qsr}	: Mutual inductance between stator and rotor in q phase referred to stator
L_{dsr}	: Mutual inductance between stator and rotor in d phase referred to stator
i_{qs}	: Stator currents in q phase
i_{ds}	: Stator currents in d phase
λ_s	: Stator flux vector
V_{qs}	: Stator voltage in q phase
V_{ds}	: Stator voltage in d phase

INTRODUCTION

Electric motors are widely used in home appliances as the prime mover of the unit. However, they also constitute the major noise and vibration source of the appliance which will directly affect the quality parameters of the product. Therefore, ever increasing demand from the market for quieter and vibration free appliances can only be fulfilled by the design and production of fault free and quieter motors.

Air-gap related faults are known to be one of the major sources of noise and vibration in compressor motors. Any static or dynamic eccentricity in the air-gap disturbs the uniformity of the magnetic field around the motor. This non-uniform distribution creates forces around the compressor body which cause vibration and noise. In addition to that, non-uniform air-gap in compressor motors also creates start-up problems.

Various techniques are proposed for detection of faults in compressor motors among which measurement and analysis of vibration signature is the most popular one. A common disadvantage of this technique is that they require a-priori information about the fault signatures in order to be able to correlate faults with signals themselves, which can only be overcome by an extensive work of analysis in form of a database. This work could be very laborious and painful and needs deep expertise of many years about the product. Another important drawback of this classical measurement method is the problem of reproducibility. As an example, vibration measurement via accelerometers is highly mounting and position dependent. Moreover, they are very sensitive to environmental (background vibration) and operational conditions (running speed, input voltage, load, etc.).

Such drawbacks can be handled with the application of a model based fault detection scheme [1, 2]. Previous applications of model based fault detection yielded successful results for the solution of fault detection problems in washing machine and vacuum cleaner motors [3, 4, 5]. In essence, this model based technique compares the output signal of a system with the output signal obtained from a mathematical model of the fault-free system. The model of the compressor motor obtained thorough application of an experimental modelling algorithm where measured inputs and outputs of the system are used to obtain the parameters of the governing dynamic equations for the system under consideration. The comparison of the modelled and measured signals is quantified in terms of the "residuals". The residuals are the difference between the signals being measured and the signals being generated by the mathematical model. Fault detection is based on the residuals exceeding some pre-determined set of threshold values. Further analysis of the residuals is carried out to determine the type of the fault. Schematic diagram of model based fault detection is depicted in Figure 1.

This paper describes the implementation of the model based fault detection technique for compressor fault detection. In order to avoid sensor replacement problems and complicated automation requirements, system is designed to perform tests on the compressors using only electrical signals. Therefore, only stator voltages (main and auxiliary) will be measured together with the stator (main winding) current. First, analytical model of the compressor motor will be presented. Analytical model of the compressor will be obtained in a way to represent the dynamics of the compressor motor in terms of stator currents and voltages which are the measurable signals. Then, modelling of the compressor motor dynamics using experimental data will be given. Since the rotor currents are not measurable for this motor, modelling will be achieved using stator currents and voltages. After that, the use of the model parameters for detection of air-gap faults will be depicted. The conclusions and suggestions for future work will be given at the final section.

DYNAMIC BEHAVIOUR

The type of the electric motors used in the compressors can be classified as single phase induction machines which are basically two phase induction machines driven by a single source. Since the rotor currents are not measurable for this motor, dynamic equation should be written in terms of stator current and voltage. In stationary reference frame, the equations of this motor can be written as [6]

$$\frac{d}{dt}\begin{bmatrix} i_s \\ \lambda_s \end{bmatrix} = \begin{bmatrix} \Gamma - J_\eta \omega_r & R_r + J_\eta L_r \omega_r \\ -R_s & 0 \end{bmatrix} \begin{bmatrix} i_s \\ \lambda_s \end{bmatrix} + \begin{bmatrix} L_r \\ I \end{bmatrix} V_s \tag{1}$$

where;

$$i_s = \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix}, \ \lambda_s = \begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \end{bmatrix}, \ V_s = \begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix}$$

and

$$\Gamma = L_r R_s + L_s R_r$$

$$\lambda_s = L_s i_s + L'_m i'_r$$

$$R_r = \sigma^{-1} R'_r$$

$$L_r = \sigma^{-1} L'_r$$

$$\sigma = L'_r L_s - L'^{\,2}_m$$

$$J_\eta = \begin{bmatrix} 0 & -1/\eta \\ \eta & 0 \end{bmatrix}$$

$$\eta = \frac{L_{dsr}}{L_{qsr}} \frac{(L_{qr} L_{qs} - L^2_{qsr})}{(L_{dr} L_{ds} - L^2_{dsr})}$$

In discrete time, equation (1) becomes

$$\begin{bmatrix} i_s \\ \lambda_s \end{bmatrix}(k+1) = \underbrace{\begin{bmatrix} (\Gamma - J_\eta \omega_r)T + I & (R_r + J_\eta L_r \omega_r)T \\ -R_s T & I \end{bmatrix}}_{A} \begin{bmatrix} i_s \\ \lambda_s \end{bmatrix}(k) + \underbrace{\begin{bmatrix} L_r \\ T \end{bmatrix}}_{B} V_s(k) \qquad (2)$$

To transform to Alpha-Canonical form, the following transformation will be applied to the above equation [7]

$$Q = \begin{bmatrix} -I & (R_r + J_\eta L_r \omega_r)T \\ I & 0 \end{bmatrix} \qquad (3)$$

Then, the equation (2) becomes;

$$\begin{bmatrix} \bar{\lambda}_s \\ i_s \end{bmatrix} = QAQ^{-1} \begin{bmatrix} \bar{\lambda}_s \\ i_s \end{bmatrix} + QBV_s(k) \qquad (4)$$

From here, state i_s can be written as

$$i_s(k+1) = \begin{bmatrix} 0 & I \end{bmatrix} \begin{bmatrix} \bar{\lambda}_s \\ i_s \end{bmatrix}(k) \tag{5}$$

Finally discrete time equation for stator current transformed into

$$i_s(k+1) = a_1 i_s(k) + a_2 i_s(k-1) + a_3 V_s(k) + a_4 V_s(k-1) \tag{6}$$

which is suitable for parameter estimation purposes. Here $a_{1..4}$ contains rotor speed and physical constants of the compressor motor.

MODEL BASED FAULT DETECTION

The model of the normal process is assumed to be a discrete time linear system described by the following state equations

$$x(n+1) = A\,x(n) + B\,u(n) \tag{7}$$

$$y(n) = C\,x(n) \tag{8}$$

where x, u and y are the nx1 state, the px1 input and the qx1 output vectors respectively. A, B, C are the known nominal matrices of the system with appropriate dimensions. The process noise, measurement noise and the modelling errors due to uncertainties in the parameters are not included for mathematical simplicity. It is assumed that the system is in a-canonical form such that the following relations hold [7] :

$$C = [0 : H^{-1}] \tag{9}$$

$$A = A_0 + K\,H\,C,\ A_0^{\mu} = 0 \tag{10}$$

$$(H\,C)_{ri}\ A_0^{m_i} = 0,\ (H\,C)_{ri}\,A_0^{l}\,K_{cj} = 0'\ for\ l \geq 0,\ \wedge\ l < \mu_i - \mu_j \tag{12}$$

Here K is a deadbeat gain and A_0 is a lower left triangular structure matrix which consists of zeros and ones only. A_0 is determined by the observability indices $\{\square_i\}$. $(HC)_{ri}$ denotes the i'th row of HC and K_{cj} denotes the j'th column of K. The matrices A, B and C of this model are determined by using the multivariable system identification technique developed. A, B, C matrices obtained are used as baseline process parameters of the system. Any changes of these parameters observed away from pre-selected threshold values are used to detect and diagnose the faults. Therefore, faulty process is assumed to be represented by the following equations;

$$x_f(n+1) = A_f x_f(n) + B_f u(n) \tag{13}$$

$$y_f(n) = C_f x_f(n) \tag{14}$$

and the residual vector is

$$r = y - y_f \tag{15}$$

Compressor motors are tested as the pump unit is assembled to motor shaft and before the welding of upper cap. The experimental model of the compressor motor is obtained for two different operating conditions. At the first operating condition, voltage is only applied to the main winding to simulate the locked rotor condition. Then, together with the main winding, auxiliary winding is energised for a short duration of time to start the compressor motor. Applied voltages to the main and auxiliary windings are measured together with the stator current. An example plot of measured signals during a test is given at Figure 1 where comparison with the modelled current output is also depicted. Modelling of the motor is achieved for both operating points separately using measured stator main winding current, and main and auxiliary winding voltages. Modelling errors are 7.2 % for the locked region and 5.1 % for the second region.

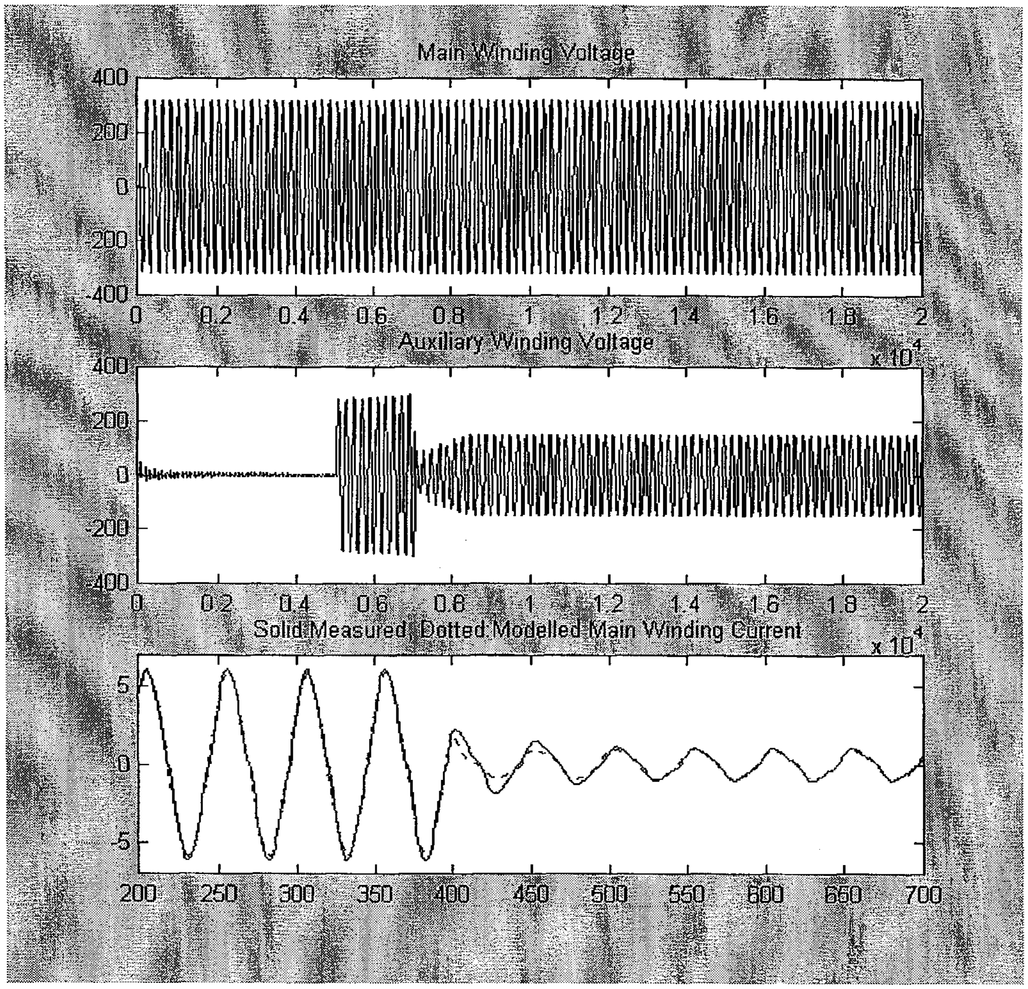


Figure 1 : Measured voltage signals and comparison of measured and modelled stator current

EXPERIMENTS

Experiments are performed to evaluate the performance of fault detection system based on the following criteria

i. Obtain overall % fault detection rate

ii. Observe sensitivity of the system to changes in air-gap

iii. Examine repeatability of the system

A set of compressor motors is received from a compressor manufacturing plant to test the above points. The motor set is composed of 20 motors, where 11 of them have out of tolerance air-gap values. The motors with normal air-gap values are measured 6 times to include the variation that might occur due to different start-up points. Then calculated model parameters for the motors with out of tolerance air-gap values are compared to motors with normal air-gap values. An example comparison plot is given in Figure 2. The comparison is achieved by plotting a model and a performance parameter in a 2-D plot. As it can be seen from the figure, 9 of the 11 compressor motors which have out-of tolerance air-gap values are separated from the normal motors. The 2 motor which are sent to have out-of tolerance air-gap values are fallen into the same group with the normal motors are further examined and their air-gap values are measured within the acceptable limits. This change is explained with a possible shock exerted on the compressors during the transportation.

For the sensitivity analysis, air-gap of a fault-free (air-gap value is in-tolerance) compressor is distorted by a skilled operator through hitting the stator body with a hammer. Fault is introduced and removed progressively so that effects of changing the air-gap can be clearly seen from parameters. An example plot is given in Figure 3 . As it can be seen from the figure, model parameters related with air-gap value varies with changing air-gap.

The aim of the repeatability analysis is to show the insensitivity of air-gap related parameters to initial conditions of the compressor (eg., wear in the piston-crank mechanism). In order to examine repeatability, one faulty and one fault-free compressor are tested for 10 times with 5 minute cool-down period between each measurement.

Result of the repeatability study showed that air-gap related model parameters are not affected by the initial conditions of the compressor. This finding can be observed from Figure 5. It is clear from the figure that air-gap related parameters of a fault-free compressor remains almost constant through out the measurements. However, parameters of a faulty motor gives a gradual deviation from expected mean from measurement to measurement, which is thought to be related with progress in the effects of the fault.

CONCLUSIONS

A successful model of the compressor motor with reasonably small modelling errors is obtained using stator current and voltages. Then, using this model, it is showed that it is possible to detect air-gap related faults of compressor motors through application of a model based fault detection scheme. Dynamic model parameters of the compressor motors carry information about air-gap faults and they produce repeatable results for fault detection.

After the completion of this study, developed model based algorithm was converted to a computer program which makes testing at the end of a compressor motor manufacturing line. In addition to that, a dedicated set of instruments was integrated and a prototype test system was obtained. This prototype was tested for a month duration at a plant for pilot testing. The observations on the system performance showed that air-gap fault detection can be performed under real production conditions as well where change in the production characteristics is a big problem for most of the fault detection systems.

For the future work, detection of other types faults will be examined. Faults on the piston-crank mechanism and electrical problems (like isolation) of the motor will be studied in near future.

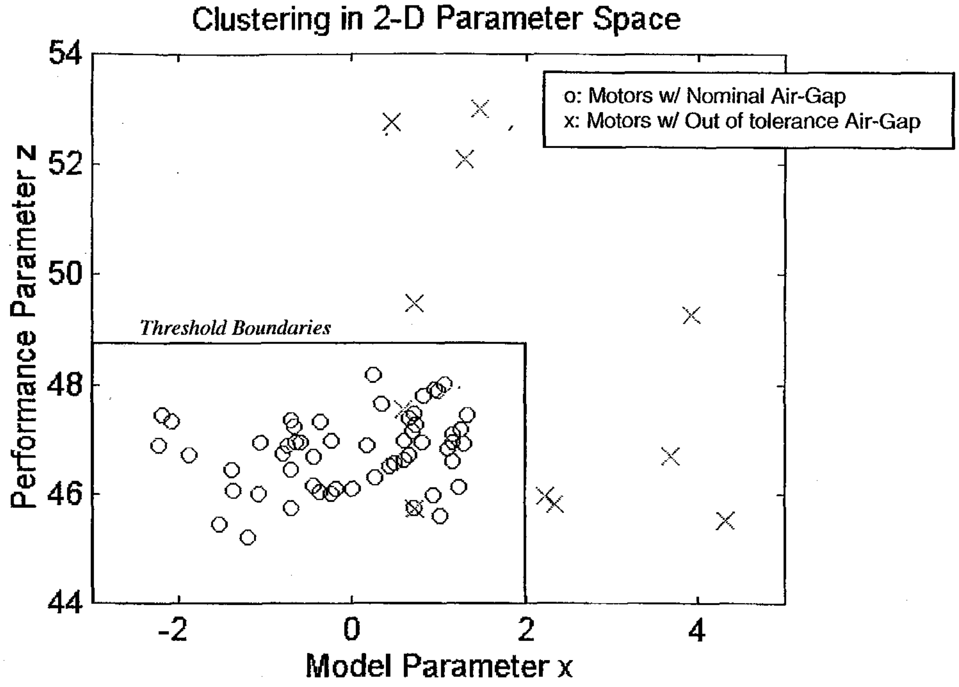


Figure 2: Separation of faulty compressors in parameter space

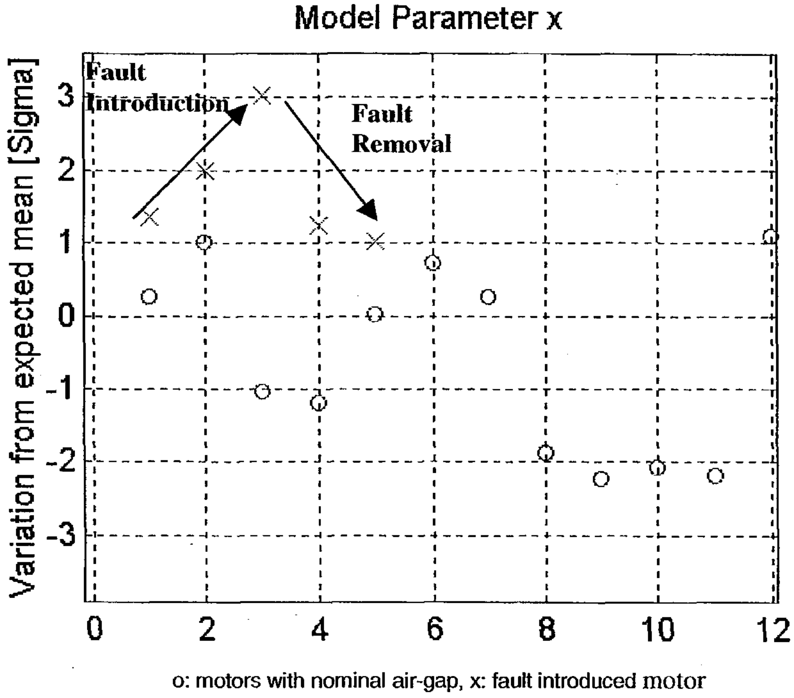
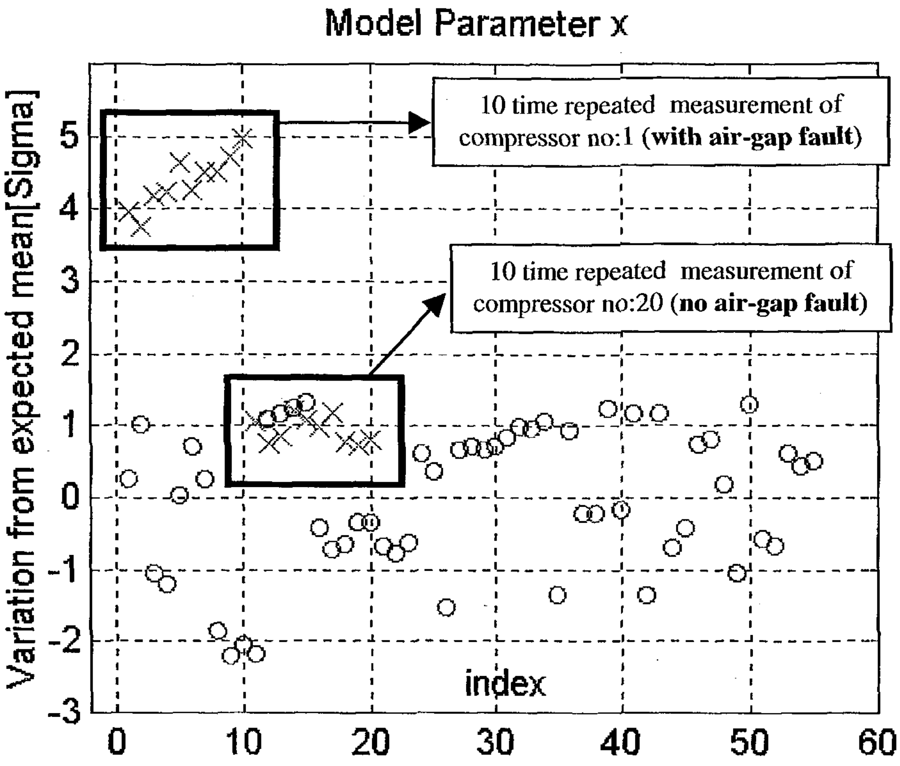


Figure 3: Air-gap fault introduction and removal from a fault-free compressor



o: motors with nominal air-gap, x: repeated motor measurements

Figure 4 : Change in model parameter x in repeated measurements

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