Online Interactive Lessons on the Principle of the Direct Torque Control of the Induction Machine

SERGIU IVANOV[1], DAMIEN GRENIER[2], FRANCIS LABRIQUE[3],
MARIA-JOSÉ RESENDE[4], BENOÎT ROBYNS[5]
[1] Faculty of Electromechanical Engineering
University of Craiova
107 Decebal Blv., 200440 Craiova
ROMANIA
sivanov@em.ucv.ro http://www.em.ucv.ro
[2] Département Mécatronique
Ecole Normale Supérieure de Cachan, Antenne de Bretagne
Campus de Ker Lann, 35170 Bruz
FRANCE
damien.grenier@bretagne.ens-cachan.fr http://www. bretagne.ens-cachan.fr
[3] Laboratoire d'Electrotechnique et d'Instrumentation
Université Catholique de Louvain
3 Place du Levant, B1348 Louvain la Neuve
BELGIUM
francis.labrique@uclouvain.be http://www.lei.ucl.ac.be
[4] Instituto Superior Técnico
Universidade Técnica de Lisboa
Av. Rovisco Pais, 1049-001 Lisboa
PORTUGAL
mresende@ist.utl.pt http://www.ist.utl.pt
[5] Département Génie Electrique
Ecole des Hautes Etudes d'Ingénieur Lille
13 rue de Toul, F-59046 Lille Cedex
FRANCE
benoit.robyns@hei.fr http://www.hei.fr

Abstract: - The modern multimedia techniques are an important lever for teaching the Electrical Engineering. The development of such tools places a large demand on human and financial resources. In consequence, an advantageous approach in order to obtain impressive results is to join the effort of several teachers or institutions. The theme of this paper is to present an experience in collaborative design of interactive tools through the example of a lesson designed and realised for teaching the Principle of Direct Torque Control (DTC) of the Induction Machine. The purpose of this lesson is to highlight the link between both main branches of the Electrical Engineering: Power Electronics and Electrical Machines.

Key-Words: - on-line lessons, interactive, electric machines, direct torque control

1 Introduction

The concepts used in Electrical Engineering (electrical charges, currents, fields) are only visible through their effects. Their understanding needs a higher level of abstraction knowledge and understanding which may be a reason for its difficult learning (and teaching). Moreover, the Information and Communication technologies have proved as being very useful tools [2], [3], [5], [6]. Thus, the students can visualize dynamically the evolution of different phenomena. They can then prove their usefulness in education context.

Firstly, the present paper presents the experience developed by a team composed of members from four European countries. The team's field of action refers to the development and usage of the multimedia tools in Electrical Engineering. Since all the developed resources are freely available on the internet and a brief description of the table of content for the four considered themes was presented in [4], this paper will refer only some additional information.

Secondly, a particular lesson will be detailed to emphasis, on one hand, the Principle of the Direct Torque Control of the Induction Machine, and on the other hand, the existing links between the different branches of the Electrical Engineering as is the case of the Power Electronics and the Electrical Machines. We consider quite important to underline such links, thus showing the students a way to overlook at the different studied disciplines not as “islands”, but only as “bricks” in connection with their knowledge.

The performed evaluation on using such resources proved that their usage strongly depend on the teacher behaviour: on how much the teacher tells about the resources during classes, on how often he shows the e-learning examples, more students are visiting the website. Despite of the high expectation level, the students that have used the resources, revealed a high satisfaction level, often higher than their expectation, which was however soon high.

2 Context

The project started in 2003 in the framework of the European Community Union Minerva action. The objective of the two years program was to develop and evaluate the use of multimedia resources designed to teach Electrical Engineering. It involved four partners from four different countries:

- Université catholique de Louvain, Belgium – coordinator of the project ([2] in the list of authors);
- École des Hautes Études d'Ingénieur, Lille, France;
- Instituto Superior Técnico - Universidade Técnica de Lisboa, Portugal;
- Faculty of Electromechanical Engineering, University of Craiova, Romania

Each of the four partners was fully responsible for one of the four themes developed in the project. The resources were developed in the native language of each partner and then, translated and adapted into the other three languages. Most of them were also translated into English, so the developed resources are presented in four languages: English, French, Portuguese and Romanian. The concerned themes regarding Electrical Engineering are:

- Electrical Circuits;
- Power Electronics;
- Electromechanical Converters;
- Renewable Energies.

It ranges then from very basic skills (Ohm's law, Kirchhoff's law) to more advanced ones such as rotating field electrical machines. Two of them cover general topics of the Electrical Engineering: Electric Circuits and Power Electronics. The other two are more specialized: Electromechanical Conversion/Electrical Machines and Renewable Energy. The former of the last two shows a particular interest in rotating field electrical machines (synchronous and asynchronous). The last one deals with complex electrical systems, such as windmills and photovoltaic converters. In order to be able to fully understand the last themes, it is useful to have previously studied the first ones (with the help of the website or by an other way).

Based on the background experience acquired by the Université catholique de Louvain [10], each package is organized separately: as an integrated tool, containing lessons, virtual laboratories and self-examination tests (multiple choices questionnaires - MCQs). It uses more or less the same basic activities than in a classical pedagogy. One of the added values of the web site is the interactive animations (Java's applets) that are inserted in several activities as often as possible in order to help students to visualize the concepts they study.

All the developed resources are finally fully available online, on the web site of the program, www.e-lee.net. The access is totally free of charge, even for students and teachers from other institutions.

Additionally, the site presents the eLEE Association that was created following the initiative of the four members listed above in order to maintain and continue the development of the website. Nowadays the Association counts more members that share the same wish to use and develop multimedia lessons for Electrical Engineering. Authors of the present paper are the representants of their institutions in the Administration Board and Scientific Board of the association.

A special component of this program concerns the evaluation from the students that used the multimedia tools during the Minerva project development. The evaluation was performed objectively, placing trust in an independent expert, external to the involved institutions. The purpose of this evaluation was not to quantify the students' knowledge, but their “feeling” about the method of teaching by means of these resources. They also provided relevant viewpoints and notices for better

use of these tools. The main results of the evaluation are also available on the website, under the “Evaluation” section,
http://www.em.ucv.ro/eLEE/EN/guide/resultats.htm

3 Tutorials Content

The tutorials for each theme are developed as an aid for either the continuous teaching/learning process, either for the exams’ preparation. The tutorials cover the most important lessons of the four themes. As some information was brought by [9], within each chapter, several representative resources will be only referred.

Most of the lessons contain suggestive graphics and animations that help the better understanding of the presented phenomenon. For viewing correctly the animations, a Java plug-in must be installed on the computer, as is recommended in the starting page of the tutorials
(http://www.em.ucv.ro/eLEE/EN/realisations/index.htm).

The first theme, “Electric Circuits”, is organized in four chapters, namely:

- General Aspects (Concept of Dipole, Kirchhoff’s Laws, Basic Components);
- Linear Circuits (Resistive Circuits, First Order Circuits, Second Order Circuits);
- Sinusoidal Regime (Sinusoidal Signals, Sinusoidal Regime of the Circuits, Powers in Sinusoidal Regime);
- Triphasic Systems (Basic Concepts, Load Connections, Powers, Power Factor Compensation).

As an example, Fig.1 presents a screenshot of the animation that plots the sum of two sinusoidal signals. The amplitude and the phase of the two signals can be easily changed online and the result will be displayed almost in real time. It helps to illustrate phasor concept in sinusoidal circuit analysis.

Moreover, most of the resources have also a final section of exercises that offer the possibility of applying and consolidating the notions presented during the lesson.

Secondly, the “Power Electronics” theme was developed towards the DC to AC conversion. Using simple animations, the basic principles of the commutations within the static converters are explained and consequently, it results the requirements imposed to the semiconductor devices. The bushiest chapter is the one that deals with the inverters. Both full wave and PWM modulation techniques are clearly presented with a special emphasis on the last one.

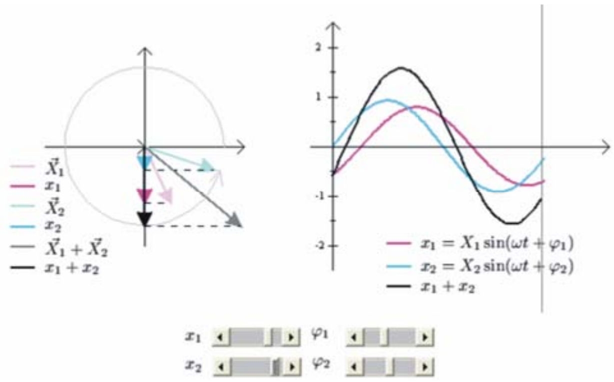

Fig.1. Example of java applet used to illustrate Electric Circuits theme
(http://www.em.ucv.ro/eLEE/EN/realisations/CircuitsElectriques/RegimeSinusoidal/GrandezasSinusoidais/5_cours.htm)

Thirdly, the “Electrical Machines” theme is organized in four chapters that cover both general principles of the electromechanical conversion, and also specific lessons and virtual laboratories for expressing the operation of the rotating field machines (synchronous and asynchronous):

- Electromagnetic Conversion is explained by means of two attractive examples for obtaining the electro-dynamic and reluctant forces (Electromagnet, Speaker, Reluctant Motor for an Electric Razor);
- Rotating field machines are explained by attractive animations, showing how a rotating field is obtained through the tri-phased AC machines (synchronous and asynchronous), Fig.2. This section also presents, throughout an interactive laboratory (with questions, answers and demonstrations), the principle of obtaining sinusoidal distributed windings;
- Synchronous Machine (Parameters Measurement, Autonomous Operation, Grid Connection, Voltage Regulation);
- Asynchronous (induction) Machine (Realization and Operation Principles, General Operation Equations and Equivalent Diagrams, Operation and Mechanical Characteristics, Classical Command of the Drive, Vector Control, Direct Torque Control – DTC) and several virtual laboratories (Measurement of the Equivalent Diagram Parameters, Determining the Mechanical Characteristics, Applications of the Command Methods, The Influence of the Inverter Type in Vector Control, The Influence of the Variation of the Parameters in Vector Control, Speed Regulation with Direct Torque Control);

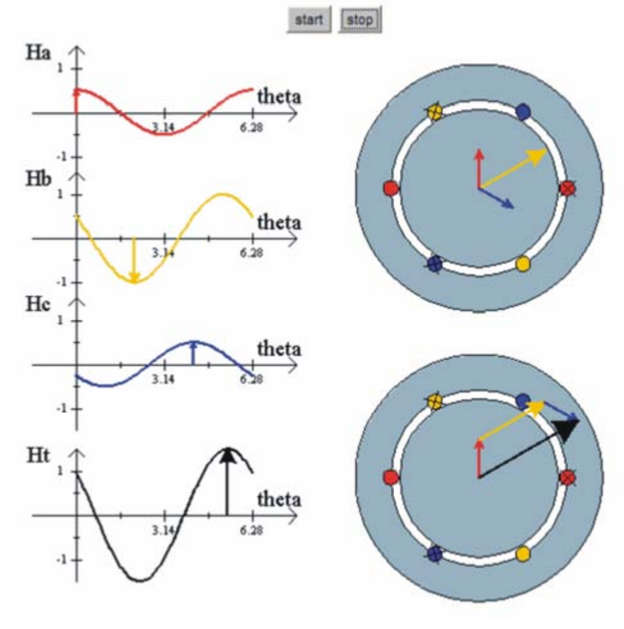

Fig.2. Final animation for obtaining rotating field in the tri-phase AC machines (http://www.em.ucv.ro/eLEE/EN/realisations/MachinesElectriques/ChampTournant/Principes/ChampTournant/8_cours.htm)

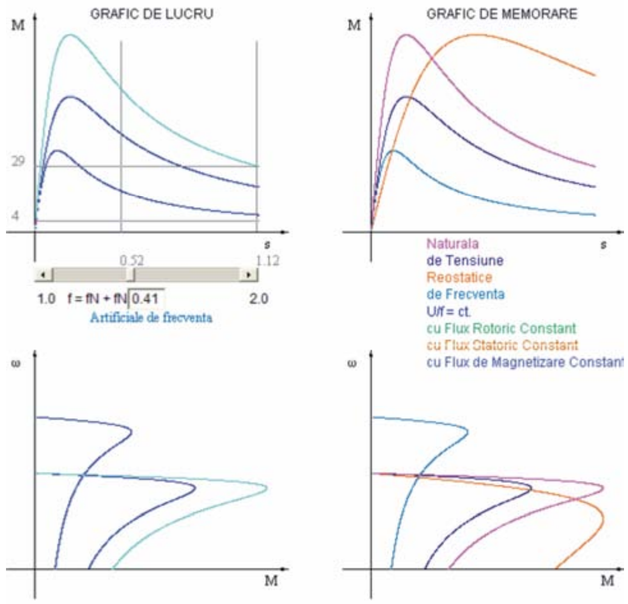

Fig.3. Lesson concerning the mechanical characteristics of the induction machine (http://www.em.ucv.ro/eLEE/EN/realisations/MachinesElectriques/Induction/CharacteristiquesFonctionnement/CharacteristiquesMacaniques/7_cours.htm)

- MCQs that cover the general theory of the electromagnetic converters, the operation principle of the rotating field machines, the motor or generator operation of the synchronous machine, the DC machine.

In conclusion, the developed resources within the asynchronous machine chapter, cover both the classical approach of the applications (construction – with short video captures during the manufacturing process, operation, characteristics – Fig.3), and also the modern control techniques (vector control, direct torque control).

In the next section, a particularly difficult lesson concerning the principle of the DTC of the induction machine is detailed.

As mentioned before, virtual laboratories were also settled, in order to allow students to study different aspects of the induction machine drive on their own. Fig.4 presents an example of such a laboratory: the plotting of the mechanical characteristics of the induction machine.

Users can choose the type of the mechanical characteristic (rated parameters, voltage, resistive, frequency characteristics), thus obtaining different points of the graphic, by changing the mechanical load of the motor by the way of the load resistance of the DC generator. Finally, based on several "experimental" points, the characteristic curve is plotted.

The fourth developed theme is the "Renewable Energies" which is also organized in four chapters, not all of them being totally developed yet:

- Generalities (Premises and Perspectives, Renewable Sources of Energy, Electricity Production Based on Renewable Energies);
- Wind Generation / Induction Generator (Different Technologies, Study of the Induction Generator);
- Solar Energy (Photoelectric Cells and Panels, Maximum Power Point Tracking Systems, Design of an Installation);
- Implementation Concerns (Grid Connection, Energy Storage, Hybrid Generation).

The "Wind Generation" chapter pays a special attention to the doubly fed induction machine as electric generator within a wind generator.

In this theme, there are two interesting interactive applications proposed for the solar generation of electric power. One is conceived for dimensioning a site not connected to the grid, and the other is designed for an application connected to the grid. The exercises allow the user to follow a basic approach that highlights the relevant points of such application. The user can easily interact with these applications by choosing different conditions (the location and, consequently, the exposure conditions, the number and the type of the loads, the types of PV generators), obtaining the economic analysis of the proposed solution.

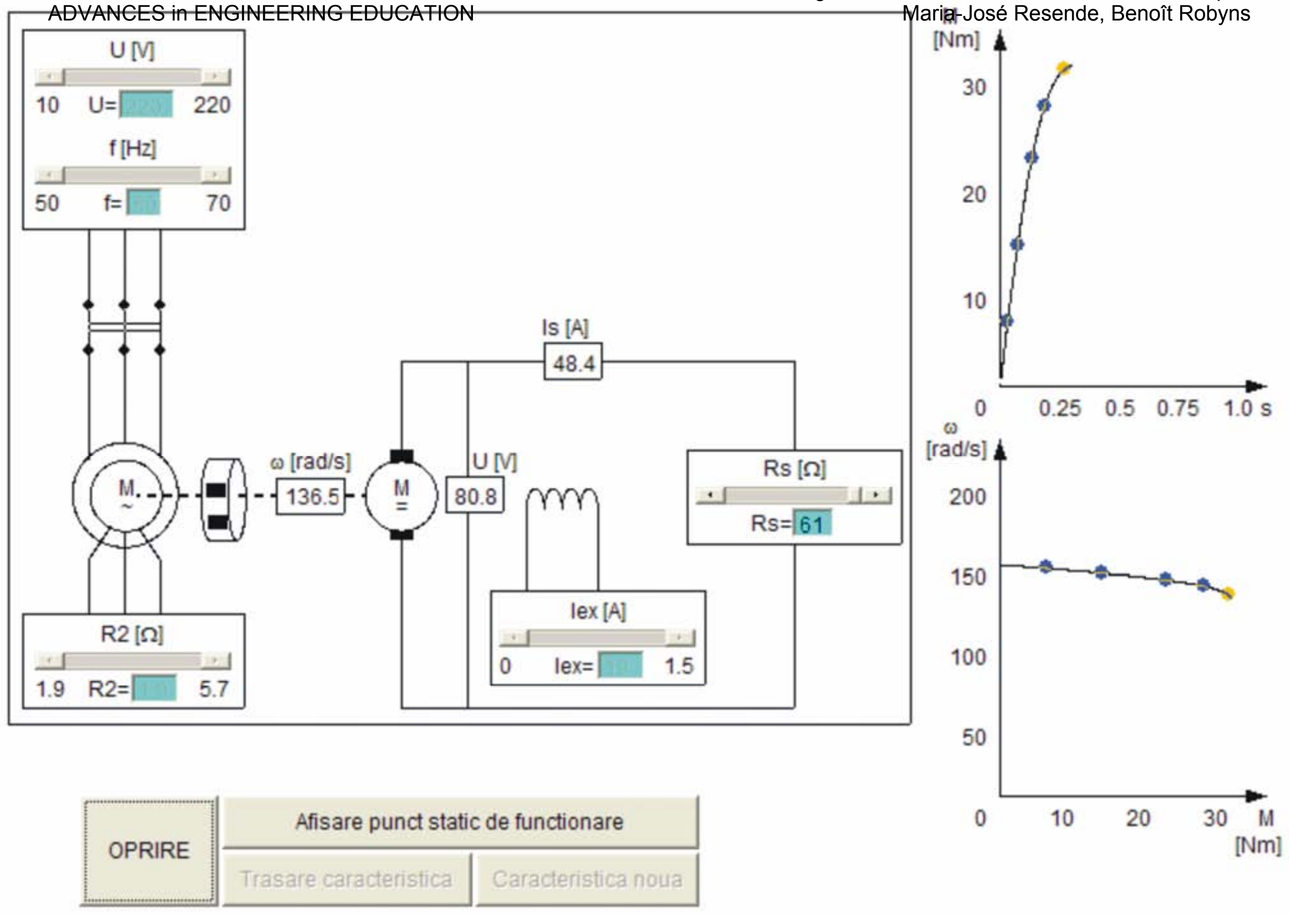

Fig.4. Laboratory for plotting the mechanical characteristics of the induction machine (http://www.em.ucv.ro/eLEE/EN/realisations/MachinesElectriques/Induction/CharacteristiquesFonctionnement/CharacteristiquesMecaniquesL/1_justification.htm)

4 Interactive Lesson for the Principle of DTC for the Induction Machine

This lesson represents a very good example of the link between the "Power Electronics" theme and the "Electrical Machines" one.

It is organised on four pages, starting with the basic principle: the electromagnetic torque developed by the induction machine can be controlled, due to its dependency on the slip, by mean of the advancement of the stator flux. Basically, there could be three possible situations (Fig.5):

- the developed torque is too small, the slip must be increased, so the flux must advance quicker (Fig.5.a);
- the developed torque is large enough, so the flux must keep its position (Fig.5.b);
- the developed torque is too large, the slip must decrease, so the flux must be retreated (Fig.5.c).

Also, the amplitude of the stator flux must be kept at the preset value. Similarly, the top of the space vector of the stator flux must describe, at different speeds, a circle.

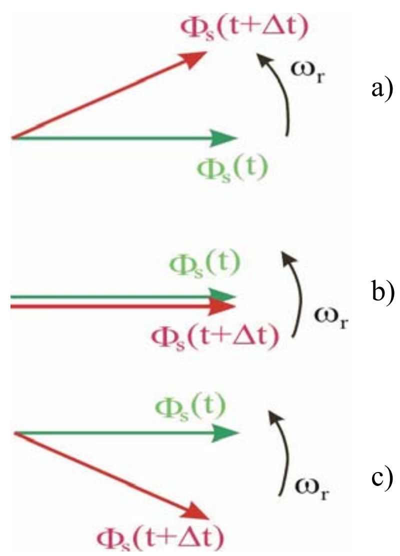

Fig.5. The possible situations for the stator flux evolution (http://www.em.ucv.ro/eLEE/EN/realisations/MachinesElectriques/Induction/DirectTorqueControl/Principe/1_cours.htm)

As the position and the amplitude of the stator flux must be permanently controlled, it results that the two magnitudes must be known. Consequently, it is presented, as it follows, the classic method for the integration of the orthogonal components of the stator equations, based on the actual values of the instantaneous values of the phase currents and voltages:

$$\Phi_{s\alpha} = \int (u_{s\alpha} - R_s i_{s\alpha})dt, \quad \Phi_{s\beta} = \int (u_{s\beta} - R_s i_{s\beta})dt. \tag{1}$$

It results:
• the modulus of the stator flux:

$$|\Phi_s| = \sqrt{\Phi_{s\alpha}^2 + \Phi_{s\beta}^2}, \tag{2}$$

• the position of the stator flux:

$$arctg \frac{\Phi_{s\beta}}{\Phi_{s\alpha}}, \tag{3}$$

• the electromagnetic torque developed by the motor:

$$t_e = \frac{3}{2} P \left(\Phi_{s\alpha} \cdot i_{s\beta} - \Phi_{s\beta} \cdot i_{s\alpha} \right). \tag{4}$$

In addition, due to the fact that the supplying source is generally a voltage source inverter, the only quantities that must be measured are the phase currents and the DC voltage. In connection to the "Power Electronics" theme, it is simply proved that the topology of the inverter univocally determines the values of the phase voltages. So, the information on the state of the switches, in addition to the knowledge of the actual value of the DC voltage, is enough for knowing the instantaneous values of the phase voltages. Fig.6 depicts an example for one of the eight possible configurations of the inverter's topologies. For each combination of the switches' states, chosen by the user, both the inverter diagram and the voltages levels are properly adapted online.

Due to the limited number of possible switches combinations, the evolution of the top of the stator flux space vector will follow the corresponding

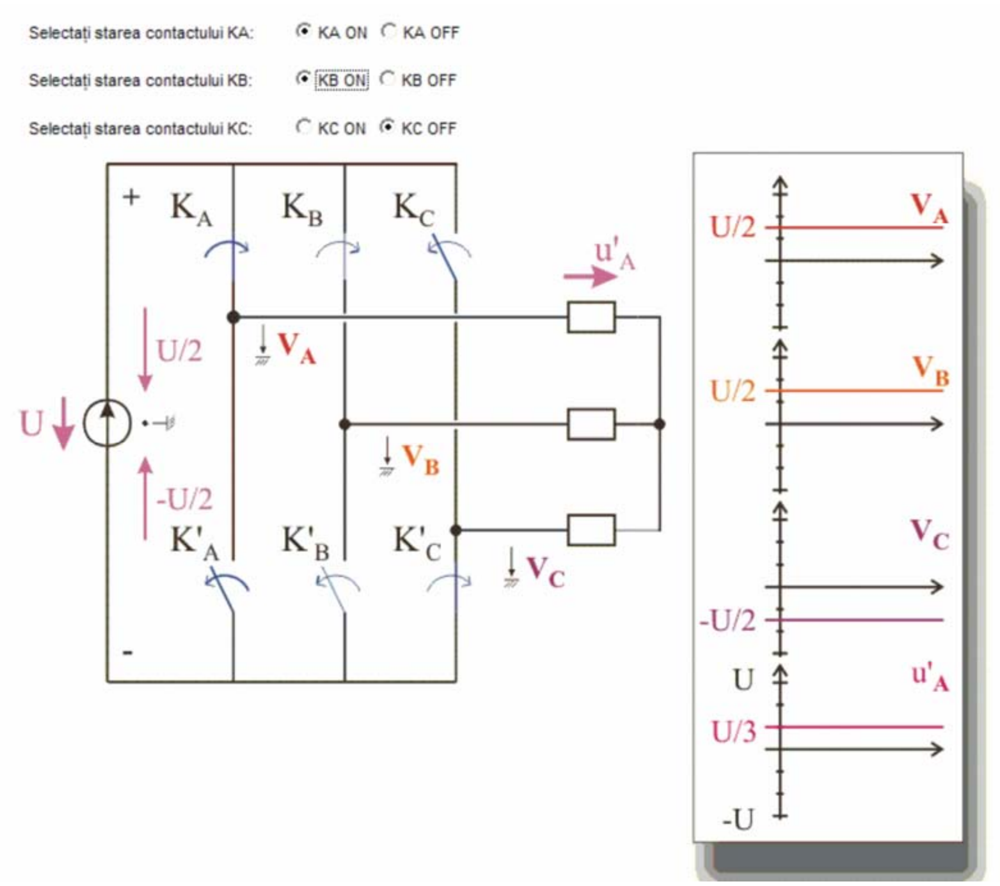

Fig.6. One possible topology of the voltage source inverter and its corresponding phase voltage (http://www.em.ucv.ro/eLEE/EN/realisations/ElectroniquePuissance/Onduleurs/Structure/4_cours.htm #topologies)

direction of the stator voltage space vector:

$$\underline{u}_s = u_{s\alpha} + ju_{s\beta} = \frac{2}{3}\left(u_{sa} + a \cdot u_{sb} + a^2 \cdot u_{sc}\right), \quad (5)$$

with $a = e^{j\frac{2\pi}{3}}$.

The link between the inverter's topology and the corresponding orientation of the stator voltage space vectors is illustrated by a graphic that displays, for each topology of the inverter chosen by the user, the corresponding direction of the stator voltage phasor. Fig.7 presents one of the eight possible configurations.

In addition, the only thing that has to be done is to choose the proper topology of the inverter, depending on:

• the actual position of the stator flux (the specific sector of the six possibilities, Fig.8);
• the necessary evolution of the stator flux magnitude;
• the necessary evolution of the electromagnetic torque developed by the machine.

The user can choose any particular value for all the above variables and by means of an intuitive animation, the corresponding topology, the stator voltage space vectors and the stator flux evolution are displayed. Fig.9 presents a capture of this animation that corresponds to one of the 36 possible combinations.

At the end, the presented resource is completed with a virtual laboratory that details the practical aspects concerning such a control of the induction machine (the type of controllers, the resulted structure of the control diagram, and the influence of the sampling period).

5 Evaluation of the Resources by the Students

To develop pedagogical tools based on information and communication technologies (here mainly web technologies) is one thing; to verify that such tools will be effectively used and useful to the students for witch they have been designed is another thing [8].

Such task has been entrusted to an expert, external to all concerned institutions. The evaluation process has been performed in 5 steps:

• Before all investigations, the project promoters and all the eventually concerned teachers (teachers belonging to several institutions, in charge of courses in one of the four themes) have been individually interviewed in order to precise their

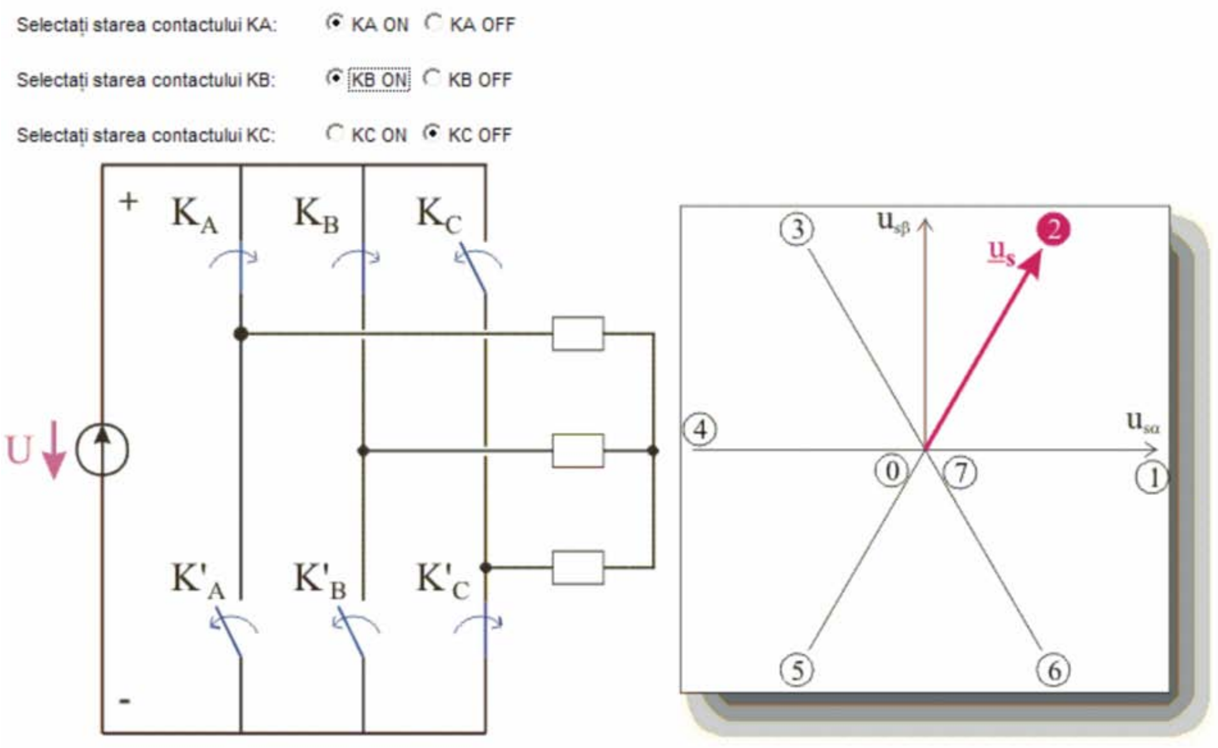

Fig.7. One possible direction of the stator voltage phasors and the corresponding topology of the inverter (http://www.em.ucv.ro/eLEE/EN/realisations/MachinesElectriques/Induction/DirectTorqueControl/Principe/3_cours.htm)

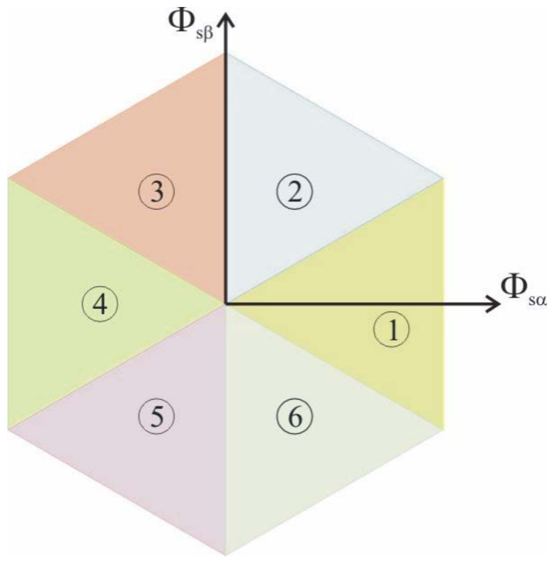

Fig.8. The six sectors of the plane $(\Phi_{s\alpha},\ \Phi_{s\beta})$
(http://www.em.ucv.ro/eLEE/EN/realisations/MachinesElectriques/Induction/DirectTorqueControl/Principe/4_cours.htm)

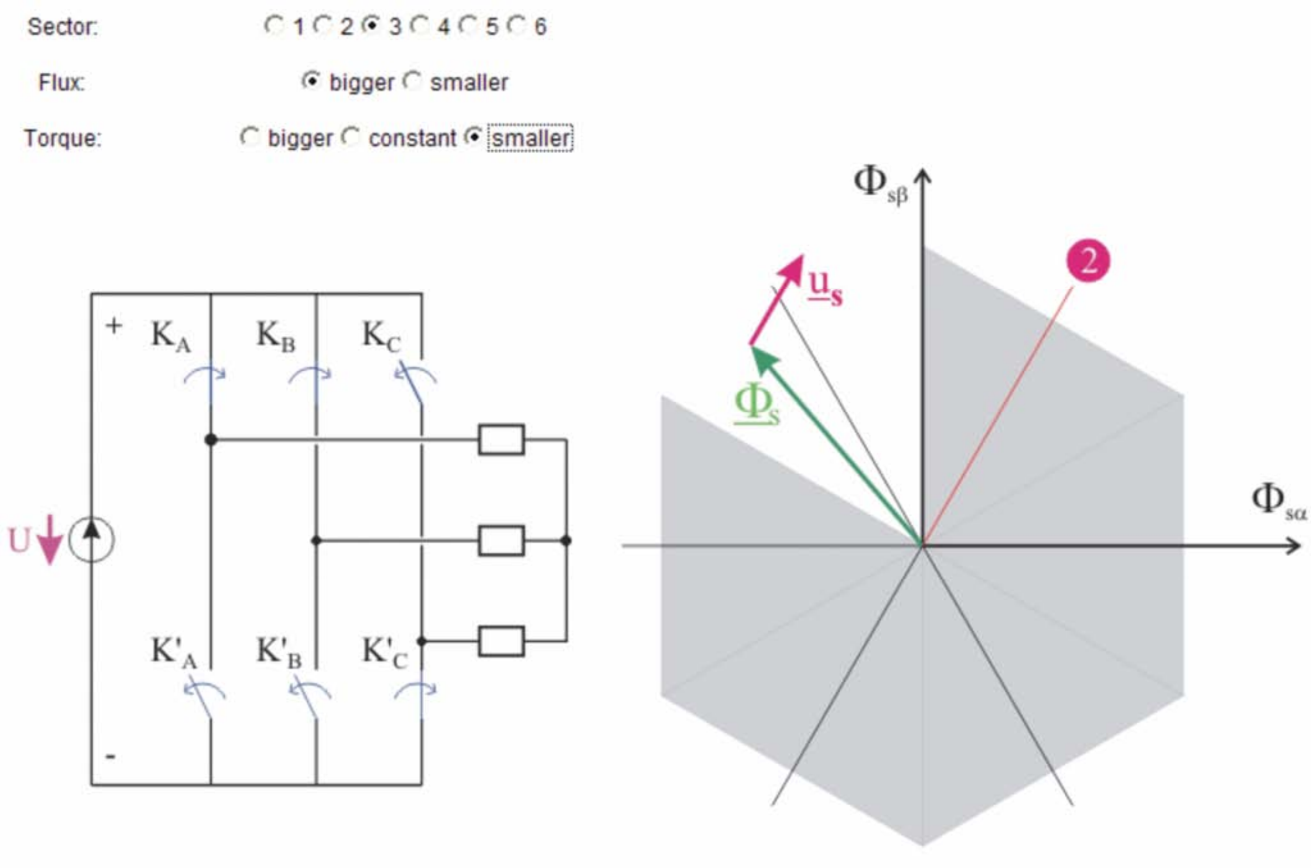

Fig.9. One possible evolution of the stator flux
(http://www.em.ucv.ro/eLEE/EN/realisations/MachinesElectriques/Induction/DirectTorqueControl/Principe/4_cours.htm)

individual objectives as well as their perception on the local context.

- In a second step, before the use of developed tools, all the students have been invited to fulfil a questionnaire (quantitative approach) about their expectations relatively to such pedagogical supports. The questionnaire contained also some questions about the pedagogical, economic and social context of the students (what do they think about their teachers? have the students a computer with internet link at their disposal at home? what is the study level of their parents? etc.). Obviously, the questionnaire was confidential. The students had the possibility to remain anonymous or to identify themselves through a code in order to link their answers with the ones given in the third step. About 800 students have been interrogated in the 4 countries involved in the study.
- In the third step (nearly 3 to 4 months after), after they have used (or not) the proposed tools, a second questionnaire has been submitted to the students. Nearly 500 students have accepted to answer to this evaluation questionnaire.
- In the fourth step, the independent expert met 32 students for one-half-hour individual interviews (qualitative approach). The aim of this dialog was to verify some hypothesis came from quantitative analysis.
- Finally, it has been asked to all the promoters of the project to fulfil independently an open questionnaire. The aim was to verify if their objectives have evolved during the project and to know how they consider the future. At this stage of the evaluation process, the promoters did not have access to all the results of the previous steps. They had equally the possibility to submit the questionnaire to other teachers of their own institution, involved in the project.

Generally speaking, the students, that have used the proposed tools, express a high satisfaction level. About 81% of them find the tools “innovating and stimulating”, 72% think that they had permit them to better understand the subjects. There are few disappointments despite to a high expectation level, especially in Romania and Portugal where the newness effect was maximal. This high satisfaction level concerns firstly the animations that (in students opinion) are the main added value of the tutorials (73% of satisfaction for animation comparing to “only” 64% for on-line lessons). MCQ’s were particularly appreciated by Belgian and Romanian students to prepare exams (83% of satisfaction comparing to 60% in other countries). In concerned institutions, exam form is indeed very close to MCQ’s (either MCQ’s or oral exams). In France and Portugal, exams consist in written problems students are required to solve problems.

The consultation of the tutorials by the students depends mainly on the behaviour of their teacher. The more the teacher talks about the tutorial, the more he (or she) shows the animations during lessons, the more the students will return to the web site to see them again. They experience the feeling that such tool is useful to understand the course.

For example, the tools were more used in Romania by the students of one teacher that was showing and speaking a lot about the tutorials than in France where the teacher has only indicate the existence of the web site. And this, despite to the fact that every student of the French concerned institution was owing a personal computer, whereas only one Romanian student out of three had easy access to internet.

The presence of the teacher is still more important to students which have some difficulties to understand the lesson subject. The best students are visiting more spontaneously the web site.

Beside to their understanding level, another key to discriminate the behaviour of the students is their interest for the tutorial subject.

The ones which are more interested by the success to the exams than by the understanding of the treated subject, have less need of the teacher. For them, a web site is a good way (but not necessarily the best way) to have indications about what is possible to be asked to the exams and to study it at their own rate, eventually without being present to lessons anymore. The usefulness of the web site to succeed the exam is directly linked by these students to the fact that the teacher had talked often or not about the tutorials (particularly at the beginning of the course).

The students more interested by the tutorial subject itself are the ones that appreciate more the web site. However, they are asking for the teacher presence for giving more explanation about animation contents. This is more necessary for the students which have difficulties to understand the tutorials or for the best students which wish to be helped to go deeper in the matter.

6 Conclusion

This paper presents a short description of the two years experience of four high education European institutions in developing and using multimedia tools for Electrical Engineering teaching/learning.

During this period, different types of resources (lessons, laboratories, MCQs) for four themes were developed. Most of them use various types of multimedia applications: pictures, videos, graphics and most of all, animations and interactive applications. All the animations are Java applications realized throughout the own effort of the participants.

All the resources have an entirely free access from the site (www.e-lee.net) developed by the association settled by the four institutions. The association is opened to any moral or physical person that intends to make use of the resources offline (CD copy) or to participate on the development of new resources for which the association offers support and the acquired practical knowledge.

In time, the resources available on the site were used in different contexts, always proofing to be valuable aids for clarifying the knowledge. As the tutorials cover both basic lessons and more specialized ones, they were used with good results for the initial formation, as well as for different courses by the ones considered right at the origin of the project.

One particular resource was described in detail in this paper: the principle of the Direct Torque Control of the Induction Machine. It represents a good example of the links between different areas of the Electrical Engineering, here the Power Electronics and the Control of Electrical Machines.

References:

[1] C. Boboila, G.V. Iordache, M.S. Boboila, *An Online System for Testing and Evaluation*, WSEAS Transactions on Advances in Engineering Education, ISSN 1790-1979, Issue 1, Vol. 5, January 2008, pp. 20-28.

[2] S. Campanella, G. Dimauro, A. Ferrante, D. Impedovo, S. Impedovo , M. G. Lucchese, R. Modugno, G. Pirlo, L. Sarcinella, E. Stasolla, C. A. Trullo, *E-learning platforms in the Italian Universities: the technological solutions at the University of Bari*, WSEAS Transactions on Advances in Engineering Education, ISSN 1790-1979, Issue 1, Vol. 5, January 2008, pp.12-19.

[3] A. Dastfan, *Implementation and Assessment of Interactive Power Electronics Course*, WSEAS Transactions on Advances in Engineering Education, ISSN 1790-1979, Issue 8, Vol. 4, August 2007, pp. 166-171.

[4] S. Enache, A. Câmpeanu, M.A. Enache, S. Ivanov, *E-learning for Education in Asynchronous Machines*, WSEAS Transactions on Advances in Engineering Education, ISSN 1790-1979, Issue 11, Vol. 4, November 2007, pp. 238-241.

[5] S. Encheva, S. Tumin, *Multimedia Factors Facilitating Learning*, WSEAS Transactions on Advances in Engineering Education, ISSN 1790-1979, Issue 10, Vol. 4, October 2007. pp 203-209.

[6] C. Escribano Iglesias, A. Giraldo Carbajo, M. Asunción Sastre Rosa, *Interactive Tools for Discrete Mathematics e-Learning*, WSEAS Transactions on Advances in Engineering Education, ISSN 1790-1979, Issue 2, Vol. 5, February 2008, pp. 97-103.

[7] V.M. Grassa, J. Lloret, C. Rodríguez, L. Romero, E. Sanabria, V. Sanchis, *Cooperative Work for Teacher Training*, WSEAS Transactions on Advances in Engineering Education, ISSN 1790-1979, Issue 2, Vol. 5, February 2008, pp. 69-76.

[8] D. Grenier, C. Bontinckx, *Evaluation par les étudiants de ressources pédagogiques en ligne*, Colloque sur l'Enseignement des Technologies et des Sciences de l'Information et des Systèmes (CESTIS 2005), Nancy, 25-27 octobre 2005 (CD).

[9] D. Grenier, S. Ivanov, F. Labrique, S. Labrique, M-J. Resende, B. Robyns, *A co-operative development of e-learning tools for electrical engineering*, 16th EAEEIE conference, Lappeenranta, 2005 (CD).

[10] S. Labrique, D. Grenier, F. Labrique, *Développement d'outils multimédia pour l'enseignement des convertisseurs électromécaniques*, Proc. of Colloque sur l'Enseignement des Technologies et des Sciences de l'Information et des Systèmes (CESTIS-EEA'2001), Clermont-Ferrand (France), October 2001, pp. 209-212.

[11] P. Vas, *Sensorless Vector and Direct Torque Control*, Clarendon Press, Oxford, 1998.

[12] www.e-lee.net.