Alternating currents first

Experiences from designing a novel approach to teaching electric circuit theory

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1 BACKGROUND

Commonly in electric circuit theory courses, circuit laws are first introduced in the context of direct current (DC) electricity. Alternating currents (AC) are usually introduced first thereafter. The idea is that DC currents and voltages are believed to be easier to grasp. Once DC-theory is understood it is assumed that circuit laws could easily be generalized to the AC-domain by replacing DC sources, currents, voltages and resistors by complex-valued ($j\omega$) phasor notation representing AC quantities. An historical explanation is that DC-electricity was first used commercially.

Although the extension of DC-theory to AC is quite easily done mathematically, using phasors and the $j\omega$-method, it is difficult conceptually for students. Studies performed in several countries have demonstrated that engineering students have difficulties in understanding phase relationships and phasor representations in AC-electricity [1-7].

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Indeed, it has been suggested that phase should be seen as a threshold concept [4, 7].

2 PURPOSE

The purpose of this study was to investigate if a re-designed introductory electric circuit course with DC- and AC-electricity taught concurrently with Dcould improve students' understanding of important concepts in AC-electricity.

3 APPROACH

3.1 Course design

In the previous design of the course much time was spent on introducing concepts, theorems and methods such as current, voltage, power, resistance, Kirchhoff's' laws, node-voltage method, mesh-current method, superposition, Norton and Thévenin equivalents in the DC-electricity-domain. However, this left little time to discuss important aspects of AC-electricity and commonly students got stuck in "DC-thinking" as discussed in the introduction.

The course was re-designed introducing AC and DC electricity simultaneously. DC was introduced as a special case of AC with frequency equals zero. The idea was that students should meet AC-circuits from the beginning. By avoiding going through similar theory twice more time would be available to discuss concepts, theorems and methods in more depth.

The re-design draw on approaches described as "design-based-research" or "design-experiments" [8-11]. These can be seen as "a systematic attempt to achieve an educational objective and learn from that attempt" [12]. Furthermore, in the design we draw on Variation theory [13, 14] and were inspired by previous application of this theory into engineering education [15-20]. A central tenet in this theory is that experiencing variation rather than similarities is a necessary condition for learning.

The course is a 6 ECTS-credits course taken each year by 30-40 first year electrical engineering students. The teaching of electric circuit theory part involves 6 lectures (2 h), 10 problem-solving sessions (2 h) and 4 labs (4 h). A minor part of the course teaches a part of a measurement technology "trail" running through several courses.

The re-designed course was taught for the first time during the spring semester 2014. A new textbook [21] was written since existing textbooks, including the one previously used [22], treated DC-electricity before AC-electricity.

The textbook [19] has the following chapters:

1. *Fundamental concepts* introducing electric potential, voltage, current, power, circuit topology and Kirchoff's laws (introduction).
2. *Complex representation* introducing complex numbers, the representation of sinusoidal signals by complex numbers and phasors, summation of sinusoidal signals using complex numbers and phasors, phase change, and solving differential equations (steady-state) by complex numbers and phasors. Although students are expected to have learnt complex numbers in mathematics we have experienced that students have difficulties to use them in the way they are used in electric circuit theory and electronics and how they are used to represent sinusoidal signals through phasors. Hence this, more mathematical chapter, is included.
3. *Circuit elements and simple circuits* introducing modelling, phasors, two-poles, active components (ideal current and voltage sources), passive components

(ideal resistors, inductances and capacitances) and simple circuits. Differential equation models as well as complex phasor representation of the elements are introduced. The DC-circuit case is introduced with frequency equals zero, i.e. with $\omega=0$ in the $j\omega$-method; hence it is natural to see an inductor as a short-circuit and a capacitator as a break for DC-currents.

4. *Circuit analysis techniques I* discussing Kirchoff's laws and Ohm's law more in depth and introducing node-voltage-analysis.
5. *Circuit simplifications I* discussing simplifications in general through, for example symmetry, and especially introducing simplification using Norton and Thevenin equivalent circuits.
6. *Magnetically coupled circuits* introducing mutual inductance, magnetic circuits and the ideal transformer.
7. *Four poles and circuit functions* introducing circuit functions such as the transfer function, reciprocity and four poles.
8. *Frequency response* introducing frequency dependency of circuits, simple filters, Bode-diagram and resonance.
9. *Power* introducing instantaneous, active, reactive and apparent power and maximum power transfer in DC- and AC-circuits.
10. *Circuit analysis techniques and circuit simplifications II* introducing mesh-current-analysis, superposition and Δ-Y-transformation.

Besides introducing AC alongside DC main features of the book is an emphasis on conceptual understanding, an emphasis on understanding modelling and what complex numbers and phasors "does" when representing AC-signals, and deliberately introducing node-voltage early in the course. Mesh-current-analysis is intentionally introduced last in the course to allow students to focus on the node-voltage-method because of its importance in electronics.

Fig 1. Interface used in labs as signal generator and to collect data.

Fig 2. Circuit board used in labs.

Furthermore, four new labs (4 h) were developed: 1. Circuit elements and simple circuits, 2. Circuits and circuit theorems, 3. Frequency dependency, and 4. Electric power. All labs treated DC- and AC-electricity in an integrated way and by using contrasting cases and comparisons variation theory was utilised in the design of labs.

During all labs PASCO Science Workshop 750 interface (see *Fig. 1*) together with PASCO Capstone software was used to generate signals and to collect data. The interface has a built in signal generator, four digital inputs and three analogue inputs. The analogue inputs are differential, i.e. had no common ground. Therefore, the circuit could not be short-circuited through interface as is a typical problem with most oscilloscopes. In this course either voltage- or current sensors were connected to the analogue inputs, but other sensors such as temperature, pH or force-sensors could be connected. Furthermore, the current through and the voltage over the output was simultaneously measured. Hence, together with a PC or Macintosh Computer the interface could serve as a differential five-ray oscilloscope. This made it possible to design experimental tasks that would not be possible to perform with standard equipment.

To focus on fundamental circuit concepts and physical principles PASCO Capstone software was used. This software is relatively easy for students' to use with a low learning threshold. LabView, for example, has a much higher learning threshold. For the same reason a relatively simple circuit board was used (see *Fig. 2*).

In the first lab *Circuit elements and simple circuits* the students' start out with measuring voltage and current as a function of time for resistors with different values of resistance R. The students were asked to display the result as time-graphs and as voltage-current-graphs. Already here variation theory is used in task design by asking students to predict the consequences for the voltage-current-graph when changing R. A second part of this first lab was measuring voltage-current-characteristics for a light bulb with AC to allow students to discover that Ohm's law is not valid for all circuit. As a third part the students measure current- and voltage-graphs for an inductor and for a capacitance using AC. Students are requested to measure the phase difference between voltage and current and construct the corresponding phasor representation mathematically with complex numbers and graphically. As the last part of this first lab simple circuits in form of a *RL*-circuit (see *Fig. 3*) and a *RC*-circuit is studied with an AC-voltage applied. The interface is used as a four-ray-oscilloscope and the output voltage $u_{\mathrm{out}}(t)$, current $i_{\mathrm{out}}(t)$, the resistor voltage $u_{\mathrm{R}}(t)$, and the inductor voltage $u_{\mathrm{L}}(t)$ is measured. The voltages $u_{\mathrm{R}}(t)$ and $u_{\mathrm{L}}(t)$ are added using features in the software (see *Fig. 4*), added using complex number phasor representation and graphical phasor representation and compared with corresponding representation of $u_{\mathrm{out}}(t)$ to demonstrate various forms of Kirchoff's voltage law.

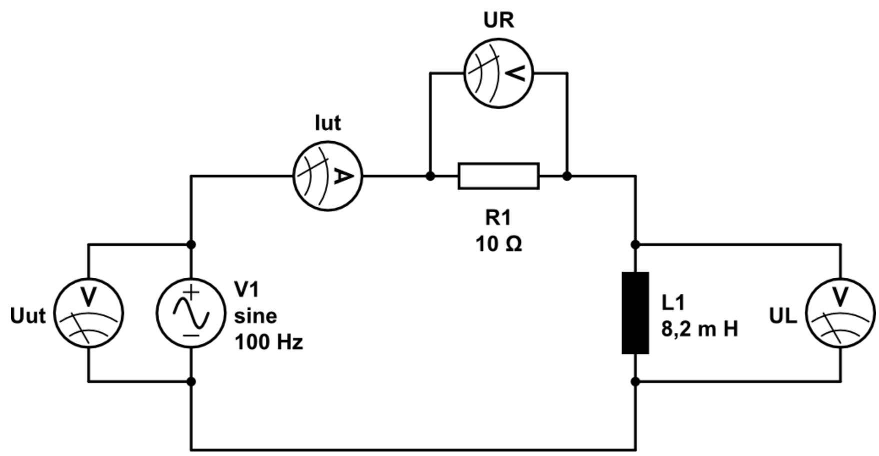

Fig. 3. An experiment in the first lab to investigate the validity of Kirchoff's voltage law. The output voltage $u_{\mathrm{out}}(t)$, current $i_{\mathrm{out}}(t)$, the resistor voltage $u_{\mathrm{R}}(t)$, and the inductor voltage $u_{\mathrm{L}}(t)$ is measured by the interface and the results displayed on the computer screen (see *Fig. 4*). The interface generates a sinusoidal output voltage $u_{\mathrm{out}}(t)$ with a frequency of 100 Hz and amplitude of 2 V.

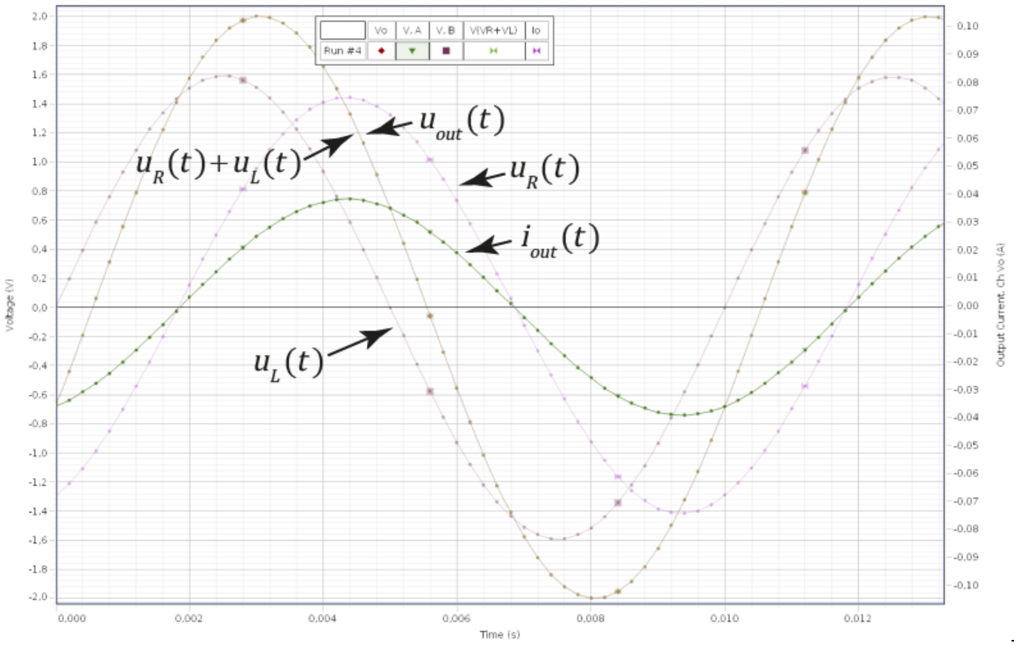

Fig. 4. Measured curves from a student lab-report for the task in *Fig. 3*. A tool in the software was used to calculate $u_R(t)$+ $u_L(t)$. As can be seen in the figure this sum is identical with $u_{out}(t)$.

The second lab is *Circuits and circuit theorems*. In this lab the first part is the measurement of voltages and the current as function of time over all components for a series *RLC*-circuit with three different frequencies for the applied AC. One frequency was approximately equal to the resonance frequency and the other two frequencies was half and twice that frequency respectively. As in the first lab the students were asked to use time function as well as phasor representation with complex numbers and in graphical form. In addition, in this lab, they were asked to calculate the complex impedance. Variation theory was utilized in the task design by asking students to observe and compare the results for the three different frequencies and especially compare the magnitudes of $u_L(t)$ and $u_C(t)$ and the phase of $i_{out}(t)$ relative to $u_{out}(t)$. In a second part parallel-circuits, with either an inductance or a capacitance parallel to a resistance, were investigated and the current through the branches were measured using current sensors. The intention was to demonstrate Kirchoff's current law.

The third lab is *Frequency dependency*. In this lab students are first measuring $u_R(t)$, $u_L(t)$, and $u_{out}(t)$ voltages in an *RL*-circuit at various frequencies and are asked to plot amplitudes and phases as function of frequency. Secondly the students are investigating an *RLC*-series-circuit as function of frequency measuring $u_R(t)$, $u_L(t)$, $u_C(t)$, $u_{out}(t)$ and $i_{out}(t)$. Students were asked to draw phasors for the lowest and the highest frequency and the resonance frequency and to note what was happening with relative magnitudes and phases.

In the fourth and last lab *Electric power* $p(t)=u(t)\cdot i(t)$ could be investigated. Features in the software allowed instantaneous values for current and voltage to be calculated from measurement. This allowed $p(t)$ to be measured for a resistance, a capacitance and an inductor and to be compared. Furthermore, measurements of $p(t)$ for the different components were made for an *RLC*-series-circuit at frequencies well below, well above, and at the resonance frequency and again students were asked to compare results.

3.2 Methodology for evaluation

Based in part on questions in reference [3] we have developed a 25 questions test to probe students' understanding of phase relationships. It was administered in 2013 to serve as a baseline and in subsequent years to evaluate the revised course.

In 2014 the students' courses of action in selected lab-groups were video-recorded [23]. Furthermore, analysis of students' lab-reports, course-evaluations, discussions with students and instructors' notes and experiences served as a guide for further development of the course after the first implementation cycle.

4 RESULTS AND EXPERIENCES

A summary of students' results on the phase conceptual test is displayed in table 1. In the first revision cycle neglible improvement was achieved, while in the second cycle some improvement was achieved with an effect size (Cohen's *d* [24]) of 0.56. This is usually considered to be a medium effect.

Table 1. Students' understanding of phase relationships in AC-circuits

Course	N	Average (%)	Effect size
Spring 2013 (baseline)	29	45.3	0 (by definition)
Spring 2014 (first cycle)	29	46.0	0.05
Spring 2015 (second cycle)	29	53.7	0.56

The lab-equipment used allowed the design of labs were tasks were designed according to Variation theory using predictions and comparisons. However, Variation theory does not only state that variation is necessary for student learning. It is also important that student focus on important aspects of the object of learning, i.e. in their focal awareness. In 2014 many students hade difficulties to complete the labs in four hours. Thus students were not focusing on all important aspects. Furthermore the course evaluation and discussions with students revealed a mixed response towards the revised course. This, together with a first analysis of video-recordings, lab-reports, and instructors' experiences served as a guide for the second cycle revisions there the number tasks were reduced with a focus on tasks that were identified as most important for contributing to the development of student understanding. As the result of the second cycle not only the learning gain improved, but also the course and the textbook was very well appreciated according the course evaluation. In the third cycle only small revisions are made.

5 CONCLUSION

The work can be considered as a continuous design-in-progress. The results show that that AC-electricity can be taught concurrently with DC. However, we would like to further develop our learning environment. In the first revision cycles we have focused on the development of conceptual labs and on the writing of the textbook. In further revision we will continue to refine the labs. But we will consider developing appropriate interactive lecture demonstrations [1, 25] for the lectures and to develop the problems along the lines of the tutorials developed by Kautz [3, 26].

Our first revision resulted in a marginal gain in student understanding and it was not well appreciated by the students. However, in the second cycle the gain was improved and the course was appreciated. This is line with previous experiences developing other courses [27]. It is important to realise that curriculum development needs a sustained effort over a considerable period of time with continuous revisions in light of gained experiences. Hence, a course revision cannot be implemented as a "one shot" experience and it is problematic that many universities only fund curriculum development projects for one year.

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