A practical approach to teaching power system transients in the electrical engineering curriculum

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Abstract Power system transients, which are always present in a system due to switching in the presence of inductance and capacitance, are unwanted things. They are an ignored topic in the electrical engineering curriculum of many institutes. This paper presents our new attempt to teach electric power system transients for graduate students of the Electric Power System Management Energy Program at the Asian Institute of Technology (AIT), Thailand.

Keywords power engineering education; power system transients; program exercise

Students' interest in electric power engineering worldwide is declining, resulting in modernization of the basic undergraduate courses and graduate curriculum in electric power engineering. There is a great need to revamp not only power engineering education but also electrical engineering as a whole at all levels to meet the challenges of technological development in industries and other work places. A curriculum for various courses of study can be developed to meet the demand for suitable technical human resources, bearing in mind the present and future needs of users. It is also important to consider students' interests, provided that no portion of basic power engineering education is omitted.[1–4]

In 1993, the Swedish International Development Authority (SIDA) provided AIT with financial support to develop a new field of study called Electric Power System Management (EPSM). The EPSM program is a direct response to some of the key issues facing the power sector resulting from an AIT-COPED core study on the power sector. This clearly showed the need to develop a regional facility to build up Asian private and institutional capabilities in the power sector. The field of study offers postgraduate education, degree and non-degree, to help countries in the Asian region to meet the challenges. SIDA provides scholarships annually for eight students from the Indochinese states (i.e. Laos, Cambodia and Vietnam), and students from other countries come with external support, i.e. paid by their home organisation or self-financed.

The students of Indochina face several problems which may include poor language skills and lack of basic knowledge of the subject matter. The students are accepted due to the compulsion of scholarship donors. In this situation it is more difficult to teach power system transients and other mathematical power systems topics. In addition, to give good lectures, PC-based assignments and tutorials will be more attractive and easily understood by the students. This paper presents a simple and practical approach to teach power system transients. Power system transients are taught under the power system design and operation course in the first trimester (i.e. January term). The proposed course consists of 2 hours of lectures and 3 hours of laboratory work. Assignments and laboratory work based on MATLAB are necessary for students to enhance their knowledge of power system transients.

Electric power system transients

Problem formulation, modelling of basic power system components and the methodology for digital simulation of transients using the time domain approach have been taught along with the Laplace transform for simple circuits. Students have already studied the Laplace transform for obtaining the power system transients of a simple circuit. The digital program explained to the students was based on the time-domain formulation proposed by Dommel.[5] It is based on Bergeron's transmission line model method and the trapezoidal rule of integration for lumped circuits.

The time domain-modelling algorithm proposed by Dommel is highly flexible and versatile in the simulation process of the transient. The transmission lines, inductors, capacitors or other devices are presented as a parallel combination of a resistor and a current source; the value of these depends on the past history of current and voltages in the circuit. This representation is used to solve for node voltages at any time t based on the known values from the previous instant (t-ΔT), ΔT being the simulation time-step. This approach has the great advantage of simplicity because an entire network can be quickly reduced to one containing resistor and current sources and from which the network admittance matrix **Y** is readily constructed. The basic numerical modelling of uncoupled linear power system components for single-phase analysis is considered. The nodal equations for different components are as follows.

Resistance

If a resistor (R) is connected between node 1 and node 2, as shown in Fig. 1, the currents flowing from node 1 to node 2 can be written as

$$i_{12}(t) = \frac{v_1(t) - v_2(t)}{R} = G\left(v_1(t) - v_2(t)\right) \tag{1}$$

where $G = 1/R$.

Inductance

If an inductor is connected between node 1 and node 2 as shown in Fig. 2, the current (i_{12}) can be written as

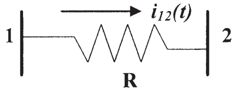


Fig. 1 *Resistor connected between node 1 and node 2.*

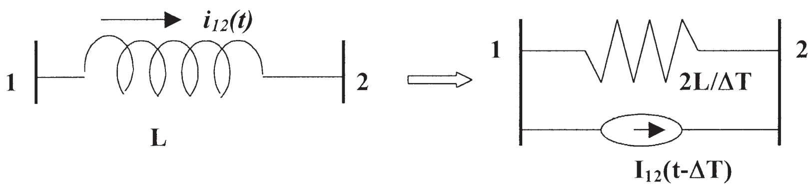


Fig. 2 *Inductor and its equivalent circuit.*

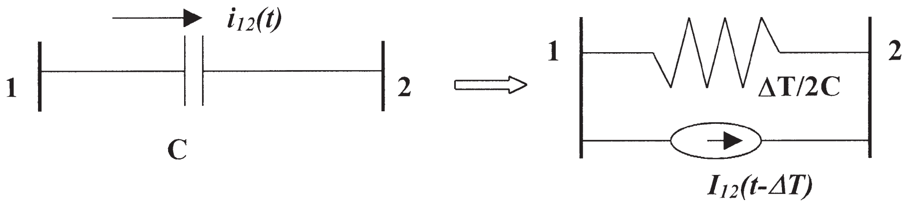


Fig. 3 *Capacitor and its equivalent circuit.*

$$v_1(t) - v_2(t) = L\frac{\mathrm{d}i_{12}(t)}{\mathrm{d}t} \tag{2}$$

Using trapezoidal rule of integration,

$$i_{12}(t) - i_{12}(t-\Delta T) = \frac{\Delta T}{L}\left[\frac{v_1(t)+v_1(t-\Delta T)}{2} - \frac{v_2(t)+v_2(t-\Delta T)}{2}\right] \tag{3}$$

The equation (3) can be written in simplified form as

$$i_{12}(t) = G[v_1(t) - v_2(t)] + I_{12}(t-\Delta T) \tag{4}$$

where $G = \Delta T/(2L)$ and I_{12} $(t - \Delta T)$ is the past history term determined from the values computed in the preceding time step as

$$I_{12}(t-\Delta T) = G[v_1(t-\Delta T) - v_2(t-\Delta T)] + i_{12}(t-\Delta T) \tag{5}$$

Capacitance

Capacitors can also be modelled as conductance and a current source as shown in Fig. 3. Current through a capacitor can be expressed as

$$i_{12}(t) = C\frac{\mathrm{d}(v_1(t) - v_2(t))}{\mathrm{d}t} \tag{6}$$

Using trapezoidal rule of integration with time step (ΔT) the above equation can be written as

$$\frac{i_{12}(t)+i_{12}(t-\Delta T)}{2} = \frac{C}{\Delta T}[v_1(t) - v_1(t-\Delta T) - v_2(t) + v_2(t-\Delta T)] \tag{7}$$

Equation (7) can be further simplified as:

$$i_{12}(t) = G[v_1(t) - v_2(t)] + I_{12}(t - \Delta T) \tag{8}$$

where $G = 2C/\Delta T$ and $I_{12}\,(t - \Delta T)$ is the past history term determined from the values computed in the preceding time step as

$$I_{12}(t - \Delta T) = G[v_1(t - \Delta T) - v_2(t - \Delta T)] - i_{12}(t - \Delta T) \tag{9}$$

Transformer

A transformer can be represented as series combination of R and L elements as shown in Fig. 4. The voltage equation can be written as

$$v_1(t) - v_2(t) = L\frac{\mathrm{d}i_{12}(t)}{\mathrm{d}t} + Ri_{12}(t) \tag{10}$$

The above equation can be simplified as

$$i_{12}(t) = G[v_1(t) - v_2(t)] + I_{12}(t - \Delta T) \tag{11}$$

where $G = \frac{1.0}{\left(R + \frac{2L}{\Delta T}\right)}$, $H = G\left(\frac{2L}{\Delta T} - R\right)$ and

$$I_{12}(t - \Delta T) = G[v_1(t - \Delta T) - v_2(t - \Delta T)] + Hi_{12}(t - \Delta T) \tag{12}$$

Transmission Line

Transmission lines are represented as distributed inductance and capacitance with resistance lumped at discrete points along the line using Bergeron's method of characteristics. The line is assumed to be transposed and distortionless. The current flowing from node k to node m can be written as follows

$$i_{k,m}(t) = \frac{e_k(t)}{Z} - I_k(t - \tau) \tag{13}$$

where $Z_0 = \sqrt{L/C}$, $Z = \frac{}{(R/4) + 1Z_0}$ and

$$I_k(t - \tau) = \frac{(R/4)}{(R/4) + Z}\left[\frac{e_k(t - \tau)}{(R/4) + Z} + i_{k,m}(t - \tau)\right] + \frac{Z}{(R/4) + Z}\left[\frac{e_m(t - \tau)}{(R/4) + Z} + i_{m,k}(t - \tau)\right] \tag{14}$$

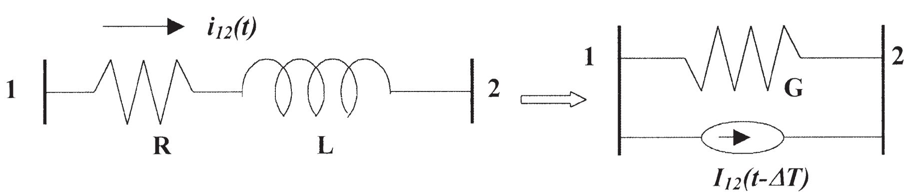


Fig. 4 *Transformer and its equivalent circuit.*

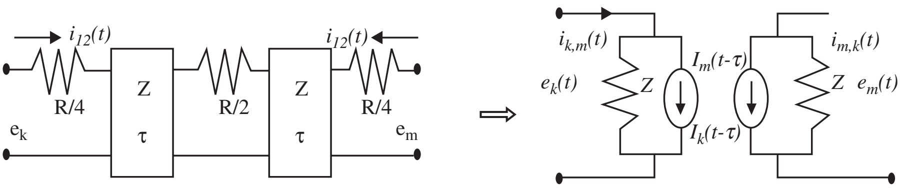


Fig. 5 *Model of transmission line and its equivalent resistive network.*

similarly, current from node m to node k can be written as

$$i_{m,k}(t) = \frac{e_m(t)}{Z} - I_m(t-\tau) \tag{15}$$

where $$I_m(t-\tau) = \frac{(R/4)}{(R/4)+Z}\left[\frac{e_m(t-\tau)}{(R/4)+Z} + i_{m,k}(t-\tau)\right] + \frac{Z}{(R/4)+Z}\left[\frac{e_k(t-\tau)}{(R/4)+Z} + i_{k,m}(t-\tau)\right]$$

The above model is shown in Fig. 5.

The mathematical formulation of transient analysis results in a system of linear algebraic equations. These are established by using nodes as the frame of reference. The matrix of the system network is formulated accordingly. The nodal equation with N nodes results in a system of N linear equations, i.e.

$$[G][V(t)] = [i(t)] - [I] \tag{16}$$

where

$[G]$ = Nodal conductance matrix
$[V(t)]$ = Column vector of node voltages at time t
$[i(t)]$ = Column vector of injected node currents at time t
$[I]$ = Known column vector (known equivalent current sources) represent the contribution of past history terms of all elements connected to nodes.

If the network contains voltage sources connected to ground, then the above equation can be partitioned into part A with unknown voltages and part B with known voltages. The unknown voltage can be found from

$$[G_{AA}][V_A(t)] = [i_A(t)] - [G_{AB}][V_B(t)] \tag{17}$$

Design of assignment and laboratory

Power engineering educators should aim to make the courses more interesting, bringing into the curriculum research topics and the latest technological innovation.[3] Potentially the largest and greatest impact on power engineering in the long term is that of power electronics and the power system restructuring which is taking place around the world. These areas have the potential of radical and major changes in power engineering. Each of these new elements in the career path of our students has its own requirement and it is clear that the focus of power engineering education needs to be broadened considerably to accommodate these needs.

Students' interest and knowledge will increase if they are given some tutorials based on personal computers (PCs). Laboratory based teaching will also attract the power engineering student to some extent. The use of MATLAB, Visual C^{++} and other software is very popular among the students. Keeping this in mind, several assignments, in addition to laboratory work, were designed and given to students for understanding power system transients and they were asked to use MATLAB for verifying the results.

Case study – I

To begin with, students are given a simple circuit consisting of a resistance R and an inductor L connected with an a.c. source and a switch as shown in Fig. 6. This problem, based on the Laplace transform, is given in several books. The current in the circuit using the Laplace transform will be

$$i(t) = \frac{E_m}{\sqrt{R^2 + (\omega L)^2}} \left[\sin(\omega t + \phi) - e^{-\frac{Rt}{L}} \sin\left(\phi - \arctan\left(\frac{\omega L}{R} \right) \right) \right] \quad (18)$$

To obtain the current in the circuit the following solution steps are required:

(i) Calculate the values of G and H for given values of R and L
(ii) Initialize the value of current and voltage at $t = t_0$.
(iii) Calculate the voltage at time $t = t_0 + \Delta T$.
(iv) Calculate the past history current using eqn (12) and current using eqn (11)
(v) Check if simulation time $t < T_{max}$, If yes, increment the time by step length (ΔT) and go to step (iii)
(vi) Otherwise stop the simulation.

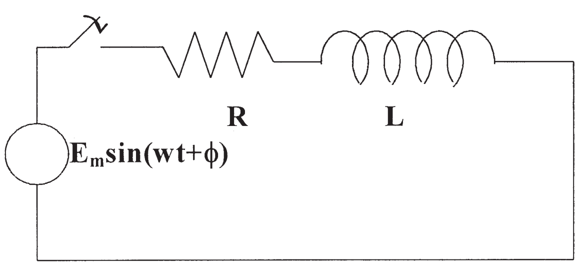


Fig. 6 R-L *circuit diagram.*

The MATLAB program for this can be written as:

```
r=1.1;
   1=0.01;
      ph= input ('Please inter the switching instant (in deg) =');
     tmax=0.2;
  delt=0.001;
f=50.0;
   w=2.*pi*f;
     em=8.0*sqrt (2.0);
   i(1)=0.;
phi=pi*ph/180;
   g=1.0/(r+1*2./delt);
   h=g*(2.*1/delt-r);
j=1;
   at (j) =0;
while t < tmax
     t=t+delt;
     j=j+1;
        at (j) =at (j-1) +delt;
        v (j) =em*sin (w*t+phi);
      v (j-1) =em*sin (w* (t-delt) +phi);
      cont=g*v (j-1) +h*ai (j-1);
     ai (j) =g*v (j) +cont;
     end
     plot (at, i, 'r')
  title ('Transisent study graph of Current Vs Time');
xlabel ('Time')
ylabel ('Current')
grid;
```

The effect of the switching transient can be explained by changing the angle ϕ. The response for different values of ϕ is shown in Figs 7(a), 7(b) and 7(c) for $R = 1.1$ ohm and $L = 0.01$ H.

From eqn (18), the transient will be high when switching instant will be

$$\phi = \pm\frac{\pi}{2} + \arctan\left(\frac{\omega L}{R}\right) \tag{19}$$

This condition can also be verified using the time domain analysis.

Case Study – II

Another case study, which was given to the student for understanding the subject, is difficult to solve with the Laplace transform. A series combination of R, L and C with a.c. source as shown in Fig. 8, was solved with the time domain analysis. This requires formulation using the node voltage concept as discussed earlier. The voltage at node 2 is unknown and it must be determined in order to obtain the current response after switching.

The current equations in the circuit can be written as

$$v_1(t) - v_2(t) = L\frac{\mathrm{d}i(t)}{\mathrm{d}t} + Ri(t) \tag{20}$$

$$i(t) = C\frac{\mathrm{d}v_2(t)}{\mathrm{d}t} \tag{21}$$

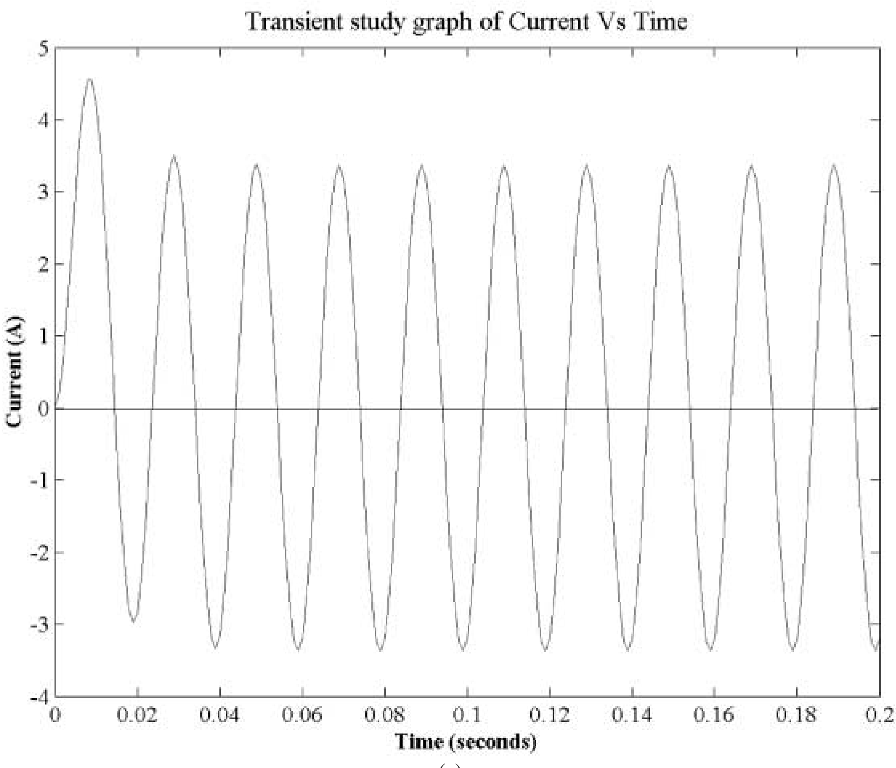
From eqns (20) and (21) can be simplified as

$$i(t) = G[v_1(t) + v_1(t-\Delta T)] - Hi(t-\Delta T) - 2Gv_2(t-\Delta T) \tag{22}$$

where $G = 1\Big/\left(R + \frac{2L}{\Delta T} + \frac{\Delta T}{2C}\right)$ and $H = G\left(R - \frac{2L}{\Delta T} + \frac{\Delta T}{2C}\right)$

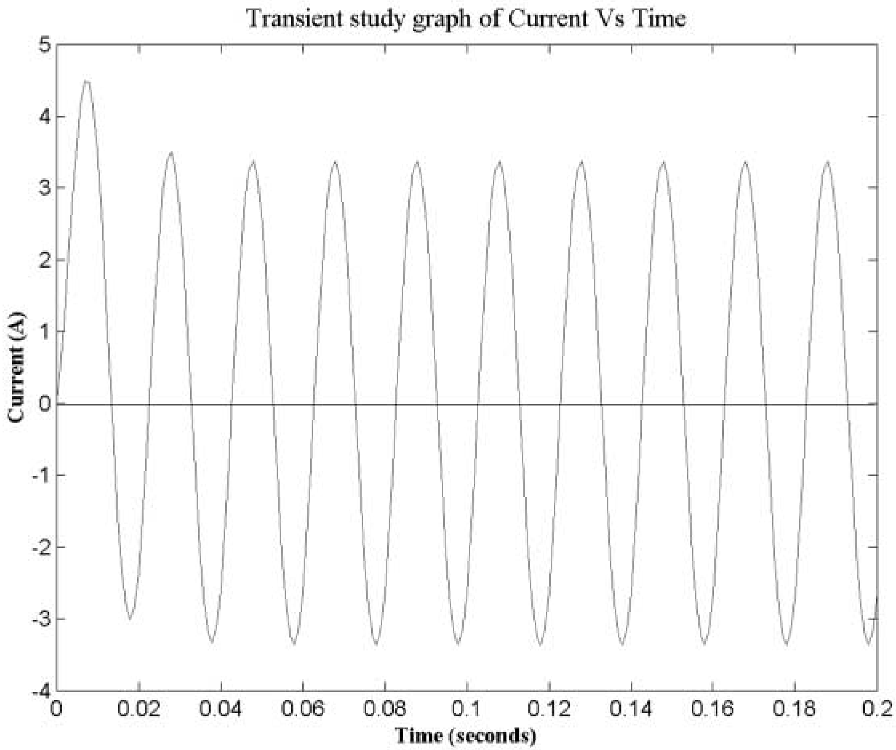
The voltage $v_2(t)$ is the voltage across capacitor which changes after the closing of switch which can be expressed as

$$v_2(t) = (\Delta T/2C)[i(t) + i(t-\Delta T)] + v_2(t-\Delta T) \tag{23}$$



(a)

Fig. 7 *Current response of the circuit at different switching instants (a) at phi = 0.0 degrees (b) at phi = 19.30 degrees (c) at phi = 70.29 degrees.*



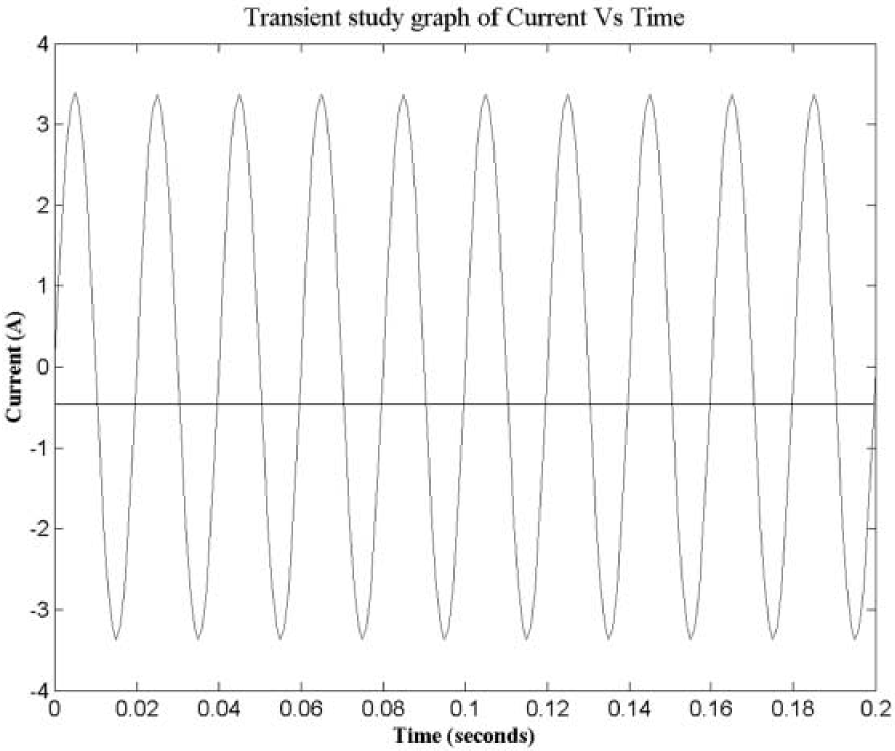
(b)

Fig. 7 *Continued*

After converting the element into the equivalent conductance and past history current source as shown in Fig. 9 this problem can also be solved using Norton's theorem. The program in MATLAB was written similar to the previous problem and the current for different cases was plotted in Fig. 10.

The same problems were first given to students for laboratory work and the problem was explained clearly and programming tips given. After checking their programs, they were asked to submit a detailed analysis with special consideration being given to the parameter variations and voltage across the capacitor at various switching instances. They submitted their assignments including a detailed discussion of the transient. It was found that students had a clear picture of the transients, even though these are a difficult power systems topic.

The same formulation can also be simulated for a d.c. ($\nu = 11.2$) source. Due to the presence of the capacitor the steady state current through the circuit will be zero after some initial oscillations with frequency dependent on the values of L and C. For $R = 2.0$ ohms, $L = 30$ mH and $C = 30\,\mu$F, the switching transient is plotted in Fig. 11.



(c)

Fig. 7 *Continued*

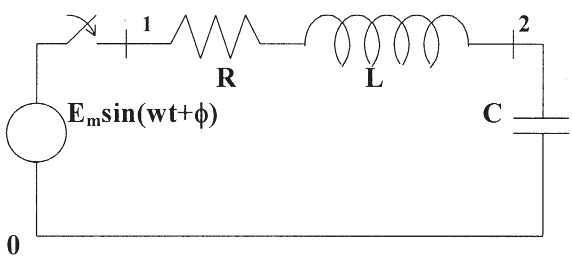


Fig. 8 R-L-C *circuit diagram.*

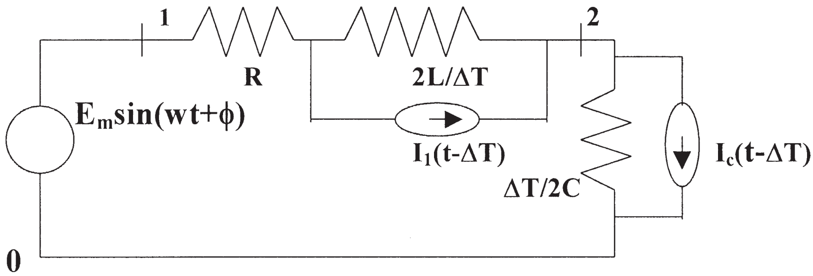


Fig. 9 *Equivalent resistive diagram of* R-L-C *circuit.*

TABLE 1 Summary of student feedback (in percentages)

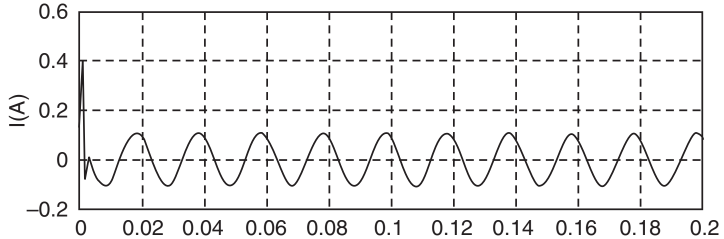
Survey statements	Strongly Agree	Agree	Disagree	Strongly Disagree
The course was challenging	8.33	75.00	16.67	0.0
I understand the subject matter	16.67	83.33	0.0	0.0
Course material was well prepared	8.33	91.67	0.0	0.0
I learnt something valuable	41.67	58.33	0.0	0.0
The assignments given were suitable	8.33	91.67	0.0	0.0
Adequate help was available	0.0	100.0	0.0	0.0
Proposed aims of the course were being achieved	41.67	58.33	0.0	0.0

Students' reactions and feedback

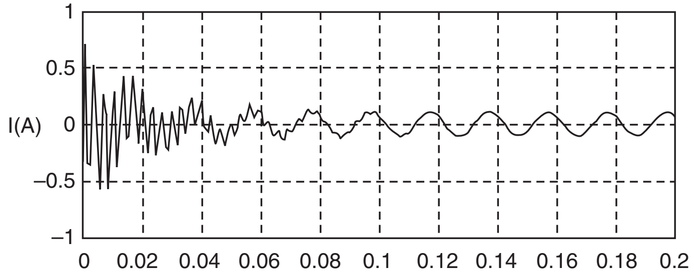
During the mid-term examination students were asked to fill an evaluation report on the instructor and the course. They gave good feedback on the subject matter and their understanding of the problems. The questions asked were mainly related to the following. A summary of the students' feedback is given in Table 1. Out of 13 participating students only one student did not respond.

Conclusions

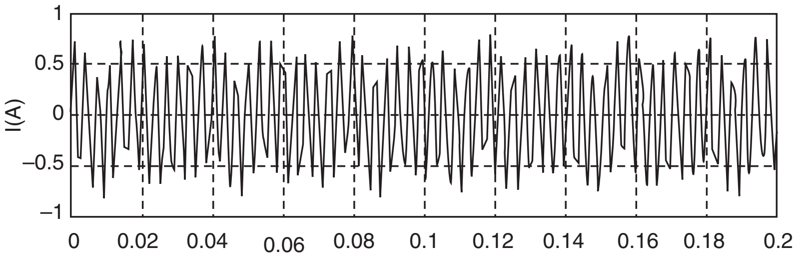
It is obvious that by constantly improving and designing good assignments and laboratory sessions the understanding of the students will be increased and moreover their interest in this complex subject will also be increased. In addition to our other efforts, such as the constant interactions with students and taking tutorial classes to enhance their knowledge about power system transients, we have increased the students' interest in electric power system management as it helped them to understand the subject matter.



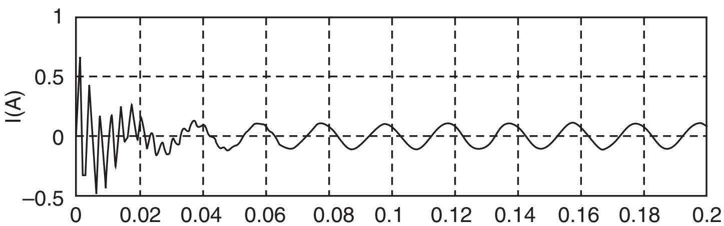
(a) R = 20 ohm, L = 0.004H, C = 30 μF, ϕ = 45°



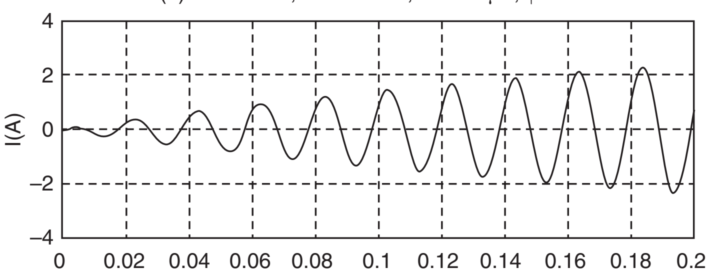
(b) R = 1 ohm, L = 0.004H, C = 30 μF, ϕ = 45°



(c) R = 0 ohm, L = 0.004H, C = 30 μF, ϕ = 45°

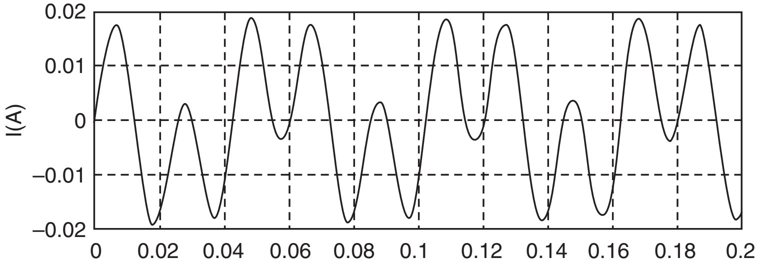


(d) R = 2 ohm, L = 0.004H, C = 30 μF, ϕ = 45°

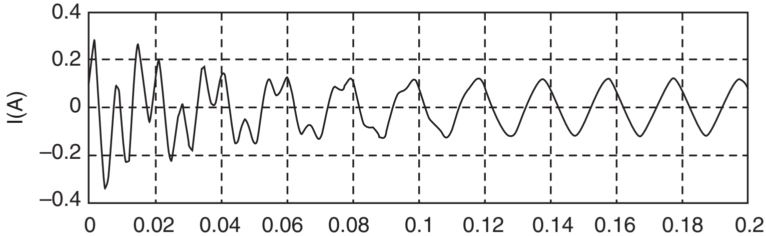


(e) R = 2 ohm, L = 0.3377H, C = 30 μF, ϕ = 45°

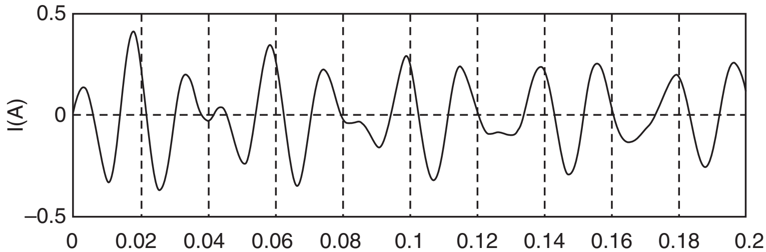
Fig. 10 *Current response in different cases.*



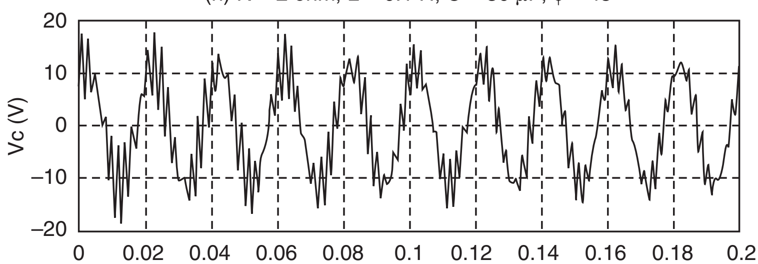
(f) R = 2 ohm, L = 3 H, C = 30 μF, ϕ = 45°



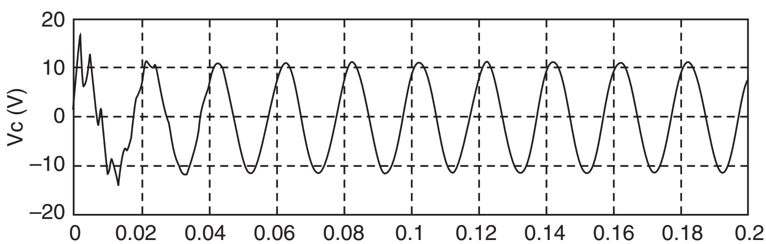
(g) R = 2 ohm, L = 0.3 H, C = 30 μF, ϕ = 45°



(h) R = 2 ohm, L = 0.1 H, C = 30 μF, ϕ = 45°



(i) R = 2 ohm, L = 0.004H, C = 3 μF, ϕ = 45°



(j) R = 2 ohm, L = 0.004H, C = 30 μF, ϕ = 45°

Fig. 10 *Continued*

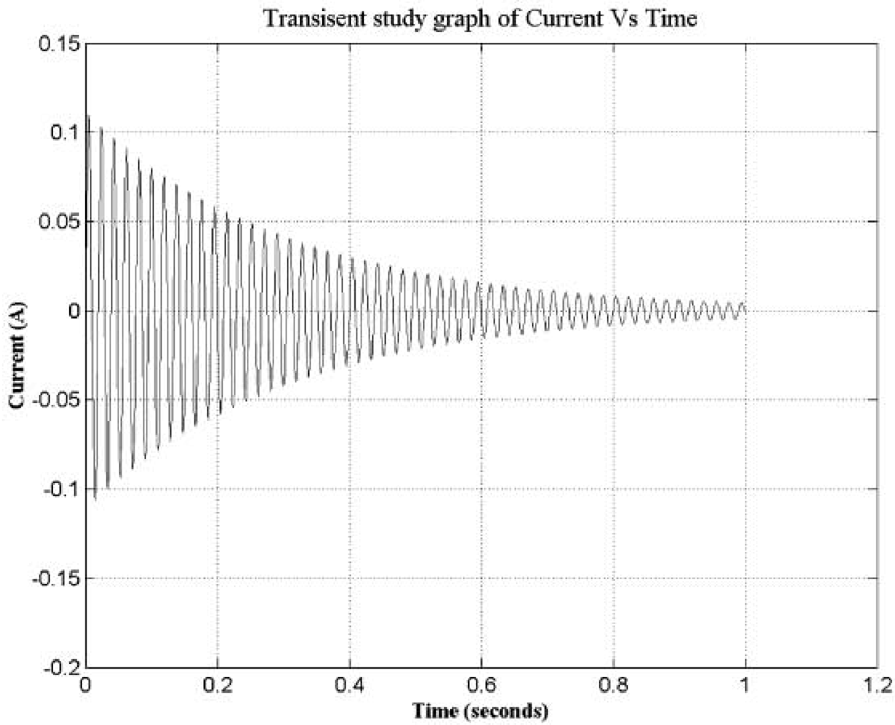


Fig. 11 *Transient response for d.c. voltage source.*

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