An Education Program for Transportation Electrification

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***Abstract*—Automotive industry is going through major changes and there is an evolving paradigm shift in transportation toward more electric vehicles (MEV). This paper presents a comprehensive program to educate students and engineers for the new generation of vehicles. The proposed program includes four courses with laboratories: (1) Power Electronics, (2) Electric Motor Drives, (3) Vehicular Electrical Systems, and (4) Electric and Hybrid Drive Trains. It also includes an interprofessional project course to enhance multi-disciplinary understanding and capabilities of the students. Each laboratory consists of several experiments, one research projects demonstration, and one major design experience. The laboratory experiments give simple practical introduction to operation and control of advanced vehicular components as well as power and propulsion systems. They are done in groups of 2-3 students. The proposed courses are appropriate for senior-level undergraduate or graduate engineering students.**

***Index Terms*—Automotive systems, drive trains, electric machines, electric motor drives, electric vehicles, engineering education, hybrid electric vehicles, interprofessional projects, modeling, plug-in vehicles, power electronics, power engineering, propulsion, real-world design, student experiments, vehicles.**

I. Introduction

Our current transportation systems are heavily based on the century-old technology of internal combustion engine (ICE). Electrification is a clear trend to improve efficiency, performance, and sustainability of transportation systems. More electric vehicle (MEV) concept is based on utilizing more and more electric and electronic systems instead of or in combination with mechanical, hydraulic, and pneumatic systems. Electrified vehicles range from conventional cars with low-power electric and electronic systems, to mild hybrids, to full hybrids, to plug-in hybrids, and to all-electric vehicles.

The long-term transportation electrification goal is to integrate the transportation industry with the electric power industry, generate electricity from Carbon-free and renewable energy sources, and use the electricity in transportation. Electricity is cleaner, greener, more affordable, and domestically produced. As the electrification levels are increased in cars, the electric power grid is getting cleaner and greener as well since more renewable energy sources provide power to the grid.

This is in fact an evolving paradigm shift in transportation industry, which is in dire need of a new generation of engineers. Therefore, the automotive industry urgently needs engineers who understand the fundamentals of electro-mechanical systems, power electronics, and electric motor drives.

At Illinois Institute of Technology (IIT) and Texas A&M University, we have developed a comprehensive program to address this dire need of the automotive industry. This paper presents four different courses and laboratories that we have developed in order to educate undergraduate and graduate students in the multi-disciplinary areas of the automotive systems.

Two proposed courses on the subjects of electric and hybrid drive trains and vehicular electrical systems were initially developed at Texas A&M University and have evolved since 1998 with the feedback received from the students and engineers in the automotive industry. These two courses are specifically focused on electrified vehicles and have been offered as graduate-level courses. They could also be offered at the undergraduate senior level.

The other two courses are undergraduate senior-level courses with hands-on laboratory experiments, which are focused on power electronics and electric motor drives. These courses and laboratories have been developed at Illinois Institute of Technology with the support of generous gifts from the Grainger Foundation. In addition, the proposed program includes an interprofessional project course, which engages multi-disciplinary teams of students in semester-long projects.

II. Power Electronics Course with Laboratory

This is a senior-level, four-credit hour undergraduate or first-year graduate-level course with three hours of lecture and three hours of lab session per week. The purpose of this introductory course in power electronics is to give an overview of the major aspects of switching power devices and circuits. Operating principles of different electronic switches as well as converters such as rectifiers, choppers, and inverters are presented. Applications of power electronics

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are explained. Guidelines to design proper switching circuits are also established. Table I presents the course outline. [1] is the proposed textbook and [2] presents automotive application examples used in this course.

The laboratory for this course consists of 14 hands-on experiments, one research projects demonstration, and one major design experience [3]. Laboratory sessions are:

- Exp. 1: Power Diode and Thyristor
- Exp. 2: Diac and Triac
- Exp. 3: Power Transistor, Power MOSFET, and IGBT
- Exp. 4: UJT, Pulse Transformer, and Firing Circuits
- Exp. 5: Single-Phase AC/DC Rectifiers
- Exp. 6: Single-Phase Full-Wave AC/DC Rectifiers
- Exp. 7: Three-Phase AC/DC Rectifiers
- Exp. 8: Single-Phase AC Voltage Controllers
- Exp. 9: Three-Phase AC Voltage Controllers
- Exp. 10: DC/DC Converters and PWM Techniques
- Exp. 11: Four-Quadrant DC/DC Converters (Inverters)
- Exp. 12: Buck, Boost, and Buck-Boost Converters
- Exp. 13: Voltage and Current Mode Control Techniques
- Exp. 14: Flyback and Forward Converters

In order to meet the course objectives, after completing this course, the student should be able to do the following things correctly.

1. Given a power semiconductor device such as power diodes, thyristors, power transistors, power MOSFETs, diac, triac, GTOs, IGBTs, and UJTs, draw the *v*-*i* characteristics and analyze the switching behavior.
2. Given a power electronic circuit including power diodes and thyristors, determine time intervals when the semiconductor devices are ON and OFF, draw the equivalent circuits for ON and OFF time intervals, analyze the circuit, and find RMS, average, harmonics, THD, and CF of the current and voltage signals.
3. Given a half-wave/full-wave controlled/uncontrolled single-phase AC/DC rectifier, find the voltage and current waveforms and analyze the equivalent circuits.
4. Given a half-wave/full-wave controlled/uncontrolled three-phase AC/DC rectifier, find the voltage and current waveforms and analyze the equivalent circuits.
5. Derive and apply the relevant equations of DC/DC converters: Buck, Boost, and Buck-Boost converters in continuous-conduction and discontinuous-conduction mode of operation.
6. Derive and apply the relevant equations of DC Switching Power Supplies: Flyback and Forward converters in continuous-conduction and discontinuous-conduction mode of operation.
7. Given a PWM/square-wave, single-phase/three-phase DC/AC inverter, find the voltage and current waveforms and analyze the equivalent circuits.
8. Derive and apply the relevant equations of single-phase and three-phase AC voltage controllers including power diodes and thyristors.

TABLE I
POWER ELECTRONICS COURSE SCHEDULE

Week	Topic
#1	Introduction to power electronics
#2	Power semiconductor devices, power diodes, thyristors, commutation techniques, power transistors, power MOSFETs, diac, triac, GTOs, IGBTs, UJTs, power computations and definitions, modeling, and simulations
#3	Single-phase, half-wave rectifiers
#4	Single-phase, full-wave rectifiers
#5	Single-phase, full-wave rectifiers Three-phase, half-wave rectifiers
#6	Three-phase, full-wave rectifiers Mid-Term Exam 1
#7	AC voltage controllers
#8	DC/DC converters Buck converter
#9	DC/DC Boost and Buck-Boost converters
#10	Discontinuous conduction mode of operation Mid-Term Exam 2
#11	DC power supplies Flyback converter
#12	Forward converter
#13	DC/AC inverters
#14	PWM techniques
#15	Three-phase inverters, applications in industrial electronics, switching power supplies, automotive systems, conclusions
	Final Exam

Assessment criteria are

1. Seventy-five percent of the class should have a semester average of C or better.
2. Seventy percent of the class should meet five of the eight objectives.

III. Electric Motor Drives Course with Laboratory

This is a senior-level, four-credit hour undergraduate or first-year graduate-level course with three hours of lecture and three hours of lab session per week. The purpose of this course is to present the basic principles of electric motor drives. Techniques to select proper electric motors for different applications based on the characteristics of the machines are also established. Furthermore, designing the suitable power electronic converters and their controllers for industrial and propulsion drives are presented. Drives for induction motors, brushless DC, switched reluctance, and electronic low-power motors are explained. In addition, several examples in propulsion systems, home appliances, electronic drives, advanced vehicles, and industrial automation systems are presented. Table II presents the course outline. [4] and [5] are the proposed reference books and [2] presents automotive application examples used in this course.

The laboratory for this course consists of 14 hands-on experiments, one research projects demonstration, and one major design experience [3]. Laboratory sessions are:

- Exp. 1: Characteristics of DC Motors: Shunt and Separately-Excited
- Exp. 2: Characteristics of DC Motors: Series and Compound
- Exp. 3: Characteristics of DC Generators
- Exp. 4: Phase-Controlled DC Motor Drives
- Exp. 5: Control of DC Motors Using DC/DC Converters
- Exp. 6: Three-Phase Induction Machines
- Exp. 7: Load Characteristics of Induction Motors
- Exp. 8: Phase-Controlled Induction Motor Drives
- Exp. 9: Inverters to Control Induction Motors
- Exp. 10: Synchronous Generators
- Exp. 11: Fault Analysis in Electric Machines
- Exp. 12: Real-Time dSPACE Implementation of DC Motor Drives
- Exp. 13: Real-Time Control of DC Motor Drives using dSPACE
- Exp. 14: Frequency Control of Induction Motor Drives

TABLE II
ELECTRIC MOTOR DRIVES COURSE SCHEDULE

Week	Topic
#1	Introduction to electric motor drives and review Fundamentals of electromagnetism, electro-mechanical power transfer systems, mechatronics
#2	DC machines, motors and generators, separately-excited, shunt, series, and compound machines, universal motors, torque-speed characteristics, equivalent circuits, speed control of DC motors
#3	Three-phase induction machines, motors and generators, torque-speed characteristics, equivalent circuits, braking, speed control
#4	Synchronous machines, torque characteristics, modeling, permanent-magnet synchronous machines (PMSM), speed control
#5	Review of solid-state devices, power electronic drivers for electric machines Mid-Term Exam #1
#6	Phase-controlled DC motor drives, braking
#7	Control of DC machines using DC/DC converters, other DC motor drives
#8	Phase-controlled induction motor drives
#9	Frequency-controlled induction motor drives, introduction to vector control of induction motor drives and field oriented control (FOC)
#10	Single-phase induction motors
#11	Other single-phase AC motor drives
#12	Stepper motors Mid-term Exam #2
#13	Switched reluctance motor (SRM) drives
#14	Brushless DC (BLDC) motor drives
#15	Low-power electronic motor drives, conclusions
	Final Exam

In order to meet the course objectives, after completing this course, the student should be able to do the following things correctly.

1. Given an electromechanical system including an electric machine and a mechanical load with different torque-speed characteristics, find torque, acceleration, speed, position, and power.
2. Given an energy conversion system, using fundamentals of electromagnetism, draw and analyze the equivalent electric circuit.
3. Derive and apply the relevant equations of electric DC machines: motors and generators, separately-excited, shunt, series, and compound machines as well as universal motors.
4. Derive and apply the relevant equations of three-phase induction machines: motors and generators. Analyze the fundamental operation and starting of single-phase induction motors.
5. Derive and apply the relevant equations of multi-phase permanent-magnet synchronous motors and three-phase synchronous generators.
6. Given an electric power source, a DC motor, and a mechanical load, design power electronic drivers using phase-controlled AC/DC rectifiers as well as DC/DC converters and analyze all operating modes.
7. Given an electric power source, a three-phase induction motor, and a mechanical load, design power electronic drivers using phase-controlled AC/AC converters as well as DC/AC inverters and analyze all operating modes.
8. Derive and apply the fundamental equations of special motor drives: switched reluctance, stepper, brush-less DC, and electronic motor drives.

Assessment criteria are

1. Seventy-five percent of the class should have a semester average of C or better.
2. Seventy percent of the class should meet five of the eight objectives.

IV. Vehicular Electrical Systems Course

The more electric vehicles (MEV) concept is based on utilizing electric power to drive vehicular subsystems, which historically have been driven by a combination of mechanical, hydraulic, pneumatic, and electric power transfer systems. Increasing use of electric power is seen as the direction of technological opportunity for vehicle power systems based on rapidly evolving technology advancements in power electronics, fault tolerant electrical power distribution systems, and electric-driven machines. This course addresses the unique characteristics of these unconventional power systems, current status, and future trends in automotive, aerospace, and naval industries.

Conventional electrical power systems of land, sea, air, and space vehicles are detailed along with the scope for improvement. New electrical loads and advanced distribution system architectures of electric and hybrid electric vehicles are presented. Current trends in the vehicular industry, such as high-voltage electrical systems for hybrid and plug-in hybrid electric vehicles, are explained.

This course is a three-credit hour course at the graduate level, which could also be offered as a senior-level undergraduate course with three hours of lecture per week. [6] is the textbook for this course. Major lectures are:

- Introduction to Electrical Power Systems
- Fundamentals of Power Electronics
- Electric Machines
- Automotive Electrical Power Systems
- Electric and Hybrid Electric Vehicles
- Plug-in Hybrid Electric Vehicles
- Aircraft Power Systems
- Space Power Systems
- Sea and Undersea Vehicles
- Fuel Cell Vehicles
- Electrical Modeling Techniques for Energy Storage Devices
- Multi-Converter Vehicular Dynamics and Control
- Effects of Constant Power Loads in Vehicular Systems

V. Electric and Hybrid Drive Trains Course

This is an advanced three-credit hour graduate-level course that could also be offered at the undergraduate senior level. This course has been evolved since 1998, when Professor Ehsani stared his first lecture on “Advanced Vehicle Technologies – Design Methodology of Electric and Hybrid Electric Vehicles” to graduate students in mechanical and electrical engineering at Texas A&M University.

This course deals with the fundamentals, theory, and design of conventional cars with internal combustion engines (ICE), electric vehicles (EV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and fuel cell vehicles (FCV). It comprehensively presents vehicle performance, configuration, control strategy, design methodology, modeling, and simulation for different conventional and modern vehicles based on the mathematical equations. The course also includes vehicle system analysis, ICE based drive trains, EV design, HEV configurations, electric propulsion systems, series/parallel/mild hybrid electric drive train design methodologies, energy storage systems, regenerative braking, fuel cells and their applications in vehicles, and fuel cell hybrid electric drive train design. This course emphasizes the overall drive train system and not just specific components. The design methodology is described by mathematical equations step by step. Furthermore, in explaining the design methodology of each drive train, design examples are presented with simulation results. [7] is the textbook for this course and major lecture topics, according to the textbook outline, are:

- Environmental Impact and History of Modern Transportation
- Fundamentals of Vehicle Propulsion and Brake
- Internal Combustion Engines
- Electric Vehicles
- Hybrid Electric Vehicles

- Electric Propulsion Systems
- Design Principle of Series (Electrical Coupling) Hybrid Electric Drive Train
- Parallel (Mechanical Coupling) Hybrid Electric Drive Train Design
- Design and Control Methodology of Series/Parallel (Torque and Speed Coupling) Hybrid Drive Train
- Design and Control Principle of Plug-in Hybrid Electric Vehicle (PHEV)
- Mild Hybrid Electric Drive Train Design
- Peaking Power Sources and Energy Storages
- Fundamentals of Regenerative Breaking
- Fuel Cells
- Fuel Cell Hybrid Electric Drive Train Design
- Design of Series Hybrid Drive Train for Off-Road Vehicles

We are in the process of developing a teaching laboratory for this course, which will include 12 experiments, one research project demonstration, and one major design project. Third edition of textbook [7], to be published in 2012, will include a detailed description of the laboratory experiments.

VI. Interprofessional Projects (IPRO) Course

Illinois Institute of Technology's interprofessional project (IPRO) course engages multi-disciplinary teams of students in semester-long projects. It provides a student team format for organizing an ongoing series of progressive, cumulative project experiences that advance both learning and research associated with advanced automotive power and propulsion systems.

This multi-disciplinary experiential approach is based on IIT's two-semester undergraduate general education requirement that accommodates students from all disciplines and professional programs, and students from the sophomore level through graduate school as part of a team. Through successive semester-long IPRO team experiences, students become familiar with the role of electrical systems in advanced automotive power and propulsion platforms, and they use simulations, actual conversions, and experimentation to investigate their potentials and limitations [8]-[11].

VII. Conclusion

Transportation electrification is the best practical solution to improve efficiency and sustainability of transportation systems. This paper presents an education program to train undergraduate and graduate students in the areas of electric, hybrid, and plug-in hybrid electric vehicles. The proposed program is based on several courses and hands-on laboratory experiments that have been developed at Illinois Institute of Technology and Texas A&M University.

References

[1] D. W. Hart, *Power Electronics*, New York, NY: McGraw-Hill, ISBN 978-0-07-338067-4, 2010.

[2] A. Emadi, *Handbook of Automotive Power Electronics and Motor Drives*, New York, NY: Marcel Dekker, ISBN: 0-8247-2361-9, May 2005.

[3] A. Emadi, "Grainger power electronics and motor drives laboratories at Illinois Institute of Technology," in *Proc. 2005 IEEE Power Engineering Society General Meeting*, San Francisco, CA, June 2005.

[4] M. A. El-Sharkawi, *Fundamentals of Electric Drives*, 1st Edition, PWS Pub. Co., ISBN: 0-534-95222-4, 2000.

[5] R. Krishnan, *Electric Motor Drives: Modeling, Analysis, and Control*, 1st Edition, Prentice Hall, ISBN: 0-13-091014-7, 2001.

[6] A. Emadi, M. Ehsani, and J. M. Miller, *Vehicular Electric Power Systems: Land, Sea, Air, and Space Vehicles*, New York, NY: Marcel Dekker, ISBN: 0-8247-4751-8, Dec. 2003.

[7] M. Ehsani, Y. Gao, and A. Emadi, *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design, Second Edition*, Boca Raton, FL: CRC Press, ISBN: 978-1-4200-5398-2, Aug. 2009.

[8] A. Emadi and T. M. Jacobius, "Interprofessional projects in advanced automotive power systems: an integrated education and research multidisciplinary approach," *IEEE Transactions on Education*, vol. 47, no. 3, pp. 356-360, Aug. 2004.

[9] S. Sadiq, T. M. Jacobius, and A. Emadi, "Automotive interprofessional projects (IPRO®) program at Illinois Institute of Technology," *Society of Automotive Engineers (SAE)*, Paper No. 2005-01-3465, 2005; and, in *Proc. SAE 2005 Future Transportation Technology Conference*, Chicago, IL, Sept. 2005.

[10] T. M. Jacobius, F. Ruiz, and G. S. Voland, "Strengthening undergraduate curricula via interprofessional learning experiences," *National Collegiate Inventors and Innovators Alliance (NCIIA) Annual Conf.*, Washington, DC, March 2000.

[11] T. M. Jacobius and G. S. Voland, "Crossing professional boundaries: the interprofessional projects program at IIT," *American Society for Engineering Education Annual Conf.*, St. Louis, MO, June 2000.