This is the Author´s Pre-print version of the following article: *I. A. Diaz-Diaz, Y. A. Zuñiga-Ventura, I. Cervantes and N. Villa-Villaseñor, "Design of a Test Bed for Teaching/Research Purposes in PHEVs," IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, Washington, DC, 2018, pp. 3021-3026.* To access the final edited and published work is available online at: https://doi.org/10.1109/IECON.2018.8591384

Design of a test bed for teaching/research purposes in PHEVs

Irwin A. Diaz-Diaz and Yuz A. Zúñiga-Ventura
Applied Mathematics Division
Institute for Scientific and Technological
Research of San Luis Potosi (IPICyT)
San Luis Potosi, SLP, Mexico
{irwin.diaz,yuz.zuniga}@ipicyt.edu.mx

Ilse Cervantes
Research Center of Applied
Science and Advanced Technology
CICATA-Queretaro
Queretaro, QRO, Mexico
cervantes.c.ilse@gmail.com

Noé Villa-Villaseñor
I. T. Electronics and Control,
Advanced Technology Center
(CIATEQ)
San Luis Potosi, SLP, Mexico
noe.villa@ciateq.mx

***Abstract*—In this paper, the design of a measurement system for teaching and research purposes in plug-in hybrid electric vehicles is presented. The implemented measurement system monitors the interest variables such as current, voltage, power consumption, battery temperature and state of charge, among many others. The test bed uses a Controller Area Network with a proposed protocol for each device. The developed system is reconfigurable allowing to test different powertrain configurations. Also, the system can be useful in the implementation of control laws, energy management strategies or vehicle-to-grid or to-home applications.**

***Keywords*—CAN bus, Plug-in Hybrid Electric Vehicle, energy storage system**

I. INTRODUCTION

Due to their lower emissions and energy consumption than internal combustion engine vehicles, hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and battery electric vehicles (BEV) have a considerable potential to decrease climate change (reducing CO_2 emissions) and struggle energy sustainability. Therefore, governments, automotive manufacturers, e.g., Toyota and Nissan, energy corporations, the academic community, among others have been pushing to popularize the expansion of the PHEV [1]. PHEV development and manufacturing are being more acceptable as battery technology advances and power electronics components enhance profitably to mass production. Governments have been putting much effort into stimulating the establishment and penetration of advanced electric drive vehicles into the market. The U.S. Department of Energy projected that about 1 million PHEVs would be on the road by 2015 and 425 000 PHEVs would be sold in 2015 alone [2]. The Electric Power Research Institute estimated that 62% of the whole U.S. vehicle fleet would consist of PHEVs by 2050 using a moderate penetration scheme [3]. Besides, many complications have restricted the demand for the electric vehicles. A significant impediment for the EV acceptance is their restricted driving range compared with internal combustion engine vehicles, range anxiety [4]. Therefore, PHEV charging systems must adequately be deployed to lighten range anxiety adequately. In spite the use of PHEVs is advantageous because of emission-free, their market penetration is limited by one disadvantage, i.e., the energy storage system (ESS); usually, batteries are used as an ESS. Unfortunately, the battery life cycle is notably limited in PHEV because of the stress produced by many charge-discharge operations. The efficiency and all-electric range of the PHEVs depend on the capability of their ESS. The essential characteristics of vehicular ESS include energy density, power density, lifetime, cost and maintenance [5]. Batteries and UCs are the most common options as an ESS. Fuel cells (FC) constitute the most suitable solution to extend the vehicle autonomy with zero emissions; furthermore, their tank can be filled in short periods of time, analogously to conventional vehicles [6], but their longtime constant limits its performance on EV. As a possible solution to enhance the range and the lifetime of the battery in PHEVs as well as overcome the drawbacks of each energy source, hybrid energy storage systems, using FC, batteries, and SC, have been widely proposed for EVs and PHEVs as an ESS [7]–[11].

Currently, with the arising concept of the smart grid, PHEVs are playing a new function, i.e., energy transfer with the power grid. PHEVs are not only capable of taking energy from the grid while the batteries are recharging but also supply energy back to the grid by a bidirectional charger in a concept called as vehicle-to-grid (V2G) or vehicle-to-home (V2H) connection. The V2G concept can improve the performance of the electricity grid in areas such as efficiency, stability, and reliability. However, the efficiency of energy conversion could become an issue in this power flow [12]. Although V2G operation can reduce the lifetime of vehicle batteries, it is projected to become economically viable for vehicle owners and grid operators [13]. In order to provide such evidence, researchers have proposed power electronics interphases between EV, HEV, PHEV, and the grid, targeting Grid-to-Vehicle (G2V), Vehicle-to-Grid (V2G), and Vehicle-to-Home (V2H) [14]–[17].

As previously mentioned, considerable research has been performed on PHEVs. Nevertheless, the educational and personnel regarding PHEVs need to meet the current and future demand. As PHEVs demand increases, there will be a massive requirement for qualified education and technical training for PHEV engineering. Therefore, engineers must have a diversified knowledge in the field of electronics, mechanics, hardware and software design, as well as industry-related technologies, e.g., standardized communication protocols in the vehicles. A few publications about PHEV education can be found in the literature. In [18] a demonstration unit of a PHEV for educational purposes is developed. The proposed unit uses a portable generator coupled to a 3-phase AC inductor motor. A virtual laboratory for E-learning purposes for an electrical drive train of HEV is presented in [19]. Two educational frameworks designed for students with a specialization in vehicle mechatronics are proposed in [20]. Unfortunately, no one of the mentioned systems is reconfigurable, only attend a specific demand.

In this paper, a reconfigurable test bed capable of demonstrating, simulating as well as teach different powertrain configurations, energy management strategies (EMS) and control laws is proposed. The test bed could help to train future generations of young engineers such as electrical, electronics and mechatronics students to understand the theory, configuration, control strategies as well as particular concepts of the PHEVs such as regenerative braking, V2G and smart grid. Also, the implemented test bed could be attractive to the research community.

The rest of the paper is organized as follows. Section II describes the proposed educational system architecture. A description of the CAN network and protocol requirements are presented in Section III. An explanation of the signal conditioning circuit is given in Section IV. In Section V, the laboratory evaluation of the platform, as well as the educational experiences, are given. Finally, Section VI presents conclusions of the developed work and future work.

II. PROPOSED EDUCATIONAL SYSTEM ARCHITECTURE

Due to the test bed will be used for educational and research purposes, it must be scalable and reconfigurable to test different powertrain configurations as well as EMS. The interest variables such as voltage, current, the temperature in the SC, batteries or CD/CD converters must be measured, monitored and sent to an electronic control unit (ECU). The ECU must be able to save the collected data to perform an offline analysis. State of the art for EVs and HEVs with a focus on architectures and modeling for energy management can be found in [21]. For the sake of simplicity, consider a PHEV with the powertrain given in Fig. 1. It is worthy of notice that other configurations presented in [21] can be carried out in the proposed system since a reconfigurable system has been considered. As we can see, the system has two different sources, a battery stack and an SC. In order to establish a DC-link for the motor drive, each energy source uses a DC/DC converter. Such configuration allows the control of shared power as well as its rate of change. An estimation of the required power at the wheels must be carried out before to develop an EMS for any PHEVs.

Monitoring and sent all the interest variables can represent a problem because of the addition of more wires to the vehicle. Added wiring increases vehicle weight, lowers performance and makes adherence to reliability standards difficult. For an average well-tuned vehicle, every extra 50 kilograms of wiring increases fuel consumption by 0.2 liters per 100 km traveled. One way to avoid the use of excessive load into the car is to use a Controller Area Network (CAN). CAN is a two-wire, half-duplex, high-speed serial communication protocol developed by Robert Bosch GmbH. Frequently, a CAN is used to provide communications between network nodes without loading down the system microcontroller (μC), also is widely used in the automotive world for the communication of different devices like electronic engine control, chassis, car unit, safety devices, comfort management, among many others. CAN networks are usually deployed in the safety-critical application in vehicles. In the automotive industry, the connector used to access the CAN buses on a vehicle is the SAE J1962 (on-board diagnostics, OBD II). CAN protocol supports distributed real-time control with very high data integrity and communication speeds of up to 1 Mbps. Using a CAN network boost the opportunity for multidisciplinary learning focused on a real case study, also the students comprehend and become familiar with the fundamentals of the development procedure of an automotive ECU.

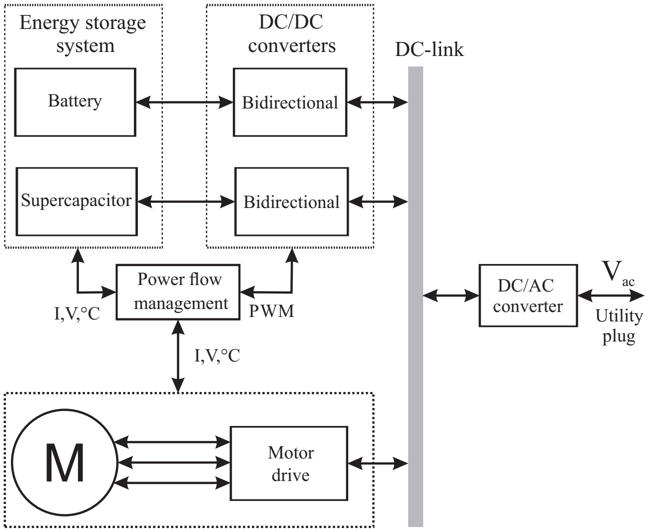


Fig. 1. Proposed system.

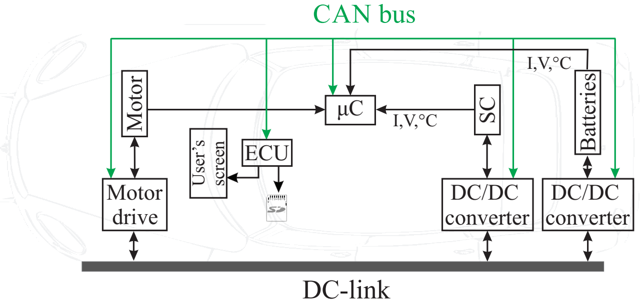


Fig. 2. Proposed CAN distributed system.

III. CAN NETWORK AND PROTOCOL REQUIREMENTS

A block diagram of the proposed network is shown in Fig. 2. This typical CAN network guarantees the cross-communication of each node to the ECU, similar to any commercial automobile with the OBD II system. Each slave must send a state message to the ECU; then, the ECU address a response to the node. Usually, the main functionality of the ECU is straightforward, and its implementation is irrelevant. Nevertheless, when the ECU must identify log and handle errors detected by the nodes, the task could become a challenging problem to solve.

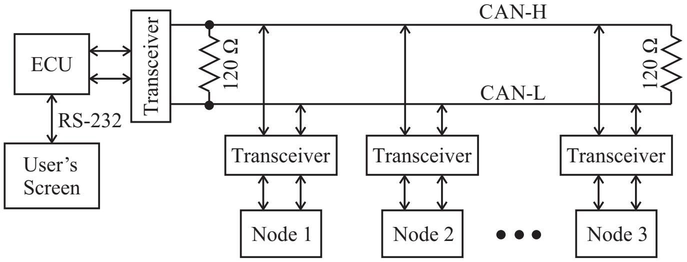


Fig. 3. CAN bus with nodes.

A. CAN requirements

All CAN implementations have a standard structure, consisting of an ECU (host μC), CAN protocol controller and CAN transceiver which interface is the between the CAN protocol controller and the physical wires of the CAN bus lines (see Fig. 3). However, there are differences in the manner of unification of the components mentioned above. CAN nodes can either use a CAN transceiver to interface to a μC or a CAN transceiver embedded into the μC.

The test bed must take into consideration the limitations of a real vehicle such as space, size, appearance, among others. For distances less than 20 m, the CAN bus has a maximum data transfer rate of 1 Mbps. Approximately, less than 20 m of the communication cable long is required to run around a compact vehicle once. Therefore, the maximum data transfer rate is used to communicate the nodes to the ECU.

B. Proposed CAN protocol

In order to communicate the ECU with the powertrain subsystems, a CAN-based communication protocol is established, it consists of commands towards and from the powertrain to transmit the required variables for the EMS as well as the status of the components. In this way, real-time communication can be established for controlling, monitoring as well as performing failure location and detection at the same time. Among the transmitted information are temperature, alarms, converter demanded current and batteries voltage, among many others. Let us consider the batteries; their status must be monitored to avoid over-charge, -discharge or -temperature in the batteries. During the monitoring process, the status is communicated to the ECU. The batteries node plays a vital role in the application because the messages from the batteries node have a significant impact on the energy efficiency and battery's life. The commands used to communicate the batteries to the ECU are shown in Table I. Also, Table II presents the commands selected to communicate the ECU to the batteries. In Table III, the commands used to communicate the SC to the ECU are shown. Notice that the current in the SC can change the direction, when the SC is supplying energy to the DC-link, the current is positive, when the SC is receiving energy from the load (regenerative braking), the current is negative, that is the reason for the positive and negative values of the current in Table III. The chosen units for the voltage and current (10 mV and 10 mA, respectively) allow a maximum measurement of 655.36 V and ±327.67 A. The rest of the protocol is not presented here due to the commands used for the other devices are similar to the presented in Table I and III. Each subsystem of the powertrain has been assigned with an alarm flag, e.g., sensor failure, high temperature, among others, some of them can stop the functioning of the vehicle, e.g., a high temperature in the battery stack will force to turn it off.

TABLE I. CAN PROTOCOL FROM BATTERY TO ECU.

Battery to ECU	Data	Range	Units	CAN ID
Byte 0	Voltage LSB[†]	0 to 65536	10 mV	0x0A0
Byte 1	Voltage MSB[‡]			
Byte 2	Current LSB	0 to 65536	10 mA	
Byte 3	Current MSB			
Byte 4	Temperature	0 to 255	*C*	
Byte 5	SoC	0 to 100	%	
Byte 6	Overvoltage warming	0 to 1	on/off	
	Voltage sensor failure	0 to 1	on/off	
	Overcurrent shut down	0 to 1	on/off	
	Current sensor failure	0 to 1	on/off	
	Over temperature shut down	0 to 1	on/off	
	Temperature sensor failure	0 to 1	on/off	
	Overcurrent warming	0 to 1	on/off	
	Low SoC warming	0 to 1	on/off	
Byte 7	Available bits			

[†] Less significant bit.
[‡] More significant bit

TABLE II. CAN PROTOCOL FROM ECU TO BATTERY.

ECU to battery	Data	Range	Units	CAN ID
Byte 0	Command to battery	0 to 1	on/off	0x01A
	Failure confirmation	0 to 1	on/off	
	Available bits			

IV. SIGNAL CONDITIONING CIRCUIT

A signal conditioning circuit is built to measure and to adapt the current and voltage levels of the batteries and SC to the input voltage level allowed by the analog-to-digital converter (ADC) of the μC, PIC18F2680. The PIC is the interface between the analog and digital signals. The acquired data are administrated by the μC and sent via CAN bus. Also, every 10 ms, all the monitored variables are stored in an SD memory.

The hardware is constituted by two circuits, one for voltage conditioning and another one for current conditioning. A block diagram for each one of these circuits is shown in Fig. 4. The current is sensed by a hall effect sensor (LEM HTFS 400-P); then, it is amplified with a low-noise operational amplifier (MC33078P). The current sensing is performed by sensing

TABLE III. CAN PROTOCOL FROM SC TO ECU.

FC to ECU	Data	Range	Units	CAN ID
Byte 0	Voltage LSB[†]	0 to 65536	10 mV	0x0C0
Byte 1	Voltage MSB[‡]			
Byte 2	Current LSB	-32766 to 32767	10 mA	
Byte 3	Current MSB			
Byte 4	Temperature	0 to 255	*C*	
Byte 5	SoC	0 to 100	%	
Byte 6	Low voltage shut down	0 to 1	on/off	
	Internal overvoltage failure	0 to 1	on/off	
	DC-Link sensor failure	0 to 1	on/off	
	Overvoltage shut down	0 to 1	on/off	
	Over temperature shut down	0 to 1	on/off	
	Temperature sensor failure	0 to 1	on/off	
	SC available	0 to 1	on/off	
	Low SoC shut down	0 to 1	on/off	
Byte 7	Available bits			

[†] Less significant bit.
[‡] More significant bit

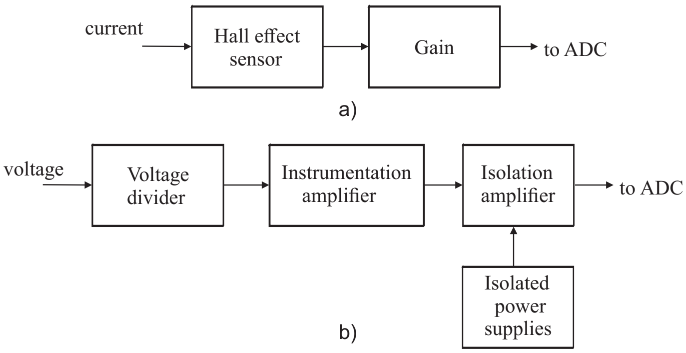


Fig. 4. Block diagram of the signal conditioning circuit.

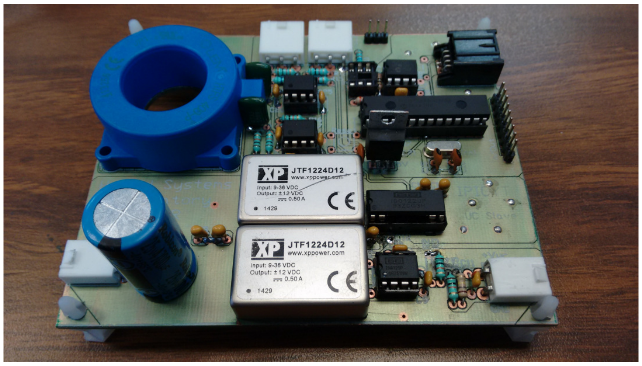


Fig. 5. Signal conditioning circuit for the SC and batteries.

the magnetic field; therefore, no isolation is needed. Due to the maximum output voltage of the current sensor is lower than the ADC input voltage (3 V), the output voltage of the sensor is amplified to the input voltage level allowed by the ADC, this is performed to use all the dynamic range of the ADC. The DC-link voltage is attenuated to 3 V with a voltage divider. A maximum voltage of 3 V is allowed by the μC ADC. Then, the attenuated voltage is measured by an instrumentation amplifier (ISO122) and adapted to the input voltage level allowed by the ADC of the μC. An isolation amplifier is used to isolate the measured voltage of the batteries and SC from the input of the ADC, avoiding any ground loop or ADC damage in case of a short-circuit. A Microchip transceiver MCP2551 is used to convert the referenced to the ground signal of the μC to a differential signal needed in the CAN bus communication. Also, a diode, NUP2105L, is used to protect the CAN transceiver in high-speed and fault tolerant networks from ESD and other harmful transient voltage events. The designed circuit is simulated in a simulation computer software. The simulation helps students to detect possible problems before to carry out the physical implementation. Once the simulated circuit is running correctly, the students implement the circuit in a breadboard to evaluate its performance in the laboratory. Finally, the design of the printed circuit board (PCB) performed. During this part, students face different issues related to components distribution, ground plane, number of sides of the PCB, among many others. The PCB of the proposed signal conditioning circuit is shown in Fig. 5.

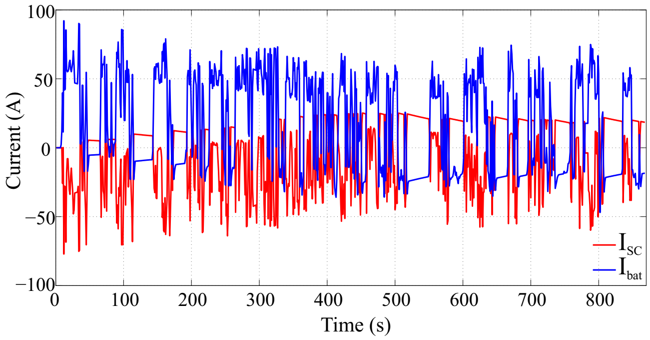


Fig. 6. Current across the supercapacitor (red) and batteries (blue).

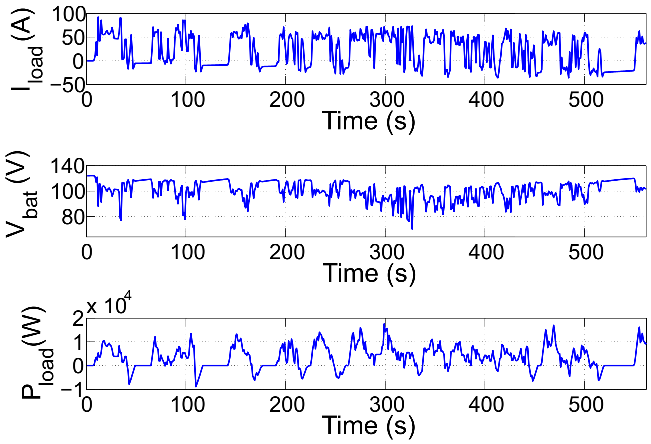


Fig. 7. Current and voltage in the batteries and power in the load.

V. LABORATORY EVALUATION AND EDUCATIONAL EXPERIENCES

Several simulations were executed in Matlab before laboratory evaluation of the proposed test bed. The simulations consist of the implementation of an energy management strategy (EMS). The EMS is out of the scope of this paper and is not presented here. Multiple simulations using the City drive cycle were carried out. Once simulations are working correctly, the developed instrumentation is set up in the laboratory. Several tests in the designed test bed were carried out for the sake of the experimental validation. The acquired current received or delivered by the SC, and batteries are depicted in Fig. 6. As we can see, the current has positive and negative values, supplying energy to the load and regenerative braking process, respectively.

The experimental measurements of the current and voltage in the battery pack without the SC connected to the DC-link are plotted in Fig. 7. As we can see, the battery voltage drops from 130 V to 80 V while the load current increases from 50 A to 95 A. With this experiment, the student can figure it out what would happen is the system has an extra energy source, an SC, feeding the DC-link. Is easy to think that the SC will supply electrical power surplus imposed by the load; therefore, the voltage drop in the batteries would be less than 40%. The batteries life cycle can be extended avoiding the excessive current peaks supplied by them.

The spectrum of the measured data of the current delivered by the batteries and SC is calculated using numerical simula-

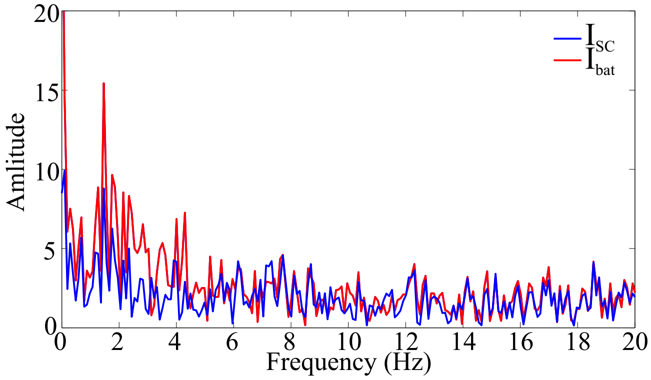
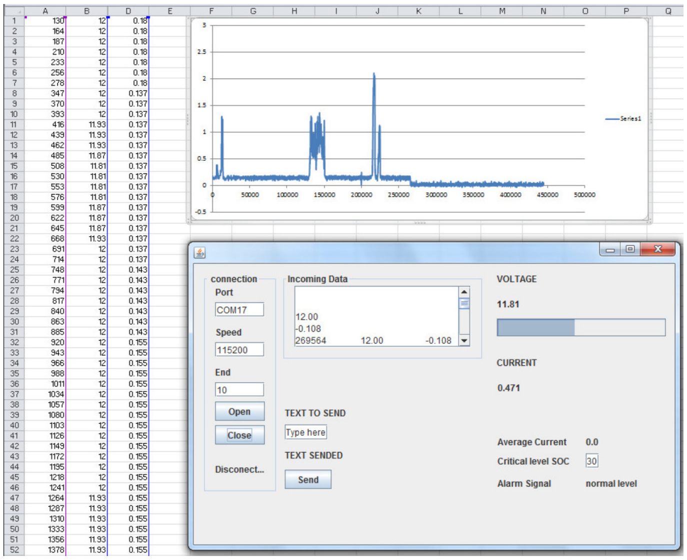


Fig. 8. Spectrum of the SC and the battery bank currents.



	A	B	D
1	130	12	0.18
2	164	12	0.18
3	187	12	0.18
4	210	12	0.18
5	233	12	0.18
6	256	12	0.18
7	278	12	0.18
8	347	12	0.137
9	370	12	0.137
10	393	12	0.137
11	416	11.93	0.137
12	439	11.93	0.137
13	462	11.93	0.137
14	485	11.87	0.137
15	508	11.81	0.137
16	530	11.81	0.137
17	553	11.81	0.137
18	576	11.81	0.137
19	599	11.87	0.137
20	622	11.87	0.137
21	645	11.87	0.137
22	668	11.93	0.137
23	691	12	0.137
24	714	12	0.137
25	748	12	0.143
26	771	12	0.143
27	794	12	0.143
28	817	12	0.143
29	840	12	0.143
30	863	12	0.143
31	885	12	0.143
32	920	12	0.155
33	943	12	0.155
34	966	12	0.155
35	988	12	0.155
36	1011	12	0.155
37	1034	12	0.155
38	1057	12	0.155
39	1080	12	0.155
40	1103	12	0.155
41	1126	12	0.155
42	1149	12	0.155
43	1172	12	0.155
44	1195	12	0.155
45	1218	12	0.155
46	1241	12	0.155
47	1264	11.93	0.155
48	1287	11.93	0.155
49	1310	11.93	0.155
50	1333	11.93	0.155
51	1356	11.93	0.155
52	1378	11.93	0.155

Port: COM17
Speed: 115200
End: 10

```
12.00
-0.108
269564        12.00        -0.108
```

VOLTAGE 11.81
CURRENT 0.471
Average Current 0.0
Critical level SOC 30
Alarm Signal normal level

Fig. 9. Screenshot of the communication between the μC and the PC.

tion software. In Fig. 8, the spectrum of both currents is shown. Doing the spectrum calculations, the students can remember Fourier transform concepts learned in their math courses. Also, they can observe the frequency content of the current delivered to the load by each source.

The interest variables such as current, voltage, temperature, speed, among others are saved in an SD memory. The saved data can be analyzed and plotted offline. A custom-made program developed in Java is done to verify the incoming data of each CAN node. The program allows the user to verify is the received data is valid or a corrupted data. A screenshot of the acquired and saved data, as well as the window of the custom-made program, is displayed in Fig. 9.

Since the beginning of the project, the students learn practical skills and put into practice the concepts of different subjects such as electric circuits, analog electronics, microcontrollers, power electronics, instrumentation. Also, the students face different problems. One of the most critical problems was the integration of distinct technologies and try to select the most suitable of them for the application. The noise problem due to analog, digital and power ground was a dispute during the development and implementation process. All the designed circuits were implemented in a PCB, getting familiar the student with CAD software to design PCBs.

The students changed their point of view about studying theories without having any hands-on training experience; for them, studying theories without having any real application means an ideal experience and sometimes esoteric.

VI. Conclusions

The implementation of a measurement system based-on CAN bus for educational, and research purposes in PHEVs were presented. The Controller Area Network protocol was proposed and used in the communication network. The system can save in an SD memory the interest variables, allowing offline analysis to the user. The implemented measurement system can be used as a platform for energy management strategies as well as for fault detection and diagnosis. Furthermore, the system can be used as a powerful didactic tool for students and engineers in the field of electric vehicles. Also, it can be extended to other scenarios such as vehicle-to-grid or vehicle-to-home applications.

Acknowledgment

Irwin A. Diaz-Diaz would like to thank the Potosino Council of Science and Technology (COPOCyT) for the financial support.

References

[1] Z. Xu, W. Su, Z. Hu, Y. Song, and H. Zhang, “A hierarchical framework for coordinated charging of plug-in electric vehicles in China,” *IEEE T. Smart Grid*, vol. 7, no. 1, pp. 428438, Jan. 2016.

[2] K. Sikes, T. Gross, Z. Lin, J. Sullivan, T. Cleary, and J. Ward, U.S. Dept. Energy, Plug-in hybrid electric vehicle market introduction study: Final report, Washington, DC, Tech. Rep. DE2010-972306, 2010.

[3] Electric Power Research and Institute, “Environmental assessment of plug-in hybrid electric vehicles,” Tech. Rep., 2009.

[4] T. Franke and J. F. Krems, What drives range preferences in electric vehicle users? Transp. Policy, vol. 30, pp. 5662, Nov. 2013.

[5] Khaligh, A.; Zhihao Li, “Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid Electric Vehicles: State of the Art,” *IEEE T. Veh. Technol.*, vol.59, no.6, pp.2806,2814, July 2010.

[6] Jensen, H.B.; Schaltz, E.; Koustrup, P.S.; Andreasen, S.J.; Kaer, S.K., “Evaluation of Fuel-Cell Range Extender Impact on Hybrid Electrical Vehicle Performance,” *IEEE T. Veh. Technol.*, vol.62, no.1, pp.50,60, Jan. 2013.

[7] Lukic, S.M.; Cao, J.; Bansal, R.C.; Rodriguez, F.; Emadi, A., “Energy Storage Systems for Automotive Applications,” *IEEE T. Ind. Electron.*, vol.55, no.6, pp.2258,2267, June 2008.

[8] Emadi, A.; Rajashekara, K.; Williamson, S.S.; Lukic, S.M., “Topological overview of hybrid electric and fuel cell vehicular power system architectures and configurations,” *IEEE T. Veh. Technol.*, vol.54, no.3, pp.763,770, May 2005.

[9] Solero, L.; Lidozzi, A.; Pomilio, J.A., “Design of multiple-input power converter for hybrid vehicles,” *IEEE T. Power Electr.*, vol.20, no.5, pp.1007,1016, Sept. 2005.

[10] Cao, J.; Emadi, A., “A New Battery/UltraCapacitor Hybrid Energy Storage System for Electric, Hybrid, and Plug-In Hybrid Electric Vehicles,” *IEEE T. Power Electr.*, vol.27, no.1, pp.122,132, Jan. 2012.

[11] Amjadi, Z.; Williamson, S.S., “Power-Electronics-Based Solutions for Plug-in Hybrid Electric Vehicle Energy Storage and Management Systems,” *IEEE T. Ind. Electron.*, vol.57, no.2, pp.608,616, Feb. 2010.

[12] Dehaghani, E.S.; Williamson, S.S., "On the inefficiency of vehicle-to-grid (V2G) power flow: Potential barriers and possible research directions," *2012 IEEE Transportation Electrification Conference and Expo (ITEC)*, vol., no., pp.1,5, 18-20 June 2012.

[13] Yilmaz, M.; Krein, P.T., "Review of the Impact of Vehicle-to-Grid Technologies on Distribution Systems and Utility Interfaces," *IEEE T. Power Electr.*, vol.28, no.12, pp.5673,5689, Dec. 2013.

[14] Pinto, J.G.; Monteiro, V.; Goncalves, H.; Exposto, B.; Pedrosa, D.; Couto, C.; Afonso, J.L., "Bidirectional battery charger with Grid-to-Vehicle, Vehicle-to-Grid and Vehicle-to-Home technologies," *IECON 2013, IEEE Ind. Elec.*, pp.5934,5939, 10-13 Nov. 2013.

[15] Chunhua Liu; Chau, K.T.; Diyun Wu; Shuang Gao, "Opportunities and Challenges of Vehicle-to-Home, Vehicle-to-Vehicle, and Vehicle-to-Grid Technologies," *Proceedings of the IEEE*, vol.101, no.11, pp.2409,2427, Nov. 2013.

[16] Xiaohu Zhou; Lukic, S.; Bhattacharya, S.; Huang, A., "Design and control of grid-connected converter in bi-directional battery charger for Plug-in hybrid electric vehicle application," *IEEE Vehicle Power*, pp.1716,1721, 7-10 Sept. 2009.

[17] Onar, O.C.; Kobayashi, J.; Khaligh, A., "A Fully Directional Universal Power Electronic Interface for EV, HEV, and PHEV Applications," *IEEE T. Power Electr.*, vol.28, no.12, pp.5489,5498, Dec. 2013.

[18] X. Xu, C. Wang, G. Liao, C. Yeh and W. Stark, "Development of a Plug-In Hybrid Electric Vehicle educational demonstration unit," 41st North American Power Symposium, Starkville, MS, 2009, pp. 1-7.

[19] V. Prasanth, P. Bauer and P. Ildik, "Drivetrain of electric car: Development of virtual laboratory for E-learning," *IEEE Int. Work. Adv. Mot.*, Sarajevo, 2012, pp. 1-6.

[20] T. Bécsi, S. Aradi and P. Gáspár, "Educational Frameworks for Vehicle Mechatronics," *IEEE T. Intell Transp.*, vol. 16, no. 6, pp. 3534-3542, Dec. 2015.

[21] C. C. Chan, A. Bouscayrol and K. Chen, "Electric, Hybrid, and Fuel-Cell Vehicles: Architectures and Modeling," *IEEE T. Veh. Technol.*, vol. 59, no. 2, pp. 589-598, Feb. 2010.