

Electrical engineering education in the field of electric circuits theory at AGH University of Science and Technology in Kraków

S.A. Mitkowski, A.M. Dąbrowski, A. Porębska & E. Kurgan

AGH University of Science and Technology
Kraków, Poland

ABSTRACT: This paper describes the electric circuit theory course offered to undergraduate students (*engineer level*) in the Faculty of Electrical Engineering, Automatics, IT and Electronics at the AGH University of Science and Technology in Kraków, Poland. This course is carried out during the second and third semesters of studies. It contains three modules: lectures, tutorial activities and laboratory classes. The curriculum is presented as a set of detailed problems undertaken by students during their laboratory classes. The work undertaken by students is to associate physical measurements with computer simulations. It was found that electrical engineering students, who were familiar with laboratory measurements and the use of real and virtual instruments, complemented their knowledge of theory received during lectures successfully, thus preparing themselves for future work.

INTRODUCTION

The Department of Electrical and Power Engineering is one of eight within the Faculty of Electrical Engineering, Automatics, Computer Science and Electronics at the AGH University of Science and Technology in Kraków. The department was set up three years ago when the Department of Electrical Engineering and the Department of Power Engineering were merged. At present, the existing department provides lectures for all specialisations within the Faculty.

The department is particularly associated with the teaching of electrical engineering. One of the basic - introductory - courses for students majoring in this field is *theoretical electrical engineering*. It contains two main subjects: the theory of electric circuits and electromagnetic field theory. In this paper the authors discuss the teaching of electric circuit theory. A separate paper devoted to electromagnetic field theory was written and submitted for presentation at this Conference.

DESCRIPTION OF THE GRADUATE STUDENT COURSE PROGRAMME ON ELECTRIC CIRCUITS' THEORY

Courses related to theoretical electrical engineering are a part of the so-called *minimum programme* specified in the teaching standards [1] introduced by regulations issued by the Polish Ministry of Science and Higher Education. These standards, in accordance with the Law on Higher Education of 2005, require the introduction of a two-level teaching process in the field of electrical engineering [2]. In accordance with these requirements, from 2007 the AGH University of Science and Technology introduced two-level (engineers and masters) studies.

The first stage (engineer level) takes 3.5 years of education (7 semesters) while the second stage (master's level) takes 1.5 years (3 semesters). Students who began their studies before 2007 continue their education within the undivided model of education, lasting 5 years (10 semesters).

Programmes presented in this paper are those carried out within the two-level studies model. They were implemented three years ago at the engineer level, while at master's level they are to be introduced into the curriculum for the first time in the next academic year.

During the first level of teaching engineering, the theory of electric circuits is presented as Electric Circuits Theory (part I) in second semester, and the Electric Circuits Theory (part II) in the third semester. The second semester course embraces 45 hours of lectures (3 hours per week) and 30 hours of practical activity (2 hours a week). In semester three, students have 45 hours of lectures, 30 hours practical and 30 hours of laboratory activities [3].

The curriculum for Electric Circuits Theory (I) includes the following:

- Definition of the electric circuit and its elements, dependencies (u-i). Dependent source, operational amplifier.
- Equations of circuits - Kirchhoff's laws.
- Differential equations of first-order circuit and second-order circuit, time constant, natural frequency. Steady-state and unsteady-state.
- DC circuits and AC (sinusoidal) circuits.
- Real power sources (voltage and current) and their equivalence. Matching the receiver to the source.
- Methods of analysis: equivalent resistance (impedance), nodal analysis, mesh analysis. Linear circuit properties - superposition principle, theorems about the equivalent source, compensation, reciprocity, equivalent moving sources.
- Sinusoidal circuits: effective values and complex values of current and voltage, complex impedance. Phasor diagrams. Sinusoidal power: instantaneous, active, reactive, apparent, and apparent complex; power factor, reactive power correction. Real elements of circuit - replacement schemes and determination of their parameters. Resonance Phenomenon. Circuits with magnetic coupling.

The curriculum for Electric Circuits Theory (II) includes the following:

- Three-phase networks (3-wire and 4-wire), symmetric and asymmetric. Calculation of voltages and currents over three-phase networks, phasor diagrams. Three-phase circuit power, measurement of power - configuration of two wattmeters (Aron Method), detecting phase sequence. Symmetric components method.
- Periodically-variable current circuits (non-sinusoidal) - distorted current, Fourier series, higher harmonics, RMS of waveform current, power: active, passive, apparent and distortion power.
- Unsteady states in electric circuits. Laplace transform, operational calculus, calculating transforms of basic time functions, operator impedance (complex), circuit elements in s-Domain. Inverse Laplace transform - calculation of a time-dependent function based on a transform; theorem about partial fraction expansion.
- Two-port networks and reactant filters.
- Method of state variables.
- Topology of a circuit, elements of graph theory. Topology matrices. Tree of a graph, meshes and fundamental cutsets. Topological methods of circuit analysis - chord currents method and cutset method.

In both courses, practical sessions are complementary to lectures. Their content is aimed at the comprehension of practical aspects of problems presented and explained during lectures.

Laboratory activities are a particularly important element of an engineer's education. The next section will discuss selected laboratory exercises.

LABORATORY ACTIVITIES

Laboratory exercises play an important role in the understanding of bases of electric circuit theory [4][5]. The Department of Electrical and Power Engineering has an appropriate didactic laboratory to conduct electrical engineering. There are 15 lab stations for students and also a station with the teacher's computer. All stations are connected to the main power supply; the set of digital measuring instruments; and the PC computer that runs programs such as Matlab and Multisim.

The laboratory can be easily adjusted to accommodate new exercises, as well as additional measuring instruments. During the laboratory exercises students are expected to build a simple electric circuit. Then they perform physical measurements of the electric circuits and compare them with the results of computer simulation created with the program Multisim. Each student must create a report from the experiment. Work which had been performed during the previous laboratory meeting is described and shown in the following week at the beginning of the laboratory classes.

Laboratory classes dedicated to the theory of electric circuits are two hours weekly.

Laboratory topics cover:

- Basic circuit elements, resistors, independent sources, Kirchhoff's Laws, volt-ampere characteristics.
- Linearity, superposition, Thevenin and Norton equivalent circuits.
- Circuits with operational amplifiers.
- Sinusoidal forcing function; phasor concept; impedance and admittance; complex power.
- Inductor and capacitor, real elements, examples of non-linear inductors and capacitors.
- Mutual inductance, linear transformer.
- Complex frequency and frequency response; series and parallel resonance.
- Three-phase systems.

- Response of the RL and RC series circuit to the step-forced input.
- Response of the RLC series circuit to the step-forced input.
- Periodic functions and complex waveform.
- Two-port networks.

Below, the laboratory exercise on transient analysis and response of the RLC series circuit to the step-forced input is described.

LABORATORY EXERCISE: RESPONSE OF THE RLC SERIES CIRCUIT TO THE STEP-FORCED INPUT

The aim of this laboratory exercise is to explore the behaviour of circuits containing resistances, inductances, capacitances, voltage DC sources and switches. The goal of transient analysis is to describe the signal of voltage or current during the transition that takes place between two distinct steady-state conditions. When a circuit contains energy-storing elements, namely inductors and capacitors, the analysis of the circuit involves finding the solution of a differential equation. If the circuit contains two energy-storing elements, L and C, the equation connecting voltage or current in the circuit is a second-order differential equation.

The response of an electrical circuit to the sudden application of voltage or current is called the transient response. The most common example of the transient response in the electrical circuit occurs when a switch is turned on or off. Transient behaviour may be expected whenever a source of electrical energy (voltage or current) is switched on or off, in AC or DC sources. In the laboratory exercise, the switch of the voltage source is realised by the function generator being set to a square waveform. The circuit tested during this laboratory exercise is shown in Figure 1.

In order to carry out measurements, students are required to read the theory of second-order transient circuit analysis.

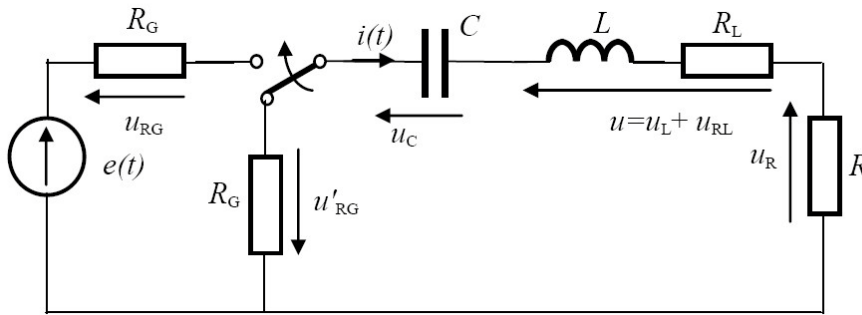


Figure 1: The second-order electric circuit.

This circuit contains two energy-storage elements, capacitors and inductor. Applying Kirchhoff's voltage law results in the following equation:

$$R_G \cdot i(t) + \frac{1}{C} \cdot \int_0^t i(t) dt + u_C(0) + L \frac{di(t)}{dt} + R_L \cdot i(t) + R \cdot i(t) = e(t) \quad (1)$$

Equation 1 is an integro-differential equation, because it contains both an integral and a derivative. This equation can be converted into a differential equation by differentiating both sides and rearranging the equation to obtain:

$$\frac{d^2 i(t)}{dt^2} + \frac{R_Z}{L} \frac{di(t)}{dt} + \frac{1}{LC} i(t) = \frac{1}{L} \frac{de(t)}{dt} \quad (2)$$

where: $R_Z = R + R_L + R_G$ is the equivalent total resistance.

The solution of the differential equation (which depends on the forcing function $e(t)$ and on initial conditions) completely determines the circuit behaviour. We assume $e(t) = E = \text{const}$ and the initial conditions are equal zero:

$$u_C(0) = 0, i(0) = 0.$$

It is noted that in the equations above, the current was chosen as the variable in the differential equation; it was also observed that the DC forcing function is zero, because the capacitor acts as an open circuit in the steady state, and the current therefore will be zero as $t \rightarrow \infty$.

The solution of equation 2 is determined by the sign of the expression below:

$$\Delta = \left(\frac{R_Z}{L}\right)^2 - \frac{4}{LC} \quad (3)$$

Three cases can be identified:

- For $\Delta < 0$ theoretical solution, there is a response of an un-damped second-order circuit (Figure 2):

$$i(t) = I_m \cdot e^{-\alpha t} \sin(\omega \cdot t) \quad (4)$$

where: $I_m = \frac{2E}{L\sqrt{-\Delta}}$, $\alpha = \frac{R_Z}{2L}$, $\omega = \frac{1}{2}\sqrt{-\Delta}$

$$T = \frac{2\pi}{\omega}, \quad A_1 = I_m \cdot e^{-\frac{\alpha T}{4}}, \quad A_2 = I_m \cdot e^{-\frac{3\alpha T}{4}} \quad (5)$$

Parameters can be calculated from a measurement as:

$$\alpha = \frac{2}{T} \ln \frac{A_1}{A_2} \quad \omega = \frac{2\pi}{T} \quad \text{where: } A_1, A_2 - \text{amplitudes, } T - \text{period, } i(t) = \frac{1}{R} u_R(t) \quad (6)$$

This is because the measurement voltages are made with an oscilloscope and the observation is the voltage u_R on the resistance R .

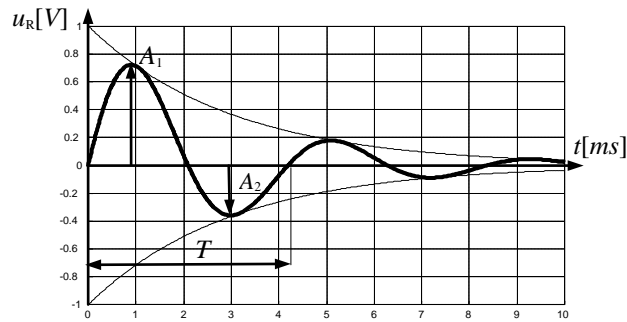


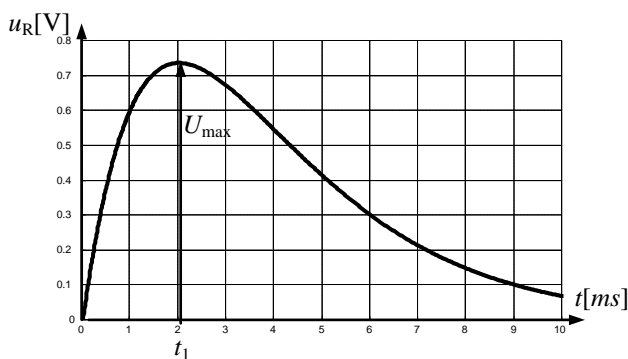
Figure 2: Response of the under damped second-order circuit.

- For $\Delta = 0$ the theoretical solution response is a critically damped second-order circuit (Figure 3a):

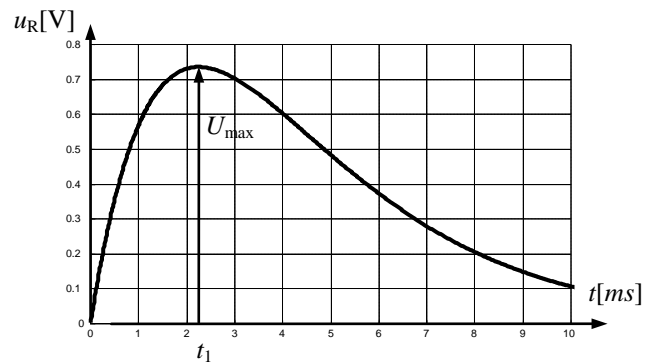
$$i(t) = C_1 \cdot e^{-\alpha t} + C_2 \cdot t \cdot e^{-\alpha t} \quad (7)$$

where: $C_1 = 0$ $C_2 = \frac{E}{L}$

$$\alpha = \frac{R_Z}{2L}, \quad t_1 = \frac{1}{\alpha}, \quad U_{\max} = R \cdot i_{\max} = \frac{2ER}{R_Z} e^{-1} \quad (8)$$



a)



b)

Figure 3: Response of critically damped a) and over damped b) second-order circuit.

- For $\Delta > 0$ the theoretical solution is an over damped second-order circuit (Figure 3b):

$$i(t) = C_1 \cdot e^{s_1 t} + C_2 \cdot e^{s_2 t} \quad (9)$$

where: $C_1 = -C_2 = \frac{E}{L\sqrt{\Delta}}$

$$s_{1,2} = -\frac{R_Z}{2L} \pm \frac{1}{2}\sqrt{\Delta}, \quad t_1 = \frac{1}{\sqrt{\Delta}} \ln\left(\frac{s_2}{s_1}\right), \quad U_{\max} = R \cdot i(t_1) \quad (10)$$

The transient response measurement of a second-order circuit takes place in the system with the diagram shown in Figure 4. The capacitance C , the inductance L and the resistance R is an element the value of which is adjusted depending on the required result of the circuit calculation. The resistance R_L is the resistance of the inductor.

The value of this resistance is measured by the ohmmeter. During the exercise students are required to connect the function generator, oscilloscope and series RLC circuit. Next, measurements are made and the computer simulation is completed.

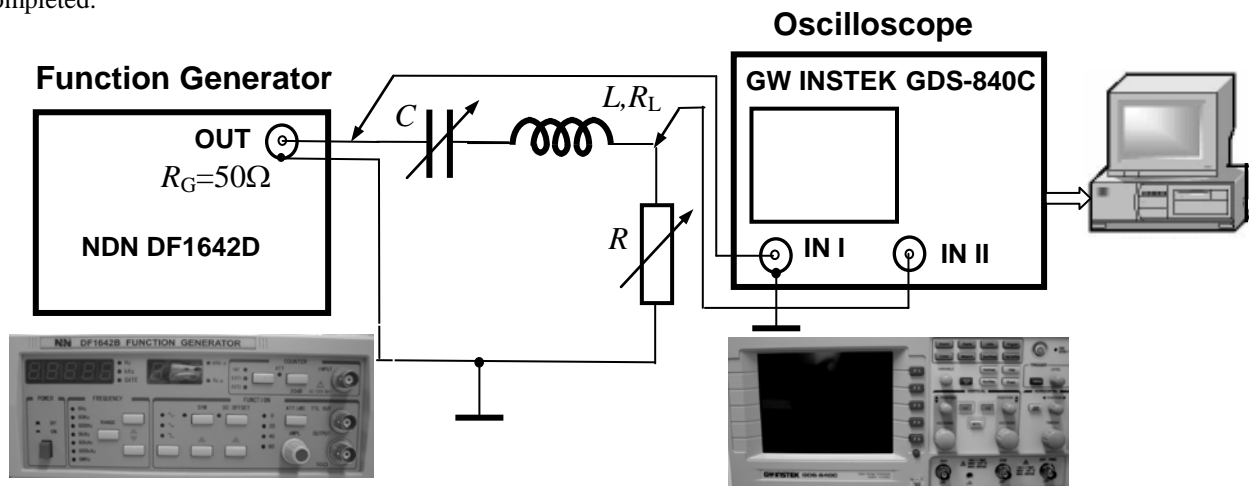


Figure 4: The schema of the system for measuring transient response in an RLC circuit.

ILLUSTRATIVE EXAMPLE

Described in this section are example results of measurements for an un-damped second-order circuit. They were obtained for the following values of circuit elements: $E = 10V$, $R = 3k\Omega$, $C = 10nF$, $L = 1H$, $R_L = 231\Omega$ (measured with the ohmmeter for 1H). These values are listed in Table 1. On the first channel of the oscilloscope, is the voltage forcing E . On the second channel of the oscilloscope, is the voltage u_R for resistance R (see Figure 5).

Table1: Values of elements for an under damped second-order circuit.

R [k Ω]	R_G [Ω]	L [H]	R_L [Ω]	C [nF]
3	50	1	231	10

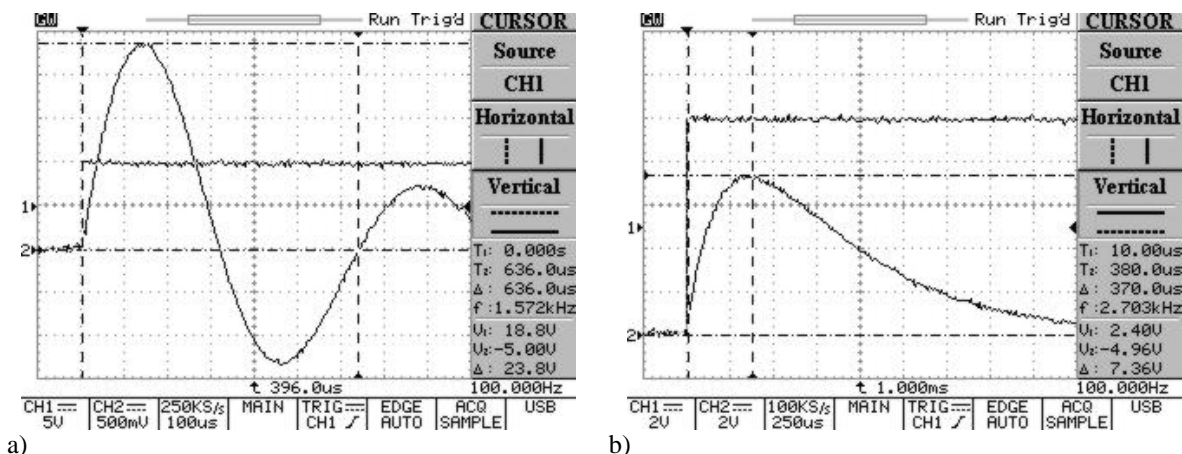


Figure 5: The oscilloscope screen showing: a) Response of un-damped second-order circuit, b) Response of critically damped second-order circuit.

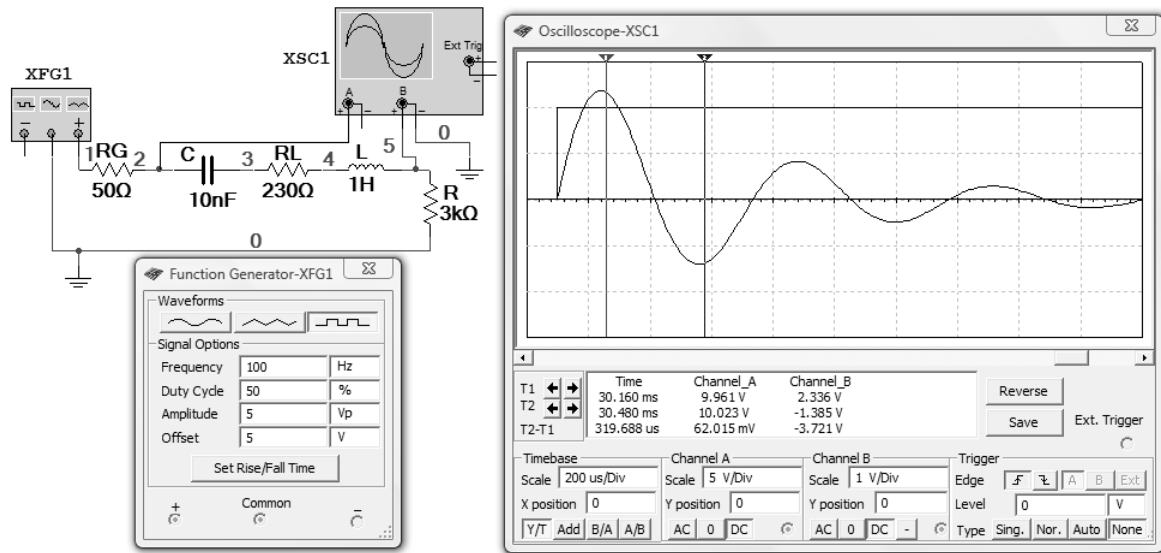


Figure 6: Computer screen showing a circuit analysis using Multisim. Response of un-damped second-order circuit.

Theoretical calculations for given parameters of the circuit, measurement of the oscilloscope and the results of the computer simulation in the Multisim program (computer screen is shown in Figure 6) are in Table 2.

Table 2: Values of parameters for the un-damped second-order circuit response.

Values calculated theoretically (Equations 3-5)					
Δ	Amplitude A_1 [V]	Amplitude A_2 [V]	Cycle T [μ s]	Frequency ω [rad/s]	attenuation α
$-3.892 \cdot 10^8$	2.342	-1.389	636,9	9865	1641
Values calculated based on measurement with the oscilloscope (Equation 6)					
Voltage source E [V]	Amplitude A_1 [V]	Amplitude A_2 [V]	Cycle T [μ s]	Frequency ω [rad/s]	attenuation α
10	2,38	-1,35	636	9879	1783
Values calculated based on the simulation in Multisim (Equation 6)					
Voltage source E [V]	Amplitude A_1 [V]	Amplitude A_2 [V]	Cycle T [μ s]	Frequency ω [rad/s]	attenuation α
10	2,336	-1,385	639	9833	1636
Measurement error δ [%]	-1.621	2.806	0.149	-0.149	-8.687

If the circuit parameters were changed so that $\Delta = 0$, the results are for a critically damped second-order circuit and if $\Delta > 0$, the results are for an over damped second-order circuit. Below is an example of the numerical calculations of the circuit in the Matlab program. Matlab can be used to compute numerical solutions for ordinary differential equations.

Matlab Function m-file:

```
function dy=diff_eq(t,y)
global R L C E
dy=zeros(2,1);
dy(1)=-R/L*y(1)-1/L*y(2)+1/L*E;
dy(2)=1/C*y(1);
```

Matlab Script m-file

```
global R L C E
R1=3000;Rg=50;RL=231;
R=R1+Rg+RL;L=1;C=10*10^-9;E=10;
[t,y]=ode45('diff_eq',[0 0.002],[0;0]);
uR=R1*y(:,1);
subplot(2,1,1)
```

```

plot(t,uR,'LineWidth',2,'Color',k),grid on
title('Response of under damped second-order circuit')
subplot(2,1,2)
plot(y(:,1),y(:,2)),grid on
title('Trajectory')

```

The graphs in Figure 7 illustrate the result of numerical solutions in Matlab for a second-order circuit.

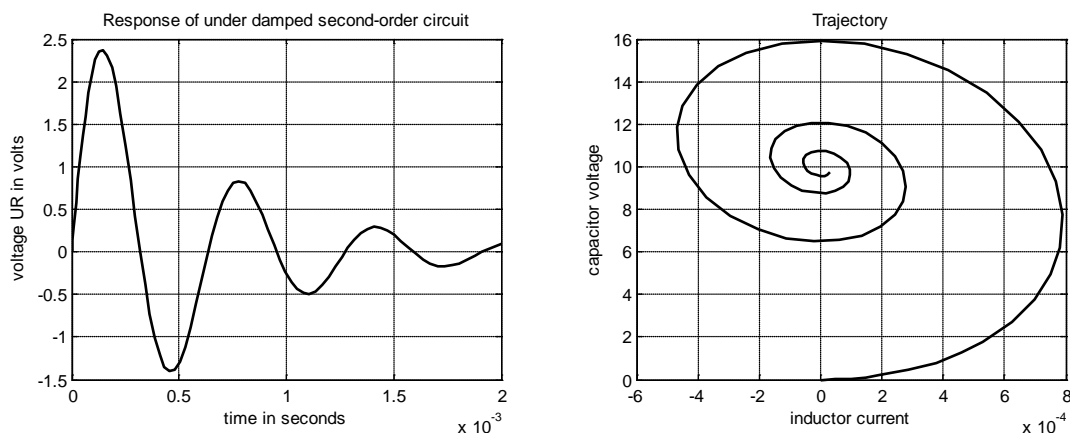


Figure 7: Transient response (left) and trajectory (right) of un-damped second-order circuit.

CONCLUSIONS

In carrying out laboratory exercises students can compare the results of experiments with computer simulation and theoretical calculations. Therefore, they have an opportunity to better understand the theory behind the problems being examined. The Multisim program allows the application of theory within a virtual environment. Moreover, students can work with computer tools useful to the practice of engineering. Electrical engineering students should be familiar with laboratory measurements and the use of real and virtual instruments. It complements the knowledge of theory received during lectures and prepares them for future work.

REFERENCES

1. Regulation of the Polish Ministry of Science and Higher Education. The standard for electrical engineering. (Rozporządzenie Ministra Nauki i Szkolnictwa Wyższego w sprawie standardów kształcenia dla poszczególnych kierunków i poziomów kształcenia, oraz trybu tworzenia i warunków, jakie musi spełniać uczelnia, by prowadzić studia międzykierunkowe oraz makrokierunki z 12 lipca 2007 roku. Poz. 24), Dz. U. Nr 164, poz. 1166 (in Polish).
2. Law on Higher Education (Ustawa z dnia 27 lipca 2005 r. *Prawo o szkolnictwie wyższym*), Dz. U. z 2005 r. Nr 164, poz. 1365 z późn. zm. (in Polish).
3. Plans and programs of electrical engineering studies at the Faculty of Electrical Engineering, Automatics, Computer Science and Electronics, AGH University of Science and Technology in Cracow, 19 June 2009, www.agh.edu.pl
4. Dąbrowski, A.M., Mathematical programs in teaching of circuits theory. *Proc. XVI BSE'2002*, Gliwice, Poland, 32-37 (2002).
5. Dąbrowski, A.M., Computer programs in teaching of electrical engineering, *Proc. XVII BSE'2003*, Vol.16., Istebna-Zaolzie, Poland, 128-133 (2003).