

An Approach to Teaching Electrical Energy

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SUMMARY The paper discusses the implementation of a new teaching programme for electrical power engineering graduates. The balance between the different parts of the curriculum (non-technical, technical non-electric, electric non-power and real electrical power) is proposed and explained given the specific context. The logical information flow throughout the education process and the links between the course topics are explained.

1. Introduction

Classical fields of engineering, such as electrical power systems and electrical machines and drives, tend to suffer from a lack of interest by the students. They are attracted by more glamorous subjects, such as electronics and mechatronics. Electrical energy and its applications are, however, an essential if not indispensable part of everyday life and of all manufacturing systems. They are generally not noticed as long as they are available.

Industry has a need for professional engineers who know how to handle problems related to the distribution and use of electrical energy in their processes. In a number of applications, optimized electrical drives offer very important energy savings. For the production of advanced materials, electro-heat may offer an environmentally optimal solution.

Starting from the basic idea that electromechanical engineering students should be educated to address the wide variety of problems related to the production, distribution and use of electrical energy in all aspects, a curriculum is set up with a broad spectrum, in order to avoid too narrow a specialization. This curriculum has to be fitted into boundary conditions as set by legislation and by the university. The total study time (including a master thesis during the last year) is 5 years. Per year, the students have to pass a maximum of ten examinations. The first two years, the so-called candidatures, are common to all engineering students. The last three technical years lead to the title of electromechanical engineer; this title is prefixed with the objective 'civil' as opposed to the military title obtained at the military academy.

2. Candidatures: The First Two Years

The key part of the first two years involves such basic skills as mathematics, physics and chemistry. The amount of real engineering-related topics is very low.

In mathematics, the following subjects are treated:

- integral and differential calculus, differential and partial differential equations and systems of equations;

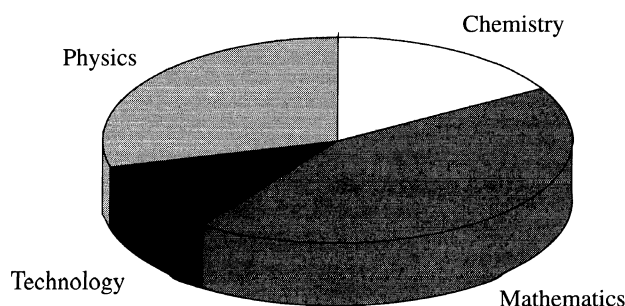


FIG. 1. Division of topics in the candidatures.

- advanced algebra and analytical geometry;
- descriptive geometry and drawing techniques;
- statistics;
- numerical analysis and basic computing.

The subjects are very general. Sometimes the link with practical applications is very tedious and the students are not able to understand fully the value of the different mathematical techniques, such as finite elements, Fourier series and Laplace transformation, if these techniques are presented purely as a difficult to understand mathematical topic, rather than as the engine of a calculating procedure that will be used by them in the three subsequent technical years.

Physics can be split into two parts:

- physics (electromagnetics, heat transfer, vibrations, acoustics, optics, wave theory, quantum physics);
- analytical mechanics.

Again, the technical aspects are remote.

In chemistry all types of reactions and basic principles are treated, both organic and inorganic, including petrochemistry and plastics. Practical implications of the theory are not provided. Emphasis is placed on reaction theory, thermodynamic aspects and quantum physics links.

Apart from this basic triangle, a few hints towards engineering are present: material science, basic thermodynamics and strength of materials. Time is also dedicated to technical drafting. The partition of the four groups is shown in Fig. 1. One course on philosophy, taken by all students, is omitted from this diagram. All courses are compulsory. Only a number of the laboratory sessions of chemistry and physics may be replaced by a small project with a technological impact.

The contents of the first two years are presently under scrutiny for two major reasons. The first is caused by the secondary schools, in which less and less mathematics is taught, changing the entrance level considerably. The second is that it is felt that the technical aspects should be introduced sooner in the curriculum. The specific mathematics, physics and chemistry will then be transferred to the last three technical years.

We will now discuss the contents of the last three technical years. Three group of courses can be distinguished:

- general technical courses;
- non-power electrical courses;
- electrical power courses.

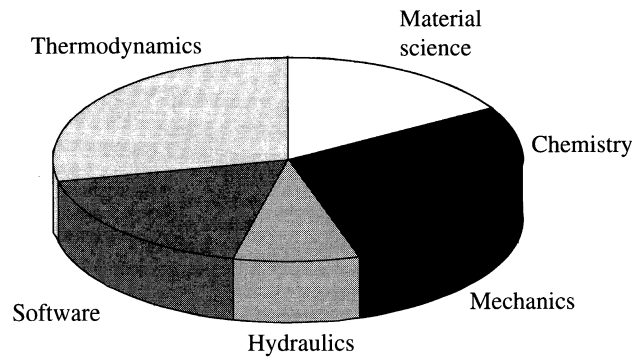


FIG. 2. General technical courses in the technical years.

All courses are compulsory. The programme as such is very strict.

3. General Technical Courses

A number of technical courses are introduced to all engineering students. The following topics are dealt with:

- material science (metallurgy, advanced composite materials, non-destructive testing);
- technical chemistry (plastics, petrochemistry, environmental aspects, etc.);
- mechanical engineering (manufacturing processes, mechanical components such as gears, couplings, shafts, etc.);
- technical thermodynamics (steam cycles of power plants, pumps, compressors, internal combustion engines, cooling engines);
- applied software design aspects;
- hydraulics.

As seen from this overview, practically all aspects of industrial applications are treated. This allows the future engineer to discuss, with the user, his/her electrical installations. He/she must be able to understand the problems of the user, without making him/her a full specialist. Therefore, the other engineering students also follow a basic course on electricity and electrical machines and drives. Figure 2 shows the relative importance of the six groups. These courses are compulsory. The scheme is very strict and most of the courses are rather theoretical, with very few exercises or laboratory sessions.

4. Electrotechnical Courses not Dealing with Power

A number of electrotechnical courses dealing with electronics, control, microprocessors and communication are taken by the power engineering students. This allows them to implement these techniques in advanced drives, distribution systems and electro-heat applications.

In basic electronics the important circuits are discussed, such as amplifiers, power amplifiers, feedback and switched power supplies. This should give the students a basic

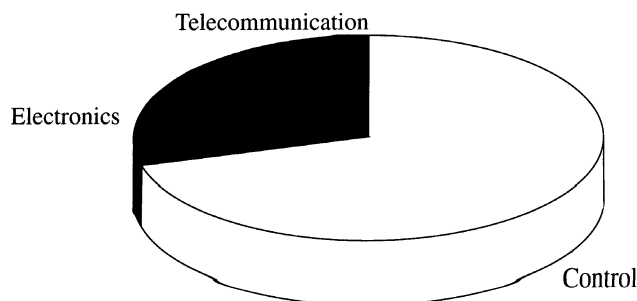


FIG. 3. Relative importance of non-power electrical courses.

feeling for the problems encountered in so-called analogue electronic circuits. It serves as input for classical control in drives and electro-heat systems.

Starting with system theory and network analysis, control theory is introduced for analogue control systems. Attention is also paid to sensor devices in feedback and servo systems. Digital control is a next step. Starting from discrete digital components, the microprocessor is introduced. Using these basic ideas, advanced microprocessor-based control systems are taught. Attention is also paid to digital filtering techniques. Digital signal processors are a main topic, as they gain increasing importance in advanced drives.

Starting with Maxwell equations, the communication aspects of electromagnetic waves are discussed. Different modulation techniques are explained. After the analogue systems, digital communication is introduced. In Fig. 3 the relative importance of these three topics is indicated. In the digital communication courses, the emphasis is on an understanding of the algorithms that are used to allow accurate and fast data transmission in an industrial environment.

5. Power Engineering Courses

During the three technical years, the importance of the specialized courses in power engineering grows. This is made clear in the three charts of Fig. 4. In the first technical year, 32% of the time is dedicated to power engineering subjects; this rises to 40% in the second year and to 70% in the third year. The last figure includes the load representing the master thesis, that has to be presented at the end of the study before the student can start his/her final examinations.

Apart from the power engineering subjects, the other electrotechnical subjects and the general technical courses, a number of non-technical courses are present in the curriculum, as seen in Fig. 4. Languages as such are not taught. In secondary school, the students have had courses on French, English and German. Via textbooks, the technical vocabulary in these languages is introduced. Foreign speakers are invited to present advanced topics, again with the secondary aim of introducing the technical language. The non-technical courses during the technical years are:

- economics (micro- and macro-economics);
- legal aspects (general legislation, safety legislation, patent law);
- management (investment criteria, pay-back strategies);
- psychological aspects of management;
- religion.

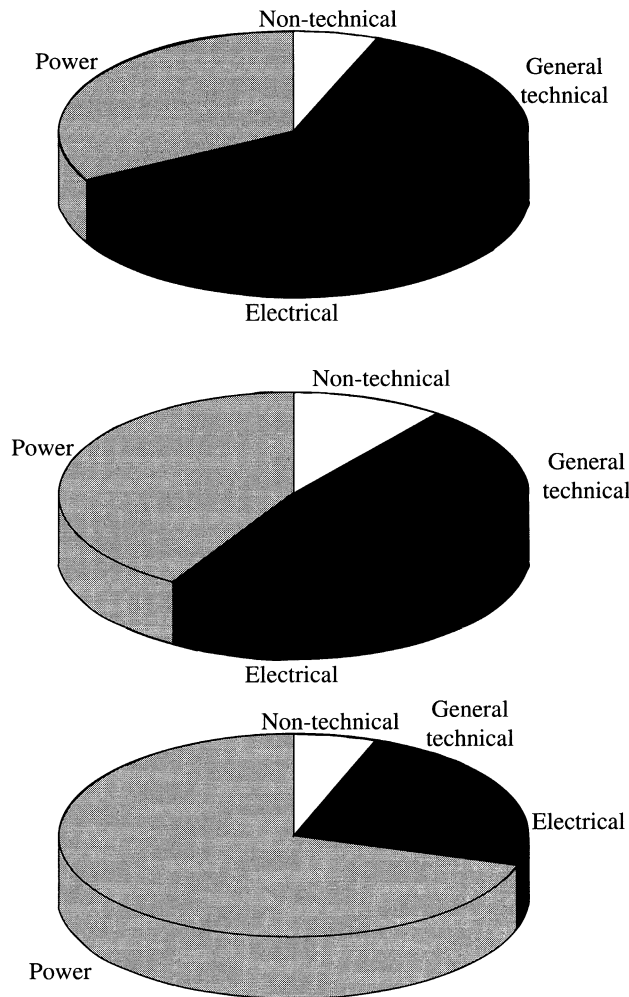


FIG. 4. Relative importance of topic groups during the technical years.

Figure 5 shows the interaction between the most important courses in power engineering. The content of each is discussed in some detail.

5.1 Basic Power Elements

In the first course, entitled 'General electricity and electrical machines and drives' (H195), also taken by electronic and mechanic engineering students, basic aspects of power engineering are provided. In the first part, five general topics are discussed:

- introduction into production, transport and distribution of electricity;
- electric and magnetic fields in power applications;
- single-phase systems, R-L-C networks, alternating current and power;
- three-phase systems;
- conduction through liquids (including batteries) and gases (including lighting sources).

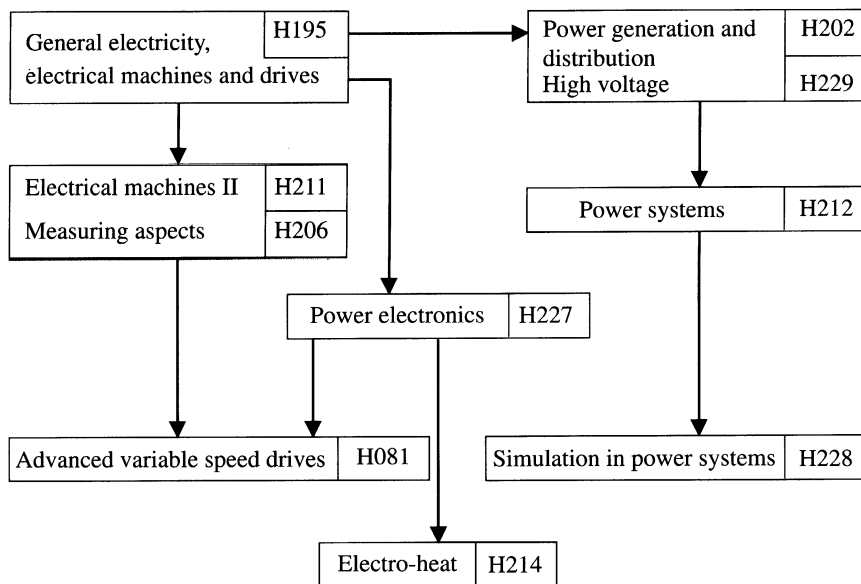


FIG. 5. Interaction between power courses (course code numbers are given).

The aim of the first part is to bring to the students all required techniques that will be applied in the subsequent courses. Particular attention is given to complex calculations as used in steady-state sinusoidal analysis. In the second part, electric machines and drives are presented. Apart from the classic machines, power electronic converters are dealt with.

Transformers are treated starting with the basic fundamental equations and leading to the equivalent circuit and practical use. Then, three-phase transformers with a balanced load are discussed. Aspects of design and of special applications conclude this topic.

DC machines are the first rotating electromechanic transducer discussed. After the basic calculations of the induced voltage and torque, the steady-state behaviour of both idealized and real machines are analyzed. The control aspects and transient behaviour of the DC motors are the last topic providing a bridge to controlled variable speed and servo drives.

In alternating current machines, rotating field theory is explained first. Then the induction motor is treated in steady-state conditions. The equivalent circuit is the basis of the study of practical situations (starting, braking, speed control). Aspects of design and construction are given. Synchronous machines are the second type. Main characteristics of their use as generators are provided. Again basics of construction are given. The topic is concluded with fundamental aspects of field-oriented control.

After this course, the students should be familiar with the basic characteristics of all electrical machines as used in practical drives. They should be able to discuss possibilities and limitations with suppliers of drives as they will later use them in their manufacturing processes. As this course is also given to non-power engineers, it is application- rather than design-oriented. This course is the basis of three complementary branches: drives, power systems and applications.

5.2 *Advanced Electrical Machines and Drives*

The first course on drives is entitled 'Electrical machines, part II' (H211). Here different topics are treated, dealing with parasitic problems and design. In transformers, asymmetric loads, audible noise, short-circuit forces and cooling are discussed. In DC machines, design aspects, specifically in permanent magnet machines, are given; commutation and armature reaction are treated in detail. In induction motors, attention is paid to the influence of space harmonics on the behaviour of machines with regard to torque, losses, vibrations and audible noise. Various methods for suppressing the harmonics are given. Asymmetric stator and rotor situations are treated. In synchronous machines, a lot of time is devoted to d-q decomposition, Parks equations, parallel operation and design. Small and special machines are the last group, with specific emphasis on single-phase machines (capacitor start-capacitor run induction motor, universal motors, stepper motors, switched reluctance motors). In design of various motors, finite elements and computer-aided design techniques are discussed. Vibrations and audible noise, including balancing of rotors, are the last topic. Special attention is given to the electromagnetic influence on the vibrational behaviour.

In the second course, on variable speed drives (H081), different aspects of high-performance systems are treated. The DC motor drives are used to illustrate strategies for optimizing the response of the system with respect to different criteria. Attention is paid to the interaction between the motor and the rectifier, especially if a high-performance, four quadrant operation is envisaged. In alternating current drives, scalar control is discussed for different machine types (squirrel cage induction motors, wound rotor induction motors, synchronous motors) in combination with the appropriate power electronic converters (current source inverter, voltage source inverter with pulse-width modulation, cycloconverter, static Kramer drive, etc.). Field-oriented control is studied in detail. Starting with the limitations of scalar control, even when adopting the necessary corrections at low and high speed, the different coordinate systems for the induction motor and synchronous motor are given. The implementation of field-oriented control is discussed, including the influence of parameter variations. Attention is also paid to different machine models, leading to sensorless drives based on the Kallmann filter technique. All techniques are brought together in the final chapter on advanced servo drives, in which the different options for these applications (DC motors, permanent magnet synchronous motors and induction motors) are compared.

The combination of both courses leads to engineers that are able to design advanced electrical machines and drives. The students should be aware of the most modern techniques, without losing sight of the underlying theory, enabling them to adapt emerging techniques in future.

5.3 *Power Systems*

The second branch deals with power systems. Starting some 8 weeks after the first course, a fundamental course on production, transport and distribution of electrical energy (H202) covers apparatus from power plant to customer. This course is a general introduction to the field of electrical power generation, transport and distribution. It consists of a technological study of all main components of a power system, except electric machines. Starting with power plants and the optimization of their parallel operation, the first part covers the description of switch yards and boards, including a detailed coverage of the technology of breakers, switches and disconnectors as well as the protective equipment of installations. The second part introduces some basic

concepts of system calculations, and gives a detailed technological description of overhead lines and cables and their accessories. It goes on to study power system protection relays and concludes by describing tariffs, metering and reactive power compensation apparatus.

This course is taught in combination with a course on high voltage techniques (H229). The latter course covers high-voltage and high-current generation and measurement techniques. It starts with three chapters dealing with high-voltage generation and measurement apparatus. These chapters deal respectively with DC, AC and impulse voltages. Two chapters treat high-current AC and impulse generation and measurement. Next, non-destructive testing of high-voltage equipment is studied, with an emphasis on partial discharge phenomena. The course concludes with a survey of the requirements for high-voltage laboratories.

These courses are followed by a more in-depth study of topics related to power systems (H212). A thorough study of per unit systems and modal analysis of power systems (with emphasis on symmetrical components of Fortescue) is the introduction to this in-depth course on power system elements. First, the parameters of overhead lines and cables are studied in great detail, including ground return formulae. Next, models of generators and transformers for power system calculations are introduced and used in hand calculations of balanced and unbalanced short circuits and of the resulting mechanical and thermal stresses. The course further covers the voltage regulation and circulation of reactive power, with a detailed study of breakers, including transient recovery voltage and initial transient recovery voltage problems. The final chapter covers power-frequency control systems.

In the last year, a finishing course on simulation in power systems (H228) focuses on modern computing algorithms. In contrast to H212, which covered hand calculations in power systems, this course deals with computer methods and modelling techniques presently used for power system computations. Short-circuit calculations using the Z-bus and its generating algorithm, load-flow calculations in Cartesian and polar form with extensions to fast decoupled LF, transient stability analysis in multi-machine systems and finally electromagnetic transients and harmonic propagation are presented in seminar form based on recent literature.

5.4 Non-motor Applications

A third main branch of interest covers non-motor applications of electricity: a course on electro-heat (H214) is taught in the last year. After a short review of modelling and calculations of heat transfer as applied to electro-heat apparatus, a survey of the different electro-heat techniques and equipment is given. This includes direct and indirect resistance heating, infra-red heating and baking, induction applications in metal heating and melting, dielectric heating and drying with high-frequency waves and microwaves of non-conductive lossy materials. High power arc furnaces and plasma, as well as power laser and electron-beam applications, are also covered.

In measurement techniques (H206), an overview is given of all quantities that may be important to assess in power systems, electrical drives and electro-heat:

- current and voltage, including various transducers;
- active and reactive power;
- resistances and impedances;
- frequency and time;
- energy;

- torques (steady state and transient);
- vibrations and audible noise;
- electric and magnetic fields;
- temperature.

In power electronics (H227) attention is first paid to the power electronic components (SCR, GTO, BJT, Power MOSFET, IGBT, etc.). Protection and control circuits are discussed. As a first application, AC to DC converters are treated (controlled rectifiers), with special emphasis on DC motor supply. Chopper circuits are the key part of DC–DC converters. The most important topic of the course is inverters. Both CSI and VSI are treated. PWM schemes are discussed. Special types of converters, such as cycloconverters and machine-controlled systems, are also covered.

5.5 Supporting Courses

Clearly, the three branches firmly interact and give a broad view of all aspects of power engineering.

Two courses, which are also within the power engineering curriculum and not taken by other electrical engineers, have to be mentioned. The first course, on nuclear power plants, supplies the students with the necessary knowledge to understand the basic aspects of the production of electrical power, starting with nuclear reactions. The second course gives aspects of standardization, at Belgian, European and worldwide levels. The AREI (the Belgian electrical code, Algemeen Reglement op Elektrische Installaties) is discussed.

6. Conclusions

In this paper, an overview is given of the curriculum of power engineering. It is shown that a very broad spectrum of many aspects of industry is supplied, rather than a highly specialized education. Industry feedback indicates that this type of engineer is very suitable for a country like Belgium, with a lot of small and medium-sized enterprises.

The students like the streamlined flow of information, given in a very coherent way with a lot of interaction between courses, avoiding overlap to a very large extent. The presence of many laboratories and the industrial visits are appreciated. The contact with practice has to be present during the whole education.

