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Impact on Failure in an Electro Mechanical Actuator Based Servo System Using Sequel

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Abstract: Main focus of this research is the modeling of Electro Mechanical Actuator (EMA) based servo system using sequel, identifying and analyzing the impact of failures on the system by simulation. EMA systems combine high performance speed, current and position control with the flexibility to adapt the systems to the rapidly changing needs of the industries. In the aerospace applications EMA is used in the field of flight control system, missiles or launch vehicles, since, it is compact and offer high power to weight ratios and motion velocities. Any undetected actuator failure lead to serious consequences. EMA consists of electrical, electronic and mechanical subsystems that result in intricate failures. Any fault in these sub-systems needs to be successfully analysed.

Key words: Electro Mechanical Actuator (EMA), sequel, weight ratios, undetected actuator, subsystems, successfully analysed

INTRODUCTION

The rapid improvement in modern bpower electronics, Electro Mechanical Actuator (EMA) finds application in high precision and demanding environment. The common element in the development of aerospace systems is restricted to hydraulic technology due to proven reliability and lack of alternative technologies. However, the development of Brushless DC Motors (BLDCM) and recent development in solid-state devices, rotor position sensing and rare earth magnetic materials, electro mechanical actuation systems became a realistic alternative.

EMA allows the elimination of local hydraulic circuits, implying a significant maintenance cost reduction due to the absence of wearing parts such as seals (Garcia *et al*., 2008). EMA form a highly integrated design, making it small enough to be installed in the reduced space. Common applications of EMA include industrial robots, aerospace flight-control actuators, astronautics, military and traffic (Yu *et al*., 2008). It finds an increasing use in aerospace applications, especially with the trend towards all-electric aircraft and spacecraft. The EMA includes the electrical part as a BLDC motor and the mechanical arrangement as a ball screw. The motor is connected to the ball screw by means of suitable gearing system. BLDC motor provides very high redundancy for the actuator. Hence, a highly redundant electromechanical actuation system comprises a relatively large number of actuation elements and is controlled in such a way that faults in individual elements is effectively detected (Jaison *et al*., 2011). Aerodynamic actuator failures have become a significant concern for flight safety. Any actuator failures lead to serious consequences. So, EMA fault diagnosis poses an interesting research as it is composed of electrical, electronic and mechanical subsystems that result in intricate failure.

Of the various kinds of actuators, EMAs were chosen for this research because of their growing role in the aerospace field. They are relatively compact and can offer high power-to-weight ratios and motion velocities (Balaban *et al*., 2009).

This study includes the modeling of BLDC motor based position servo system; the different failure modes of the system are identified and analyzed the impact of failures on the system by simulation. The circuit level implementation of BLDC motor based position servo system is presented here. Compensated system is provided by designing a classical PI controller. The simulation results are presented by sequel.

MATERIALS AND METHODS

BLDC motor based position servo system: The electro mechanical actuation system includes main drive element, BLDC torque motor and a high precision ball screw

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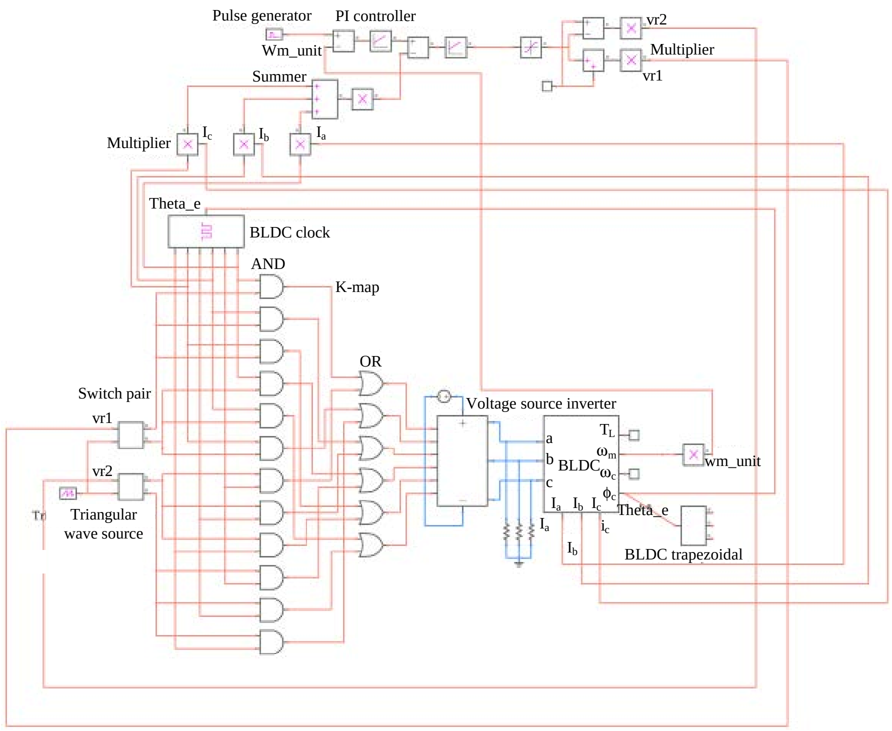

Fig. 1: BLDC motor based position servo system

actuator. The simulated model of overall system is shown in Fig. 1. It represents a closed loop position control of BLDCM with an inner current and speed control loop. The rotor position output is compared with reference input. The error signal is given to the compensator system and its output forms the reference speed. Then the rotor speed is compared with reference speed and its error signal is given to another PI controller which forms the reference current.

The BLDCM is driven by inverter with the power supply of 400 V. The commutation logic is implemented by means of logic gates. The switch pair is used to generate signals to drive a pair of switches in a non-overlapping manner. Triangular wave source drives the switch pair to generate the PWM signals. The closed loop control structure in this system is normally used to achieve the steady state as well as transient performance. The fastest loops in terms of time response are the innermost loop. Here, it is current loop and the reference for the current loop comes from the previous outer loop, viz. and the speed loop.

The design of complete system includes major elements such as BLDCM, BLDC clock, BLDC trapezoid, inverter and switch pair. BLDCM is a brushless DC machine model with terminals a-c. The three currents I_a, I_b and I_c are made available as general variables and can be used for controlling the motor. The three terminal currents I_a, I_b, I_c and the electromechanical torque T_{em} are made available as output variables. The following model equations are used:

$$L_s \frac{dI_a}{dt} = V_a - R_s I_a - E_a \quad (1)$$

$$L_s \frac{dI_b}{dt} = V_b - R_s I_b - E_b \quad (2)$$

$$L_s \frac{dI_c}{dt} = V_c - R_s I_c - E_c \quad (3)$$

$$E_a = k_e I_m E_{a0} \quad (4)$$

$$E_b = k_e I_m E_{b0} \quad (5)$$

$$E_c = k_e I_m E_{c0} \quad (6)$$

$$E_a I_a + E_b I_b + E_c I_c = T_{em} \omega_m \quad (7)$$

$$J(d\omega_m/dt) = T_{em} - T_l - B\omega_m \quad (8)$$

Where:

T_l = Load torque

J = Moment of inertia

B = Friction coefficient

Table 1: Motor fault modes

Component	Fault	Failure
Connectors	Degraded operation	Disconnect
Stator	Stator coil fails open (results in degraded EMA performance)	Disconnect
	Insulation deterioration	Short circuit
Rotor and magnets	Rotor-magnets chemical bond deterioration	Complete magnet separation, likely leading to motor failure

Table 2: Sensor fault modes

Components/Faults	Failures
Sensor	
Bias	Change over the nominal value (%)
Scaling	Values are scaled up/down
Drift	Change over the nominal value (%)
Noise	Incorrect feedback

Electrical rotor speed and position are related by:

$$d\theta_e/dt = (P/2)*\omega_m \quad (9)$$

where, P = Number of poles in the motor. BLDC clock is used to generate clock pulses required for a BLDC motor. It takes theta_e (θ_e) as input and produces g1t, g1b, g3t, g3b, g5t, g5b as output. BLDC trapezoid is used to generate trapezoidal waveforms required for a BLDCM. It takes theta_e (θ_e) as input and produces three waveforms, e1-e3 as outputs. An inverter has gating signals g1-g6 as inputs and produces a-c phase voltages.

Transient simulation is enhanced in the solve block. In this, the circuit equations are solved at several time points and the quantities of interest are stored in a file at each time point. The Back Euler method with automatic time step is opted for this work. The BLDCM produces trapezoidal back EMF.

Falures and impact in the BLDC motor based position servo system: Space vehicles use EMAs for functions such as positioning of antennas, movement of robotic arms etc. Some rocket launcher designs use EMAs for their thrust vector control. The faults in EMAs are loosely distributed among four general categories: sensor, mechanical or structural, motor and electronic or electrical faults (Zhang *et al*., 2005). The four categories of faults are listed in Table 1-4.

All mentioned faults above cannot be simulated they are beyond the scope of visibility. Some faults like bias in feedback, change in compensator value, triangular wave frequency change and stuck-at-fault can be simulated in sequel. Table 5 shows the different possible failure modes in the system and their observations.

Table 3: Mechanical/structural fault modes

Components	Faults	Failures
Screw	Spalling (mild)	Severe vibrations, metal flakes
Nut	Spalling (mild)	Severe vibrations, metal flakes
	Degraded operation	Seizure/disintegration
Ball return (s)	Jam	Seizure/disintegration
Bearings	Spalling	Severe vibrations, metal flakes
	Binding/sticking	Seizure/disintegration
Balls	Spalling	Severe vibrations, metal flakes
	Excessive wear	Backlash
Lubricant	Contamination	Seizure/disintegration
	Chemical breakdown	Seizure/disintegration

Table 4: Electrical/electronic fault modes

Components	Faults	Failures
Power supply	Short circuit	Support bearing failure
	Open circuit	Support bearing failure
	Thermal runaway	Dielectric breakdown of components, leading to open or short circuits
Solder joints	Intermittent contact	Disconnect

Table 5: Other failure modes

Failure	Observation
Bias in feedback	Change from the nominal value. The angular position settles at a different value from the normal value
	For command = 1 and positive bias = 0.5, the settling value is approximately 0.5
	For command = 1 and negative bias = 0.5, the settling value is 1.5
Change in compensator value	The system doesn't settle. Changing K_p and K_i value oscillates the system
	For change in K_p, (i.e., K_p = 3) with K_i = -0.015 as constant, the system oscillates. Similarly for change in K_i, (i.e., K_i = -5) with K_p = 2 as constant, then the response is oscillatory
Stuck-at-fault	No settlement of the system. Employing stuck at 0 and stuck at 1 at the OR gate in commutation logic makes the system to oscillate
Triangular wave frequency	Settling time varies depending on the frequency

RESULTS AND DISCUSSION

Simulation background: The BLDC motor based position servo system runs on sequel platform. Sequel (a solver for circuit equations with user-defined elements) is a general purpose circuit simulation package which allows simulation of a wide variety of circuits and systems. It has been extensively used for R&D activities.

Sequel includes a large number of elements which the user can call from the "Circuit file". This is much like using a program like SPICE where the user simply specifies the connections of various elements in the circuit to be simulated and asks for specific analyses to be performed. However, a distinguishing feature of sequel is that it allows the user to add completely new elements to the element library. It is a circuit simulator developed at IIT Bombay.

Figure 2 shows a simplified block diagram of sequel. This circuit file (a text file) contains a description of the

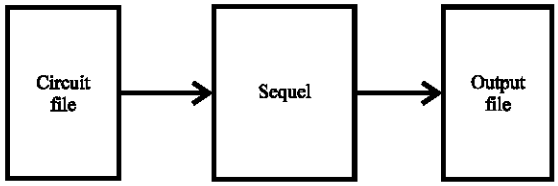

Fig. 2: Simplified block diagram of sequel

circuit that the user intends to simulate. Sequel takes this file as input and produces output files which can then be viewed with a suitable plotting program. The advantages of using sequel are (Raju and Karnik, 2009):

- It has a good collection of different circuit simulation examples which will aid the user to learn the package quickly
- It has a nice Graphical User Interface (GUI) which will facilitate the user to enter the circuit schematic, specify analysis options and view simulation results
- It comes with its own comprehensive documentation which will help the user to use this software package easily
- It can simulate circuits having elements from electrical, thermal, general and digital
- Switching functions are essential in power electronic circuits, therefore, simple switch models are readily available for preliminary analysis
- It can carry out DC analysis, AC analysis, transient analysis and Steady State Waveform (SSW) analysis
- SSW analysis is more suitable to demonstrate steady state behaviour of power converters in class room or laboratory without spending unduly long time on conventional transient simulation
- Different numerical solvers are available which will aid in selecting a solver suited to a particular circuit simulation
- It is available on windows as well as on linux platforms and is easy to install on both platforms with no specific hardware requirements
- Circuit schematic as well as output results which are in graphical form can be exported to various graphical formats, so as to prepare impressive documents

Simulation results: According to the model of closed-loop position servo system for BLDCM mentioned in Fig. 3 some vital simulation works have been conducted. The electrical signal input and corresponding actuator position obtained are shown in Fig. 4 and 5. The simulation curves of the current and the back EMF for three phases are shown from Fig. 6-8.

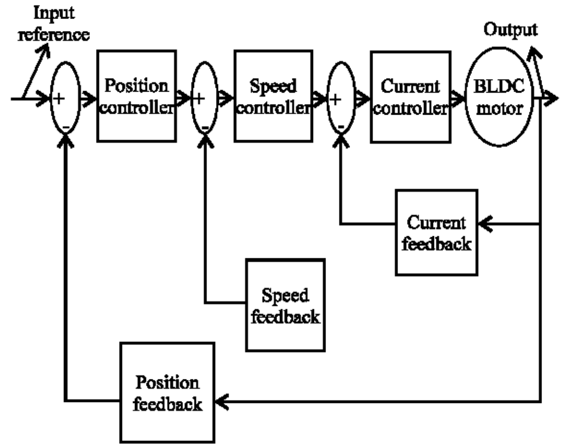

Fig. 3: Block diagram of simulated model

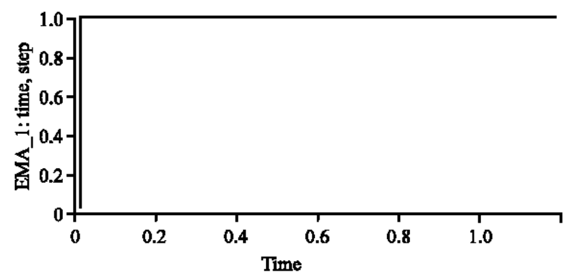

Fig. 4: Input signal

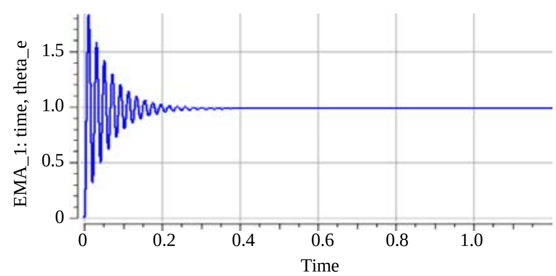

Fig. 5: Angular position: theta_e

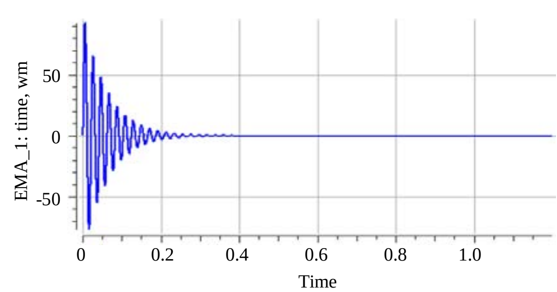

Fig. 6: Rotor speed: ω_m

Figure 3 represents the block diagram of the simulated model with position, speed and current as feedback. The feedback is obtained from the output of BLDC motor. The input reference is the step signal. For the electrical step input signal, we obtain the following output shown in Fig. 5-8.

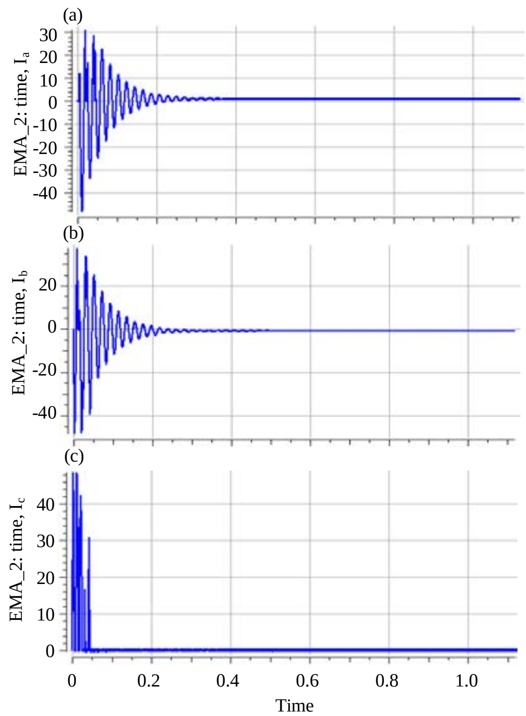

Fig. 7: Stator current: a) I_a; b) I_b and c) I_c

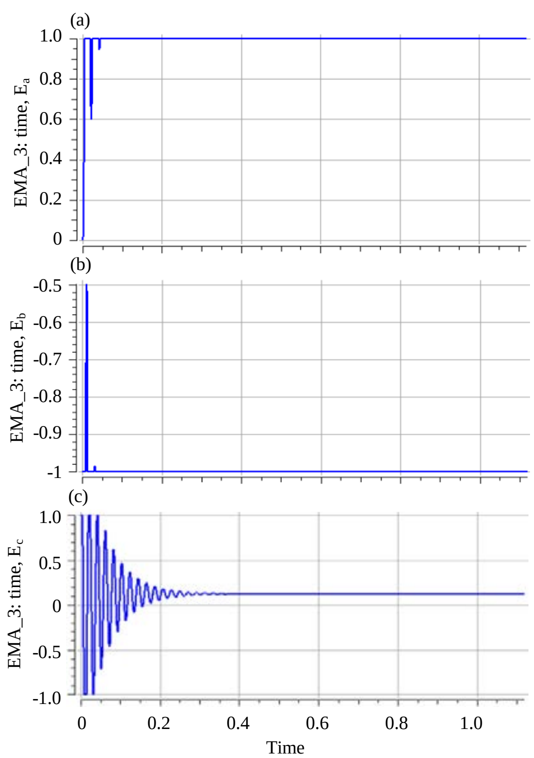

Fig. 8: Back EMF: a) E_a; b) E_b and c) E_c

Figure 5 shows the angular position of the rotor with time in x-axis and theta_e in y-axis. The rotor position settles to the value equivalent to the command signal.

During start up, the motor raises up slowly due to the initial inertia of rest and finally occurs stability. From Fig. 6 it is clear that on reaching stability the motor stops rotating (i.e.,) the speed decreases and finally reach zero. Figure 7 denotes the stator current for three phases a-c of the BLDCM. Upon settlement of the system, the stator current becomes zero.

The motor back emf shows a similar variation to that of rotor speed initially, since, the back emf is directly proportional to speed. Figure 8 notes the back emf for three phases a-c, respectively with time in x-axis and back emf in y-axis.

Figure 9 shows the bias in feedback. The term bias means, the amount by which the average of a set of values departs from a reference value. Electrical, mechanical, magnetic or other force (field) applied to a device to establish a reference level to operate the device. Both positive and negative biasing is introduced in feedback to know the shift of the settling value from the reference value. Figure 9a and b denotes the angular position for positive and negative shift, respectively.

Change in PI compensator constant value (K_p and K_i) makes the system to have oscillatory response. The angular position for K_p = 3, K_i = - 0.015 and for K_p = 2, K_i = -5 is given in Fig. 10a and b.

A stuck-at fault is used to mimic a manufacturing defect within a circuit. In this research, stuck-at-0 and stuck-at-1 fault is modeled in the OR gate of commutation logic to model the behavior of a defective circuit that cannot switch its output. Both cases the motor rotates, hence, the system is oscillatory. The simulated results are shown in Fig. 11a and b.

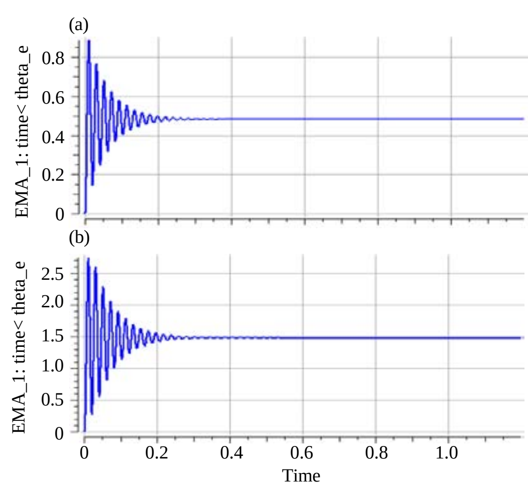

Fig. 9: Bias in feedback: a) Angular position for positive shift and b) Angular position for negative shift

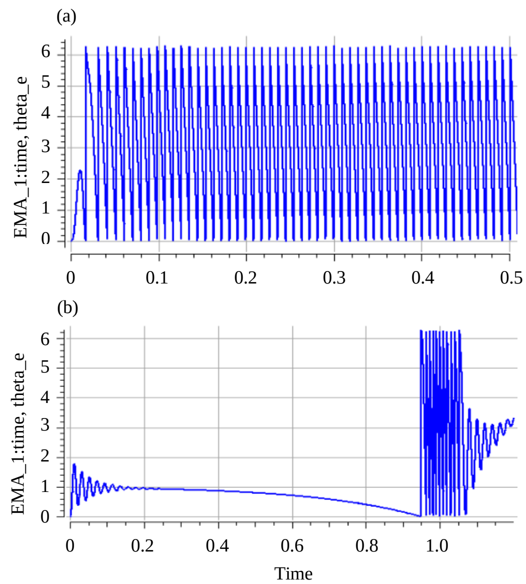

Fig. 10: Angular position for compensator constant change: a) Angular position for compensator value change with K_p = 3 and K_i = 0.015 and b) Angular position for compensator value change with K_p = 2 and K_i = -5

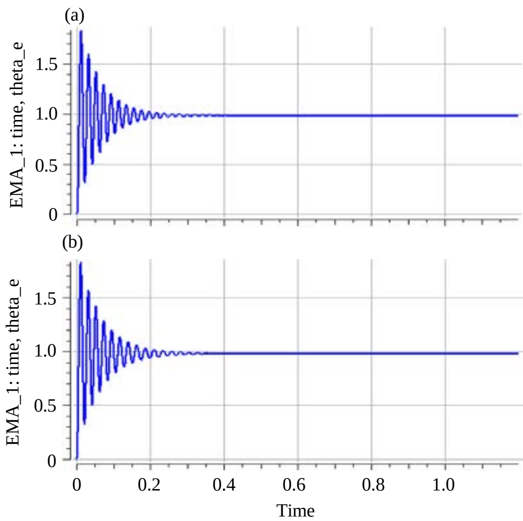

Fig. 11: Stuck-at-fault: a) Angular position for stuck at 0 in the or gate and b) Angular position for stuck at 1 in the or gate

For the triangular wave generator with frequency 1.25 kHz the settling time is approximately 0.4 sec and for frequency 50 kHz, the settling time is near to 0.35 sec whereas the reference system settles at 0.35 sec. This is because the settling time is inversely proportional to the frequency (Fig. 12a and b).

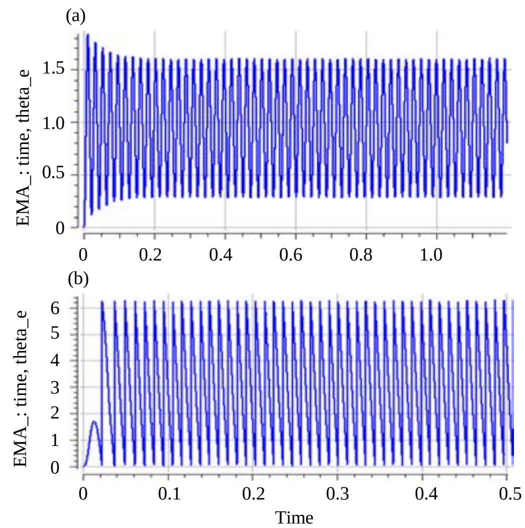

Fig. 12: Triangular wave frequency change: a) Triangular wave frequency 1.25 kHz and b) Triangular wave frequency 50 kHz

CONCLUSION

A BLDC motor based position servo system has been designed using sequel and the simulation results are presented. This study categorizes fault modes for electro-mechanical actuators and different failure conditions are simulated. Four main classes of faults are presented: mechanical/structural, motor, electrical/electronic and sensor. A subset of faults bias in feedback, change in compensator value, triangular wave frequency change, stuck-at-fault was then selected for detailed study and is simulated.

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