

Analysis of DC Electrical Circuits Using a System of Linear Equations Based on Kirchhoff's Laws

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Abstract—A system of linear equations is a fundamental concept in linear algebra, with numerous applications in engineering and science. One important application of a system of linear equations is in the analysis of direct current (DC) circuits. In a DC circuit, the relationship between current, voltage, and resistance can be modeled using Kirchhoff's laws, resulting in a system of linear equations. This paper discusses modeling a DC circuit into a system of linear equations and solving it using the Gaussian elimination method

Index Terms—linear equation systems, DC electric circuits, Kirchhoff's laws, Gaussian elimination

I. INTRODUCTION

Linear algebra is a branch of mathematics that plays a fundamental or crucial role in the development of science and technology, particularly in various engineering fields such as electrical engineering, physics, and informatics. Basic concepts in linear algebra, such as vectors, matrices, and systems of linear equations, can be widely used to model, analyze, and solve various complex engineering problems. Many physical problems or phenomena and engineering systems can be represented as linear relationships and solved using concepts in linear algebra, making linear algebra methods an important tool in mathematical analysis and decision-making.

One real-world application of systems of linear equations can be found in the analysis of direct current (DC) electrical circuits. In DC circuits, the relationships between electrical quantities such as current, voltage, and resistance follow the basic laws of electricity, specifically Kirchhoff's current and voltage laws. Through Kirchhoff's current and voltage laws, an electrical circuit can be mathematically modeled as a set of linear equations that represent the current balance conditions at branch points and the voltage balance conditions at each circuit loop. Thus, the problem of analyzing electrical circuits can be reduced to solving systems of linear equations.

In electrical circuits with simple structures, determining current and voltage can still be done manually. However, as the number of branches, nodes, or loops in the circuit increases, the manual approach becomes inefficient and prone to calculation errors. This situation demands a more systematic and structured approach. In this case, linear algebra offers an effective solution through the representation of the circuit in matrix form and the application of methods for solving systems of linear equations, such as the Gaussian elimination

method. This approach allows for consistent circuit solutions, regardless of the complexity of the circuit being analyzed.

This paper aims to discuss how a direct current circuit can be modeled as a system of linear equations based on Kirchhoff's laws, and how to solve this system using the Gaussian elimination method. Furthermore, this paper also presents a simple program implementation to calculate the current in each branch of a DC circuit. Through this discussion, it is hoped that readers will understand the strong relationship between linear algebra concepts and their application to real-world engineering problems, particularly in the field of electrical circuit analysis.

II. BASIC THEORY

A. System of Linear Equations

A system of linear equations is a collection of several linear equations involving a number of variables with the highest power, namely one. In general, a system of linear equations can be written in matrix form as

$$Ax = b \quad (1)$$

where A is the coefficient matrix, x is the vector of unknown variables, and b is the constant vector. Solving a system of linear equations aims to determine the values of the variables that satisfy all equations simultaneously.

Furthermore, a system of linear equations can be represented in matrix or augmented matrix form, thus allowing for direct connection with the Gaussian elimination method. Through this matrix representation, the process of solving a system of linear equations can be carried out systematically and structured by applying elementary row operations until a row-echelon or reduced-row-echelon form is obtained. Thus, the solution to a system of linear equations can be determined effectively and efficiently, both to identify a single solution, an infinite number of solutions, and to conclude that the system has no solutions. An example of such a matrix form is as follows:

$$\begin{bmatrix} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n \\ \vdots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{bmatrix} \quad (2)$$

or in the form of an augmented matrix as follows

$$\left[\begin{array}{cccc|c} a_{11} & a_{12} & \cdots & a_{1n} & b_1 \\ a_{21} & a_{22} & \cdots & a_{2n} & b_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} & b_m \end{array} \right] \quad (3)$$

In the context of electrical circuit analysis, the variables in a system of linear equations generally represent the magnitude of the electric current in each branch of the circuit. Therefore, forming and solving a system of linear equations is the primary step in determining the operating conditions of an electrical circuit.

B. Overview of Singular Value Decomposition

Singular Value Decomposition expresses a matrix A as:

$$A = U\Sigma V^T \quad (4)$$

where U and V are orthonormal matrices, and Σ is a diagonal matrix containing singular values. Large singular values indicate the dimension that stores the most significant information.

Although Singular Value Decomposition (SVD) is not directly applied in this study, it is introduced to provide broader insight into matrix-based analysis. SVD plays an important role in understanding matrix rank, numerical stability, and solution behavior of linear systems, especially in large-scale engineering problems.

C. Direct Current (DC) Electric Circuit

A direct current (DC) circuit is an electric current that flows in one constant direction within a closed circuit. This direct current differs from alternating current (AC), which changes direction periodically. A direct current circuit consists of components such as a direct current source (usually a battery or similar power source), resistors, switches, and other components placed in a closed circuit. The simplest example of a direct current circuit is a battery connected to a resistor. Another example of a direct current circuit is

- 1) Car headlights receive direct current from the car battery. This current flows through wires and other components to illuminate the headlights.
- 2) When you charge your phone or laptop battery using a charger, you're using direct current. The charger converts alternating current from the power source into direct current, which is used to charge the battery.
- 3) In various electronic devices such as radios, televisions, or music players, there are electronic circuits with various components such as resistors, capacitors, and transistors that receive direct current to function.
- 4) The water pump engine in a vehicle usually uses direct current to flow water to the radiator or engine cooling system.

The relationship between current, voltage, and resistance in a DC circuit follows Ohm's law, which states that voltage is proportional to the product of current and resistance. This law

forms the basis for forming linear equations in electrical circuit analysis.

$$V = I \cdot R \quad (5)$$

This law forms the basis for forming linear equations in electrical circuit analysis.

D. Kirchhoff's Law

Kirchhoff's laws, created by German scientist Gustav Kirchhoff, are a set of fundamental laws used to analyze electrical circuits. Kirchhoff's laws contain two main principles:

- 1) *Kirchhoff's First Law* (Kirchhoff's Current Law/KCL): This law states that the total amount of current entering a branching point (node) is equal to the total amount of current leaving that point.

$$\sum I_{enter} = \sum I_{exit} \quad (6)$$

- 2) *Hukum Tegangan Kirchhoff* (Kirchhoff's Voltage Law/KVL): This law states that in any closed circuit (loop), the algebraic sum of the changes in electric potential is zero. This law is the basis for the formation of a System of Linear Equations (SLS) in mesh analysis. Mathematically, it is formulated as:

$$\sum V + \sum (I \cdot R) = 0 \quad (7)$$

All of these equations can then be applied to a system of linear equations to find the value of current, voltage, or intensity.

E. Gaussian elimination method

The Gaussian elimination method is one method used to solve systems of linear equations. This method is an effective method for solving a large number of variables. This method is performed as follows:

- 1) Express the SPL in augmented matrix form
- 2) Apply OBE to the augmented matrix until a row echelon matrix is formed.

$$\left[\begin{array}{cccc|c} a_{11} & a_{12} & \cdots & a_{1n} & b_1 \\ a_{21} & a_{22} & \cdots & a_{2n} & b_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} & b_n \end{array} \right] \sim \text{OBE} \sim \left[\begin{array}{cccc|c} 1 & * & * & \cdots & * \\ 0 & 1 & * & \cdots & * \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \vdots & 1 \end{array} \right]$$

- 3) Solve the corresponding equations in a row echelon matrix using the back subtraction technique.

This method is performed by converting a system of linear equations into an augmented matrix, then performing elementary row operations to obtain row echelon form. Through the elimination process, the system of linear equations can be simplified so that the variable solution can be determined systematically.

The Gaussian elimination method is particularly suitable for use in electrical circuit analysis because the system of equations resulting from Kirchhoff's laws is generally linear and can be represented in matrix form.

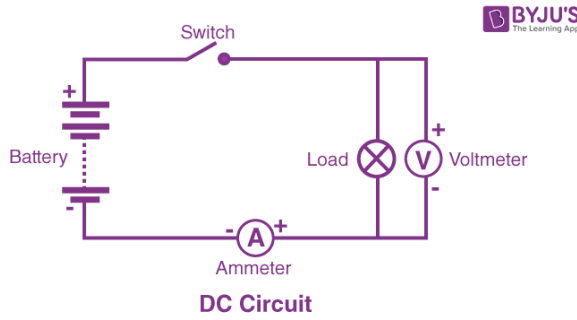


Fig. 1. Basic DC electrical circuit consisting of a voltage source, switch, load, ammeter, and voltmeter

III. SYSTEM DESIGN

This section explains the system design for analyzing direct current (DC) circuits using a linear algebra approach. The system design aims to transform a physical problem, an electrical circuit, into a mathematical problem in the form of a system of linear equations that can then be solved computationally.

The designed system receives input in the form of electrical circuit parameters, namely the voltage source value and the resistance value of each resistor. The electrical circuit is represented in the form of nodes and branches, with the current in each branch designated as an unknown variable. With this designation, each current variable becomes an element in the solution vector of the system of linear equations.

The system of linear equations is formed by applying Kirchhoff's laws. Kirchhoff's current law is used to form the current balance equation at each node, while Kirchhoff's voltage law is used to form the voltage balance equation for each closed loop in the circuit. The resulting equations are linear with respect to the current variable and can therefore be arranged in the form of a coefficient matrix.

Once all the equations are formed, the system of linear equations is represented in the form of an augmentation matrix. This matrix then serves as input to the system solution stage using the Gaussian elimination method. With this approach, the electric current calculation process can be carried out systematically, in a structured manner, and is easy to implement in a computer program.

Figure 1 illustrates a basic DC electrical circuit configuration commonly used for introductory circuit analysis. The figure is adapted from [9].

IV. MATHEMATICAL MODELING OF ELECTRICAL CIRCUITS

In the mathematical modeling stage, a direct current (DC) electrical circuit is represented as a system of linear equations. This modeling aims to transform the physical problem into a mathematical model that can be solved using linear algebra.

Each branch in the electrical circuit is assumed to have a flowing current, and this current is expressed as an unknown variable. Thus, if there are n branches in the circuit, n

current variables will be created, the values of which must be determined.

The equations are formed by applying Kirchhoff's laws. Kirchhoff's current law is used to express the current balance at each node, while Kirchhoff's voltage law is used to express the voltage balance in each closed loop. By applying these two laws, a set of linear equations is obtained that relate the current variables.

The resulting linear equations are then arranged into a system of linear equations. In general, the system can be written in matrix form as

$$Ax = b \quad (8)$$

where A is a coefficient matrix representing the relationship between currents, x is a vector of current variables, and b is a constant vector originating from the voltage source in the electrical circuit.

Through this matrix representation, DC electrical circuit analysis can be performed systematically and structured. The mathematical model thus created serves as the basis for solving the system of linear equations using the Gaussian elimination method.

A. Matrix Properties in Circuit Analysis

In linear algebra-based circuit analysis, the properties of the coefficient matrix play a crucial role in determining the nature of the solution. The rank of the matrix, its determinant, and its conditioning are directly related to the physical validity of the electrical circuit.

A full-rank coefficient matrix with a nonzero determinant indicates the existence of a unique solution, which corresponds to a stable and well-defined circuit. On the other hand, a singular matrix may indicate redundant equations, dependent loops, or improper circuit connections.

This interpretation highlights the strong relationship between abstract matrix properties and real physical behavior in electrical systems.

B. Geometric Interpretation of Linear Systems

From a geometric perspective, a system of linear equations can be interpreted as the intersection of geometric objects in a multidimensional space. Each linear equation represents a hyperplane, while the solution of the system corresponds to the point or set of points where these hyperplane intersect.

In the context of DC electrical circuit analysis, each equation derived from Kirchhoff's laws defines a linear constraint on the current variables. When the number of independent equations is equal to the number of unknown currents and the coefficient matrix is full rank, the system has a unique solution. Geometrically, this corresponds to a single intersection point of all hyperplanes, representing a physically stable operating condition of the circuit.

If the coefficient matrix is rank-deficient, the system may possess infinitely many solutions. Geometrically, this situation corresponds to an intersection along a line or plane, which can be interpreted as a circuit containing redundant paths or

dependent loops. Conversely, if the system has no solution, the hyperplanes do not intersect at any point, indicating an inconsistent or physically invalid circuit configuration.

This geometric interpretation highlights the close relationship between linear algebra concepts and physical circuit behavior. The existence and uniqueness of solutions are not only algebraic properties but also reflect meaningful physical conditions in electrical circuit analysis.

V. SOLUTION METHOD

After the direct current circuit is modeled as a system of linear equations, the next step is to solve the system to obtain the current values in each branch of the circuit. In this paper, the method used to solve the system of linear equations is the Gaussian elimination method.

The Gaussian elimination method works by transforming the system of linear equations into an augmented matrix, which contains the coefficient matrix and constant vector in a single representation. Through a series of elementary row operations, the matrix is converted into row echelon form. Allowed elementary row operations include interchanging two rows, multiplying one row by a nonzero constant, and adding one row by a multiple of another row.

The elimination process is carried out to eliminate variables gradually, starting from the first variable to the last. Once the matrix is in row echelon form, the value of the current variable can be obtained through back substitution. With this approach, the solution to the system of linear equations can be determined systematically and consistently.

The Gaussian elimination method is particularly suitable for analyzing DC circuits, because the system of equations resulting from the application of Kirchhoff's laws is linear and can be represented directly in matrix form.

Furthermore, this method is easy to implement in a computer program, thus supporting computational calculations for circuits with higher levels of complexity.

A. Alternative solution methods

Besides Gaussian elimination, other linear algebra techniques can also be used to solve systems of linear equations in electrical circuit analysis. One such method is matrix decomposition, including Singular Value Decomposition (SVD).

Although SVD is not directly applied in this paper, it is important to note that SVD can be used to analyze the numerical properties of the coefficient matrix, especially in large-scale or ill-conditioned systems. In particular, SVD can help determine whether a system is close to being singular and can be used to compute approximate solutions in the presence of numerical instability.

However, due to its higher computational complexity and the educational focus of this paper, Gaussian elimination is chosen as the primary solution method.

VI. IMPLEMENTATION

This section explains the implementation flow for solving direct current circuits without relying on a specific programming language. The main focus of the implementation is to

apply mathematical computational steps based on a linear algebra system to obtain the current solution for each branch of the circuit.

The first stage in implementation is identifying the structure of the electrical circuit, including the number of nodes, branches, and loops. Each branch of the circuit is assumed to have a single current, which is used as an unknown variable. With this determination, the number of variables in the system is equal to the number of currents whose values are to be determined.

The next stage is the formation of a system of linear equations based on Kirchhoff's laws. Kirchhoff's current law is used to formulate the current balance equations at each node, while Kirchhoff's voltage law is used to formulate the voltage balance equations for each closed loop. The resulting equations are arranged in the form of coefficient matrices and constant vectors, forming a system of linear equations in matrix form.

Once the system of linear equations is formed, the equations are represented as an augmentation matrix. This matrix is then processed using the Gaussian elimination method, which involves performing elementary row operations to obtain row-echelon form. From this form, the value of the current variable can be determined through back-substitution.

Through this implementation flow, DC circuit solutions can be performed systematically and structured. This approach demonstrates that linear algebra concepts can be applied directly to electrical circuit analysis, without relying on manual calculation methods.

A. Example of Matrix Formation

To illustrate the implementation process, consider a simple DC circuit consisting of two closed loops with two branch currents, I_1 and I_2 . Each loop has a voltage source and several resistors connected in series.

By applying Kirchhoff's voltage law to each loop, two linear equations are obtained that represent the relationship between the current and the circuit elements. These equations can generally be written as

$$\begin{aligned} (R_1 + R_2)I_1 - R_2I_2 &= V_1 \\ -R_2I_1 + (R_2 + R_3)I_2 &= V_2 \end{aligned} \quad (9)$$

The system of linear equations is then arranged into a coefficient matrix and constant vector as follows:

$$\begin{bmatrix} R_1 + R_2 & -R_2 \\ -R_2 & R_2 + R_3 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \quad (10)$$

The matrix can then be represented as an augmented matrix as the initial step in applying the Gaussian elimination method. This example clearly demonstrates how a DC circuit can be modeled and implemented as a system of linear equations using a linear algebra approach.

B. Implementation Flow Description

The overall implementation process follows a structured sequence of steps, starting from circuit identification to the determination of branch currents. Initially, the electrical circuit

topology is analyzed to identify nodes, branches, and loops. Each branch current is then defined as an unknown variable.

Next, Kirchhoff's laws are systematically applied to generate a set of linear equations. These equations are assembled into a matrix representation, which serves as the input for the Gaussian elimination process. Finally, back substitution is performed to obtain the numerical values of the branch currents.

This structured flow ensures that the solution process is systematic, scalable, and suitable for computational implementation.

C. Numerical Example and Physical Interpretation

To further illustrate the application of linear algebra in DC circuit analysis, consider a simple two-loop DC circuit with the following parameters: $R_1 = 2\Omega$, $R_2 = 4\Omega$, $R_3 = 6\Omega$, $V_1 = 12V$, and $V_2 = 6V$. Let I_1 and I_2 denote the currents flowing in the first and second loops, respectively.

By applying Kirchhoff's Voltage Law to each loop, the following system of linear equations is obtained:

$$\begin{aligned}(2 + 4)I_1 - 4I_2 &= 12 \\ -4I_1 + (4 + 6)I_2 &= 6\end{aligned}\quad (11)$$

This system can be expressed in matrix form as:

$$\begin{bmatrix} 6 & -4 \\ -4 & 10 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 12 \\ 6 \end{bmatrix}\quad (12)$$

Using the Gaussian elimination method, the augmented matrix is transformed into row echelon form, yielding the solution:

$$I_1 = 2.67 \text{ A}, \quad I_2 = 1.67 \text{ A}\quad (13)$$

From a physical perspective, these values represent the steady-state currents flowing through each loop of the circuit. The positive values indicate that the assumed current directions are consistent with the actual physical behavior of the circuit. This numerical example demonstrates how abstract matrix operations directly correspond to measurable electrical quantities.

VII. RESULTS AND DISCUSSION

Based on the mathematical modeling and solution methods discussed in the previous section, a direct current circuit can be systematically represented as a system of linear equations. Each equation formed represents the application of Kirchhoff's laws to a single loop or node in the circuit, while the variables represent the electric currents in each branch.

The main result obtained from this approach is the formation of a coefficient matrix that reflects the structure of the electric circuit. The resistance values act as matrix elements, while the voltage sources form a constant vector. With this representation, a circuit analysis problem that was originally physical can be transformed into a well-defined linear algebra problem.

The application of the Gaussian elimination method to the augmentation matrix allows the electric current solution to be determined in a structured manner. The elimination process produces a system of equations in row echelon form, allowing

the current values to be obtained through back substitution. This approach has proven effective for small to medium-sized circuits, because the steps are deterministic and easy to implement computationally.

From a linear algebra perspective, the existence of a unique solution depends on the nature of the coefficient matrix. If the determinant of the matrix is nonzero, the system of equations has a unique solution that represents the stable and consistent physical state of the circuit. Conversely, if the matrix is singular, the system can have an infinite number of solutions or no solutions at all, which can be physically interpreted as a circuit with an invalid configuration or interdependent equations.

Although the Gaussian elimination method provides accurate results, this approach has limitations when applied to circuits with a very large number of branches and loops. The increased matrix size can lead to high computational complexity and potential numerical errors. Nevertheless, for educational purposes and basic DC circuit analysis, this method remains relevant because it provides a solid understanding of the relationship between systems of linear equations and real-world engineering problems.

In practical applications, the matrix-based approach provides several advantages over manual analysis. It allows engineers to handle complex circuits with multiple loops and branches more efficiently. Additionally, the matrix formulation enables the use of computational tools to automate circuit analysis.

This approach is particularly useful in educational environments, as it helps students understand the direct relationship between mathematical models and physical systems. By visualizing circuits as systems of equations, students can develop a deeper conceptual understanding of both linear algebra and electrical circuit theory.

A. Physical Interpretation of the Mathematical Solution

The solution obtained from the system of linear equations represents the steady-state operating condition of the DC electrical circuit. Each current value corresponds to the actual physical current flowing through a specific branch of the circuit.

From a physical perspective, a unique solution indicates that the circuit operates in a stable and consistent manner. This condition occurs when the circuit is properly connected and all components satisfy linear behavior. On the other hand, the absence of a unique solution may indicate redundant loops, short circuits, or improper circuit configurations.

B. Computational Perspective

From a computational perspective, the matrix-based formulation enables automation of DC circuit analysis. Once the coefficient matrix and constant vector are constructed, the solution process can be fully handled by numerical algorithms.

This approach forms the foundation of many circuit simulation tools, where complex circuits are solved using matrix operations. Thus, the method discussed in this paper is not only

educational, but also closely related to modern engineering software.

C. Scalability and Computational Complexity

From a computational standpoint, the Gaussian elimination method has a time complexity of approximately $O(n^3)$, where n denotes the number of unknown variables in the system. For small to medium-sized DC circuits, this computational cost is acceptable and allows solutions to be obtained efficiently.

However, as the size of the electrical circuit increases, the number of nodes, branches, and loops grows, resulting in a larger coefficient matrix. In such cases, the computational cost and memory requirements may become significant. Numerical stability issues may also arise, particularly when the coefficient matrix is ill-conditioned.

In practical engineering applications, large-scale circuit analysis often relies on alternative numerical methods, such as iterative solvers or matrix factorization techniques. Nonetheless, Gaussian elimination remains highly valuable for educational purposes, as it provides a clear and deterministic framework for understanding how linear algebra techniques are applied to real-world circuit problems.

This discussion further emphasizes the relevance of linear algebra not only as a theoretical tool but also as a foundational component of modern computational engineering systems.

VIII. LIMITATIONS AND FUTURE WORK

Although the Gaussian elimination method is effective for solving systems of linear equations, it has limitations when applied to very large-scale circuits. As the number of branches and loops increases, the size of the coefficient matrix grows, leading to higher computational cost and potential numerical instability.

Future work may explore the application of alternative numerical methods, such as iterative solvers or matrix factorization techniques, to improve computational efficiency. In addition, extending the model to analyze alternating current (AC) circuits or incorporating dependent sources could further enhance the applicability of the proposed approach.

In addition, future studies may incorporate computer-based simulations to automatically generate system matrices from arbitrary circuit topologies. This extension would further demonstrate the practical usefulness of linear algebra in modern engineering applications, particularly in circuit simulation software.

IX. CONCLUSION

Based on the previous discussion, it can be concluded that the concept of a system of linear equations plays a crucial role in modeling and analyzing direct current electrical circuits. By applying Kirchhoff's laws, the relationship between current, voltage, and resistance can be formulated mathematically in the form of structured and consistent linear equations.

The linear algebra approach allows physical electrical circuit problems to be transformed into mathematical problems in matrix representation. By using the Gaussian elimination

method, the current solution for each branch of the circuit can be determined systematically and easily interpreted. This demonstrates that the linear algebra method is not only theoretical but also applicable in solving real-world engineering problems.

In addition to providing structured solutions, this approach also helps understand the properties of the circuit system through the characteristics of the coefficient matrix. The existence of a single solution, multiple solutions, or the absence of a solution can be directly related to the physical conditions of the electrical circuit being analyzed. Thus, linear algebra acts as a bridge between abstract mathematical concepts and their implementation in electrical engineering and engineering.

In conclusion, this paper is expected to provide a clear picture of the relationship between systems of linear equations and DC circuit analysis. The discussed approach can serve as a basis for further method development, both in the analysis of more complex circuits and in the application of numerical computations to other engineering problems.

A. Limitations and Future Work

Although the linear algebra approach presented in this paper provides a systematic method for analyzing DC circuits, several limitations should be noted. The analysis is restricted to linear components under steady-state direct current conditions. Nonlinear elements such as diodes and transistors, as well as time-varying signals in AC circuits, are not considered in this study.

Furthermore, the Gaussian elimination method, while effective for small-scale systems, may become computationally inefficient for large and complex circuits. Numerical stability issues may also arise when the coefficient matrix is ill-conditioned.

Future work may extend this study by incorporating more advanced numerical methods, such as matrix factorization or iterative solvers, to handle larger systems. Additionally, the modeling approach can be expanded to include AC circuit analysis using complex numbers and phasor representation, further demonstrating the broad applicability of linear algebra in electrical engineering.

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PERNYATAAN

Dengan ini saya menyatakan bahwa makalah yang saya tulis ini adalah hasil karya saya sendiri, bukan saduran, terjemahan, maupun hasil penjiplakan dari karya orang lain. Seluruh sumber yang digunakan dalam penyusunan makalah ini telah dicantumkan secara benar sesuai dengan ketentuan penulisan ilmiah yang berlaku.

Bandung, 24 Desember 2025

A handwritten signature in black ink, appearing to read 'Hartawan', with a long horizontal stroke extending to the right.

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13524147