# An Innovative Approach to Electromechanical Actuator Emulation and Damage Propagation Analysis

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*Abstract*—As the aviation industry evolves toward next generation fly-by-wire vehicles, hydraulic and electro-hydrostatic actuators (EHA) are replaced with their electro-mechanical counterparts. By eliminating fluid leakage problems while reducing weight and enhancing vehicle control, the feasibility of electromechanical actuators (EMA) in avionic applications has been established. However, due to the inherent nature of electronic components and systems to fail, improved diagnostic and prognostic methods are sought to keep the all-electric aircraft safe. An innovative approach to the emulation of avionic EMA operation is presented. Realistic load profiles can be applied to a scaled-down EMA testbed while executing the in-flight actuator motion commands in real-time. The proposed EMA Emulator is designed to enable the insertion of degraded electronic components, such as the power transistors of the motor drive, to analyze the servo loop response of an aged actuator system. That is, the EMA motion trajectory, or position, data is acquired with various levels of power electronics degradation to populate a fault-to-failure progression (FFP) database of actuator servo loop response signatures. Ultimately, the FFP signature database is leveraged to develop prognostic methods to assess the State of Health (SoH), estimate Remaining Useful Life (RUL), and support Condition Based Maintenance (CBM) of avionic EMA systems[1].

*Index Terms*—Electromechanical Actuator, Emulator, MOSFET, Damage Propagation, Singular Value Decomposition, Principle Component Analysis, Fault Dictionary

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## 1. INTRODUCTION: FLY-BY-WIRE SYSTEMS

Fly-by-wire systems have been heralded as the savior of an industry while also being condemned as unsafe [1]. Fly-by-wire aircraft use computerized systems to control engine fuel-flow rate, flight surface movements, and other activities. A computer can make hundreds of flight corrections and updates per second, far more than a human pilot. In theory, this should lead to more economical, smoother, and safer air flight. Greater, more precise control has, in turn, made possible aircraft that are aerodynamically unstable. With the pilot removed from direct connection to the flight control surfaces in a fly-by-wire aircraft, knowledge of component failure modes has become critical in an industry already filled with maintenance issues and mission-critical equipment.

## 2. NASA'S IVHM PROJECT

The goal of NASA's Integrated Vehicle Health Management (IVHM) project is to improve the safety of both near-future and next-generation air transportation systems by reducing system and component failures as causal and contributing factors in aircraft accidents and incidents. The IVHM project should develop technologies to determine system/component degradation and damage early enough to prevent or gracefully recover from in-flight failures. These technologies will enable nearly continuous on-board situational awareness of the vehicle health state for use by the flight crew, ground crew, and maintenance depot. A main emphasis of the project is to develop automatic methods for detection, diagnosis, and prognosis of the vehicle at a system and subsystem level. This is accomplished through analysis of electro-, thermo-, and mechanical failure, the analysis of the interaction of environmental hazards on vehicle systems and subsystems, and the study of damage and degradation mechanisms to more accurately assess the vehicle's health state.

## 3. RIDGETOP GROUP'S ROLE

Ridgetop's role in the IVHM project is to assist NASA in the development of diagnostic and prognostic methodologies to assess the state of health (SoH) and estimate the remaining useful life (RUL) of the power electronics employed in a typical avionic EMA subsystem. Through

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quality collaboration with the Ames Research Center (ARC), a model-based laboratory testbed is delivered to identify and characterize the fault-to-failure progression (FFP) signatures of dominant failure modes associated with the EMA servo drive and to analyze the propagation of damage through the drive. A high-fidelity computer model is developed and correlated with the laboratory testbed to enable further analysis of simulated motor drive faults and damage propagation. The Ridgetop testbed is integrated with the ARC Advanced Diagnostics and Prognostics Testbed (ADAPT), shown in Figure 1, and, to simulate in-situ EMA failure modes and logistics. Potentially, the testbed is adapted for in-flight emulation of real-time actuator control signals and load profiles.

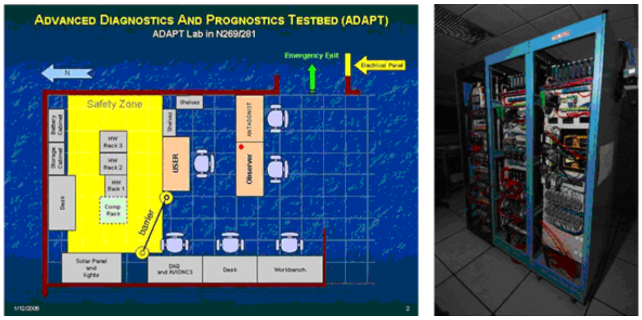


Figure 1 - ADAPT Laboratory at NASA/Ames

## 4. THE RIDGETOP EMA EMULATOR

Based on the concept that damage or degradation of a servo loop is manifested in the characteristic "ringing" response to a load change or disturbance stimulus, position control or regulation of a BLDC motor system is an ideal candidate for application of Ridgetop's patent-pending RingDown$^{TM}$ technology. Specifically, we assert that actuator health can be assessed by measuring the following error, or difference between the target position and actual position, associated with an EMA motion command. The suitcase testbed, shown in Figure 2, was constructed to test our hypothesis on a scaled-down model of an avionic EMA system.

Figure 2 - EMA Emulator Testbed

User-programmable motion trajectories and load profiles are applied to the testbed to investigate the servo drive response to various fault conditions. Properly interfaced to an avionic control system, the scaled-down testbed is capable of in-flight emulation of EMA operation under realistic load conditions and actuator damage profiles.

A functional illustration of Ridgetop's EMA Emulator Testbed is provided in Figure 3. Identical BLDC motors are coupled to emulate actuator motion and load behavior. The actuator motor, on the left-hand side of the diagram, is configured in position mode, while the load motor, on the right-hand side of the diagram, is configured in torque mode. Depending on the desired emulation mode, the torque load can be programmed to oppose or assist actuator motion. Sophisticated load profiles, including combinations of static, step and impulse loads, can be created and synchronized with the motion trajectory to emulate actual avionic flight control scenarios.

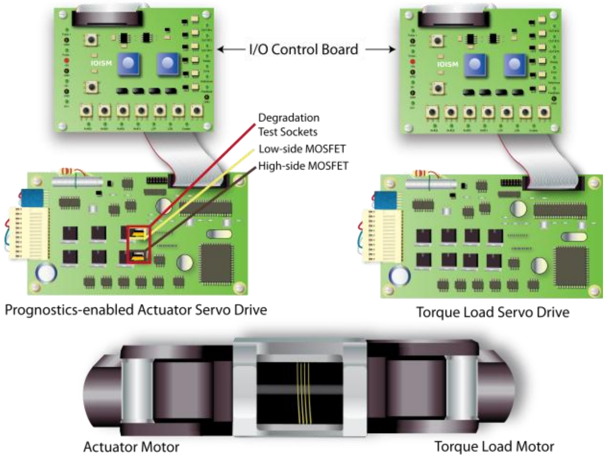


Figure 3 - EMA Emulator Functional Diagram

Once again, matching servo drives and general-purpose Input/Output (I/O) control boards are employed to drive the emulator motors. The prognostics-enabled actuator servo drive has been retrofitted with test sockets to enable insertion of degraded or damaged MOSFET devices into a single phase of the H-bridge. This way, the servo loop response of a damaged actuator can be compared to that of a healthy actuator to develop prognostic analysis methods for the H-bridge power electronics.

## 5. EMULATOR HARDWARE

A close-up image of the EMA Emulator suitcase top panel is provided in Figure 4. Separate Technosoft ISM4803 Servo Drives provide control of the actuator and torque load NEMA-17 BLDC motors. The ISM4803 utilizes a TI DSP to control International Rectifier (IR) power electronics employed in the three-phase H-bridge. Each H-bridge phase is comprised of an IR2102S gate driver integrated circuit (IC) and high- and low-side IRFZ44NS MOSFETs. As shown in Figure 4, the IRFZ44NS D2PAKs of Phase A have been replaced with Molex test sockets to facilitate experimentation with ARC-aged MOSFETs.

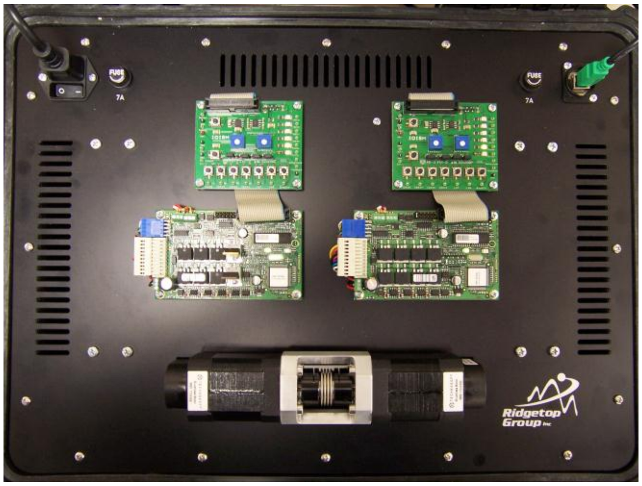


Figure 4 - EMA Emulator Suitcase Panel Top View

Along with the actuator and torque load servo drives and motors, each side of the testbed top panel includes a Technosoft IOISM extension board, which provides an external reference source for position/velocity control as well as general-purpose digital I/O pushbuttons for triggering user-defined motion profiles.

As shown in Figure 5, separate 24 VDC supplies are mounted to the bottom side of the EMA Emulator suitcase panel to isolate the motor power of the prognostic-enabled actuator from the torque load motor. A shared 5 VDC supply, on the other hand, provides power for both the actuator and torque load servo drive controller logic. All of the motor power supply and encoder cabling is routed underneath the top panel.

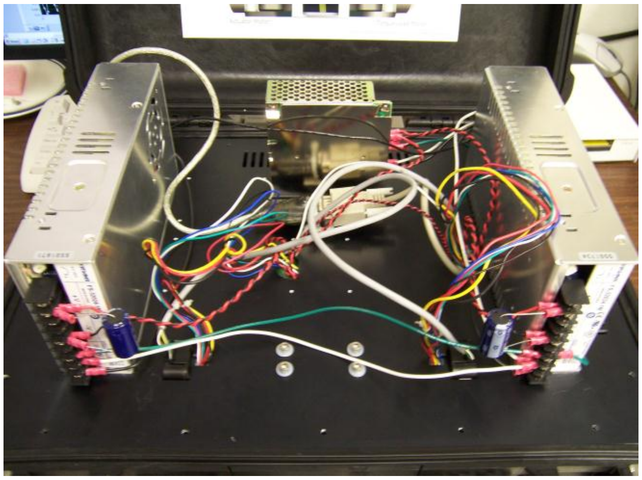


Figure 5 - EMA Emulator Suitcase Panel Bottom View

In addition to the power supplies, a commercial USB-to-Serial adapter is included to enable connection to the EMA Emulator Testbed via a standard USB port. Although the USB-to-Serial adapter appears as a traditional COM port to the host computer and an RS-232 interface is used to communicate with the servo drives, the USB-to-Serial adapter alleviates the requirement of the host computer including a legacy serial port. During setup of the EMA Emulator Testbed, a device driver is installed to enumerate the host computer COM port used to communicate with the testbed.

The ISM4803 Controller Area Network (CAN), depicted in Figure 6, allows multiple servo drives to be configured in a multi-axis motion control application. The EMA Emulator Testbed utilizes this feature of the ISM4803 to synchronize the torque load with the actuator motion trajectory. In this configuration, the actuator drive acts as the CAN bus master with an Axis ID of 255, while the torque load drive acts as a CAN bus slave with an Axis ID of 1.

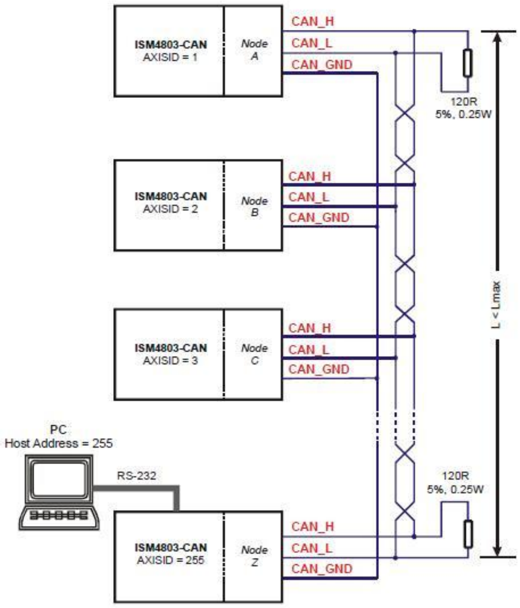


Figure 6 - ISM4803 Multi-Axis CAN Bus Network

The actuator master drive receives motion commands from the host via an RS-232 serial interface and transmits them to the torque load slave drive over the CAN bus. A twisted pair cable, also routed underneath the suitcase top panel, is fabricated to connect the master and slave drives with 120 Ohm termination at either end of the transmission line.

## 6. EMULATOR SOFTWARE

Featuring a simple graphical user interface, or GUI, the Ridgetop EMAEmulator application allows the user to select between a Motion tab and Status tab to execute motion profiles and view the servo drive status upon completion. After selecting a Torque Load, the user presses the RUN button to start the actuator emulation. Basically, the actuator servo drive, configured in position mode, executes a standard trapezoidal motion trajectory while the user-selected load profile is applied by the torque load servo drive, configured in current mode. As described in the previous section, the Technosoft Motion Language (TML) includes commands to synchronize the motion of a multi-axis application like Ridgetop's EMA Emulator.

Figure 7 presents a screen capture of the EMAEmulator Motion tab. The Torque Load control has been dropped down to illustrate the available load selections: None, +3A Static, -3A Static, +3A Step, -3A Step, +3A Impulse and -3A Impulse. Static loads emulate constant forces applied to the actuator. The weight of a wing flap is an example of a static load. While raising the wing flap, the weight of the wing flap opposes the actuator motion, resulting in positive static load. While lowering it, on the other hand, the weight of the wing flap assists the actuator motion, resulting in negative static load. Similarly, step and impulse loads can be both positive and negative relative to the actuator motion.

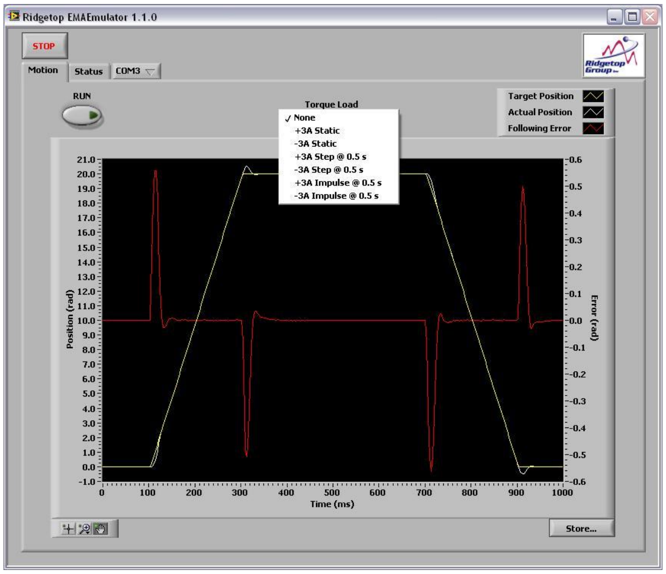


Figure 7 - Ridgetop EMAEmulator GUI

A LabVIEW graph indicator is used to plot the position data acquired from the actuator servo drive. Target Position, in yellow, and Actual Position, in white, are plotted in radians on the left Y-axis, while Following Error, in red, is plotted in radians on the right Y-axis. The motion plot reveals the expected characteristic "ringing" in the Following Error at each position jog or disturbance. Figure 8, Figure 9, and Figure 10 present screen shots of the actuator position servo loop response for positive and negative static, step and impulse load emulation, respectively.

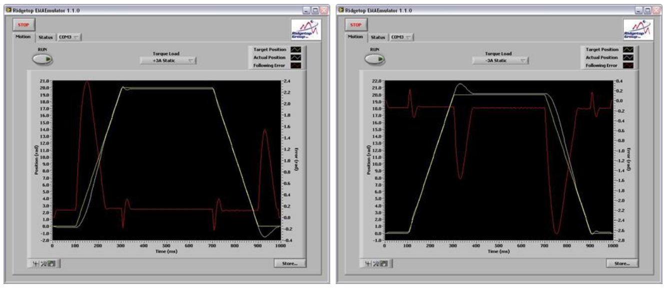


Figure 8 - Static Load Emulation

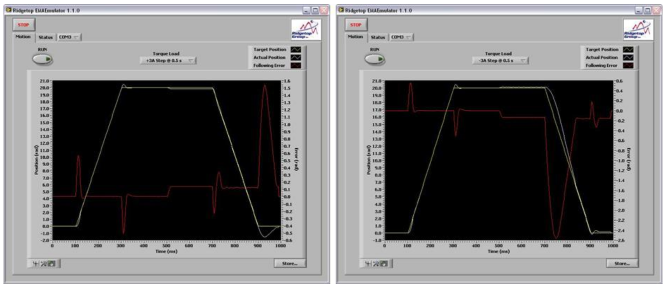
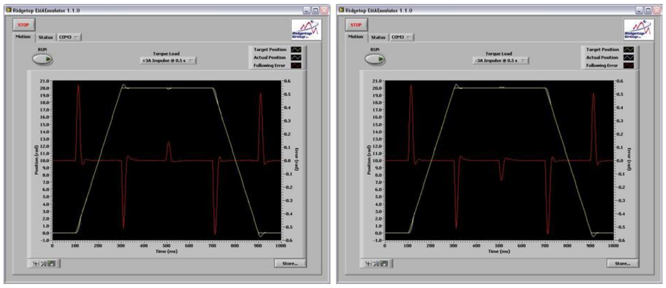


Figure 9 - Step Load Emulation

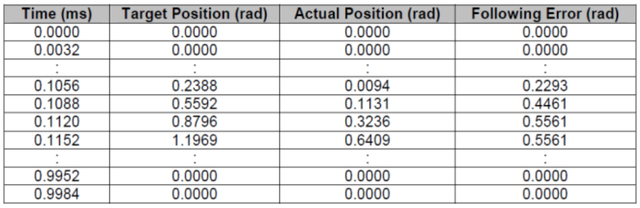


Torque Load +3A Impulse @ 0.5 s

Torque Load -3A Impulse @ 0.5 s

Figure 10 - Impulse Load Emulation

The Store button at the bottom right corner of the Motion tab is used to log the tab-delimited motion data to an ASCII text file. The format of the data log is provided in Figure 11.



| Time (ms) | Target Position (rad) | Actual Position (rad) | Following Error (rad) |
|---|---|---|---|
| 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 0.0032 | 0.0000 | 0.0000 | 0.0000 |
| : | : | : | : |
| 0.1056 | 0.2388 | 0.0094 | 0.2293 |
| 0.1088 | 0.5592 | 0.1131 | 0.4461 |
| 0.1120 | 0.8796 | 0.3236 | 0.5561 |
| 0.1152 | 1.1969 | 0.6409 | 0.5561 |
| : | : | : | : |
| 0.9952 | 0.0000 | 0.0000 | 0.0000 |
| 0.9984 | 0.0000 | 0.0000 | 0.0000 |

Figure 11 - Ridgetop EMAEmulator Data Log Format

Using a controlled aging process, such as that provided by the ARC's Accelerated Aging and Characterization System, degraded MOSFET devices are inserted into the servo drive test sockets to acquire FFP signatures of the actuator Following Error, from no degradation to total device failure, under various load conditions. The acquired data is recorded in a database and used to develop prognostic methods, or analysis algorithms, to assess the SoH and estimate the RUL of the actuator power stage.

## 7. DATA ANALYSIS

In pursuit of a method that actively determines the state of health (SoH) and remaining useful life (RUL) of a system, Ridgetop Group developed the platform and methodology described herein. Ridgetop has invested a great deal of time in describing the near-end-of-life behavior of a MOSFET, which has led to exceptional clarity regarding the direction to be taken. The first and most obvious statement is that degradation of the MOSFET does not appear to be linear at this time. The question then naturally arises as to how anyone can determine the age of a system without using extremely invasive methods. The variation in a system is the only reliable indicator of the SoH as it pertains to MOSFET degradation.

The method used by Ridgetop Group, Inc. was to develop an Electromechanical Actuator Emulator. The EMA Emulator is used to simulate various operational anomalies that a typical EMA would encounter during its life. Several tests are applied to force different types of Following Error plots. The Following Error indicates a system's ability to follow a given command. Variations in Following Error between any two iterations of the same test are difficult to detect with the naked eye, so transformations must be performed to make data more amenable to analysis. These tests are then repeated at least 30 times to ensure that statistical sampling size is sufficient. With the aid of MATLAB, the data, which is collected through a LabVIEW interface, is subjected to a Singular Value Decomposition (SVD). SVD is used to reduce a very large amount of related data to one number. The standard deviation and average SVD of healthy and degraded MOSFETs are plotted together.

The key to knowing exactly how a degraded MOSFET affects your system is to fully characterize the healthy system. Once characterized using the EMA Testbed, a plot of healthy operation is obtained (see Figure 12).

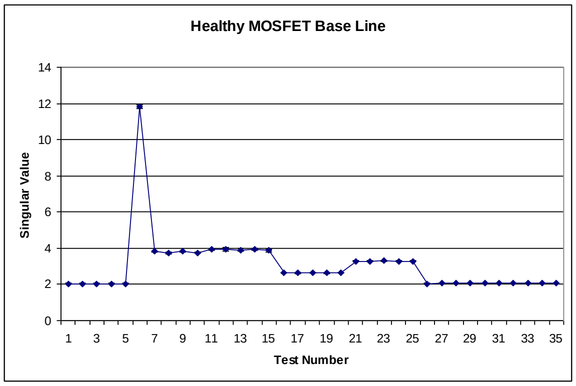


Figure 12 - Singular Value vs. Iteration of Healthy System

As explained earlier, the y-axis is the Singular Value of the Following Error of the system, which is obtained from the output through a LabVIEW interface and processed in MATLAB. Each dot actually represents the performance of the system through a test; each test is repeated 5 times per run, and each run is completed 30 times.

Figure 12 shows an average of all those tests, with standard deviation bars that are barely visible, for a healthy MOSFET. The extreme repeatability of the system where the average percent deviation is less than 1% is a signal that a system is still very healthy.

For example, consider an IRFZ44N device named T55 which has undergone sufficient aging to suggest that some form of degradation has occurred. When subjected to the same testing regime as the device in Figure 12, the reliability that the system will perform as well has decreased. A comparison is shown in Figure 13.

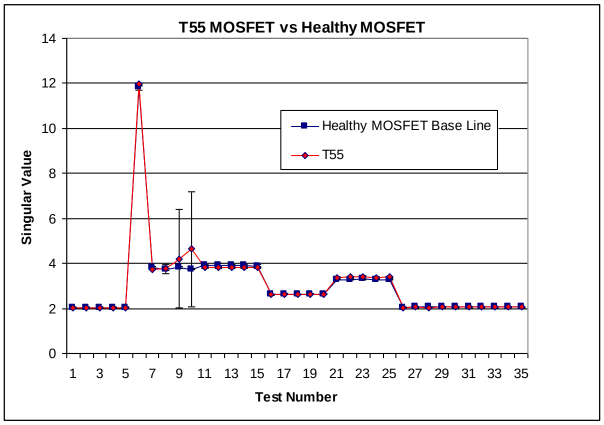


Figure 13 - Healthy Compared with Degraded System

The red or diamond line shows the system with only the high side of Phase A replaced with T55. The result is large amount of instability in test 2, which is a static 3A load torque test; this simulates a constant opposing force to the motor. Also notice that as the 5 iterations of test 2 progress, the instability in repeatability increases.

Of the aged devices received from NASA, very few have had the full statistically significant sample size taken because it is a very time-consuming process. Several devices have been aged and do not exhibit any variation, such as T56 and T57, which were reportedly aged all the way to a point of destruction. These two devices exhibit no visible signs of degradation in the Following Error.

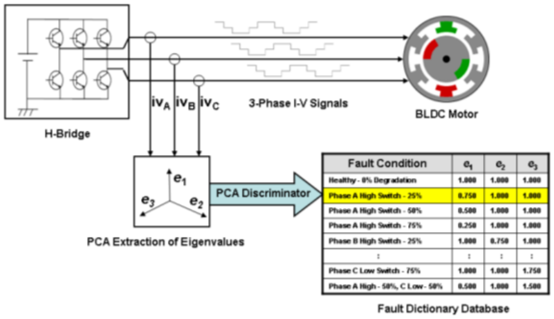
The T55 example provides one clear indication that variation in performance indicates a near-end-of-life device. The reasoning behind the results is that as the MOSFET approaches the end of RUL, it will spend more time in the triode region of operation, causing the device to become less efficient and generate more heat. Heat generates thermal noise, which translates to less precise operation. This project has provided evidence of what all end users already know: a device performs erratically right before the end of useful life.

Tests can be applied non-invasively to check the heat of a transistor using thermocouples, because a degraded device will have decreased efficiency that translates to heat, and the relative heat of a degraded MOSFET will be higher. The physical mechanism that causes this heat is related to the threshold voltage ($V_T$), which has been analyzed and evaluated throughout the course of this research. The increase in $V_T$ is believed to be related to a decrease in carrier mobility in the channel.

In the future, projects like this should undertake the task of finding additional signs of degradation so that a full dictionary of failures can be compiled. With time and with enough warning signals discovered, a full description of the RUL of MOSFET devices can be extrapolated. The solution will not involve a single parameter changing linearly, as this team had hoped at the beginning of this project. The solution becomes even more complicated when the only way to evaluate the performance of a system is through the output. The next steps for Ridgetop Group, Inc. will be to try to calculate the efficiency of the system, and try to find a change with degraded MOSFET devices in the system. Another theoretical approach is to evaluate the Fourier Transform to look at the frequency component shift as the MOSFET responds to a square pulse. The ideal goal of detecting the age of the device at all stages is not yet within reach, but with the tools presented herein, future work will bring us a few steps closer to that goal.

## 8. CONCLUSION

Leveraging Ridgetop's patent-pending RingDown technology with its flagship prognostic health management software platform, Sentinel PHMPro®, offers an established foundation for developing an EMA fault dictionary tool with considerable benefits to NASA’s IVHM initiative. One possible approach for implementing such a tool, employing Principal Component Analysis (PCA), is illustrated in Figure 12.



| Fault Condition | $e_1$ | $e_2$ | $e_3$ |
|---|---|---|---|
| Healthy - 0% Degradation | 1.000 | 1.000 | 1.000 |
| Phase A High Switch - 25% | 0.750 | 1.000 | 1.000 |
| Phase A High Switch - 50% | 0.500 | 1.000 | 1.000 |
| Phase A High Switch - 75% | 0.250 | 1.000 | 1.000 |
| Phase B High Switch - 25% | 1.000 | 0.750 | 1.000 |
| : | : | : | : |
| Phase C Low Switch - 75% | 1.000 | 1.000 | 1.750 |
| Phase A High - 50%, C Low - 50% | 0.500 | 1.000 | 1.500 |

Figure 12 - Ridgetop EMA Fault Dictionary Tool

Essentially, an artificial neural network (ANN) is trained to discriminate FFP signatures stored in a fault dictionary. The optimized ANN is integrated into the EMA Emulator Testbed for evaluation of real-time fault detection and isolation (FDI) effectiveness. The steps involved are summarized below:

(1) Transient servo loop response signatures for progressive degradation of selected H-bridge components are acquired and catalogued in a fault dictionary, e.g., MOSFET switch: 0% (healthy), 25%, 50%, 75%, and 100% degradation (catastrophic gate-to-source short circuit fault).

(2) Multidimensional, or multivariate, data (e.g., servo loop following error, motor phase voltages and/or phase currents) are logged directly from the servo drive controller program.

(3) PCA is used to reduce the multivariate fault signature data to its principal covariance eigenvalue matrix.

(4) Eigenvalues derived from SVD define classification spaces corresponding to target degradation levels (e.g., 0%, 25%, 50%, 75% and 100% degradation) and are used to train an ANN to discriminate damage level and location.

(5) Various ANN algorithms are prototyped and tested with the fault dictionary to achieve optimal performance with 100% FDI accuracy.

Power system integrity is critically important to the safety and mission effectiveness of next generation aerospace vehicles. An innovative, non-intrusive method for identifying failure modes and measuring off-nominal conditions of an avionic EMA power system has been presented. Linked to an IVHM system, corrective actions, such as fault-mitigation or load-shedding strategies, are facilitated. System availability is improved while maintenance costs are reduced by combining effective prognostic sensing techniques with advanced fault trending analysis to accurately predict the remaining service life of the EMA power system [2].

## 9. ACKNOWLEDGMENTS

The authors would like to acknowledge Kai Goebel from NASA/Ames Research Center for his support of Ridgetop's work.

## 10. REFERENCES

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## 11. BIOGRAPHY

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