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Development of Hardware-In-Loop Automated Test Bench for Failure Mode Effects Tests and Closed-Loop Feature Tests of Liquid-Assisted After-Treatment Control Systems

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Abstract: Air pollution is caused due to harmful exhaust gases comprising of Oxides of Nitrogen (NO_x) and Particulate-Matter (PM) coming out from automotive vehicle engines after the fuel is combusted. To meet the statutory Emission Norms and satisfying the required vehicle torque-speed performance, the quantities of these NO_x and PM particles going into the environment have to minimised, which can be done by after-treating the exhaust gases upon dosing Urea (AUS-32). The After-Treatment system comprises of various mechanical processors and Urea Dosing Unit along with its set of various sensors and actuators. The dosing action is performed using a control-system, called After-Treatment Control-System. To meet the precise performance, accuracy and system durability, this control-system has to be tested rigorously in the Test-Labs before they are implemented on the Vehicles. The tests carried out include Failure Modes Effects Tests (FMET), Functionality Tests and Closed-Loop Feature-Tests. These tests have to be repeated and reproduced for each regular software releases. Usually, these tests are conducted using a manual-test bench method – which consumes considerable time, prone to manual errors thus increasing overall testing time and programme cost. This paper discusses about the development of automation for these tests using Hardware-In-Loop (HIL) Automated-Test-Bench Technique, using the hardware combination of ACCEPTS (Automated Common Controls Electronic Product Test System), NI hardware and In-house developed Integrated Circuit Logics. The automated test scripts and hardware control logics are developed using automation programming tools like NI-TestStand and NI-LabVIEW. Comparing to the manual test bench method, automated test bench method have reduced the testing time and thus proved to be cost-effective, while increasing the testing efficiency by 23%.

Keywords: After-Treatment Control-System, Electronic-Control-Module, Urea Dosing Unit, Hardware-In-Loop Technique, Closed-Loop Tests Simulation, ACCEPTS, NI-Hardware, NI-TestStand, NI-LabVIEW and MATLAB/Simulink.

I. INTRODUCTION

The main source of air emissions is On-highway vehicles. Emissions of air pollutants such as Hydrocarbon (HC), Carbon Monoxide (CO), Particulate Matter (PM), NOx, Sulphur Oxide (SO), Volatile Organic Compounds (VOCs) etc.., have been shown different negative effects on environment viz. global warming, acid rain, respiratory diseases etc.., In order to regulate the level of air pollutants produced by internal combustion engines Government of India introduced Bharat Stage Emission Standards (BSES). To meet these statutory emission norms, After-treatment system to treat the exhaust gases can be used which includes Diesel Particulate Filter (DPF) with Selective Catalyst Reduction (SCR) technology [5]. After-treatment System includes Doser which consists of set of various Sensors and Actuators. Doser is used to dose urea solution, called as Diesel-Exhaust-Fluid (DEF) with 32.5% concentration [4]. The NO_x (Nitrogen Oxides) in the exhaust gas reacts with the ammonia of DEF inside the catalyst chamber, once they have passed through the catalyst and forms harmless nitrogen and water vapour that is released back into the atmosphere through the tailpipes.

A. *After-Treatment Control-System*

Electronic Control Module (ECM) and its software is used to control the Doser based on set of various sensor inputs and actuators like DEF Injector, DEF Electric Pump forms the core of the Liquid-Assisted After-Treatment control system. This system's performance for each software release cycle is analysed by engineer in the Test-Lab by purposefully inputting various error/noise conditions into the system viz. tampering, obstructing and damaging both physically and functionally. The control logics have to perform as per the expected results during these fault/noise conditions as well [3]. The types of the fault conditions include FMET, functionality test, and features test.

II. MANUAL TEST BENCH METHOD

A. *Description*

In this method, the test engineer purposefully introduce various error/noise conditions through manual actions into the system like performing tampering, obstructing and damaging both physically and functionally the signal, supply and fluid flow lines, connecting / disconnecting external and internal components of the Doser Unit. Fig. 2 illustrate, set up of manual test bench with Liquid-Assisted dosing system.
Usually these tests are performed using Manual-Test-Bench method, which comprises of the ECM, Manual-Break-Out-Box, wiring harness and dosing system. This method is time consuming, less efficient and prone to manual errors.

B. *Manual Simulation of Circuit Continuity FMET*

FMET (Failure Mode Effects Tests): An FMET is used to analyse system failure modes by introducing various fault conditions in the Test-Labs.

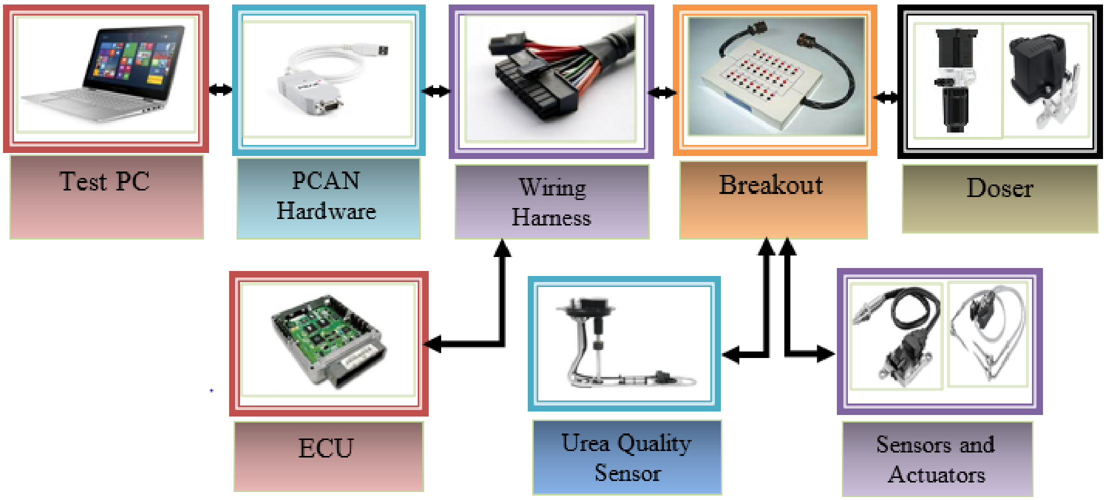

Fig. 1 Block diagram of Manual Test Bench of Liquid-assisted Dosing system

This type of tests consist of circuit continuity faults simulation such as Open-Circuit, Short-Circuit to Battery Ground and Short-Circuit to Battery Positive (5V/24V). In liquid only urea doser system FMET is performed on the following components of it:

- Pump Motor Supply
- Pump Motor PWM
- Sensor Signals (Pressure, Temperature, Level)
- Sensors supply
- Sensor return
- Communication lines of various other ECMs/Sensors

In this FMET, manual-breakout-box is used to simulate all circuit continuity fault conditions such as open circuit, short to ground, short to battery positive. Using a breakout box, engineer makes / opens the electric circuits using jumper wires for each pin of manual-test-bench corresponding to each fault condition[4] [5].

C. *Manual simulation of Functionality Tests*

These tests are simulated by tampering / obstructing the functionality performance of the system by bypassing or replacing the ECM command with external supply voltage or components. To simulate functionality fault condition manually, remove the sensors from corresponding connectors to stop/disrupt command signals between the ECM and the sensors/actuators. Similarly, performance and functionality of control software is tested against the tampering of corresponding suction line from the DEF tank by manually partially / fully blocking it [4].

D. *Manual simulation of Features Tests and Closed-Loop Tests*
To validate the performance of control logics of various features of After-Treatment Controls, these tests are conducted and the closed-loop type of tests which needs to emulate the sensors / actuators transfer functions if they are not available like automated-dosing tests needs to be tested in the test-labs during proto-testing phases.

E. *Problem Statement*

The manual test bench method have the following limitations and disadvantages:
1) Time-Consuming: During the simulation of circuit-continuity FMET fault-conditions using manual-break-out-box, the test engineer needs to perform various manual actions like searching for the corresponding pin's jumper wires and make / open the circuits as per the test sequence and timing, in addition to the logging and varying the test conditions by changing the values of certain calibration parameters. This will consume certain time for creating the fault conditions and within the specified timing the jumper wires are either if not connected / disconnected, the fault condition may not be set, and once again the test have to be repeated from the start. This will consume much time and manual efforts.

2) Tests which cannot be done manually – like 'Key Switch Cycle Tests' which needs to vary the positions of the Key Switch and Battery Cut Off Switch from On to Off and immediately vice-versa within very less time duration and these actions have to repeated for longer time durations, say 3 hours etc.., which is very difficult to implement using the manual-test-bench method.

3) Tests which are lengthy and needs timely updates -
- Pressure Control Test which requires manual intervention only after certain period of time duration to change values of few parameters / change the direction of the tests.
- Doser Accuracy Test – to monitor the basic functionality tests of the developed software.

4) Limited available resources / test benches – for access across various locations i.e. the same setup has to be used by various teams located at various distant points. Therefore, the engineers either have to travel to the established test bench at the test-labs or they need to develop new manual-test benches at each individual locations.

5) During the proto-testing of the software, if any component / sensors are not available and they are critical in performing the tests, those tests cannot be performed till all the required hardware components are available.

Under Liquid Assisted Dosing After-Treatment system, two category of ECMs with different set of sensors and actuators are available. The number of tests needed to be performed per one ECM set are approximately 40 tests, the manual testing time duration = 150 hours. Likewise there are 4 regular software releases per a year, 2 × 40 = 80 tests per ECM per annum. For 2 ECM systems, it becomes 160 tests. Total Testing time = 4 × 150 = 600 hours per annum.

Also, the demand for the testing is increasing and the testing results have to be produced very fast to meet the stringent programmes' timelines with the available resources and test engineers.

III. AUTOMATED TEST BENCH USING ACCEPTS HARDWARE-IN-LOOP TEST BENCH

This paper focuses on automation of Liquid-Assisted After-Treatment control-system using Hardware-In-Loop (HIL) technique in order to overcome the limitations and the disadvantages of the manual-test-bench method as mentioned above[6][7].

A. *Hardware-In-Loop Simulation Technique*
HIL simulation technique provides an effective and efficient platform for automated testing platform [1][2]. This HIL automated test bench developed basically consists of an ECM, set of sensors and actuators, Doser unit and corresponding hardware combination of ACCEPTS Load-Box, NI-Hardware and In-house developed Integrated-Circuit Logic Boards.

The characteristics of these sensors and actuators are simulated with the help of ACCEPTS (Automated Common Controls Electronic Products Test System) Load-Box as part of HIL Automated-Test-Bench setup. The automated sequential steps of these tests as per their test-procedures are programmed using NI-TestStand and hardware controlling by NI-LabVIEW respectively.

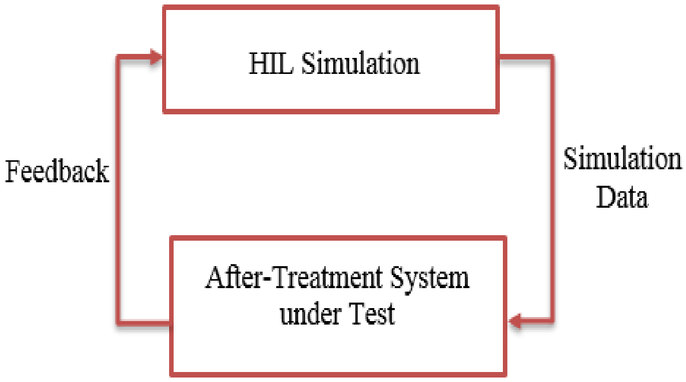

Fig. 2 General Block diagram of HIL simulation technique for After-Treatment Control-System

B. *Challenges*

- To automate the manual actions like

a. Opening and shorting the jumper wires of corresponding signal wires as per required timing and order.

b. Plugging and unplugging of mating connectors, connecting / dis-connecting of desired components and changing the positions of various components.

- To define the transfer function characteristics of various sensors / loads for emulating them.
- To develop the required hardware and implementation of the developed circuit-logics in-house in the test-lab.

C. *Constraints*

- Implementation and realisation of the developed control-logics in-house as corresponding hardware and its components are not readily available.
- Very little reference is available for this type of Liquid-Assisted Dosing System Automated Testing, so developed automated test bench for this from scratch.

D. *Design*

Following are the components of automated develop LUIS bench setup with the help of NI hardware:

1) Test PC / Computer: All the required software tools are controlled through the test PC. The monitoring software is used to continuously monitor the system while doing the manual testing. The NI-Teststand software is used for the automation of steps as per the test-procedures. The NI-TestStand software tool directly monitors the parameters from the ECM. NI-LabVIEW software is used to develop the auto-commanding codes for controlling corresponding components of the Integrated Circuit Board, which in turn helps to control connected valves/components.

2) Electric Control Module: Electronic control module (ECM) is like central processing unit, which is responsible for all the decision making operations and the controlling operations required in the system. Simulation of any fault code/condition is detected by the ECM & thus if the fault code is generated it transmit it over CAN which is connected with the test PC to show the corresponding Active & Inactive status of the fault [4].

3) NI-Hardware: The hardware consists of a combination of NI DAQmx Data Acquisition Card and output generating cards, which works with industrial logic levels and signals to directly connect to a wide array of industrial switches, transducers, and devices. Each channel of the output generating card is compatible to generate the command signals from 5V to 30V. This will be run as per the instructions provided by the NI-LabVIEW auto-commanding programme to generate the output command pulses as per set timing, events and sequential order.

4) ACCEPTS Load-Box: is proprietary load-box which can able to generate the load conditions and emulate the sensors or actuators transfer functions. This ACCEPTS load-box consists of a real-time processor which will simulate the test conditions in real time environment as per the instructions programmed for it. The NI-Hardware is used to generate the required output command signals to simulate the tampering / obstructing conditions by controlling the corresponding connected components like valves. To develop NI-TestStand automated test-scripts and developing the test procedures, MATLAB/Simulink software tool is necessary to study the software logic models.

Fig. 3 Block diagram of automated Test Bench using ACCEPTS load box and NI hardware.

5) Integrated Circuit Logics Board: In-house Relay circuit board (IC Board) has been developed to automated simulation of the circuit-continuity fault conditions regarding high-current carrying lines and communication lines. IC Board receives the commands from NI DAQmx Card and changes the positions of the actuators as per the circuit-logics.

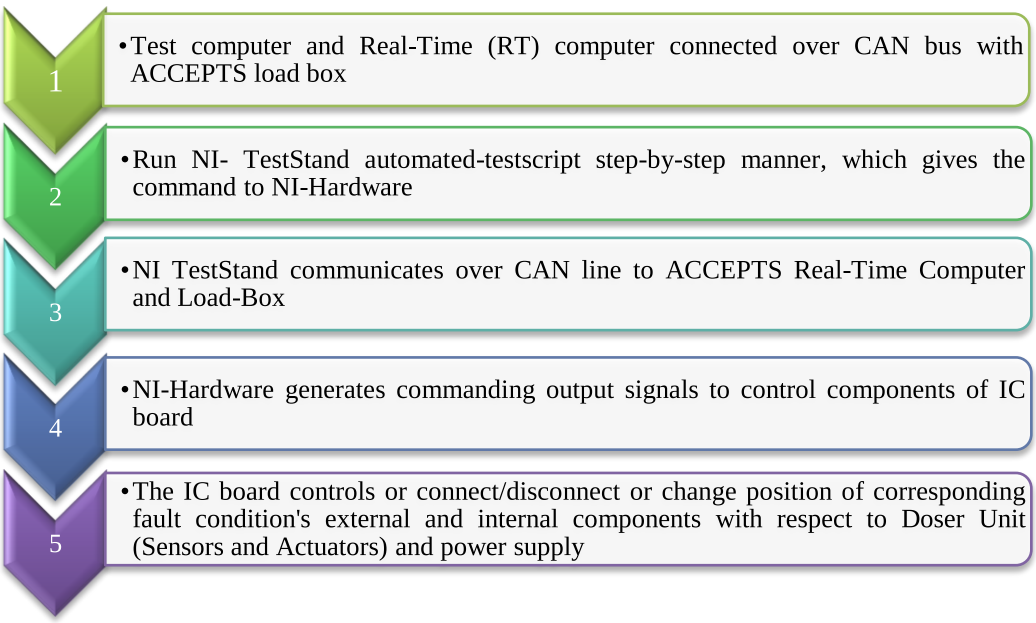

Fig. 4 Flow chart of system signal flow automated Test Bench using ACCEPTS load box and NI-Hardware

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IV. RESULTS AND IMPLEMENTATION

A. *Implementation of FMET fault conditions simulation*

As a case study Urea Quality Check (UQS) sensor open circuit fault condition is considered.

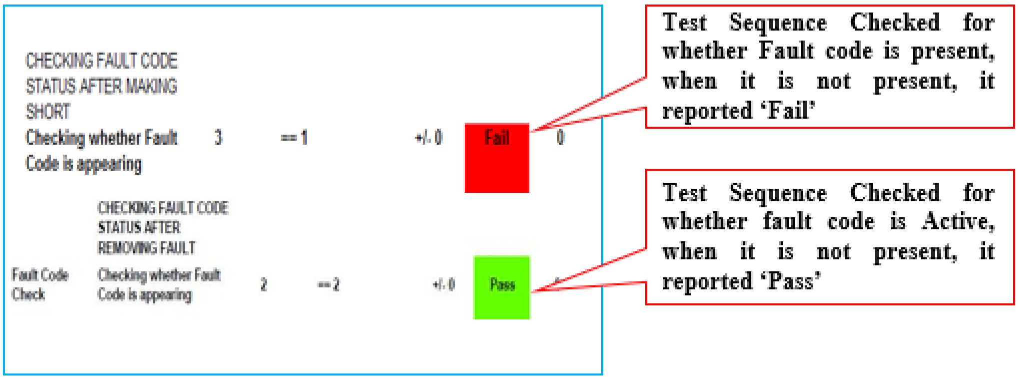

Fig. 5 Fault code status of Result

Initial step is to configure the complete bench setup by performing Total Bench Configuration (TBC) by using required calibration and the configuration files. Then to establish the session by writing scripts in the NI-TestStand. Next step is to open the Feature test report sheet. It is generated automatically showing the behaviour and the status of the fault condition. If the fault code appears then it is automatically updated in the test report sheet. If the Actual value of calibration parameter is equal to the Target value it shows the PASS status in the feature test report sheet and if the actual value of calibration parameter is not equal to the target value it will show FAIL status in the feature test report sheet. The next step is to call the sequence file for the UQS sensor open circuit fault condition which contains the step-by-step procedure to simulate the fault condition.

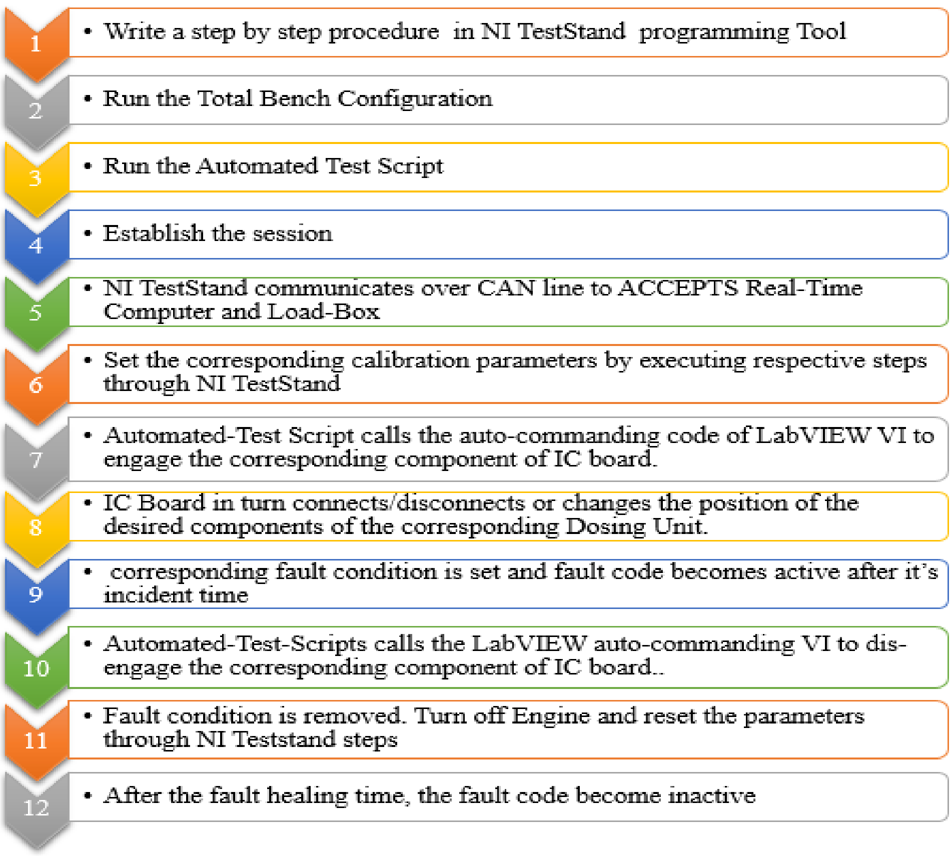

Fig. 6 Algorithm to simulate UQS Open circuit fault condition

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Automated-Test Script calls the auto-commanding LabVIEW code to engage the corresponding component of IC board. IC board in turn controls or connects/disconnects or changes the position of the desired internal or external components of the corresponding Dosing Unit. The corresponding fault condition is set and fault code becomes active after its incident time. Automated-Test-Scripts calls the LabVIEW auto-commanding code to dis-engage the corresponding component of IC board. Fault condition is removed. Turn off Engine and reset the parameters through NI-TestStand steps and after the fault healing time, the fault code becomes inactive. Fig.5 shows the result of UQS Open-Circuit Fault condition active / inactive status in terms of pass / fail.

B. *Implementation of closed-loop fault simulation*

As a case study Diesel Particulate Filter soot i.e. PM and ash estimation closed-loop fault condition is consider. DPF is used in exhaust side which consists of temperature and differential pressure sensor.

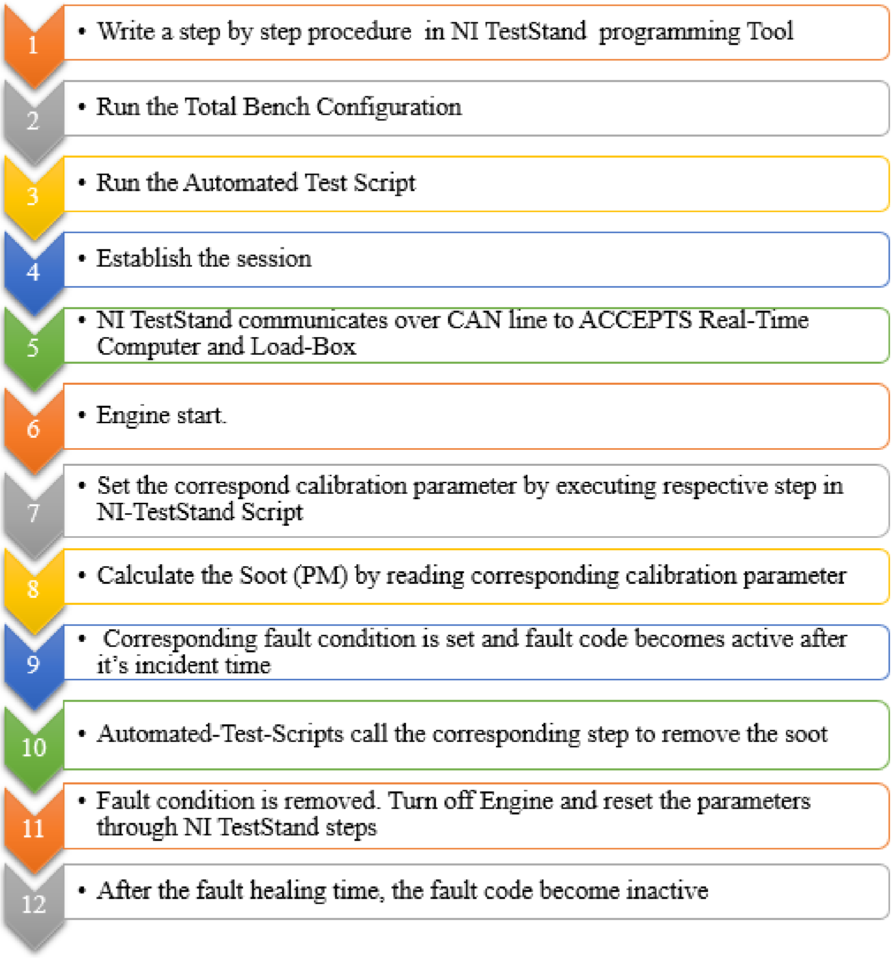

Fig. 7 Algorithm to simulate DPF soot and ash estimation closed-loop fault condition

Inside that porous ceramic walls is present which help capture soot and ash from exhaust. Regeneration is a process which help to removing the accumulated soot from the DPF. The following figures shows the graphs for analyses of the corresponding fault conditions i.e. Fig. 8 is for UQS Sensor Open circuit Fault condition and Fig. 9 is for DPF soot and ash estimation closed-loop fault condition.

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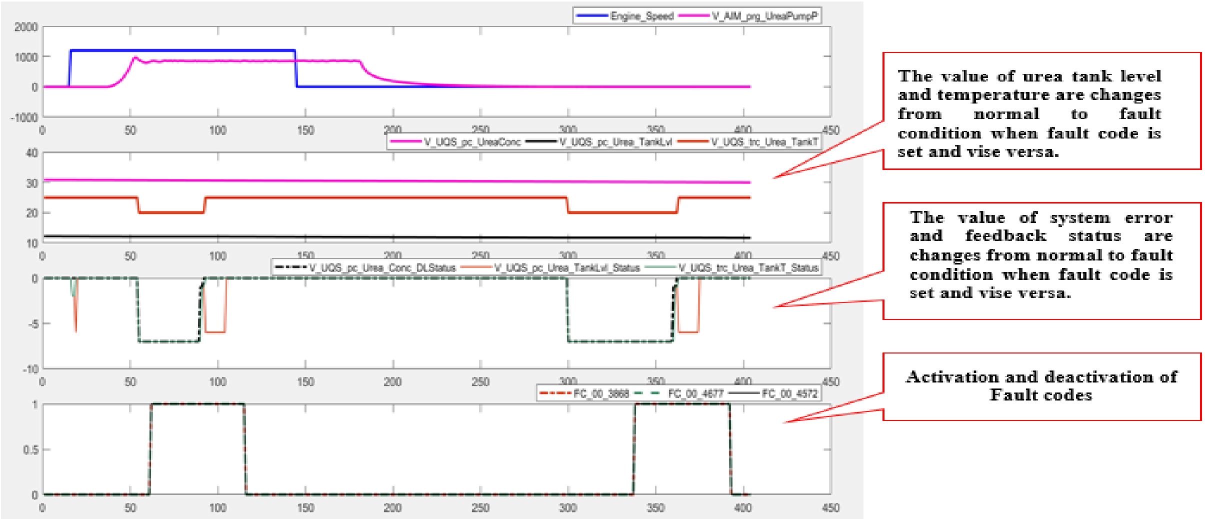

Fig.8 Graph of UQS Sensor Open circuit Fault condition

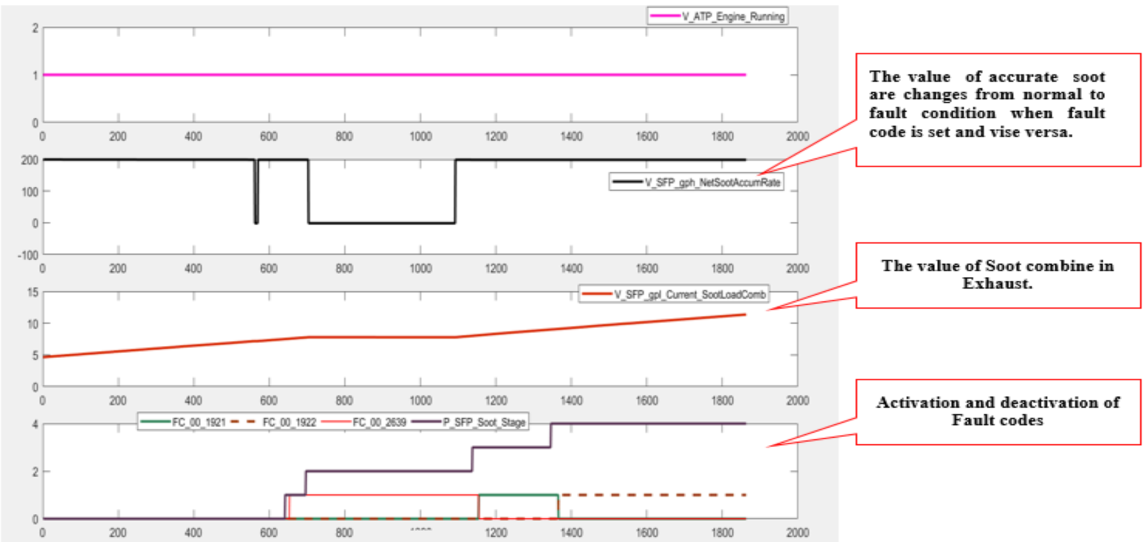

Fig. 9 Graph of DPF soot and ash estimation closed-loop fault condition

C. *Results*

- Development of the Integrated-Circuit Control Logics for integrating the manual actions into automation for connecting / disconnecting, plugging/unplugging and shifting the positions of the corresponding components.
- In-house development of required hardware in the test-lab for realisation and implementation of the above integrated circuit logics.
- Development of Pin configuration and interconnection circuit schematic for connecting all the components of the hardware-in-loop automated test bench viz. ACCEPTS Load-Box, ECM, Doser Unit – Sensors and Actuators, Integrated-Circuit-Board, NI-Hardware etc..,
- In-house development of its Wiring Harness in the test-lab, which helped to reduce the development time and cost as well.
- Development of Automated Test-Scripts as per test-procedures in step-by-step sequential order and timing.
- Development of Auto-Commanding programmable codes to control the NI-Hardware and the Integrated Circuit-Logics.
- Tested all the 40 tests of one ECM and Doser Unit. The total time consumed is 57.75 hours. Total duration of time to complete the tests for two ECMs is 462 hours per annum using automated test bench method.

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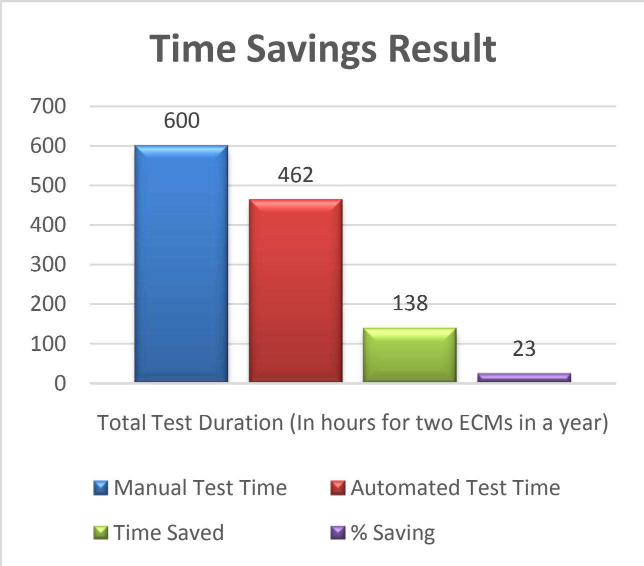
V. CONCLUSION

The Developed Hardware-In-Loop Automated Test Bench for Failure Mode Effects Tests and Closed-Loop Feature Tests of Liquid-Assisted After-Treatment Control Systems gives faster delivery of Test Results, minimize Manual Efforts and Errors.



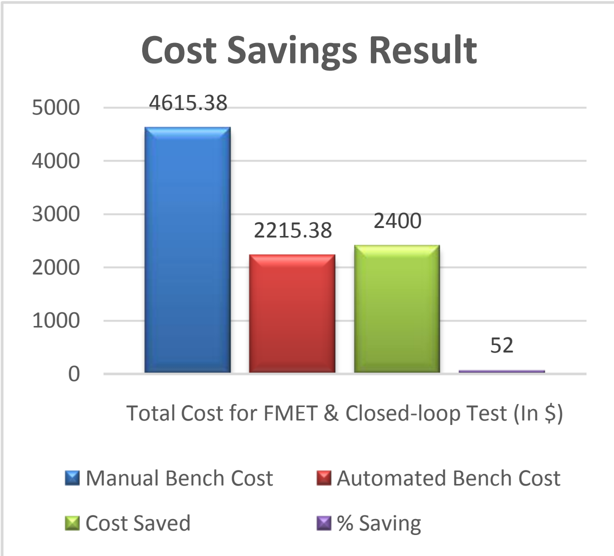


Fig. 10 Comparison of savings in the testing time and overall cost by HIL automated test bench method over manual test bench method *(figures indicated per annum basis)*

Using of Automated test bench help to reduce Man-Power and Cost–Saving, through which On-Time Delivery and Right First Time can be enhanced. Overall Total Time Savings w.r.to Manual Test-Bench Method is 23% approx. Automation of Liquid-Assisted After-Treatment Control-System and in-house development of wiring harness reduced the total cost of development of bench. Total cost saving is $ 2400/- approx. If test scripts as per procedures are developed one time, the same scripts can be applied for any number of tests. The developed automated bench can be carried forward for other dosing systems and ECMs also. The bar graph for the comparison of time required performing FMET on conventional bench and the automated bench is given in Fig.10. The bar graph for the comparison of cost required performing FMET on conventional bench and the automated bench is given in Fig.11.

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