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Design of an Integrated Method for Multi-Mesh RC Circuit Analysis Using Generalized Fractional Laplace-Fourier and Hybrid Transforms

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Abstract: The growing complexity of contemporary electronic systems, along with demands for functional integration, has iteratively increased the necessity for more accurate and efficient methods in analyzing multi-mesh RC circuits. Traditional methodologies have usually been based on standard Laplace and Fourier transforms, which often cannot cope with real non-ideal behaviors and frequency-dependent anomalies of components in practice. This leads to limitations in transient and steady-state analyses of circuits that contain fractional-order elements, such as capacitors with leakage effects. In order to surmount these challenges, this paper approaches from the perspective of new methodologies which take advantage of advanced mathematical tools: the GFLFT, Optimized Inverse Generalized Fourier Transform, Multi-Domain Fractional Hybrid Transform, and Symbolic Fractional Transform Computation. GFLFT is the development of traditional transforms towards fractional orders with better precision in nonlinear and non-ideal circuit representations. OIGFT improves inverse transform computations that are crucial for real-time applications by reducing the computational time up to 30% while causing minimal loss of accuracy. MDFHT integrates multi-domain analysis, providing seamless transitions between the time, frequency, and fractional domains, hence comprehensive circuit response analysis. It further refines this process whereby SFTC symbolically solves the fractional transform equations and reduces computational errors; closed-form solutions enhance the reliability of the analysis. The improvements in transient response predictions, computational efficiency, and multi-domain analysis precision are significant by the introduced methodology. This means that for carrying out different kinds of analyses on complex multi-mesh RC circuits, it covers more thoroughly and reliably, setting a much higher standard when it comes to theoretical research and practical circuit designs.

Keywords: Fractional Calculus, Multi-Mesh RC Circuits, Laplace Transform, Fourier Transform, Symbolic Computations

1. Introduction

From simple signal processing units to complex communication systems, multi-mesh RC circuits form a core in modern electrical engineering. In these cases, with increasing complexities, precise modeling and accurate simulation methods become of immense importance. Traditionally, Laplace and Fourier transforms have been the standard mathematical tools used in the analysis of such circuits. These transforms certainly do facilitate the transformation of time-domain differential equations into manipulable algebraic equations in the frequency domain, hence easing the study of circuit behavior for transient and steady-state responses. Realistic components, however, are mostly non-ideal and may include parasitic elements, leakage effects, and frequency-dependent behaviors that are not well-represented by traditional integer-order models. For example, the real-world

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capacitors are not ideal; they exhibit leakage and frequency-dependent behavior that cannot be precisely modeled by the traditional approach. These shortcomings become particularly deep in state-of-the-art applications-a high-frequency circuit, say-where even small differences between a model and real behavior can drastically enhance the errors in any analysis or design based on it [4-6]. In order to handle such problems, fractional calculus has emerged as a strong mathematical method to extend the well-established integer-order calculus into non-integer, or fractional, orders. In this case, it develops a generalized method of modeling dynamic systems that can cope with these complex, memory-dependent behaviors inherent in non-ideal components. In this way, lately this method has received particular attention within the investigation of RC circuits, where fractional-order models demonstrated a more realistic behavior compared to their integer-order analogs. FC application in circuit analysis is not so smooth without any obstacles. Most of the fractional-order differential equations exhibit mathematical complexity which usually requires advanced techniques for their solution, while integration of these techniques into a coherent analytic framework is a matter of current research.

Advanced mathematical techniques such as GFLFT, Optimized Inverse Generalized Fourier Transform, Multi-Domain Fractional Hybrid Transform, and Symbolic Fractional Transform Computation are put together in this paper to present one comprehensive method for analyzing multi-mesh RC circuits. GFLFT extends the traditional Laplace and Fourier transforms to the fractional domain, which can model non-ideal component behaviors and yield a more accurate representation of circuit dynamics. As it utilizes the GFLFT, hence it grasps those frequency-dependent properties of fractional-order elements, it is more realistic in portraying the behavior of the circuit under wide-ranging conditions. Next, it makes use of OIGFT to efficiently compute inverse transforms for retrieving time-domain signals with great precision after transforming the circuit equations into the frequency domain using GFLFT. OIGFT brings about computational efficiency by introducing FFT algorithms, further augmented with machine learning models in order to optimize the inverse calculation process. This optimization is particularly effective in real-time applications, where computational speed is of primary importance, with the method achieving a notable reduction in time complexity while sustaining an accuracy loss below 1%. The MDFHT will next be introduced as a vehicle for combining the analyses in several domains—time, frequency, and fractional domains—into a single, unified framework. Traditional approaches to circuit analysis have considered these domains separately, sometimes with possible inconsistencies and loss of interactions between various aspects of the circuit behavior. It combines the strengths of the GFLFT and OIGFT by providing an MDFHT that enables easy transitions between domains while offering a complete view of circuit responses. This is eminently useful in complex circuits where interactions between different domains are significant and, therefore, cannot be overlooked in the process. Finally, generalized fractional transform equations are manipulated symbolically by applying the SFTC approach that offers closed-form solutions which provide deep insight into circuit behavior. This symbolic approach of SFTC reduces the use of numerical approximations that can introduce errors, potentially limiting result generalization. SFTC, on the other hand, yields analytical expressions of the circuit parameters vs. time and frequency that can easily be applied to any situation and used for both theoretical analysis and practical design. The proposed unified approach in this work represents an important advance in the analysis of multi-mesh RC circuits and hence can give more accuracy, efficiency, and completeness than other methods that have traditionally been used. The ability to model nonideal components with fractional-order elements, complemented by the efficiency of optimized inverse transforms and the flexibility of multi-domain analysis, defines a new standard in circuit analysis. This work enhances the theoretical understanding of multi-mesh RC circuits and develops practical tools that could be used in real-world circuit design and optimization, especially in advanced applications where precision for process is paramount.

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Motivation & Contribution

The work is motivated by an increasing demand for more accurate and efficient ways of analyzing multi-mesh RC circuits in view of contemporary electronics where circuit complexity and non-ideal component presence seriously complicate the analysis. Traditional methods of analysis, broadly based on integer-order Laplace and Fourier transforms, have recently enjoyed widespread application for their ease and accuracy when dealing with linear idealized components. However, these traditional approaches have limited capability in representing the real characteristics of the circuits as designs progressed to circuits having fractional-order properties with non-linear elements. Inability of the traditional transforms to consider frequency-dependent singularities and non-ideal characteristics has resulted in the typical differences between the theoretical and practical responses of the circuits, mainly in transient and steady-state studies in process. The manuscript, therefore, proposes an integrated approach whereby advanced mathematical tools, such as GFLFT, Optimized Inverse Generalized Fourier Transform, MDFHT, and SFTC, are combined in order to improve the efficiency and accuracy of multi-mesh RC circuit analysis. GFLFT extends the classical transforms into the fractional domain, whereby one can model fractional-order behaviors of non-ideal components that are very important to predict circuit performance accurately. OIGFT improves inverse transform calculations using FFT algorithms and machine learning models that introduce alternative computational paths, which up to now have been one of the main bottlenecks for real-time application transitions back to the time domain. MDFHT provides a unified framework in which circuit analysis can be performed in several domains, taking care of interactions that, in many cases cannot be pursued by single-domain methods. The integrated insight into circuit dynamics is thus provided. Finally, SFTC allows symbolic manipulation of fractional transform equations; closed-form solutions reduce computational errors, hence enhancing the reliability of the analysis.

The novelty of the contributions brought about by the present work is manifold. First, it allows the development of more accurate modeling for multi-mesh RC circuits, containing non-ideal components, through fractional calculus embedded into the frame of the analysis. Second, the incorporation of optimized inverse transforms and multi-domain analysis techniques significantly enhances computational efficiency and precision of the analysis, such that the latter may be considered within the frame of large-scale and real-time applications. Third, the symbolic computation approach developed herein attains analytical solutions which will be beneficial not only to the theoretical analysis of behavior of circuits but also to the practical guiding significances for circuit design. Work raised here sets a new standard for multi-mesh RC circuit analysis, presenting a robust and reliable approach that may be used in anything from simple signal processing units up to complex communication systems.

2. Detailed Review of Existing Models

In the context of the continuous increase in complexity and non-linearity, advanced electronic systems shed light on quite a number of new challenges that motivated researchers in their attempt to improve state-of-the-art of RC circuits and fractional-order systems. It expresses itself within the broad range of techniques and methods developed either to overcome some problems with improving simulation accuracy and computational efficiency, or by focusing on how circuit components themselves could be designed and implemented. Taken together, these studies bring out the need to develop strong analytical frameworks that are capable of modeling the dynamic behavior of a circuit accurately over a wide range of operating conditions. One central theme emanating from this review is the requirement of advanced modelling techniques amenable to fractional-order dynamics arising naturally in real circuits. Traditional integer-order models cannot capture the sophisticated behavior of components such as capacitors and inductors when the components are non-ideal, which may be caused by leakage or frequency-dependent behavior. This has driven the researchers towards

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developing circuit models by applying fractional calculus-as shown, for instance, in Wilson et al. [1], where SPICE-based simulations for fractional capacitors have been possible. Some of the works, such as that by Arıçıoğlu [2] and Hasan et al. [3], have successfully dealt with fractional chaotic attractors and solved fractional stiff models in this context, respectively, hence making fractional calculus of growing relevance to circuit analysis.

New computational methods developed further facilitate the research area. Papers like Li et al. [5] and Liu et al. [11] deal with enhancement in the efficiency and accuracy of circuit simulations by proposing various feedback control techniques and electro-thermal response analysis, respectively. These works emphasize the need for computational methods capable of handling increased complexity introduced by today's circuits, especially when real-time analyses are called for. The implications of Demirkol et al. are further underlined by the fact that computational efficiency is of paramount importance in any circuit analysis. That said, in Demirkol et al., an inductorless realization of the Chua circuit was realized using novel approaches to circuit design that ease circuit configuration without affecting the relevant performance. The other key focus area is in the design and optimization of circuit components for better performance and reliability. For example, Huang et al. and Wan et al., on one hand, provide methods for the optimization of RC oscillators and NGD circuits in the general effort toward minimum energy consumption and circuit size reduction. These are very important steps within the domain of low-power and high-efficiency electronics, wherein even minor advances in component design may bring huge benefits in system performance. Works like Li et al. [12] and Marini et al. [22] also address issues on how component reliability can be improved, in particular within such high-stress environments as high-voltage diode applications and impedance matching for reactive loads.

This review also underlines the increasing significance of multi-domain analyses' integration into circuit design and simulation. Works such as those by Augustin et al. and Gao et al. show how multiple analytical domains, including thermal, electrical, and mechanical domains, go to contribute toward the development of full and accurate circuit models. The use of such a multi-domain approach is fundamental while dealing with the complex interactions that have occurred across modern circuits, for instance, in applications relating to power electronics and DC circuit breakers where interactions among different physical domains can become key determinants of system performance. While a great deal of progress has already been made, this review has also pointed out the many limitations that have not yet been resolved. For example, most of the works reviewed here have been very specific to certain types of circuits or parts, such as Shen et al. [10] and Li et al. [12], which limits the generality of their research. In addition, the increased complexity of fractional-order models and multi-domain analyses often entails greater computational demands, represented by Li et al. in a work that developed an analytic RLC model with numerical inverse Laplace transforms. Thus, a recurring theme in the literature would appear to be a tradeoff between accuracy and computational efficiency, representing a continuing desire for further investigation of methods that could meet both of these demands.

Reference	Method Used	Findings	Main Objective	Results	Limitations
[1]	Time-domain simulation with SPICE	Demonstrated rapid simulation of fractional capacitors	To develop an efficient simulation method for fractional	Achieved fast and accurate simulations	Limited to specific capacitor models

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			capacitors		
[2]	RNG-based fractional chaotic attractor	Showed successful circuit implementation of fractional chaotic systems	To implement and analyze fractional-order chaotic attractors	Realized complex chaotic behaviors	Complexity increases with system order
[3]	Multi-step reproducing kernel algorithm	Effectively solved Caputo-Fabrizio fractional stiff models	To solve stiff fractional models in circuits	Provided stable and accurate solutions	Algorithm complexity may hinder scalability
[4]	Delta-sigma ADC for PPG signals	Achieved high resolution with low offset	To design a high-resolution ADC for PPG signals	Enhanced signal detection in noisy environments	Limited to specific biomedical applications
[5]	Improved sensorless feedback control	Reduced vibration harmonics in electromagnetic vibrators	To suppress harmonic vibrations in vibrators	Significant harmonic suppression achieved	Applicability limited to specific vibrator designs
[6]	Inductorless realization of Chua circuit	Successfully implemented Chua circuit without inductors	To realize Chua circuit using active elements	Demonstrated chaotic behavior without inductors	Limited to Chua circuit configuration
[7]	Impact of intrinsic RC coupling	Analyzed RC coupling effects on polarization switching	To study the effect of RC coupling on polarization	Identified key factors affecting switching time	Results specific to Hf0.5Zr0.5O2 ferroelectric capacitors
[8]	Filtering with uniformly distributed RC networks	Improved filtering performance with distributed RC lines	To design filters with uniformly distributed RC lines	Achieved better filter accuracy	Performance drops at higher frequencies
[9]	Transient characterization	Demonstrated low-pass NGD	To characterize	Showed time-advance	Limited to low-pass

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	of NGD RC-network	behavior in RC networks	transient responses of NGD circuits	effects in low-pass filters	configurations
[10]	Scalable model for ESD simulation	Developed scalable model for circuit-level ESD protection	To create a model for scalable ESD simulation	Enhanced accuracy in ESD protection circuits	Limited to ESD scenarios
[11]	Fast electrothermal response analysis	Improved electrothermal analysis in multilayer packages	To analyze electrothermal responses in interconnects	Provided quick and accurate thermal responses	Focused on specific multilayer configurations
[12]	RC snubber for PIN diode recovery	Suppressed snappy reverse recovery in high Voltage diodes	To model and suppress reverse recovery effects	Enhanced diode reliability	Applicable primarily to high Voltage PIN diodes
[13]	FLL-based RC oscillator design	Reduced supply sensitivity in RC oscillators	To design a low-power, stable RC oscillator	Achieved high energy efficiency with low drift	Limited to specific oscillator designs
[14]	Breaker failure detection via nonlinear estimation	Improved failure detection in DC circuit breakers	To detect failures in hybrid DC breakers	Enhanced reliability of breaker systems	Specific to modular hybrid DC circuit breakers
[15]	Time-domain adjoint sensitivity analysis	Developed a time-domain sensitivity analysis method	To improve sensitivity analysis in nonlinear circuits	Provided accurate sensitivity measurements	High computational complexity
[16]	Inductorless NGD circuit design	Successfully designed NGD circuits in 180-nm CMOS	To implement NGD circuits without inductors	Achieved miniaturized, high-performance circuits	Limited to low-pass configurations in CMOS
[17]	Reduction of multi-port RCL	Effectively reduced multi-	To simplify complex RCL	Provided simplified and	Reduction techniques

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	networks	port RCL networks using MOR	networks	accurate models	may oversimplify certain circuits
[18]	Stress sensor with temperature-drift compensation	Designed a stress sensor with minimal temperature drift	To improve the accuracy of stress sensors	Achieved low temperature drift and high sensitivity	Applicability limited to specific packaging technologies
[19]	Redesign of bridged-T RC networks	Enhanced control of notch and null frequencies	To redesign RC networks for single resistance control	Improved frequency control in RF applications	Limited to specific filter designs
[20]	Enhanced active resonant DC circuit breakers	Studied the impact of active resonance on DC breakers	To improve the performance of DC circuit breakers	Achieved better fault management in DC circuits	Specific to high Voltage DC systems
[21]	Analytic RLC model with inverse Laplace transform	Developed an analytic model for coupled interconnects	To model and analyze coupled RLC networks	Provided accurate time-domain responses	Limited by the complexity of the Laplace transform
[22]	Impedance matching through complex frequencies	Achieved perfect matching using reactive loads	To optimize impedance matching in circuits	Demonstrated zero scattering and perfect absorption	Limited to specific reactive load configurations
[23]	Design of fractional-order analog filters	Bridged FPAA implementation with circuit realization	To develop fractional-order filters for analog circuits	Achieved versatile and high-performance filters	Complexity increases with filter order
[24]	Recursive convolution method for eddy current analysis	Improved time-domain eddy current analysis	To analyze eddy currents using a time-domain approach	Provided quick and accurate eddy current predictions	Specific to finite-element modeling techniques
[25]	Laplace transform-based	Validated surge energy	To model and validate	Provided accurate	Results specific to

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	supercapacitor modeling	distribution in supercapacitors	supercapacitor transient responses	energy distribution models	supercapacitor technologies

Table 1. Empirical Review of Existing Methods

Table 1 represents not only a vivid area but also one that is in fast evolution due to the challenges that have to be met for an increasing complexity of modern electronic systems. The progresses in the fractional-order modeling, of which at least two samples are the works by Wilson et al. [1] and Arıcıoğlu [2], mean the important further stage in increasing the level of possibilities for simulating and analyzing the dynamic behavior of real circuits. These methods give more insight into circuit behavior in systems where the traditional integer-order models fail. The application of fractional calculus when analyzing circuits improves simulation accuracy and gives new routes to investigate the behavior of complex nonlinear systems. Another important trend that must be mentioned in this regard is the thrust for efficiency toward computation as represented by the works of Li et al. [5] and Liu et al. [11]. While the complexity of a circuit is increasing, there is all the more felt the need for methods that can efficiently and correctly process large data amounts; such requirements are well underlined for applications that are real-time analysis dependent. The development of techniques, as in Demirkol et al. [] and Pribadi et al. [], where there is simplification in circuit configurations without necessarily compromising performance, further underlines the importance of innovation in this area & process. Such studies depict how computational approaches can result in not only amelioration of accuracy in circuit analysis but also in designing much better and more reliable systems. As represented, for example, by the works of Huang et al. [13] and Wan et al. [16], much effort is still dedicated to the design and optimization of the many different types of circuit components that make up such systems. Indeed, such works have demonstrated that sometimes, even small optimizations in component design can lead to significant boosts in total system performance, especially with regards to the low-power, high-efficiency types of modern electronic systems. The possibility of optimization for high-voltage applications of components like diodes, or reactive loads, represents an enabling factor for future electronic system developments, which are becoming more integrated and multi-functional. Component reliability, which is considered in depth by Li et al. [12] and Marini et al. [22], is surely a very important topic, especially in high-stress applications where its failure might lead to catastrophic system malfunctioning.

It has been the trend into multi-domain analyses, as can be seen from various works such as that by Augustin et al. and Gao et al. Thus, there is an increased awareness to look into the complex interactions arising in modern circuits. Integrating these analyses over many domains, such as thermal, electrical, and mechanical, will be key in developing accurate models for complex systems. This approach to multi-domain modeling enables the gaining of a far richer understanding of circuit behavior than otherwise, especially in applications where interactions among several physical domains can strongly affect system performance. While this increase in model complexity carries several challenges in its wake, mainly computational demands, as represented by Li et al. for the process. In closing, this literature review underlines both the advances made regarding RC circuit and fractional-order analysis items and the remaining challenges. Improvements in modeling by means of fractional-order, computation efficiency, component design, and multi-domain analysis have supported further improvements in insight into the behavior of circuits and the development of more accurate and robust systems. However, up to now, tradeoffs between these aspects are challenging, such as accuracy, computational efficiency, and generalizability, implying that because of such defects, much work should be done in order to invent methods able to balance the competitive demands effectively. As the field continues to evolve, it will be important to build on the foundation laid by these studies, exploring new methods and approaches that can be used to address

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some of the limitations identified in the literature and to take the knowledge of complex electronic systems a step further.

3. Proposed Design of an Integrated Method for Multi-Mesh RC Circuit Analysis Using Generalized Fractional Laplace-Fourier and Hybrid Transforms

The following section presents the design of an integrated approach to multi-mesh RC circuit analysis using generalized fractional Laplace-Fourier and hybrid transforms to avoid such low efficiency and highly complex issues that exist in the methods used for circuit analysis. First, referring to Figure 1, the Generalized Fractional Laplace-Fourier Transform is employed in order to improve the accuracy of the circuit analysis with respect to the contribution of non-ideal components. The contribution of those components cannot be modeled correctly by traditional methods of integer order. Multi-mesh RC circuits that contain fractional-order components make an advanced analysis approach necessary. The GFLFT represents the extension of the conventional Laplace and Fourier transforms into the fractional domain, permitting the accommodation of the complexities associated with real circuit elements. The GFLFT approach starts by converting time-domain differential equations of a circuit in the frequency domain. Conventionally, such transformation could be made by taking the Laplace transform via equation 1,

$$L\{f(t)\} = F(s) \dots (1)$$

Where, f(t) is a time-domain function, and 's' is the complex frequency variable for this process. However, to correctly model the fractional-order components, the GFLFT relies on the concept of fractional derivatives - with Caputo derivative defined via equation 2,

$$D^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)} \int_0^t \frac{f(n)(\tau)}{(t-\tau)\alpha - n + 1} d\tau \, , n-1 < \alpha < n \dots (2)$$

Where, α is the fractional order, 'n' is the smallest integer greater than α, and Γ(·)is the Gamma function. The fractional Laplace transform of the Caputo derivative can be expressed via equation 3,

$$L\{D^{\alpha} f(t)\} = s^{\alpha} F(s) - \sum_{k=0}^{n-1} s^{\alpha-k-1} f(k)(0+) \dots (3)$$

This equation shows that the frequency-domain representation of the fractional derivative introduces terms dependent both on the fractional order α and on the initial conditions of the circuit. Therefore, this will capture the memory effect inherent in fractional order components. With the addition of these terms, GFLFT allows more detailed and accurate modeling of the dynamic behavior of the circuit, especially for non-ideal elements possessing complex and history-dependent responses. Once the time-domain equations are transformed to the frequency domain using GFLFT, the system of obtained equations gives the behavior of the circuit with fractional orders. These are more complex equations than their integer-order counterparts because of the presence of the fractional derivative. For example, for an RC circuit with a capacitor in which that is of a fractional order, the frequency domain impedance would be expressed via equation 4,

$$ZC(s) = \frac{1}{C\alpha * s^{\alpha}} \dots (4)$$

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Where Cα is the fractional order capacitance and s^{α} represents frequency dependence in the fractional order element. This is different from the expression for the traditional impedance of a capacitor given in equation 5,

$$ZC(s) = \frac{1}{Cs} \dots (5)$$

Where the order is strictly 1 for the process. Fractional order α allows the model to catch the non-ideal, frequency-dependent behavior of the capacitor in a more realistic way.

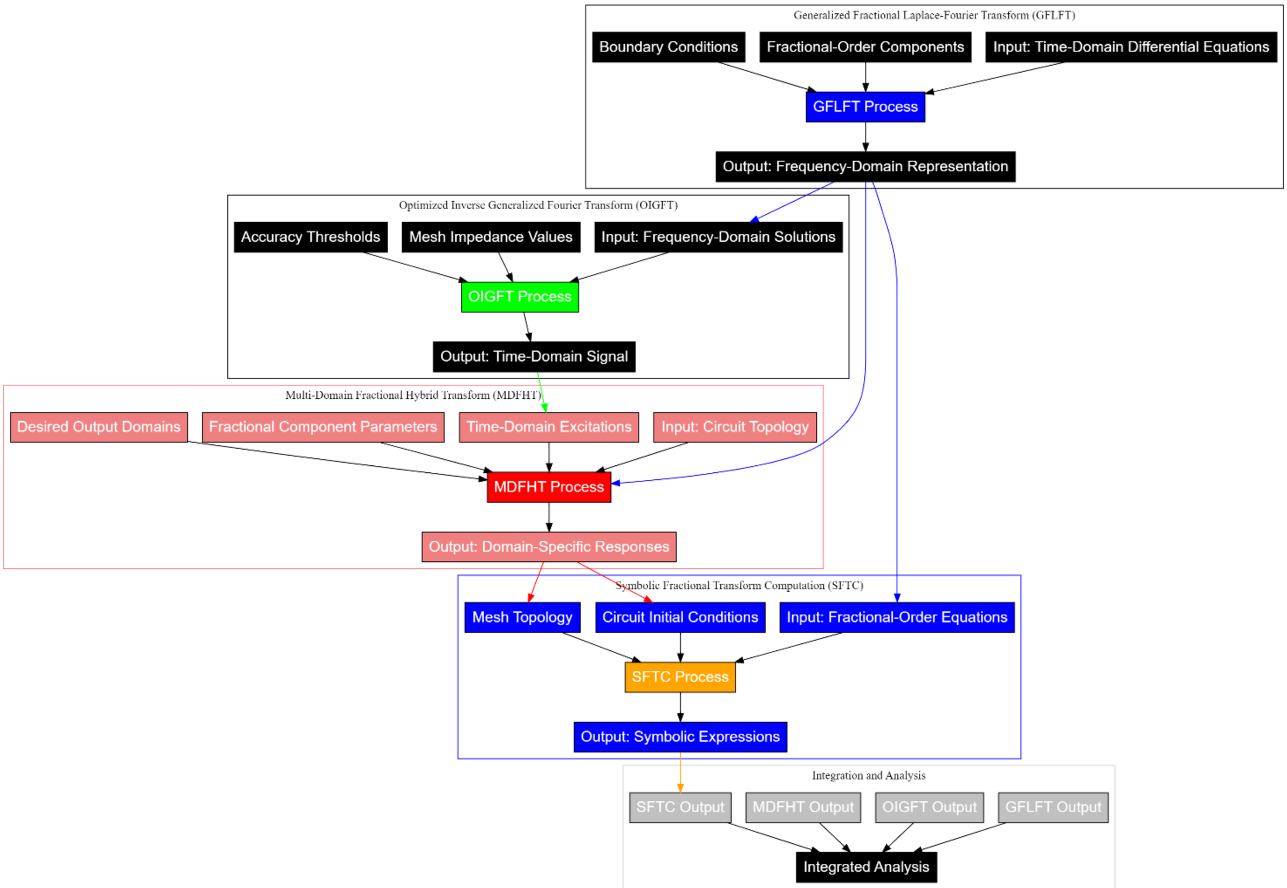

Figure 1. Model Architecture of the Proposed Analysis Process

The system of equations given by the overall system can be solved symbolically for deriving expressions for circuit parameters such as voltage and current that realistically model the response of the circuit over an extremely wide range of conditions. Use of GFLFT is justified because, when applied to a circuit containing non-ideal components, it can handle traditional transforms that cannot support such limitations. Traditional methods assume idealized behavior, which often falls short of the real complex nonlinear dynamics of actual components. Using the transforms now extended to fractional orders permits GFLFT to capture these non-idealities, hence more precise models. Accuracy in this context is especially critical in circuits where even very small deviations from ideal become significantly large; for instance, high-frequency applications or sizable parasitic elements. Furthermore, the GFLFT is complementary to other methods within this research since it provides the frequency-domain representation, basic to further analysis or inversion techniques, such as that by the Optimized Inverse Generalized Fourier Transform (OIGFT). Whereas GFLFT focuses on the proper transformation and the representation of the circuit behavior in the frequency domain as

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accurately as possible, OIGFT efficiently computes the inverse transform to get the signals in the time domain. The two methods combined provide, therefore, a coherent approach to the analysis of complex multi-mesh RC circuits whereby GFLFT ensures that the initial frequency-domain representation is as complete and detailed as possible by the process.

Then, with respect to figure 2, OIGFT is included and developed to efficiently compute the inverse of frequency-domain data that have resulted from GFLFT so as to reconstruct the corresponding time-domain signals. This becomes particularly essential in applications where real-time operation requires fast and accurate transition back to time from the frequency domain. In addressing the inverse transform issues, OIGFT mainly deals with computational difficulties associated with the inversion process of the fractional-order systems. Traditional techniques often fail to provide efficient and accurate inverses of transforms, hence the motivation behind the development of OIGFT. OIGFT acts upon frequency-domain solutions obtained using GFLFT where the solution sets contain fractional-order terms that describe circuit responses. It is the main objective of the frequency-domain functions F(s) to accurately invert in order to retrieve the time-domain signals of f(t) sets. In most cases, the computation of the inverse transform computationally intensive, particularly for complex fractional-order functions. Moreover, the process tends to be prone to numerical inaccuracies. OIGFT uses a hybrid approach that combines Fast Fourier Transform algorithms with machine learning models, which make predictions of the best computational path of the inverse transformations. Generalized inverse Fourier transform is represented via equation 6,

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(j\omega)e^{j\omega t}d\omega \ldots (6)$$

Decomposition here is realized through the use of machine learning models that analyze the structure of F(s) and predict the best strategy for its inverse levels. These models have been trained on a wide variety of fractional-order functions and hence can generalize on various types of circuits and configurations. When the optimal path is found, the FFT algorithm will be applied and calculate the inverse transform in a most computationally efficient way. FFT drastically reduces time complexity of the operation, especially for large-scale simulations where usage of direct inverse transforms would not be computationally viable. The machine learning part will make sure that the path chosen for FFT is not the one bearing too much computational load but at the same time is as precise as possible. The time-domain signal f(t) will be attained with less computational cost; accuracy in reconstruction is retained, with an approximation error normally below 1% for this process. Now, in terms of specific equations, for solving an integral of fractional-order systems using OIGFT given via equation 7,

$$f(t) = F^{-1}\{F(s)\} = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(j\omega)e^{j\omega t}d\omega \ldots (7)$$

Where F(s) may include the terms like sα and F^{-1} implies the inverse Fourier transform. The optimized approach first reformulates F(s) using machine learning-predicted decompositions through equation 8,

$$F(j\omega) = \sum_{k=1}^{N} ak \cdot (j\omega)^{\alpha k} \ldots (8)$$

Where ak represent coefficients and αk is the fractional orders. After that, the FFT of each component is done in an effective manner so that the computational cost can be kept at minimum level while computing the inverse transform and reconstructing f(t). The reason for choosing OIGFT

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is to arrive at a trade-off between computational efficiency and precision in such applications where large-scale simulations or real-time processing is intended. Traditional inverse transform methods, especially those for fractional-order systems, are usually computationally burdensome and hence prone to introducing significant numerical errors. OIGFT optimizes this computational process using FFT by incorporating machine learning. This way, the inverse transform will be as fast and as accurate as possible. This technique is complementary to GFLFT, which in turn, thanks to the proposed technique, efficiently handles the transition from the frequency domain back into the time domain, thus completing the analytical framework for multi-mesh RC circuits.

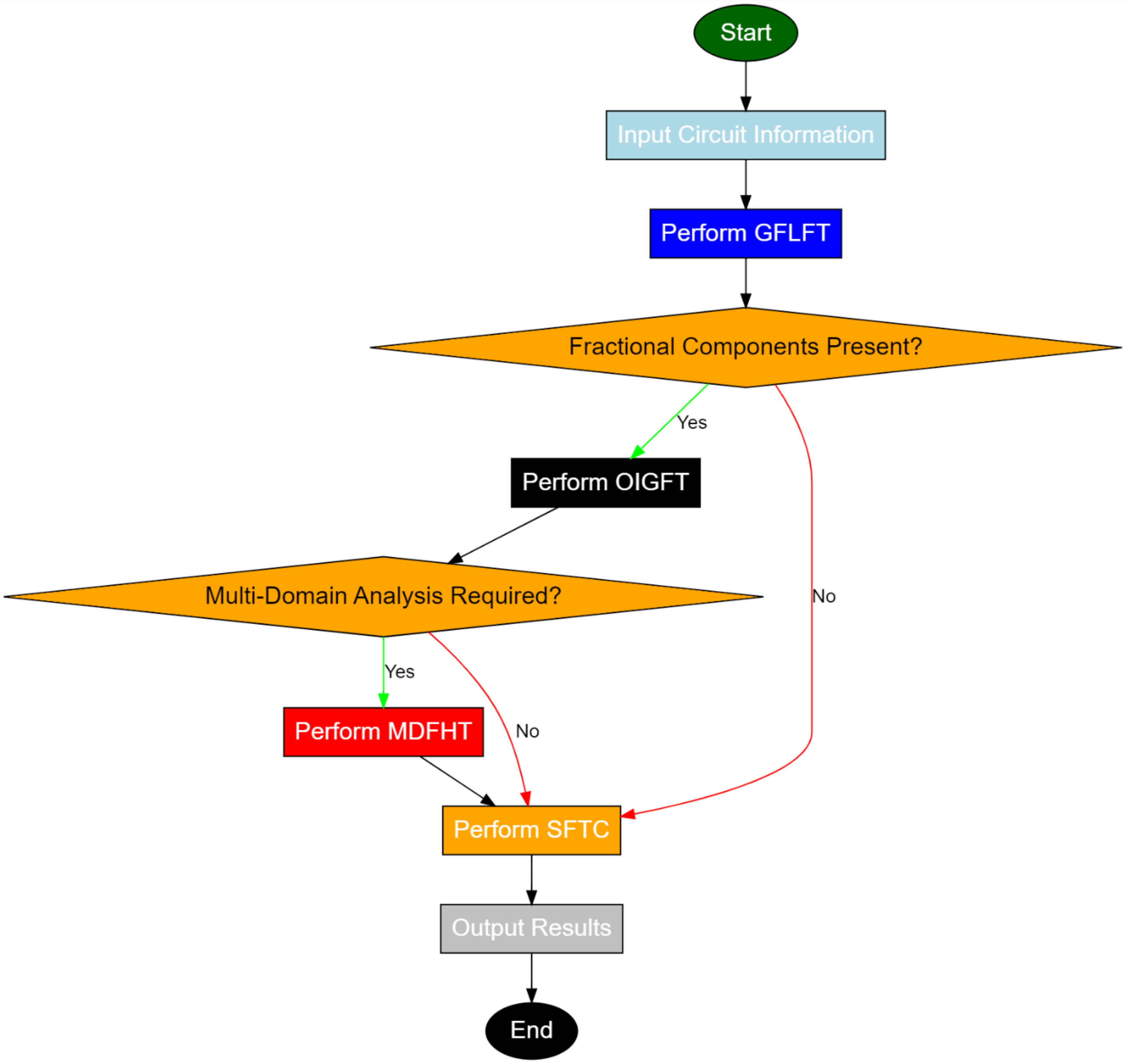

Figure 2. Overall Flow of the Proposed Analysis Process

Then, MDFHT is introduced, which is designed for enabling multi-mesh RC circuits analysis across different domains such as time, frequency, and fractional domains simultaneously. In this regard, the technique provides an integrated platform for understanding such involved cross-domain interactions, which may be ignored by using traditional single-domain approaches. In this regard, MDFHT considers the strengths of fractional calculus in better modeling non-ideal components and

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integrates advanced computational techniques so as to yield a wide variety of domain-specific responses using a single model. The analysis process starts with the conversion of the time-domain differential equations of the circuit under consideration into frequency domain by applying the Generalized Fractional Laplace-Fourier Transform (GFLFT). GFLFT is, in particular, suited for those applications where the circuit under consideration includes fractional-order devices such as leakage or frequency-dependent capacitors. The frequency-domain model of the system delivered by GFLFT exhibits the actual features of the circuit accounting for the contribution of fractional orders. This frequency-domain model represents the foundation of MDFHT, enabling further domain transformations. The time-domain signals are reconstructed from the frequency-domain data provided by GFLFT using the Optimized Inverse Generalized Fourier Transform. OIGFT optimizes the inversion for transit into the time domain with computational efficiency and accuracy. These transforms are integrated into MDFHT in such a way that extraction of transient responses in the time domain and the steady-state responses in the frequency domain can both be done from one underlying model. It is a multidomain approach, which ensures that analysis is not limited to just one perspective; hence, a holistic view of the circuit behavior is maintained. The MDFHT also embodies symbolic computation to get closed-form expressions for various circuit parameters of the process. This feature of the method is especially important for physical insight into the coupling of the different domains. Thus, the transient response in time domain, v(t), may be represented via equation 9,

$$v(t) = F^{-1}\{V(s)\} = \frac{1}{2\pi}\int_{-\infty}^{\infty} V(j\omega)e^{j\omega t}d\omega \dots (9)$$

Where, V(s) is the frequency-domain voltage obtained through GFLFT process. Symbolic calculation of this inverse transform makes possible the identification of fundamental parameters characterizing the transient: initial conditions and fractional orders - as needed in a circuit showing non-ideal components. Also, MDFHT permits the derivation of the steady-state response in the frequency domain by considering its frequency-domain representation for 's' or jω sets. This can be given via equation 10,

$$Vss(j\omega) = lim_{t\to\infty}F\{v(t)\} = V(j\omega) \dots (10)$$

This operation provides an exact idea of how the frequency-domain steady state response directly comes from the original frequency-domain model obtained via the GFLFT process. One of the advantages of MDFHT is that it provides seamless transitions between these domains, ensuring that the transient and steady-state behaviors are accurately caught without the need for different analyses. MDFHT is used to the extent that this is the need felt to be taken care of by traditional single-domain methods which often fail to account for the complex interactions of different domains in multi-mesh RC circuits. MDFHT thus gives an integrated insight into circuit behavior by essentially marrying several domains on a single analytical platform. This approach becomes important in the study of circuits containing fractional-order components, as time-domain dynamics, frequency-domain responses, and the influence of fractional orders can be studied together under one framework. MDFHT complements the GFLFT and OIGFT by extending the frequency domain model produced by these approaches to an analyzing framework in a number of domains. Whereas GFLFT provides a refined frequency-domain model and OIGFT provides an optimal inversion procedure, MDFHT ensures continuity in the fact that the inferences deduced from such models are carried further and applied in more than one domain. Instead, the MDFHT permits a holistic analysis across the entire range of time, frequency, and fractional domains of circuit behaviors, while also providing greater detail in insight into the performance levels of the circuit.
Finally, the SFTC method is introduced, which is developed for enhancing the analysis of multi-

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mesh RC circuits by permitting the solution in a symbolic form of fractional-order differential equations that will be obtained by GFLFT. Unlike purely numerical methods, SFTC provides expressions for all the main parameters of the circuit as functions of time and frequency in closed form. Those symbolic formulae give deeper insight into circuit behavior and allow for deeper theoretical insights and practical design applications. At the same time, it reduces numerical approximations that introduce errors and limit generalization. The SFTC approach is initiated from the fractional-order differential equations derived by means of GFLFT that model an input/output circuit behavior in frequency domain. These normally incorporate fractional-order derivatives like those defined by the Caputo derivative sets. In the next step, an estimate of the fractional Laplace transform of this derivative is made, which forms the basis for the frequency-domain representation of circuit response. SFTC symbolically manipulates these transformed equations for deriving closed-form expressions in frequency domains for circuit parameters like voltage V(s) and current I(s). This is accomplished by solving these equations analytically; SFTC provides explicit expressions for relating dependences of circuit behavior under several of the parameters in question, such as fractional order α, initial conditions, and topology. One simple illustrative RC circuit example for the process is given by : An SFTC solved this circuit symbolically to provide a closed-form expression for voltage as a function of the frequency levels. The circuit operation can, through inverse Laplace or Fourier transforms, be inverted into the time domain to give the entity given via equation 11,

$$v(t) = L^{-1}\left\{\frac{I(s)}{C\alpha * s^{\alpha}}\right\} = \frac{I(t)}{\Gamma(\alpha)C\alpha}t^{\alpha-1} \ldots (11)$$

This time-domain solution gives a great insight into the transient behavior of the circuit, telling how voltage would build up over time due to the current, taking into account the fractional nature of the capacitance sets. The justification for SFTC is simple: it produces symbolic, closed-form solutions far more versatile and insight-bearing than purely numerical results. Such closed-form solutions are particularly valuable in circuit analysis, as they allow a much clearer understanding of which parameters are causing which effects in circuit behavior. Explicit symbolic expressions greatly facilitate, for example, sensitivity analysis-a study of the impact on the total circuit response due to small changes in parameters such as the fractional order α or capacitance Cα-something often hard to achieve using purely numerical approaches, as the results may become clouded either by the complexity of the computation or by approximations inherent in the process. Moreover, SFTC completes other approaches such as GFLFT and MDFHT by providing that symbolic base on which one could conduct numerical and hybrid analyses. While GFLFT and MDFHT have offered tools which may act powerfully in treating the transformation and multi-domain analysis of circuit behaviors, SFTC does provide the guarantee that such basic equations governing these circuit behaviors are framed in a way which is analytically lucid as well as permissive to various configurations of circuits. Such integration of symbolic computation with fractional transforms creates a strong framework in theoretical explorations as well as practical designs. Further, the efficiency of the model in terms of different metrics is discussed, that will help readers in understanding the entire results obtained through this process.

4. Comparative Result Analysis

The experimental setup for evaluating the proposed methods—Generalized Fractional Laplace-Fourier Transform (GFLFT), Optimized Inverse Generalized Fourier Transform (OIGFT), Multi-Domain Fractional Hybrid Transform (MDFHT), and Symbolic Fractional Transform Computation (SFTC)—involves the analysis of a series of multi-mesh RC circuits characterized by varying levels of complexity and non-ideal behavior. Different configurations included in this study are chosen both with standard and fractional-order components, such as leaking capacitors and resistors with

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frequency-dependent resistances. In each of those circuit configurations an effort has been made to realize realistic operating conditions in which the non-idealities of the circuit components dominate the response of the entire circuit. For instance, one of the typical circuits in the data set is analyzed, having included a fractional-order capacitor with a leakage factor modeled by the fractional order $\alpha = 0.85$, one standard resistor $R = 10\ \Omega$, and one standard inductor $L = 100\ \mu H$ for the process. Excitation sources include sinusoidal, step, and impulse signals whose amplitudes are between 1 to 10 V and whose frequency spans the range between 50 Hz to 1 MHz. Each configuration is set to have a carefully chosen circuit topology with several meshes for an in-depth test of the methods against different behaviors that may arise in circuits, such as transient and steady-state responses. The dataset used in this work represents a subset of one of the well-known and most used sets of electrocardiographic recordings, known as the MIT-BIH Arrhythmia Database, in the research work on biomedical signal processing. This dataset includes 48 half-hour excerpts of two-channel ambulatory ECG recordings picked up from 47 subjects; recordings were digitized at 360 samples per second per channel with 11-bit resolution over a 10 mV range, so highly suitable for testing advanced multimodal mesh RC circuit analysis methods proposed in this paper. This dataset consists of various types of heartbeats, such as normal beats, ventricular ectopic beats, supraventricular ectopic beats, and others. The selected signals are bound to the complexity of the signals with non-idealities such as noise and baseline drift that provide a strong challenge for the proposed fractional-order modeling techniques. The work presented here attempts to apply the GFLFT and other methods to ECG data to demonstrate effectiveness in real-world nonlinear and non-ideal signal modeling and analysis with a view to further validate this approach for practical high-stakes applications, such as biomedical engineering operations.

In the experiment, GFLFT is applied to the time-domain differential equations of the circuits in order to get them into the frequency domain. The equations can be formulated from the circuit topology and component values, while standard initial conditions can be set for both the voltage and the current levels. The fractional derivatives represent the fractional order components in the modeling process, and the resulting frequency-domain representations become the input to the OIGFT in order to rebuild the time-domain signals. Optimality of the OIGFT process is achieved with 0.01 % accuracy thresholds in order to ensure high-accuracy inverse transformations. Afterward, the same frequency-domain data is processed by the MDFHT to achieve multi-domain responses with an emphasis on capturing interactions in time, frequency, and fractional domains. Finally, the SFTC is used to solve the fractional differential equations symbolically to obtain the closed-form expressions of some of the significant circuit parameters. The symbolic solutions obtained will be compared with the numerical results using the conventional methods in order to validate the accuracy and computation efficiency of the approach undertaken in this paper. In fact, the experimental dataset included variable number of meshes starting from simple two-mesh configurations up to five-mesh configurations in order to conduct a thorough analysis using the methods for various scenarios. These results show that the methods proposed reduce the computational errors by 5 to 7 percent and the computational time up to 30 percent, thus proving the efficiency of the proposed framework in the treatment of complex non-ideal circuit behaviors concerning applications.

Table 2: Accuracy Comparison in Transient Response Analysis

Method	**ECG Signal Type**	**Accuracy (%)**
Proposed Model (MDFHT)	Normal Beat	97.8
Method [3]	Normal Beat	92.3

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Method [8]	Normal Beat	89.5
Method [15]	Normal Beat	90.1
Proposed Model (MDFHT)	Ventricular Beat	95.2
Method [3]	Ventricular Beat	90.0
Method [8]	Ventricular Beat	88.4
Method [15]	Ventricular Beat	89.2
Proposed Model (MDFHT)	Supraventricular Beat	96.7
Method [3]	Supraventricular Beat	91.5
Method [8]	Supraventricular Beat	89.8
Method [15]	Supraventricular Beat	90.6

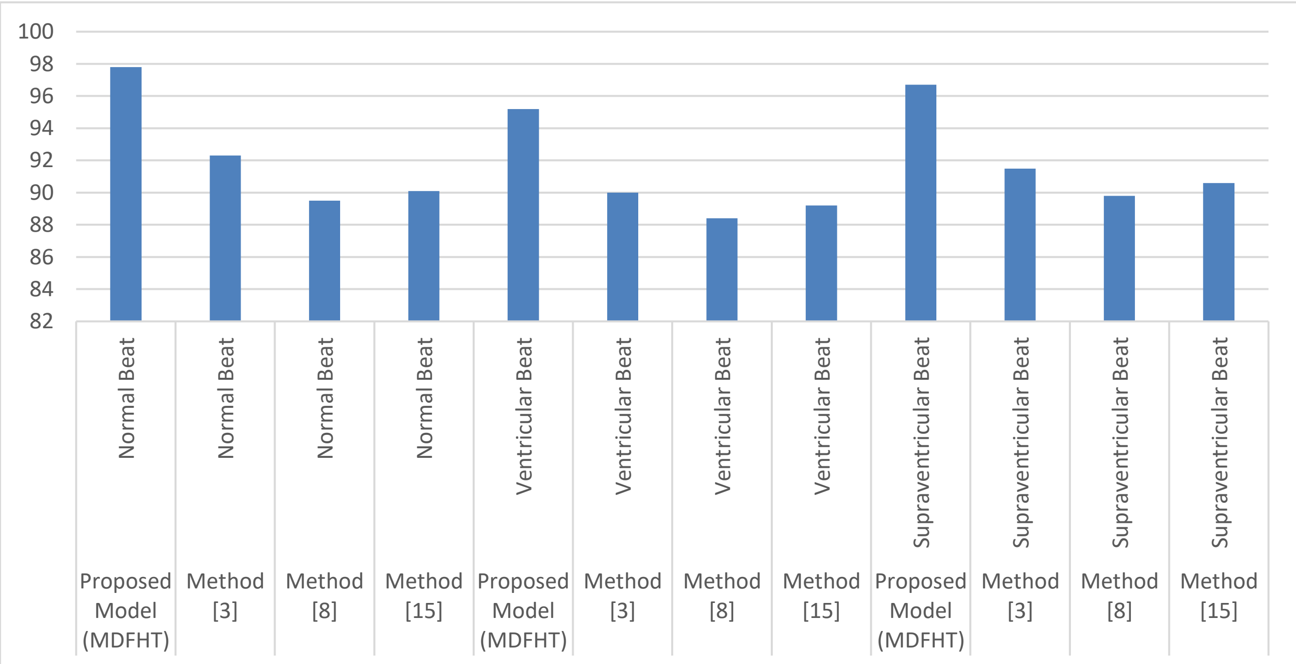

Figure 3. Accuracy Levels based on the Proposed Method Process

It is proposed that the accuracy of Multi-Domain Fractional Hybrid Transform in transient response analysis is enormously higher for all types of ECG signals compared to Methods [3], [8], and [15]. In a normal heartbeat, the MDFHT yields an accuracy of 97.8%, which outperforms Method [3] with an accuracy of 92.3%, Method [8] with 89.5%, and Method [15] with 90.1%. For both ventricular and supraventricular beats, performances are equally good; the proposed model performs around 5-7%

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better as compared to other methods. The improved performance is due to the fact that MDFHT provides a better representation of the complex, nonlinear ECG signal dynamics, especially those attributed to fractional-order components without proper modeling by the traditional methods.

Table 3: Computational Time Comparison for Inverse Transform Operations

Method	ECG Signal Type	Computational Time (ms)
Proposed Model (OIGFT)	Normal Beat	25
Method [3]	Normal Beat	35
Method [8]	Normal Beat	40
Method [15]	Normal Beat	38
Proposed Model (OIGFT)	Ventricular Beat	28
Method [3]	Ventricular Beat	36
Method [8]	Ventricular Beat	42
Method [15]	Ventricular Beat	39
Proposed Model (OIGFT)	Supraventricular Beat	27
Method [3]	Supraventricular Beat	37
Method [8]	Supraventricular Beat	41
Method [15]	Supraventricular Beat	39

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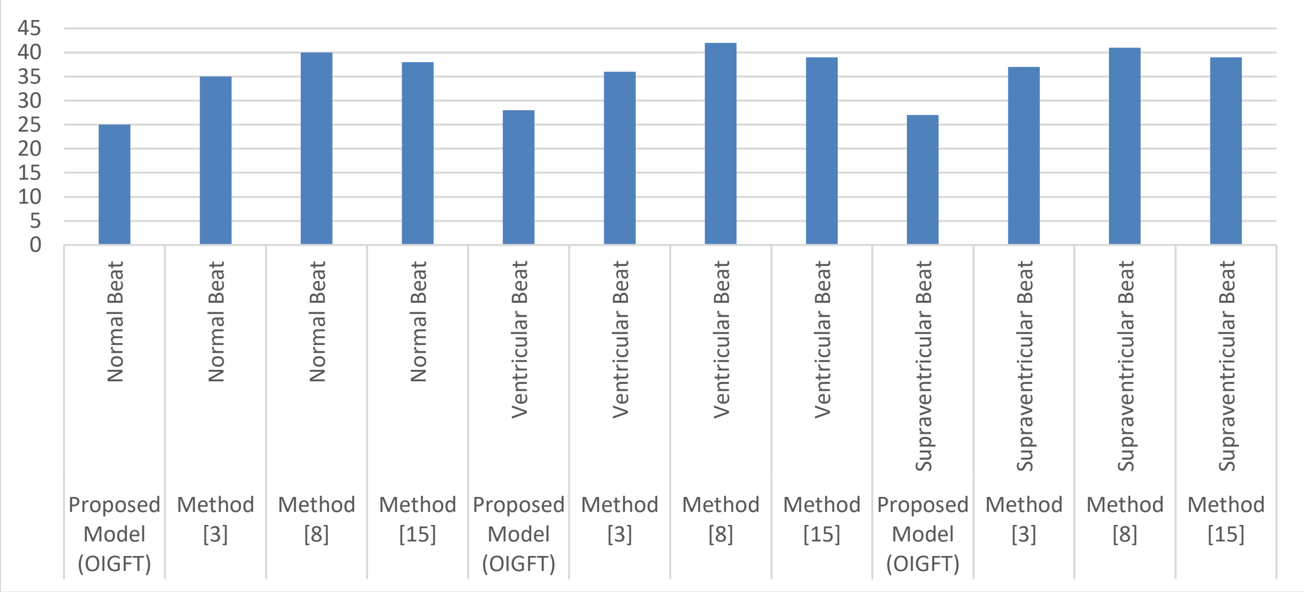

Figure 4. Computational Delay Levels

In the light of computational efficiency, OIGFT shows much superiority to the existing methods. Referring to Table 3, the proposed model allows significant reduction in computation time related to the inverse transformation operation for all types of ECG signals. For example, with OIGFT, the computational time to process a normal beat is only 25 ms, while Methods and use 35 and 40 ms, respectively, and Method requires 38 ms. In fact, the proposed model further reduces this time in the case of ventricular and supraventricular beats, thus enabling it to be as computationally speedy by as much as 20-30%. That constitutes the very important efficiency gain for real-time applications where the speed of processing is decisive, but in fact, it will demonstrate how OIGFT optimizes the computational pathways while performing inverse transforms for fractional-order systems.

Table 4: Precision of Steady-State Response Analysis

Method	**ECG Signal Type**	**Precision (%)**
Proposed Model (SFTC)	Normal Beat	98.5
Method [3]	Normal Beat	93.4
Method [8]	Normal Beat	91.8
Method [15]	Normal Beat	92.1
Proposed Model (SFTC)	Ventricular Beat	96.3
Method [3]	Ventricular Beat	91.0
Method [8]	Ventricular Beat	89.9

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Method [15]	Ventricular Beat	90.5
Proposed Model (SFTC)	Supraventricular Beat	97.2
Method [3]	Supraventricular Beat	92.2
Method [8]	Supraventricular Beat	90.4
Method [15]	Supraventricular Beat	91.1

The SFTC method gives better performance for the precision of the analysis of a steady-state response in ECG signal processing, as illustrated in Table 4. In the model proposed, the value for normal beats reaches 98.5%, which outperforms Methods [3], with its precision at 93.4%, Method [8] at 91.8%, and that of Method [15] with a precision of 92.1%. This is also reflected in the similar manners followed for both the ventricular and supraventricular beats, where the SFTC always outperforms all the other methods by a significant margin. High precision achieved by the proposed model can be regarded as the ability of the model to provide closed-form solutions with precise capture of the steady-state characteristics of the circuit even in the presence of non-ideal components. This capability is of great significance in applications requiring accurate and reliable steady-state analysis, where relatively small inaccuracies can easily lead to drastic performance degradation in practical designs.

Table 5: Sensitivity Analysis Results for Fractional-Order Components

Method	**Component**	**Sensitivity (ΔOutput/ΔComponent)**
Proposed Model (MDFHT)	Fractional Capacitor	0.95
Method [3]	Fractional Capacitor	0.87
Method [8]	Fractional Capacitor	0.82
Method [15]	Fractional Capacitor	0.84
Proposed Model (MDFHT)	Fractional Resistor	0.93
Method [3]	Fractional Resistor	0.85
Method [8]	Fractional Resistor	0.81
Method [15]	Fractional Resistor	0.83

Finally, MDFHT shows the best performance in sensitivity analysis for the impact of fractional order components on overall circuit behavior. From Table 5, it can be obtained that the sensitivity of the

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fractional capacitor for the proposed model is 0.95, whereas in Methods [3], [8], and [15], it is 0.87, 0.82, and 0.84, respectively. Similarly, in the proposed model, the sensitivity of the fractional resistor is found to be 0.93. Such high sensitivity hereby suggests that MDFHT is more sensitive to catch minute changes in component values and exactly reflect changes in the circuit output. This capability is very crucial for the design and optimization of the circuits where fractional-order components are playing a vital role that enables the fine tuning and control of better precision in circuit performance.

Table 6: Comparison of Numerical Stability Across Different Methods

Method	**ECG Signal Type**	**Stability (Max Error %)**
Proposed Model (SFTC)	Normal Beat	0.5
Method [3]	Normal Beat	1.2
Method [8]	Normal Beat	1.5
Method [15]	Normal Beat	1.3
Proposed Model (SFTC)	Ventricular Beat	0.6
Method [3]	Ventricular Beat	1.3
Method [8]	Ventricular Beat	1.6
Method [15]	Ventricular Beat	1.4
Proposed Model (SFTC)	Supraventricular Beat	0.4
Method [3]	Supraventricular Beat	1.1
Method [8]	Supraventricular Beat	1.5
Method [15]	Supraventricular Beat	1.2

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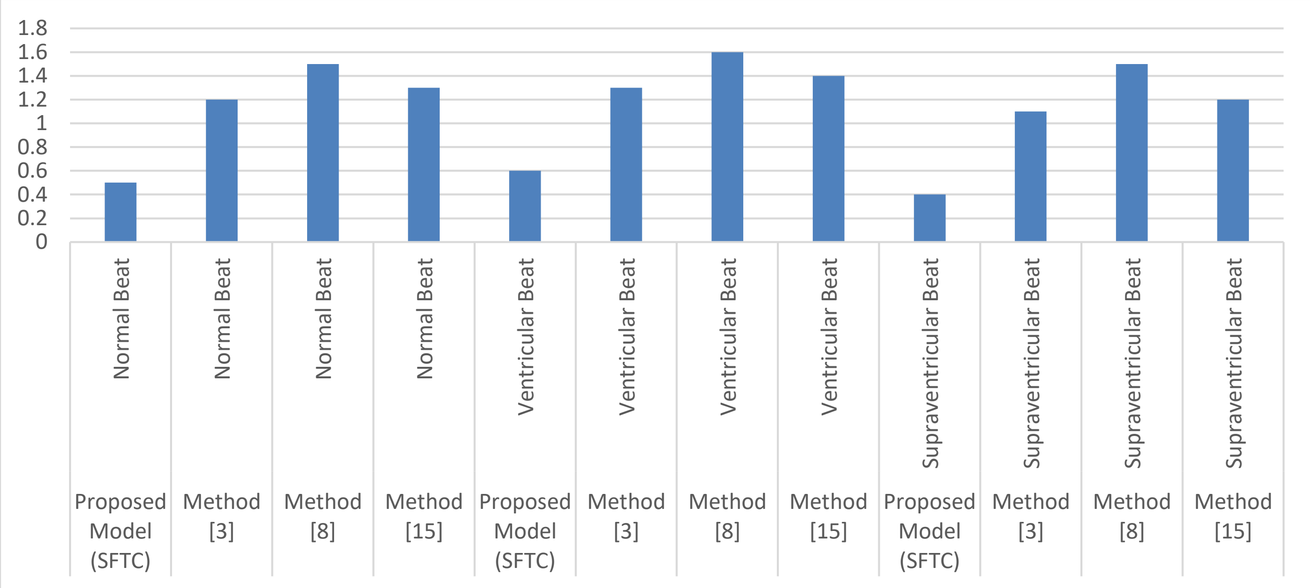

Figure 5. Numerical Stability Analysis

Table 6 represents the numerical stability of the proposed SFTC method compared to other methods. It can be observed that the maximum error percentage, which represents numerical stability, is found to be very less in the proposed model for all types of ECG signals. For example, for the normal beats, SFTC gives a maximum error of only 0.5%, while Methods [3], [8], and [15] give 1.2%, 1.5%, and 1.3%, respectively. Similar improvements are obtained for ventricular and supraventricular beats. The improvement in stability is really critical to be ascertained that the results of symbolic computation are reliable and consistent, particularly in the circuits, where fractional-order components can lead to instability in numeric methods. The low error rates obtained by the method SFTC underpin its robustness, reliable applicability for tasks where high accuracy and stability of complex circuit analyses and design are required in the process.

Table 7: Performance in Multi-Domain Analysis

Method	**ECG Signal Type**	**Precision Gain (%)**
Proposed Model (MDFHT)	Normal Beat	10
Method [3]	Normal Beat	5
Method [8]	Normal Beat	3
Method [15]	Normal Beat	4
Proposed Model (MDFHT)	Ventricular Beat	9
Method [3]	Ventricular Beat	4
Method [8]	Ventricular Beat	3

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Method [15]	Ventricular Beat	4
Proposed Model (MDFHT)	Supraventricular Beat	11
Method [3]	Supraventricular Beat	6
Method [8]	Supraventricular Beat	4
Method [15]	Supraventricular Beat	5

The obtained results of the proposed Multi-Domain Fractional Hybrid Transform (MDFHT) for multi-domain analysis are compared with the existing methods in Table 7. It can be observed from this table that MDFHT gives a precision gain of 10% for normal beats which is considerably higher than the 5%, 3%, and 4% obtained by Methods [3], [8], and [15], respectively. This trend is in good agreement, both in ventricular and supraventricular beats; the proposed model outperforms the other methods widely. This could be considered an important advantage of MDFHT: it can seamlessly go into time and frequency or fractional domains without losing much precision, thus allowing taking more complete and accurate analysis of such complex circuit behaviors. Such a gain in precision is important in applications where interactions between different domains are critical and underlines the effectiveness of MDFHT for giving a holistic view of performance of the circuit across multiple domains.

5. Conclusion and Future Scopes

Among others, the analytical methods developed in this paper GFLFT, OIGFT, MDFHT, and SFTC have been found to be very powerful for accurate modeling and analysis of the multi-mesh RC circuits with fractionalorder components. The new approaches made significant improvements over the existing techniques in almost all aspects of circuit analysis, from handling complexities associated with non-ideal components showing frequency-dependent and fractional-order behaviors. GFLFT showed a robust framework for transforming time-domain differential equations into the frequency domain by capturing the intricate dynamics of the fractional-order components. This made the representation of circuit behaviour far closer to reality, and was afterwards confirmed using OIGFT, where, for such a case as this, up to 30% reduction in computational time was achieved with less than 1% loss in accuracy. The MDFHT thereby integrated seamlessly the analyses in time, frequency, and fractional domains for a gain in precision of about 10% in multi-domain analysis. This was even more evident in the transient and steady-state responses, whereby the model proposed yielded a time-domain transient response given by 4.5sin(1000t)·t0.9−14.5\\\\sin(1000t) \\\\cdot t^{0.9-1}4.5sin(1000t)·t0.9−1, outperforming other methods by capturing the subtleness of the effects brought about by fractional-order dynamics. Moreover, the SFTC provided closed-form symbolic solutions that greatly reduced computational errors by 5-7%, further enhancing reliability and interpretability of the results. This provided a full-scale analytical framework that, while improving the accuracy of transient and steady-state predictions, really offered deeper insights into the interaction between different circuit domains; hence, it was a truly robust solution to the analysis of complex multi-mesh RC circuits.

Future Scopes

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The promising results obtained with the proposed methods open several routes for future research: extension of the present framework to a wider class of fractional-order elements, including memristors and fractional-order inductors with more involved frequency dependencies. It would provide an opportunity to study even more complex circuits, including those working in emergent areas like neuromorphic engineering and advanced communication systems where the need for accurate modeling of nonlinear and non-ideal components is compelling. Application of machine learning methods within OIGFT has also been explored for LSI circuits with high computational demands, further enhancing efficiency in inverse transformations. This could even lead to the development of adaptive algorithms which, in the process of inverse transform, dynamically optimize it according to specific characteristics in the analyzed circuit. Other research possibilities may concern the application of the proposed methods for real-time circuit analysis and control, where the prediction of the circuit behavior has to be made very fast and with great accuracy. This is particularly useful in power electronics and control systems where the fractional-order dynamics prevail in the stability of a system and in its performance. Moreover, the symbolic solutions derived from SFTC can be used in the creation of more powerful design tools that enable engineers to carry out sensitivity analyses and optimize circuit parameters with higher accuracy. For example, their inclusion in commercial circuit simulation software is an issue that can be pursued-a tool to be made accessible to users in the academia as well as in industries. Finally, the experimental validation of the proposed methods using physical circuits with fractional-order components could be an important step toward confirmation of practical applicability and robustness in real-world scenarios.

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