IGBT Prognostics Used in Trains and Traction Drive Systems

Overview of Traction Drive Systems

The traditional DC (direct current) electric motor driving a locomotive is a machine consisting of a case containing a fixed electrical part, the stator (called the stator because it is static and comprising what is called the field coils) and a moving electrical part, the rotor, because it rotates (or armature as it is often called). As the rotor turns, it turns a pinion which drives a gear wheel. The gear wheel is attached to the axle and thus drives the wheels of the train.

The motion of the motor is created by the interaction of the magnetism caused by the currents flowing through the stator and the rotor. This interaction causes the rotor to turn and provide the drive for the train. The stator and the rotor of the DC motor are connected electrically. Electrical commutation of motors eliminates the need for replacement of brushes on the armature of motors. The commutation consists of applying insulated-gate bipolar transistors (IGBTs), which are configured to switch from ON to OFF under program control to the gate of the IGBT.

IGBT as a Switch

The IGBT combines the simple gate-drive characteristics of the metal-oxide semiconductor field-effect transistor (MOSFET) with the high-current and low-saturation-voltage capability of bipolar transistors by combining an isolated gate field-effect transistor (FET) for the control input, and a bipolar power transistor as a switch, in a single device. The IGBT is used in medium- to high-power applications such as switched-mode power supply, traction motor control and induction heating. Large IGBT modules typically consist of many devices in parallel and can have very high current handling capabilities in the order of hundreds of amperes with blocking voltages of 6000 V, equating to hundreds of kilowatts.

Commutation of Electric Field with IGBTs

IGBTs require full protection to avoid damage resulting from conditions such as:

- Overload
- Short circuit
- Under voltage
- High voltage spikes from ON and OFF state transitions
- Parasitic turn-on from Miller capacitance

Degradation and Aging Effects of IGBTs

Ridgetop Group has worked with NASA Ames and other organizations on examining the effects of degradation of power converters used to drive actuators, such as electromechanical actuators (EMAs). IGBTs can be made to age artificially using highly accelerated life testing (HALT) from thermal overstress to the devices. NASA has degraded IGBT data sets containing aging data from six devices, one device aged with DC gate bias and the rest aged with a squared signal gate bias. Several variables are recorded and in some cases, high-speed measurements of gate voltage, collector-emitter voltage, and collector current are available.

The data set is provided by the Prognostics Center of Excellence at NASA Ames. The set is in MATLAB and text format, and has been compressed.[1]

From Ridgetop's analysis, it was determined that there is a wide variety of power supply topologies available, and much is dependent on the end-application, the stress levels, and load factors. Root cause analysis of degradations in the power converter can stem from the IGBTs, but also the capacitors that form the filter network, and feedback components such as opto-isolators. For that reason, a more extensible approach is recommended to accommodate this range of IGBT-based drives.

Ridgetop's Universal Prognostic Solution with RingDown™

For ease of adoption, non-invasive solutions are preferred for prognostics-enabling of electronic subsystems. Toward that end, Ridgetop's patented RingDown technology, originally developed for electronic power system prognostics, has been extended to the servo loops found in motion control systems like those employed in locomotive drive systems. For the example presented, disturbances in the electrical and mechanical elements of the actuator system are manifested in the "following error," or offset between the actual and commanded shaft position. More specifically, ringing can be observed in the following-error waveform captured in response to an electrical or mechanical impulse imposed on the EMA.

The DC motor servo loop, diagrammed in Figure 1, utilizes position feedback provided by a resolver or Hall sensors to execute a motion profile.

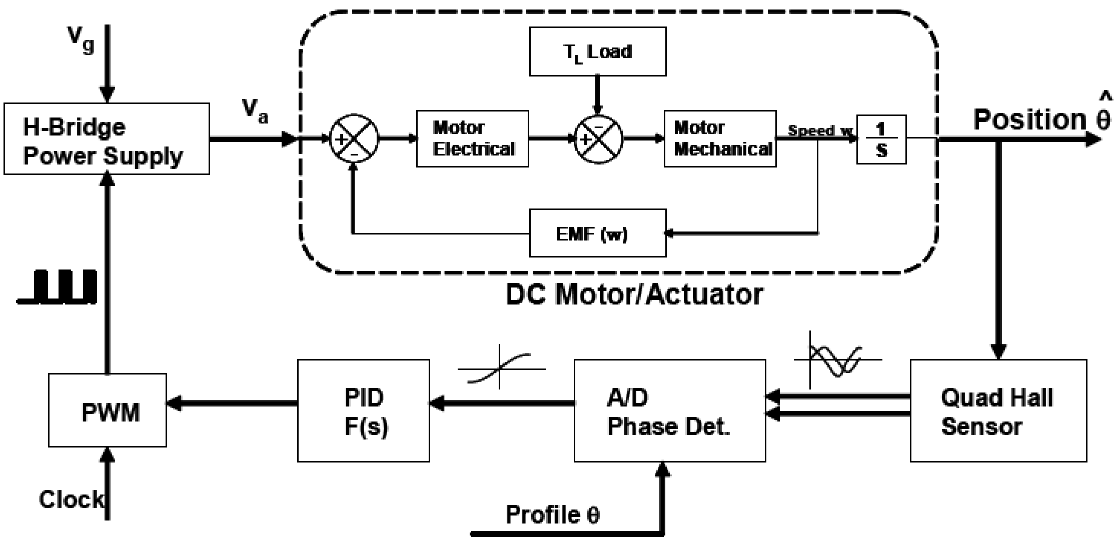

Figure 1: Block diagram of brushless DC motor servo loop

The following error of the motion control system can be analyzed to assess the state of health (SoH) of the H-bridge circuit common to brushless DC motor servo drives. Figure 2(a) provides graphs of the position and following error when all of the components of the H-bridge circuit are healthy. When the H-bridge is working normally, the rotor position closely tracks the target position, resulting in nearly zero following error until a change in direction is commanded. The overshoot and oscillations observed at the start of the simulation and the point where the rotor position changes direction are a function of the servo loop damping factor, and are normal behavior.

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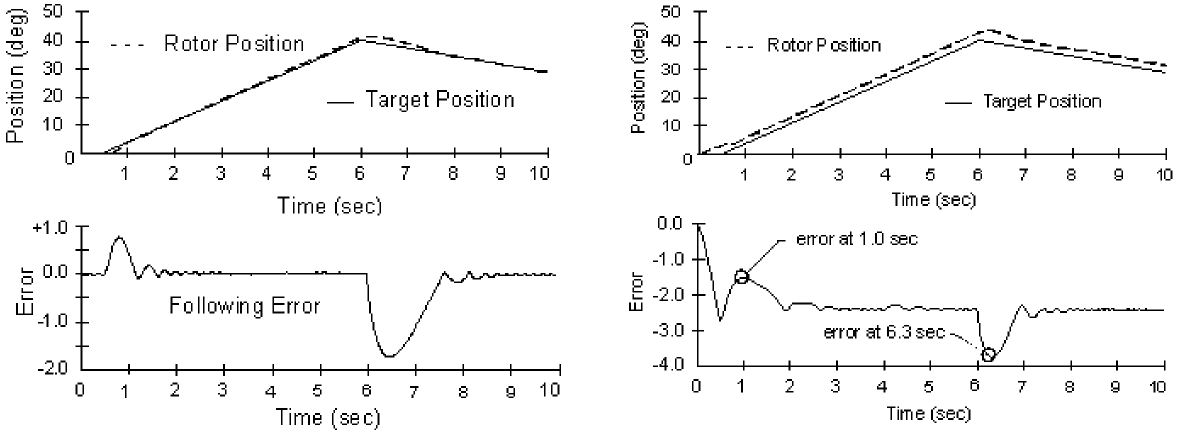
[1] J. Celaya, Phil Wysocki, and K. Goebel (2009), "IGBT accelerated aging data set," NASA Ames Prognostics Data Repository [http://ti.arc.nasa.gov/project/prognostic-data-repository], NASA Ames, Moffett Field, CA.

The H-bridge power stage comprises pairs of IGBT switches. For a three-phase brushless DC motor, there are three pairs of IGBT switches, one per winding phase. Using pulse width modulation (PWM) techniques, the IGBT switches control the current through the coil windings and hence, rotation of the rotor. Essentially, the duty cycle of the PWM signal is adjusted to change direction of the rotor or to hold it steady at a commanded position. That is, a 50% PWM duty cycle yields no movement, less than 50% causes movement in one direction (e.g., clockwise), while more than 50% causes movement in the opposite direction (e.g., counter-clockwise).



(a) (b)

Figure 2: H-Bridge waveforms where (a) is a healthy IGBT and (b) has a damaged IGBT

Figure 2(b) illustrates the effect of degradation (e.g., increased internal resistance) on one IGBT switch in a single phase of the H-bridge. As can be seen in Figure 2(a), the rotor position is greater than the target position throughout the simulation. When a change in direction is commanded, the rotor position overshoots slightly, compensates and then attempts to follow the target position. The following-error graph reveals the anomalous control loop behavior. The increased following error, noted at simulation times of 1.0 and 6.3 seconds, is caused by the degraded IGBT switch. This results in faster than normal rotor response to the commanded position change, and the offset observed between the actual rotor position and target position.

The observed system response will be different depending on which IGBT switch is damaged. For example, if one of the high-side IGBT switches is degraded, the rotor position leads the target position and a positive following error is observed, as shown in Figure 2(b). Clearly, degradation of individual H-bridge components, like the IGBT switches, can have a profound effect on the operation of an EMA system.

As shown in Figure 3, Ridgetop's approach to EMA H-bridge damage propagation analysis involves:

1. Applying various fault conditions to each critical component of the EMA H-bridge, starting with the gate driver amplifiers (D1) and progressing to the IGBT switches (D2) and coil windings (D3) of each phase.
2. Conducting lab experiments to acquire and characterize the actuator following error associated with each fault condition and the resulting stress effect on the other components in the system.
3. Analyzing fault-to-failure progression (FFP) signatures on the acquired test bed data.

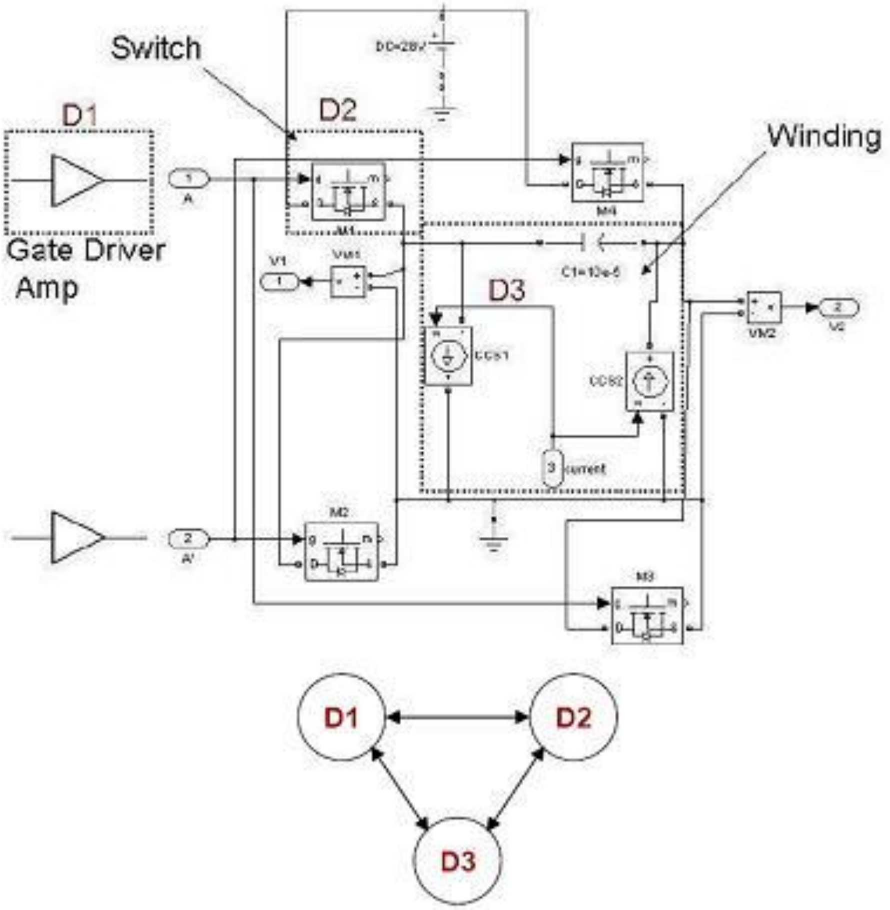


Figure 3: Ridgetop's H-bridge damage propagation analysis approach

The purpose of the gate driver, common to servo drive H-bridge circuits, is to boost the TTL or CMOS low- and high-side PWM commutation signals generated by the motion control logic (for example, microcontroller or digital signal processor (DSP)) to levels suitable for driving the IGBT or IGBT switches of the H-bridge. Typically, gate driver IC failures are manifested in open-circuit conditions on the driver outputs due to degradation or transient electrical conditions, such as destructive current impulses. Similarly, environmental factors such as temperature and vibration stress can lead to open-circuit failures on the H-bridge gate driver ICs. The initial damage propagation research analyzes the effect of open-circuit gate driver circuit failures on the IGBT switches of the servo drive H-bridge.

Measurement Results

Ridgetop's RingDown employs a method of assessing component degradation through analysis of the eigenvalues. Eigenvalues are the set of unique response time constants and frequencies that represent the characteristics of the system under test. A second-order, closed-loop control system will have a characteristic step or impulse response that carries the natural frequencies that show the power systems' characteristics, as shown in Figure 4. Rather than restricting the focus of prognostic analysis to IGBTs, Ridgetop's method provides more extensive analysis of faults within the drive stage, including the gate driver ICs, capacitors, feedback loop components (e.g., opto-isolators) and other degraded components.

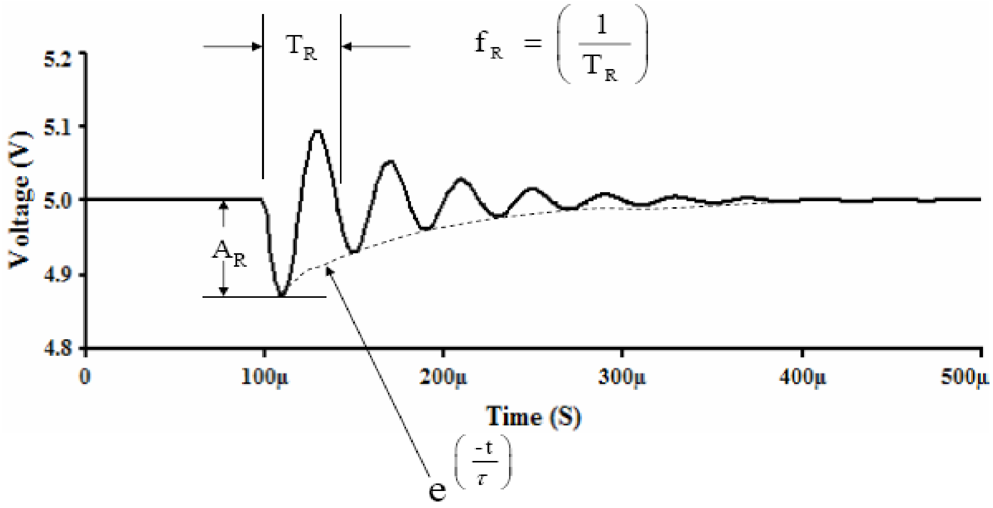


Figure 4: Power system transient response profile

The method is based on observing the transient response waveform, captured with a non-intrusive current transformer clipped onto the output of the IGBT. With this waveform captured, the interesting aspects are shown in Figure 5.

With degradation of internal components, such as IGBTs, opto-isolators and other components, the output waveforms will become distorted. The various characteristic waveform signatures can populate a fault dictionary, and be applied for maintenance purposes, as shown in Figure 5.

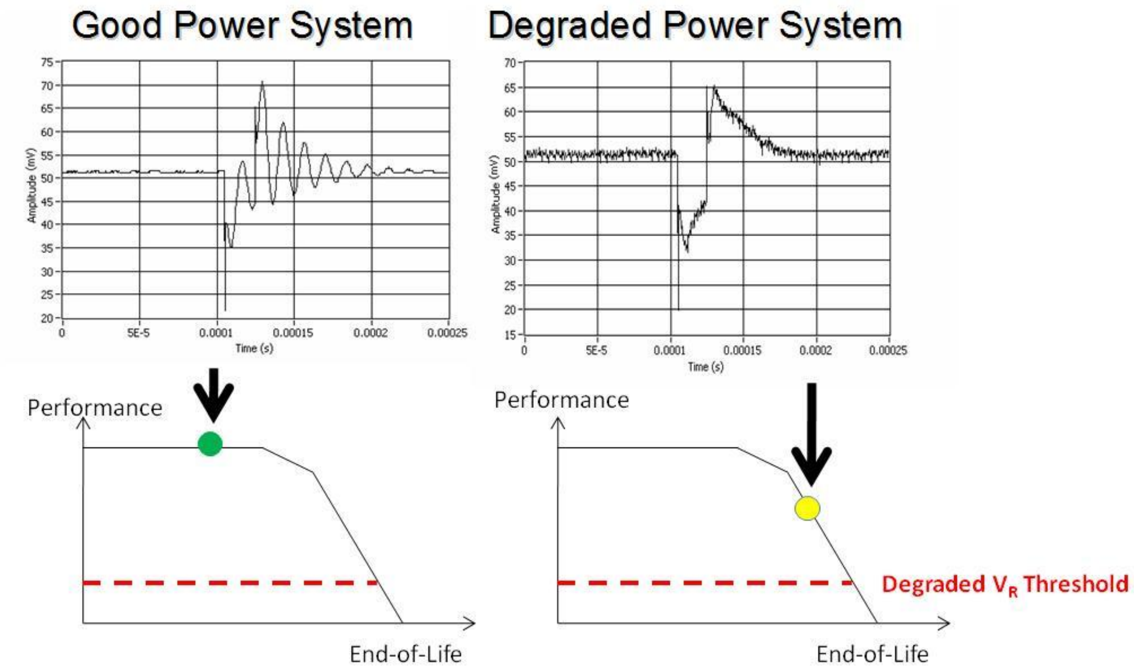
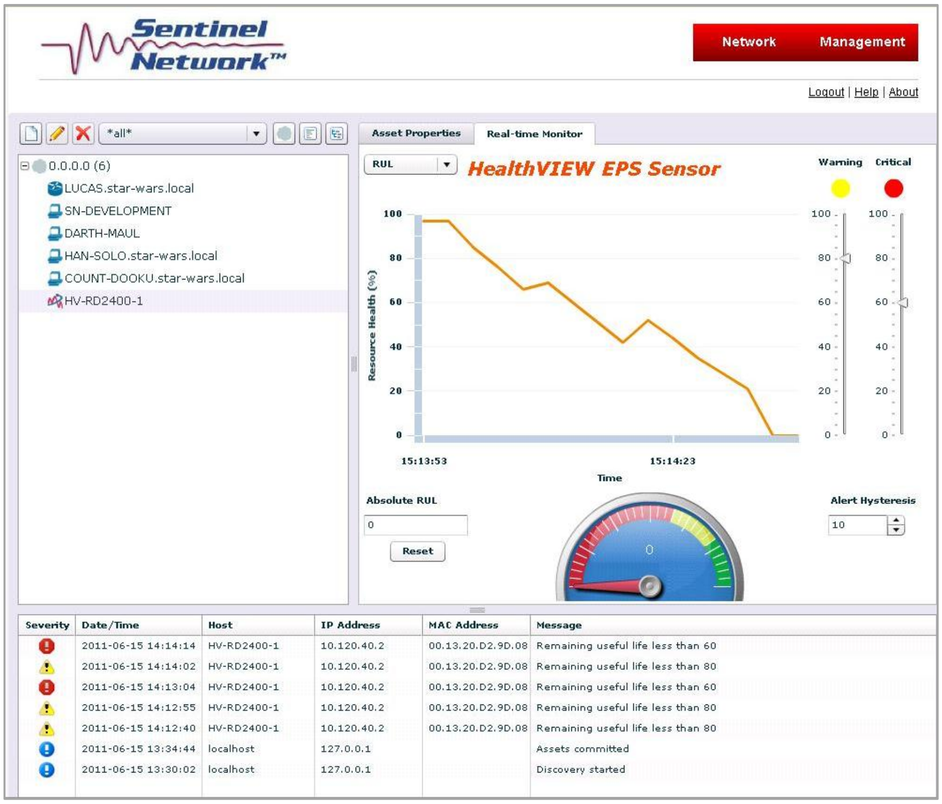


Figure 5: Good and degraded power system waveforms

Total Solution for Online Monitoring of Health

Ridgetop offers an effective software tool to collect the measured data, where it can be processed by special algorithms into useful information to support condition-based maintenance (CBM) procedures. A sample display is shown in Figure 6.



Absolute RUL: 0

Alert Hysteresis: 10

Severity	Date/Time	Host	IP Address	MAC Address	Message
❗	2011-06-15 14:14:14	HV-RD2400-1	10.120.40.2	00.13.20.D2.9D.08	Remaining useful life less than 60
⚠	2011-06-15 14:14:02	HV-RD2400-1	10.120.40.2	00.13.20.D2.9D.08	Remaining useful life less than 80
❗	2011-06-15 14:13:04	HV-RD2400-1	10.120.40.2	00.13.20.D2.9D.08	Remaining useful life less than 60
⚠	2011-06-15 14:12:55	HV-RD2400-1	10.120.40.2	00.13.20.D2.9D.08	Remaining useful life less than 80
⚠	2011-06-15 14:12:40	HV-RD2400-1	10.120.40.2	00.13.20.D2.9D.08	Remaining useful life less than 80
ℹ	2011-06-15 13:34:44	localhost	127.0.0.1		Assets committed
ℹ	2011-06-15 13:30:02	localhost	127.0.0.1		Discovery started

Figure 6: Processed data from power drive system

Conclusion

It has been shown that it is possible to prognostic-enable critical power drive stages for power systems, electromechanical actuators and other types of electromechanical equipment. With RingDown and Ridgetop's Sentinel Network™ Prognostics Analysis Platform, rigorous prognostic capabilities can be incorporated into complex systems. This can be especially useful when deploying into harsh environments.