8th International Symposium on Magnetic Bearing
August 26-28, 2002, Mito, Japan

PRODUCTION TEST OF A SINGLE-FAULT TOLERANT BEARINGLESS MOTOR

Petra Jucker
Laboratory of Electrical Engineering and Design, Swiss Federal Institute of Technology Zurich, 8005 Zurich, Switzerland
jucker@eek.ee.ethz.ch

ABSTRACT

Electrical devices for medical use have to be tested rigorously. A concept for production tests of a single-fault tolerant bearingless motor, that is used in a LVAD (Left Ventricular Assist Device), has been developed. This concept includes not only a verification of the function under normal operating conditions. In addition, the correct reaction of the system to any possible fault has to be guaranteed. The fault tolerance tests were implemented and tested with several motors.

INTRODUCTION

A single-fault-tolerant motor for use in an LVAD has been presented in [1]. It was demonstrated with several animal tests that this motor fullfills the requirements for an implantable centrifugal bloodpump. The motor consists of two identical subsystems, each containing two bearing windings, one drive winding and an electronic system. These two subsystems, called A and B from now on, work together in "hot redundancy" during normal operation. In case of a fault in system B, either in the motor or the electronic part, the intact system A takes over the function of the defect system without interruption and vice versa. In addition, only the defect part of system B is turned off to maintain the system in maximal possible fault tolerance. The whole electronics apart from the power supply is integrated in the motor to reduce size.

If these motors are used in a medical device, rigorous production tests are required. First of all, a faultless operation of the motor under normal operating conditions has to be guaranteed. Further, the correct reaction of system A to a an error in system B and vice versa has to be checked. A correct reaction would be to shut down the defect part of system B before the occurred error affects the intact system. In order to test the fault tolerance of the system, faults must be generated without destroying the motor.

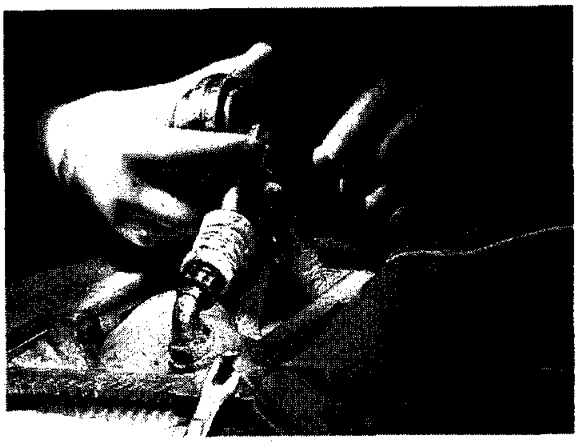

FIGURE 1: Implantation of a LVAD in a calf

As the implantable motor has its electronics fully integrated and is potted, it is more complex to simulate faults. Errors cannot be generated with hardware intervention as for example short cuts of a phase. Therefore, faults than can occur in the motor have to defined distinctly. It has to be determined, which errors can be simulated by software in an assembled motor and for which ones it is necessary to check the fault detection in advance.

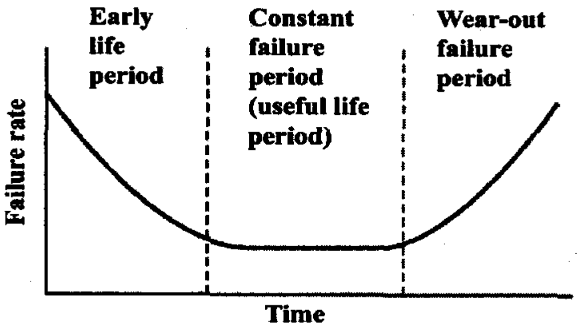

FIGURE 2: Variation of failure rate with time [2]

CONCEPT FOR TESTING

The whole production test can be divided into three main parts:

- Burn-in
- Function test
- Fault tolerance test

Burn-in

The reliability of a system over time is described in [2] and [3] with the bathtub curve (see Figure 2). Most of the failures caused by weak components occur in early life of a system. A burn-in of the motors attempts to get the system beyond the early life period. During the burn-in the system is cycled through a test pattern of low and high speeds to accelerate the aging of the system and therefore pass the early-life period as fast as possible.

Function test

The function test validates the performance of each subystem in a stand-alone mode as well as working together in "hot redundancy". This test has to be executed under operating conditions with a water ciruit in order to measure the pump characteristics. Power consumption, flow and pressure between in- and outlet are logged and compared to the default values. The transient behaviour of the motor in case of a fault is not checked with this test. It only has to guarantee that each subsystem works correctly during normal operation.

Fault tolerance test

Fault tolerance tests have to show that the system reacts correctly in case of an error. The transient behaviour in case of a failure must be analyzed, as the system has to run continuously without any interruption.

The algorithms of the fault tolerance are divided into four main groups:

- Position sensor error detection
- Field sensor error detection
- Overcurrent error detection
- Openloop error detection

The **position sensor error detection** treats all kind of errors that can occur in position measurement. In case of a position error in System B the measured position of the intact system A is transmitted to B, which now uses the measurements from A for the position control. The **field sensor error detection** is responsible for any fault in the field measurement. The same mechanism as described for the position measurement enables the faulty system to use the correct field measurements of the other system. If there is a shortcut of a bearing or drive phase, or a shortcut in one of the power-switches, the **overcurrent error detection** reacts and shuts down the faulty power channel. The last error group, the **openloop error detection**, handles faults like open coils or failures in current measurement that cause an open current control loop.

In Table 1, the four main error groups are divided into errors that can be simulated by software and errors for which the fault tolerance test have to be excecuted prior to the assembly of the motor.

TABLE 1: Software or Hardware Intervention

Error group	Software	Hardware
Position sensor error	X	
Field sensor error	X	
Overcurrent error		X
Openloop error	X	

Only the overcurrent detection and reaction to this error is implemented in hardware. This is necessary as the high current in case of a short cut destabilizes the system within μs. An integrated circuit handles the alert of the overcurrent detection and disables the faulty power channel within μs. The control unit only gets a notification that the specific power channel was shut down. For safety reasons during normal operation it is not possible to generate currents high enough that the overcurrent detection responds by setting the PWM outputs to the maximum. The only possibility to generate defined overcurrents is to change the load of the power-bridges by hardware intervention. For this reason, it is impossible to test the overcurrent detection when the motor is fully assembled and potted. Pre-assembly tests of the power-stage PCB are necessary.

All of the other error detection algorithms are implemented in software. The measured field, position and

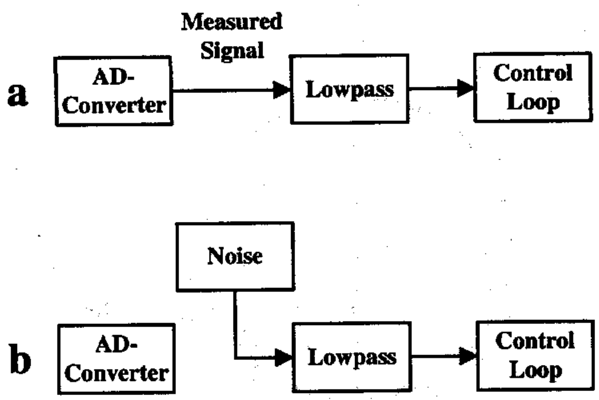

FIGURE 3: Insertion of noise

currents are compared to thresholds and the control unit decides wheter an error occurred or not. Therefore these errors can be simulated by changing the input variables in the controller software.

Misinterpretations. Furthermore, the fault tolerance tests have to guarantee that no part of a system is shut down because of misinterpretations. They might occur in case of faults in the error detection of the system or thresholds that are too tight. The only way to guarantee that no partial shutdown of a subsystem occurs because of misinterpretations is to run the motor for several hours and to check if any error occurred. This part of the fault tolerance tests can already be done during burn-in.

IMPLEMENTATION

The sequence of reading sensor signals for the control loop is shown in Figure 3a. The AD-converted signal is low-pass filter before it is fed into the control loop. For the error simulation by software, the AD-converted sensor signal is replaced by a special noise signal (see Figure 3b).

Noise Signal

The used noise signal is generated according to [4]. The linear congruential method that was introduced by D. Lehmer in [5] has the following form:

$$RN(n) = [RN(n-1) * m) + i]\, modM \qquad (1)$$

with

RN(n)	current random number
RN(n-1)	previous random number
RN(1)	seed (first random number)
m	multiplier (constant)
i	increment (constant)
M	modulus (defined by word width of processor)

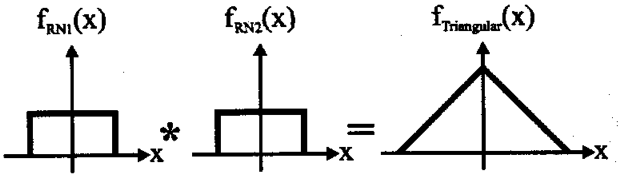

FIGURE 4: Density Function of Noise Signal

These random numbers are uniformly distributed. As we want to generate a noise signal that corresponds as good as possible to a real noise signal, a triangular distribution is preferred. This means, that the values around zero are more probable than far away from zero. A triangular distribution can be formed by multiplying two random number generated with the linear congruential method. According to the convolution theorem for the Fourier transformation, the density function of two multiplied random signals is (see [6]):

$$Triangular(n) = RN1(n) \cdot RN2(n) \qquad (2)$$

$$f_{Triangular} = f_{RN1} * f_{RN2} \qquad (3)$$

The density function of the uniformly distributed signal and of the noise resulting from the multiplication of two random signals is shown in Figure 4.

Other noise signals that also have a triangular density function can be generated by simple modifications of the signal defined in Equation (2). If the noise signal is scaled with an amplitude and shifted with an offset (see Equation (4)) the mean value and the maxmimal and minimal value of the noise signal can be generated [7]. The resulting density function is shown in Figure 5.

$$Noise(n) = RN1(n) \cdot RN2(n) \cdot amplitude + offset \qquad (4)$$

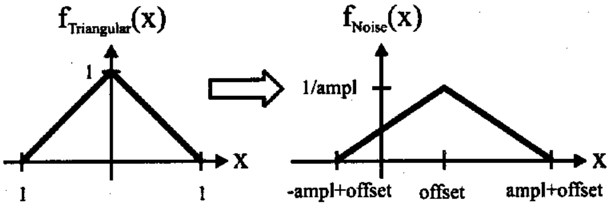

FIGURE 5: Shifted and Scaled Density Function of Noise Signal

The resulting noise signals for different settings of amplitude and offset are shown in Figure 6 and 7. The noise signal is plotted against time supposing that every ms a random signal is generated.

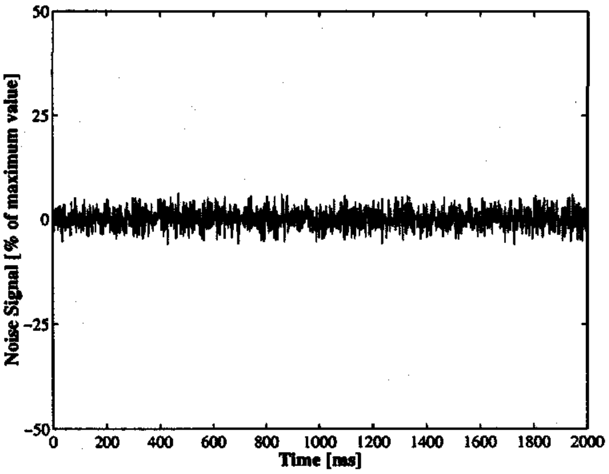

FIGURE 6: Noise signal with amplitude of 12.5% and no offset

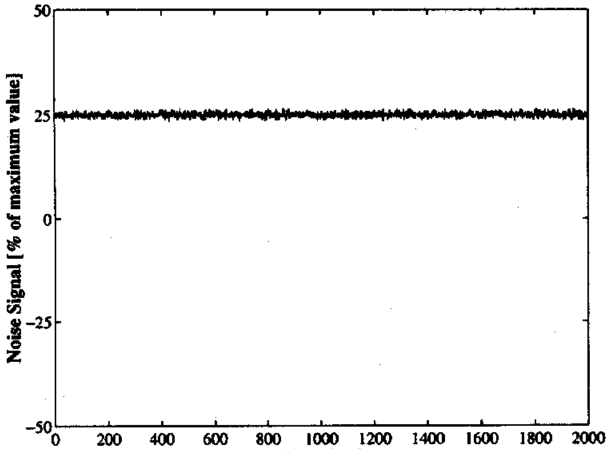

FIGURE 7: Noise signal with low amplitude and offset of 25%

Field Sensor Error

The error detection for the field sensors calculates the position of the measured field in an x-y-plot. The value of the radius has to be in between the upper and lower limit as shown in Figure 8.

The possible field sensor signals in case of an error are:

1. Field sensor signal is around the reference signal of the field measurement (represents no field measured)
2. Field sensor signal goes into saturation (maximal and minimal field measurement value)
3. Amplitude of field sensor signal is multiplied with a factor

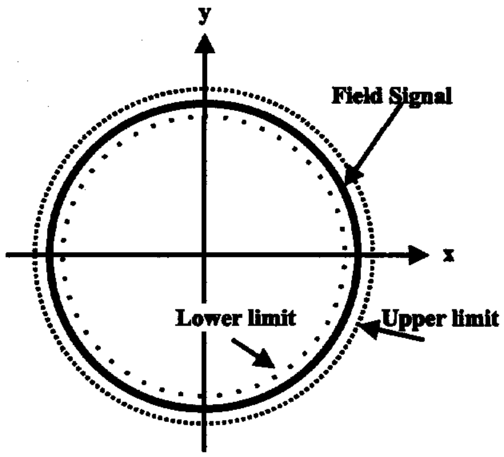

FIGURE 8: Error detection for field sensors

Errors 1 and 2 can be simulated by replacing the measured signal with a noise signal described above. For both of the errors the amplitude can be choosen very small and the offset has to be zero for error 1 and maximal for error 2. The required values for amplitude and offset are listed in Table 2.

TABLE 2: Simulated Signals for Field Sensor Error

Error Nr.	Amplitude	Offset
1	small	0
2	small	max/min

Error 3 can be simulated by multiplying the measured field signal with a factor and feeding the scaled value to the input of the controller.

Position Sensor Error

The position error detection first checks if the difference between the measurements of system A and system B is within a specified range. Moreover, the difference between the last two measurements is calculated and an error is detected, if this difference is smaller than a threshold. As the orbit of the position sensors is very small at low speeds, the second part of the detection algorithm is only executed at speeds higher than 400rpm.

In case of the two most likely position sensor errors, the measured position signals are:

1. Position sensor signal is around the reference signal of the position measurement (represents no displacement)
2. Position sensor signal goes into saturation (maximal and minimal position measurement value)
3. The amplitude of the position sensor signal is scaled

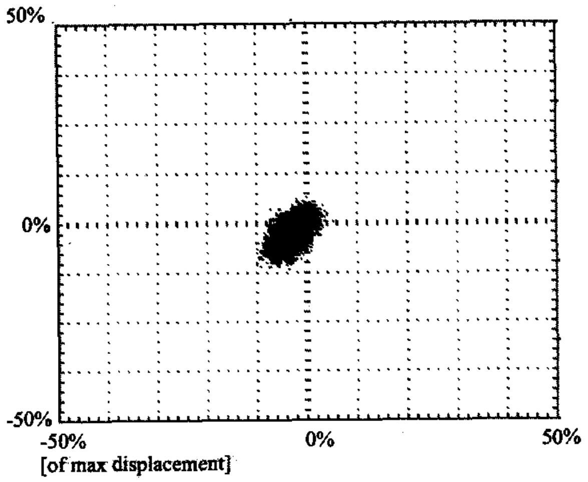

FIGURE 9: X-Y-Plot of Position Measurement at 4500rpm

The reference value of the position controller is normally zero. So the orbit of the position measurement is always about zero (see Figure 9). Therefore it is very difficult to detect errors of type 1, as this error causes a signal that has constantly the same value as the reference signal. So the simulated noise signal for this error detection algorithm has to have an offset of zero and an amplitude smaller than the one in normal operation mode.

Errors of type 2 are detected by comparing the measured position of system A and B. For testing this part of the error detection algorithm, the inserted noise has to have a large offset and a large amplitude. If the amplitude is choosen big enough, not part 1 of the detection (difference between last two measured values) responds but part 2.

TABLE 3: Simulated Signals for Position Sensor Error

Error Nr.	Amplitude	Offset
1	small	0
2	higher than normal difference between two following measurements	max/min

With the noise signals proposed in Table 3, the error detection for all of the possible errors is tested, as error 1 is the most difficult one to detect. The difference in position sensor signals between system A and B is much easier to detect and a simulation of the worst case is sufficient. A scaling of the measured position signal as described for the field sensor error simulation checks the detection of type 3 errors.

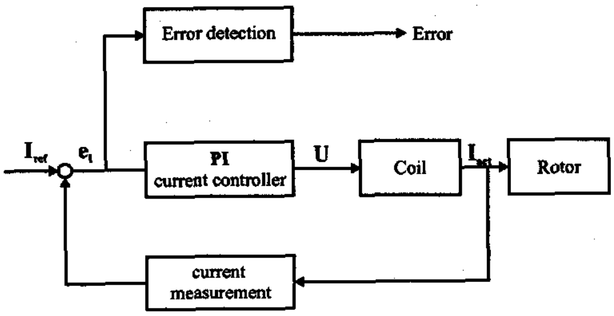

FIGURE 10: Openloop detection

Openloop Error

The open loop detection is different for the bearing windings and the drive windings as only reference value of the bearing current controller is about zero. The reference value for the drive current controller is dependent on the set speed.

Bearing Windings. The algorithm for the open loop detection of bearing windings is based on monitoring the control error (e_I) of the current controller. If the control loop is no more closed, the error e_I will increase. If the control error e_I crosses a threshold, the algorithm signalizes that an error occurred. This algorithm detects every interruption of the control loop as broken current measurement, open coils, open power-bridges etc.

Similar to the position sensor detection, an error which generates currents close to the reference value is most difficult to detect. This can happen if there is an open coil, an error in the current measurement. These kind of errors are simulated with a noise signal with no offset and a small amplitude.

Drive Windings. For the drive windings, the current is not zero in normal operation mode. The error detection algorithm compares the measured current with the reference current. If the difference between measured and set current is higher than the threshold, an open loop drive error is detected.
The choosen noise signal to simulate a drive winding error has an offset of zero and a small amplitude. Further investigations to determine the optimal error simulation are necessary. Amplitude and offset of the noise signal for the openloop detection check are listed in Table 4.

TABLE 4: Simulated Signals for Openloop Errors

Error	Amplitude	Offset
Bearing	small	0
Drive	small	0

SUMMARY AND OUTLOOK

A concept for production tests including a burn-in, a function test as well as a fault tolerance test have been developed. The simulation of the worst case errors is made possible with a random noise signal with adjustable offset and amplitude. The fault tolerance tests were executed with several motors. All of the possible errors could be induced.

In the future, the signals that occur in case of an error have to be investigated more precisely. With the results of these measurements, the accurate amplitude and offset of the noise signal can be determined. Further, manipulated systems which do not respond correctly to errors are needed. With these systems it can be shown that the fault tolerance tests detect faults in the error detection.

References

1. Schoeb, R. et al, A Bearingless Motor for a Left Ventricular Assist Device (LVAD), Proc. of the 7th Int. Symp. on Magnetic Bearings, ETH Zurich, Switzerland, Aug. 23-25, 2000

2. Lala, P., Self-Checking and Fault-Tolerant Digital Design, San Francisco, Morgan Kaufmann, 2001

3. Johnson, B., Design and Analysis of Fault-Tolerant Digital Systems, Addison Wesley, 1989.

4. Wilbur, E., Random Number Generation on a TMS320C5x, TMS320 DSP Designer's Notebook, Texas Instruments, 1994

5. Lehmer, D. H., in Proc. 2nd Symp. on Large-Scale Digital Calculating Machinery, Harvard Univ. Press, Cambridge, p. 141, 1951

6. Schüssler, H., Digitale Signalverarbeitung Band 1, Analyse diskreter Signale und Systeme, Springer Verlag, Berlin, 1988

7. Schwartz, S. and Shaw, L., Signal Processing, New York [etc.] McGraw-Hill, 1975