Simulation of Electrical Fault Handling Techniques for Sensor Integration with Virtual ECU

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Abstract:- This paper proposes a comprehensive method of conducting an electrical fault testing/Failure Mode Effect Analysis test(FMEA) for the development of virtual ECU's. The study discusses the importance of fault diagnosis of faulty sensor connections to the ECU and the effect it has on the safety of the driver/passenger. This method utilizes virtualized ECUs and circuit simulators on MATLAB/SIMULINK® and SIMSCAPE to analyze the effects of circuit-level faults on ECU models, thereby saving prototyping costs. The study demonstrates the effectiveness of FMEA through simulations, where engine and control system performance are affected by a hardware fault. Results show that FMEA can perform software verification with circuit-level faults while minimizing speed degradation. The paper also discusses the importance of complying with functional safety standards like ISO26262 and the need for software verification to support safety-critical automotive systems. Overall, this method offers a promising approach to enhancing software safety verification in complex automotive electronic control systems, contributing to the advancement of functional safety in the automotive industry.

Keywords*:* ISO 26262, FMEA, Virtual ECU, Electrical Fault Testing, Simulink.

1. Introduction

ECUs (Electronic Control Units) are the brains of modern vehicles and machines which manage everything from engine, vehicle motion, control, vehicle dynamics to airbags. Since they play such a crucial role, ensuring their proper function under normal and abnormal conditions is necessary. Modern cars rely on increasingly complex electronic control systems with vast amounts of software. To ensure these systems meet safety standards, rigorous verification is crucial. However, in-depth testing creates an increase in the number of test cases that need to be conducted. As a result, completing all the safety verifications within a development cycle can become a challenge. This is where electrical fault testing comes in. Imagine driving down the road and experiencing an electrical glitch in the ECU. This could lead to erratic engine behavior, malfunctioning brakes, or even a complete loss of control. By simulating electrical faults during the design and manufacturing stages, engineers can predict and address potential issues before they occur on the road. This proactive approach has hence enhanced safety and reliability.

1.1 IEC 61508

IEC 61508 is an international standard published by the International Electrotechnical Commission (IEC) that deals with the functional safety of electrical, electronic, and programmable electronic(E/E/PE) safety-related systems. The standard emphasizes assessing potential risks and hazards associated with a system. Based on this assessment, it helps determine the necessary safety measures to control or avoid failures. The standard covers the entire lifecycle of a. safety system, from concept and design to operation and maintenance. The risk is a function of frequency (or likelihood) of the hazardous event and the event consequence severity. The risk is reduced to a tolerable level by applying. safety functions which may consist of E/E/PES, associated mechanical devices, or other technologies.

IEC 61508 has the following views on risks:

- Zero risk cannot be reached, only probabilities can be reduced
- Non-tolerable risks must be reduced to the minimum
- Optimal, cost-effective safety is achieved when addressed in the entire safety lifecycle

So, what are the typical Electrical Faults Simulated?

- Short Circuits: When two wires with different polarities touch, causing a surge in current.
- Open Circuits: When a wire breaks, disrupting the flow of electricity.
- Ground Faults: When a current leak occurs within the vehicle's chassis.

1.2 ISO 26262

In 2011, the ISO 26262 standard was introduced in regard to the IEC 61508 regulation to address functional safety in passenger car electronics. It ensures that electrical and electronic systems crucial to safety are developed with a focus on preventing failures throughout their lifecycle, from design to disposal. The standard establishes four distinct safety levels, known as Automotive Safety Integrity Levels (ASILs),to determine the rigor required for different systems. There are four ASIL levels, ranging from A to D, with D being the most severe. The higher the ASIL level, the stricter the safety measures required during development to minimize risk.

Here's a breakdown of ASIL levels [5]:

- ASIL D: Represents the highest risk, where malfunctions could lead to severe or fatal injuries. Examples include braking system failure or steering system malfunctions.
- ASIL C: Indicates a high risk of serious injury. Examples include airbag deployment systems or anti-lock braking systems (ABS).
- ASIL B: Represents a moderate risk of injury. Examples include seatbelt reminder systems or headlight controls.
- ASIL A: Represents the lowest risk, where malfunctions are unlikely to cause injury. Examples include turn signals or interior lighting.

Since safety-critical systems carry an ASIL rating of C or D, verifying software behavior under simulated failures of automotive components becomes essential for ensuring functional safety.

2. Risk assessment

1.2 ASIL rating

Table 1: ASIL rating in comparison to the frequency of occurrence

Consequence				
Likelihood	Catastrophic	Critical	Marginal	Negligible
Frequent	I	I	I	II
Probable	I	I	II	III
Occasional	I	II	III	III
Remote	II	III	III	IV
Improbable	III	III	IV	IV
Incredible	IV	IV	IV	IV

1.3 Based on the likelihood/Frequency of occurrence

Frequent- Could Occur Many times during its lifetime.

Probable- Can Occur Many times during its lifetime.

Occasional- Once in a Life time.

Remote, Improbable- Could Rarely Occur.

Incredible- Could never Occur.

Class I is unacceptable, II is undesirable, III is Tolerable and IV is ignorable. Electronic control unit (ECU) software, developed and integrated in accordance with the ISO 26262 standard and needed up to the highest Automotive Safety Integrity Level, ASIL D.

Effect of Faulty ECU on the Steering System [2]- ASIL-D(Class-I)

Effect of Faulty ECU on the Braking System-ASIL-D(C-1)

Effect of Faulty ECU on the Transmission-ASIL-D(C-1)

Effect of Faulty ECU on Acceleration-ASIL-C(C-1)

Effect of Faulty ECU on Supplementary Safety Systems-ASIL-C, ASIL-D(C-2)

3. Methodology

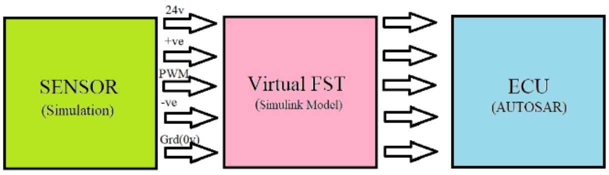

Fig 1. EFT Model

Figure 1 gives us an overview of the Electrical Fail Safe Test simulation modelled in Simulink.[6] The type of Sensors which are used in contention are Analog Sensors. Analog Sensors takes in Continuously Changing Voltages or Currents. Unlike digital sensors with on/off signals, analog sensors provide a continuous electrical output. This output, typically voltage or current, directly reflects the strength of the physical quantity being measured. Increasing the value of the stimulant increases the output of the sensor [4]. Ideally, this change is proportional, meaning a small increase in temperature results in a small voltage increase from the sensor. However, some sensors might have a non-linear relationship, requiring adjustments to translate their output accurately.[4]

A. Sensor communication to ECU

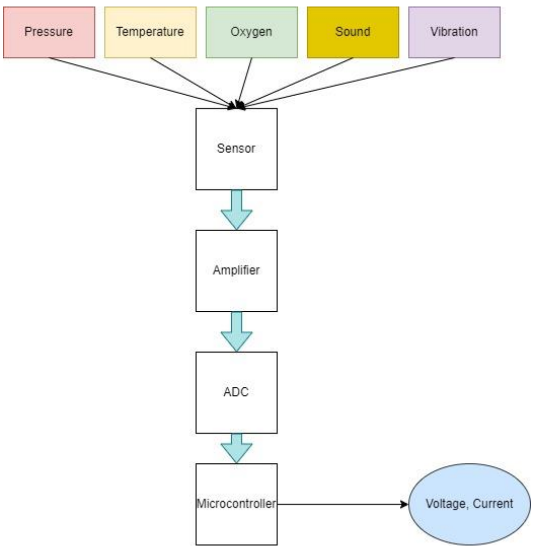

Fig 2. Sensor to ECU Communication Principle

They collect data on various parameters like engine temperature, air pressure, or wheel speed. Figure 2 depicts the functioning of an Automotive sensor and how it converts physical inputs into electrical outputs. Sensors and ECUs use specific communication protocols, like CAN bus or Ethernet, to transmit data in a structured format. Once received, the ECU processes the sensor data and makes decisions based on pre-programmed algorithms. The car's computer (ECU) communicates with various sensors in a controlled manner. Each sensor can transmit one or more pieces of information (signals) to the ECU at a specific time within a designated communication cycle. This communication between sensors and the ECU uses a technique called current modulation. In this method, a change in the electrical current level represents the data being sent. By modulating the current at a specific frequency, the sensor's output signal can be separated from low-frequency noise sources like power line hum. This allows for clearer and more accurate measurements. Modulating the current can be used to perform internal checks on the sensor's functionality. By analyzing the response of the sensor to the modulated current, potential issues can be identified

- A sudden decrease in current (falling edge) denotes a logical 1.
- Conversely, a sharp increase in current (rising edge) denotes a logical 0.

Analog sensors provide continuous output signals, typically voltage or current, that are proportional to the physical quantity being measured. These raw sensor outputs are often weak and may not be directly compatible with digital processing units like microcontrollers. To address these limitations, a signal conditioning stage is typically employed.

This stage may include:

Amplification: Weak sensor outputs are amplified to a acceptable level for further processing. This ensures the signal strength is significant for accurate data acquisition.

Analog-to-Digital Conversion (ADC): The amplified analog signal is then converted into a digital format (a series of discrete voltage levels) using an Analog-to-Digital Converter (ADC). This conversion process allows microcontrollers to interpret and process the sensor data effectively.

By employing signal conditioning and digitization, the system bridges the gap between the analog world of sensors and the digital domain of microcontrollers. This enables robust and accurate data acquisition for various applications.

3.1 CAN Communication

A Controller Area Network (CAN bus) is a vehicle bus standard designed to allow microcontrollers and devices to communicate with each other's applications without a host computer. The CAN bus system enables each ECU to communicate with all other ECUs without using any complex dedicated wiring. The sensor converts its reading (temperature, pressure, etc.) into a digital format (0's and 1's). This data is then bundled along with an identifier and other information into a CAN frame. The sensor transmits this CAN frame onto the CAN bus, which consists of just two wires (CAN High and CAN Low). This broadcast system with CAN arbitration (prioritization) ensures efficient communication even if multiple sensors try to transmit data simultaneously. The sensor with the higher priority message will win and successfully transmit. CAN H (high) and CAN L (low) refer to the two wires that make up a Controller Area Network (CAN) bus. They're not simply data and ground wires like you might see in other communication systems. Instead, they work together using a differential signal to transmit information. The data on a CAN bus is encoded by the voltage difference between the CAN H and CAN L wires. A higher voltage on CAN H compared to CAN L represents a dominant bit (logical 0), while a lower voltage on CAN H compared to CAN L represents a recessive bit (logical 1). Each device connected to the CAN bus acts as a node. These nodes have a CAN transceiver chip that converts the digital signals from the device (like a sensor) into the differential voltage levels for transmission on the CAN H and CAN L wires. Receivers on the bus can then interpret the voltage difference to recover the original data. Unlike traditional communication systems where one device might actively drive the data line, no single node actively drives both CAN H and CAN L on a CAN bus. Instead, the transceiver monitors the bus state and adjusts its own outputs on CAN H and CAN L to create the necessary voltage difference for dominant or recessive bits

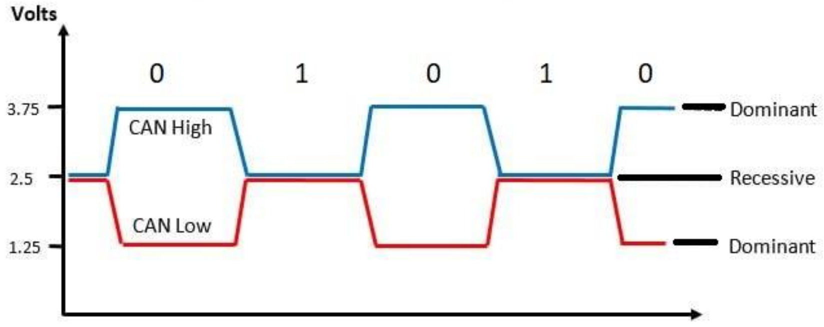

Fig. 3. CAN bus Voltage Levels

Figure 3 illustrates a CAN bus with differential voltage of 2 volts.

3.2 Working of Electrical Fault Testing System

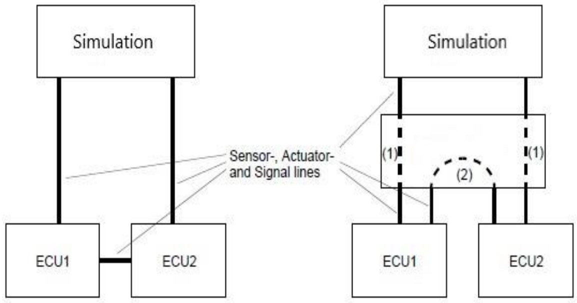

Fig. 4. Simulation with and without EFT System

Figure 4 depicts a multi ECU Simulation and one with the virtual model imitating the sensor inputs.

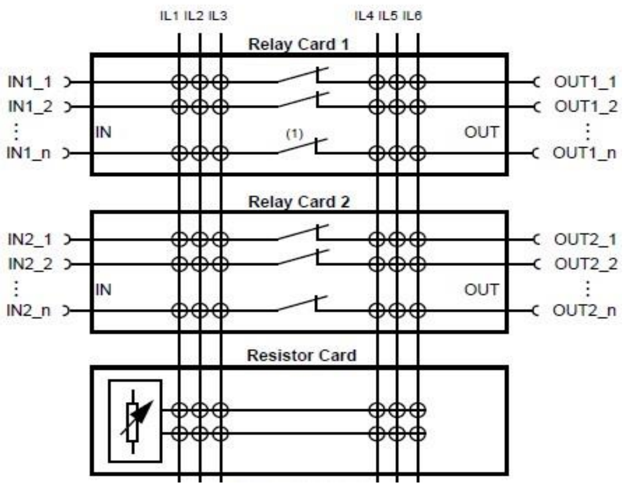

Fig. 5. Interlink Lines providing a communication between multiple Channels

Figure 5 sketches the multiple channel and how the concept of interlink lines connects the channels together. When multiple channels needs to be short circuited with each other, these lines provide an electrical connection between them.

3.3 Flowchart

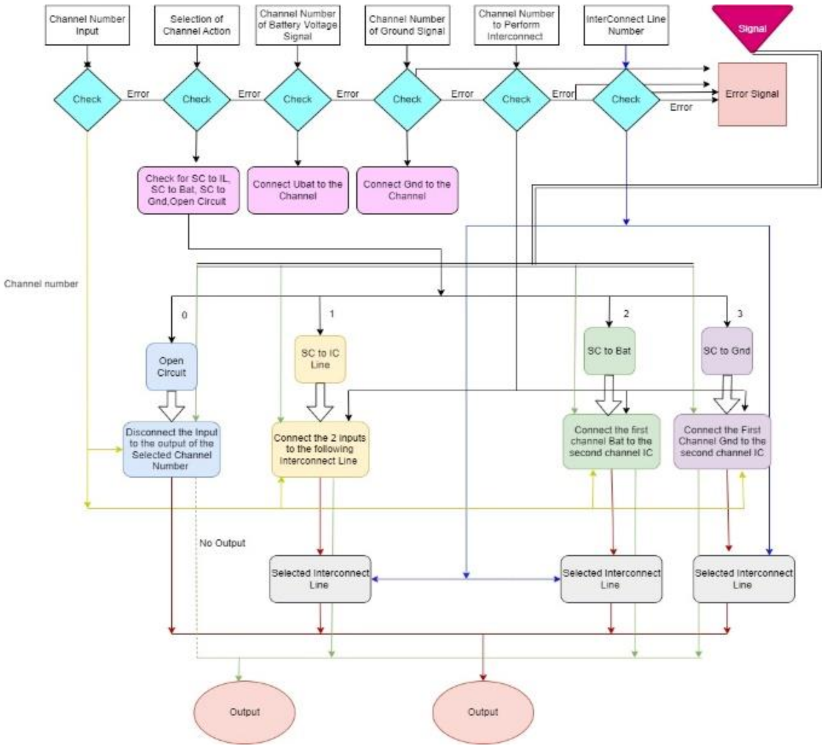

Fig. 6. The Flow Chart denotes the Working Principal of the Simulink Model.

Figure 6 provides a pictorial representation of on overview of the Controller Model which takes in the input from the user and the actions to be performed to give the accurate output. The Specific Channels required for conducting the tests are accepted from the user. All the voltages required in each channel is accepted from the user. The battery Voltage and Ground Voltage are then input by the User. The interlink Lines for the tests to be conducted on are accepted from the User. Any Errors in input is checked and an Error signal is given out. Channel Action is read, and the User requirement is determined. The Three User Inputs are 1. Open Circuit, 2. Short Circuit to Battery 3. Short Circuit to Ground. The Interlink line to provide a connection between the channels is input by the user.[9]

4. Model

4.1 Sensor

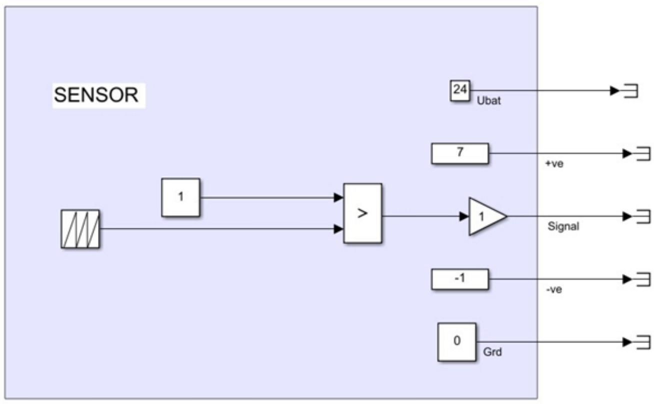

Fig. 6. A Sensor Model in Simulink

The Pressure Sensor in concern has a 5 Channel Architecture.

- Battery Voltage Terminal
- Positive Terminal
- PWM Terminal
- Negative Terminal
- Ground Terminal [7]

4.2 Input Error Switch

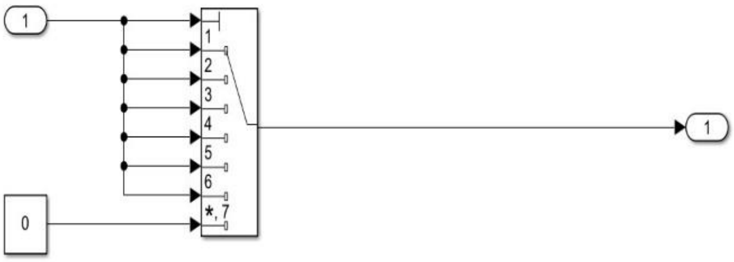

Fig. 7. Input Error Rectifier Logic

4.3 Channel

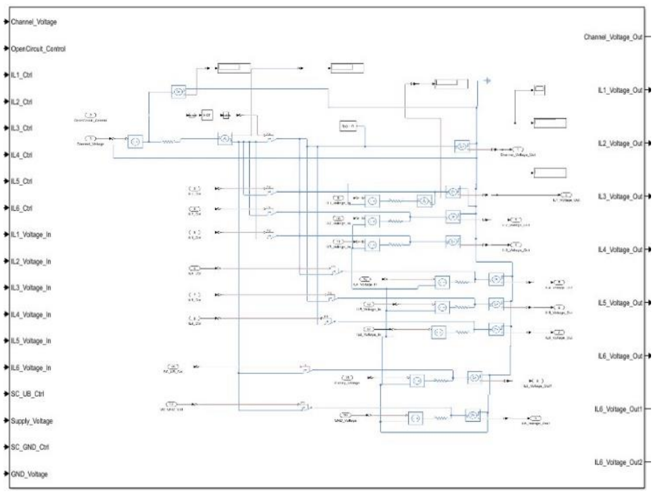

Fig. 8. A Single Channel with Interlink line connections

- Channel Voltage: This is the voltage input given into the channel.
- Open Circuit Control: Accepts the Boolean input required to open Circuit the Channel
- Interlink Lines: Interlink lines are connection lines created within the channel to provide a controlled electrical contact between Channels to simulate different Fault scenarios. A Total of 6 Interlink lines have been created, to increase the permutations of error types that can be produced.
- Interlink Line Control (IL_Ctrl): Accepts the Boolean input required to Connect the Channel Input to the corresponding Line.
- Interlink Line Voltage Input (IL_Voltage_In): Accepts the Voltage from the precedent Channel On the same IL Line.

- Short Circuit to Battery Voltage (SC_UB_Ctrl): Accepts the Boolean input required to Short Circuit the Channel Voltage to the Battery Voltage.
- Short Circuit to Ground (SC_UB_GND): Accepts the Boolean input required to Short Circuit the Channel Voltage to Ground.
- Supply Voltage: The Battery Voltage or the Working Voltage of the Channel.
- Ground Voltage (GND_Voltage): The Ground Voltage connection.
- Channel Voltage Out: The Voltage which is Going out of the Channel.
- Interlink Line Voltage Output (IL_Voltage_Out): Provides the voltage connection to the subsequent Channel Input on the same IL Line

We can create any number of Channels depending upon the specifications of the Sensor. Hence the model has a comprehensive implementation on all sensor applications.[8]

4.4 Channel Model

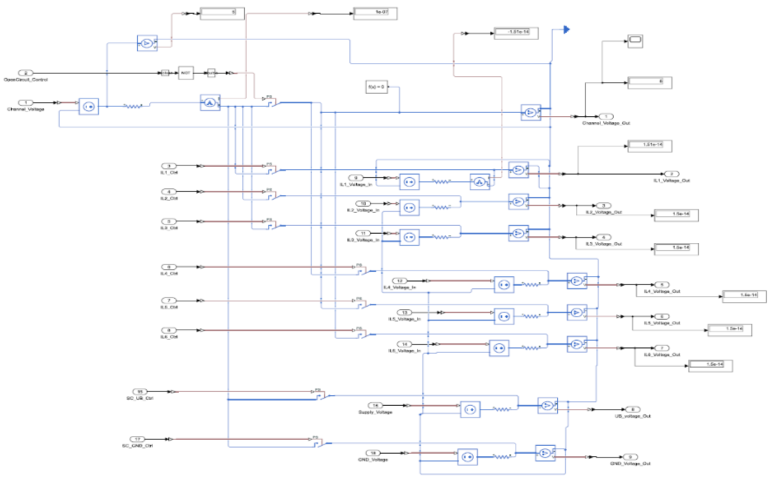

Fig. 9. Overview of Simscape Model of the Channels Electrical Connections

Figure 9 depicts the internal connections within a Channel. The individual channels are modelled in Simscape®. All the Interlink Lines are connected to an SPST (Single Point Single Throw) Switch to control the Interlink line input. The Interlink Line Voltages are connected to a controlled Voltage source. Voltmeters are connected to measure the respective Voltages.

4.5 Controller Input

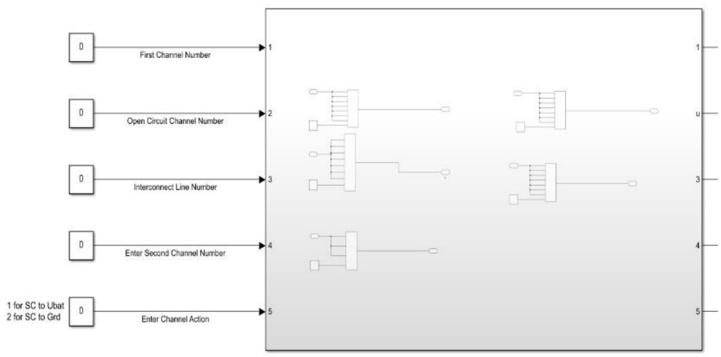

Fig. 10. Controller Block for Taking Test case Conditions

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The Controller inputs the specific Data required for the Tests such as

- First Channel of Significance
- The Channel Number for Open Circuit Test Case
- Interlink line Number
- Second Channel of Significance
- Channel Action (whether the test should be Short to Ground or to the Battery)

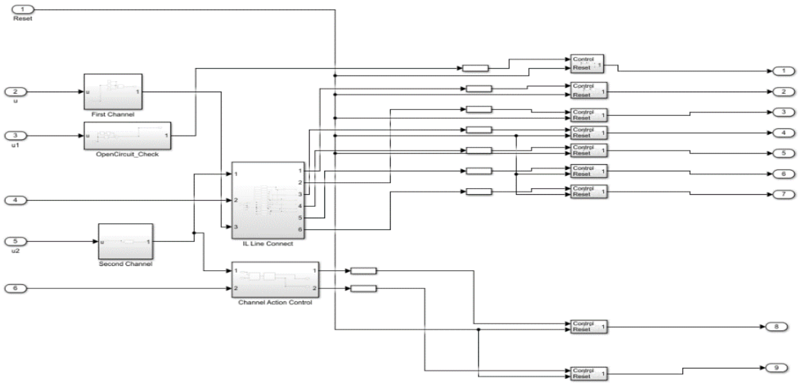

Fig. 11. Interlink Line Logic

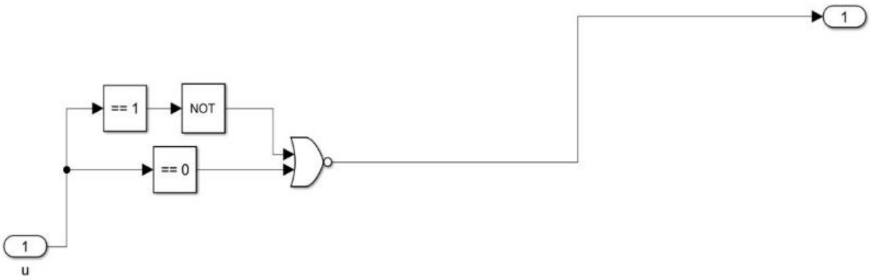

Fig. 12. Input Logic

Figure 12, Input Logic Uses NAND and NOT gate Block sets for Activation

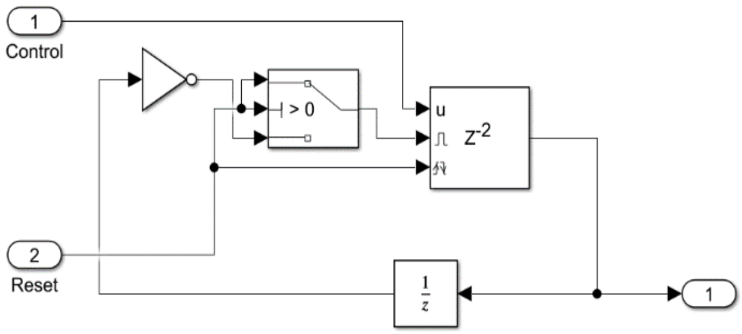

Fig. 13. Memory Block

Figure 13, Memory Block Uses Not Gate Block set, along with Enabled Delay and a Unit delay for Channel Activation until Reset control is given by the user.

5. Results and discussion

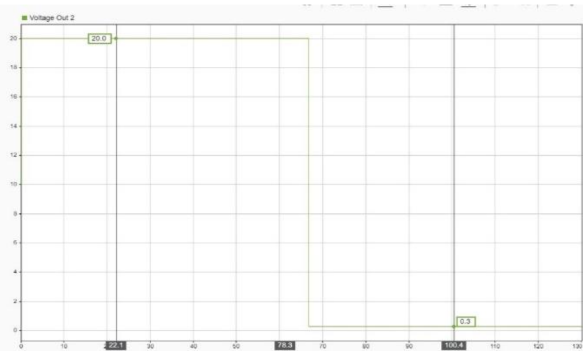

Fig. 14. A Short circuit to Ground Test Conducted on a 20V Channel input

The short Circuit to Ground test in conducted on the 67th second of the simulation, depicts the voltage fall to 0.3 volts signifying a successful test.

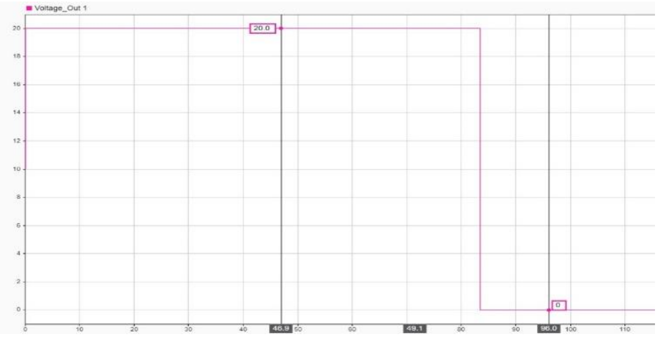

Fig. 15. An Open Circuit Test Conducted on a 20V Channel Input

An open circuit test on the 20volts input supply is conducted on the 83rd second of the simulation where the output voltage of the channels falls to 0 volts suggesting an accurate result.

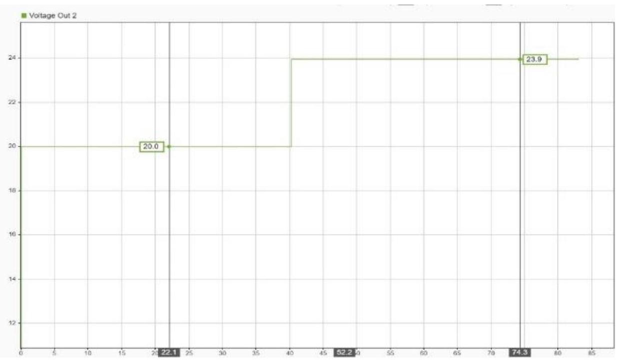

Fig. 16. A Short to Battery Test Conducted on a 20V Channel Input.

A Short to Battery condition test is conducted on the 40th second of the simulation where the input voltage of 20 volts rises to 24 volts signifying an accurate result.

5.1 Test Cases and Results

Test Case	Input	Output
Interlink Line 4 Short Circuit to Battery Voltage Channel 2	Channel 1 Voltage- 12V Channel 2 Voltage-5V	Channel 2 Voltage Out=23.76V IL4 Voltage= 23.7V
Interlink Line 3 Short Circuit to Ground Channel 2	Channel 1 Voltage- 12V Channel 2 Voltage-5V	Channel 2 Voltage Out= 0.171V IL3 Voltage= 0.23V
Open Circuit Channel 3 Interlink Line 1	Channel 1 Voltage- 5V Channel 2 Voltage-5V	Channel 3 Voltage Out= 0.001V IL1 Voltage= 4.98V
Open Circuit Channel 4 Interlink Line 2	Channel 1 Voltage- 12V Channel 2 Voltage-12V	Channel 4 Voltage Out= 0.002V IL2 Voltage= 11.98V
Interlink Line 1 Short Circuit to Battery Voltage Channel 2	Channel 1 Voltage- 24V Channel 2 Voltage-12V	Channel 2 Voltage Out= 23.79V IL1 Voltage= 23.8V

Supply Voltage- 24v

Ground- 0v

Fig. 17. Test Cases and results

The test cases include a 5v-pressure sensor and a 12v-height sensor (Virtual sensor specifications modelled in reference to WABCO® Commercial Truck Sensors). The conditions of Test cases have been denoted and the output is measured in the Model. The results obtained in the simulation are accurately close to the optimal values need to be obtained for validation [1].

5.2 Kirchhoff's Law

Kirchhoff's Voltage Law (KVL) states that the algebraic sum of voltages or potential difference (EMF Sources) across any closed loop in a circuit must be equal to zero.

Consider two voltage sources 24V(V_1) and 5V(V_2) comes in contact.

Therefore, According to KVL when two voltage sources comes in contact with each other, it essentially creates a path between the two voltage sources with nearly zero resistance. This path acts like a direct connection between the two terminals of the voltage sources. Since short circuit has near zero resistance, the voltage drop across it will also be near zero.

Therefore, Resultant Voltage(V) $=V_1+V_2$

$=I_1R_1 + I_2R_2$ volts (Ohm's Law)

Since $R_2=0$, $V_2=0$

Therefore $V=V_1=24V$

Hence this provides a theoretical confirmation to the Simulation Result.

6. Conclusion

The paper presents a comprehensive approach for verifying control software in automotive electronic systems. By utilizing virtualized ECUs and circuit simulators, EFT testing enables the analysis of circuit-level faults and their impact on ECU models, thereby facilitating software verification in the presence of hardware faults.

The study demonstrates the effectiveness of EFT through case simulations, showcasing how the method can identify and analyze the effects of hardware faults on system performance. Overall, Electrical Fault testing provides a valuable methodology for addressing circuit-level faults in ECU hardware, ensuring compliance with functional safety standards like ISO26262. The paper underscores the importance of virtual ECU testing in improving the safety and reliability of automotive electronic control systems, contributing to advancements in functional safety within the automotive industry.

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