AC 2011-1013: HEV GREEN MOBILITY LABORATORY

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Dr. Gover holds a Ph.D. in nuclear engineering and an MS in electrical engineering from the University of New Mexico. He is retired from Sandia National Laboratories and has been Professor of electrical engineering at Kettering University for 13 years. His honors include selection as IEEE Fellow and recipient of IEEE Citation of Honor. He has served IEEE in numerous conference positions and as Congressional Fellow and Competitiveness Fellow.

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Allan Taylor attained his BSEE degree from Kettering University in Spring 2009 with honors (Magna Cum-Laude) and is a member of Eta Kappa Nu electrical engineering honor society. Allan is currently working on his Master's in Engineering (with concentration in ECE) and has been awarded a full scholarship and assistantship at Kettering University. Allan has had extensive experience with HEV related topics in his undergraduate and graduate coursework and has volunteered time as a Power Electronics & Electrical Drive Train engineer for Kettering's fuel cell formula race car team for which he has been developing computer controls system models. Allan has been selecting equipment for the Green Mobility Laboratory and aiding the design of experiments and simulations for the lab.

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Michelle Pomeroy attained her BSEE from Kettering University in June 2002 receiving the Presidents Medal given to only 2% of each graduating class for professionalism in the workplace, community involvement and participation in professional societies. Since graduation Michelle has received her MS in Engineering Management from Oakland University, a Masters Certificate from Villanova University in Project Management and is currently pursuing a Master's of Science in Engineering with a concentration in Electrical and Computer Engineering from Kettering University. She worked for Delphi from 1997 to 2009 in various positions, most recently focusing in applications engineering and project management. Michelle is doing project management support activities and assisting with software development for the Green Mobility Laboratory.

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Kevin Bai received B S and PHD degree in Department of Electrical Engineering of Tsinghua University., Beijing, China in 2002 and 2007, respectively. He was a post-doc fellow and research scientist in Univ of Michigan-Dearborn, USA, in 2007 and 2009, respectively. Now he is an assistant professor in Department of Electrical and Compurter Engineering, Kettering University, MI, USA. His research interest is the dynamic processes and transient pulsed power phenomena of power electronic devices, including variable frequency motor drive system, high voltage and high power DC/DC converter, renewable energy and hybrid electric vehicles.

Hybrid Electric Vehicle "Green Mobility" Laboratory

Abstract

The implementation of a Hybrid Electric Vehicle (HEV) Green Mobility Laboratory to aid in the development of an innovative and flexible educational program in transportation electrification is described. The high level objectives of the program are: (1) to provide unique and timely educational opportunities for undergraduate students as a basis for the advancement of transportation electrification, and (2) to provide research facilities and opportunities for graduate students and faculty in the Department of Electrical and Computer Engineering (ECE) that will establish the future direction of electric transportation for the country and the world.

The Green Mobility Laboratory consists of three open-bench, hybrid electric vehicle drive train control, simulation, and data acquisition systems. The hybrid drive train components on each bench include a DC power supply / battery pack simulator, 3-phase DC-AC Pulse Width Modulated (PWM) controlled inverter motor drive, 5 kW permanent magnet synchronous motor (PMSM), and Eddy current dynamometer load. Power and waveform measurements are made with a Precision Power Analyzer and PC based data acquisition system. The drive train components and instrumentation are integrated in a flexible control and simulation laboratory for utilization in several curricular and research activities. Two new courses utilizing the Green Mobility Laboratory are being developed for the ECE curriculum. Details of the laboratory implementation and utilization within the ECE curriculum focusing on transportation electrification are described.

Introduction

In the United States, national and state transportation policy experts consider electric and hybrid electric vehicles (HEVs) to be a key technology for reducing dependence on oil imports and for lowering the production of greenhouse gas emissions generated by the transportation sector. The Institute of Electrical and Electronic Engineers (IEEE) Energy Policy Committee emphasize the importance of HEV power trains in its recommendations to Congress. HEV power trains are more complex and operate much differently than conventional vehicle power trains in many respects. Thus, well established and existing conventional design techniques, control algorithms, and testing methods are not directly applicable to HEVs. Education of a new generation of engineers with interdisciplinary knowledge capable of meeting the challenges presented by the electrification of the transportation industry must serve as a central component in a strategy to gain U.S. energy independence. To this end, the implementation of a Hybrid Electric Vehicle Green Mobility Laboratory to aid in the development of an innovative and flexible educational program in transportation electrification is described in this paper. The high level objectives of the program are: (1) to provide unique and timely educational opportunities to undergraduate students as a basis for the advancement of transportation electrification, and (2) to provide research facilities and opportunities for graduate students and faculty in the Department of Electrical and Computer Engineering (ECE) that will establish the future direction of electric transportation for the country and the world.

This program was initiated in response to a definition of hybrid electric industry education needs identified by the *Michigan Academy for Green Mobility* and is supported by the United States Department of Energy with funds provided by the American Recovery and Reinvestment Act.

Background & Motivation

To help reduce emissions from internal combustion engines, increase fuel economy, realign transportation energy needs toward domestic resources, and generally assist the U.S. automobile industry in meeting the economic and technical challenges of a new era of electric vehicles, engineering programs must provide transportation electrification ("green mobility") educational opportunities to undergraduate and graduate students. The Michigan Academy for Green Mobility was established to provide an ongoing government-industrial-academic partnership with a goal to support the transformation of the domestic automotive industry in the State of Michigan. The education needs, desired courses, and laboratory requirements to support this transformation were determined through active participation by more than thirty OEM and supplier companies working in the hybrid vehicle sector and from more than ten regional colleges and universities.

A meaningful educational program in transportation electrification must involve an integrated and interdisciplinary curriculum that includes; energy storage systems, power electronics, electric drives, digital electronic control, local area network communications, and the mechanics of automotive power trains. The Michigan Academy for Green Mobility determined, as part of this effort, that Michigan universities should develop undergraduate and graduate education programs to fulfill the identified needs. A preponderance of these new educational needs were in electrical engineering. It was concluded that industry supportive undergraduate education requirements could be met at Kettering University by: (1) existing courses (from the standard Electrical and Computer Engineering (ECE) and Mechanical Engineering curricula), (2) development of two new ECE courses that fulfill specialized needs identified by industry, and (3) utilizing battery controls courses being developed and taught at the University of Michigan. To properly teach this curriculum with equal emphasis on theory, simulation and hands-on laboratory experiences, would require the cross-disciplinary (electrical engineering, computer engineering, and mechanical engineering) development of an integrated hybrid vehicle power electronics laboratory. The HEV Green Mobility Laboratory is the outcome of this effort.

The Green Mobility Laboratory has been designed to support hands-on undergraduate student experiments, faculty demonstrations, independent studies, and graduate student research projects. The laboratory opened for the Fall 2010 academic semester and was utilized in the first new course, *Design, Simulation, and Control of Power Electronic Circuits for Electric Drive Trains* for several demonstration exercises. The first offering of this course was via a "special topics" class with a limited enrollment of 5 students. Laboratory development continued through the Winter 2011 semester with refinements to the system control software, hardware, and user interface to make it easier and safer for undergraduate students to perform hands-on experiments. Examples of the control interface and a sample laboratory exercise are presented in this paper. Starting with the Spring 2011 academic term, the Green Mobility Laboratory should be fully functional for undergraduate laboratory experiments associated with the second new course, *Semiconductor Switching: Electrical and Thermal Effects.* For the 2011-2012 academic year, the

Green Mobility Laboratory will be utilized in both new courses and two existing courses (*Power Electronics and Applications*; and *Hybrid Electric Vehicle Propulsion*) with a projected total student enrollment of 75 students. The laboratory is currently ready for industry sponsored graduate student research projects.

Laboratory Hardware Description

The Green Mobility Laboratory consists of three open-bench, hybrid electric vehicle drive train control, simulation, and data acquisition systems. The hybrid drive train components on each bench include:

- Programmable DC power supply / battery pack simulator
- 3-phase DC-AC Pulse Width Modulated (PWM) controlled inverter motor drive and cooling loop controller
- 5 kW permanent magnet synchronous motor (PMSM)
- Eddy current dynamometer load / vehicle dynamics simulator

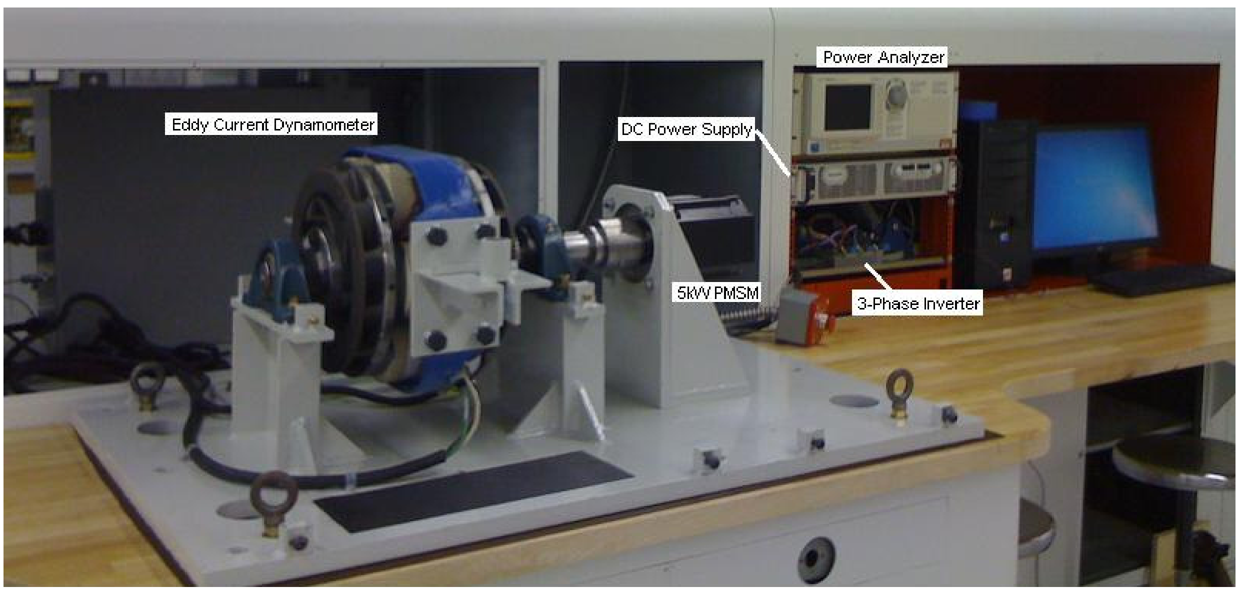

Figure 1. Green Mobility Laboratory station (one of three)

Power and waveform measurements are made with a Precision Power Analyzer and PC based data acquisition system. The drive train components and instrumentation are integrated with a flexible control and simulation software, developed at Kettering University and written with National Instruments LabVIEW 8.6. The Graphical User Interface (GUI) communicates with each device either through serial communication (RS-232) or through an Ethernet connection.

As depicted in the system block diagram of Figure 2, electrical and mechanical power measurements are made with a Yokogawa Power Analyzer. The DC electrical output power of the power supply, 3-phase AC electrical power of the inverter, and the mechanical output power of the motor are measured. Thus, efficiencies for the inverter and motor can be calculated under any operating condition.

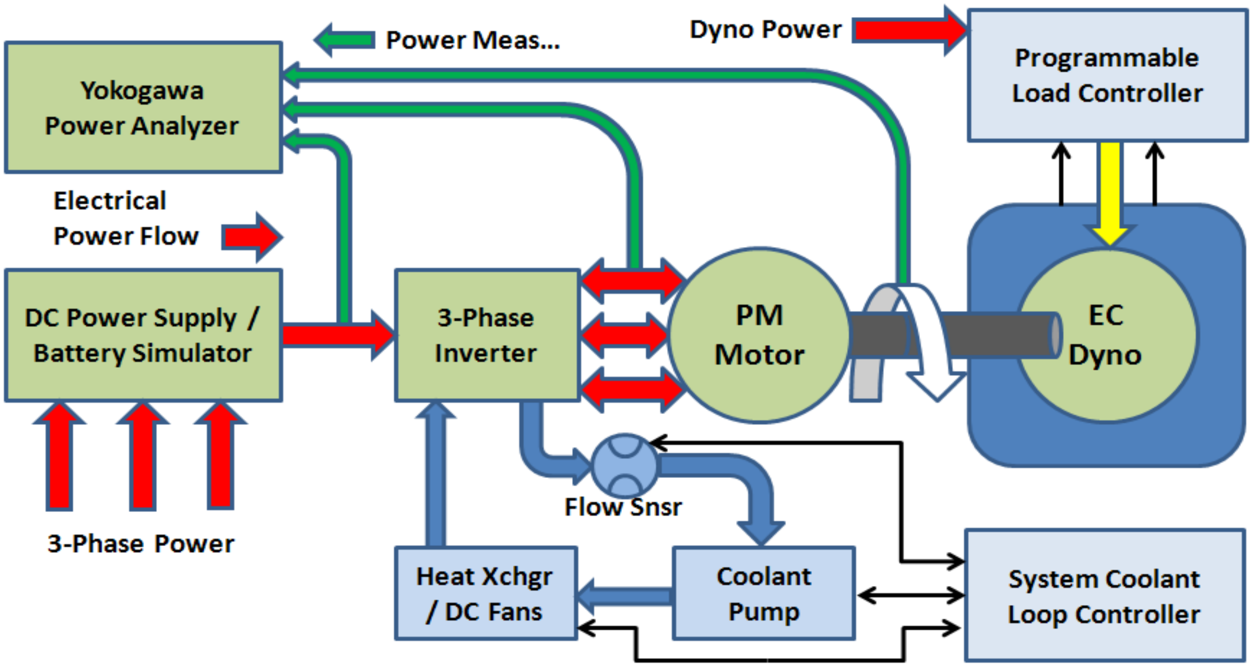

Figure 2. Green Mobility Lab system-block-diagram

Also shown in the system block diagram, the 3-phase inverter is water-cooled. Temperature and flow sensors have been included in the inverter coolant loop to allow thermodynamic calculation of heat loss. This calculation can be experimentally compared to the measured inverter electrical power loss from the power analyzer.

The coolant loop is controlled by a National Instruments Compact Reconfigurable I/O (cRIO). The cRIO communicates with the host PC's software GUI to generate 3 PWM signals. These PWM signals drive three DC/DC step-down converters to generate three variable DC voltages from a single fixed 24 V DC power supply (Figures 3 and 4). Thus, fan speed, pump speed, and 12 V inverter logic can be powered and controlled through software.

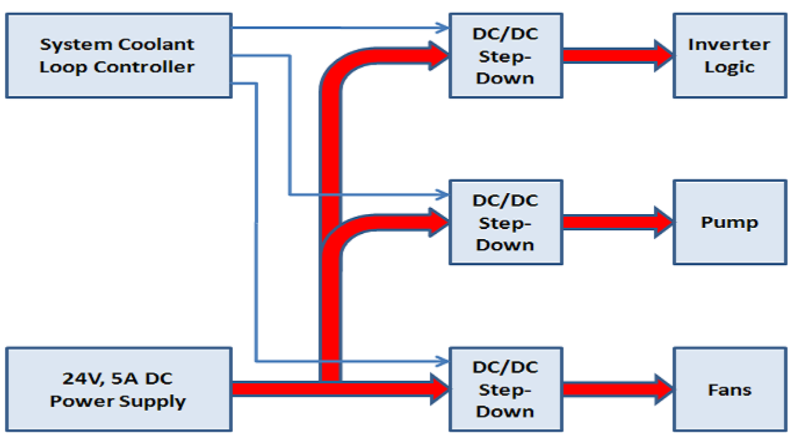

Figure 3. Coolant loop controller block diagram

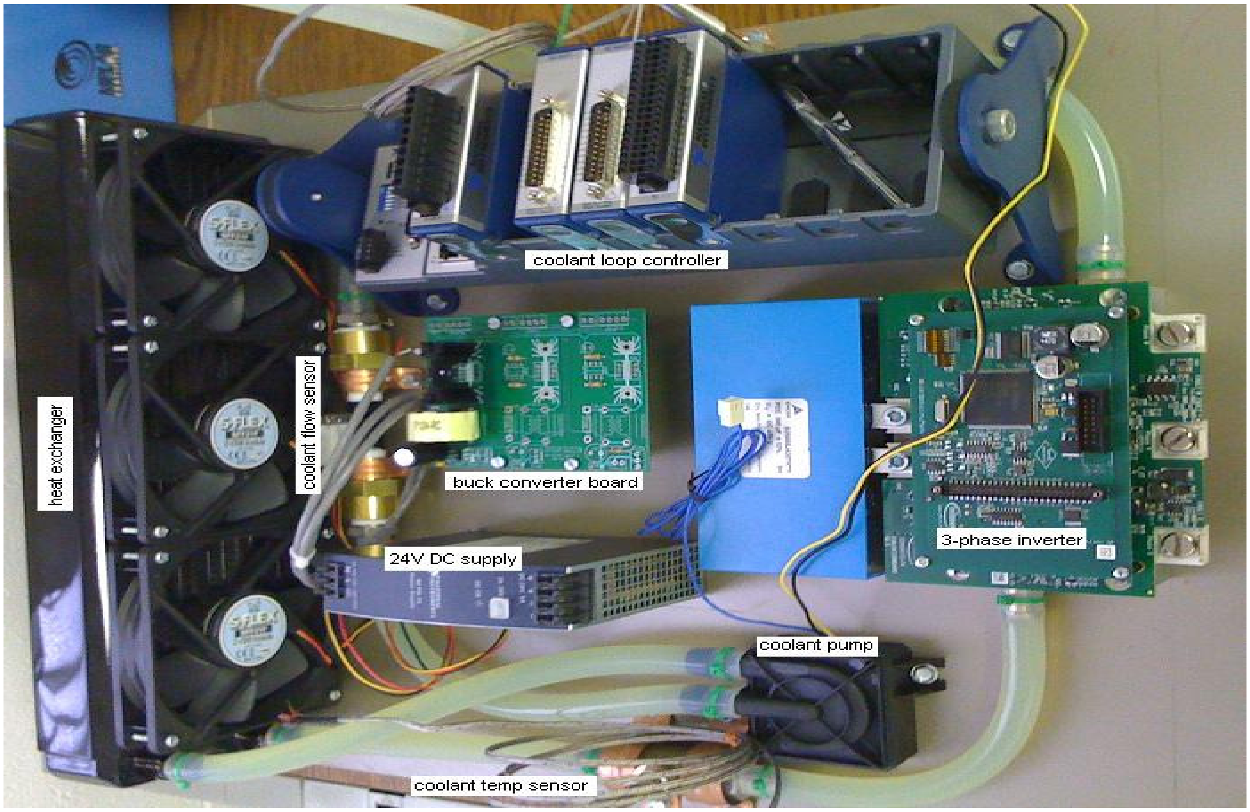

Figure 4. Coolant loop hardware

The high-voltage DC power supply is controlled through software to provide a fixed DC output voltage or a traction battery pack simulation. The simulation uses a constant-current discharge model based on Peukert's Law. A MATLAB / Simulink model was developed (shown in Figure 5), and the model was ported into the LabVIEW environment. The DC output voltage of the Simulink model is determined by equation (1),

$$V_t(t) = MaxVolt - \frac{1}{C_p}\int_0^t I_s{}^k dt \cdot (MaxVolt - MinVolt) - I_s R_b \tag{1}$$

where the terms *MaxVolt*, *MinVolt*, C_p, R_b, and k are input parameters. The output current of the supply (I_s) is sampled every 100 ms, and the output voltage is adjusted. This model does not simulate the polarization curve of a battery's series resistance.

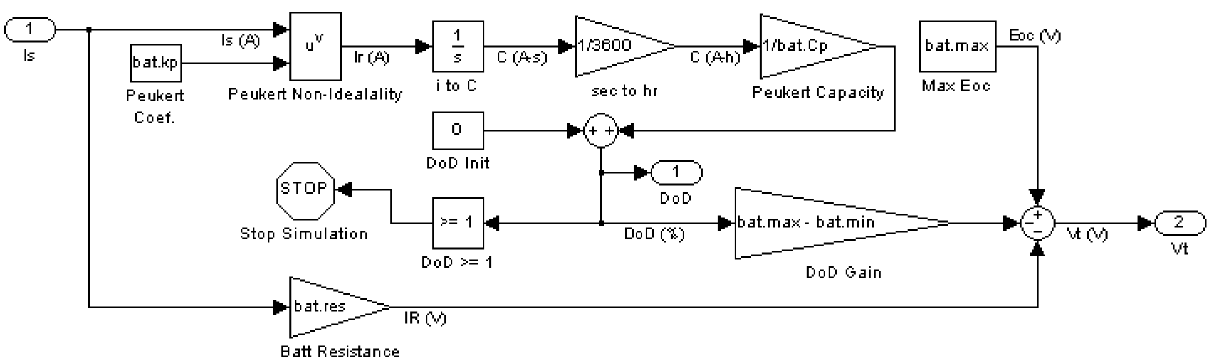

Figure 5. Simulink constant-current-discharge battery model

The GUI software panel for the programmable DC power supply / battery pack simulator is shown in Figure 6. Through the software panel, students can enter the modeling parameters of the battery, reset the Depth of Discharge (DoD) counter, and toggle the supply output to simulate a wide variety of HEV traction battery packs and conditions.

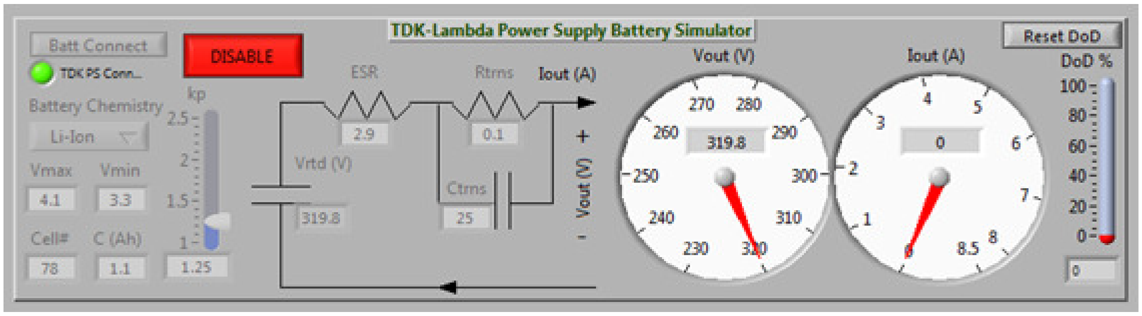

Figure 6. Software panel for DC power supply / battery pack simulator

The DC output voltage of the power supply / battery pack simulator is converted into variable frequency 3-phase AC electrical power to drive a 5 kW permanent magnet synchronous motor (PMSM) representing the HEV traction motor. The DC-AC power inverter performs a vector-control algorithm by utilizing a resolver-type position sensor and current sensors on each phase of the PMSM. The inverter uses 600 V rated IGBT's, capable of handling up to 400 A per phase.

The 3-phase alternating current from the inverter produces an electromagnetic torque in the motor. This torque acts against the inertia and mechanical load produced by the Eddy current dynamometer. The dynamometer's drive strength (mechanical load), along with the motor's electromagnetic torque, can be controlled through the GUI software control panel shown in Figure 7. Students can choose to operate the system under constant speed or constant torque set-points for data collection. The dynamometer can also be programmed to simulate vehicle dynamics, based on the vehicle model of equation (2) which accounts for vehicle rolling resistance and aerodynamic drag[1]. The opposing dynamometer torque is a function of the angular velocity of the mechanical system. The mechanical system has a maximum rotational speed of about 3000 RPM.

$$T_{dyno} = T_0 + T_1 \cdot \omega + T_2 \cdot \omega^2 + T_{inertia} \quad (2)$$

During experiments, students can collect a wide variety of electrical measurements from the Yokogawa power analyzer. Instantaneous current, voltage, and power measurements, waveform graphs, and Fourier series plots showing signal harmonics (due to PWM switching) can all be obtained from the analyzer. The analyzer uses four internal watt-meters, connected as shown in Figure 8, to make the electrical measurements. Mechanical torque and speed measurements from a load cell and shaft encoder are also used by the power analyzer after being conditioned by the dynamometer's load controller.

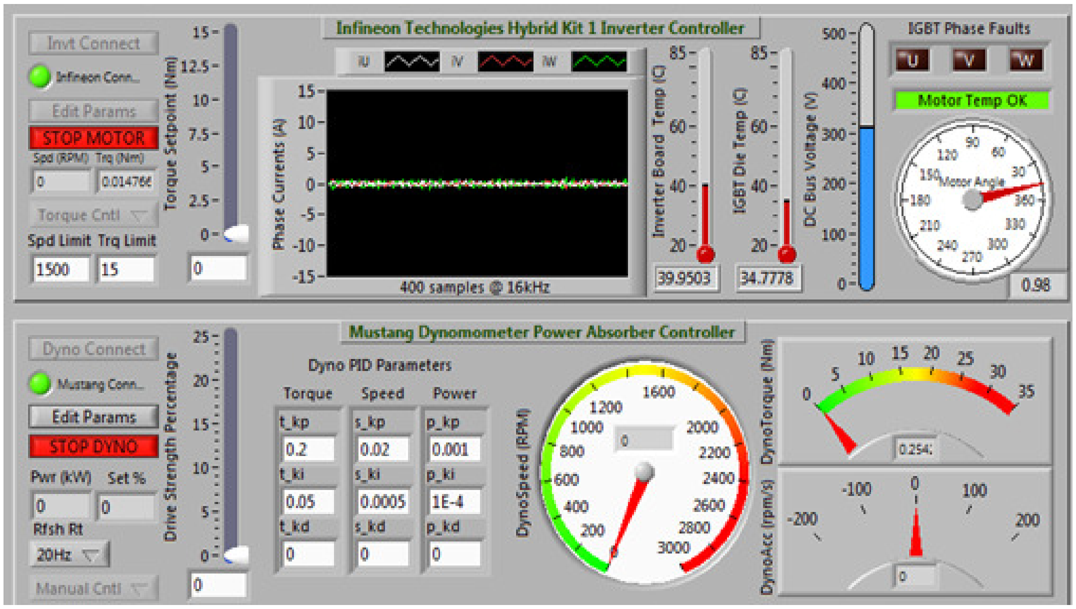

Figure 7. Inverter and dynamometer software control panels

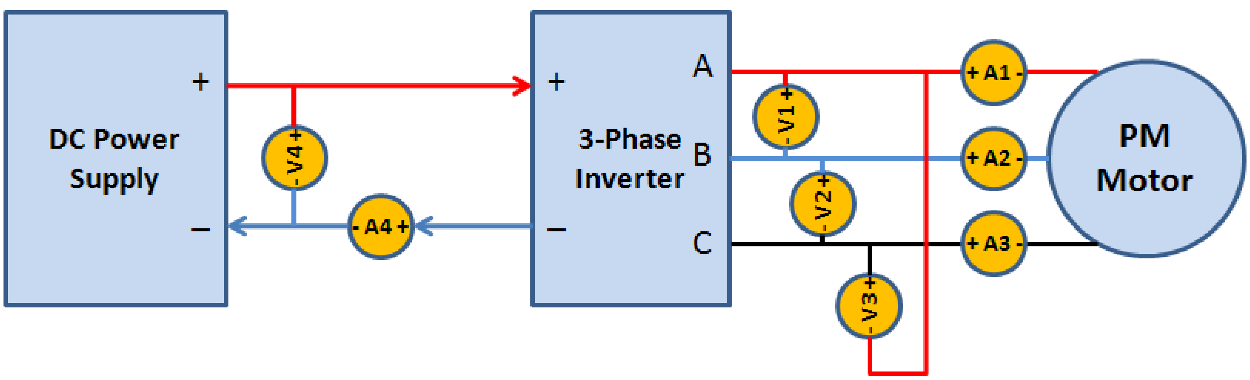

Figure 8. Yokogawa electrical power measurement connections

New Electrical Engineering Courses Utilizing the Green Mobility Laboratory

Two new courses utilizing the Green Mobility Laboratory are being developed for the ECE curriculum 1) *Design, Simulation, and Control of Power Electronic Circuits for Electric Drive Trains*, and 2) *Semiconductor Switching: Electrical and Thermal Effects*. Outlines of the course descriptions and laboratory time allocation for each course within the ECE curriculum are presented in Figures 9 and 10.

New ECE Course Outline (1): *Design, Simulation, and Control of Power Electronic Circuits for Electric Drive Trains*

- Introduction to the application and roles of power electronics in EV/HEV/PHEV drive trains.
- Analytical circuit design, simulation using Multi-Sim, control and testing with limitation for use in EV/HEV/PHEV systems highlighted
    - State variable models of traditional uni-directional, IGBT switched, pulse width modulated (PWM), DC-DC converters
    - State variable models of bi-directional, isolated, PWM, DC-DC converters
    - State space models of IGBT-switched DC-AC inverters under different PWM conditions
- Electromagnetic Interference (EMI) in electric drive trains.
- Review of commercially available power IGBT devices, power modules and testing methods.

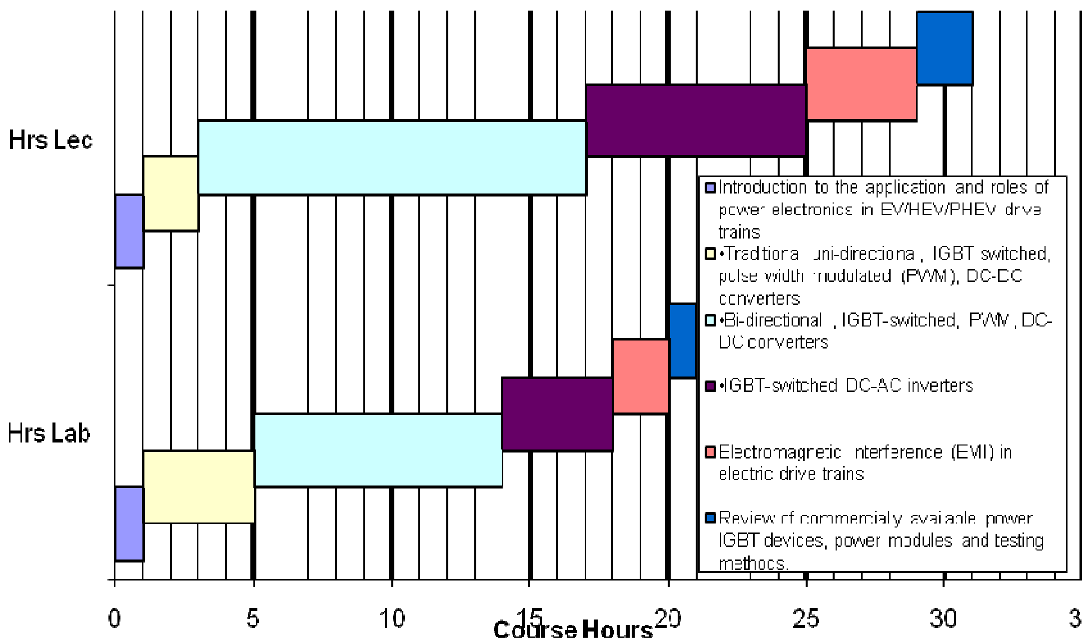

Figure 9. Design, Simulation, and Control of Power Electronic Circuits for Electric Drive Trains: Lecture and laboratory time allocation

New ECE Course Outline (2): *Semiconductor Switching: Electrical and Thermal Effects*

- Relationship between IGBT electrical heating, cooling system design and IGBT electrical behavior
- Introduction to power semiconductors, semiconductor internals & analytical models
- IGBT physical & electrical characteristics and IGBT parasitic effects
- Power losses in IGBT switches
- Analytical models of heat transfer due to power losses in IGBT switches by heat sinks with liquid cooling
- Design and simulation of IGBT cooling system for EV/HEV/PHEV
- Advanced IGBT cooling methods
- Impact of Silicon Carbide & other high-temperature semiconductors

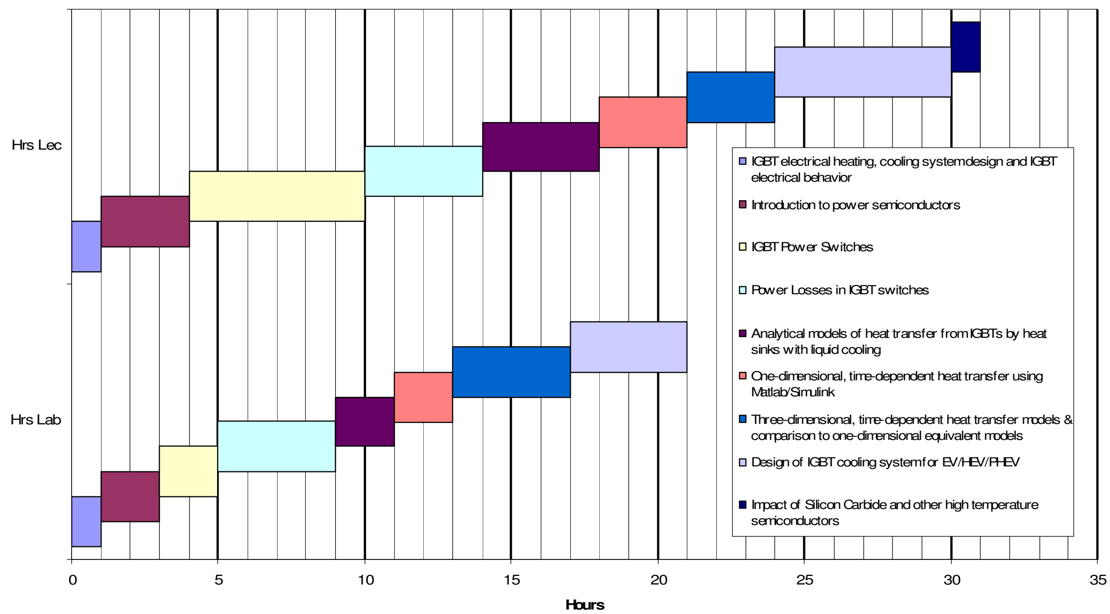

Figure 10. Semiconductor Switching: Electrical and Thermal Effects: Lecture and laboratory time allocation

A Green Mobility Laboratory sample hands-on laboratory exercise appropriate for students enrolled in the new ECE course, *Design, Simulation, and Control of Power Electronic Circuits for Electric Drives*, or for students enrolled in the existing ME course *Hybrid Electric Vehicle Propulsion* is presented in the appendix to this paper.

Conclusions

A Green Mobility Laboratory has been developed to support an Electrical, Computer, and Mechanical Engineering cross-disciplinary education program in transportation electrification. The design, implementation and utilization of this open-bench HEV drive train laboratory has been described within the ECE curriculum. The Green Mobility Laboratory supports hands-on undergraduate student experiments, faculty demonstrations, independent studies, and graduate student research projects in an effort to educate a new generation of engineers possessing the interdisciplinary knowledge and capabilities to meet the challenges of HEV development. Students achieve a basic understanding of HEV drive train design techniques, control algorithms, and testing methods and an appreciation for the complexity and real world constraints facing the transportation electrification industry.

Bibliography

1. G. Sovran & D. Blaser, "*A Contribution to Understanding Automotive Fuel Economy and Its Limits*"

Appendix

Green Mobility Laboratory Sample Exercise

HEV INVERTER DRIVE AND TRACTION MOTOR EFFICIENCY MAPPING

The purpose of this experiment is to characterize the efficiency of electric vehicle drive train components in the Green Mobility Laboratory over the full range of operating conditions for a given DC bus voltage. For each part of the experiment, you will be collecting electrical and mechanical power measurements at various torque loadings, while holding the speed constant.

On a torque vs. speed plot, a constant power will appear as a decaying exponential curve. The laboratory supply is limited to 5 kW (8.5 A at 600 V) of electrical power. This is illustrated by the yellow shaded area in Figure A-1. Note that running at lower DC bus voltages will enlarge this region. The mechanical losses of the dynamometer (while unloaded) are dominated by frictional losses (due to the large mass of the dynamometer's flywheel). The aerodynamic losses due to rotation are negligible. This is depicted by the blue shaded area in Figure A-1. The point where the yellow and blue regions intersect is the maximum unloaded speed of the system. For this experiment, you will operate the equipment between these two regions, collecting a data at regular torque and speed increments.

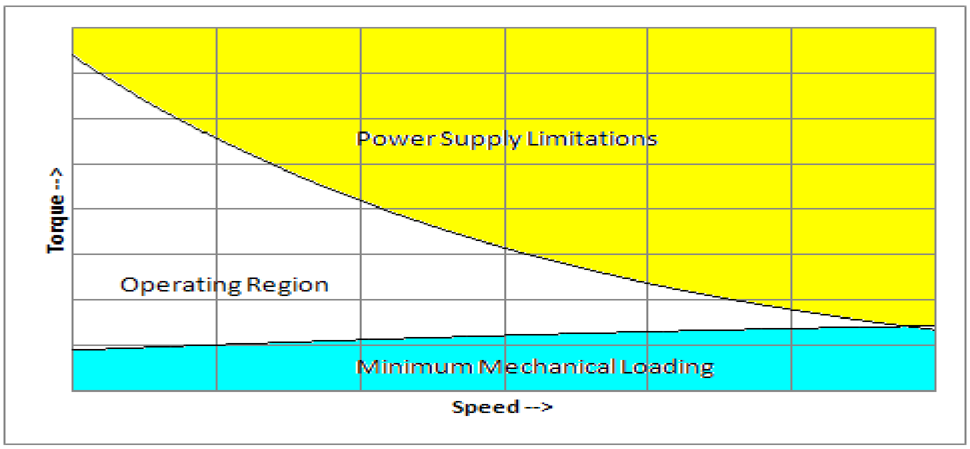

Figure A-1. Depiction of mechanical operating ranges

To begin, first apply power to the laboratory hardware equipment:

1. Pull the red emergency-stop switch out to supply power to the power supply and dynamometer controller.
2. Flip up the switch on the far left of the TDK-Lambda power supply to power the supply.
3. Press in the blue power switch on the bottom left of the Yokogawa power analyzer.

Once the laboratory equipment is powered, you can now run the Green Mobility Lab software (GrMoLab.exe) to connect the controller to each component:

1. To connect the hardware, click the "Connect" button in the upper left corner of each corresponding software pane. All devices except the inverter can be connected at this time.

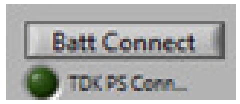

Figure A-2 Software “connect” button for power supply

2. To connect to the inverter, the 12 V logic must first be powered. In the coolant loop control pane, switch on the power to the inverter as well as the coolant pump. You should see the green power LED light up, both in the software panel as well as on the inverter hardware. You should now be able to connect to the inverter on the inverter software pane.

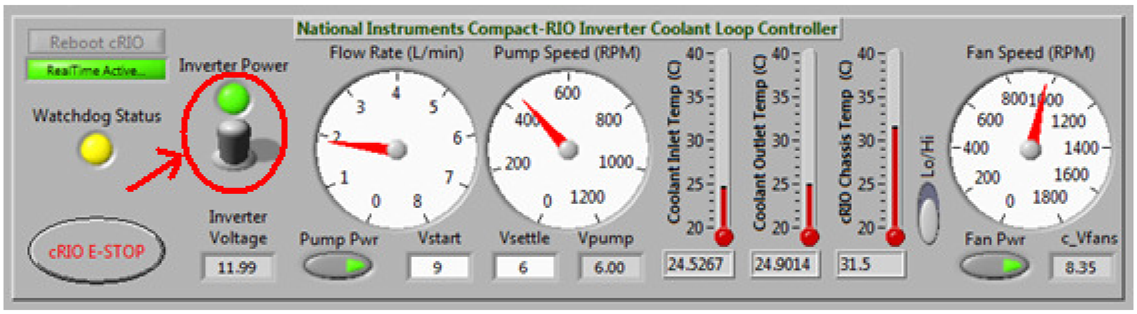

Figure A-3 Coolant loop control pane depicting inverter power

If you receive any connection errors, have your instructor assist you to check if the device is powered. In order for the dynamometer and power supply to operate, the main circuit breakers must be enabled.

Before running the equipment, you must ensure that the Yokogawa power analyzer’s Ethernet channel buffer is configured to transmit the appropriate data channels:

1. On the Yokogawa software pane, click the “Configure Channels” button. A dialog box listing all possible channels will open.
2. Check the boxes next to each channel to be logged. The channels needed for this laboratory exercise are: P4, PSIGM, TORQ1, SPE1, and PM1.
3. Click “Update Channel Buffer”. The screen will close. You should now see the selected channels displayed at the top of the Yokogawa software pane.

You are now ready to begin configuring the equipment. You must now set the operating modes of the power supply, inverter, and dynamometer:

1. In the power supply control pane, click the “Battery Chemistry” drop-down box to select the “Fixed Vltg” mode. This will disable the battery simulation, and run the supply as a fixed DC voltage source. You should also select a DC operating voltage at this time by entering a value into the “Vrtd” numeric box. Your instructor will inform you of what voltage to use.
2. In the inverter control pane, click the dropdown box to select “Speed Cntl”. This will command the inverter to maintain constant motor speed. You should also set the maximum inverter speed and torque values. The maximum achievable operating speed is a function of the DC bus voltage. Your instructor will tell you what speed to enter in the “Speed Lim” numeric box. In the “Torque Lim” numeric box, enter a value of “25” Nm.
3. In the dynamometer control pane, click the dropdown box to select “Torque Cntl”. This will command the dynamometer controller to apply fixed load torques to the motor.

Once the operating modes have been set, you can begin testing. You will collect data at constant speeds (starting at 500 RPM) with 2.5 Nm increasing torque intervals. Once the power supply limits have been reached, you will gradually remove the dynamometer loading, increase the motor speed by 500 RPM, and begin loading at 2.5 Nm intervals again. You will repeat this procedure until the entire Operating Region of Figure A-1 has been covered.

1. Enable the DC power supply by clicking the green "Enable Supply" button.
2. Enable the inverter by clicking the green "Start Motor" button.
3. Set the inverter set speed to 500 RPM. Wait for the motor to come up to speed.
4. Once at the desired speed, you can capture your first data point. This operating condition will represent a "no-load" point at the bottom of the Operating Region (limited by the mechanical loading of the inherent losses presented by the motor and dynamometer).
    a. To capture a data point, first switch over to the Yokogawa control pane.
    b. In the upper right corner, click the "Hdr → Clipbrd" button. This will copy all of the signal names to the Windows clipboard (this step only needs to be done once!).

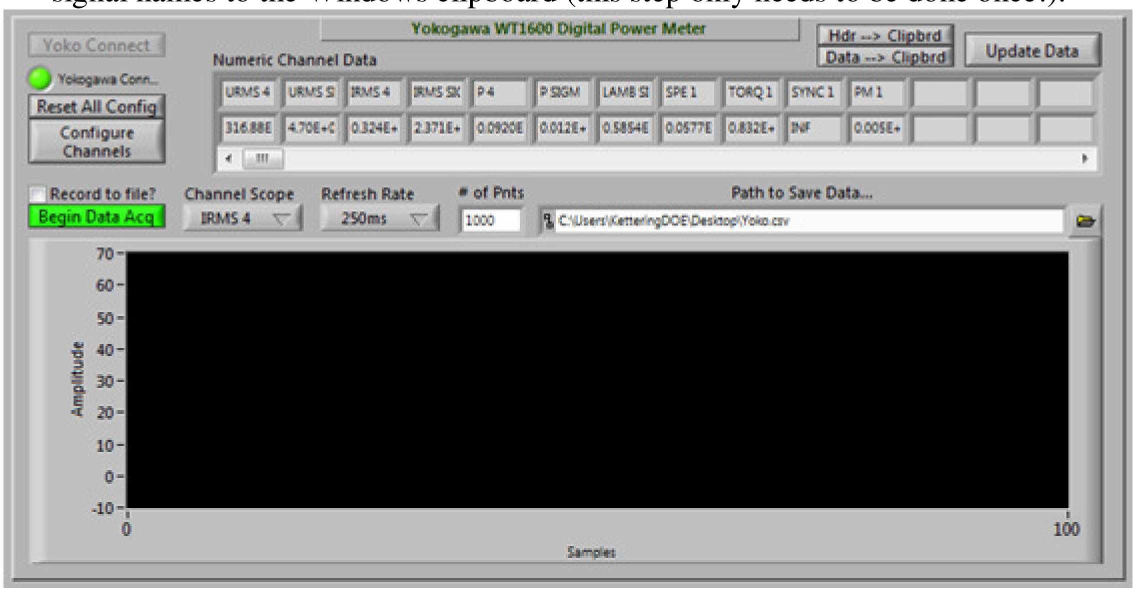

Figure A-4 Yokogawa software control pane

    c. Open Microsoft Excel and press Cntl+V to paste the signal names. This will make a header row for the data you will collect (this step only needs to be done once!).
    d. Next, press the "Update Data" button in the Yokogawa control pane to refresh the signal data in the software GUI.
    e. Now press the "Data → Clipbrd" button to copy all of the signal data to the Windows clipboard.
    f. Paste this data into the Excel sheet to log your first data point.
5. Once you have grabbed your first "no-load" data point, you can enable the dynamometer by clicking the green "Start Dyno" button. You should hear a relay click from the dynamometer's control box.
6. Set the dynamometer's torque set-point to an increment of 2.5 Nm (you may have to start from a torque value of 5 Nm due to excessive mechanical losses). Wait for the motor's speed to re-adjust to 500 RPM .
7. Capture the next data point and paste it into your Excel spreadsheet as in Step 4.

8. Continue increasing the dynamometer load, collecting data at every interval, until you are operating near the power supply's limits. This can be determined by examining the dc supply output current. If you are drawing near or above 7.5 A from the dc supply, you can then proceed to the next step to adjust the speed set-point.
9. Before adjusting the speed, gradually reduce the dynamometer load to zero. The motor should now be free-wheeling at the speed set-point once again. You can also disable the dynamometer at this time by pressing the red "STOP DYNO" button.
10. Adjust the speed, increasing it by 500 RPM. Wait for the motor to come up to speed.
11. Repeat this process, starting at step 4, by collecting the "no-load" data point, and the subsequent data points at increasing torque levels. Continue until you have reached the speed limit given by your instructor.

You should now have an Excel spreadsheet data set full of power measurements at varying torques and speeds covering the entire Operating Range of the system. The operating points at which you collected data should be *similar* to the points indicated on the graph below in Figure A-5.

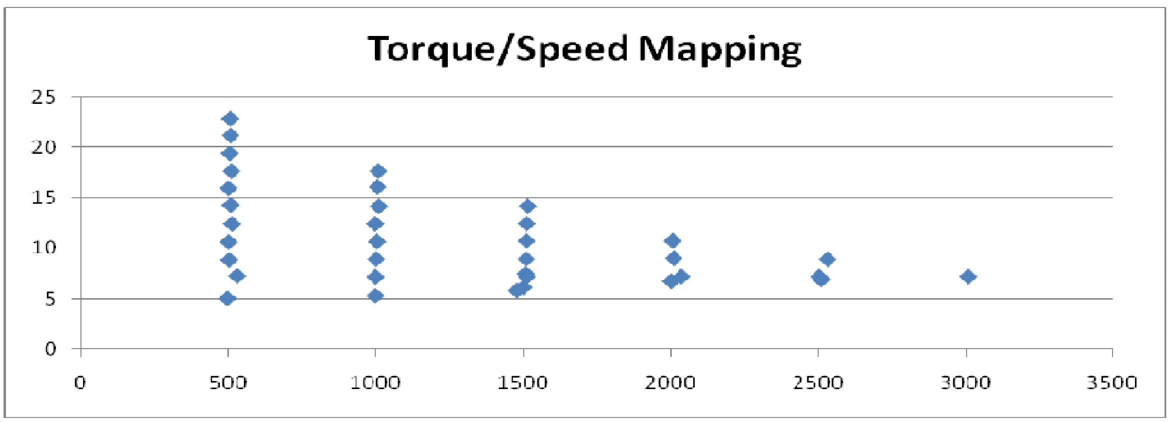

Figure A-5 Sample data collection operating points

Things to include in your write-up for this laboratory exercise:

- For the table of data you have collected, calculate the efficiencies of the 3-phase inverter and the permanent magnet synchronous motor. Place these data in separate columns.
- Using MATLAB, create contour maps of the efficiency versus torque on the y-axis and speed on the x-axis. Since your data isn't "perfectly" sampled at regular intervals, you will want to use the "GRIDDATA" command to interpolate all of your data before using the "CONTOUR" command.
- Multiply the two efficiencies found earlier together to get the over-all inverter-motor system efficiency. Create a contour plot of the over-all efficiency.
- Answer the following questions:
    - In what operating region is the inverter most efficient? In what operating region is the motor most efficient?
    - Looking at the over-all system efficiency contour map, which component appears to be more "dominant" in terms of power loss, the inverter or the motor? In other words, which efficiency plot does the over-all efficiency map more closely resemble? Why do you think so?

Green Mobility Laboratory Sample Exercise Data and Response

Example torque, speed, and power data at a DC bus voltage of 320V are shown below in Table A-1. The calculated efficiencies for the inverter and motor are also shown.

Table A-1. Sample laboratory exercise experimental data

Spd (RPM)	Trq (Nm)	Pdc (W)	Pac (W)	Pmt (W)	InvEff (%)	MotEff (%)
493.6	3.396	379.6	270	51	0.706189	0.188889
527	5.83	566.4	415	197	0.73006	0.474699
500.4	7.804	658.9	481	284	0.726816	0.590437
499.1	9.886	791.1	575	392	0.724874	0.681739
511.1	11.841	945.3	683	509	0.720356	0.745242
505.7	14.138	1088.3	777	624	0.712174	0.803089
499.5	16.008	1219.1	862	713	0.70531	0.827146
505	17.793	1374.6	963	816	0.697703	0.847352
503.1	19.828	1527.8	1048	920	0.684328	0.877863
504.2	21.706	1697	1152	1021	0.677515	0.886285
505.2	23.455	1858.9	1254	1116	0.672612	0.889952
994.7	3.385	688.1	555	228	0.803285	0.410811
997.4	5.558	934.2	741	456	0.791001	0.615385
1000.6	7.574	1159.3	915	669	0.78748	0.731148
1001.1	9.687	1385	1079	891	0.777408	0.825765
997.5	11.768	1612.7	1236	1104	0.765519	0.893204
1008.2	13.735	1858.6	1401	1325	0.752738	0.945753
1003.6	15.767	2115.1	1564	1532	0.737537	0.97954
1499.1	4.183	1136.1	948	532	0.832622	0.561181
1507.2	5.57	1383.5	1147	754	0.827548	0.657367
1479.6	3.598	1071.5	892	433	0.83019	0.485426
1509.4	5.294	1334.8	1109	712	0.829039	0.64202
1507.5	7.254	1653.4	1356	1020	0.819236	0.752212
1510	9.396	1985.7	1602	1361	0.805532	0.849563
1510.9	11.439	2304.8	1825	1685	0.790542	0.923288
1513.5	13.349	2628.8	2040	1991	0.77464	0.97598
2002	4.103	1612.5	1378	760	0.852935	0.551524
2036	4.88	1744.8	1487	916	0.850819	0.616005
2011.2	6.966	2122.8	1807	1342	0.850523	0.742667
2007.1	9.005	2524.8	2107	1768	0.833488	0.839108
2510.7	3.935	1981.9	1757	910	0.885324	0.517928
2505.3	4.392	2088	1814	1027	0.867395	0.566152
2535.8	6.433	2610.3	2232	1584	0.853885	0.709677
3016.6	3.549	2470.6	2188	996	0.884663	0.45521

Example MATLAB generated contour plots of the inverter efficiency, motor efficiency, and over-all system efficiency are shown in Figures A-6, A-7, and A-8, respectively.

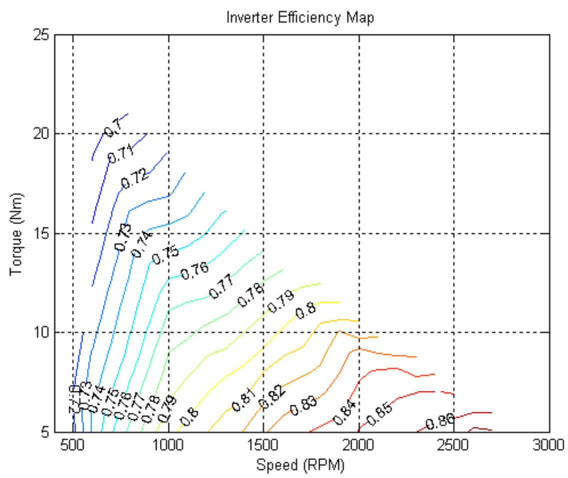

Figure A-6. Inverter efficiency map

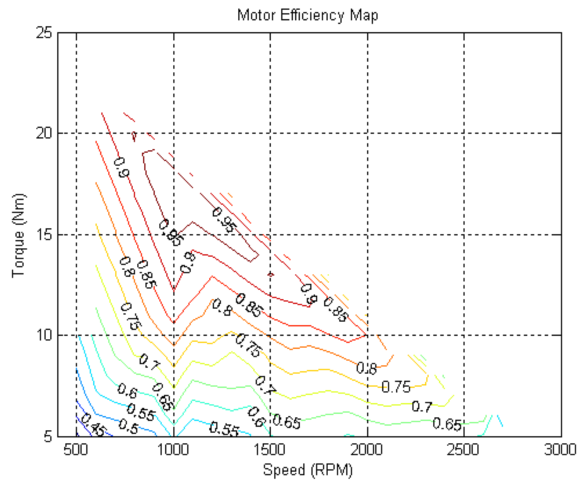

Figure A-7. Motor efficiency map

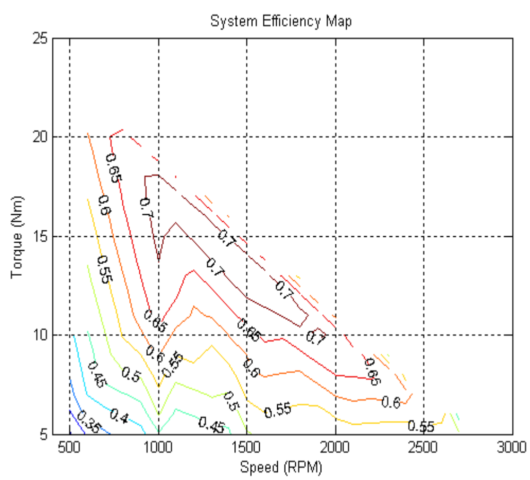

Figure A-8. System efficiency map

Looking at Figure A-6, the inverter is shown to be most efficient at high speeds and low torques. At low torques, the output current is low, thus the I^2R losses are minimized. At high speeds, the back-EMF of the motor is considerably large, such that the amplitude modulation index of the inverter is close to 1. This helps to reduce harmonic content. Figure A-7 shows that the motor is most efficient in the mid-speed range, and high torque. At high speeds and low torques, friction and windage losses reduce output power. At low speeds and low torques, little power is produced, thus the loss-terms begin to dominate.

Looking at the over-all system efficiency plot of Figure A-8, it most closely resembles the motor efficiency plot. The motor efficiency has a much larger swing over the operating ranges since it is being operated near the "edges" of the operating region (near-zero torques and speeds). At these locations, the power, and thus the efficiency, must be zero.