COMPONENT AND SUBSYSTEM EVALUATION IN A SYSTEMS CONTEXT USING HARDWARE IN THE LOOP

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Abstract: **It is generally acknowledged that Hardware in the Loop (HIL)/Rapid control prototyping (RCP) is a cost and time effective approach to test controllers/components/subsystems in a system context. Argonne National Laboratory has been using HIL to evaluate the potential of a plug-in hybrid battery in a vehicle (battery hardware in the loop). Argonne has also constructed a vehicle platform on wheels to evaluate different power train components on a chassis dynamometer – the Mobile Advanced Technology Testbed (MATT). This paper describes these two HIL projects and gives some preliminary results on 'All electric range (AER)' tests conducted on both HIL platforms. These results are compared to simulation results obtained from Argonne's power train system analysis toolkit – PSAT.**

I.INTRODUCTION

The phrase 'Hardware in the Loop' is generally derived from the practice of testing an electronic control unit (hardware) with a real time computer that behaves like a system (vehicle) in a closed loop. The other end of the spectrum is Rapid Control Prototyping, the practice of testing control software with a real system. Often, both use the same control software development approach.

The current HIL/RCP projects at Center for Transportation Research (CTR) at Argonne National Lab fall somewhere in between, since both projects use some 'virtual components' and some physical hardware components, although in vastly varying degrees. Argonne National Lab is testing a high energy Li-ion battery, in a virtual vehicle environment (Battery hardware in the Loop). This system consists of one major component (the battery) in the loop with a virtual vehicle. The other project is the Mobile Advanced Technology Testbed (MATT). This is a test bench on wheels, with power train components on individual bedplates, mounted on a ladder frame. This project is much closer to RCP, yet involves some 'emulated components'. Battery HIL and the MATT platform are complements of each other – Battery HIL uses a real battery with a virtual powertrain, while MATT is a virtual battery with a real power train. Comparison of battery and vehicle level results between the two HIL set-ups and the PSAT model end up validating the virtual component models and/or understanding the difference between the three. Development of control code/software for the HIL projects is done in PSAT-PRO, an extension of PSAT [1] for HIL/RCP applications.

II. PSAT-PRO

PSAT-PRO, derived from PSAT, provides a framework in Matlab / Simulink for easy transition from modeling (PSAT) to prototyping for any kind of configuration, and is being used for all HIL/RCP activities at Argonne. PSAT-PRO can be used to emulate parts of components using computer models, originally developed for PSAT. PSAT-PRO can be used for the following applications:

1. Real time simulation – The vehicle system controller and the vehicle simulation models are downloaded onto different real time processors which communicate to each other. The vehicle model, which now reacts in real time, can be used to tune the vehicle controller.
2. HIL – A particular hardware component can be tested in a systems context by simulating the remaining power train in real time.
3. Rapid Prototyping – The controller can be integrated into a vehicle control unit; results from the tests can be used to populate the model of the power train and to tune the control strategy and calliberate its variables.

PSAT-PRO has been previously used for various component HIL and RCP experiments at Argonne [2], [3]. Currently, PSAT-PRO is being used for the Battery HIL and MATT experiments, which are described in the further sections.

III. BATTERY HARDWARE IN THE LOOP

Battery temperature and battery state of health are factors which impact battery performance in a hybrid vehicle. The impact is much more pronounced in a plug-in hybrid vehicle (PHEV), which has significant 'electric only' operation, because of the use of a high energy battery which can be charged over-night by plugging it to the wall.

It is important to study the impact of degradation in battery performance on the 'petroleum displacement' of a PHEV. Battery Hardware in the Loop (BHIL) is an ideal tool to evaluate battery performance using an emulated vehicle. BHIL can also be used to modify the vehicle energy management strategy, in order to compensate for (lack of) battery performance at extreme temperatures or due to battery state of health. Since the vehicle is emulated, there is complete flexibility in the vehicle configuration, vehicle class, and the energy management strategy for the vehicle. Thus, using BHIL, a real battery can be evaluated for a variety of vehicle types, configurations and energy management strategies.

Figure 1 shows the conceptual block diagram of the BHIL set-up at Argonne National Lab.

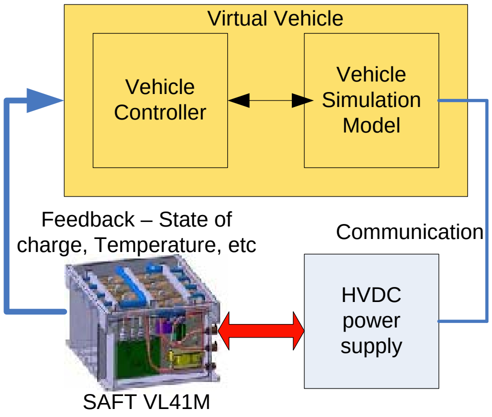

Fig 1.Block diagram of the Battery HIL test

The virtual vehicle subjects the battery to charge and discharge power profiles as if the battery were in a real plug-in hybrid electric vehicle. The high voltage DC power supply is able to sink and source power to and from the battery. Thus, the battery is 'exercised' as if it were in a real vehicle. CAN bus signals from the battery (state of charge, temperature etc) are fed back to the vehicle controller in real time, and used by the vehicle controller for energy management, as in a real vehicle.

For example, the vehicle controller is reading state of charge as a feedback variable from the battery. If the vehicle controller detects a low state of charge, the controller will use the engine more often, as the vehicle follows the vehicle speed trace. The virtual vehicle is following standard dynamometer cycles like the UDDS or the highway. Similarly, the vehicle controller continuously monitors the battery module temperature as a feedback variable, and controls the battery cooling system and the virtual vehicle so as to maintain battery temperature within prescribed limits and also achieve other control strategy goals (maximize on fuel economy etc).

The vehicle model is developed in PSAT and migrated into PSAT-PRO for Battery HIL. In PSAT-PRO, the following changes are made to the original PSAT model:

1. The battery model is replaced by I/O and communication blocks to the real battery.
2. Safety features are incorporated into the virtual vehicle to react to situations of over voltage, under voltage, temperature limits, current limits etc.
3. The Battery has a Battery Management Controller (BMC) which provides feedback on a CAN bus. Specifically, the Battery CAN provides information on :
    a. Minimum and maximum module temperatures
    b. Battery state of charge
    c. Fault alarms
    d. Voltage, Current

   These feedbacks are provided to the vehicle controller. Battery voltage and current are measured externally and are used as a feedback, instead of the CAN bus voltage and current data.
4. The PSAT vehicle management strategy is also modified/tuned to work with a real battery feedback instead of the original battery model used in PSAT simulation.
5. PSAT-PRO is also used to log battery CAN and virtual vehicle data to an ftp server, using National Instruments' Compact-Rio to convert CAN frames into data.

In the BHIL set-up at Argonne, the PSAT-PRO vehicle model and controller are created in a Simulink/Matlab environment and compiled and downloaded into a Dspace system for HIL applications. Figure 2 (a and b) shows the Battery HIL set-up at Argonne.

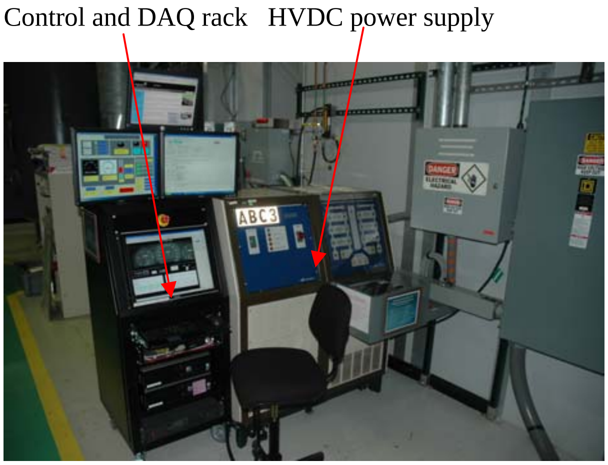

Fig 2(a).Battery HIL control and data acquisition Rack, and high voltage DC power supply

The Battery is located behind the High voltage power supply and the control and DAQ rack. The HVDC power supply is connected to the battery through fuses and contactors. The VL41M is liquid cooled, and is currently being cooled by lab process water. For temperature testing, the battery will be placed in a thermal chamber to emulate hot and cold ambient temperatures.

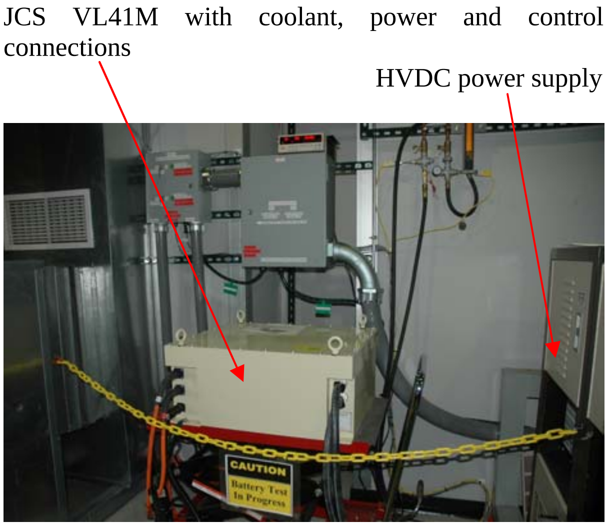

Figure 2(b).The JCS Battery with the power, communication and the coolant connections.

IV. MOBILE ADVANCED TECHNOLOGY TESTBED

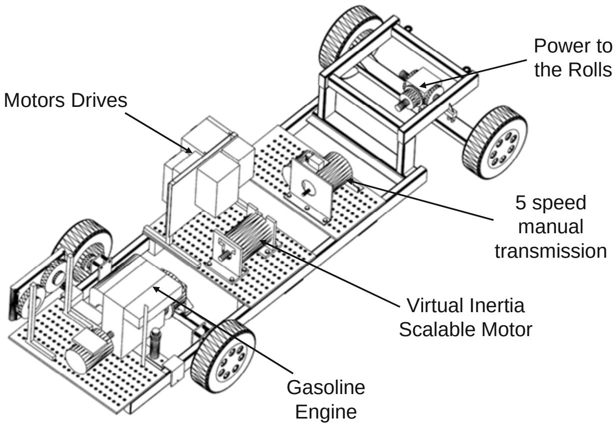

Fig.3.MATT- Mobile Advanced Technology Testbed-Concept

The MATT is closer to the RCP end of HIL activities. Fig 3. Illustrates the concept where individual component plate are mounted on a frame and connected together by driveshafts. Each plate is composed of a powertrain component, such as an engine or a motor, and the supporting subsystem required by that component. This approach allows testing of different technologies in hybrid environments. For example the first engine on MATT is a gasoline engine and the second engine scheduled to be tested is a hydrogen engine.

In this first version of the pre-transmission parallel hybrid configuration shown above, PSAT-PRO©, controls all the component on the hardware level and executes the higher level control strategy. The motor-inverter-battery combination is emulated in the software [4] while a physical electric machine which is plugged in to the wall adds the physical torque in the powertrain from the emulated motor. Fig.4. which shows a picture of MATT on a Clayton dynamometer presents the physical hardware and points out the emulated components.

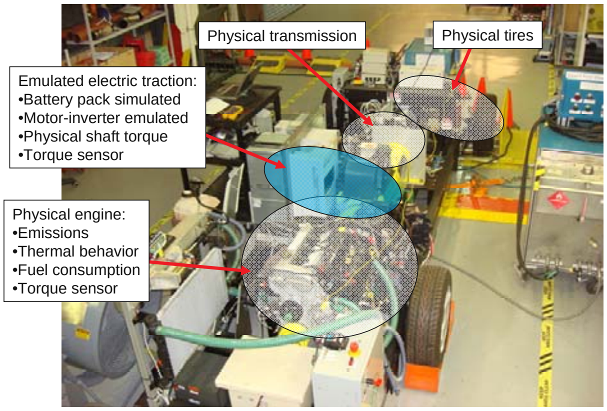

Fig.4.MATT – Physical hardware and emulated components

This HIL platform enables degree of hybridization studies with a single hardware setup. The current configuration can be tested as a conventional vehicle with no electric assist all the way to an electric vehicle or Plug-in hybrid vehicle.

The open plate form also eases instrumentation of the components. Each power train component has a torque and speed sensor recording its performance. So during all times the engine efficiency can be calculated based on the fuel metering and the torque sensors reading.

V. ALL ELECTRIC RANGE STUDY – COMPARISON OF PSAT, BHIL AND MATT RESULTS

A. *PSAT, Battery HIL and MATT – matrix of real and simulated components*

It can be seen from the description of Battery HIL and MATT, that the two HIL platforms are complements of each other, as far as real hardware and emulated components is concerned. The following table shows the distribution of real and virtual (simulated /emulated) components on BHIL, MATT and PSAT.

Table 1
MATRIX OF REAL AND SIMULATED COMPONENTS

	PSAT	**BHIL**	**MATT**
Battery	simulation	hardware	simulation
Electric Motor	simulation	simulation	Emulation
Remaining power train components	simulation	simulation	hardware

B. All electric range tests on PSAT, BHIL and MATT – design of experiment

The biggest difference between charge sustaining hybrids currently in production and the plug-in hybrid electric vehicles is the significant all electric range (AER), i.e. these vehicles can cover a significant distance as electric vehicles. This is possible because of the high capacity battery packs used for the plug-in vehicles. Therefore, the PHEV battery is sized to provide enough energy to run a certain pre-defined AER, for example - 10 miles/20 miles/ 40 miles. The battery and motor power are sized based on maximum power demand, which is a function of control strategy. The battery, motor peak power demand will be different if the vehicle is controlled to run in EV only, or if the vehicle is controlled to run in a blended mode (engine turns ON at a certain power demand threshold).

For a given PHEV battery (SAFT VL41M), an AER test is important to determine:

1. Distance covered in miles (All electric range).
2. Battery capacity depleted (Ah).
3. Energy consumed (Wh).
4. Energy consumption per mile (Wh/mile).
5. Battery temperature rise.

All the above parameters are necessary to benchmark the battery performance (Battery capacity depleted, temperature rise, etc) as well as to quantify the vehicle energy demand (Wh/mile). AER tests are also important to quantify PHEV battery requirements [5].

To determine the AER of a PHEV, the vehicle (in PSAT, BHIL and MATT) follows consecutive urban drive cycles (UDDS). The initial SOC of the battery, at the start of the test, is 90%, and the test is stopped as the SOC reaches 30 %. At this low state of charge, the vehicle would run like a conventional hybrid, and would no longer be in a electric only mode.

The focus of this paper is to compare the AER results from PSAT, BHIL and MATT. Also, the AER results comparison will validate the following:

1. Virtual vehicle model in BHIL
2. Simulated Battery model and emulated motor on MATT
3. Battery and power train model in PSAT

Tables 2 and 3 provide information on the specifications of the JCS VL41M and the vehicle. It should be noted that PSAT, BHIL and MATT have identical energy management strategies.

Table 2
MAIN SPECIFICATIONS OF THE VL41M BATTERY

Capacity	41 Ah
Operating Voltage range	194.4 – 288 V
Peak discharge power	60.2 kW at 50% SOC for 30 s
Operating Temperature range	10 to 40 degrees C, liquid cooled

Table 3
VEHICLE SPECIFICATIONS

Vehicle configuration	Pre-transmission parallel
Vehicle Mass	1325 kg
Coefficient of Drag,	2.06 square meters
Frontal Area	0.31
Electric Motor	UQM, 75 kW peak power
5 speed Manual Transmission gear ratios with final Drive	13.11,8.21,5.56,3.95,2.95

Since the comparison is on Electric only results, engine specifications for the vehicle have not been provided.

C. Results

The following plot (fig.5) shows the decrease in state of charge of the Vl41M battery/battery model as a function of time for an AER test. The state of charge drops from 90% to 30% in about 3 urban cycles.

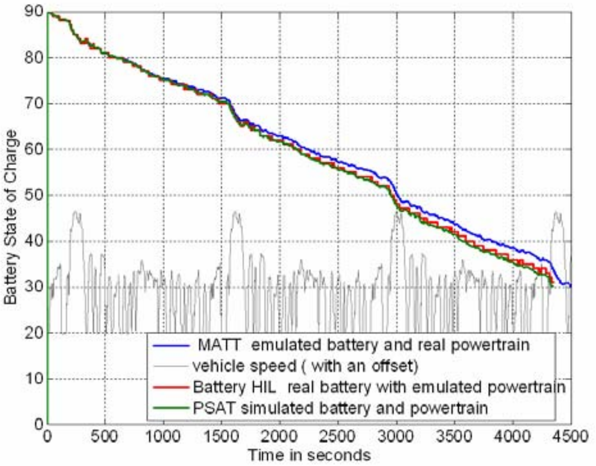

Fig.5.Battery Discharge from 90% to 30% for consecutive urban cycles in EV mode – MATT, BHIL and PSAT.

Table 4 shows the comparison of the results for the AER simulation in PSAT, testing on BHIL and emulation on MATT.

Table 4
AER RESULTS

	PSAT	BHIL	MATT
Distance (miles)	23.4	23.5	25.8
Energy (kWH)	6.2	6.4	6.2
Wh/mile	266.5	273	241.5
Battery capacity discharged (Ah)	24.6	24.3	24.4

In addition, Figure 6 shows the temperature rise of the Battery modules over the AER of the SAFT Vl41M from the BHIL test-

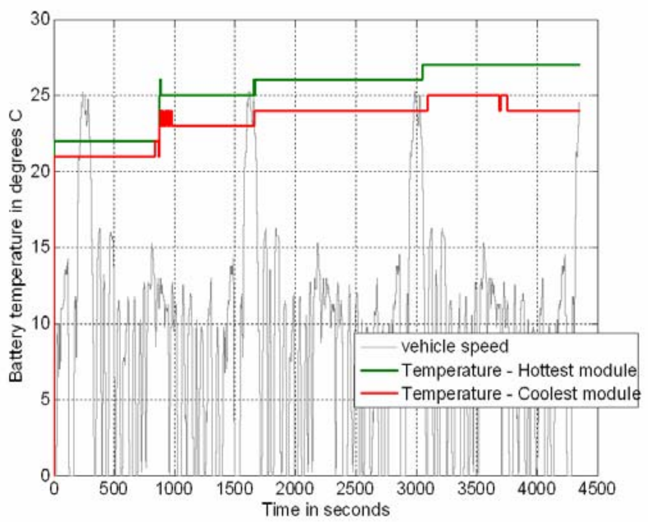

Fig.6.Rise in module temperature over the AER test

It can be seen that the PSAT and BHIL results for Wh/mile are close (within 5 %) but the results of MATT are slightly lower (by 9%) as compared to PSAT simulations, and about 10 % as compared to BHIL. While it is impossible to find out every reason for the differences between the three, couple of reasons could be identified.

D. Explanation of difference in Wh/mile results between MATT and PSAT/BHIL

1. The electric motor on MATT is mechanically coupled to the 5 speed manual transmission, without any mechanical clutch in between. During an up-shift, say from gear 1 to 2, the motor should reduce speed so that its speed matches with the shaft speed downstream of the transmission, so that the shift from 1st to 2nd is complete and transfer of traction torque to the wheels from the motor is possible. Due to the inertia of the motor, it takes time for the motor to slow down and match the shaft speed downstream of the transmission. This results in a shift time of over a second and MATT loses the vehicle trace. In order to overcome this problem, the vehicle controller forces the motor to match the shaft speed downstream of the transmission by providing a large negative (breaking torque) and actively controlling the motor speed to match the speed downstream of the transmission. This negative torque results in a large charging current to the emulated battery, for a period of about half a second. This current spike is shown in figure 7. This current pulse occurs at every up shift, with a net result of charging the battery. It should be noted that a positive torque (current) pulse is applied by the motor (battery) during a downshift. But because of the shift strategy of MATT, downshifts generally occur when the vehicle is close to a stop, which implies lower speed differences between the motor and downstream of the transmission. Blending of the mechanical brake at low speeds also dilutes the effect of a positive torque pulse.

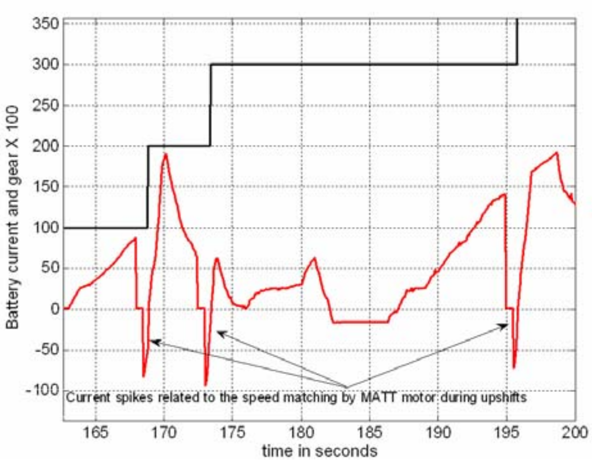

Fig.7.Negative current to the battery during the speed matching of MATT motor for a shift

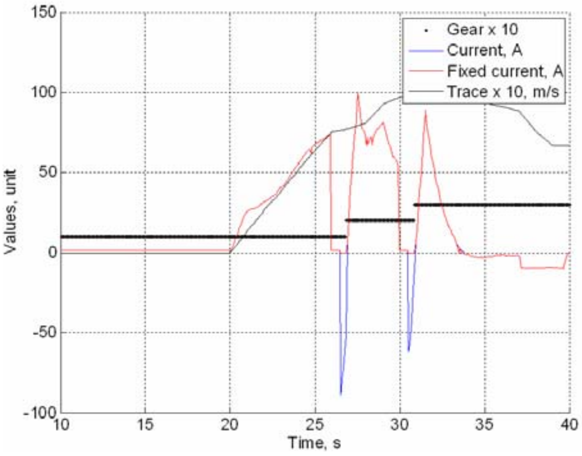

Fig.8.MATT Battery current profile after eliminating the current pulses during shifting

2. Another difference between BHIL/PSAT and MATT is the shift strategy (schedule). In order to have apples to apples comparison, the virtual vehicle in PSAT was simulated using the MATT shift schedule. Comparison of PSAT-Wh/mile after changing the shift schedule and MATT- Wh/mile after deleting the shift current pulse is shown in Table 5.

Table 5

WH/MILE COMPARISON BETWEEN PSAT AND MATT AFTER CHANGES IN PSAT SHIFT SCHEDULE AND MATT AH CALCULATION

	PSAT	MATT
Wh/mile	260.05	249.9

The Wh/mile values are within 4% of each other. Unfortunately, due to time constraints, it was not possible to repeat the BHIL AER test with the MATT shift schedule. Based on Table 4, the BHIL AER test Wh/mile is more than PSAT Wh/mile by 2%. Assuming this difference remains constant between PSAT and BHIL, the Wh/mile difference between MATT and BHIL, with the changes in shift strategy on BHIL could be estimated around 6%.

Further investigation will be done to evaluate the cause for the difference in the Wh/mile numbers. Possible reasons for the difference in numbers are:

1. Reduction in component losses with a rise in component temperature (transmission, wheels) might account for lower Wh/mile numbers on MATT.
2. The AER test was conducted for an SOC window from 90% to 30%. The SOC for BHIL was predicted by the BMC, while the SOC for the battery model in PSAT and MATT was calculated using current integration.

VI. CONCLUSIONS

From the AER test results above, it can be concluded that

1. The Battery models used in MATT and PSAT co-relate closely with the actual battery in BHIL
2. The virtual vehicle in PSAT and BHIL is representative of the real hardware on MATT in terms of losses and effort and flow numbers (engine not considered).
3. The Wh/mile results for AER test on PSAT, BHIL and MATT are within 6% (Difference between Wh/mile values for MATT and BHIL is estimated to be less than 6%).

One can thus conclude that the complementary virtual and real components on MATT and BHIL mutually validate each other as a power train system. The analytical simulation performed in PSAT also matches closely with the HIL results.

VII. FUTURE WORK

The hardware in the loop facilities at Argonne will be used to investigate critical bottlenecks in the introduction of Plug-in hybrids to the market. BHIL will be used to consider impact of battery temperature and battery state of health on petroleum displacement, while MATT, with a real engine, will study issues related to cold start emissions for Plug-ins.

VIII.ACKNOWLEDGEMENTS

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