Development of a Bench-Type Experiment for an Electric-Drive Vehicle Powertrain

Y. Gene Liao, Wayne State University

Abstract

The industry consensus is that vehicle electrification is the currently available technology for increasing propulsion system efficiency and decreasing pollutant emissions. However, the electric drivetrain operates much differently than conventional vehicle powertrains. There is a need for training automotive engineers and educating students in this new and emerging technology of electric drivetrains. In this study, an interactive, industrial-component-based bench unit was developed as an educational tool for two different configurations of electric drivetrains: battery-electric and series-hybrid electric. The unit is capable of demonstrating, illustrating and displaying multiple energy flows in the electric-drive vehicle, based on its configuration and driving conditions. The integrated unit serves as a hands-on-experience workstation for multidisciplinary students enrolled in the electric-drive-vehicle technology courses. The hands-on experience not only enhances their vehicle electrification training and education, but also sparks student interest in the green movement of transportation.

Introduction

The new Corporate Average Fuel Economy (CAFE) standards were passed to decrease our dependence on fossil fuels by increasing the standards on new vehicles to 35.5 miles per gallon (MPG) by model year 2016 [1-2]. One important method of actualizing this required efficiency is vehicle electrification. Vehicle electrification involves electric drivetrain and electrically powered automotive auxiliary subsystems that are at the heart of Battery Electric Vehicles (BEV), Hybrid Electric Vehicles (HEV) and Plug-in Hybrid Electric Vehicles (PHEV). The electric drivetrain operates much differently than conventional vehicle powertrains. Therefore, existing development, design and maintenance techniques, and guidelines created for conventional powertrains, do not apply well to electric drivetrains. There is a need for training automotive engineers and educating engineering students in this new and emerging technology of electric drivetrains.

In response to the need of a trained and educated workforce in vehicle electrification, several universities and colleges have recently developed projects, courses and degree programs for training students, automotive engineers and technicians in electric-drive vehicle technology [3-8]. Developing new education and training for electric-drive vehicles requires careful planning of laboratory equipment and facilities. Existing courses in power electronics and electrical machines can be expanded and their laboratory resources leveraged with moderate cost. However, the costs will increase if the instruction includes hands-on experience with electric-drive propulsion components or dynamometer testing equipment. An overview course can be introduced with minimal laboratory impact, provided existing electric machinery equipment already exists. Laboratory instruction can include exercises on DC motors, AC induction or synchronous motors to build a solid foundation of the basic principles of electromechanical conversion such as torque, power and efficiency. Vehicle subsystem tests could involve a vehicle chassis dynamometer, an electric motor dynamometer, and electronic control-unit integration.

Although several curricula, short courses and training programs have been developed and delivered in the emerging technology of vehicle electrification, very few integrated electric-drive vehicle laboratories have been established for educational purposes. Several project-based laboratory activities on instrumentation for electric-drive components have been presented [8-10]. Software-based computer simulators such as LabVIEW for virtual hybrid electric vehicles have also been reported [11-12]. The tremendous capital investment and tedious and time-consuming tasks required to establish a fully functioning vehicle electrification laboratory is convincing evidence that colleges and universities are in need of a low-cost unit (less than U.S. $5,000) with industrial, electric-drivetrain functionality.

The motivation behind this project was to develop an interactive, industrial-component-based bench unit for two different configurations of electric drivetrains (battery-electric and series-hybrid). The unit is capable of demonstrating, illustrating and displaying (on the digital screens) the multiple energy flows in the electric-drive vehicle based on its configuration and operating conditions. The integrated unit serves as a hands-on-experience workstation for multidisciplinary students enrolled in the electric-drive-vehicle technology courses. The learning-by-doing experience not only enhances their vehicle electrification training and education, but also sparks their interest in the green movement of transportation.

Features of Electric-Drive Vehicles

The potential features of HEV include engine idle stop-start, engine-off driving (pure electric vehicle launch), power boost (maximum acceleration) and energy recuperation (regenerative braking). These typical HEV features during a simple driving cycle are illustrated in Figure 1 where the shaded areas represent the engagement of the electric system. As previously mentioned, electric drivetrains include propulsion systems of BEV, HEV and PHEV. In the BEV, the batteries must supply all of the energy needs. There is no onboard charging system except for regenerative braking. The batteries provide the power to propel the vehicle and to power all accessories such as air conditioning and power steering. The traction power of the BEV is provided by an electric motor using electrical energy stored in a battery rather than utilizing a heat engine. The range, or distance, that a vehicle can travel when operating exclusively on electrical power is called the All Electric Range (AER).

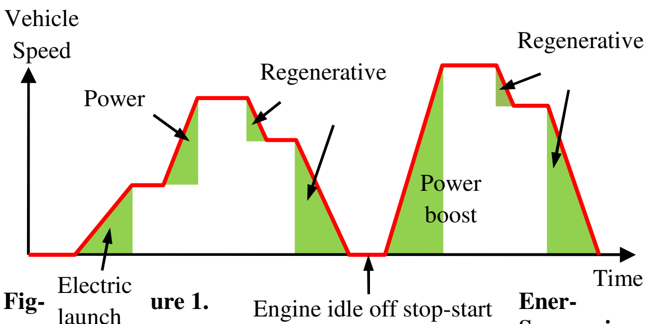


Figure 1. Energy Sources in a Typical HEV Subject to Driving Conditions

There are two basic HEV configurations, series and parallel. The main difference between them is how the propulsion power from the heat engine and electric machine are distributed. In a series HEV, a small heat engine directly drives a generator to generate electricity. The electricity is then distributed through the power bus, partially to drive the electric motor with the rest being stored in the battery pack. The engine turns on and begins to recharge the battery pack when it is drained to a certain level. The engine can be operated within a narrower and more efficient range of speeds because it is not directly connected to the drive wheels. However, the peak power required for acceleration and high -speed cruising is limited by the capability of the electric motor. A parallel HEV is configured with two power sources so that either the heat engine or the electric propulsion system, or both, can be used to produce the power to send to the drive wheels. Since the power from the heat engine and electric motor can simultaneously propel the vehicle, a higher peak power will be achieved compared with the series configuration. A mechanical coupler, such as a planetary gear set, for torque and speed summation is needed, which increases the complexity of packaging and control. Figure 2 show the typical layouts of a BEV, a series HEV and a parallel HEV [13].

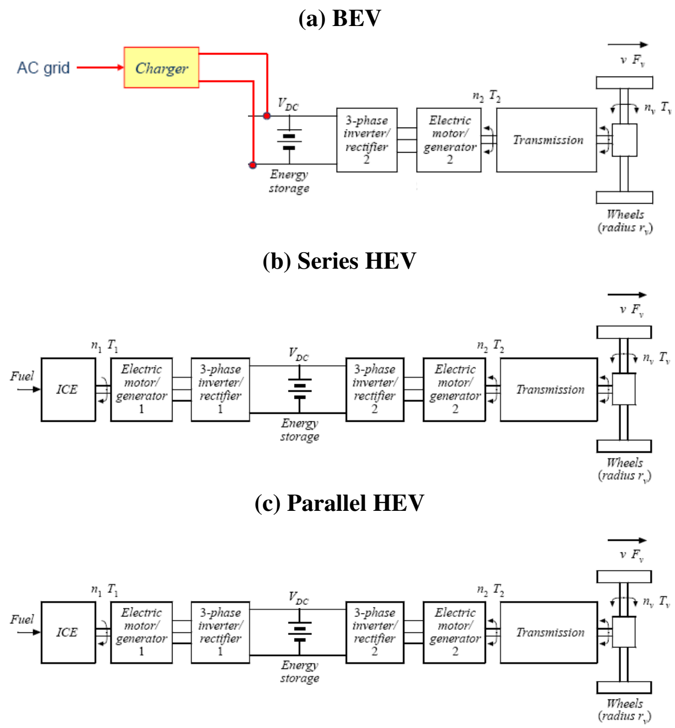


Figure 2. Typical Layouts of Electric-Drive Vehicles [13]

The bench unit developed in this study is capable of demonstrating the features of the BEV and series HEV electric propulsion systems. This includes the charge-depleting mode of the BEV during which the vehicle travels on electric power alone until its battery's State Of Charge (SOC) is depleted to a predetermined level. The charge-sustaining mode is also demonstrated in the bench unit for a series HEV. A series HEV combines the operation of the two energy sources in a manner such that the vehicle operates as efficiently as possible and keeps the battery SOC within a predetermined range.

Establishment of an Electric-Drivetrain Bench Unit

Figure 3 shows the block diagram of a teaching tool for the electric-drive powertrain bench unit. It is a state-of-the-art combination of battery-electric and series-hybrid electric drive technologies. The major components include engine, alternator, system controller, battery, electric motor, voltmeter, current meter, switch, motor-speed controller and real vehicle accelerator pedal. A three-phase AC alternator is operated by an engine in the system. A battery controller (or a battery management system) is applied to manage the charging and discharging process of the battery pack. A DC motor controller drives the motor in order to achieve the desired torque-speed characteristic curve. The motor shaft connects to the tire via a rotating drum. The load applied to the tire from the drum simulates the road load. The system controller is a microprocessor-based system that is commonly taught and utilized in the engineering technology curricula and laboratory experiments [14-15].

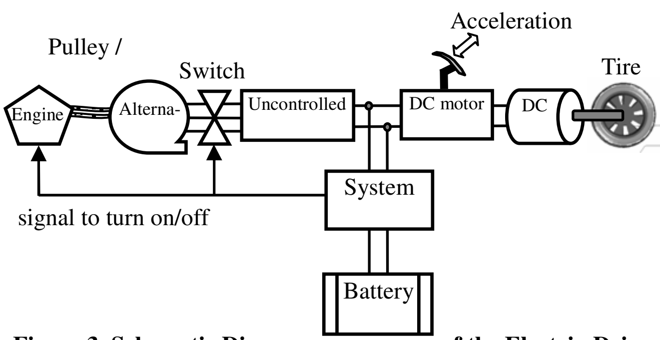


Figure 3. Schematic Diagram of the Electric-Drive Bench Unit

Hardware of the Bench Unit

The major components of the bench unit are listed in Table 1. Figure 4 illustrates the major components and their connections to the bench. There are four main functional blocks in the bench, as illustrated in Figure 4: battery and battery management, motor drive and brake system, internal combustion engine and alternator, and system controller.

- Battery and battery management
  By measuring the current flow and voltage at the battery terminal, the battery SOC meter will calculate and keep track of the remaining capacity of the energy in the battery. The output of the SOC meter is connected to the system controller to initiate the action of starting the engine and generating the charging current that will be sent to the battery.

- Motor drive and brake system
  The motor drive and brake system is designed to simulate the road load of the vehicle. Like normal vehicles, the accelerator pedal is used to command the speed controller to drive the motor. The brake system adds a load to the motor in order to consume the energy from the battery.

Table 1. Major Components of the Bench Unit

Engine	Generac, 250 c.c., 7.8 hp, OHV, electric and recoil start, horizontal mounting.
Alternator	Remy, automotive generator.
Battery	YTZ7S AGM maintenance free battery
Electric motor	Dayton, permanent magnet DC, 1 hp, 1800 rpm, armature 12 VDC.
Motor controller	Dart, 65E60-12, variable DC speed control, output voltage 12 VDC, power rating 1/8 – 1 hp, speed range 30:1, maximum current 60 amps.
Microprocessor	BasicATOM, Pro 28-M
Voltmeter	Blue Sea, 8028 DC analog micro voltmeter.
Battery SOC meter	Xantrex, LinkPro/LinkLite battery monitor.
Main switch	Motormite 85988, battery isolator switch.
Fuse blocks	Littelfuse, MEGA, 298 series, 100A and 250A, 32V.

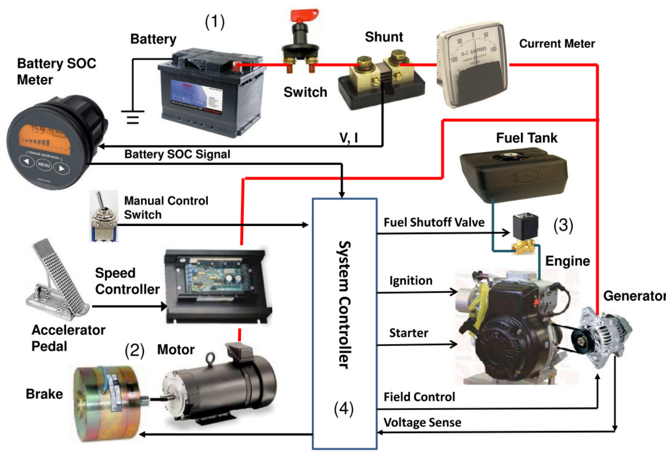


Figure 4. The Connections of the Hardware in the Bench Unit

- Internal combustion engine and alternator
  In the series HEV architecture, there is no mechanical connection from the internal combustion engine to the traction motor. The only device attached to the engine from the belt drive is the generator. For this demonstration bench, a vehicle alternator was coupled with the engine to generate electricity and charge the battery. The pulley ratios on both the engine and alternator shafts were carefully selected such that it would keep a minimum speed on the alternator to effectively generate power.

● System controller
The system controller is the brain of the bench. It monitors the SOC of the battery from the Battery SOC meter and determines what, if any, action is needed by the engine and alternator. It will also control the current from the alternator and braking power of the brake.

Integration of the Bench Unit

The system controller, as shown in Figure 5, is a microprocessor-based device that includes five functions:

- The input filtering stage removes voltage spikes and noise in order to protect sensitive electronic components.
- The power supply will step-down the +12V from the battery to +5V for the microprocessor.
- The input-signal conditioning stage adjusts the input voltage level and filters noise from the wire harness.
- The microprocessor executes the software commends.
- The output driver stage will increase the current capability in order to drive external devices (solenoid).

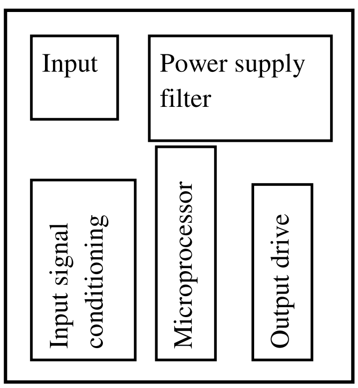


Figure 5. Microprocessor-Based System Controller

The detailed connection of the system controller is illustrated in Figure 6. The engine is connected directly to the alternator via a pulley and drive belt. The engine has an electric starter which is connected to the system controller via two connections:

1) The positive terminal of the starter is connected to the solenoid, which is connected to the starting relay in the system controller. The solenoid is also connected to the positive terminal of the battery. The negative terminal of the battery is directly connected to the negative terminal of the electric motor.

2) The wire coming out from the engine ignition coil to the manual ON/OFF switch is extended out and connected to the stopping relay in the system controller. The stopping relay replaces the original manual ON/OFF switch in the engine. The other end of the wire is connected to the spark plug. Thus, the stopping relay is the connection between the spark plug and the ignition coil and this connection is the secondary ignition circuit. The secondary ignition circuit always needs to be connected in order to avoid having the primary ignition circuit become activated. The secondary ignition circuit is active until it is connected and complete so that the primary circuit will not be activated. The reason to avoid the use of the primary circuit is that there is no control for stopping the engine, thus it will continue running until it runs out of fuel or is stopped by tempering the throttle and fuel ratio, which should only be done by a technically qualified person.

Four control signals are used to control the engine/alternator system. The fuel shutoff valve is the first signal that needs to be turned on before initiating the engine cranking sequence. Ignition and starter are two signals from the system controller to start the engine. Alternator field control is the signal to control the current output from the alternator. The engine cranking sequence will be automatically repeated in the event of an engine no-start that is detected by sensing the voltage produced from the alternator.

The alternator is connected to the battery and the system controller. The positive terminal of the alternator, denoted as BAT on the alternator, is connected with the positive terminal of the battery. The negative terminal of the alternator, denoted as GND on the alternator, is connected with the negative terminal of the battery. The direct connection between the alternator and the battery terminals is to ensure an active connection, even when the main switch is turned off. The purpose of making these direct connections is that in case the main switch is turned off all of a sudden, the alternator will still have a buffer (battery) connected to it to store the electric energy it generates. If a switch disconnects the battery from the alternator, the alternator will have no buffer to store the power it generates when the switch is turned off. When the sudden power generated by the alternator runs into the entire system, it will result in the burning of the microprocessor in the system controller and other electric devices in the system (voltmeter and current meter).

In the system controller, a 15Ω resistor is connected to the alternator field terminal, denoted as "F" on the alternator. The alternator selected for this bench unit was an automotive alternator which did not directly generate electricity during startup. The current passing through the 15Ω resistance to the field terminal on the alternator provides external energy to the field windings of the alternator. As the field windings get energized, the alternator produces the

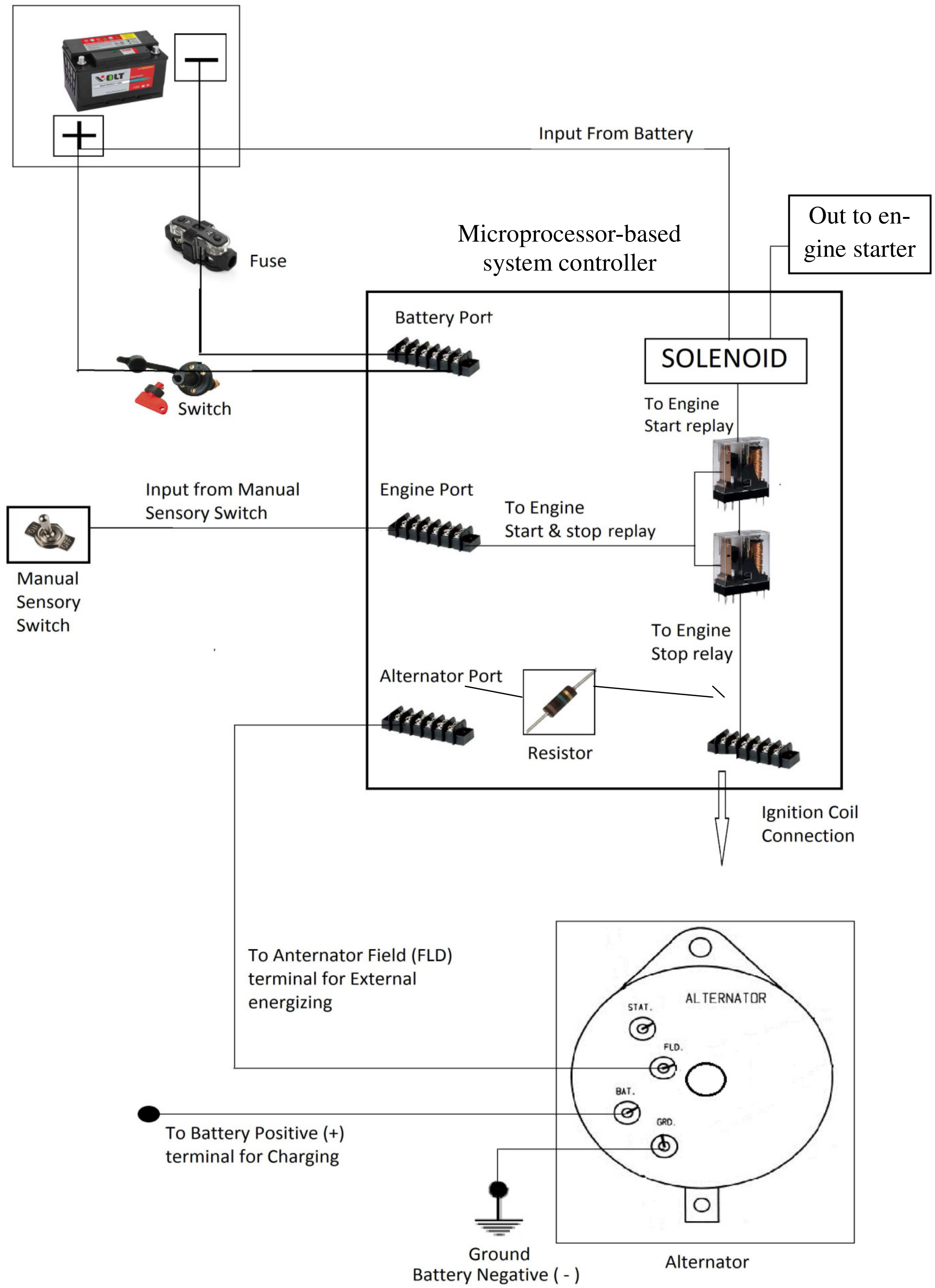


Figure 6. The Connections of System Controller

electricity, which is then used to charge the battery. The resistance value is inversely proportional to the electrical output from the alternator. The value of the resistor was determined by several experiments. The 15Ω resistance was selected for generating the appropriate charging current to the battery in the system.

This controller is operated by a real vehicle accelerator pedal, or the throttle pedal. The accelerator pedal and motor controller were calibrated to provide a real feeling of driving. The motor stalls (no rotation speed) when the accelerator pedal is fully released. The motor speed is increased gradually according to how much and how fast the accelerator pedal is depressed.

The Bench Unit

The development of an electric-drive bench unit for use as a teaching tool was a team effort lead by a faculty member and group of undergraduate and graduate students, as shown in Figure 7. The team consisted of students with multidisciplinary backgrounds including mechanical engineering, electrical engineering and computer science. The task of development, design, layout, fabrication and assembly of the bench unit was done in the campus laboratory. The team also performed functional tests on the unit, modification of components, programming and system validation. The electric-drive bench unit is shown in Figure 8. The entire bench unit was installed on a movable cart. The cart can be moved to any classroom, laboratory, training room or demonstration and display area.

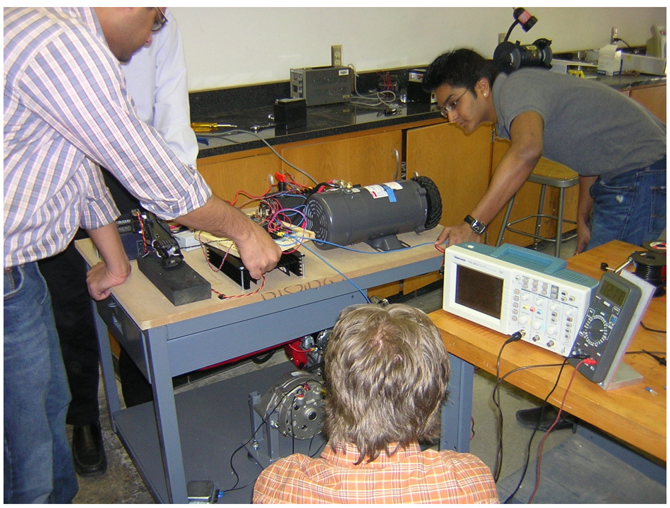


Figure 7. Students Working on the Unit

The battery and series-hybrid electric drivetrains were installed in the upper and lower portions of the cart, respectively. All of the battery electric-drive components–drive shaft, wheel, electric motor, motor controller, battery, system controller, and accelerator pedal–were installed on the top of the table. The engine, alternator and gasoline tank were mounted in the lower portion of the cart. The gasoline tank was installed in a specially designed drawer, which provides safety and convenience when filling the engine with gasoline.

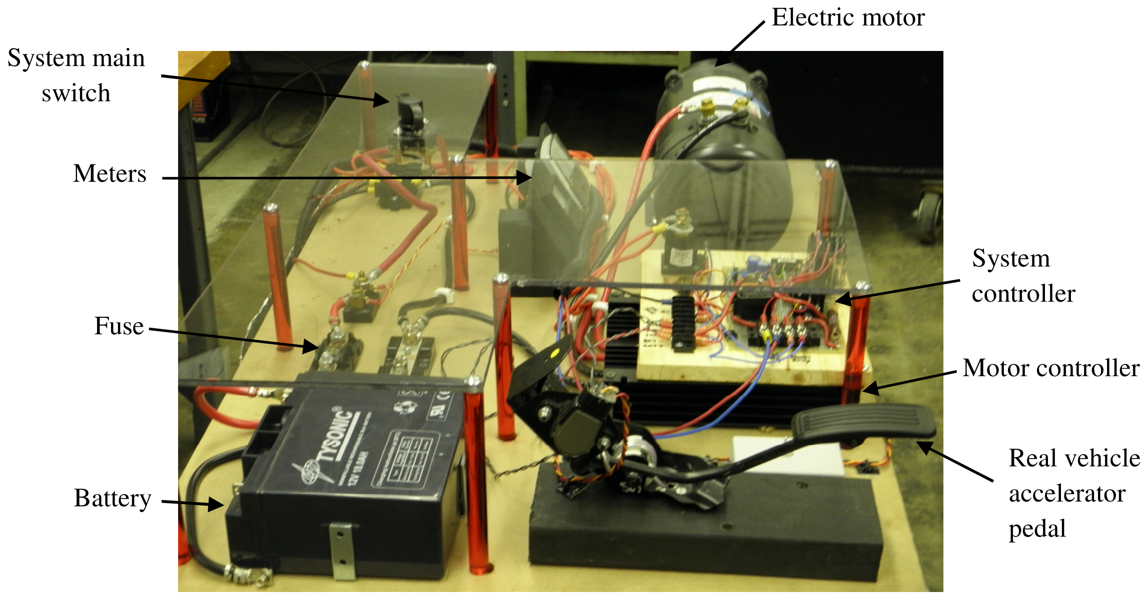
The establishment of a functional electric-drive laboratory requires a tremendous investment of capital and time. One might think that the best option would be to purchase a production electric vehicle or hybrid electric vehicle for the laboratory. However, the manufacturer's warranty and safety will become issues when students tear down the vehicle and test the electric-drive components in the laboratory. Only a few commercial units for electric-drive training or education are available on the current market [16]. Some production-type electric powertrains can be modified for educational purposes; however, it is difficult to utilize all of the functions of the drivetrain in a laboratory environment.

Operations of the Electric-Drivetrain Bench Unit

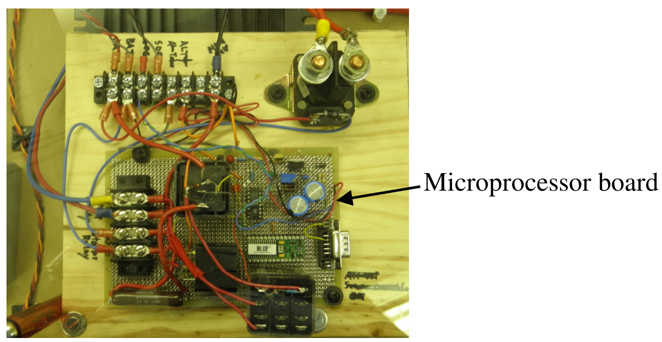
The electric motor draws energy from the battery and is the driving unit for the vehicle. The motor controller is used to control the speed of the motor and is operated by a real car accelerator pedal. The battery SOC or voltage can be checked by monitoring the voltmeter attached to the battery. Also, the operating status of the battery, charging or discharging, can be visualized by monitoring the current meter attached to the battery. Once the main switch of the system is turned on, the battery gets connected to the system controller and the power is delivered to the microprocessor. The operational stages are classified into BEV and series-HEV demonstrations:

BEV demonstration
- The system is completely operational once the main switch of the system is turned on. The accelerator pedal can be depressed or released to any angles within the pedal's travel range. The position of the accelerator pedal determines the wheel speed.
- The engine and alternator are always off. The battery SOC/voltage is continuously depleted as long as the accelerator pedal is depressed.

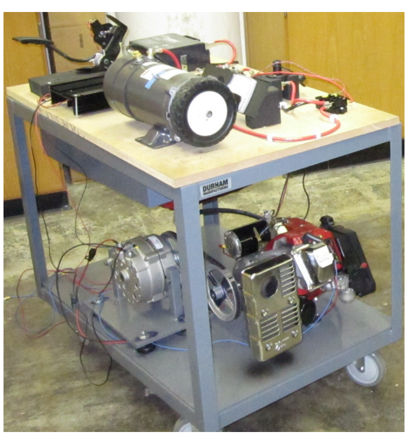
Series-HEV demonstration
- The main switch of the system is turned on.
- As soon as the manual switch is triggered, it sends a signal to the system controller to trigger the solenoid switch through the starting relay.
- When the solenoid is triggered, the current is sent to the starting motor, which starts the engine.
- The starting motor gets current through the solenoid, which is triggered by the opening of the starting relay. This starting relay is programmed to stay open only for 5 seconds after it gets triggered. This means that the current supply to the starting motor stops after 5 seconds, which allows sufficient time to start the engine.
- The engine is connected to the alternator via a pulley and drive belt. Thus, the generator starts running along with the engine.
- The alternator is directly connected to the battery from its output so that the electricity generated by it can be directly stored in the battery.



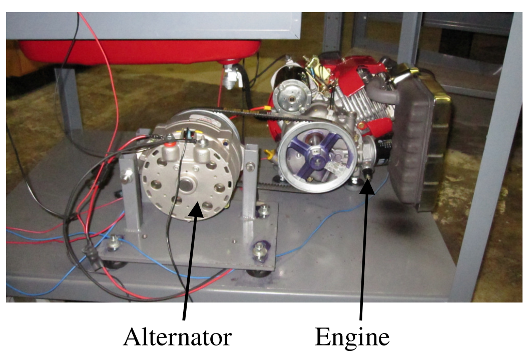
(a) Battery electric-drive portion on the top of cart



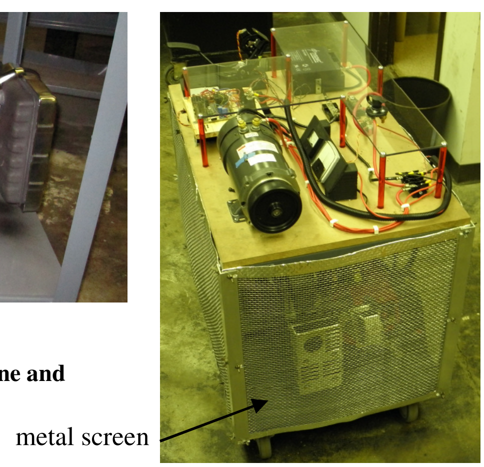
(b) Enlarged view of system controller



(c) Series electric-drive portion on the



(d) Belt connection between engine and alternator



(e) Metal screen covered rotational parts

Figure 8. A Developed Electric-Drive Bench Unit

- The entire circuit remains completed and active as long as the manual switch is depressed, and can remain so if needed. Once the switch is released, the trigger is off.
- The microprocessor is programmed in such a way as to control the engine's on and off conditions. As soon as the battery voltage/SOC reaches a pre-defined value, the stopping relay in the ignition is off and circuit opens. The open circuit breaks the supply of current to the spark plug, thus stopping the engine.
- The entire circuit stops once the engine stops, at which point the system operates in a BEV mode.
- The engine will be started again only when the battery voltage/SOC decreases below a pre-defined value.

Integration of the Electric-Drivetrain Bench with the Curriculum

The University has two degree programs and one graduate certificate program related to hybrid and electric vehicles: an M.S. degree program in Electric-Drive Vehicle Engineering (EVE), a B.S. degree program in Electric Transportation Technology (ETT), and a Graduate Certificate in EVE. Three courses have used this electric-drivetrain bench unit as part of the laboratory experiments for students. This bench unit provides students with practical, hands-on experiences that favor typical learning styles, encouraging students to learn by doing. The short description of each course is listed below.

EVE5110 *Fundamentals of Electric-drive Vehicle Engineering* (4 credit hours). This course provides an introduction to electric, hybrid and fuel-cell-hybrid vehicles explaining the advantages and disadvantages of electric-drive vehicles in comparison to conventional internal-combustion-engine vehicles. The fundamentals of electric machines, power electronics and energy storage devices for electric drives are provided and demonstrated in lab exercises. The application of electric drives in hybrid and electric vehicles utilizing a variety of powertrain architectures is presented. Elementary analyses of electric-drive vehicle performance and fuel economy are included.

EVE 5310 *Electric-drive Vehicle Modeling and Simulation* (4 credit hours). This course focuses on the overall energy conversion, storage, utilization and optimization of complete ground vehicle systems for conventional, hybrid and electric vehicles. A methodology for constructing general models of internal-combustion engines, electric machines, energy storage and power flow processes in hybrid and electric vehicles is developed and implemented using Matlab/Simulink, GT-Drive, or AVL/Cruise.

ETT4150 *Fundamentals of Hybrid and Electric Vehicles* (3 credit hours). General background of HEV-related technologies including technical concepts, design factors, energy analysis and unified modeling approaches is presented. Discussion of hybridization, hybrid powertrain architectures, internal-combustion engines for hybrid electric vehicles, associated types of transmissions used, PHEVs, fuel-cell vehicles and on-board energy storage is also presented.

The EVE5110 course was offered in the Fall 2010 term and had 21 students. The EVE5310 and ETT4150 were offered in the Winter 2011 term with 22 and 18 students enrolled, respectively. The students had several stand-alone laboratory experiments in each course, such as electric machines, power electronics, electric energy storage and control. Computer simulation software was also utilized in these courses for vehicle system and sub-systems modeling and simulation. The electric-drivetrain bench is an integrated unit consisting of all the major components in HEV/BEV and is capable of demonstrating, illustrating and displaying the multiple energy flows in the electric-drive vehicle based on its configuration and driving conditions. This integrated laboratory experiment provides students with the in-depth knowledge and hands-on experience of the interface and control of each component in each of the electric-drive propulsion systems.

Conclusion

An increasing quantity of production HEV/PHEV/BEV vehicles offers much promise for our society. Due to this fact, the next generation of students will need more educational training in this area, especially for those students engaged in engineering and technology programs. In this study, an interactive, industrial-component-based bench unit was developed as an educational tool for two different configurations of electric drivetrains: battery-electric and series-hybrid electric. The unit is capable of demonstrating, illustrating and displaying multiple energy flows in the electric-drive vehicle, based on its configuration and driving conditions. The integrated unit provides students with practical, hands-on experiences that favor typical learning styles, encouraging students to learn by doing.

The implementation of the electric-drivetrain bench unit was a resounding success and initial student reaction was quite enthusiastic. The hands-on experience not only enhances their vehicle electrification training and education, but also inspires multidisciplinary students to become interested in the green movement of transportation. For safety concerns, the current bench is powered by a low–voltage, 12V lead-acid automobile battery, though there are plans to upgrade it in the future to other types of battery chemistries such as NiMH or Li-Ion. The development of the second bench unit is ongoing.

Acknowledgements

This work was supported in part by the National Science Foundation, CCLI-Phase I: Exploratory, under grant number DUE-0941809.

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Biographies

Y. GENE LIAO is currently Director of Electric Transportation Technology Program and Associate Professor of Engineering Technology Division at Wayne State University. He received the B.S. in Mechanical Engineering from National Central University, Taiwan, Mechanical Engineer from Columbia University, and Doctor of Engineering from the University of Michigan, Ann Arbor. He has over 15 years of industrial practices in the automotive sector prior to becoming a faculty member. Dr. Liao has research and teaching interests in the areas of multi-body dynamics, hybrid vehicle powertrain, advanced energy storage systems, and CAE applications in products development and manufacturing. Dr. Liao may be reached at geneliao@wayne.edu