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# Fault Diagnostics of Solenoid Valve in Oxygen Injection System

**Vaishali Vinayaga[1], A L Amutha[2], Jackulin Mahariba A*[3]**

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**Abstract:** The life support system within a submarine ensures crew safety and sustenance during underwater missions. The Oxygen Injection System within the Life support system is crucial for supplying breathable air to the crew through various oxygen valves. The working of a two way internally piloted solenoid valve is checked to provide the right amount of oxygen to the crew. The solenoid valve works on the principle of electromagnetism and hence the opening & closing of these valves are set to be checked using a multimeter which detects the voltage/current supply provided to the valve. Also, a pressure gauge is introduced on both sides of the valves to detect the in/out flow of pressure which identifies the leakage in oxygen valves by monitoring the two-way internally piloted solenoid valves in the Oxygen injection system. This is implemented through MATLAB Simulink and Python for various time intervals in the operational range by displaying the fault condition and statement.

***Keywords:*** *Fault identification, Life support system, MATLAB, Oxygen Injection System, Solenoid valve*

## 1. Introduction

The fault diagnosis of the two-way internally piloted solenoid valves in the oxygen injection system, involves a comprehensive approach to identifying and diagnosing potential faults. The process includes testing the solenoid valves to verify their voltage and current ratings by the anomaly analysis of the multimeter deflection, checking the port configuration to determine if they are normally closed (NC) or normally open (NO), and monitoring the regulated air pressure from the oxygen generator using a pressure gauge. The resistance and voltage testing with a multimeter is conducted to ensure proper current flow for smooth valve operation. The fault diagnosis is based on four key conditions: when the valve is open and no fault is identified, when the valve is open but a fault is detected due to low pressure, when the valve is closed and a fault is identified because the valve remains un-energized, and when the valve is closed and a fault is detected due to a power supply or oxygen supply being turned off. By systematically evaluating these conditions and monitoring critical parameters, the fault diagnosis process aims to ensure the optimal functioning and reliability of the internally piloted solenoid valves in the oxygen injection system of the submarine's life support system. This systematic approach helps in ensuring the reliability and efficiency of the solenoid valves within the submarine's life support system.

## 2. Related Works

In a literature survey exploring fault detection in solenoid valves, one study focused on using vibration signal measurement via LabVIEW Signal Express system. This involved placing a vibration sensor [1] at the end of the valve to collect vibrations. The study emphasized that changes in the vibrational signal waveform could indicate the degradation of the valve field, offering insights for condition-based maintenance operations.

*[1,2,3] S.R.M Institute of Science & Technology , Chennai – 603203, INDIA*
** Corresponding Author Email: vaishalivinayaga@gmail.com*

Another study proposed a fault diagnosis method using a Multi-Kernel Support Vector Machine model [2] with multiple kernel learning weights. By analysing the current signal of the six modes of the solenoid valve and extracting their characteristics through Empirical mode decomposition, the study achieved a high accuracy rate of 98.9%. It also noted the advantages of SVM over tree-based classifications in improving classification accuracy. Soo-Ho Jo et.al [3] described the fault detection for coil burnout in solenoid valves using the dynamic thermal loading mechanism. His work was directed towards the discovery of an equivalent current model based on Kirchhoff's voltage law and building a predictive regression model to find temperature relationship with electricity and Utah Michael Ngbede et.al [4] claimed that detection of the solenoid valve fault condition can be done using artificial intelligence methods to process the coil's signature. To extract the coil signature characteristics in form of wavelets, which were aimed at optimizing valve predictive maintenance, a convolutional neural network was used. Study of solenoid valve operations and control strategies reveals several key findings which focused on pneumatic diaphragm operation driven by PWM solenoid valves, developing mathematical models and a PWM control law[5] to optimize parameters such as frequency response and stiffen factors whereas emphasizing the significance of vacuum solenoid valves in regulating processes and throttle valves, highlighting the impact of performance changes on actuator control and overall engine operation is very important for better functioning. Lack of feedback mechanisms in electronic control units [6] for these valves was identified as a challenge for diagnosis, stressing the importance of understanding dependencies for environmental performance.

Additionally, research delved into monitoring coil resistance of electromagnetic solenoid valves using supervised machine learning coupled with a photonic Fiber squeezer as a force sensor. The study aimed to define initial responses of an Open Loop system [7] and achieve transfer functions based on EMS parameters like coil resistance. Another investigation compared the use of on/off solenoid valves with Pneumatic Proportional and

Service Valves for controlling pneumatic actuators. It evaluated a modified controller utilizing four on-off solenoid valves and explored different operating modes [8] combined with PWM, demonstrating effectiveness at specified frequencies Works showed that the modified controller is working with frequencies less than or equal to 0.1 Hz. Further introducing an optimization method for proportional solenoid structural parameters was more efficient [9] and the study validated their 3D finite element method simulation model through force-displacement characteristic experiments, observing a significant 20.1% increase in the average electromagnetic field, with parameters like displacement, armature length, and arc radius influencing these findings.

Another investigation focused on the behavior of solenoid valves in ship engine rooms, particularly examining current changes during valve operations. Data collection using a specialized CAN [10] node for pneumatic valve management facilitated accurate assessment, aided by an algorithm with low computational complexity executed on the node's MCU. This approach proved effective in determining the true state of solenoid valves and swiftly identifying common faults, showcasing precision and efficiency in real-world scenarios. Seungjin Yoo et.al[11] study focused on the failures of hydraulic solenoid valves, highlighting potential system outages and safety hazards. Their data-driven approach utilized voltage and current signals from normal and damaged valve samples, employing clustering and autoencoder techniques to classify data with a 98% accuracy rate across different fault categories. Another investigation delved into solenoid valve failure mechanisms, revealing a correlation between coil thermal expansion [12] and valve malfunctions. This study emphasized the progressive nature of valve failures characterized by changes in coil resistance and temperature, providing insights into thermal dynamics influencing valve performance.

Further research suggested an analytical method for detecting solenoid valve faults, utilizing sensor signals like electrical current and pressure to quantify the state of valves with various failure modes with additionally, a proposed novel method [13-14] based on plunger signals showed promise in accurately monitoring valve movements and minimizing systematic errors in operational monitoring systems. The plunger's signal makes it possible to determine with a minimal systematic error of under 2 ms when the diaphragm or pinch solenoid valves open and close. In a survey on solenoid valve advancements by Torsten Brune et.al [15], one study focused on detecting switching points using a signal-based approach. This involved using derivatives, Euler's initial order approximation, and neural networks to establish the pressure and switch points relationship, exploring the valve's potential as an intelligent pressure sensor. Another significant contribution introduced a modified pulse-width modulation (MPWM) valve pulsing algorithm, aiming to replace costly servo valves with on/off solenoid valves. The algorithm incorporates position, velocity, and acceleration feedback in a continuous controller and uses a learning vector quantization neural network (LVQNN) in the pneumatic actuator's switching algorithm [16,17], showcasing its adaptability and capability in controlling different external loads with smooth switching. Vacuum solenoid valves are crucial in regulating processes in internal combustion engines and experimental research reveals the impact of parameters like vacuum system and power supply on valve operation, aiding diagnostics due to the absence of feedback signals. A 2V difference [18-20] in supply voltage can lead to significant errors in maintaining set values, especially at higher duty cycles. Another approach to control solenoid actuators by analysing signals, focusing on optimizing motion control in thermal power plants [21]. The study involved designing static converters (VTAs) using Arduino and Raspberry Pi boards to improve plant reliability. Analysing gas valve actuator signals enabled optimized regulation and smooth solenoid valve movement, reducing vibration and noise in operations. By adjusting voltage amplitudes at specific time points, an optimized control strategy is developed, leading to smooth actuator operation without shocks. Future work includes implementing VTA control modules and conducting functional tests for validation. Hao Tian et.al. [22] study emphasize to derive an analytical model for sensing spool displacement in direct-acting solenoid on-off valves by correlating coil inductance with air gap width and magnetic reluctance. An optimized method is proposed to solve for inductance from coil current, validated with a laser triangulation sensor experiment showing estimation errors within ±7%. The electromagnetic model derived [23] from coil inductance allows for predicting air gap width, tested in both air and hydraulic oil environments with promising accuracy. Future improvements could include addressing nonlinearities and unmodeled dynamics for enhanced accuracy. Further, Heitor V. Mercaldi [24] work focuses on controlling application rate and regulating pressure on sprayer booms in precision agriculture, crucial for droplet size and application quality. It proposes controlling a set of solenoid valves to achieve desired flow rates independently of pressure changes. By calculating fluidic resistance [25-26], the control system maintains pressure within acceptable limits to ensure consistent droplet sizes. Simulation and preliminary experimental results validate this approach, showing promise for improving spraying efficiency in agricultural applications.

## 3. Methodology

The methodology generally included two main phases i.e. fault diagnostics in solenoid valve using MATLAB and python.

### 3.1. Fault Diagnostics in solenoid valves

Fault Identification and Diagnosis in Oxygen Injection system can be done by finding the faults present in the oxygen supplying valves. Oxygen supply valves are essential for controlling the flow of oxygen to different compartments within the submarine. These valves are typically electronically controlled [1][3] and can be adjusted as needed to maintain the desired oxygen levels. The oxygen supply valves used in the oxygen injection system are basically solenoid valves. The opening and the closing of the solenoid valves are monitored with the help of the multimeter [10][15] present by varying the voltage supply that is required accordingly. Opening and closing of the valves depends on the energized state and the current supply to the coil. A solenoid valve is an electromechanical device used to control the flow of fluids, such as liquids or gasses, through a pipe or tubing system. It works on the principle of electromagnetism. The magnetic field strength inside the solenoid valve is calculated using "(1)".

$$\boldsymbol{B} = \frac{\boldsymbol{\mu_0 NI}}{\boldsymbol{L}} \qquad (1)$$

Where , B = Magnetic Field
I = Current of the solenoid
N = Number of turns of solenoid
L = Length of the solenoid
$\mu_0$= Permeability of free space

The amount of flow of oxygen in the solenoid valve of the submarine is estimated using the pressure loss, inlet/outlet pressure, specific gravity and temperature as per “(2)” & “(3)”. The unit for the same is $Nm^3/h$.

Subsonic: $\Delta P < \frac{p1}{2} \rightarrow Q_n = 30{,}8 \,.\, K_v \,.\, \sqrt{\frac{\Delta P . P_2}{\gamma . T}}$ (2)

Supersonic: $\Delta P > \frac{p1}{2} \rightarrow Q_n = 30{,}8 \,.\, K_v \,.\, \frac{p1}{2 . \sqrt{\gamma . T}}$ (3)

Where, $Q_n$ = Flow rate
dP = Pressure Loss (bar)
$K_v$ = Flow coefficient ($m^3$/hour)
P1 & P2 = Inlet/Outlet pressure (bar)
T = Absolute temperature in kelvin

**3.2. Process of Fault Testing**

Firstly, the two-way solenoid valve’s voltage and current ratings according to the operational values are checked and the solenoid valve port configuration is ensured which can be either normally closed (NC) or normally open (NO)[15] as in Fig 1.

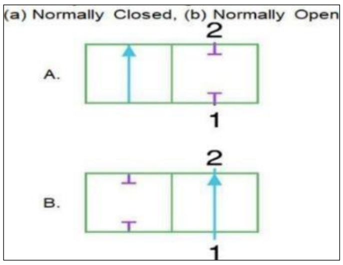


**Fig . 1.** Two way solenoid valve

The regulated air pressure with optimal conditions that is generated from the oxygen generator is ensured with help of a pressure gauge that is present besides the solenoid valve in OIS. Later, as given in Fig 2, the air supply port from the oxygen generator is connected to the solenoid valve inlet port and the current supply is connected to the valve terminals. Once power supply is initiated, with the help of pressure gauge, gauge pressure is monitored to confirm that the valve is energized (the pressure should increase) [15][16].

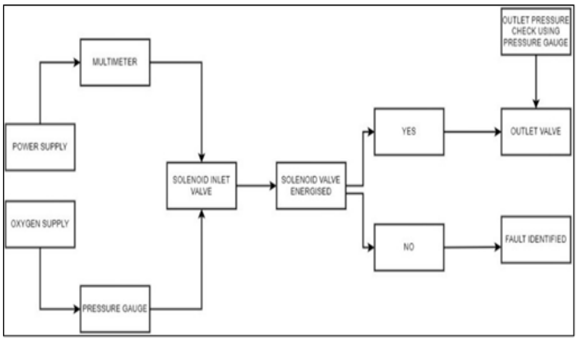


**Fig . 2.** Process of fault testing in two way solenoid valve

At de-energized state NO valve is open and NC valve is closed and pressure is decreased. During the valve core motion, friction is generated from two primary sources: the friction between the valve core and the valve body, fv, and the friction between the valve core and oil, f. Therefore, total friction F calculated is given below in “(4)”.

$$F_2 = f_v + f = (C_0 + C_f)\,\frac{dx}{dt} \quad (4)$$

Where ,

$C_v$ = Coefficient of dynamic friction b/w solenoid valve and valve body
x = displacement of spring
t = time of motion
f = viscous damping coefficient of oil

Further with the help of the multimeter, resistance testing and voltage testing is done to ensure that the current flow inside the valve is regulated that provides smooth opening and closing of valve. If the current supply is the given operational range, then it energized and flow of air across the valve is regulated and the flow ends in the outlet port. The pressure is checked again in the outlet port to ensure there is no leakage of oxygen. Thus, if the given current supply is in the operational range and the pressure is correct, valve would be energized, opening and closing of valves occur and no faults will be detected.

**3.3. Conditions for Fault Testing**

The four fault identification conditions and statements are:

*I. Condition 1 - Valve opened, no fault is identified*:
In this condition, the solenoid valve is open, and no faults are detected in its operation. It signifies that the valve is functioning correctly, allowing the controlled flow of oxygen into the submarine's environment without any issues or abnormalities. This condition ensures that the oxygen supply remains uninterrupted, supporting the life support system within the submarine.

*II. Condition 2 - Valve opened, Fault Identified – Low pressure is exerted:*
When this condition occurs, the solenoid valve is open, but a fault is detected due to low pressure exerted in the system. Low pressure can indicate a potential risk to the oxygen supply, leading to inadequate oxygen levels within the submarine's sphere.

*III. Condition 3 - Valve closed, Fault Identified – Valve not energized:*
In this scenario, the solenoid valve is closed, but a fault is detected because the valve is not energized. A non-energized valve means that the mechanism responsible for opening and closing the valve is not functioning correctly, leading to a disruption in the oxygen supply process.

*IV. Condition 4 - Valve closed: Fault Identified – Power supply or oxygen supply is off:*
This condition occurs when the solenoid valve is closed, and a fault is detected due to the power supply or oxygen supply being off. A loss of power supply or oxygen supply can severely impact the submarine's life support system, risking the crew's safety and well-being

**3.4. Working principle of solenoid valves**

The works use an indirectly operated solenoid valves, that are also known as servo valves or pilot valve that operate with a pressure differential between the medium in front of the outlet port from which the valve is opening and closing. Accordingly, it is typical that they require a minimal differential pressure of about 0.5 bar.

They used for a high flow rate and high pressure. A rubber sleeve, also called a diaphragm, separates the inlet and outlet ports. In order to allow the oxygen to pass into the upper part of the chamber from the intake, there is a small hole in the membrane. When the oxygen becomes clogged, it generates a shutdown force due to its larger displacement area at the top of the diaphragm.

When the valve is opened, the core opens the orifice, releasing pressure from the top of the diaphragm. Then the valve will open as a result of pressure on the line. The inlet pressure under the membrane and support spring above it shall ensure that the valve is closed for a normally closed indirect actuator solenoid valve.

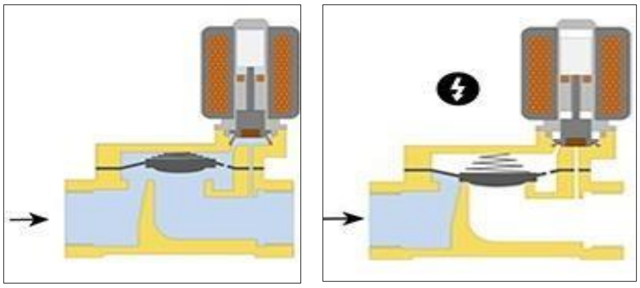

**Fig .3a. & Fig. 3b.** solenoid valve-not energized and solenoid valve energized

A small channel according to Fig 3a,3b shall connect the chamber beneath the membrane to a port at low pressure. The pilot orifice opens as soon as the solenoid is activated, causing a decrease in pressure on the membrane. The membrane shall be raised, allowing the medium to pass out of the inlet port into the outlet port due to differences in pressure on both sides of the membrane. There are identical components in a standard open valve, but it works the other way. The extra pressure chamber above the membrane acts like an amplifier, which means a small solenoid will still be capable of controlling very high flow rates.

### 3.5. Operational range for fault testing in solenoid valves

Common DC voltages used in solenoid valves are 6, 12, 24, 120 and 240 volts, while common AC current at 50 Hz is 110 to 220 volts according to Table 1. The circuit will close and the solenoid valve will be activated when the solenoid is connected to the power source. The diameter of the pipe, orifice size, operating pressure and current supply is considered to calculate the power supply using the formula $P = I^2R$ and displayed in Watts(W). The power consumed by each valve is generally different because of the size of the coil and also the valve stem which is opened and closed. With the help of a multimeter, two kinds of testing [10] shall be carried out on solenoid valves:

*I. Resistance Testing (ohm):* A resistance test ensures that the circuit within the solenoid valve is stable operating condition.

*II. Voltage Testing:* A voltage test ensures that an electric solenoid is receiving or functioning in accordance with the correct level of electrical current supplied by a power source.

**Table .1.** Operational Values of V&I

| Current Flow | Voltage |
|---|---|
| Direct Current | 6V to 24V DC |
| Alternating Current | 110V to 230V AC |

## 4. Implementation

The fault testing in the solenoid valve is done with the help of a multimeter. Multimeter is an instrument used to measure multiple parameters such as voltage, current and resistance. Basically, the solenoid valve will be activated by the electrical current that is supplied to it and its opening or closing shall be regulated. This multimeter that displays the voltage is used to determine the correct amount of current supply. After that, the multimeter probes shall be connected to the solenoid valve's two electrical terminals and shall be checked if the reading on the multimeter is within the specified range of the solenoid valve through the monitor. The V-I graph (Fig 4) shows the drop and increase in voltage. This can therefore be used to determine the current drop and increase in solenoid valves that result in valve regulation, as well as oxygen supply.

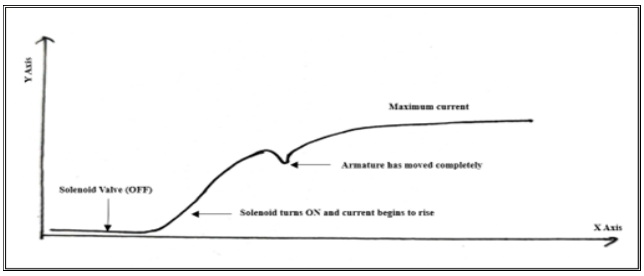


**Fig . 4.** V-R curve for fault testing

### 4.1. Experimental analysis using python

The Python code is a simulation over a one-minute period, generating random data for various parameters such as power supply, oxygen supply, and solenoid valve status. Firstly, the code utilizes the random module to generate random binary values (0 or 1) for the power supply, oxygen supply, and solenoid inlet valve. These values simulate the on/off states of these components, crucial for the system's operation. The loop iterates 60 times, corresponding to each second of a one-minute duration, capturing the system's behavior over time.

Within each iteration, the code checks the status of the power supply and oxygen supply. If both are on 1, it proceeds to check the status of the solenoid inlet valve. The status of these components determines whether the system proceeds with further checks and actions. The code simulates the use of instruments like a multimeter and a pressure gauge. If the power supply and oxygen supply are on, it assumes these instruments are active. The pressure threshold is set at 10 bars, defining a critical level for system operation. If the pressure exceeds this threshold, the outlet valve is turned on, indicating normal system operation.

Conversely, if the pressure is below the threshold, a low-pressure fault is detected, and the code flags this as a fault condition. Additionally, the code checks the status of the solenoid inlet valve. If this valve is not energized while the power supply and oxygen supply are on, it indicates a fault condition related to the solenoid valve. Throughout these checks, the code updates a list (y value) with binary values (0 or 1) representing fault detection status for each second of the simulation. A value of 0 indicates no fault detected, while a value of 1 indicates a fault was detected during that second.

The resulting graph plots convey that these fault detection statuses against time, with the x-axis representing time in seconds (from 0 to 59) and the y-axis representing the fault detection status (0 for no fault, 1 for fault). Each point on the graph corresponds to a second of the simulation, showing how the system's fault detection status changes over time. The graph's title, "Fault detection analysis," reflects the varying combinations of input parameters (power supply, oxygen supply, solenoid valve status) that influence the system's behavior and fault detection. The axis labels, "Time(seconds)" for the x-axis and "Status" for the y-axis, provide context for interpreting the graph's data.

### 4.2. Experimental analysis using MATLAB

The graph generated by the MATLAB code displays the system's status (fault detection) against different input combinations. The x-axis of the graph represents the input combinations, ranging from 0 to 8, where each number corresponds to a unique combination of power supply, oxygen supply, and solenoid valve status. The y-axis represents the system's status, specifically whether a fault is detected or not. The graph uses blue circles connected by lines ('bo-') to plot the system's status for each input combination. A blue circle represents a detected fault, while a blank space between circles indicates no fault detected. The graph's title is "Fault Detection Graph," indicating its purpose of visualizing fault detection based on input conditions. The x-axis label is "Time (seconds)," which in this context represents different input combinations rather than actual time. The y-axis label is "System Status," denoting whether the system is functioning correctly (no fault) or has encountered a fault. The y-axis limits are set between -0.1 and 1.1, ensuring that only two distinct values (0 and 1) are displayed, corresponding to the absence or presence of a fault. This setup aligns with your request to show only binary system status on the graph without in-between values. Overall, the graph effectively visualizes how different input combinations impact the system's status, highlighting fault detection scenarios and normal operation instances. It provides a clear and concise representation of the system's behaviour under varying conditions, aiding in understanding fault patterns and system performance.

## 5. Results

The fault analysis of solenoid valve is done using MATLAB and python. In MATLAB, the result analysis involves defining input combinations and system statuses in binary format, stored in a 2D matrix and an array respectively. Through iterative processes, all possible combinations are generated and evaluated during simulation, determining the system's operational status based on conditions like power and oxygen supply. Subsequently, a customized graph is plotted, depicting input combinations against system status, with labels, title, limits, ticks, and grid for clarity. In this graph, a status of 0 represents a fault detected, while a status of 1 indicates the system is working without fault. Conversely, Python's analysis simulates system states using random numbers and tracks fault detection performance over time. By assessing conditions and updating fault detection variables, a line graph is generated with time on the x-axis and fault detection status on the y-axis, showcasing instances of fault detection throughout the simulation. Both approaches offer insights into system behaviour and fault detection, utilizing distinct methodologies and visualization techniques for different time intervals.

### 5.1. Result obtained using python

The code simulates various system states such as power supply, oxygen supply, and solenoid inlet valve status using random numbers (random.randrange(0,2)). These states are crucial for determining the fault detection process within the system. The y value list collects the values of fault_detected over time (60/180 iterations) and this data is essential for analysing the system's fault detection performance (Fig 5a,5b ,6a , 6b) across multiple time points. If conditions are met (e.g., pressure is above a threshold), the code sets fault detected to 0, indicating no fault. Otherwise, it sets fault detected to 1, indicating a fault detected.
The fault detected variable keeps track of whether a fault has been detected during each iteration of the simulation. A line graph using Matplotlib is generated, where the x-axis represents time (60 seconds/180seconds) and the y-axis 66 represents the fault detection status (0 for no fault, 1 for fault detected). A horizontal line at 0 indicates no faults detected, while spikes at 1 indicate instances of fault detection during the simulation.

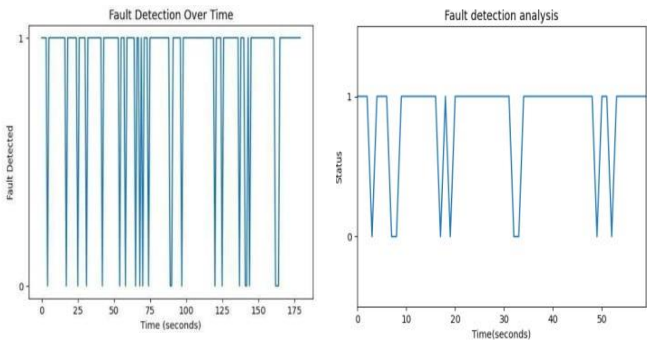


**Fig . 5a. & Fig . 5b.** Fault detection output graph with python

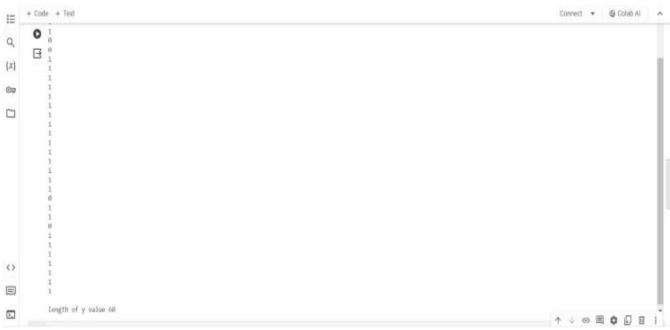

**Fig . 6a.** Displaying Fault status for 60 secs using python

**Fig . 6b.** Displaying Fault status for 180 secs using python

### 5.2. Result obtained using MATLAB Simulink

The code defines input combinations as binary values representing power supply, oxygen supply, and solenoid inlet valve status.

These combinations are stored in a 2D matrix, while the system's statuses, indicating whether it's working or not, are stored in an array. To generate input combinations, the code iterates from 0 to 8, representing all possible combinations in binary. It converts each iteration value to binary using the `dec2bin` function and subtracts '0' to get numeric values. This process ensures that all possible input combinations are generated for the system. During simulation, the code evaluates the behaviour of the system for each input combination. It checks if the power supply and oxygen supply are ON and if the solenoid inlet valve is energized.

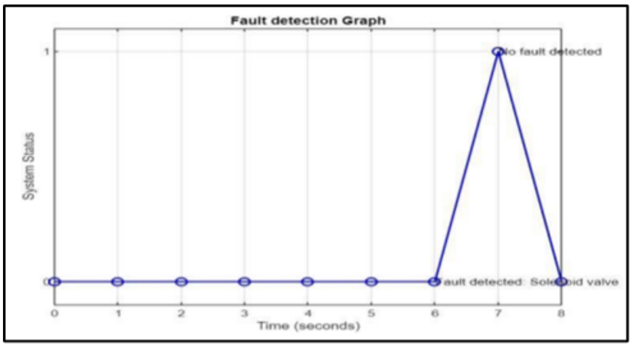


**Fig .7.** Fault detection output graph with MATLAB

Based on these conditions, it determines whether the system is working (outputs(i+1)= true) or not working (outputs(i+1)= false).After simulating the system for all input combinations, graph is plotted using MATLAB's plotting functions. The x-axis of the graph represents the input combinations (0 to 8) while the y-axis represents the systems status where 0 for not working i.e. fault detected and 1 is working i.e. no fault detected. Furthermore, the plot (Fig 7,8) is customized with labels for the axes (`xlabel`, `ylabel`) and a grid (`grid on`).

```
Outputs
    {'Power supply or oxygen supply is OFF'        }
    {'Power supply or oxygen supply is OFF'        }
    {'Power supply or oxygen supply is OFF'        }
    {'Power supply or oxygen supply is OFF'        }
    {'Power supply or oxygen supply is OFF'        }
    {'Power supply or oxygen supply is OFF'        }
    {'Fault detected: Solenoid valve not energized'}
    {'No fault detected'                           }
    {'Power supply or oxygen supply is OFF'        }
```

**Fig . 8.** Displaying Fault status for 8 secs using MATLAB

## 6. Conclusion

Fault diagnosis in two way internally piloted solenoid valves of OIS is critical for submarine LSS, monitored through periodic statements based on four conditions: Valve opened - no fault, Valve opened - low pressure, Valve closed - not energized, Valve closed - power or oxygen is off. MATLAB Simulink and Python Collab are utilized for fault diagnosis, with binary outputs indicating fault detection status as 0 & 1. The system provides status updates every second, aiding in fault diagnosis and decision-making for optimal oxygen supply. Analysis of system outputs reveals strong fault detection capabilities across various input scenarios, suggesting potential for improvement through enhanced algorithms and broader testing. Integration with real-time data acquisition systems and sensors could enhance simulation realism and practical applicability.

## 7. Further Enhancements

Further enhancements for fault diagnostics in solenoid valves may include advanced anomaly detection techniques such as deep learning models for more accurate and robust detection of subtle deviations in system behaviour. Developing predictive maintenance algorithms based on machine learning can also be considered, allowing for proactive maintenance scheduling, and reducing downtime by predicting potential failures before they occur. Implementing a comprehensive fault response system that includes automated decision-making based on predefined rules or machine learning algorithms can further streamline corrective actions and reduce manual intervention. Furthermore, leveraging cloud-based solutions for real-time data processing, predictive analytics, and collaborative decision-making can enhance scalability, flexibility, and accessibility of the fault detection and response system. Continuous monitoring and optimization of fault response strategies, including refining algorithms for automatic valve shutdown, alternate route activation, and emergency oxygen supply management, should also be part of the ongoing enhancements to ensure optimal system performance and reliability.

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## Author Contributions

**Vaishali Vinayaga:** Conceptualization, Methodology, Software, Field study, Data curation, Research and Analysis, Writing-Original draft preparation.

**Jackulin Mahariba A:** Guidance, Visualization, Investigation, Writing-Reviewing

**A L Amutha:** Guidance, Writing-Reviewing

## Conflict of Interest

The authors declare no conflicts of interest.

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