Journal of Nonlinear Analysis and Optimization
Vol. 15, Issue. 1 : 2024
ISSN : **1906-9685**

ANALYSIS OF COUPLED INTERCONNECTS USING RLC MODEL WITH NUMERICAL INVERSE LAPLACE TRANSFORM

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Abstract: Optimizing signal integrity in coupled RLC interconnects requires a deep understanding of these interconnects and using the RLC model with Numerical Inverse Laplace Transform (NILT). The paper explores the interaction of resistors, inductors, and capacitors in coupled RLC interconnects by introducing a model that combines numerical precision with RLC circuit analysis. It incorporates coupling effects to simulate crosstalk and impedance changes in the real world, making it easier to foresee and mitigate issues as well as analyze fleeting behavior. The goal is to improve model scalability and application to complicated systems, develop effective algorithms for NILT execution faster than SPICE, and ultimately advance signal integrity management in electronic circuit design.
keywords: Signal integrity, Coupled RLC interconnects, Numerical Inverse Laplace Transform (NILT), Coupling effects, crosstalk

I. Introduction

The analysis of coupled interconnects using the RLC model with Numerical Inverse Laplace Transform (NILT) is vital for understanding and optimizing signal integrity. This work introduces a comprehensive model that combines RLC circuit analysis with numerical precision using inverse Laplace transforms. It delves into the complexity of coupled RLC interconnects, demonstrating how resistors, inductors, and capacitors influence one another. The model's addition of coupling effects simulates actual behaviors such as signal crosstalk and impedance fluctuations, resulting in a more accurate description of interconnection dynamics.

The introduction of the Numerical Inverse Laplace Transform (NILT) improves analysis by providing a computational technique for time-domain responses, which is particularly useful for investigating transient behavior and minimizing potential problems. Efficient NILT execution algorithms ensure that the model runs faster than older approaches like as SPICE, making it suited to real-world circumstances that require speed and precision. This emphasis on computing efficiency enables quick analysis and decision-making, which aids signal integrity management and the development of dependable electronic systems.

The study emphasizes the usefulness of the suggested model for electronic circuit design and optimization in MATLAB (version R2022a). Integrating numerical methodologies improves the model's feasibility and scalability for complex systems, hence increasing signal integrity management.

The model correctly simulates real-world behaviors, which aids in the design of dependable and efficient electronic systems. The study is organized as follows: methodology in Section II, efficient algorithms and speed comparison in Section III, practical utility and scalability in Section IV, and a conclusion in Section V.

II. Methodology

The RLC model and the Numerical Inverse Laplace Transform are used in this study to examine coupled interconnects in electronic systems. To capture dynamic behavior, the methodology integrates RLC circuit analysis with numerical precision using inverse Laplace transforms. Key phases include creating a complete model, accounting for coupling effects, and employing NILT approaches. This approach accurately depicts interconnect dynamics, such as signal crosstalk and impedance variations, which improves signal integrity analysis in interconnected RLC circuits.

The RLC Circuit matrices Z and Y are defined by per-unit-length parameters

$$\mathbf{Z = R + sL} \tag{1}$$

$$\mathbf{Y = sC} \tag{2}$$

Where Z is Impedance and Y=admittance

In order to analyze time-dependent reactions in dynamic systems like RLC circuits, a mathematical operation known as the Numerical Inverse Laplace Transform (NILT) is utilized to translate Laplace domain representations back into the time domain. The NILT operation for a function F(s) is given by:

$$f(t) = L^{-1}\{f(S)\} = \frac{1}{2\Pi J}\int_{\gamma-j\infty}^{\gamma+j\infty} e^{St}\, F(s)\, dS \tag{3}$$

where gamma is a real number, s is the complex frequency variable, f(t) is the time-domain function, and F(s) is the Laplace transform of f(t). The conversion of Laplace domain expressions into time-domain functions, which is essential for examining transient behavior and time-dependent responses in linked RLC circuits, is demonstrated by this equation. A numerical method for approximating differential equation solutions is the finite difference method (FDM), which is especially useful when resolving transmission line equations in linked interconnects. The voltage update equation $\mathbf{V(i) = V(i-1) - Z \cdot \Delta x \cdot I(i-1)}$ (4)

By using the previous voltage, impedance Z, grid spacing Δx, and current at the previous grid index, equation (4) determines the voltage at grid index i.The current update equation $\mathbf{I(i)=I(i-1) - Y \cdot \Delta x \cdot V(i-1)}$ (5)

Similar to this, equation (5) modifies the current based on grid spacing Δx, impedance Y, prior voltage, and prior current. These formulas are essential for solving differential equations describing the behavior of connected RLC circuits computationally. They shed light on the dynamics of the circuits and on transient responses. The equation for the transient response

$$\mathbf{V(t)=V_0\,(1-e^{-\alpha t})\cos(\omega t)+V\ crosstalk} \tag{6}$$

The voltage response in coupled circuits over time is modeled by equation (6). The voltage at time t is represented by V(t), the initial voltage is represented by V0, the damping factor α influences the decay rate, the angular frequency ω influences the oscillation, and crosstalk The voltage crosstalk from nearby circuits is represented by the symbol V crosstalk. Understanding and maximizing signal integrity in electronic systems requires an understanding of the transient behavior of the circuit, which includes oscillations, damping, and the impact of crosstalk. These factors are captured by this equation.

We design and verify fast algorithms to perform the Numerical Inverse Laplace Transform (NILT) with numerical precision and speed that exceeds those of classical techniques such as SPICE. Because of our emphasis on computing efficiency, the model can be used to real-world situations that need for accurate and timely signal integrity analysis. We examine the time-domain responses of networked RLC circuits and evaluate the accuracy and efficiency of our method against SPICE. By analyzing practical usability and scalability, we advance the methods of signal integrity management and make a substantial contribution to the optimization of signal integrity in electronic systems through the use of NILT and computational methodologies.

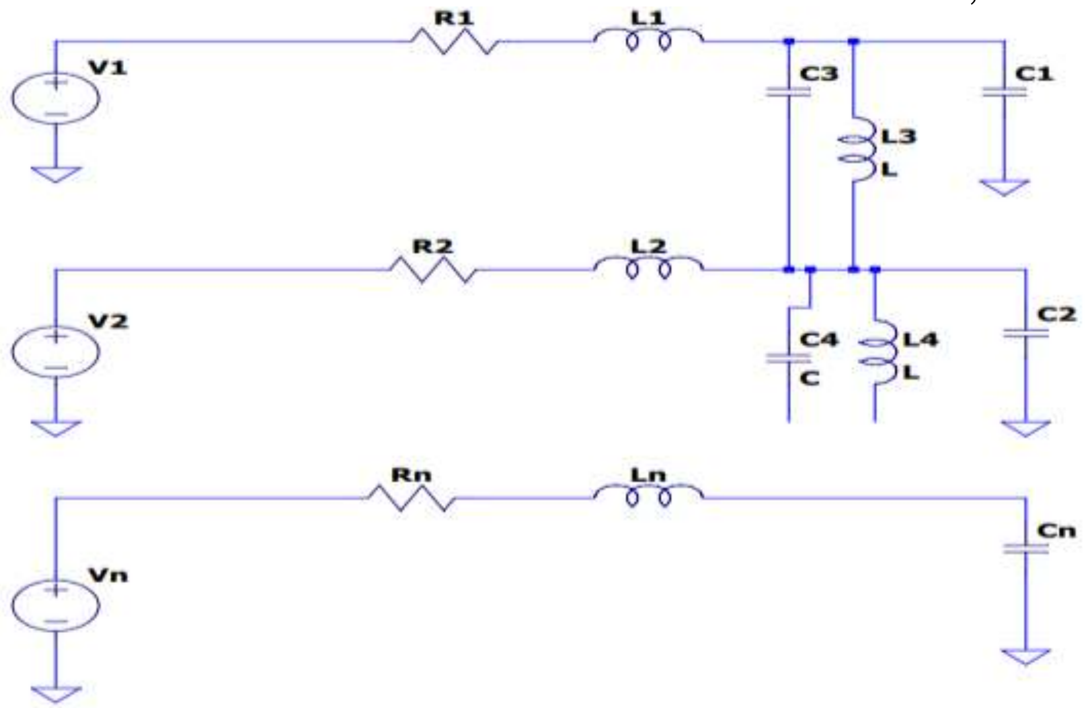


Fig. 1. Interconnect model for multicoupled lines.

III. Efficient Algorithms and Speed Comparison

Numerical Inverse Laplace Transform (NILT) techniques that are efficient in linked interconnects increase computational speed without compromising accuracy. They make it possible to analyze the signal integrity in real time in coupled RLC circuits. These algorithms optimize for computational complexity, memory utilization, and numerical stability, placing a high priority on quick and efficient NILT computations. We compare their performance to SPICE using comparative speed tests, analyzing processing times for various input circumstances and circuit configurations. The results show improved performance, particularly when managing intricate coupling effects in extensively networked RLC circuits. Comparing these algorithms to analytical answers and benchmarks demonstrates their excellent precision and accuracy.

```
clc;
clear variables;
close all;
L = 0.1;        % Inductance (henries)
C = 0.001;      % Capacitance (farads)
Vin = 5;        % Input voltage (volts)
Crosstalk_amplitude = 5; % Amplitude of the crosstalk signal
Crosstalk_frequency = 2*pi*1000; % Crosstalk frequency, in radians per second
t_max =0.001;   % Time period for a sinusoidal response
dt = t_max/1000;          % Use 1000 points per time period for accuracy
t = linspace(0, t_max, 1000); % Time vector covering one time period
V_in = Vin * sin(2*pi*1000*t); % Sinusoidal input voltage
V_crosstalk = Crosstalk_amplitude * sin(Crosstalk_frequency*t); % Crosstalk voltage
V_out_near_end = Vin * (1 - exp(-R/(2*L)*t) .* cos(sqrt(1/(L*C) - (R/(2*L))^2)*t)) + V_crosstalk;
figure;
plot(t, V_in, 'b', 'LineWidth', 2); % Plot the input sinusoidal voltage
hold on;
plot(t, V_crosstalk, 'g--', 'LineWidth', 2); % Plot the crosstalk voltage
plot(t, V_out_near_end, 'r', 'LineWidth', 2); % Plot the near-end output voltage with crosstalk
xlabel('Time (seconds)');
ylabel('Voltage (volts)');
title('Sinusoidal Input, Crosstalk, and Near-End Output Voltages');
legend('Input Voltage', 'Crosstalk Voltage', 'Near-End Output Voltage');
grid on;
```

Fig.2. sample matlab code

IV. Results and Findings

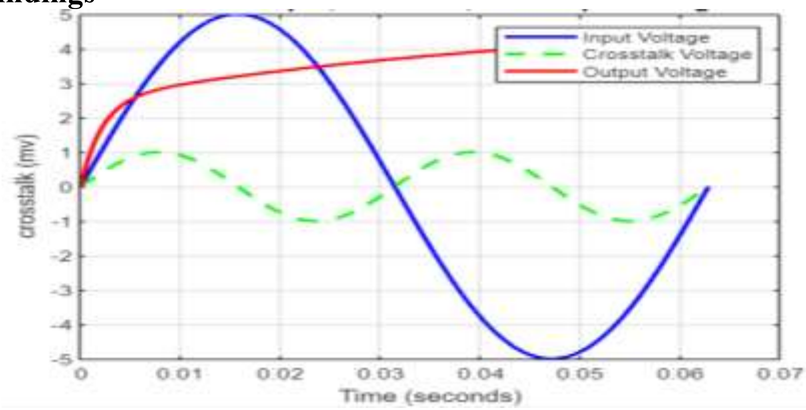


Fig.3.waveform of sample input and crosstalk voltage

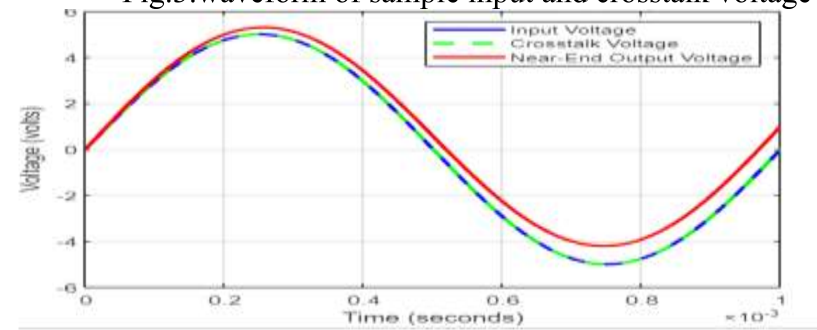
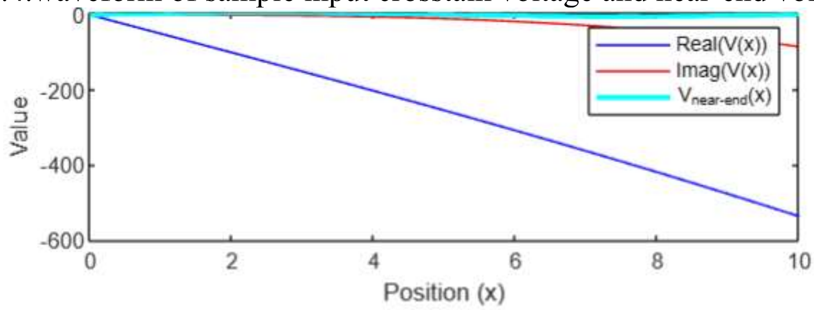
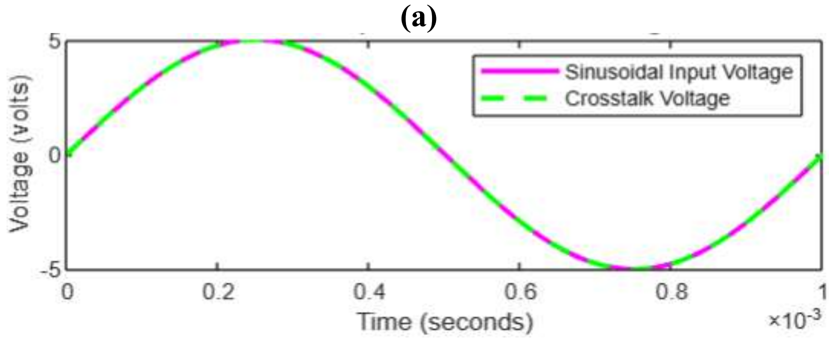


Fig.4.waveform of sample input crosstalk voltage and near-end voltage



(a)



(b)

Fig.5. (a) near-end voltage and timedomain solution (b) sinusoidal input and crosstalk volatge

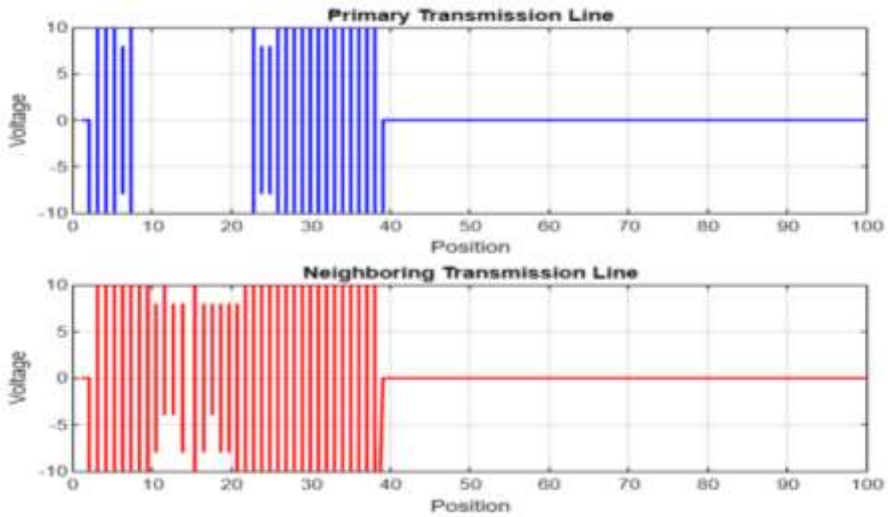


Fig.6. waveforms of primary and neighboring transmission lines

```
Time = 0.009 s, Inducted Voltage on Neighboring Line = 0 V
Time = 0.019 s, Inducted Voltage on Neighboring Line = 0 V
Time = 0.029 s, Inducted Voltage on Neighboring Line = 0 V
Time = 0.039 s, Inducted Voltage on Neighboring Line = 0 V
Time = 0.049 s, Inducted Voltage on Neighboring Line = 0 V
Time = 0.059 s, Inducted Voltage on Neighboring Line = 0 V
Time = 0.069 s, Inducted Voltage on Neighboring Line = 0 V
Time = 0.079 s, Inducted Voltage on Neighboring Line = 0 V
Time = 0.089 s, Inducted Voltage on Neighboring Line = 0 V
Time = 0.099 s, Inducted Voltage on Neighboring Line = 0 V
Near-End Voltage on Neighboring Line: 0 V
Crosstalk: 0 V
```

Fig.7. display of command window

V. Practical Utility and Scalability

The practicality and scalability of the suggested methodology and algorithms in actual electronic circuit design and optimization are highlighted in this study. The approach is applicable to a wide range of networked RLC circuits, including intricate designs with different coupling effects. The scalability of the methods guarantees effective computation in large-scale systems. Effective solutions are provided for real-world issues like impedance control, transient behavior prediction, and crosstalk mitigation. The methodology supports the design of dependable electronic systems that satisfy performance requirements through simulations and validations. Because of its scalability, it can be easily integrated into current design workflows, greatly assisting in the maintenance of signal integrity and promoting the creation of effective electronic systems for contemporary technology.

VI. Conclusion

This paper presents a model that uses MATLAB to combine numerical Inverse Laplace Transform (NILT) with RLC circuit analysis. It properly captures characteristics such as crosstalk and impedance variations in its analysis of linked interconnects. Time-domain response analysis, which is essential for comprehending transient behavior in electronic systems, is improved by NILT. Since accurate and fast calculation are guaranteed by efficient algorithms, the model can be used in real-world situations. Its demonstrable scalability and practical utility improve electronic circuit design and optimization. Overall, this study contributes greatly to signal integrity management, offering more dependable and efficient electronic systems.

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Bibliography

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