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Development of HiL (Hardware-in-Loop) Technique for MCU Testing and BLDC Motor Simulation

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Abstract: Air pollution is significantly driven by harmful exhaust gases emitted from automotive engines. Conventional vehicles predominantly rely on petrol and diesel, which not only release hazardous pollutants but are also derived from non-renewable resources. To mitigate air pollution and address the finite availability of fossil fuels, transitioning to Electric Vehicles (EVs) is imperative. EVs do not depend on crude oil and emit no harmful gases, making them a sustainable alternative. This paper focuses on the essential components of EVs, including the battery for energy storage, the motor for propulsion, and the Motor Control Unit (MCU), which regulates motor speed and torque. The MCU interprets driver inputs and controls the inverter that generates signals to operate the Brushless DC (BLDC) motor efficiently. To ensure optimal performance of EVs, it is essential to test and validate both the vehicle and its individual components. Traditional testing methods are costly and time-consuming, as they require physical vehicle prototypes and iterative installation and removal of components. To address these limitations, this research proposes the design and implementation of a Hardware-in-the-Loop (HiL) system. The HiL system enables simulation-based validation of EV components in a controlled environment, significantly reducing development time and costs while enhancing testing efficiency.

Keywords: Motor Control Unit, Hardware-in-Loop Technique, Closed-Loop Tests Simulation, VT system, BLDC motor Simulation, Automated Test Bench Setup

I. INTRODUCTION

Air pollution is significantly caused by harmful exhaust gases, including oxides of nitrogen (NOx) and particulate matter (PM), which are emitted from automotive engines during fuel combustion. Currently, most vehicles operate on petrol or diesel, both of which release hazardous pollutants that are detrimental to the environment. Additionally, petrol and diesel are non-renewable resources with limited availability, further emphasizing the need for alternative energy solutions. In response to these concerns, there is a growing shift towards Electric Vehicles (EVs). EVs do not rely on crude oil and do not emit harmful gases, making them a viable alternative for reducing air pollution and conserving finite energy resources.

This research focuses on the essential components of EVs—particularly the battery for electricity storage, the motor for vehicle propulsion, and the Motor Control Unit (MCU), which regulates motor speed and torque to ensure smooth operation. The MCU processes driver inputs and transmits appropriate control signals to the inverter, which in turn generates three-phase signals required to drive the Brushless DC (BLDC) motor. By examining these components, the study aims to highlight the operational advantages and technical functionalities of EVs, emphasizing their potential to replace traditional petrol and diesel vehicles in the automotive sector.

To ensure optimal performance and reliability of EVs, it is essential to rigorously test and validate both the entire system and its individual components. Traditional testing methods, which involve physical evaluation of components using actual EVs, are both costly and time-consuming. These methods require repeated installation and removal of components, leading to significant increases in development time and expenses. To overcome these challenges, this research proposes the design and implementation of a Hardware-in-the-Loop (HiL) system. The HiL system enables simulation and validation of EV components within a controlled environment, thereby significantly reducing testing time and costs. This study focuses on the development of an efficient HiL system to streamline the testing process, ultimately enhancing the development and validation of EV technology.

Problem Statement: Traditional methods for testing and validating the Motor Control Unit (MCU) and motor of an Electric Vehicle (EV) are both costly and time-consuming.

Constraints: Signal Fidelity, Component Modelling, Modularity, Configurability, Interface Compatibility, Hardware Compatibility.

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Materials: For testing of MCU and Simulation of the BLDC motor:

To test and control the MCU, we require various Virtual Technology (VT) modules provided by the VT System platform by Vector [1]. These modules are referenced from the VT System manual and are essential components of the Hardware-in-the-Loop (HiL) setup. The modules used are as follows:

1. VT7001: Power supply module (60V).
2. VT2820: General Purpose Relay Module.
3. VT2004: Digital input Output Module.
4. VT5838: E-Machine Module.

Methods: There are total 2 methods for the testing of MCU (Motor Control Unit) of electric vehicle which are as follows:

1. Manual test bench method to test the MCU
2. Automatic test cases to test the MCU

II. MANUAL TEST BENCH METHOD

Description: In this method, the test engineer purposefully operates the system under various conditions through manual actions such as accelerating the throttle, applying sudden braking, and reversing the motor direction. These actions are performed both physically and functionally by manipulating signals, power supply, and connecting or disconnecting external and internal components of the VT system through a breakout box.

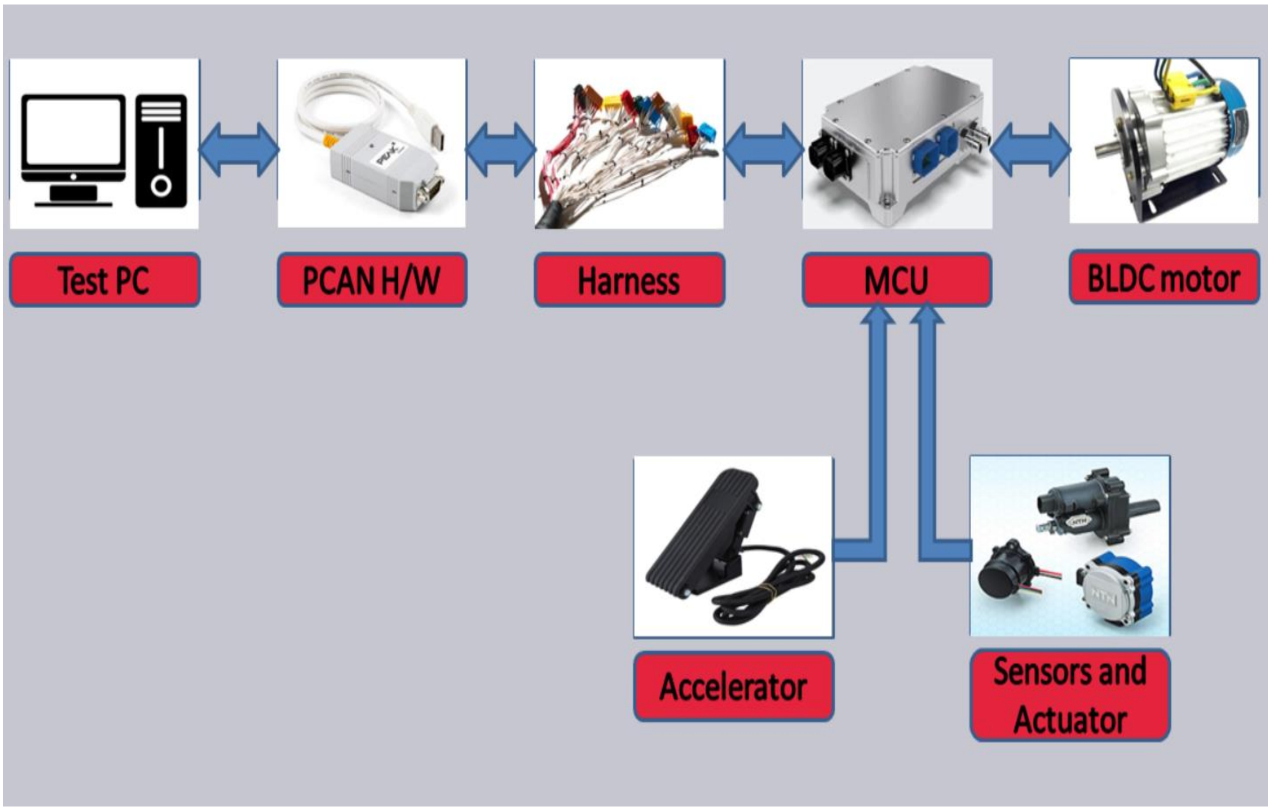

Fig.1 Block Diagram of Manual Test Bench method to test MCU unit

Figure 1 illustrates the setup of the manual test system integrated with the Motor Control Unit (MCU). These tests are typically conducted using a Manual Test Bench approach, which consists of the MCU, power supply, key switch, accelerator pedal, various sensors and actuators, inverter, and the BLDC motor. This method is time-consuming, less efficient, and susceptible to manual errors.

At the beginning of the test process, the power supply must be connected to the MCU. Once connected successfully, the start/stop switch should be activated internally to bring the BLDC motor into a ready state. The accelerator allows control over the speed and torque of the motor and also enables regenerative braking functionality.

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Manual Simulation of Circuit Continuity FMET (Failure Mode Effects Tests):

Failure Mode Effects Testing (FMET) is used to analyze potential system failure modes by intentionally introducing various fault conditions within controlled test-lab environments. This testing involves simulating circuit continuity faults such as open circuits**,** short circuits to ground (0V)**,** and short circuits to battery positive (5V/24V)**.** In a BLDC motor control system, FMET is typically performed on the following components:

- Power Supply
- Motor Control Unit (MCU)
- Accelerator Pedal
- PWM sensor signals (e.g. Hall Sensor)
- Communication lines of Electronic Control Unit (ECU)
- Switches (e.g. Start/Stop)

During FMET, a manual breakout box is used to introduce various circuit continuity fault conditions such as open circuit, short to ground, and short to battery positive. Using the breakout box, the test engineer manually creates open or short circuits at each connector of the manual test bench by inserting banana connectors, thereby simulating fault conditions. These artificially induced faults allow test engineers to observe the system's behaviour in response. If the system continues to operate normally despite the fault, the Motor Control Unit (MCU) under test is considered faulty and unsuitable for use in an Electric Vehicle (EV). However, if the MCU detects the fault and either stops operation or generates diagnostic error codes immediately after the fault is introduced, the unit is functioning correctly and is considered suitable for EV applications.

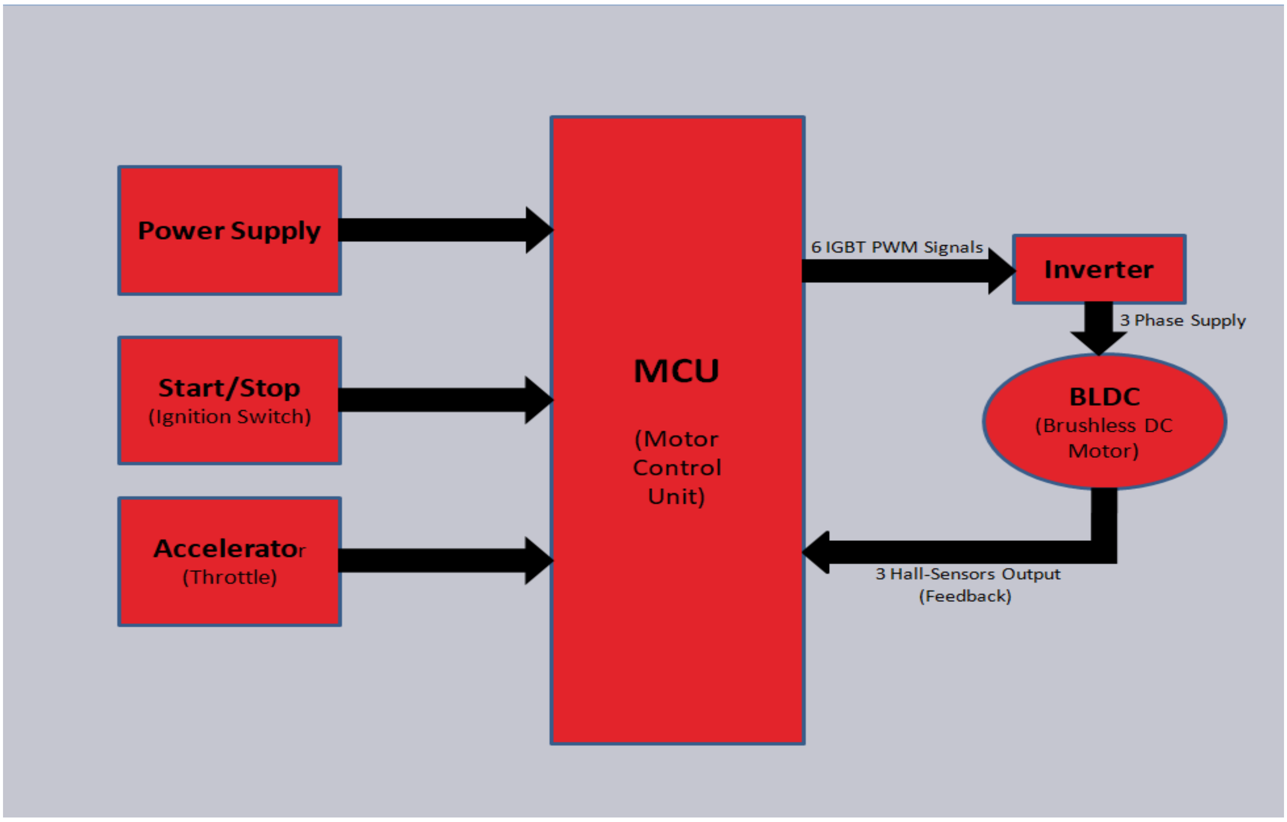

Fig.2 Block diagram of manual setup to test the Motor Control unit

In the closed-loop test, as shown in the above block diagram Fig. 2, six IGBT input signals are provided by the MCU to the inverter for generating a three-phase supply to drive the motor. The motor rotation depends on this three-phase input. For efficient motor operation, the stator windings must be energized in the correct sequence. To achieve this, Hall sensors are employed to detect the rotor magnet's position and send feedback signals to the MCU. Based on this feedback, the MCU generates the appropriate six IGBT control signals for the inverter. Therefore, closed-loop system testing is essential for ensuring the efficient functioning of the BLDC motor.

Figure 2 illustrates the manual test setup used to control and evaluate the Motor Control Unit (MCU) through the VT (Virtualization Technology) system. In this method, test engineers manually operate the brushless DC motor to

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assess MCU performance. This procedure requires manual intervention to vary parameters and signal values such as the accelerator position, PWM signals, and different operating modes of the control unit.

The manual test bench method has the following limitations:

1) Time-Consuming: During the simulation of circuit-continuity FMET fault conditions using a manual breakout box, the test engineer must perform several manual actions, such as locating the corresponding pins or jumper wires and opening or closing the circuits according to the test sequence and timing. In addition, the engineer must log data and vary the test conditions by adjusting certain calibration parameters. This process requires considerable time to create the fault conditions, and if the jumper wires are not connected or disconnected within the specified time, the fault condition may not be established. As a result, the test must be repeated from the beginning, leading to significant time consumption and manual effort.

2) Tests which cannot be done manually: Tests such as "Accelerator Control Tests" require varying the values of the accelerator input and the PWM signals of the IGBTs. The accelerator pedal must transition rapidly from low to high and vice versa within a very short time, and these actions need to be repeated over extended durations. Implementing such tests using the manual test bench method is extremely difficult.

3) Tests which are lengthy and needs timely updates:
    - Traction Control Test – To prevent skidding of the vehicle on slippery roads, the traction control mode of the system must be enabled. This test involves continuous monitoring and analysis of each wheel's speed using speed sensors. These sensors detect wheel speed and apply braking as necessary to maintain traction and avoid skidding.
    - Battery Status Check Test – This test requires periodic monitoring of the battery's current status. During regenerative braking, the battery parameters change, including both operating mode and status values, which must be evaluated as part of the test.

4) Limited available resources / test benches: To enable access across various locations i.e., when the same setup must be used by multiple teams situated at different sites, engineers are either required to travel to the established test bench at centralized test labs or develop new manual test benches at each individual location.

5) During software prototype testing, if any components or sensors—such as Hall sensors—are unavailable and are critical for performing the tests, those tests cannot be executed until all the required hardware components are available.

Additionally, the demand for testing is increasing, and test results must be produced quickly to meet stringent timelines with the available resources and test engineers.

III. AUTOMATED TEST BENCH METHOD

This paper focuses on the automated testing of the Motor Control Unit (MCU) of electric vehicles (EVs) using the Hardware-in-the-Loop (HIL) technique to overcome the limitations and disadvantages of the manual test-bench method described above.

Hardware-in-Loop Simulation Technique: The HIL simulation technique provides an effective and efficient platform for automated testing. The developed HIL automated test bench method consists primarily of an MCU, a set of sensors and actuators, a BLDC motor, and the corresponding hardware combination of an inverter, hall sensors, and in-house developed integrated circuit logic boards. The characteristics of these sensors and actuators are simulated using various Virtualization Technology (VT) cards as part of the HIL automated test bench setup. The automated sequential steps of the tests, according to their test procedures, are programmed using CAPL, while hardware control is managed by CANoe.

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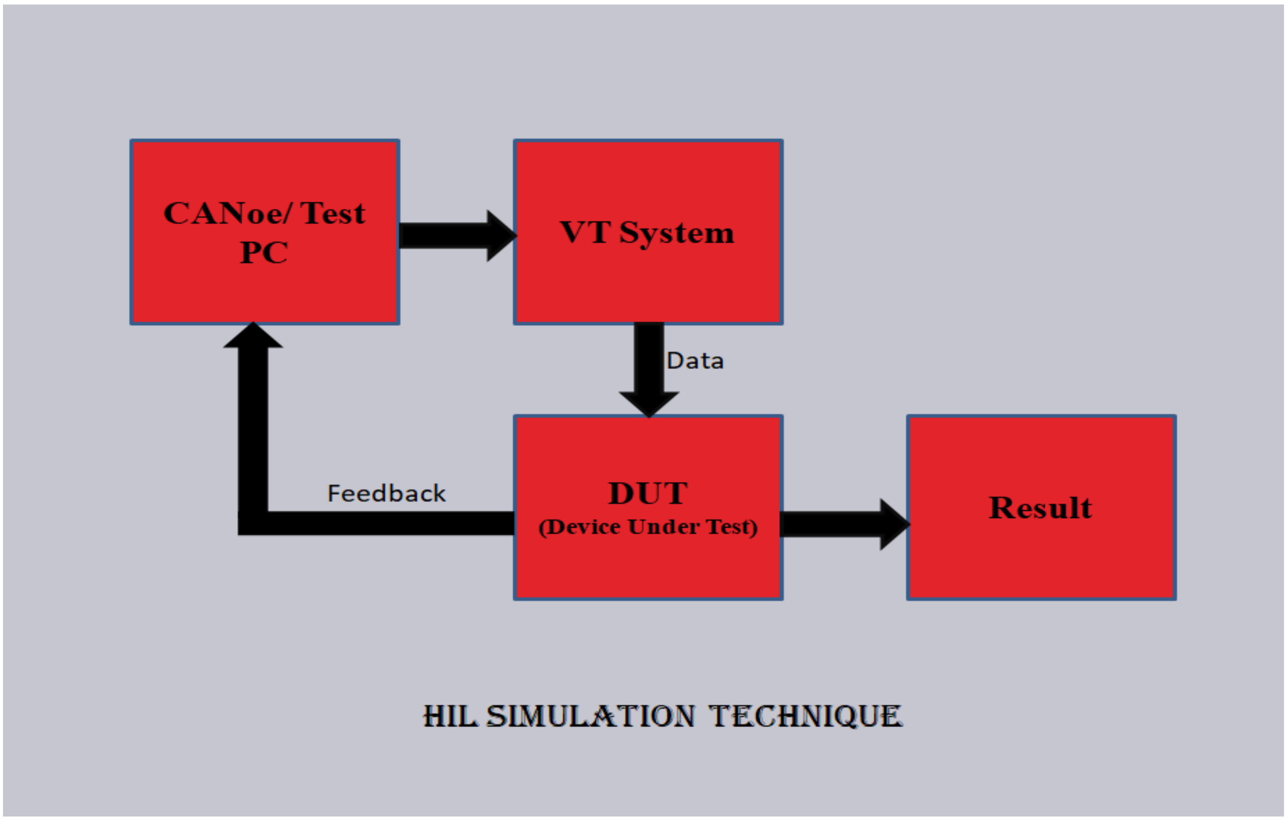

Fig.4 Block Diagram of HiL Simulation Technique

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 / disconnecting of desired and changing the positions of various components.

• To define the transfer function characteristics of various sensors and loads for their simulation, appropriate modelling techniques are employed.

• To develop the required hardware and implementation of that developed CAPL test cases in the CANoe.

Constraints:

• Implementation and realization of the developed CAPL test bench as corresponding hardware and its components are not readily available.

• Very little reference is available for this type of MCU Testing through BLDC motor simulation, so developed automated test bench setup for this from scratch.

Design: Following are the components of automated developed HiL setup with the help of VT hardware and CANoe:

1) Test PC / Computer: To configure and regularly update the tools in the HIL system, the test PC plays a crucial role. It is capable of controlling the entire MCU testing process and also generates reports for validation purposes. The system requires periodic updates to tools and firmware to operate effectively and efficiently. The test PC is used to continuously perform updates and diagnostics during testing and validation. The Vector Tool Platform (VTP) is used to connect the test PC to the industrial PC. It also helps in diagnosing errors or faults in the system and assists in resolving issues.

2) Industrial PC: All the required tools for testing are controlled through the test PC, including CANoe. CANoe is an open-environment tool used to control and monitor the test execution process of the Device Under Test (DUT). It is configured via the test PC to perform specific tests. CANoe is used to continuously monitor the system during testing and enables automation of test steps according to predefined test procedures. The CANoe software directly monitors parameters from the MCU. CAPL is used to develop auto-commanding scripts that control the corresponding components of the VT system, thereby managing the connected sensors and actuators.

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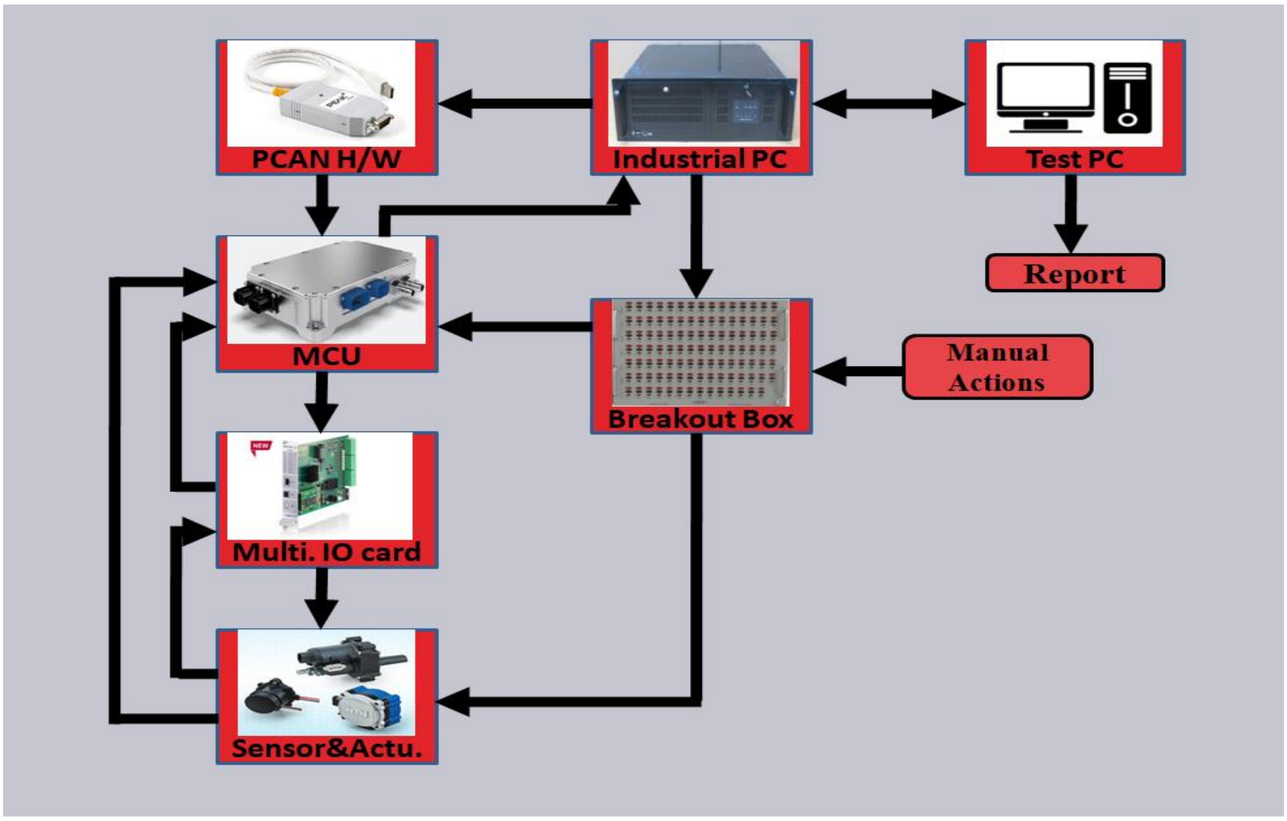

Fig.5 Block diagram of Methodology for HiL

3) Motor Control Unit: The Motor Control Unit (MCU) functions as the central processing unit responsible for all decision-making and control operations within the system. It detects simulated fault codes or conditions, and upon detection, transmits the corresponding fault code over the CAN network, which is connected to the test PC to display the active or inactive status of the fault. The MCU receives user input from the accelerator and regulates the speed of the BLDC motor accordingly. It processes a combination of analog, digital, and PWM signals to control and manage the vehicle's speed. An analog signal, varying in voltage and passing through a 10k-ohm resistance, is used to control motor speed. The inverter, controlled by the MCU, converts DC power into a 3-phase AC supply, which drives the BLDC motor to reach the desired speed. To effectively regulate this speed, six Hall sensors are connected to the BLDC motor, providing rotor position feedback and enabling efficient motor operation.

4) PCAN H/W: It enables communication over the CAN network with other Electronic Control Units (ECUs) to transmit real-time data. It connects the MCU with other ECUs as well as with sensors and actuators to ensure efficient operation.

5) VT5838 (Multi. IO card): This card, known as the E-Machine module, consists of multiple input/output signals capable of simulating the behaviour of a BLDC or electric motor using the VT System platform by Vector [2]. It also has the capability to simulate inverter behaviour to generate a 3-phase AC signal for driving the electric motor. The card can generate digital signals with an input range of -15V to +15V and an output range of -5V to +5V. It is capable of generating various load conditions and simulating both digital and analog signals. Additionally, the card includes an onboard user-programmable FPGA, which can be configured for specific operations.

6) Sensors and Actuators: Many sensors and actuators are used in electric vehicles (EVs) to ensure efficient and smooth operation on roads. The speed sensor measures the vehicle’s speed and sends this data to the dashboard as well as to the Traction Control System (TCS) to help prevent skidding on slippery surfaces such as soil or wet roads. Modern electric vehicles are equipped with regenerative braking systems, which require continuous monitoring of deceleration and braking actions taken by the user. These actions are converted into energy used to recharge the vehicle’s battery. During this process, the 3-phase power supply to the electric motor must be turned off. To achieve this, a switch acts as an actuator, disconnecting the power supply to the inverter and immediately switching the battery to charging mode.

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7) Break-out Box: The breakout box provides the connection between the MCU, power supply, sensors, actuators, and other hardware components. Its primary purpose is to introduce errors or faults into the system to observe the MCU's behaviour under faulty conditions. These faults are manually introduced by test engineers. Banana connectors are used to establish the connections within the system. By removing or breaking any connection, a fault condition is created, allowing the test engineer to validate the MCU's response under such fault scenarios.

Implementation of closed loop technique in HiL for MCU test:

Closed-loop Hardware-in-the-Loop (HIL) simulation for MCU testing requires the simulated behaviour of an electric motor. For this purpose, the VT5838 card is used to simulate the behaviour of electronic components such as the inverter, electric motor, and hall sensor. These components operate in a closed loop for efficient functioning, and the output depends on the input conditions.

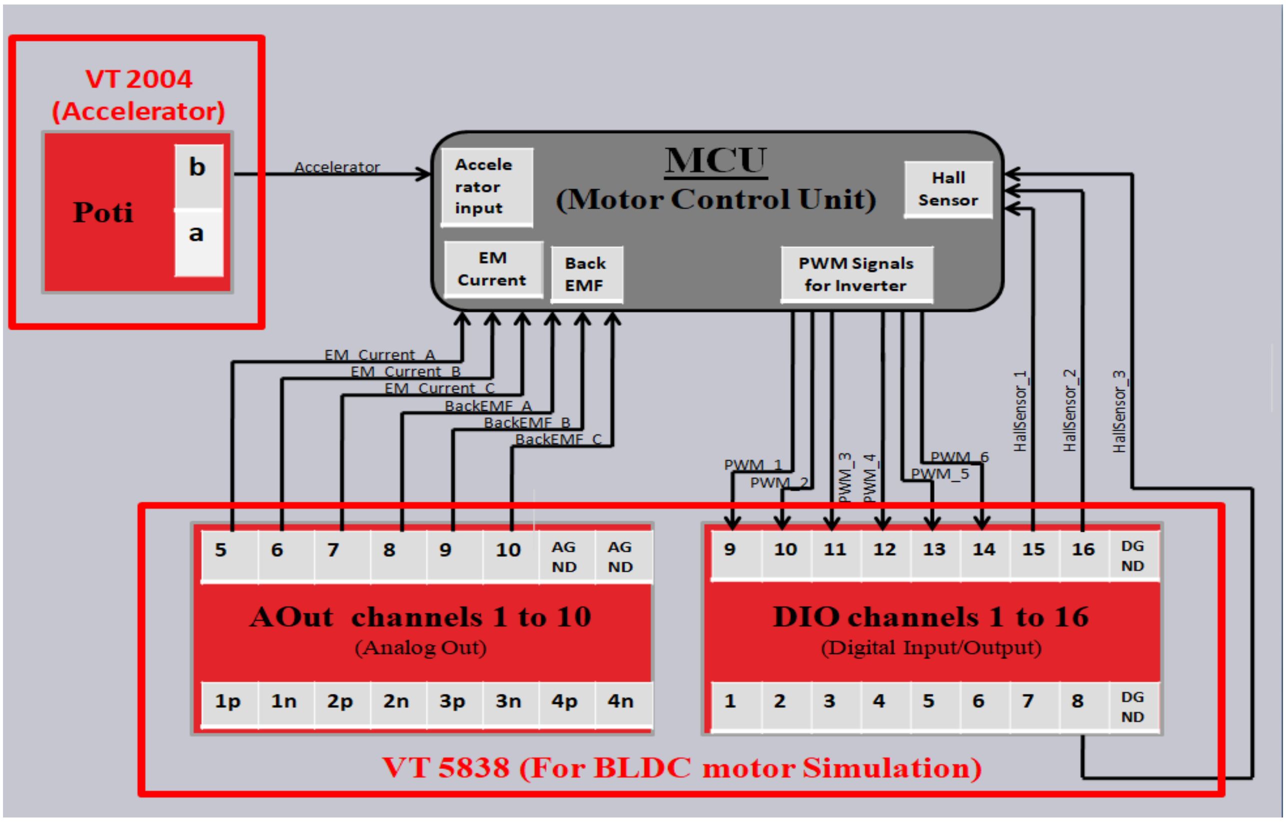

Fig.6 Closed loop technique to test MCU

The closed-loop feedback mechanism of the Motor Control Unit (MCU) and the BLDC motor is illustrated in Figure 6. The primary purpose of the MCU in an electric vehicle (EV) is to regulate and monitor the BLDC motor to control the vehicle's speed. For efficient and effective operation of the electric motor, the MCU must operate with high performance and robustness. The MCU processes various parameters such as electromagnetic (EM) current, back EMF signals, PWM signals, and Hall sensor signals, all of which are crucial for the motor's normal operation.

When the user accelerates the EV to increase its speed, signals are sent to the MCU, which in turn generates PWM signals for the inverter. The inverter converts DC current into three-phase AC current, which continuously powers the electric motor. During this process, the stator windings generate a voltage opposing the supply, known as back EMF. This back EMF helps prevent over speeding of the motor and maintains its speed within a safe range. To reduce the vehicle's speed or bring it to a stop, brakes must be applied. When braking is initiated, the MCU switches from driving mode to regenerative braking mode. In this mode, the electric motor functions as a generator and produces EM current, this is then fed back to the battery for recharging.

For the efficient operation of the electric motor, Hall sensors play a critical role. These sensors provide feedback signals to the MCU regarding the position of the rotor magnets. The logical truth table governing the operation of the BLDC motor, along with the Hall sensors, PWM signals, and three-phase supply, is as follows:

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Hall sensors			PWM signal						3-Phase		
H1	H2	H3	Q1	Q2	Q3	Q4	Q5	Q6	A	B	C
0	0	0	0	0	0	0	0	0	0	0	0
1	0	1	1	0	0	0	0	1	+ve	0	-ve
1	0	0	0	0	1	0	0	1	0	+ve	-ve
1	1	0	0	1	1	0	0	0	-ve	+ve	0
0	1	0	0	1	0	0	1	0	-ve	0	+ve
0	1	1	0	0	0	1	1	0	0	-ve	+ve
0	0	1	1	0	0	1	0	0	+ve	-ve	0

Fig.7 Logical Truth table for electronic components of BLDC motor

As discussed earlier regarding the operation of the MCU and BLDC motor, Figure 7 illustrates the sensor signal values during operation. It demonstrates how the Motor Control Unit (MCU) controls the BLDC motor. To achieve this, the MCU receives inputs from the motor and generates corresponding outputs. Specifically, Figure 7 shows the input-output relationship between the BLDC motor and the control unit. In this process, three Hall sensor signals are provided as inputs to the control unit from the motor. Based on these inputs, the control unit generates six PWM signals. These PWM signals are sent to the inverter, which produces the three-phase output required to operate the motor. To simulate this process, automated test cases are written in CAPL code. These test cases define the set of input and output signals used during operation, as shown in the table above. The inverter operates in a closed loop, meaning the output signals correspond directly to the given input signals. As a case study, a Brushless DC (BLDC) motor and closed-loop simulation test have been considered. The Motor Control Unit plays a critical role in driving an electric vehicle efficiently and effectively. In this setup, the VT5828 card plays a key role in simulating the behavior of the BLDC motor. Additionally, other VT cards are used to simulate the behaviour of various sensors such as the accelerator pedal, brake, etc.

Figure 8 illustrates the steps and algorithm for the Closed-Loop Fault Simulation technique in Hardware-in-the-Loop (HIL) testing. This structured process is used to evaluate the performance and reliability of a Motor Control Unit (MCU) under both nominal and fault-induced conditions. The method begins by powering on the HIL test bench and ensuring that all connected systems—including simulation tools and hardware components—are active. The MCU, acting as the Device Under Test (DUT), is connected via an ODU connector, which forms the hardware interface between the test equipment and the control unit. Next, the connections in the breakout box are verified to ensure that all signal paths are correctly established. This step is essential for accurate data acquisition, fault injection, and monitoring. Once the setup is validated, the test process is initiated. Although initial control may be manual, it is quickly transferred to automated tools such as CANoe for consistency and efficiency. Predefined test scripts are loaded onto the HIL system, enabling it to stimulate the MCU with input signals that replicate real-world vehicle conditions, including speed, torque, and throttle. These simulations are conducted in real time to ensure that the MCU responds as it would in an actual environment. A core component of the closed-loop fault simulation involves the deliberate injection of faults—such as signal loss, short circuits, or sensor anomalies—into the test system. This step is critical for assessing how the MCU identifies, handles, and recovers from abnormal conditions.

The system observes the MCU's behaviour to determine whether it responds appropriately by generating fault codes, entering safe states, or failing to react. After the fault conditions are removed, the MCU's recovery behavior is evaluated. Upon completion of all test cases, the automated scripts are terminated, and the system generates a

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comprehensive test report. This report includes outcomes such as pass/fail status, timing logs, and fault response data. The closed-loop approach ensures a dynamic interaction between the simulated environment and the DUT, enabling high-confidence validation of control logic in safety-critical automotive systems.

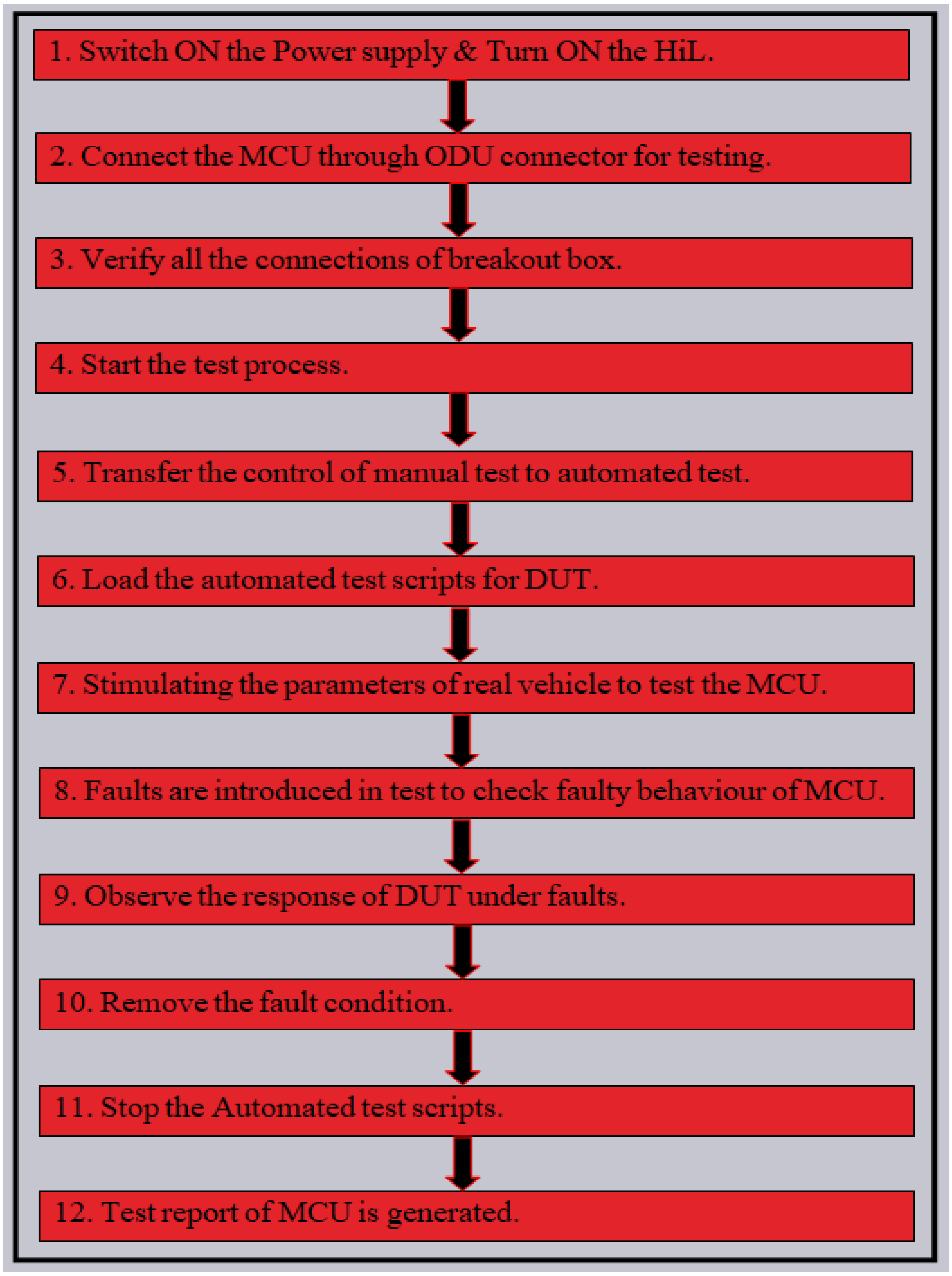

Fig.8 Algorithm to Simulate BLDC motor & Sensors for Closed-Loop Fault Simulation

The proposed algorithm presents an efficient approach for automated testing of a Motor Control Unit (MCU) using a Hardware-in-Loop (HiL) system i.e. Fig. 8. This methodology ensures precise validation by simulating real-world conditions and injecting controlled faults to evaluate the MCU's performance and fault tolerance. The process begins with system initialization, progresses through automated test execution, and concludes with comprehensive response monitoring and report generation. By eliminating manual intervention, the algorithm enhances repeatability, accuracy, and test coverage. This structured testing approach is crucial for ensuring the reliability and safety of MCU applications, particularly in electric vehicle (EV) systems.

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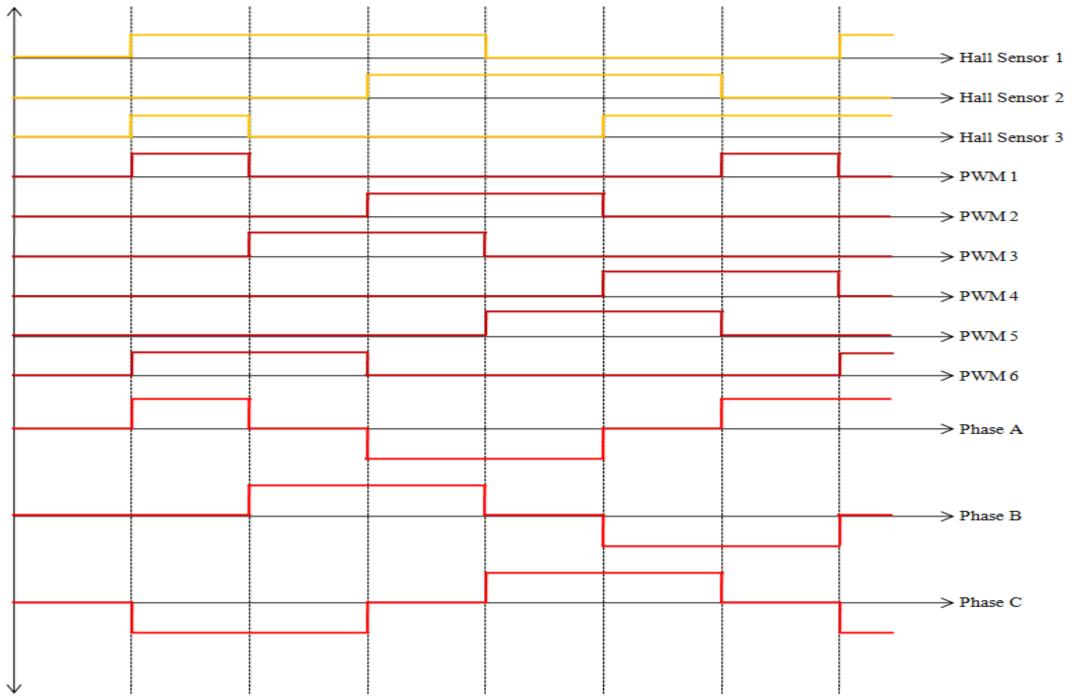

Fig.9 Graph of BLDC motor's parameter under normal condition

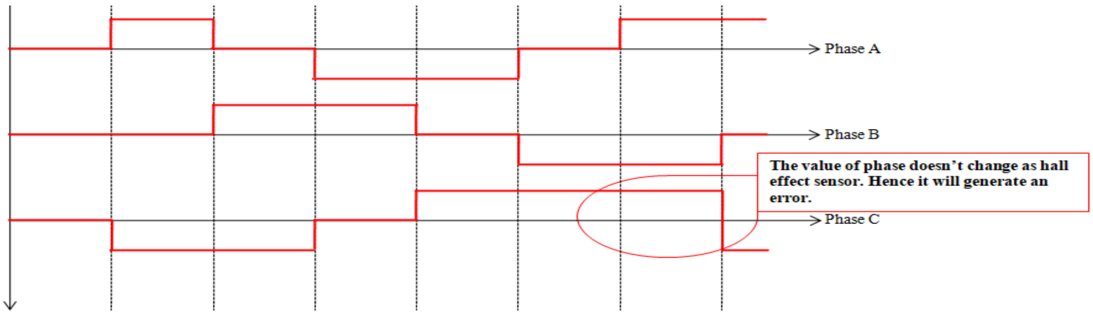

Fig.9 Graph of BLDC motor's parameter after fault injection

The comparison between the normal and fault-injected waveforms of the BLDC motor validates the necessity of incorporating reliable fault detection mechanisms in the MCU firmware. The test highlights that any discrepancy between the Hall sensor signals and corresponding phase transitions can lead to abnormal behaviour shown in Fig. 9, potentially damaging the motor or degrading its performance. Continuous monitoring of phase alignment with sensor feedback is essential to ensure accurate commutation. Upon detecting mismatches, the system should promptly initiate corrective actions. This fault detection strategy enhances system robustness, improves safety, and ensures operational integrity under both nominal and adverse conditions. Hence this test confirms the importance of implementing robust fault detection algorithms in MCU firmware. The system must continuously verify phase transitions against Hall sensor inputs to ensure motor reliability and to initiate corrective actions upon detecting phase mismatches.

RESULTS

- Successfully developed a Hardware-in-the-Loop (HiL) simulation system for testing the Motor Control Unit (MCU) of an Electric Vehicle (EV), eliminating the need for physical EV integration during early validation stages.
- Reduced testing time and cost significantly compared to the traditional manual test bench method by eliminating the need for repeated component removal and installation.
- Demonstrated the effectiveness of automated test scripts in evaluating MCU functionality, improving consistency, repeatability, and fault detection capability.
- Verified that the HiL system accurately simulates real vehicle conditions and allows for controlled fault injection to evaluate MCU robustness under abnormal scenarios.

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- Observed precise phase switching and signal generation by the MCU in response to Hall sensor inputs during normal conditions using the VT-based HiL system.
- Identified faulty behaviour in the MCU when intentional phase mismatches were injected, validating the need for fault detection algorithms in firmware.
- Achieved seamless integration and operation of the MCU with VT modules: VT7001 (Power Supply), VT2820 (Relay), VT2004 (Digital I/O), and VT5838 (E-Machine) to simulate a full BLDC motor environment.
- Demonstrated that the proposed HiL system is modular, configurable, and compatible with various testing interfaces, ensuring adaptability for future EV components testing.

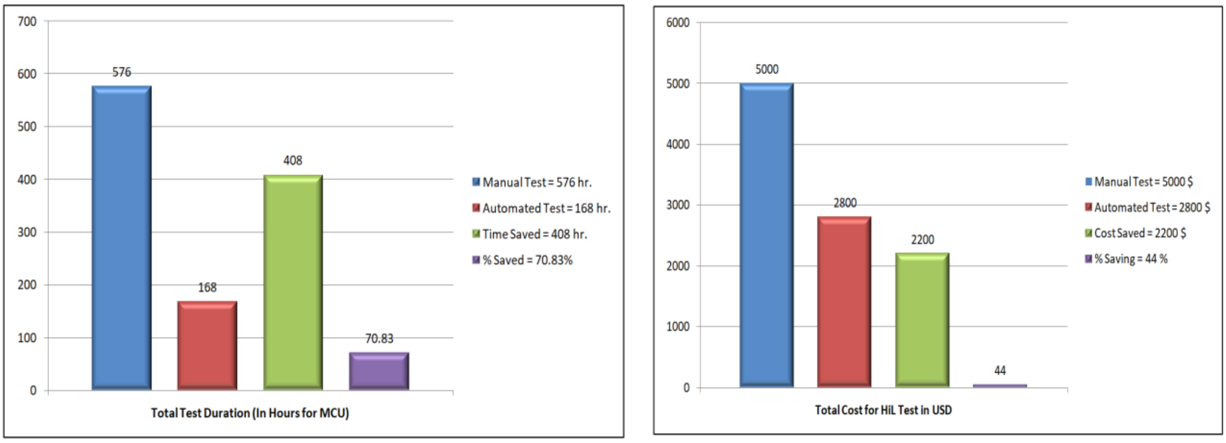

Fig.10 Comparison of savings in testing time and overall cost by HIL automated test bench method over manual test bench method

The results obtained from the implementation of automated test cases using the Hardware-in-the-Loop (HiL) system demonstrate a significant improvement in both testing efficiency and cost-effectiveness i.e. shown in Fig. 10. As illustrated in the first bar graph, the total duration required for manual testing of the Motor Control Unit (MCU) was 576 hours, whereas the automated testing process completed the same validation in just 168 hours. This resulted in a time savings of 408 hours, equating to a 70.83% reduction. Similarly, the second bar graph highlights a substantial cost benefit. The cost associated with manual HiL testing was $5000, while the automated method reduced this to $2800, saving $2200 or 44% of the total expenditure. These findings validate that automated testing not only accelerates the development cycle but also significantly minimizes the financial burden, making it a highly efficient and scalable approach for MCU validation in electric vehicles.

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REFERENCES

[1]. Vector Informatik GmbH, *VT System – Modular Test Hardware for Hardware-in-the-Loop Applications*, Vector Group, Stuttgart, Germany, [Online]. Available: https://www.vector.com (Accessed: Feb, 2024).
[2]. Vector Informatik GmbH, *Multi-IO / E-Machine Module VT5838*, Vector Group, Stuttgart, Germany, [Online]. Available: https://www.vector.com (Accessed: March, 2024).