Advanced Hardware in Loop Concept for Validation of Hybrid / Electric Vehicles

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Abstract— The paper describes the methodology and key concepts which once employed in a Hardware In Loop (HIL) environment can result in precise testing of the Inverter ECUs used in Hybrid Electric Vehicles. The concepts described in this paper aims at bringing the simulated environment generated by HIL systems as close as possible to the real world, thereby leading to in depth testing of the components in Hev/EV in simulated environment and early detection of crucial bugs in the system. Some concepts of failure injection in to the components of Hev/Ev in a simulated environment is also described. A unique methodology is also described in this paper, which can be used to compress lengthy real world drive cycles to a short effective drive cycle , which can be then used for accelerated testing of Hybrid/Electric vehicle systems in lab environment like HIL or on Chassis Dynamometer. An accurate modelling of the real world components of Hev/Ev like electric motor, power electronics , battery etc will lead to a possibility to test and validate close to 80% of the components even before piloting it in the real car and thereby leading to huge savings in cost, time and effort.

Key words: Portland Pozzolana Cement (PPC), Silica Fume, Steel Fiber, Compressive Strength, Compressive Testing Machine

I. Introduction

In comparison to conventional vehicles, there are more electrical components used in electric, hybrid, and fuel cell vehicles, such as electric machines, power electronics, electronic continuously variable transmissions (CVT), and embedded powertrain controllers. With rapid advancement in research, more are the non-linearity and complexities adding to the system. In addition to these electrification components, conventional internal combustion engines (ICE) and mechanical and hydraulic systems may still be present. The dynamic interactions among various components and non-linearities added make it difficult to test newly designed hybrid electric vehicle (HEV), especially in a simulated environment. Prototyping and testing each design combination is cumbersome, expensive, and time consuming. This demands robust modeling and simulation solutions for concept evaluation, prototyping, and analysis of HEVs. In recent years, research in hybrid electric vehicle (HEV) development has focused on component architecture, engine efficiency, reduced fuel emissions, materials for lighter components, power electronics, efficient motors, and high-power density batteries. More the research progresses, more the complexity in testing the hybrid components arises. This means that demand for a robust testing platform for any HEV/EV is on high.

The design of a high dynamic HIL is complex for several reasons [7]. Very high bandwidth of motor drives and very less sampling rates (in range of less than 50 us) of controllers are creating many challenges. This demands the corresponding motor drive emulator should have time response well below the controller sampling rate so it may not differ too much from the real motor drive closed-loop response. The latency between an IGBT gate action and the corresponding motor current slope reversal must be kept to a minimum, since current loop is widely used. A particular case as in synchronous acquisition where analog inputs of the controller are synchronized with the fast gate signals.

In this paper a HIL model is proposed for testing a Hybrid/Electric vehicle Inverter ECU running a PMSM motor using a 6 step IGBT based Inverter circuitry. The Lab-drive is integrated to HIL box and is capable of performing various dynamic test cases. The HIL box is the miniaturized version of the Inverter ECU and basically contains the mother board, housing the main microcontroller board which has the complete logic running on it to switch the IGBT inverter circuitry for functioning the PMSM motor at designed speed and torque. The HV Battery, DC Link Capacitor, Power Electronic and the PMSM motor is modeled in the HIL simulation. To simulate the transient and dynamic use/mis-use cases at component level for electric machine, a high dynamic, transient model of electric machine and power electronics is integrated in Lab-drive. Care has been taken to enhance motor simulation fidelity by importing finite element models. These motor models are equipped to take into consideration about nonlinearities that are ignored in HIL simulations. Inverter and PMSM equation solved in FPGA for very fast current loop dynamics etc. Advantages of FPGA models [6] for application of interest are perfect resolution for high frequency PWM -IGBTgating, good latency etc.

The paper is targeted at optimization of testing period to a minimum possible duration to reduce the cycle time of the product. The paper aims at elucidating the concept with algorithms and plant model and no proprietary codes and data are shared.

First section in the paper describes methodology to convert actual drive cycle from road testing of Hybrid/ Electric vehicle to an accelerated cycle of similar characteristics using a unique methodology using Monte-Carlo algorithm. It is quite evident that Indian driving cycle (IDC) may not represent the actual traffic pattern in many practical situations as actual emission results and fuel efficiency may not completely match with IDC results. The drive cycle in its compressed form is mentioned as real time drive cycle (RTDC).RTDC is derived for different terrains. Based on the percentage time vehicle usage in each terrain, a combined RTDC is formulated to serve as input to vehicle model together with driver inputs. Load cycles for hybrid components are extracted from vehicle model which serves as input for advanced HIL system.

Second section describes the dynamic capability of the labdrive model demonstrating the electromagnetic (FEA) machine model incorporated into it. A benchmark study for a popular hybrid vehicle is done[1]. To preserve the proprietary details, this paper explains the dynamic model of electric/traction motor in HIL module with the support of details from[1]. Electromagnetic model of the motor is incorporated in the labdrive model. Real life test cases like insulation failure, IGBT switch failure, etc can be performed with the model. A demonstration of one of the failure cases is elucidated as proof of concept

Third section explains about the capability of the HIL module in performing dynamic and robust test cases incorporating the inputs from Monte-carlo algorithm, vehicle model and dynamic machine model.A short insight on advantages of FPGA based system over conventional systems is discussed.

II. MONTE-CARLO ALGORITHM BASED ACCELERATED DRIVE CYCLE DEVELOPMENT

A drive cycle is a compressed version of series of data of vehicle characteristics like speed versus time representing actual driving pattern of the vehicle over a defined terrain. The success of generating a proper drive cycle lies in the fact that the generated compressed drive cycle and the actual road drive cycle should match in the basic characteristics, for example average acceleration, speed etc. This actually represents driving behavior for a particular driver for a specific terrain. In literatures and studies, it is mentioned that a vehicle spends its 55% of life time in urban terrain and 35% in highway terrain and 10% in ghats terrain. This scale factor is used in deriving the cumulative drive cycle which spans less than 3600sec.

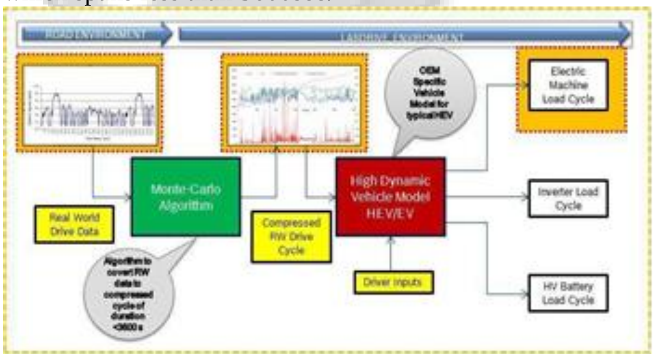

Fig. 1: Drive Cycle Generation

Figure 1 describes the block diagram representation of drive cycle generation. For demonstration, only load cycle for electric machine is explained in this literature.

Monte-Carlo Algorithm is explained in figure 2 as follows,

- Step 1 Collection of real world data consisting of trials over hundreds of hours. Data loggers can be employed here. GPS also is desired to mark the terrain type. Logs are taken for various trial of urban, highway and ghats.
- Step 2 For real time cluster of data, formulate speed-acceleration matrix. Identify the target parameters like standard deviation, RMS value of velocity, acceleration, percentage motoring etc.
- Step 3 Generate small trips called mini-trips for terrain defined conditions. E.g.: for city, a mini trip is defined as start of vehicle to next stop of vehicle.
- Step 4 Define a matrix with same set of target parameters as in step 2 for mini-trips.
- Step 5 Assign terrain defined weightage for each target parameters
- Step 6 Formulate a weighted sum of each mini-trips
- Step 7 Compare the each weighed sum with that of maintrip after optimizing with Monte Carlo simulation. Here we will find most optimized weighed sum. Tool used is Oracel Crystalball
- Step 8 Group the mini trips based on weightage comparison and form the final drive cycle (RTDC)for a particular terrain combining selected mini-trips which are similar to main data.
- Step 9 Speed acceleration matrix of RTDC and main data should represent similar cluster
- Step 10 Repeat the same steps for different terrain. Combine each RTDC for each terrain in the order- Urban-55%,Highway-35%,Ghats- 10%.Form a drive cycle with less than 3600s duration

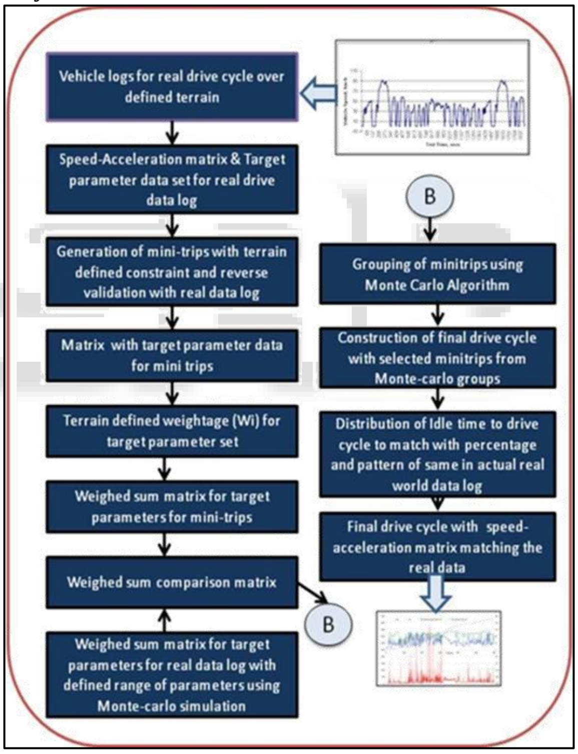

Fig. 2: Monte-Carlo Algorithm

Parameters	Accelerated Cycle	Main Cycle
Time_Idle(%)	12.88	12.97
Time_deceleration(%)	33.46	32.76
Time_acceleration(%)	45.46	46.07
Mean speed(kmph)	22.46	22.87
Max.speed(kmph)	88.56	88.56
Max.acceleration(m/s2)	3.5	3.5
Max.deceleration(m/s2)	-3.8	-3.8
Time_cruise(%)	8.2	8.2
RMS_Speed	23.46	23.86
RMS_acceleration	1.734	1.736
RMS_deceleration	-1.46	-1.47

Table 1: Comparison of drive cycle parameters

Table 1 explains the comparison of accelerated/ compressed RTDC with actual data from main trial.

The drive cycle generated would be given as input to O.E.M specific vehicle model as shown in figure 1 to extract load cycle for hybrid components. Here the vehicle model is not explained to preserve confidentiality

The final drive cycle with hybrid component dynamic software testing plots are as shown in figure 3

III. High Dynamic HIL Motor Model

This section describes a high dynamic machine model integrated into the labdrive model. Previous section elucidated a dedicated load cycle for electric machine which can be used for dynamic software testing in HIL setup. But this isn't possible without a dynamic electric motor model which can perform dynamic or transient tests adding more fidelity to model. HIL drive is integrated with a high dynamic machine model with capability to simulate component level faults. As the machine model is proprietary, we are presenting the concept through modeling a hybrid electric machine based on specifications given in [1].

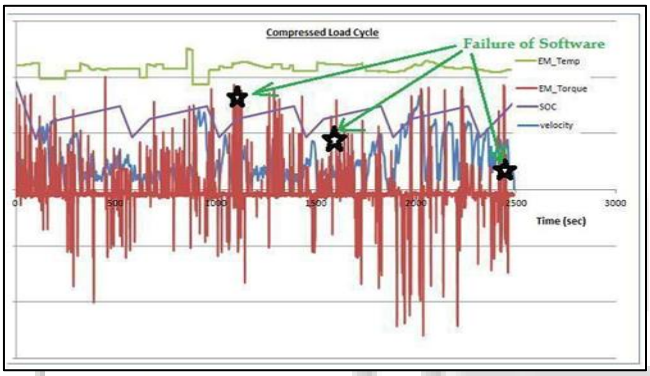

Fig. 3: Real Time Drive Cycle and Dynamic Software Testing

The modeled machine is of a PMSM type with inner rotor configuration. Output power rating is 12.4kW at 144V.Rated torque is140Nm@840 rpm. Figure 4 elucidates the finite element plots of the model. The conditions like toggling effect of rotor or uneven airgap causing harmonics, removal of one of phase wires due to jerks, short circuit of phase wires or stator due to insulation failure etc. can be simulated with this dynamic model. These kinds of failures can be simulated and the behavior of the Inverter ECU can be observed in the proposed HIL setup. The specification for the motor model is given in table 2.

Finite element analysis (FEA) of the machine is done using after-market softwares like JMAG, Ansys Maxwell etc. The analysis of the motor can be broadly classified into three steps[4][5].Basic CAD model, FEA simulations and transient analysis. Finite Element Analysis is performed to do a field study for conditions of saturation, demagnetization etc. The model is subjected to adaptive meshing. For best results tetrahedral meshes are used in 3D FEA. Finite Element Analysis (FEA) is conducted to determine the state of saturation of the stator material. Also it is used to check whether the permanent magnet is demagnetized by electrical loading. This is especially important in case of magnets having lesser coercive force (Hc).Adaptive meshing is performed using tetrahedral meshes for better results. Finite Element results are as shown in Figure 4.Here meshing is very fine at air gap and large meshes are used in areas having least possibility of saturation. If the electrical loading overcomes the magnetic energy, then it will undermine the entire performance of the motor. Finite element analysis is done at no load condition and at loaded state. The actual performance of the motor is given by doing FEA simulations in loaded condition.

Transient analysis is done to know the performance of motor under transient condition.3 dimensional motion analysis is done using electromagnetic packages. The plots of instantaneous torque and input current are given in Fig. 5.

The machine model is capable of performing dynamic tests like IGBT failure, insulation failure, stall-current cases etc. The dynamic and transient curves are as shown in figure 5.Major characteristics like speed vs torque, instantaneous torque vs. time, and winding current vs. time should match with that of actual motor

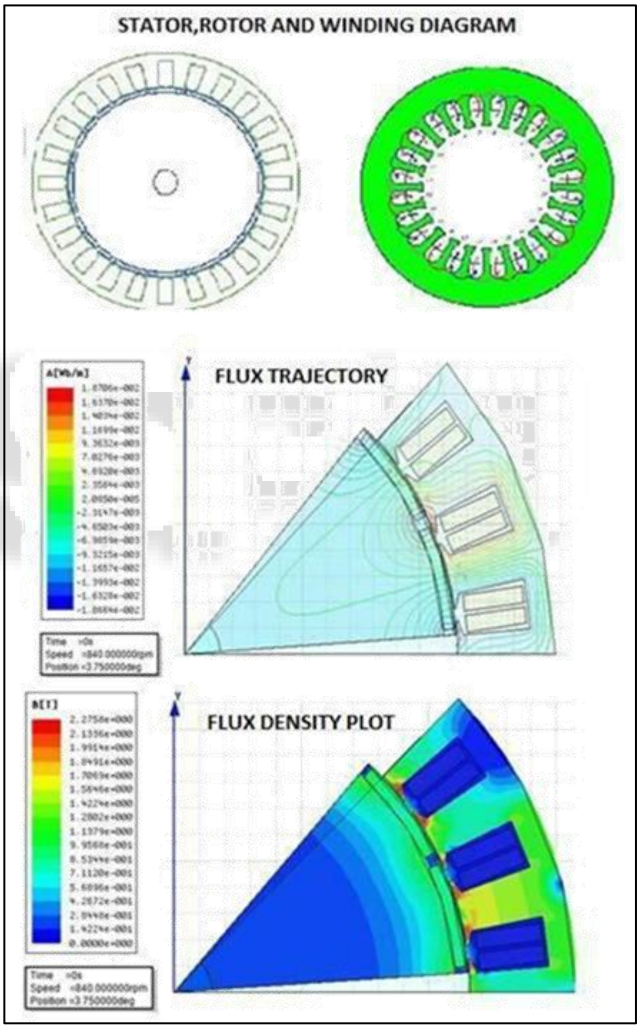

Fig. 4: Finite Element Analysis Plot of PMSM

To validate the machine model fidelity, a test for failure is demonstrated. The motor is set at stall current condition, by increasing the Terrain Load condition on the motor shaft. Once the terrain load torque matches with the motor torque, the motor get stalled and results in drop in motor speed and high stator currents, as the back EMF becomes zero and maximum current (I = V/R) gets injected in stator windings. A screen shot of the testing done in the lab using the proposed HIL System is seen in Figure 6.Due to the motor stall simulation in HIL system the DFCs are set in the Inverter ECU

Rated Output Power (kW):	12.4
Rated Voltage (V):	144
Number of Poles:	16
Rotor Position:	Inner
Number of Stator Slots:	24
Outer Diameter of Stator (mm):	315.5
Inner Diameter of Stator (mm):	232
Top Tooth Width (mm):	15.214
Bottom Tooth Width (mm):	19.3769
Length of Stator Core (mm):	40.1
Air Gap (mm):	1
Thickness of Magnet (mm):	4.46
Width of Magnet (mm):	39.8562
Synchronous Speed (rpm):	840
Rated Torque (N.m):	141.018

Table 2: Simulation Data-E-Machine

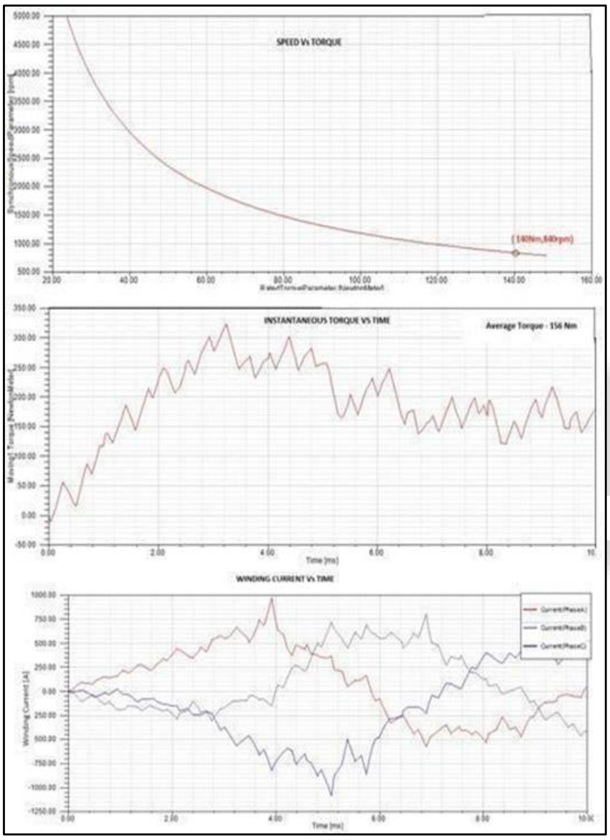

Fig. 5: Dynamic Plots of E-Machine

SW, which helps to validate the behavior of the SW in actual stall conditions in a real vehicle. The table 3 shows the software DFCs popped up when motor is held in stall current state. Figure 7 shows the demagnetization plot as a result of stall current pushing the magnet to operating limits outside the safe operating zone

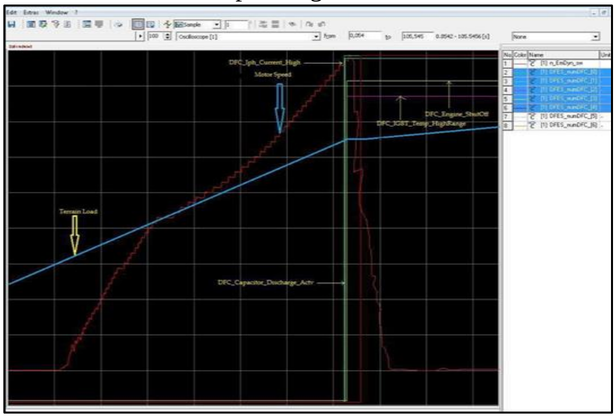

Fig. 6: Effect of Simulating Stalled motor on Inverter ECU Software

IV. DYNAMIC HIL MODEL WITH INTEGRATED MACHINE MODEL

The Inverter ECU which is the main controller of the electric motor in a hybrid/electrical car needs a lot of closed loop sensor signal feedback for example, the rotor position sensor, the 3 phase stator current sensor signals , the power electronic component temperature signals etc to correctly control the electric motor at the desired speed and torque. Testing an Inverter ECU with real HV battery, power electronic circuit(PEU), sensors and real motor is not practical all the time and is more tedious, dangerous(due to presence of HV battery) and time consuming. In this paper the concept of HIL system is presented where only the control board of the Inverter ECU(mother board also known as HIL Box) is real and rest all of the components consisting of the HV Battery, the DC-Link Capacitor, the IGBT based power electronics board, sensors ,electrical motor and the terrain load on the drive shaft is purely modeled in software (for example in MATLAB) .

DFC ID	Description
DFC_Iph_Current_High	This DFC pops up due to High Currents detected on any of the phase of stator winding.
DFC_Capacitor_Discharge_Actv	High Voltage detected on DC- Link capacitor.
DFC_IGBT_Temp_HighRange	High temperature across IGBT causes this DFC to set
DFC_Engine_ShutOff	This DFC sets to indicate immediate shut off of engine and electric motor.

Table 3 :DFCs at out of limit current state

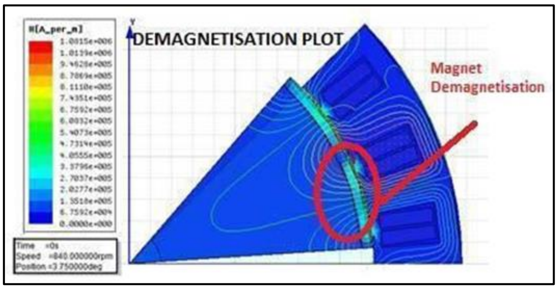

Fig. 7: Demagnetization

The Matlab/FPGA based models are then interfaced to HIL Based hardware modules like DAC, ADC, Digital In/Out etc. to give the accurate and real time closed loop signals back to the Control Board. The gate driver switching pulses coming from the HIL Box is fed via the Digital Input cards present in the HIL system directly to the power electronics model. The output 3 phase voltage signals are generated in simulation environment by the power electronics module based on the gate driver pulses and fed to the Electric Motor simulation block. Electric Motor simulation is conducted in FPGA at nanosecond speeds to give real time motor data and interfaced to Hardware .Using this approach, the controller board gets cleverly fooled to think that it is interfaced to a real electric drive.

The communication from other ECUs are simulated by using CAN or Flexray or similar bus simulations using CAN Controller/Flexray interfaced to PCI slots .Fig 1 shows a HIL System with simulated HV Battery, DC Link Capacitor, IGBT stages, PMSM motor and the Load. Following sensor signals are simulated in the HIL system and fed back to the HIL Box:

1) Position sensor signals , which are directly coupled to the electric motor model and fed via DAC cards in case of resolver sensors.
2) 3 Phase stator current sensor signals , again coupled in real time to the electric motor model giving the accurate values for each of the phases based on current speed and torque of the motor, and fed back via DAC cards to the HIL Box. Current sensors normally have a voltage range of 0-5V and this is taken in to consideration in the hardware.
3) Stator Temperature sensor signals , coupled in real time to the electric motor model giving a voltage range of 0-5V via DAC cards
4) The IGBT temperature of each legs are also simulated by means of getting the IGBT temperature values from the IGBT power electronic model and based on [13] and [14].
5) The HV Battery Voltage sensor getting impacted by the charging and discharging of the battery by coupling with an HV battery model .
6) DC-Link capacitor voltage sensor.
7) All the sensor signals mentioned above are tightly coupled to the FPGA or HIL simulation environment to accurately and on real time send valid closed loop sensor signals to the Inverter HIL Box.

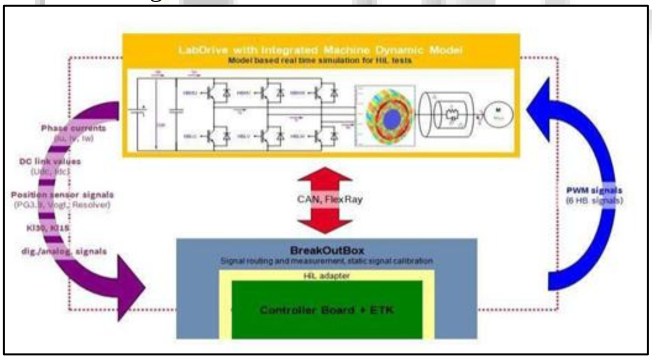

Fig. 8: HIL Module with integrated dynamic machine model

The proposed HIL concept has the capability to inject failures in to individual simulated components and thereby it helps to assess the behavior of the Inverter ECU in these failure situations. Interference signals can also be mapped on to the sensor signals helping in jitter analysis of the sensor signals and impact on the Inverter ECU software.

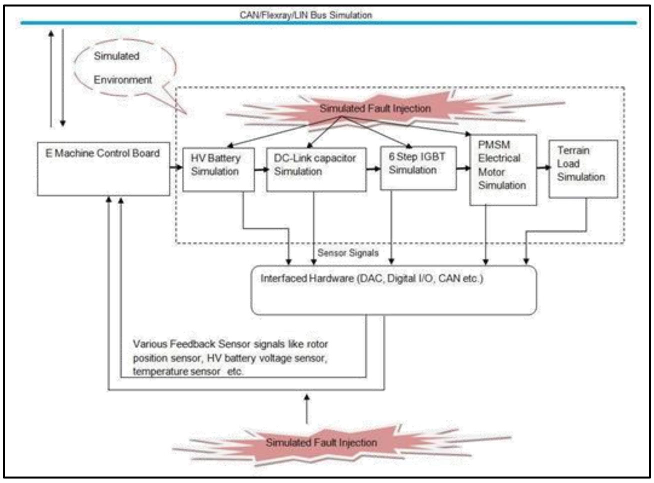

Fig. 9: Block diagram of high dynamic HIL module

By accurately modeling each of the simulated components, it is possible to find out critical errors in the system when a real world compressed drive cycle is simulated in the HIL. Many of the safety critical testing and FMEA analysis can be simulated on the HIL environment and the Inverter ECU performance can be assessed to find the sleeping bugs in the system in a much early stage.

V. SUMMARY

The Paper describes a high dynamic HIL model which is capable of simulation real time test conditions. The paper aims at optimization of testing time to a minimum reducing the life cycle of a product development. The methodology of derivation of load cycle from actual vehicle drive data using Monte-carlo simulation is explained. The dynamic modeling of electric machine required for utilization of the load cycle in HIL and lab drive set-up is mentioned. An integrated labdrive module with the above mentioned capabilities is elucidated. Bosch specific proprietary models are not published, instead the concept is explained with modeling using already published data

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