

Study of electrical switching processes with NI USB data acquisition systems and MATLAB-SIMULINK environment

Titu Niculescu, Florin Gabriel Popescu, Marius Marcu and Ioan Razvan Slusariuc

Abstract— For the study, the evaluation and visualization of switching processes, modern computer-aided measurement elements associated with high-speed data acquisition systems are used. In the paper is presented a method of study of switching phenomena using a NI USB data acquisition system produced by National Instruments. It is well known that the acquisition software provided by the manufacturing company is LabView. In the paper is presented a more efficient alternative method, based on the use of MATLAB software, and a design interface circuit attached to the NI USB system. In industrial electrical installations frequently occur situations where inductive circuits are connected to alternating current sources. The operation is accompanied by the emergence of transient modes characterized by the presence of surges and high instantaneous power for very short duration at the terminals of the inductive circuit. They can endanger the circuit elements. For two values of the connected circuit inductance, the voltage variation diagrams on the coil and the instantaneous power dissipated on them are plotted. Two methods of data acquisition are presented in the paper. The first method to study this, is the acquisition of data using a MATLAB program designed for the interface circuit presented in the paper and the NI USB data acquisition system. The second method of measurement is based on the use of the Simulink program package. Because there is no support software for data acquisition in Simulink in 64-bit systems, the paper presents a method that does this. The measurement method highlights its superiority compared to the use of LabView software. In the paper, both aspects of the switching are addressed, both by connecting an inductive circuit to an alternative voltage source and by disconnecting it from the source. Because in the introduction of the paper the theoretical phenomenon is presented both during connection and disconnection, in the conclusions are explained the differences that occur between the theoretical situation and the experimental results obtained from the measurement process with the help of the described method.

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I. INTRODUCTION

IN industrial electrical installations frequent switching of inductive circuits occurs at alternating voltage sources, this phenomenon leading to the occurrence of transient modes that may become dangerous under certain conditions. At the coil terminals they often cause overvoltages that can become dangerous if they are not evaluated and no specific action is taken. In the paper is described a modern method of analysis of such modes based on the use of a high resolution data acquisition system produced by National Instruments and the MATLAB software. For the measurements, an interface circuit was designed, which takes the electrical signals and introduces them into the acquisition system connected to the PC. Two representative situation of an inductive circuit for different circuit inductance values were considered for the study.

As it is known, the software provided by National Instruments, for such applications is the LabView. In the paper, the switching phenomena of inductive loads are studied with MATLAB software. The superior processing capabilities of the results are well known by using this software, compared to the one provided by the DAQ system maker.

In the beginning of the paper is presented the theoretical phenomenon that considers ideal circuit elements, both when connecting and disconnecting an inductive circuit. To achieve this goal is presented in the paper a circuit of its own design interface, which make the connection between the circuit-specific electrical quantities and the NI USB 6003 data acquisition system.

Two methods of data acquisition are presented in the paper. The first method is based on programming. A MATLAB program was developed that drives the data acquisition process and is presented in the paper. It generates, along with the whole system, the variation diagrams of voltage, current and instantaneous power on the coil.

The second measurement method is based on the Simulink program package. As is well known, MathWorks provides support software for data acquisition in Simulink for 32-bit systems only. In the last part of the paper is presented a procedure that makes possible the acquisition of data in Simulink on 64-bit systems.

In the conclusions, the differences between the theoretical situation described in the paper and the practical result of the measurement process are highlighted. It is emphasized the use of this acquisition method in studying fast electrical processes.

II. THEORETICAL CONSIDERATIONS

A. Connection Mode

It is considered an inductive resistance circuit R and inductance L that initially connects to an alternating voltage source [4]:

$$e(t) = \sqrt{2}E \sin(\omega t + \beta) \quad (1)$$

Where E is the amplitude of the voltage and its initial phase when the circuit is connected.

If the parasitic capacities and the power supply cable capacity are neglected and circuit elements are considered to be ideal, the expression of the transient current in the circuit is:

$$i(t) = \sqrt{2}I \sin \left[\sin(\omega t + \beta - \varphi) - \sin(\beta - \varphi) \cdot e^{-\frac{t}{T}} \right] \quad (2)$$

where:

$$I = \frac{E}{\sqrt{R^2 + (\omega L)^2}} \quad (3)$$

is the actual value of the current and φ is the phase difference between the voltage at the coil terminals and the current in the circuit.

The voltage at the coil terminals during the transient mode has the expression:

$$u_L(t) = \sqrt{2}LI \left[\omega \cdot \cos(\omega t + \beta - \varphi) + \frac{1}{T} \sin(\beta - \varphi) \cdot e^{-\frac{t}{T}} \right] \quad (4)$$

B. Disconnection Mode

It is considered an inductive circuit with a resistance R and inductance L that is powered by an alternating voltage source and at initial moment it is disconnected. It is believed that the disconnection is done when the current is zero, and the voltage source has the expression:

$$e(t) = U_m \sin(\omega t + \varphi) \quad (5)$$

Where U_m is the voltage amplitude and φ is the phase difference between the voltage and the current in the inductive circuit.

If the real case is considered where the power cord has C capacity, the electrical scheme of the circuit with concentrated parameters is presented in fig. 1.

At the initial moment it is considered that the circuit breaker k opens.

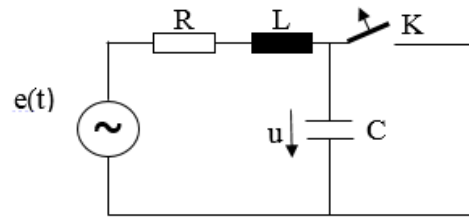


Fig. 1. The electrical scheme of the disconnected circuit

The differential equation of the voltages in the circuit is:

$$R \cdot i + L \frac{di}{dt} + u = e(t) \quad (6)$$

Laplace transform applied to the circuit leads to obtaining the expression of disconnection current that takes the form [10], [12]:

$$i = I_m \cdot \cos(\omega t + \varphi - \phi_1) + \frac{DU_m e^{-\delta t}}{2\omega_e L} \cdot \left[\cos(\omega_e t - \gamma) - \frac{\delta}{\omega_0} \sin(\omega_e t - \gamma) \right] \quad (7)$$

Transient voltage at the coil terminal takes the following form:

$$u_L(t) = L \frac{di}{dt} = \frac{D \cdot U_m}{2} \left[\left(\frac{\omega_p}{\omega_e} \right)^2 e^{-\delta t} \cdot \sin(\omega_e t - \gamma) - 2 \frac{\delta}{\omega_e} e^{-\delta t} \cdot \cos(\omega_e t - \gamma) \right] - I_m \omega L \cdot \sin(\omega t + \varphi - \phi_1) \quad (8)$$

In the expressions (3) and (4) the following notations are made:

- δ is a dumping factor:

$$\delta = \frac{R}{2L} \quad (9)$$

- ω_0 is the resonance angular frequency of the circuit:

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad (10)$$

We also used the following notations:

$$\omega_e = \sqrt{\omega_0^2 - \delta^2} \quad \omega_p = \delta^2 - \omega_e^2$$

$$D = \sqrt{A^2 + B^2 - 2AB \cos(\beta - \alpha)} \quad (11)$$

$$\operatorname{tg}\gamma = \frac{A \sin \alpha - B \sin \beta}{A \cos \alpha - B \cos \beta} \quad (12)$$

$$\alpha = \varphi_3 + \varphi \quad \beta = \varphi_2 - \varphi \quad (13)$$

$$\varphi_1 = \operatorname{arctg} \frac{2\omega\delta}{\omega_0^2 - \omega^2} \quad \varphi_2 = \operatorname{arctg} \frac{\delta}{\omega_e - \omega} \quad \varphi_3 = \operatorname{arctg} \frac{\delta}{\omega_e + \omega} \quad (14)$$

$$A = \frac{I}{\sqrt{\left(I + \frac{\omega}{\omega_e}\right)^2 + \left(\frac{\delta}{\omega_e}\right)^2}} \quad B = \frac{I}{\sqrt{\left(I - \frac{\omega}{\omega_e}\right)^2 + \left(\frac{\delta}{\omega_e}\right)^2}} \quad (15)$$

$$I_m = \frac{U_m}{\sqrt{R^2 + \left(\frac{I}{\omega C} - \omega L\right)^2}} \quad (16)$$

III. INTERFACE CIRCUITS

For the experimental evaluation of electrical quantities, a NI-USB 6003 data acquisition system was used with a 100kS sampling rate produced by National Instruments, and the software environment used is the MATLAB program. To make the measurements, it was necessary to design an interface circuit that takes the electrical quantities from the inductive circuit and transfer it to the data acquisition system. The circuit of the interface is presented in Fig. 2 [11], [19].

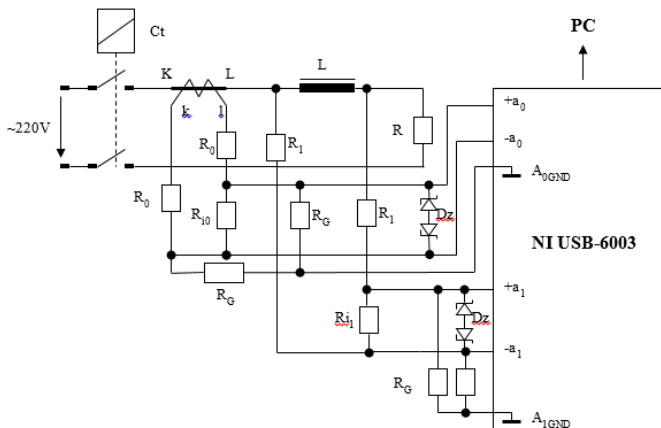


Fig. 2. The electrical circuit of the measurement system

To avoid the connection of the voltage phase directly to the input of the acquisition system, symmetrical voltage dividers were used at which R_{i0} and R_{i1} resistors are connected in parallel with the inputs of the measurement system a_0 and a_1 . The drops voltage on these resistors are proportional to the inductive voltage and current in the circuit. For the protection of analog inputs against destructive surges which exceed the range $-10V \dots +10V$, four D_z Zener diodes have been used [13], [18].

IV. MEASURING PROCESS IN MATLAB

Measurements were made with the NI-USB 6003 data acquisition system with a 100kS sampling rate. The software used was MATLAB 2014b which, prior to the measurements,

required the creation of a specific program for the acquisition process. It allows the acquisition of electrical signal from the interface and the display of the variations of voltage on the coil, the current in the circuit and the instantaneous power dissipated on the coil. The MATLAB program allows you to trace induction voltage variation and inductive current curves on the same graph and instantaneous power curve [9], [13].

```
s = daq.createSession('ni');
addAnalogInputChannel(s,'Dev1', 0, 'Voltage');
addAnalogInputChannel(s,'Dev1', 1, 'Voltage');
s.Rate = 45000;
s.DurationInSeconds = 1.5;
[data,time] = s.startForeground;

figure;
data(:,1)=data(:,1)*163;
data(:,2)=data(:,2)*27;
[ax,p1,p2] = plotyy(time,data(:,1),time,data(:,2),'plot');
ylabel(ax(1),'Voltage[V]'); % label left y-axis
ylabel(ax(2),'Current[A]'); % label right y-axis
xlabel('Time[secs]'); % label x-axis
grid;

figure();
power=data(:,1).*data(:,2);
plot(time,power,'r');
xlabel('Time (sec)');
ylabel('Inst. power[W]');grid
```

As can be seen from the program, it has three groups of instructions. The first group makes it possible to acquire the data for 1.5 seconds for two measurands, each with a sampling rate of 45000S.

The second set of instructions generates the inductive voltage and current circuits in the circuit on the same graph, and the third generates the instantaneous power diagram dissipated on the coil.

Two constants with values of 163 and 27 were used in the program.

These were determined experimentally, taking into account the resistance values in the resistive dividers and the fact that the physical measurement system has a finite input impedance.

V. EXPERIMENTAL RESULTS

The measurements were made for two values of the coil inductance. The following circuit parameter values were used for the first measurement:

- $L=12\text{mH}$; $R=100\Omega$; $U=220\text{V}$.

For the situations of connection and disconnection several diagrams were plotted with the voltage and current variations, but also instantaneous power dissipated on the coil.

For the situation of connecting of an inductive load to an alternating power source, the following diagrams were obtained:

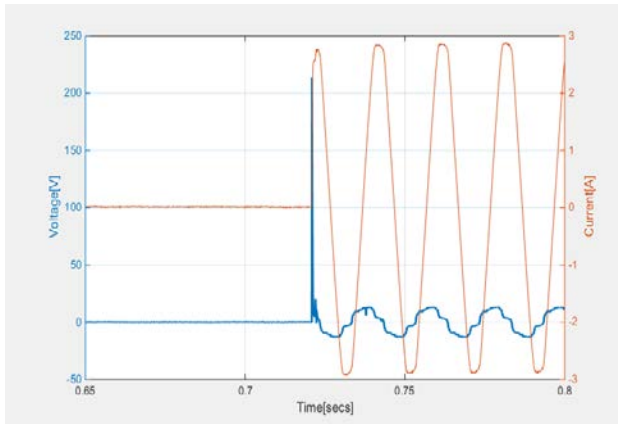


Fig. 3. Voltage variation on the coil and the current at connecting for $L=12\text{mH}$

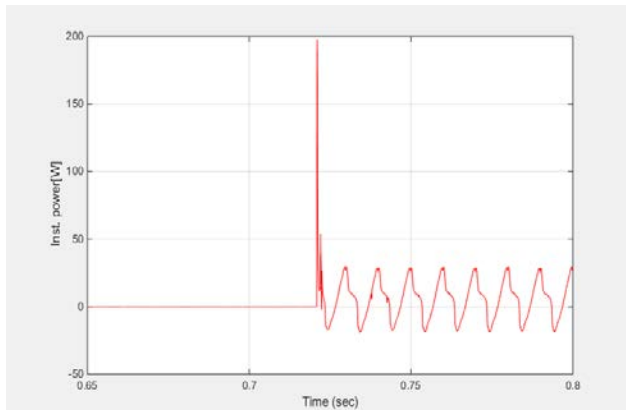


Fig. 4. Instantaneous power variation on the coil at connecting for $L=12\text{mH}$

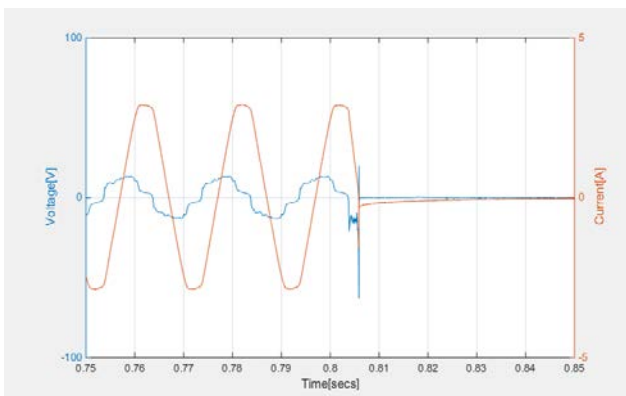


Fig. 5. Voltage variation on the coil and the current at disconnecting for $L=12\text{mH}$

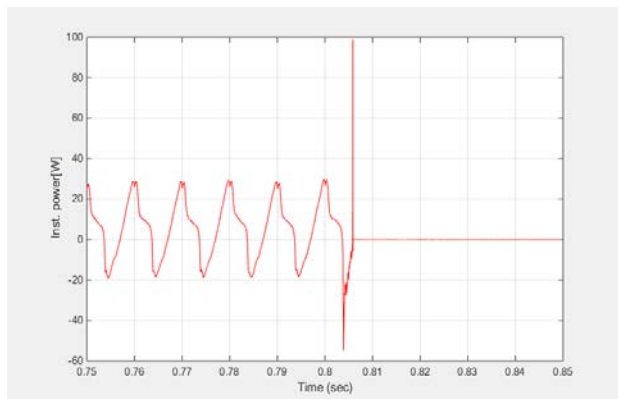


Fig. 6. Instantaneous power variation on the coil at disconnecting for $L=12\text{mH}$

The second measurement was performed with the following values of the circuit parameters:

- $L=2\text{mH}$; $R=100\Omega$; $U=220\text{V}$.

The two aspects of the switching phenomenon, the connection and the disconnection of the circuit have also been considered.

There have also been chosen from several measurements the cases where the highest surge voltage values appear on the coil.

If the circuit is disconnected from an alternative power source, the following diagrams were obtained:

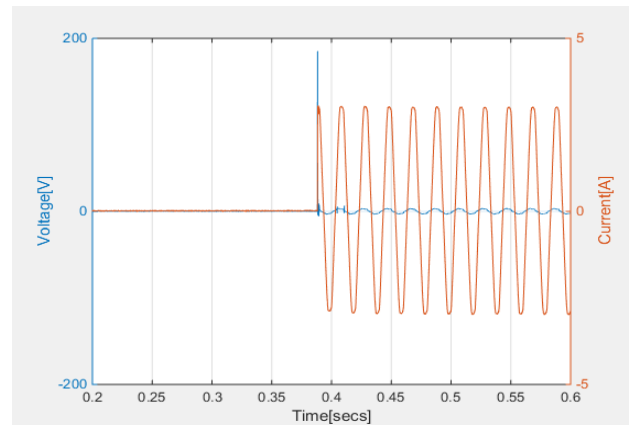


Fig.7. Voltage variation on the coil and the current at connecting for $L=2\text{mH}$

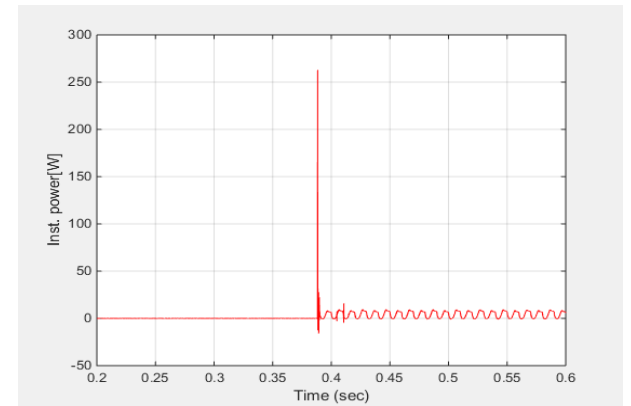


Fig. 8. Instantaneous power variation on the coil at connecting for $L=2\text{mH}$

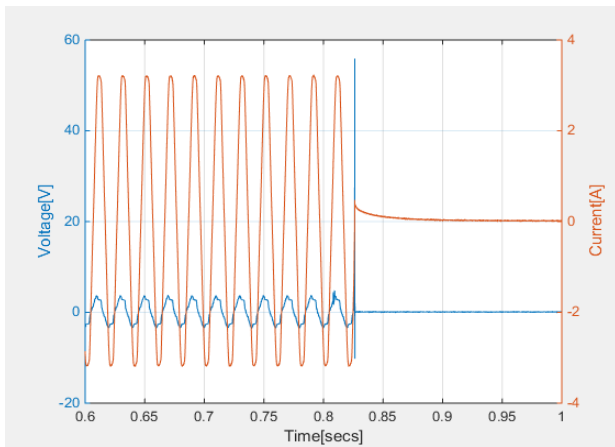


Fig. 9. Voltage variation on the coil and the current at disconnecting for $L=2\text{mH}$

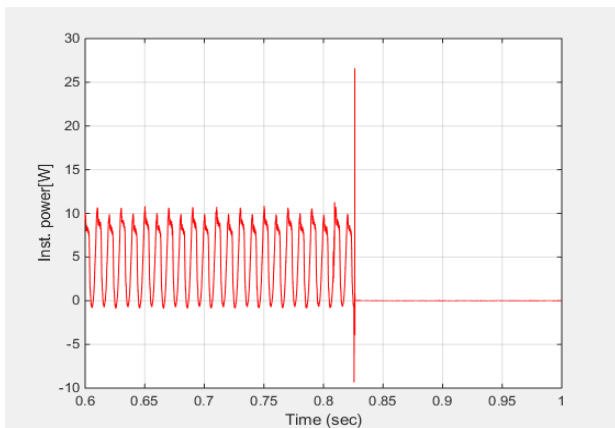


Fig. 10. Instantaneous power variation on the coil at disconnecting for $L=2\text{mH}$

In the case of connecting of the inductive circuit is observed and commutation overvoltage that appears immediately after closing the circuit. The value of this overvoltage is dependent of the value of circuit's inductivity. It has to be remembered that this overvoltage is not constant in all the measurements that were made, it depends on the moment of disconnecting the circuit. This overvoltage is also reflected in the instantaneous power curb at the coil terminals. The peak of the inductive voltage leads to the apparition of a power spike, right after connection. Several measurements were made and the most representative case was presented here.

In the care of disconnecting the circuit the following diagrams were obtained:

At disconnection point is observed the appearance of a commutation overvoltage right after disconnecting the circuit from the power source. The value of the overvoltage is dependent of the inductivity of the circuit. This overvoltage is not constant in all the measurements we made, for it depends of the moment of disconnecting the circuit. This overvoltage is also reflected in the instantaneous power curb at the coil terminals. The peak of the inductive voltage leads to the apparition of a power spike, right after disconnection. Out of the all the measurements that were made, the most representative case was presented here.

VI. MEASURING PROCESS IN SIMULINK

Another method of measuring and studying switching phenomena is the data acquisition in Simulink. This paragraph presents a new and modern method to study the transient phenomena that occurs when switching the inductive charges to an AC power source, using the MATLAB-SIMULINK software package. It is known that NI-USB data acquisition systems manufactured by National Instruments are not recognized by the Simulink software package in 64-bit systems. That is why a 32-bit system is obligatory. From this point of view, the paragraph presents a method by which this disadvantage is eliminated, making the data acquisition process possible in Simulink software package in 64-bit systems.

Experimental measurements were made with a data acquisition system type NI USB-6003 with a rate of 100kS/sec., and the measurements were processed by 2014b MATLAB version, which recognizes only data acquisition system in MATLAB, not in Simulink. Data processing in Simulink involves the following steps [10], [14]:

- It makes the appropriate data acquisition in MATLAB (using specific program lines for data acquisition system type);
- It saves the Workspace generated by the measurement (for further processing);
- The Data file from the Workspace opens ;
- The Time file from the Workspace opens;
- Undock command is given to these files (Fig.12);
- The Time column is copied in the Data file and it's placed at the beginning of the columns. The time column must be the first (Fig.13).
- It executes the Dock Variables command and saves the new Workspace.

At this moment the Data folder from the Workspace can be read from a Simulink simulation model. This is shown in Fig.11:

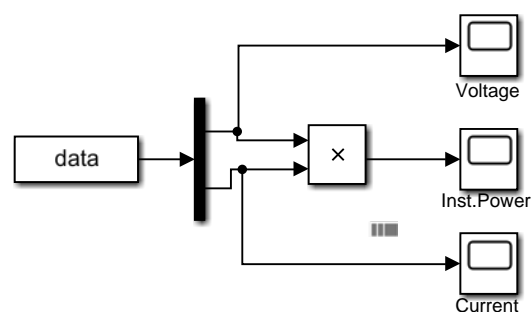


Fig. 11. Simulink model for study the transient phenomena

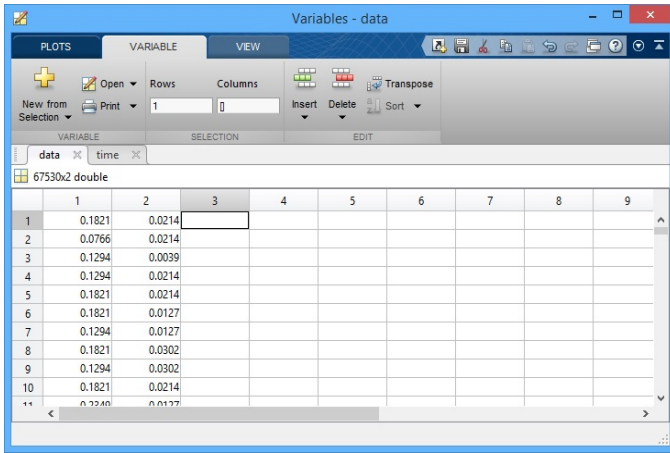


Fig. 12. Original content of the Data folder from the Workspace

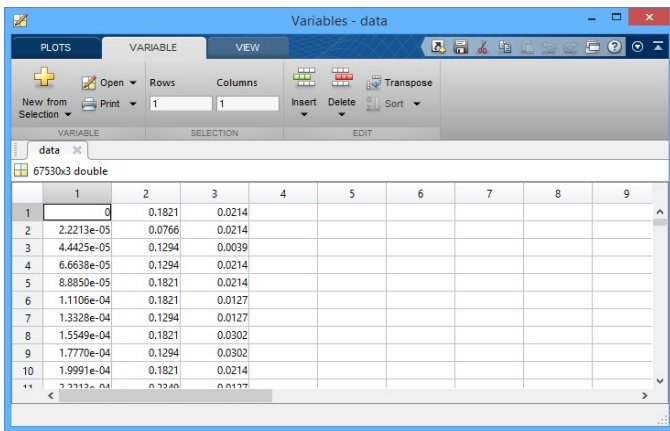


Fig. 13. Modified content of Data folder from the Workspace

The application of the previously described process has led to the experimental results described below. Because the transient phenomena are less significant in the current variation curve, it was chosen to show only the voltage variation at the coil terminals and the instantaneous power dissipated thereon. The situation of connecting and disconnecting an inductive load has been considered.

For electrical parameter values:

- $L=12\text{mH}$; $R=100\Omega$; $U=220\text{V}$, the following diagrams were obtained:

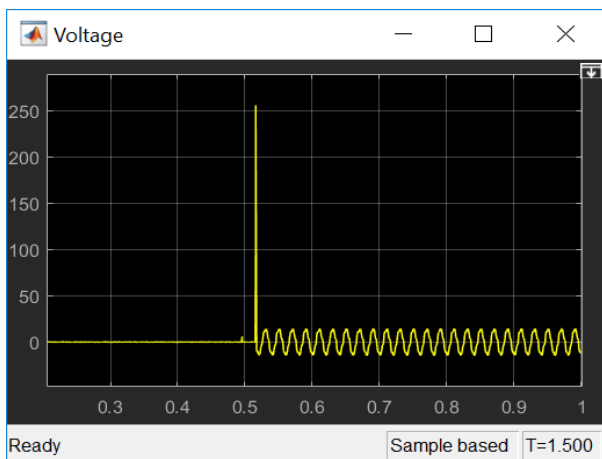


Fig. 14. Voltage variation on the coil at connecting for $L=12\text{mH}$

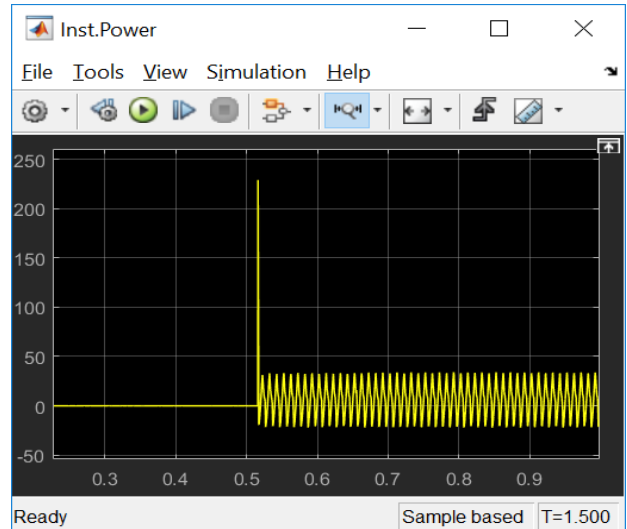


Fig. 15. Instantaneous power variation on the coil at connecting for $L=12\text{mH}$

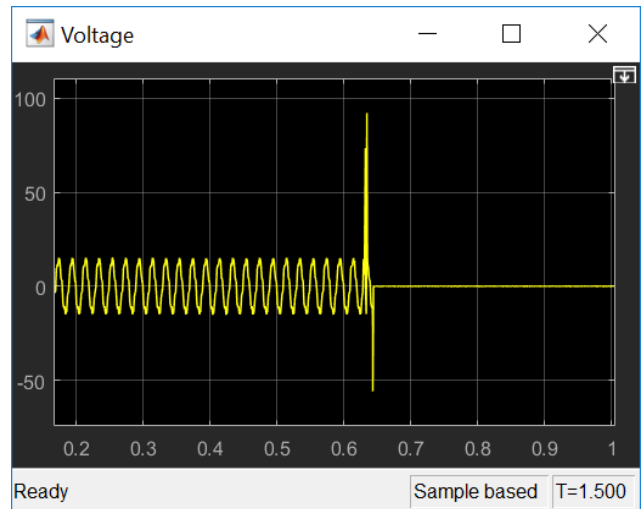


Fig. 16. Voltage variation on the coil at disconnecting for $L=12\text{mH}$

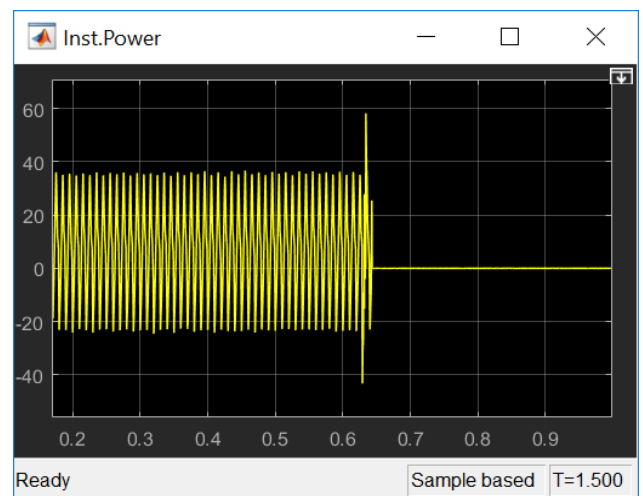
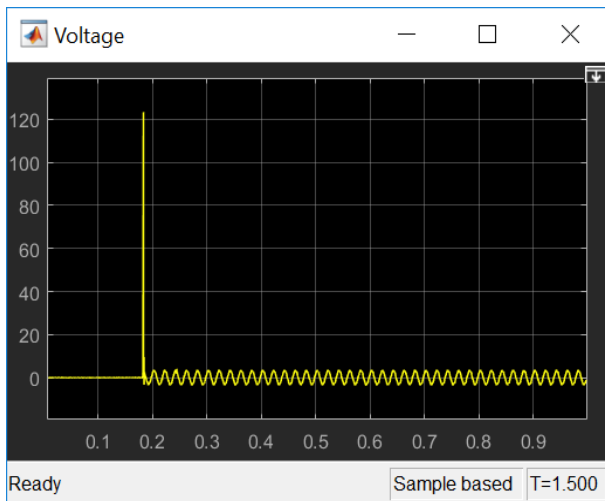
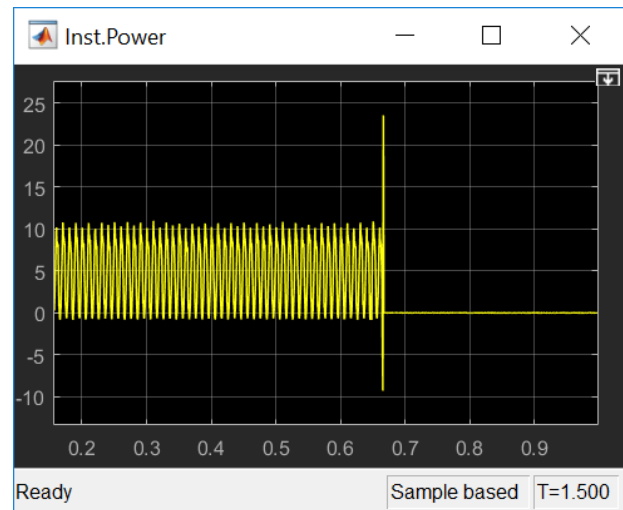
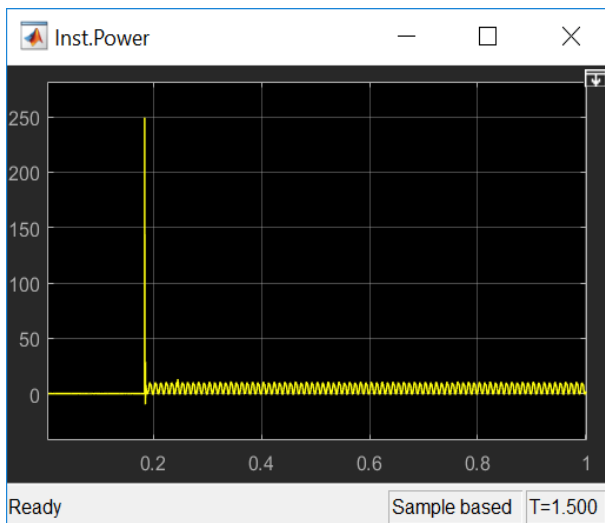
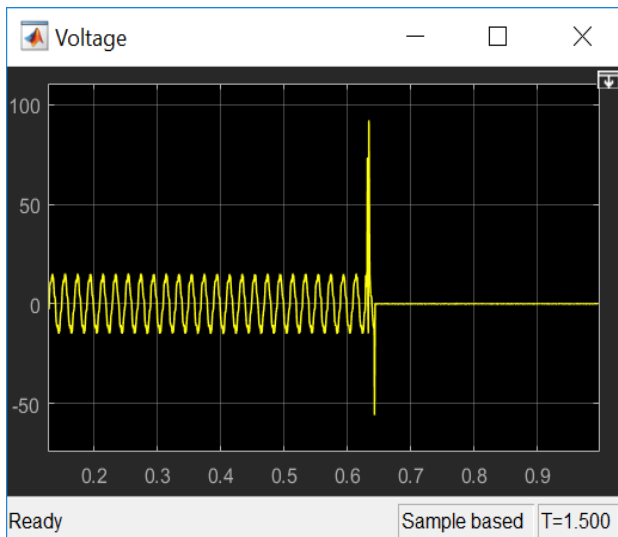


Fig. 17. Instantaneous power variation on the coil at disconnecting for $L=12\text{mH}$

For the same values of the electric parameters, but with the inductance value L of 2mH , the following variation diagrams were obtained:

Fig. 18. Voltage variation on the coil at connecting for $L=2\text{mH}$ Fig. 21. Instantaneous power variation on the coil at disconnecting for $L=2\text{mH}$.Fig. 19. Instantaneous power variation on the coil at connecting for $L=2\text{mH}$ Fig. 20. Voltage variation on the coil at disconnecting for $L=2\text{mH}$

VII. CONCLUSION

The diagrams presented in the paper show that when switching inductive circuits to an alternative voltage source, there is a very high slope overvoltage that can become dangerous for the physical elements of the circuit. This voltage peak is dependent on the value of the inductance and the moment of the circuit switching. Various measurements were chosen from the most representative cases. From the measurements made it was observed that the ratio between the overvoltage and the voltage on the coil prior to switching is the higher when the value of the inductance decreases. Also, the duration of the overvoltage pulse decreases as the inductance decreases.

The method of study of the switching phenomenon of inductive loads to alternative voltage sources based on the use of data acquisition systems is a modern one and allows for focusing on the event at any time of the transient switching mode.

The electrical capacities that appear in the circuit in the real situation make the diagrams obtained by the measurements to be different from the theoretical situation presented in the paper, where the phenomenon was presented and these capacities were neglected, the elements of the circuit being considered ideal. Their presence leads to the emergence of short-duration oscillating modes and very high amplitude compared to the permanent regime.

The measurement method is based on the use of the MATLAB program that has the possibility of further processing of the results of the measurements with superior accuracy, compared to those resulting from the use of the LabView software provided by the manufacturer.

It is necessary to mention that high-speed data acquisition systems are required for the study of fast electrical processes. The NI USB 6003 Data Acquisition System, which has a sampling rate of 100kS, is sufficient to study such switching phenomena.

As presented in the paper, a modern and efficient method of

studying these kinds of phenomena is based on data acquisition in Simulink. Subsequent possibilities of processing the results through this method are huge. MATLAB 2014b software was used for data acquisition, and MATLAB 2018a was used to process the results. Two versions of MATLAB were used, as the latter does not have support software for NI USB data acquisition systems, but has superior processing capabilities for data acquisition results.

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