

MATLAB-Based Transient Analysis of Linear Electrical Circuits

Dao Thi My Linh¹, Tran Minh Hai^{1*}, ²Nguyen Thi Xuan Mai

¹Faculty of Technology and Engineering, Thai Binh University

²Thai Nguyen University of Technology

ABSTRACT

In engineering, modern simulation and computational tools play a central role by enabling the precise, efficient, and safe analysis, design, and evaluation of complex systems and processes without a complete reliance on physical prototyping. The adoption of such technologies not only shortens research timelines and reduces experimental costs but also improves accuracy and reliability in the development of engineering solutions.

As systems grow in scale and exhibit increasingly complex nonlinear dynamics, modern simulation platforms such as MATLAB & Simulink have emerged as preferred choices due to their powerful computational capabilities, intuitive interfaces, and extensive model libraries. This trend facilitates researchers and engineers in implementing analytical, optimization, and verification methods from the early stages of design, while also meeting the stringent performance and reliability requirements of modern engineering systems.

This study utilizes MATLAB & Simulink to analyze transient responses in linear electrical circuits. Specifically, numerical computations are performed using M-file programming based on the state-space equation approach to achieve fast and flexible results. In addition, the integration of Simulink and Simscape Electrical allows for a visual representation of voltage and current waveforms across individual circuit elements. This combination not only enhances the accuracy and visualization of the results but also highlights the critical role of digital technologies in the research, education, and design of complex electrical systems.

Keywords—Transient response; M-file; Simscape Electrical.

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I. Introduction

Transient phenomena commonly occur in various types of circuits and engineering systems, such as electrical, radio frequency, measurement, and automatic control systems. Accurate analysis of this transitional phase is essential for evaluating the dynamic characteristics of systems, predicting transient parameters, and proposing solutions to enhance performance and ensure operational safety [1], [2], [9].

In many cases, if transient currents or voltages are not properly assessed and controlled, they may significantly exceed the steady-state values. Such occurrences can not only reduce the accuracy of measurement instruments or prolong the startup time of electric motors, but also pose safety risks to both equipment and personnel [1]. Therefore, studying transient behavior is not only theoretically meaningful but also has practical applications in the design and operation of modern engineering systems [2].

A substantial body of research has focused on transient responses in electrical circuits. For example, [3] analyzes the transient response of R-L-C circuits connected to a constant DC source using classical integration methods and Laplace transforms, emphasizing their relevance in estimating voltage/current at the moment of switching and applications in energy storage system control and measurement. Meanwhile, [4] proposes two novel approaches for transient analysis in electrical circuits: one combining Fourier series with the Laplace–Carson transform in the complex domain, and another utilizing the Fourier transform for energy conversion circuits, with results validated through MATLAB/Simulink simulations.

However, for complex transient problems, theoretical calculations can become significantly demanding, posing challenges for students and practitioners in applying and interpreting the results effectively.

II. Methodology

The transient process in an electrical circuit is defined as the transitional phase in which the system evolves from an initial steady state to a new steady state due to sudden changes in operating conditions [1], [2], [9]. Such changes typically result from switching actions (i.e., turning switches on or off), variations in power sources, or modifications in circuit parameters such as resistance, inductance, or capacitance. During this period, electrical quantities, contain current and voltage, do not remain constant but vary with time. This behavior is often described by a system of linear or nonlinear differential equations, depending on the characteristics of the circuit. The transient phase concludes when all electrical variables settle to their new steady-state values, and the system reaches dynamic equilibrium.

Beyond physical considerations, the choice of analytical method significantly affects the accuracy and efficiency of the calculations. Classical approaches, such as direct integration or Laplace transform techniques, yield exact time-domain solutions but often require advanced mathematical skills and become increasingly complex for higher-order circuits. In contrast, modern computational and simulation tools—exemplified by MATLAB and Simulink—offer powerful means to solve state-space equations and perform intuitive simulations. These tools help shorten processing time and minimize errors arising from manual transformations and analytical procedures [6]–[8], [10].

The transient analysis of an electrical circuit begins with the identification of the characteristic state variables of the state-space system [5], which are typically chosen as the capacitor voltages u_C and the inductor currents i_L . The number of state variables corresponds to the total number of energy storage elements in the circuit, including both capacitors and inductors. Therefore, it is necessary to determine the appropriate number of state variables according to the circuit configuration. Once these variables are selected, a system of differential equations is established to describe their time-domain variations by directly applying Kirchhoff's first and second laws. The resulting system of equations (1) fully characterizes the dynamic behavior of the circuit immediately after the switching operation occurs.

$$\left\{ \begin{array}{l} \frac{dx_1}{dt} = f(x_1, x_2, x_n, u_k \dots) \\ \frac{dx_2}{dt} = f(x_1, x_2, x_n, u_k \dots) \\ \dots\dots\dots \\ \frac{dx_n}{dt} = f(x_1, x_2, x_n, u_k \dots) \end{array} \right. \quad (1)$$

Transform the system of differential equations describing the circuit into the matrix form (2).

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dots \\ \dot{x}_n \end{bmatrix} = [A]_{n \times n} \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{bmatrix} + [B]_{n \times k} \begin{bmatrix} \dot{u}_1 \\ \dot{u}_2 \\ \dots \\ \dot{u}_k \end{bmatrix}$$

$$\dot{x} = Ax + Bu \quad (2)$$

with the state variable vector is defined as $x = [x_1, x_2, \dots, x_n]^T$,

$x_1, x_2, \dots, x_n$ is the state variable.

The input vector, also referred to as the excitation, is defined as $u = [u_1, u_2, \dots, u_k]^T$

A and B are coefficient matrices, where A is a square matrix of order n, and B is a matrix with n rows and k columns.

The number of output variables is determined by the electrical quantities to be computed in the circuit. Based on the problem requirements, the corresponding system of equations describing the outputs is then formulated as expression (3).

$$\begin{cases} y_1 = f(x_1, x_2, x_n, u_k, \dots) \\ y_2 = f(x_1, x_2, x_n, u_k, \dots) \\ \dots \\ y_m = f(x_1, x_2, x_n, u_k, \dots) \end{cases} \quad (3)$$

Transform the system of equations (3) into the matrix form (4).

$$\begin{bmatrix} y_1 \\ y_2 \\ \dots \\ y_m \end{bmatrix} = [C]_{m \times n} \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{bmatrix} + [D]_{m \times k} \begin{bmatrix} u_1 \\ u_2 \\ \dots \\ u_k \end{bmatrix}$$

$$y = Cx + Du \quad (4)$$

In which the output vector y is the vector to be determined. $y = [y_1, y_2, \dots, y_m]^T$

C and D are coefficient matrices. By combining equations (2) and (4), the complete state-space system is established.

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \quad (5)$$

To solve a transient linear circuit problem numerically using an M-file, the computation follows the algorithmic flowchart shown in Fig. 1.

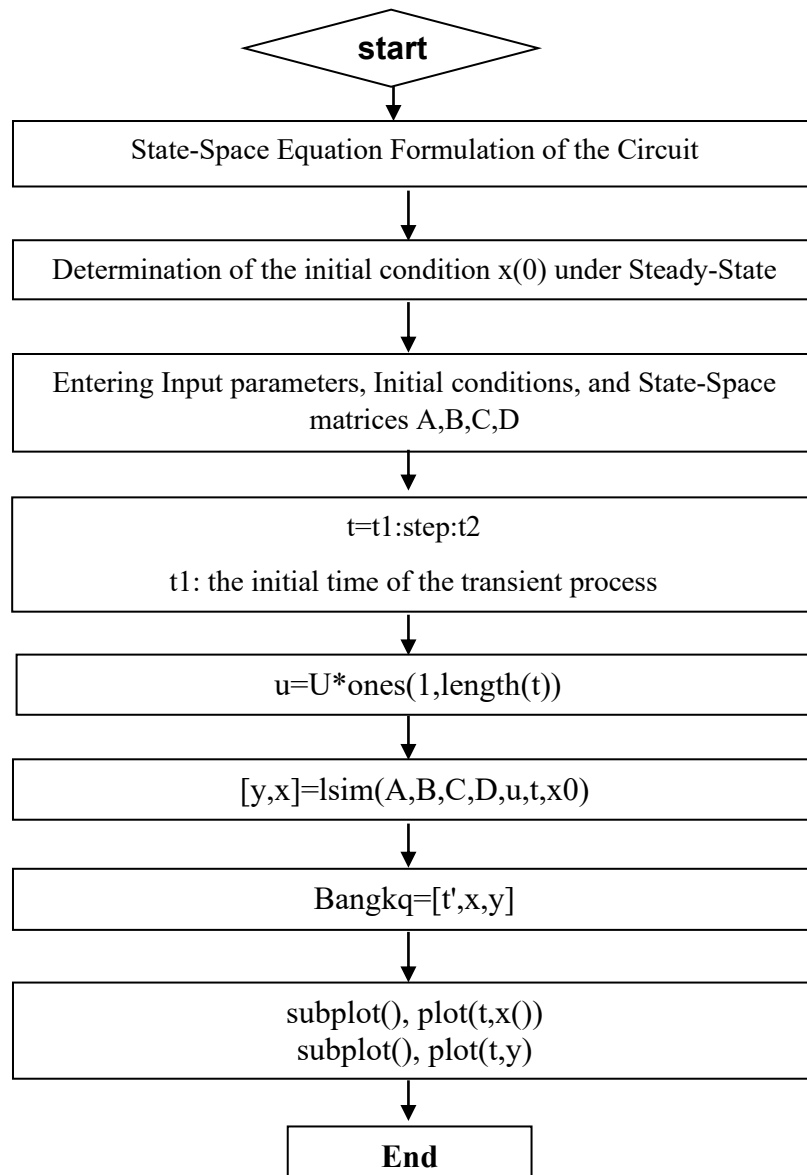


Fig. 1. Algorithm flowchart for solving linear electrical circuits in the transient state using MATLAB M-file.

2.3.Simulation of Transient Response Using Simulink Based on the State-Space Equations

Based on the state-space model, a block diagram can be constructed in Simulink to simulate the transient behavior of the system. This approach enables direct observation of the time-domain responses of the state variables and facilitates comparison with theoretical calculations for accuracy verification. Specifically, the state-space equations of the electrical circuit, as expressed in (5), are derived from the system of differential equations describing the circuit in (1).

In the MATLAB environment, the initialization process is carried out through an M-file, where the coefficient matrices A, B, C, and D, as well as the initial conditions and input signals, are defined. Subsequently, in Simulink, the simulation model is constructed using fundamental blocks such as *State-Space*, *Source*, and *Scope*, which are interconnected to form the complete block diagram. These blocks are configured by specifying the system parameters, input signal characteristics, simulation time, and selecting an appropriate solver. Once the simulation is executed, the system responses can be directly observed on the *Scope* block, allowing for detailed analysis of the transient characteristics of electrical quantities such as currents and voltages.

2.4 Simulation of Transient Response Using Simulink – Simscape Electrical Based on the Physical Circuit Model

This approach enables an accurate representation of passive elements (R, L, and C) and their interactive characteristics within the circuit. Moreover, the simulation results provide an intuitive visualization of the transient response in the form of voltage and current waveforms over time. It can be considered an effective tool for evaluating and optimizing electrical system designs throughout the transient process.

In the Simulink environment, the simulation process using this method is carried out by directly constructing the circuit diagram based on the physical model [6], [7]. Electrical components such as resistors, inductors, and capacitors are selected from the Simscape – Simscape Electrical library, dragged and dropped into the simulation workspace, and interconnected to form a complete circuit. Subsequently, the technical parameters of each element are precisely specified according to the problem data, ensuring accurate reflection of the system's real characteristics. The simulation is executed using the Run command, and the transient response of the circuit can be visually observed through the Scope block.

3. Kết quả mô phỏng và đánh giá

Để minh chứng cho ứng dụng phân tích và mô phỏng mạch điện bởi phần mềm MATLAB ta tiến hành giải mạch điện quá độ tuyến tính sau đây để tìm các đáp ứng dưới dạng đường cong $u_C(t)$, và $u_{RL}(t)$ trong cảm môi trường M-file và môi trường Simulink, cụ thể Mạch điện quá độ tuyến tính cho trên hình vẽ (Hình 2)

Simulation Results and Evaluation

To demonstrate the application of MATLAB in the analysis and simulation of electrical circuits, a transient linear circuit is solved to obtain the time-domain responses $u_C(t)$, $i_L(t)$, and $u_{RL}(t)$, the analysis is carried out in both the M-file environment and the Simulink environment for comparison and validation purposes.

The transient linear circuit under consideration is illustrated in Fig. 2.

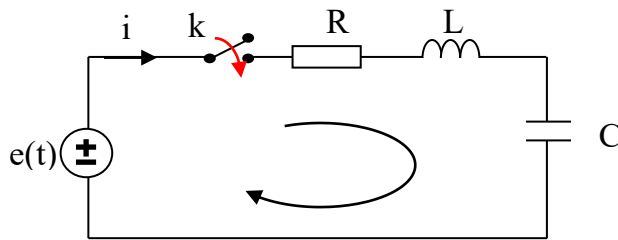


Fig. 2. Schematic diagram of the linear transient circuit.

with $R = 5\Omega$, $L = 0,5\text{ H}$, $C_1 = 100\text{ }\mu\text{F}$, $E = 110\text{ V}$; $e(t) = E \cdot (\sin \omega t + \pi/3)$ (V), at time $t = 0$ the switch K is closed.

1. Determine the approximate solutions using an M-file, and plot the response curves $u_C(t)$, $i_L(t)$, and $u_{RL}(t)$ using figurecharts to visualize the results.
2. Simulation of $i_L(t)$, $u_C(t)$, and $u_{RL}(t)$ in the time interval 0–0.05s using Simulink based on the SSE.
3. Simulation of $i_L(t)$, $u_C(t)$, and $u_{RL}(t)$ in the time interval 0–0.05s using Simulink/Simscape based on the physical model.

The state-space system in form (5) for the circuit is formulated as follows:

$$\begin{cases} \begin{pmatrix} \frac{di_L(t)}{dt} \\ \frac{du_C(t)}{dt} \end{pmatrix} = \begin{bmatrix} -\frac{R}{L} & -\frac{1}{L} \\ \frac{1}{C} & 0 \end{bmatrix} \begin{pmatrix} i_L(t) \\ u_C(t) \end{pmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} (e(t)) \\ u_{RL}(t) = [0 \quad -1] \begin{pmatrix} i_L(t) \\ u_C(t) \end{pmatrix} + [1]e(t) \end{cases}$$

where the coefficient matrices are given by:

$$A = \begin{bmatrix} -\frac{R}{L} & -\frac{1}{L} \\ \frac{1}{C} & 0 \end{bmatrix}; B = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}; C = [0 \quad -1]; D = [1]$$

By programming the algorithm in an M-file according to the flowchart shown in Fig. 1, the transient response simulation results are obtained and illustrated in the figure plot presented in Fig. 4a.

Using the Simulink simulation method based on the state-space system, the corresponding state-space model is constructed with the following matrices:

$$A = \begin{bmatrix} -\frac{R}{L} & -\frac{1}{L} \\ \frac{1}{C_1} & 0 \end{bmatrix}; B = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}; C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & -1 \end{bmatrix}; D = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

Based on the established state-space model, the system is simulated within the Simulink environment.

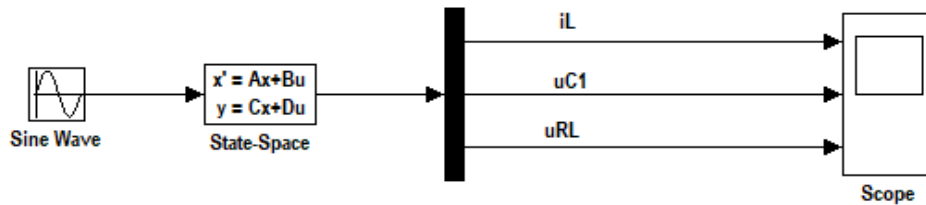
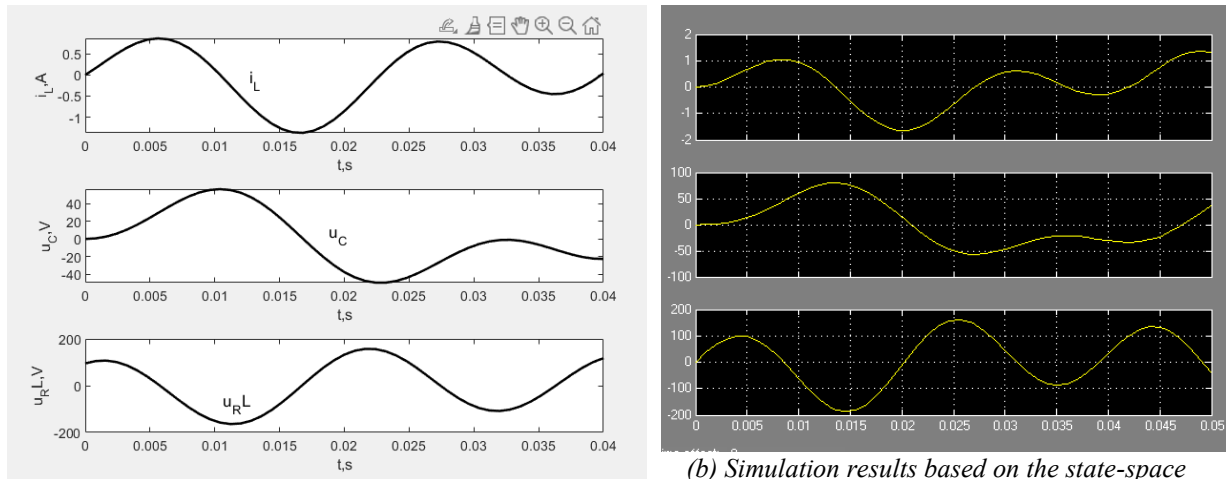


Fig. 3. Block diagram of the circuit represented by the state-space system in Simulink.

Figure 4 presents the simulation results obtained using two approaches: (a) the M-file implementation illustrating the transient response via a figure plot, and (b) the state-space model representation in Simulink. The close agreement between the two results confirms the consistency of the developed state-space formulation as well as the reliability of the M-file based computational method



(a) Simulation results obtained from the figure plot in the M-file

(b) Simulation results based on the state-space system.

Fig. 4. Transient response simulation $i_L(t)$, $u_C(t)$, $u_{RL}(t)$

The transient circuit constructed in Simulink – Simscape based on the physical model is illustrated in Fig. 5a. The corresponding transient response simulation results obtained using this method are presented in Fig. 5b.

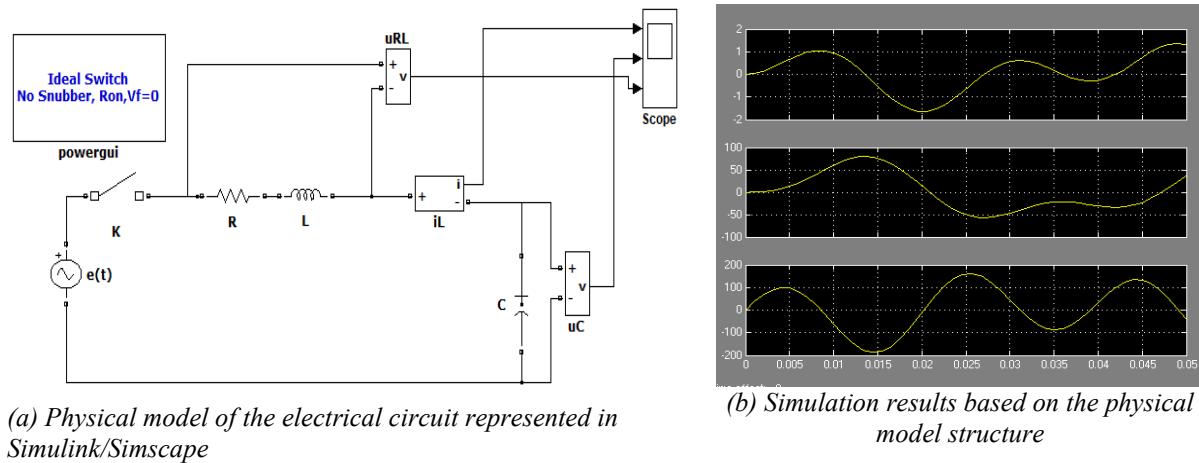


Fig. 5. Simulation of the transient responses $i_L(t)$, $u_C(t)$, and $u_{RL}(t)$ in Simulink/Simscape.

By examining the simulation results of the physical circuit model in Simulink/Simscape, as illustrated in Fig. 5(b), it is observed that the transient responses are in close agreement with those obtained from the previous two approaches. This agreement confirms the consistency among the three modeling methods and further demonstrates the reliability and accuracy of the proposed simulation framework.

IV. Conclusion

This study confirms that MATLAB is a reliable computational and simulation tool, particularly effective for the transient analysis of linear electrical circuits. The M-file programming approach based on the state-space representation enables fast and flexible processing, allowing easy modification or replacement of state-space models without hardware constraints, while providing accurate quantitative data for system design and optimization. In addition, the use of Simulink and Simscape Electrical to simulate circuit responses, either from state-space models or physical circuit representations, offers intuitive visualization and realistic reproduction of voltage and current variations during the transient period. These simulation results not only verify the accuracy of theoretical calculations but also help identify transient phenomena that may affect the safety and performance of electrical systems.

While this study focuses on linear circuits, the presented approaches can be extended to more complex systems, including nonlinear circuits, multi-source networks, and power electronic converters. For such systems, MATLAB, Simulink, and Simscape Electrical provide powerful environments to handle nonlinear dynamics, switching behaviors, and coupled multi-domain effects. This capability highlights the potential of the proposed framework to support advanced studies in circuit design, stability analysis, and control of modern power and electronic systems.

References

- [1]. Nguyen Binh Thanh, Le Van Bang, *Giaotrinhlythuyetmachdien* [Textbook of Electrical Circuit Theory], Nhaxuat ban Giaoduc (Education Publishing House), 2010.
- [2]. Phuong Xuan Nhan, Ho Anh Tuy, *Lythuyetmach, tap 2* [Circuit Theory, Vol. 2], Nhaxuat ban Dai hoc Bach Khoa HaNoi (Hanoi University of Science and Technology Publishing House), 2023. ISBN: 978-604-471-676-3, ISBN: 978-604-471-678-7.
- [3]. Anuradha S. Deshpande, "Transient Analysis of R-L-C Series Circuit to Step Voltage by Engineering Methods," *International Journal of Computational and Applied Mathematics*, vol. 9, no. 2, pp. 63–70, 2014.
- [4]. M. Beňová, B. Dobrucký, J. Šedo, M. Praženica, R. Koňarik, J. Šimko, and M. Kuchař, "A Novel Approach to Transient Fourier Analysis for Electrical Engineering Applications," *Applied Sciences*, vol. 14, no. 21, p. 9888, 2024. doi: 10.3390/app14219888.
- [5]. N. Phạm Công, *Lythuyetdieukhientudong* [Automatic Control Theory], Nhaxuat ban Khoa hoc và Ky thuat (Science and Technics Publishing House), 2006.
- [6]. Tran Quang Khanh, *MATLAB ung dung, tap 1* [MATLAB Applications, Vol. 1], Nhaxuat ban Khoa hoc và Ky thuat (Science and Technics Publishing House), 2013.
- [7]. Nguyen Phung Quang, *Matlab& Simulink danhchokysudieukhientudong* [MATLAB & Simulink for Control Engineers], Nhaxuat ban Khoa hoc và Kythuat (Science and Technics Publishing House), 2008.
- [8]. Steven T. Karris, *Circuit Analysis II with MATLAB Applications*, Orchard Publications, 2003.
- [9]. R. C. Dorf and J. A. Svoboda, *Introduction to Electric Circuits*, 9th ed. Hoboken, NJ, USA: Wiley, 2014.
- [10]. S. J. Chapman, *MATLAB Programming for Engineers*, 5th ed. Boston, MA, USA: Cengage Learning, 2016.