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Matrix methods for enhanced DC analysis: A Python-based approach

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***Abstract*— This study aims to provide an enhanced approach to analyze circuits using matrix analysis and Kirchhoff's Current Law (KCL). Matrices were employed for the integration of power parameters, and KCL provided the basis for power flow analysis throughout the system. Using these, the researchers were able to demonstrate successful circuit analysis, resulting in a faster and more systematic knowledge of power distributions in different regions of the circuit. The simulations demonstrated the faster approach to obtaining circuit parameters using Python-based solutions, which can be further expanded to more complex circuit configurations requiring longer solutions. These research findings can contribute to the growth of circuit analysis methods, giving researchers an in-depth understanding of the optimal planning and development of electrical systems.**

***Keywords*— Circuit analysis, Matrices, Node Voltage Method, Mesh Current Method**

I. Introduction

Circuit analysis is a fundamental concept in electronics engineering and involves the study of electric circuits, which are composed of interconnected electrical components. The main objective of circuit analysis is to identify the behavior of electrical currents and voltages inside a circuit, as well as to compute critical circuit characteristics such as resistance, capacitance, inductance, and impedance. In circuit analysis, challenging electrical issues are resolved by utilizing a variety of mathematical methods and ideas. These techniques include Kirchhoff's laws, Ohm's law, network theorems (such as Thevenin's theorem and Norton's theorem), and mesh and nodal analysis.

The research focuses on Kirchhoff's current law (KCL), a widely used tool in electrical circuit examination and investigation developed by German scientist Gustav Kirchhoff in the 1800s. The foundation of Kirchhoff's Current Law, or KCL, is the idea of charge conservation. It asserts that the sum of the currents entering and exiting a node is the same. This law arises from the fact that charges cannot be produced or destroyed within a circuit. In exploring the intricate realm of circuit analysis, Willy McAllister sheds light on a pivotal strategy: the formulation and resolution of a set of distinct equations. This method serves as the cornerstone for comprehending the intricacies inherent in complex circuits.

The circuit analysis unfolds through three primary approaches, each yielding similar outcomes. Fundamental laws, such as Ohm's Law and Kirchhoff's Law, find immediate application in the initial scenario. While effective for less intricate circuits, their efficacy diminishes as the complexity of the circuits increases. In response to this challenge, engineers have proactively formulated the Node Voltage Method and the Mesh Current Method as simplified approaches. These methodologies are geared towards enhancing efficiency by lowering the number of simultaneous equations. They present themselves as systematic, step-by-step procedures for navigating the intricacies of circuits. McAllister's insights further extend to the Loop Current Method, closely related to the Mesh Method, demonstrating applicability in distinct scenarios [1]. Let's dive into some examples focusing exclusively on resistors and ideal sources as we delve deeper into the intricacies of circuit analysis. This intentional focus on these components simplifies the mathematical aspects, facilitating a concentrated exploration of the methods employed for effective circuit solutions. Remarkably, even as circuits become more complex with an expanding number of nodes and branches, utilizing these methods makes circuit analysis more manageable and comprehensible.

In the context of Kirchhoff's concepts, Cramer's rule is a mathematical tool used to solve for unknowns by calculating the determinants of matrices derived from the original coefficient matrix. The matrix representation writes the circuit equations as a set of linear equations in matrix form and represents the current and voltage variables in the circuit as column matrices. By solving the matrix equation, the unknown values of currents in the circuit can be determined.

Some uses of circuit analysis include:

- power systems engineering
- aiding in the design
- study of electrical distribution networks
- calculating power flows
- finding fault currents

The researchers use Python to work with matrices and perform matrix operations using NumPy, a powerful library for numerical computing. Then perform manual computations to verify and check matrix computations using mathematical rules and formulas for matrix operations.

The ability to scrutinize circuits both conceptually and manually is a crucial skill to cultivate. This skill not only enhances one's understanding of how circuits operate but also grants insights that designing a circuit and relying solely on a computer can't provide. Developing the skills in circuit analysis allows engineers to mentally envision how a circuit works just by glancing at a schematic diagram. This mastery contributes to a more profound and comprehensive understanding of electrical systems [1].

Bayard and Shmarak, emphasized the importance of basic electric circuits course for electrical and electronics engineering programs. The study pointed out that students from all fields of engineering backgrounds often signed up for this course to meet their core requirements. In their research project, the main focus was teaching students about nodal and mesh analysis–those essential methods for tackling electric circuit problems. Moreover, the study provided some insights in mastering nodal and mesh analysis, along with the practical tools to enhance analytical skills in applying equations such as Kirchhoff's law and Ohm's law. According to Bayard and Shmarak, this hands-on approach provides the firsthand knowledge on how changes affect the solution process, providing more intuitive outcomes [2].

Robert S. Eisenberg discussed Kirchhoff's Law and its precision in his article. Normally, Kirchhoff's current law is believed to explain how charged particles move through resistors. However, it is commonly applied to describe the flow of current in high-speed devices. At high frequencies or short durations, the movement of current involves more than just particle translation–there are sudden changes called transients. To tackle this, people often add extra capacitance to resistors, trying to mimic real-world scenarios. But this approach doesn't really solve the problem; it merely masks it. The issue lies in not knowing the exact location, value, and dielectric properties of these additional capacitances. Eisenberg suggests a more precise method. If we redefine current based on Maxwell's equations, regardless of dielectric properties, Kirchhoff's law becomes precise, and transients occur naturally without any uncertainty. In essence, Eisenberg proposes a clearer way to understand and apply Kirchhoff's Law in high-speed devices without the complications introduced by arbitrary capacitances [3].

The goal of circuit analysis research is to improve our understanding of electrical circuits and their behavior, which is an essential part of electronics engineering. It advances technical innovation by integrating new methods and strategies to enhance circuit performance and address challenges across many applications.

II. Methodology

A well-defined and standardized procedure is required for research to be valid, repeatable, and trustworthy. The following provides a methodological foundation for carrying out the activity that enhances overall understanding in general.

A. Description of the Development

This paper emphasizes the use of a Python-based computational framework to apply matrices and Cramer's Rule to analyze electrical circuits. The researchers will answer the question, "How does the integration of Python-based matrix analysis, utilizing Cramer's Rule and symbolic mathematics through Tkinter GUI, enhance the efficiency and comprehension of circuit analysis in comparison to traditional manual methods among engineering students?". The proponents of this study used a wide range of Python libraries, including but not limited to Tkinter, used for the graphical user interface, NumPy for carrying out numerical computations, SymPy for handling symbolic mathematics, and PIL for displaying images. The code has two main tabs within the GUI: one dedicated to entering matrix values and a vector representing the system of equations derived from circuit configurations. The other tab focuses on defining resistor values essential for circuit analysis.

The study of Robert Eisenberg delves into the widespread application of Kirchhoff's current law in the design of circuits, particularly those with nanosecond response times [4, 5, 6]. Over the course of almost a century, Kirchhoff's law has been instrumental not only in shaping the functionality of rapid-response circuits but has also found utility in designing slower circuits[7]. Kirchhoff's current law revolves around the flux of charges in circuits, often pertaining to the flux of electrons. Notably, this law doesn't directly address the rate of change of the total charge within the circuit. The conventional formulation of Kirchhoff's current law lacks a specific term related to the rate of change. However, in circuits responding within nanosecond timeframes, the rates of change concerning charge and electric field are far from negligible [8]. The article emphasizes that the behaviors of current flow, encompassing the mechanisms and properties, exhibit substantial variation between nanoseconds and seconds, particularly in the context of wires. This dynamic behavior is pivotal to understanding the intricacies of circuits operating at different time scales. The article underscored the enduring significance of Kirchhoff's current law in guiding the design of circuits, both swift and gradual in their response times, shedding light on the nuanced aspects of charge and electric field dynamics, particularly in the rapid nanosecond domain [9, 10].

Cramer's Rule, named after the mathematician Gabriel Cramer, serves as a valuable method for solving systems of linear equations through a distinctive approach rooted in determinants [11]. Having a collection of equations with unknowns, and the objective is to determine those unknown values, Cramer's Rule can be useful when the number of equations matches the number of unknowns, and the process can be utilized unless the initial matrix has a zero determinant.

This rule is particularly useful in engineering applications, addressing problems in circuits, fluid dynamics, etc. However, it is important to note that Cramer's Rule excels in situations involving smaller sets of equations and encounters difficulties when dealing with larger, more intricate systems. To comprehend the intricacies of this method, one should be familiarized with determinants, which are special numerical values derived from matrices. Matrices, resembling well-organized arrays of numbers, hold the secret to the effectiveness of Cramer's Rule, with the determinant of the Coefficient Matrix playing a crucial role.

In the scholarly investigation conducted by researchers Babarinsa and Kamarulhaili, two distinct methods were employed to apply and enhance Cramer's rule, a method commonly used for solving systems of linear equations. The first approach uses conventional way, following established procedures. The second approach introduced a novel dimension by incorporating programming tools. These methodologies, though grounded in theoretical considerations, underscore the versatility of implementing Cramer's rule without compromising the generality of the coefficient matrix.

B. Design and Structure

The program created by the proponents is a Tkinter-based GUI application that includes code that allows users to solve circuit analysis problems with less difficulty. It is Python's de-facto standard GUI package and the most used toolkit. The program includes a layout structure that centers around the Tkinkter library for developing a graphical user interface as well as handling user interactions. It utilizes the use of 'ttk.Notebook' to structure the two primary tabs, Cramer's Rule tab and Circuit tab. The Cramer's Rule tab allows the user to encode matrix values and solve equations, and the 'solve button' allows the function to solve linear equations using Cramer's rule depending on the values the user has provided. The Circuit tab displays the image of the circuit and provides input fields for resistor values to generate equations based on Kirchhoff's Current Law utilizing symbolic manipulation 'sympy'.

An application such as the Visual Studio IDE may be utilized for running the program. It is a single-location developer utility that facilitates the completion of the entire development cycle. It functions as an all-encompassing integrated development environment (IDE) for constructing, debugging, writing, and executing programs.

C. Explanation of Code Functionalities

Prior to the program in solving the equation, the matrix and vector must be input. By selecting the "solve" button, the equation solutions acquired through Cramer's rule will be displayed. Once the resistor values have been entered and configured, the user will be prompted to affirm whether they wish to populate matrices with the calculated values. During the running of the program, the user will be notified of any errors that have occurred.

The program's design centers on the development of a well-organized and interactive graphical user interface (GUI) using Tkinter. This GUI enables users to input circuit parameters, carry out calculations, and display results. Additionally, it offers a user-friendly environment for circuit analysis, employing Cramer's rule and symbolic mathematics. The program's compatibility of codes and techniques enables simple modifications of functionality.

III. Results and Discussion

With the aid of the python programming, which was used to ascertain the circuit analysis through the verification of manual computation like Kirchhoff's Current Law and Cramer's Rule, the project's findings are presented and analyzed in this chapter. As the diagram of the circuit was specifically illustrated and the parameters were applied, the researchers acquired all of the necessary information and utilized a formula to determine what was asked. Below are the results and findings, along with a computation.

A. Codes

```
import tkinter as tk
import numpy as np
from tkinter import PhotoImage, ttk,
messagebox
from sympy import symbols, Rational,
simplify
from PIL import Image, ImageTk
from tkinter import *

# Define global variables for resistor
values
R1 = 0.0
R2 = 0.0
R3 = 0.0
R4 = 0.0
CS = 0.0

  # Calculate the solution as the ratio
of determinants divided by det_A
            solution = det_A_i / det_A
            solutions.append(solution)

        # Divide Va, Vb, Vc by det_A
        formatted_solutions = [det /
det_A for det in determinants]

        # Display the results
        result_text = f"Va =
{formatted_solutions[0]:.2f} V    Vb =
{formatted_solutions[1]:.2f} V    Vc =
{formatted_solutions[2]:.2f} V"

result_label.config(text=result_text)

        # Define the variables
        A, B, C = symbols('A B C')

        # Define the first equation
        equation1 = (A - B) / R2 + (A -
C) / R1 - CS
   # Simplify the first equation
        simplified_equation1 =
simplify(equation1)

        # Extract coefficients from the
first equation
        coefficients1 =
simplified_equation1.as_coefficients_di
ct()

        # Define the second equation
        equation 2a = B / R3 + (B - C)
/ R4 - (A - B) / R2

        # Simplify the second equation
        simplified_equation2 =
simplify(equation2)

        # Extract coefficients from the
second equation
        coefficients2 =
simplified_equation2.as_coefficients_di
ct()
        # Define the third equation
        equation3 = (A - C) / R1 + (B -
C) / R4 - 2 * (A - B) / R2

        # Simplify the third equation
        simplified_equation3 =
simplify(equation3)

        # Extract coefficients from the
third equation
        coefficients3 =
simplified_equation3.as_coefficients_di
ct()
```

```
    # Create a matrix for constant
coefficients
        const_matrix =
np.array([[Rational(coefficients1.get(1
, 0)).limit_denominator()],

[Rational(coefficients2.get(1,
0)).limit_denominator()],

[Rational(coefficients3.get(1,
0)).limit_denominator()]])
 # Create the main window
 window = tk.Tk()
 window.title("Circuit and Cramer's
 Calculator")

 # Create the tab control
 tab_control = ttk.Notebook(window)

 # Create the Circuit tab
 circuit_tab = ttk.Frame(tab_control)
 tab_control.add(circuit_tab,
 text=("Cramer's Rule"))

  clear_button = tk.Button(button_frame,
  text="Clear", command=clear_inputs)
  clear_button.grid(row=0, column=1,
  padx=5, pady=5)


  # Add the tab control to the main
  window
  tab_control.pack(expand=1, fill="both")

  # Start the main event loop
  window.mainloop()
```

B. Graphical User Interface (GUI)

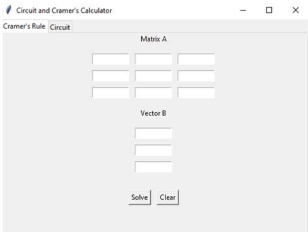

Fig. 1. Cramer's rule.

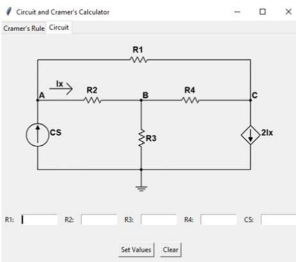

Fig. 2. Circuit.

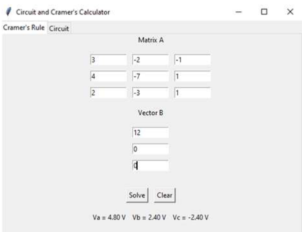

Fig. 3. Cramer's rule with analytical solution.

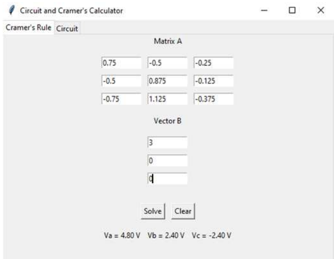

Fig. 4. Crkt analyzer.

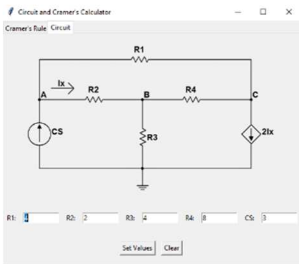

Fig. 5. Applying values.

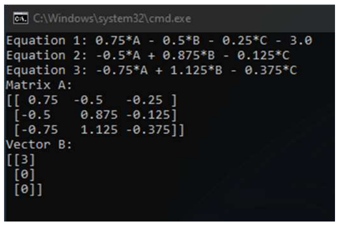

Fig. 6. Output.

C. Manual Computation

Consider the circuit shown below, determine the voltages at the nodes.

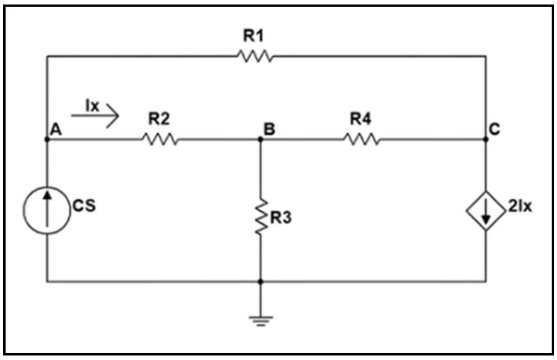

Fig. 7. A sample circuit to determine the nodes and voltages.

Apply KCL at each node: $\sum i_{in} = \sum i_{out}$

At node A: $3 = i_x + i_1$

$3V_A - 2V_B - V_C = 12\,(equation\ 1)$

At node B: $i_x = i_b + i_c$

$4V_A - 7V_B + V_C = 0\,(equation\ 2)$

At node C: $i_1 + i_c = 2i_x$

$2V_A - 3V_B + V_C = 0\,(equation\ 3)$

Solution by using CRAMER'S Rule

$$\begin{bmatrix} 3 & -2 & -1 \\ 4 & -7 & 1 \\ 2 & -3 & 1 \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \begin{bmatrix} 12 \\ 0 \\ 0 \end{bmatrix}$$

$$E = \begin{bmatrix} 3 & -2 & -1 \\ 4 & -7 & 1 \\ 2 & -3 & 1 \end{bmatrix}$$

det E = - 10

det A = - 48

det B = - 24

det C = 24

Here, solve for the voltages

$$V_A = \frac{\det A}{\det E} = \frac{-48}{-10} = 4.8\ V$$

$$V_B = \frac{\det B}{\det E} = \frac{-24}{-10} = 2.4\ V$$

$$V_C = \frac{\det C}{\det E} = \frac{24}{-10} = -2.4\ V$$

Solving for the value of i_x, i_c, and i_b

$$i_x = \frac{4.8 - 2.4}{2} = 1.2\ A$$

$$i_c = \frac{2.4 - (-2.4)}{8} = 0.6\ A$$

$$i_b = \frac{2.4}{4} = 0.6\ A$$

The manual computation in this study is used to verify the accuracy of the Python coding program. The study's findings apply Cramer's Rule and Kirchhoff's Current Law. The researchers determined the voltages at the nodes as the circuit diagram was clearly depicted and the parameters were also displayed. Here, the method used to determine the voltages of the nodes in a circuit is called nodal analysis. It is based on a systematic application of Kirchhoff's Current Law (KCL). Its foundation is Kirchhoff's Current Law (KCL), applied methodically. KCL applications at nodes A, B, and C are computed so that the total current entering and exiting adds up to the same amount. Ohm's law will be applied to the mathematical equation after it has been completed, substituting the given values. Multiplication will eliminate the denominator, allowing for its simplification.

Three equations have been produced here, and they will be applied to the Cramer's Rule solution. A system of linear equations with as many equations as unknowns can be solved using Cramer's Rule. This is computed using matrices in which the determinants are found. The researchers used the value of determinant E, A, B, and C to create the matrix for V_A, V_B, and V_C and solved for the values of voltages.

IV. Conclusions & Recommendations

The combination of Kirchhoff's Current Law with matrix methods for circuit analysis utilizing Cramer's Rule gives a powerful and efficient approach to analyzing complex electrical circuits. This method enables the simultaneous study of numerous loops and nodes inside a circuit, allowing engineers to solve for unknown currents and voltages with improved precision and speed. Using Python programming, this approach enables automation and scalability in circuit analysis, easing the design and optimization procedures for electrical systems. Furthermore, using Cramer's Rule improves the computing efficiency of solving circuit equations, providing a systematic and dependable way for dealing with complex circuit designs.

Integrating Kirchhoff's Current Law with Matrix Methods for Enhanced Circuit Analysis in Python provides the benefit of offering a systematic and efficient approach to analyzing complex electrical circuits, allowing for precise current and voltage estimation. This integration also allows for the use of strong computational tools to address circuit challenges, which leads to a better knowledge and optimization of circuit performance. Implementing Cramer's rule in larger circuits, might result in increased processing time and will require greater amount of computing power. While acknowledging limitations in practical numerical scenarios, particularly for larger systems, these approaches demonstrate efficacy in mitigating relative residual errors in small but complex systems. The study concludes by positing that additional refinements to these methodologies hold the potential to enhance their efficiency and stability. Both the conventional and programming approaches are acknowledged for their effectiveness in preserving the adaptability of applying Cramer's rule, particularly when dealing with small, complex systems. The study indicated that despite limitations in practical numerical scenarios, especially for larger systems, there is promise in the methodologies, including the programming tool. The conclusion further recommends that ongoing refinements to these methodologies may yield improvements, fostering broader applicability and increased efficacy [12].

Future research in this area could include developing advanced algorithms to efficiently handle large-scale circuit analysis, exploring the integration of machine learning techniques to enhance the accuracy and speed of circuit analysis, and investigating the application of this approach in real-time systems for improved performance and reliability.

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