Educational Development and Skills in Clean Mobility at IFP School

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Abstract. In this paper, we explore the innovative academic initiatives at IFP School, France, designed to equip master's degree students with essential skills for advancing clean mobility. We highlight the dynamic evolution of our educational programs in response to the global energy transition, providing detailed insights into course structures that focus on sustainable mobility, electrification, and smart grids. Our curriculum is uniquely integrated with practical training methods, including virtual reality, laboratory experiments, and extensive industry collaborations. This comprehensive approach ensures that our graduates are well-prepared to meet the current and future demands of the rapidly evolving automotive and energy sectors.

Keywords :Clean mobility, electric vehicles, hybrid powertrains, sustainable mobility, virtual reality training, energy transition, battery recycling.

1. Introduction

Under the increasing imperative for electrification and sustainable energy solutions, universities worldwide are revising their academic programs to include a broader range of courses and initiatives centered on electrification. This strategic shift aims to equip students with the skills necessary to contribute to the global transition towards a greener future.

To enhance their electrification programs, universities are forming strong collaborations with industry leaders, research, and governmental organizations. These partnerships provide students with opportunities for internships, research projects, and practical experience with electrification technologies.

Universities are also fostering a culture of research and innovation in the electrification field, encouraging the development of new technologies, improvement of existing systems, and creation of innovative solutions for sustainable electrification.

Additionally, universities are organizing practical training sessions, workshops, and simulation exercises to help students gain relevant problem-solving skills. They are addressing policy and regulatory aspects to provide students with a comprehensive understanding of the subject.

IFP School [1; 2] has expanded its programs to include electrification, offering courses related to energy and electric powertrains, batteries and power electronics, energy markets, sustainable mobility, and smart grids. These programs focus on preparing future engineers to design and implement innovative solutions.

To remain competitive, IFP School's programs are built on three pillars: evolving towards new international academic partnerships, cultivating new industrial partnerships, and continuously updating program content. This paper highlights the evolution of teaching programs at IFP School, emphasizing courses that have received positive feedback and are successfully delivered in our engineering and research Master's programs.

The practical components include electrical test benches with electric machines and power converters, data processing using Matlab on high-power machines, and a focus on battery recycling. Examples of these practical components have been introduced in the Master's programs at IFP School to provide students with hands-on experience in electric machines, data processing, and sustainable practices like battery recycling.

2. Evolution of Teaching Programs at IFP School

At IFP-School it is given a high importance to the dialogue between industry and academic worlds: from one side the School can get aware about the needs of industry, the technological-state-of-art of the field and gain a wider overview on a given domain; on the other side, it is the role of the School to be able to process all this information to build a structured and consistent teaching program for the students to make them fully operational in industry at the end of schooling. To make this approach a virtuous one, students have to face and deal as much as possible with environments and situations that professional engineering encounter in their daily lives.

Furthermore, based on the lessons learned in dealing with the transformation of automotive propulsion systems underway in recent years (see [10]), the teaching programs at the School allow to the students to get into the fundamental knowledge of different domains of an EV powertrain, without neglecting the overall system knowledge, and in a particular way paying attention to understand the interfaces between the different engineering specialties (e.g. electrochemical engineer, electrical engineer, …) and within them the different professions (e.g. testing engineer, simulation engineer, …). This last aspect, which streamlines the interaction among

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teams, is fundamental in the today industry in which the system are more and more integrated and project development times increasingly short.

In this section, we give an overview on tools and methodologies we are using at IFP School in laboratory, virtual reality, and computer sciences halls to perform the learning and expertise technics for engineers. The main purpose of these technics consists of exposing and practicing the whole process, from the global architecture to specific subsystems, of green mobility transformation (for details and standards see [3]). An example of a powertrain structure transformation of a generic passenger car growing up toward green mobility, with the representation of the required subsystems for building it, is given in Figure 1.

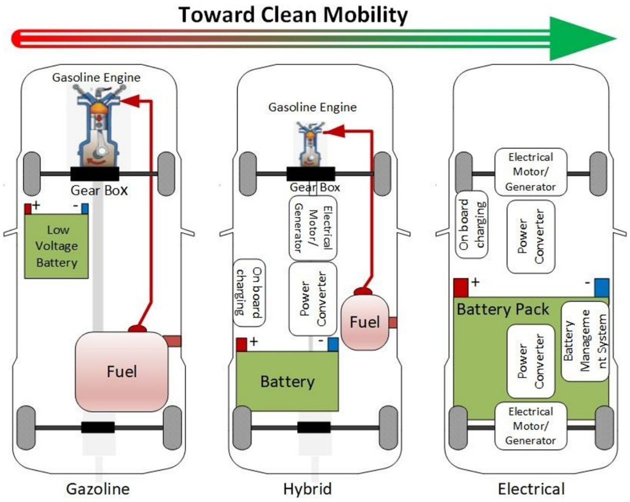

Figure 1: Vehicle electrification

2.1 Vehicle electrification architecture

At the IFP School, we are using Virtual Reality (VR) experience to introduce students to vehicle electrification. This choice was retained to bypass the risks related to high voltage systems, while maintaining the immersive experience of visualization and manipulation of components. For this purpose, three successive teaching modules are proposed to the students to explain the architecture of hybrid and electrical vehicles. To validate an activity the student must be able to identify and assembly all the subsystems that make up the global system. The three activities proposed with VR are:

- Plug-in Hybrid Electrical Vehicle (PHEV): We consider for this activity a series/parallel complex hybrid transmission powertrain including gasoline engine and electrical motors. Students identify, first the different subsystems of the global system and connect them virtually to get finally to an animated system, showing all the power flows and exchanges in the PHEV.

- Electrical Vehicle (EV): For this activity, a four-wheel drive example is considered by using three electrical motors for traction. Also, students identify all elements of this system, which are thermal circuit, the power DC/AC inverters and DC/DC converters, electrical motors, on board charger, electrical connectors, and bus bars. The power flow of the system can be animated virtually when all the subsystems are well connected.

- Battery Pack and Management System: This activity concerns the vehicle battery pack composition and its management system. Starting from unitary battery cells, students can build, virtually, modules by connecting cells in series or/and in parallel, according to the battery required voltage and capacity, then assembly modules by means of busbars, and finalize the complete pack with safety and management systems.

Figure 2 gives an example of an electrical vehicle included in this activity. VR experiences users are invited first to identify the main components of this architecture and then connect them properly to finally show the power flowchart.

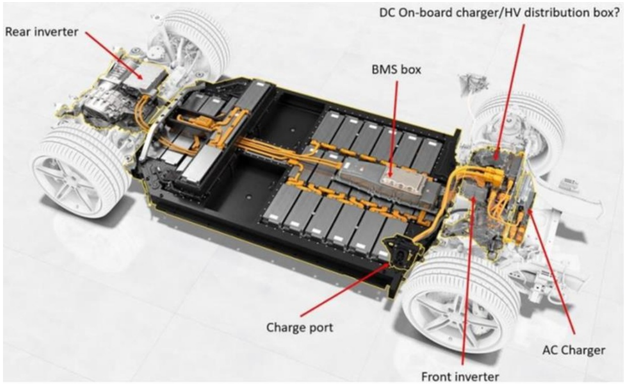

Figure 2: example of VR of an EV

2.2 Power converters characterization and control

This sub-section considers the study of power electronic converters commonly present in EV powertrains (see [11]), this includes choppers and inverters. To make the student manipulation possible, extra-low voltage are considered in laboratory for tests. The goal of this teaching activity is twofold:

- Make students comfortable with the comparison between the theoretical evolution of the variables in terms of voltage and current in switches and diodes seen during the lectures and the real ones observed at the bench,
- Evaluate how the converters behaves when supplying electric power. For this, R, RL and DC and AC electric motors are used as loads.

In addition to the before mentioned loads, experimental equipment includes adjustable DC power supply, representing the EV battery, a fully flexible power converter made up of six IGBT, Figure 3, and a software dictating the control strategy of the switches.

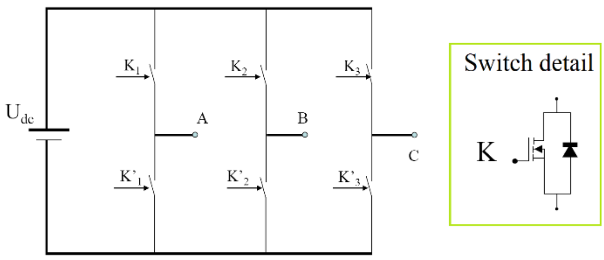

Figure 3: schematic of power electronic converter

Thanks to the flexibility of the above-mentioned facility, the converters studied can range from simple buck and 4Q choppers to 1f and 3f inverters. Dedicated measurements instruments provide detailed access to current and voltage data within the system, as well as to the Fast Fourier Transform (FFT) of signals.. The software's versatility allows for the implementation of various control strategies depending on the type of converter being studied. For instance, in the case of a 3ϕ inverter, control strategies can range from full-wave control to Sinusoidal Pulse Width Modulation (SPWM) control. For any given setup it is finally possible to adjust the operating conditions of the system, highlighting specific aspects such as control performance, control limitations, harmonics contents of the signals, …

2.3 Electrical machines characterization and control

This sub-section focuses on the characterization and control of electrical motors, which are a crucial component of electrification. The major objective of these activities is to assist students to match system and module requirements by selecting appropriate control strategies and accurately identifying motor characteristics .

Two types of electrical motors are widely used for vehicle electrification synchronous AC motors and induction motors. Synchronous AC motors, which make up approximately 80% of plug-in hybrid electric vehicle (PHEV) and electric vehicle (EV) production, are illustrated in Figure 4 on the right side. Induction motors, accounting for the remaining 20%, are shown on the left side of Figure 4. The course includes characterization and identification of these two motor types using Matlab/Simulink and laboratory experiments.. The motors are compared to to highlight their respective advantages and on disadvantages of every motor as listed in TABLE I.

Figure 4: Induction and synchronous motors.

TABLE I. MOTORS COMPARISON

Induction Motor	***Synchronous Motor***
Low-cost technology (No magnet)	High-cost due to magnet
Low power density	High power density
Important ripples	Lower ripples
Low efficiency	High efficiency
Longer life cycle due to magnet temperature	Shorter life cycle due to magnet temperature

- <u>Electrical machine characterization</u>,

Many technical and industrial aspects are considered and discussed during this activity; they can be listed as following:

1. Electromechanical and electromagnetic characterization: computation of produced power and losses relation, produced power to DC supply limitation.
2. Thermal modelling and characterization: evaluation of performances according to temperature
3. Vibration characterization: analyzation of torque ripples, system resonance and vibration
4. Acoustic characterization: vibro-acoustic analysis
5. Operational safety: estimation of open and short circuits, materials damaging, …
6. Electromagnetic Compatibility (EMC): displaying of electric motor connected to inverters and electronic cards and cables.
7. Life cycle analysis: displaying construction materials and influence of motor variables and operating profile

Experimental data are produced from sophisticated control strategies of electrical motors (see [5], [6] and [9]), such as Field Oriented Control (FOC) with their forms direct and indirect using Pulse Width Modulation (PWM) technics to control motors in variables speed regions as mentioned in [5], [7], [8] and [8]. However, same data are produced under several thermal conditions and physical constraints such as battery voltage and current limitation. Students are invited to make a whole study of motor characterization and analysis using these data under Matlab/Simulink. Below in Figure 5, students are invited to compute and describe the power flow chart from power supply to mechanical shaft using the experimental data. Also, they can evaluate the electromechanical characterization motor as shown in Figure 6.

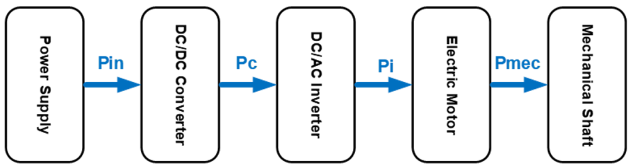

Figure 5: Power flow chart.

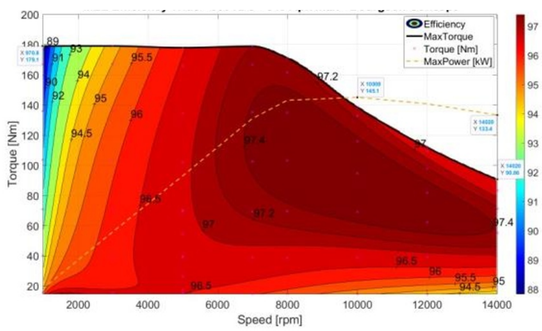

Figure 6: motor characterization.

- <u>Electrical machine identification</u>

A small power induction motor and a synchronous motor operating at extra-low voltage are considered in laboratory for tests; this allows student manipulations of the electrical equipment by excluding any safety risk. Three major activities are performed at the bench:

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- Study of the electrical source,
- Characterization of the motor performance,
- Identification of the motor parameters.

The results of these activities allow to bridge the theoretical knowledge acquired during the lectures to experiments (see [12]).

Using a programmable three phase power supply with variable voltage and frequency (see Figure 7), the motor, connected to a programmable active charge, is supplied with suitable input variables.. Dedicated instrumentation enables access to electrical and mechanical variables under various operating conditions. This setup allows for the quantification of motor performance and the determination of the system's energy balance .

Figure 7: Laboratory motor bench test.

Ad hoc manipulations and different system configurations allows to get to an estimate, and so to identify, the equivalent electrical circuit parameters of the motor, Figure 8. As an example, for an induction motor, a test at synchronism conditions of the motor allows to reduce its equivalent circuit to a simple RL circuit. Thanks to the test results the value of the inductance, L, can be identified properly and independently from other parameters.

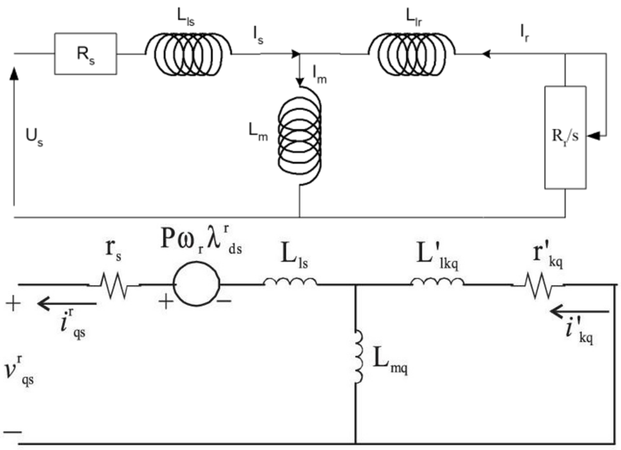

Figure 8: identified equivalent circuits of induction and synchronous motors.

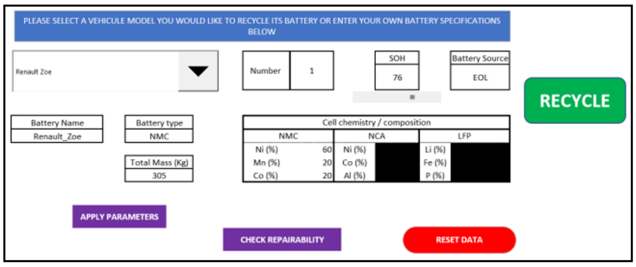

Figure 9: The battery recycling tool interface.

Required tests and configurations for offline identification of electrical parameters are no-load, stalled rotor, freewheeling and open circuit and self-braking tests. Using the parameters identified from these tests, the equivalent electrical circuit of the motor is constructed, allowing for numerical determination of the machine's performance. To validate the findings, the numerical results are compared and discussed alongside the experimental data..

3. Battery Recycling Classwork

The widespread electrification of transportation in recent years, combined with the EU's mandate to incorporate 10% more recycled materials in all new batteries, necessitates the study and estimation of the costs and CO2 impacts of recycling. this project students are tasked with developing a tool to determine whether batteries should be recycled or can be repurposed for a second life . This decision hinges on the State of Health (SOH) of the battery and its source (end of life battery, damaged battery or scraps). Students are expected to deliver a simulation tool to assist companies in evaluating the potential for reusing or recycling old automotive batteries, damaged batteries, or scrapsIn [13, 14, 15].

- *Recycling process*

The aim of the Li-ion battery recycling process is to recover the critical materials in used batteries. The process consists of two main processes : Pretreatment and hydrometallurgy.

- *Pretreatment process*

First, battery packs are deactivated for the safety of next steps. Battery packs are then dismantled manually to separate the batteries from the unnecessary parts such as cables, plastics, etc. Next, batteries undergo a grinding step to obtain a mixture of metal salt powder called “Black Mass”. This “Black Mass” is subsequently prepared by an organic solvent and then transferred to the hydrometallurgy process.

- *Hydrometallurgy process*

The hydrometallurgy process is preferred to the pyrometallurgy process because of its low energy-consumption and high recovery rate of metallic salts (about 94%). The “Black Mass” resulting from the previous process undergoes first step called “Leaching” under the sulfuric acid medium to dissolve all desired materials. Undissolved materials containing mainly graphite are separated and packaged. The solution containing ionic metals goes to the next step to precipitate the copper using the sodium hydrosulfide solution. The copper salt obtained is then separated and packaged. The solution then goes through the same steps but under the phosphoric acid medium to eliminate the aluminum and iron. The solution now consists of manganese, cobalt, nickel, sodium and lithium ions undergoes the solvent extraction and purification steps. They are successively and selectively extracted by different solvents. All the salts obtained during the process are then sold to specific manufacturers to purify further before reusing them.

3.1 Example of User Interface

An example of the tool designed for this purpose is shown in Figure 9. This tool is modular, allowing the user to select either a vehicle model corresponding to a specific battery from the provided database or to enter custom battery specifications, including chemistry, composition, and mass. For preselected model, the usermust input the number of vehicles available, whose battery needs to be recycled, the average State of Health (SOH) of all the batteries (if their SOH differs, it will be necessary to do the study for a smaller number of batteries with the same SOH, or even one by one) and the source of the battery (End of Life EOL, Scrap, Damaged). If the user chooses to enter custom battery specifications, they must select from the three most commonly used battery technologies in automotive applications today: NMC, NCA, or LFP, and specify the molar composition in percentage.. In both cases, the user must specify the SOH and the source of the battery.

3.2. Results

Once the user has finished entering the data, (s)he has to click on the “Apply Parameters” button (Fig 9) to incorporate the data into the model. Afterthis , if all the data has been entered within the acceptable range, a new button labeled “Check Repairability” will appear. This allows the user to assess whether the battery can be given a second life or should be recycled directly by clicking the main "RECYCLE" button The model assumes that for a battery to be considered for a second life, its State of Health (SOH) must be greater than 80% and it must be sourced from End of Life (EOL) batteries, as it is deemed too risky to reuse damaged batteries

Even if the SOH exceeds 80%, the “RECYCLE” button can still be activated.

Upon clicking this button, two sheets are displayed: one presenting the worst-case scenario in terms of energy costs, carbon footprint, and the lowest selling prices for the recovered materials, and the other presenting the best-case scenario. These 2 sheets contain several graphs (Fig 10) detailing the investment and profit realized, the quantity of materials from the entirety of batteries, quantities of salts obtained after the recycling process and their associated price, amounts of gas, electricity (in energy) and water used, a comparison between 3 countries where the process could be conducted and a comparison between the price of recycled battery with the projected recycling rates for 2031 and the price of a similar new battery available on the market.

Figure 10: Output of the battery recycling model.

4. Motivation for a new Mastère Spécialisé in Battery Engineering at IFP School

Europe's commitment to reducing greenhouse gas emissions and achieving carbon neutrality by 2050, and EU regulations, require industry to switch to 100% electric vehicles by 2035 at the latest. Europe, aiming to become a leader in EV production, requires a skilled workforce proficient in battery engineering to design, produce, and recycle advanced battery systems.

In the other hand, the rapid expansion of renewable energy sources like solar and wind power requires efficient and reliable energy storage solutions. Batteries are crucial for balancing supply and demand, ensuring grid stability, and facilitating the transition to a low-carbon economy.

Finally, batteries are a strategic sector for the European economy. Strengthening local production, reducing dependency on non-European sources, and fostering innovation are critical for economic growth and security. A Mastère Spécialisé program dedicated to battery engineering will support these objectives by producing highly skilled professionals.

The objectives of our program are to:

Educate Future Leaders: train engineers with in-depth knowledge of battery technology, including materials science, electrochemistry, and thermal management, preparing them for leadership roles in the industry.

Support Industry Needs: align the curriculum with the needs of the battery industry, ensuring graduates possess the skills required for production, design, use and recycling/reuse of batteries.

Promote Innovation: foster a culture of innovation and research, encouraging students to develop new technologies and processes that enhance battery performance and sustainability.

IFP School will contribute to European Battery Industry development :

Creating a Skilled Workforce : a dedicated program will ensure a steady supply of highly trained professionals equipped to tackle the challenges and opportunities in the battery industry, supporting the growth and development of the sector.

Driving Innovation : the program will produce engineers capable of driving technological innovations, from enhancing battery materials for cell design to developing new recycling methods, but also all the electronic and power electronic design around batteries contributing to Europe's competitive edge in the global market.

Enhancing Production Capabilities : graduates will bring advanced knowledge and skills to the European battery production industry, improving manufacturing processes, increasing efficiency, and reducing costs.

Education on Recycling Processes : the program will include courses on the latest recycling technologies, focusing on methods with low environmental impact and closed-loop recycling processes. Courses will also cover the principles and applications of LCA (Life Cycle

Assessment), enabling students to assess the environmental impacts of different recycling methods and make informed decisions about sustainability.

5. Conclusion

This contribution presented three-year experience of two courses developed within the Master teaching program at IFP School, France. It started by highlighting the goals of this new teaching program, and ways to achieve them. The methodology adopted for the definition of this new program was introduced. It consisted of working very closely with our industrial and academic partners.

In conclusion, the efforts at IFP School to adapt and expand its educational programs in response to the global shift towards electrification and sustainable energy have been highly impactful. By incorporating industry partnerships, practical training, and cutting-edge technologies such as virtual reality, IFP School ensures that its graduates are well-prepared to drive innovation and sustainability in the automotive and energy sectors. These initiatives not only align with global energy transition goals but also provide students with a comprehensive and practical skill set, positioning them to contribute effectively to the future of clean mobility.

References

[1] https://view.genial.ly/5f05cda42f66c00dba15512d

[2] https://www.ifp-school.com/en/training/specialized-engineering-graduate-degree/powertrain-engineering

[3] Müller, Beate, and Gereon Meyer, eds. “Electric Vehicle Systems Architecture and Standardization Needs.”, Cham: Springer International Publishing, 2015. http://dx.doi.org/10.1007/978-3-319-13656-1

[4] Blaschke, F. (1972)., “The principle of field orientation as applied to the new transvector closed-loop control system for rotating field machines”, Siemens Review, vol. 34, no. 1, pp. 217–220, 1972.

[5] B. Bose, “Modern Power Electronics and AC Drives”, Prentice Hall, 2001. ISBN-0-13-016743-6.

[6] Lorenz, Robert D., Thomas Lipo, and Donald W. Novotny. “Motion control with induction motors.”, Proceedings of the IEEE, Vol. 82, Issue 8, August 1994, pp. 1215-1240.

[7] W. Leonhard, “Control of Electrical Drives”, 3rd ed. Secaucus, NJ, USA:Springer-Verlag New York, Inc., 2001.

[8] Briz, Fernando, Michael W. Degner, and Robert D. Lorenz. “Analysis and design of current regulators using complex vectors.”, IEEE Transactions on Industry Applications, Vol. 36, Issue 3, May/June 2000, pp. 817-825.

[9] Texas Instrument, . “ Field Orientated Control of 3-Phase AC-Motors. ”, technical Note, Literature Number: BPRA07, Texas Instruments Europe, February 1998.

[10] Badin, F., HYBRID VEHICLES “From Components to System”, Editions Technip, 2013.

[11] Mohan N., Undeland T.M., Robbins W.P., “Power Electronics: Converters, Applications, and Design, 3rd Ed.”, Wiley, 2002.

[12] Chatelain, J., “Machines Electriques”, Presses Polytechniques Romandes, 1989.

[13] *https://www.actu-environnement.com/media/pdf/news-35541-rapport-recyclage-batterie-lithium.pdf*

[14] *https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/chiffres-cles-energie-2022/14-gaz-naturel*

[15] *https://www.carbone4.com/publication-importation-gaz*