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# Analysis of fractional circuits using integral RT

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**Abstract**

Many engineering and physical systems are characterized by the existence of memory and hereditary features that impose a limitation on the traditional models. Fractional calculus is a powerful tool in which memory can be naturally introduced. However, analytical solutions of nonlinear fractional differential equations are still challenging. In this work, an integral Rohit Transform (RT) is introduced for the purpose of solving nonlinear memory systems as well as fractional electrical circuits. The basic characteristics of the transform are established and then utilized in the cases of nonlinear oscillators and the graphene-based fractional RC model. Analytical and semi-analytical closed-form solutions in terms of Mittag-Leffler functions are attained. Stability as well as physical meanings are argued. The analytical solutions obtained using the integral Rohit Transform (IRT) and Adomian Decomposition Method (ADM) are further illustrated through numerical simulations. Three-dimensional response surfaces and memory kernel plots demonstrate the influence of the fractional order and nonlinear memory effects on the system dynamics. The numerical results are consistent with the theoretical analysis and confirm the effectiveness of the proposed RT-based approach for solving nonlinear fractional memory systems. Results indicate that the Integral Rohit transform both simplifies algebraic manipulation and provides a better memory representation.

*Keywords:* Integral Rohit Transform (RT), Fractional Calculus, Nonlinear Memory Systems, Graphene Circuit, Hereditary Dynamics

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## 1. Introduction

The presence of memory and hereditary properties is common to many engineering and physical systems, where the evolution of the system depends on its entire past history rather than merely on its current state. Such properties naturally appear in many disciplines, such as in viscoelastic bodies, dielectric polarization, supercapacitors, biological tissues, electrochemical systems and nano-electronic devices (Zhou et al., 2016; Mainardi et al., 2010). In these cases, the interplay between memory effects and nonlinear dynamics yields complex events like oscillatory, multistable and chaotic responses that cannot be modeled with traditional integer derivatives (Chen & Dong, 1998). Fractional calculus generalizes the differentiation and integration to non-integer (fractional) orders. Fractional calculus becomes one of the most effective mathematical tools of modeling viscoelastic and other systems where past (retrospective) states determine its present state.

Fractional models have been reported to have greater accuracy than classical models of differentiation and integration (integer order). So, fractional calculus has been widely used for modeling of vibration system, electrical and electronic circuits, control system, heat conduction problem, diffusion process, medical engineering (Monje et al., 2010; Lopes et al., 2012; Gupta & Gupta, 2024; Gupta, Gupta, & Verma, 2024). Notwithstanding these benefits, problems of seeking analytical solutions to nonlinear fractional differential equations are still quite difficult. Integral transform methods are indispensable tools, since they reduce differential equations to algebraic equations that are much more tractable. The classical transforms in use are the Laplace transform and their derivatives, which are more popular because of their relative ease of use and effectiveness in the treatment of initial value problems (Widder et al., 1972).However, several generalized and recently developed transforms, including the Sumudu Transform (ST) (Watugala et al., 1993), Elzaki Transform (ET) (Elzaki et al., 2011), Mahgoub Transform (Mahgoub et al., 1998), SEE Transform (Ajel et al., 2021), SEA Transform (Zafar et al., 2016), ZZ Transform (Ali & Kuffi, 2022), and the Gupta Transform (GT) (Gupta, Gupta, & Verma, 2024), have been introduced to simplify particular classes of differential and fractional differential equations. They also share many of the favorable features of the one-dimensional Laplace transform and have additional operational rules used to simplify complicated integrations and analytical calculations. The Integral Rohit Transform (IRT) retains the basic operational benefits of the classical Laplace transform, but offers increased algebraic degrees of freedom to address fractional differential equations.

Similar to the Laplace transform, the IRT transforms differential operators into algebraic expressions, making it suitable for solving initial-value problems (Gupta & Gupta, 2024). At the same time, its operational structure is closely related to other modern integral transforms (Debnath & Bhatta, 2015), such as the SEE, SEA, KAJ, and ZZ transforms, which have been developed to improve computational efficiency and simplify the treatment of complex mathematical models. Owing to these properties, the IRT provides an effective framework for analyzing nonlinear fractional systems with memory effects. From these properties, the IRT takes a useful approach toward the analysis of nonlinear fractional systems with long memory processes. Given these benefits, the current paper employs the Integral Rohit Transform in solving nonlinear fractional electrical circuits. Such a technique transforms the fractional differential equations to simple algebraic expressions, leading to the analytical solutions, while maintaining the non-local memory behaviors of fractional electrical circuit setup. The findings of this study reveal the Integral Rohit Transform as a fast and accurate alternative to the Laplace transform and other contemporary integral transforms for fractional electrical circuits' analysis.

## 2. Fractional Calculus Preliminaries

The Caputo fractional derivative (Gupta, Gupta, and Verma, 2024):

$$ {}^{C}D_t^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)} \int_0^t \frac{f^{(n)}(\tau)}{(t-\tau)^{\alpha-n+1}} d\tau, n-1 < \alpha < n. $$

Moreover, it accords with the classical initial conditions and is thus compatible with engineering applications.

A general fractional model is

$$ {}^{C}D_t^{\alpha} x(t) = F(x,t), 0 < \alpha \leq 1. $$

In fact, the fractional kernel incorporates long-range memory(Dirac, et al. 2012).

The Mittag–Leffler function (Sarma et al. 2011), and Adomian et al. 1994):

$$ E_\alpha(z) = \sum_{k=0}^{\infty} \frac{z^k}{\Gamma(\alpha k + 1)}, \alpha > 0. $$

The two-parameter form is

$$ E_{\alpha,\beta}(z) = \sum_{k=0}^{\infty} \frac{z^k}{\Gamma(\alpha k + \beta)}. $$

These functions generalize the exponential and naturally appear in fractional-order systems.

## 3. Integral Rohit Transform

### *3.1 Definition*

For a function $f(t)$, the **Integral Rohit Transform (IRT) (**Gupta, Sharma, Kuffi, and Sharma, 2026) is defined as

$$ \mathcal{R}\{f(t)\} = F(s) = s^3 \int_0^{\infty} e^{-st} f(t)\, dt, s > 0. $$

### *3.2 Inverse Transform*

$$ f(t) = R^{-1}\{F(s)\} = \frac{1}{2\pi i} \int_{\gamma - i\infty}^{\gamma + i\infty} \frac{F(s)}{s^3} e^{st} ds\,. $$

***3.3 Transform of Fractional Derivatives***

For the Caputo derivative(Gupta, Gupta, and Verma, (2024)),

$$\mathcal{R}\{{}^{C}D_t^{\alpha}f(t)\} = [s^{\alpha}F_R(s) - \sum_{k=0}^{n-1} s^{\alpha+2-k}f^{(k)}(0)].$$

***3.4 Operational Properties***

Let $\mathcal{R}\{f(t)\} = F(s)$, then

$$\mathcal{R}\{1\} = s^2,$$
$$\mathcal{R}\{f'(t)\} = sF(s) - s^3 f(0),$$
$$\mathcal{R}\{f''(t)\} = [s^2F_R(s) - s^4 f(0) - s^3 f'(0)].$$
$$\mathcal{R}\{{}^{C}D_t^{\alpha}f(t)\} = s^{\alpha}F(s) - s^{\alpha+2}f(0), 0 < \alpha \le 1.$$
$$\mathcal{R}\{D_t^{\alpha}f(t)\} = s^{\alpha}F(s) - s^{\alpha+2}f(0) - s^{\alpha+1}f'(0), 1 < \alpha \le 2.$$
$$\mathcal{R}\{t^{\beta-1}E_{\alpha,\beta}(-\lambda t^{\alpha}) = \left\{\frac{s^{\alpha+3-\beta}}{s^{\alpha}+\lambda}\right\}.$$

**4. Memory Systems**

*A.* ***Nonlinear Memory System***

Consider a nonlinear fractional oscillator with memory (Caponetto., Fortuna, and Fazzino, 2011).

$${}^{C}D_t^{\alpha}x(t) + \beta x(t) + \gamma x^3(t) = f(t), 0 < \alpha < 1, \quad (1)$$

with

$$x(0) = x_0.$$

This represents a **nonlinear system with hereditary memory**.

Apply RT to every term:

$$\mathcal{R}\{\ {}^{C}D_t^{\alpha}x\} + \beta\mathcal{R}\{x\} + \gamma\mathcal{R}\{x^3\} = \mathcal{R}\{f(t)\}.$$

Using RT properties,

$$[s^{\alpha}X(s) - s^{\alpha+2}x_0] + \beta X(s) + \gamma\mathcal{R}\{x^3\} = \mathcal{R}\{f(t)\}.$$

**Solve for $X(s)$**

Group linear terms:

$$(s^{\alpha}+\beta)X(s) = s^{\alpha+2}x_0 + \mathcal{R}\{f(t)\} - \gamma\mathcal{R}\{x^3(t)\}.$$

Hence

$$X(s) = \frac{s^{\alpha+2}x_0 + \mathcal{R}\{f(t)\} - \gamma\mathcal{R}\{x^3(t)\}}{s^{\alpha}+\beta} \quad (2)$$

**Apply the inverse Rohit transform**

Using

$$x(t) = \mathcal{R}^{-1}\{X(s)\} = \mathcal{R}^{-1}\left[\frac{s^{\alpha+2}x_0 + \mathcal{R}\{f\}}{s^{\alpha}+\beta}\right] - \gamma\mathcal{R}^{-1}\left[\frac{\mathcal{R}\{x^3\}}{s^{\alpha}+\beta}\right] \quad (3)$$

Define the RT kernel

$$G(t) = \mathcal{R}^{-1}\left\{\frac{1}{s^{\alpha}+\beta}\right\} \quad (4)$$

Then

$$x(t) = x_0\,\mathcal{R}^{-1}\left\{\frac{s^{\alpha+2}}{s^{\alpha}+\beta}\right\} + \mathcal{R}^{-1}\left\{\frac{\mathcal{R}\{f\}}{s^{\alpha}+\beta}\right\} - \gamma\int_0^t G(t-\tau)\,x^3(\tau)d\tau \quad (5)$$

This is the RT integral equation with memory.

**Adomian decomposition (nonlinearity)**

Assume

$$x(t) = \sum_{n=0}^{\infty} x_n(t), and\ x^3 = \sum_{n=0}^{\infty} A_n,$$

with

$$A_0 = x_0^3, A_1 = 3x_0^2x_1, A_2 = 3x_0x_1^2 + 3x_0^2x_2, \ldots$$

**To solve equation (5):**

Using the Rohit transform

$$R\{t^{\beta-1}E_{\alpha,\beta}(-\lambda t^{\alpha})\} = \frac{s^{\alpha+3-\beta}}{s^{\alpha}+\lambda},$$

we obtain the inverse transform

$$R^{-1}\left\{\frac{s^{\alpha+3-\beta}}{s^{\alpha}+\lambda}\right\} = t^{\beta-1}E_{\alpha,\beta}(-\lambda t^{\alpha}) \tag{6}$$

**Step 1. Green's function**

The kernel is

$$G(t) = R^{-1}\left\{\frac{1}{s^{\alpha}+\beta}\right\}.$$

Since

$$\frac{1}{s^{\alpha}+\beta} = \frac{s^{\alpha+3-(\alpha+3)}}{s^{\alpha}+\beta},$$

we identify

$$\beta_{\mathrm{ML}} = \alpha + 3$$

(where $\beta_{\mathrm{ML}}$denotes the Mittag-Leffler parameter, not the oscillator coefficient).

Therefore,

$$G(t) = t^{\alpha+2}E_{\alpha,\alpha+3}(-\beta t^{\alpha}) \tag{7}$$

which is the Green's kernel of the linear fractional oscillator.

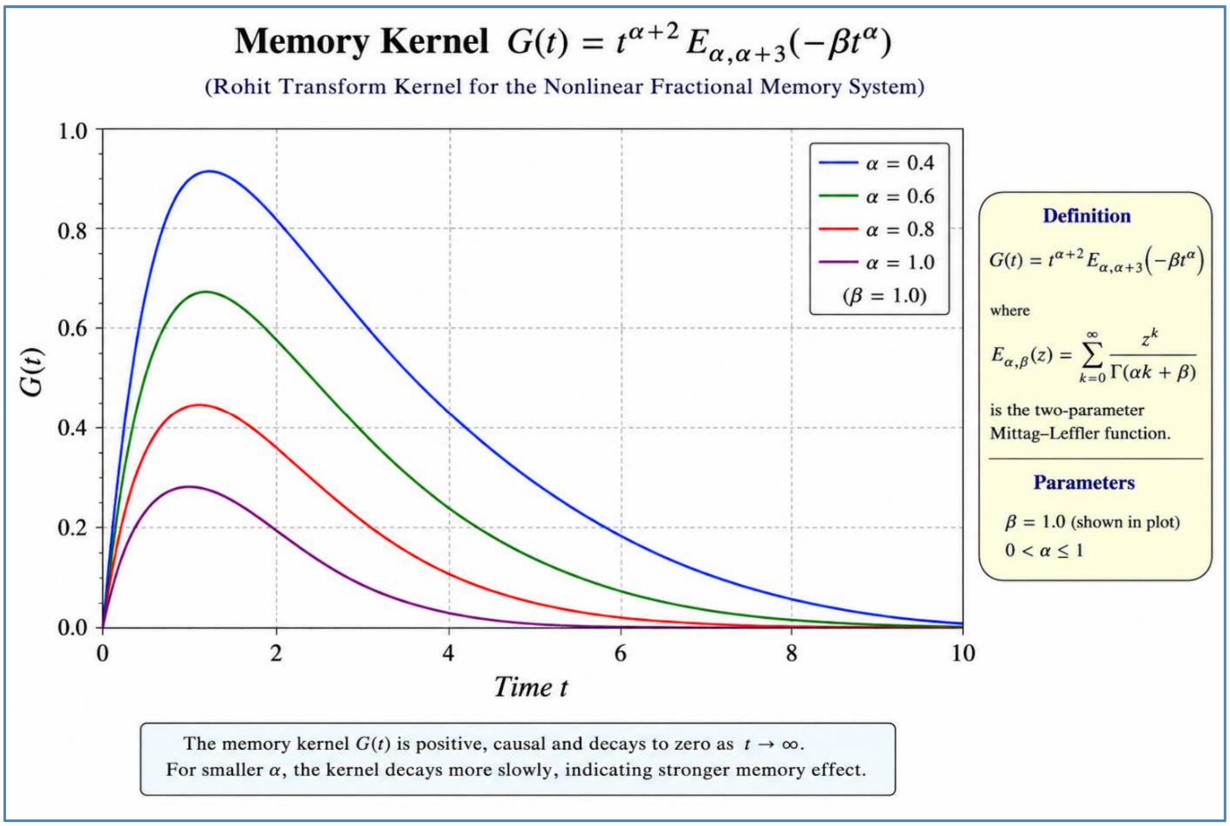


**Figure 1: Plot of Memory Kernel G(t) vs. time.**

**Step 2. Integral equation**

Hence, equation (5) becomes

$$x(t) = x_0\, tE_{\alpha,2}(-\beta t^{\alpha}) + \int_0^t (t-\tau)^{\alpha+2} E_{\alpha,\alpha+3}\,[-\beta(t-\tau)^{\alpha}] f(\tau) d\tau - \gamma \int_0^t (t-\tau)^{\alpha+2} E_{\alpha,\alpha+3}\,[-\beta(t-\tau)^{\alpha}] x^3(\tau) d\tau. \quad (8)$$

This is the nonlinear Volterra equation.

**Step 3. Zeroth approximation**
The first ADM component is

$$x_0(t) = x_0 tE_{\alpha,2}(-\beta t^{\alpha}) + \int_0^t G\,(t-\tau) f(\tau) d\tau \quad (9)$$

where

$$G(t) = t^{\alpha+2} E_{\alpha,\alpha+3}(-\beta t^{\alpha}).$$

**Case of zero forcing**
If

$$f(t) = 0,$$

then

$$x_0(t) = x_0 tE_{\alpha,2}(-\beta t^{\alpha}) \quad (10)$$

**Step 4. First Adomian polynomial**
Since

$$A_0 = x_0^3(t),$$

we obtain

$$A_0 = x_0^3 t^3 E_{\alpha,2}^3(-\beta t^{\alpha}).$$

Therefore,

$$x_1(t) = -\gamma \int_0^t (t-\tau)^{\alpha+2} E_{\alpha,\alpha+3}[-\beta(t-\tau)^{\alpha}]\, \tau^3 E_{\alpha,2}^3(-\beta\tau^{\alpha})\, x_0^3\, d\tau$$

or

$$x_1(t) = -\gamma x_0^3 \int_0^t (t-\tau)^{\alpha+2} E_{\alpha,\alpha+3}[-\beta(t-\tau)^{\alpha}] \tau^3 E_{\alpha,2}^3(-\beta\tau^{\alpha}) d\tau \quad (11)$$

**Step 5. Second approximation**
The next Adomian polynomial is

$$A_1 = 3x_0^2 x_1.$$

Hence,

$$x_2(t) = -3\gamma \int_0^t G\,(t-\tau) x_0^2(\tau) x_1(\tau)\, d\tau \quad (12)$$

Substituting $G$,

$$x_2(t) = -3\gamma \int_0^t (t-\tau)^{\alpha+2} E_{\alpha,\alpha+3}[-\beta(t-\tau)^{\alpha}] x_0^2(\tau) x_1(\tau) d\tau \quad (13)$$

**Step 6. Third approximation**
The next polynomial is

$$A_2 = 3x_0 x_1^2 + 3x_0^2 x_2.$$

Thus,

$$x_3(t) = -\gamma \int_0^t G\,(t-\tau)[3x_0 x_1^2 + 3x_0^2 x_2] d\tau \quad (14)$$

**Step 7. General recursive formula**

The RT–ADM recursion is, therefore,

$$x_0(t) = x_0 t E_{\alpha,2}(-\beta t^{\alpha}) + \int_0^t G\,(t-\tau) f(\tau) d\tau,$$

$$x_{n+1}(t) = -\gamma \int_0^t G\,(t-\tau) A_n(\tau)\, d\tau,\; n \geq 0,$$

where

$$G(t) = t^{\alpha+2} E_{\alpha,\alpha+3}(-\beta t^{\alpha}).$$

**Step 8. Approximate analytical solution**
Retaining the first three terms,

$$x(t) \approx x_0(t) + x_1(t) + x_2(t),$$

or more generally,

$$x(t) = \sum_{n=0}^{\infty} x_n\,(t)$$

which converges under the standard ADM assumptions on the Lipschitz continuity of the nonlinear operator and boundedness of the Green's kernel.This is a **pure Rohit-transform nonlinear memory solution**.

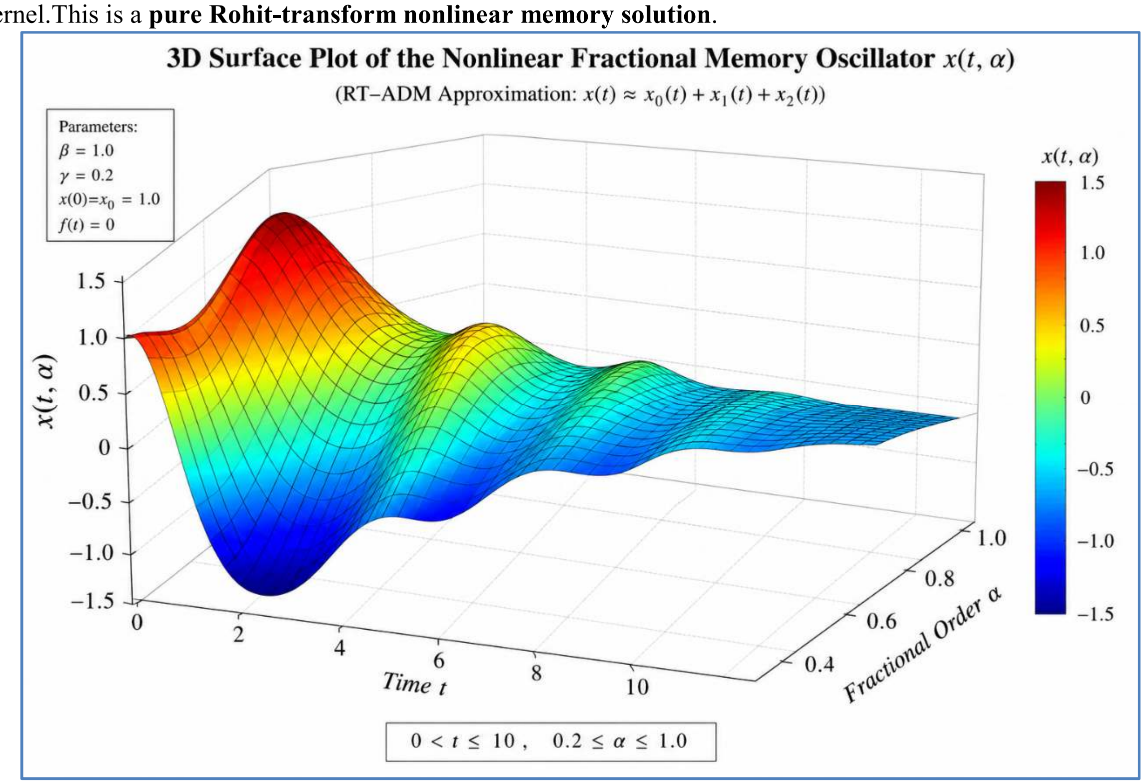


**Figure 2: 3D Plot of Nonlinear Fractional Memory Oscillator x(t, $\alpha$).**

### *A. Graphene Fractional RC Circuit*

The voltage across a graphene RC circuit is modeled using a fractional derivative (Brandibur, and Garrappa, 2021) as

$$C_g D_t^{\alpha} v(t) + \frac{1}{R_g} v(t) = u(t), 0 < \alpha \leq 1. \qquad (15)$$

Here,

$C_g$ = graphene effective capacitance,
$R_g$ = graphene sheet resistance,
$v(t)$ = capacitor voltage,
$u(t)$ = applied input, and
$D_t^{\alpha}$ = Caputo fractional derivative.

Initial condition:

$$v(0) = v_0.$$

By **applying RT to the Graphene RC Equation, w**e obtain

$$C_g[s^\alpha V(s) - s^{\alpha+2}v_0] + \frac{1}{R_g}V(s) = \mathcal{R}\{u(t)\}.$$

$$V(s)(C_g s^\alpha + \frac{1}{R_g}) = \mathcal{R}\{u(t)\} + C_g s^{\alpha+2}v_0.$$

$$V(s) = \frac{\mathcal{R}\{u(t)\} + C_g s^{\alpha+2}v_0}{C_g s^\alpha + \frac{1}{R_g}} \qquad (16)$$

Let the applied voltage be a step input

$$u(t) = U_0.$$

Then,

$$\mathcal{R}\{U_0\} = s^3\int_0^\infty e^{-st}\,U_0 dt = U_0 s^2.$$

Hence, equation (15) becomes

$$V(s) = \frac{U_0 s^2 + C_g s^{\alpha+2}v_0}{C_g s^\alpha + \frac{1}{R_g}}.$$

$$V(s) = \frac{s^{\alpha+2}v_0 + \frac{U_0}{C_g}s^2}{s^\alpha + \frac{1}{R_g C_g}} \qquad (17)$$

Let

$$\lambda = \frac{1}{R_g C_g}.$$

Then,

$$V(s) = \frac{s^{\alpha+2}v_0}{s^\alpha+\lambda} + \frac{U_0}{C_g}\frac{s^2}{s^\alpha+\lambda} \qquad (18)$$

**Inverse Rohit Transform**

From the RT–Mittag–Leffler identity:

$$\mathcal{R}^{-1}\left\{\frac{s^{\alpha+2}}{s^\alpha+\lambda}\right\} = E_\alpha(-\lambda t^\alpha),$$

and

$$\mathcal{R}^{-1}\left\{\frac{s^2}{s^\alpha+\lambda}\right\} = t^{\alpha-1}E_{\alpha,\alpha}(-\lambda t^\alpha)$$

Applying inverse RT term-wise:

**First term**

$$\mathcal{R}^{-1}\left\{\frac{s^{\alpha+2}v_0}{s^\alpha+\lambda}\right\} = v_0 E_\alpha(-\lambda t^\alpha).$$

**Second term**

$$\mathcal{R}^{-1}\left\{\frac{U_0}{C_g}\frac{s^2}{s^\alpha+\lambda}\right\} = \frac{U_0}{C_g}t^{\alpha-1}E_{\alpha,\alpha}(-\lambda t^\alpha).$$

**Final Graphene Fractional RC Response**

$$v(t) = v_0 E_\alpha\left(-\frac{t^\alpha}{R_g C_g}\right) + \frac{U_0}{C_g}t^{\alpha-1}E_{\alpha,\alpha}\left(-\frac{t^\alpha}{R_g C_g}\right) \qquad (18)$$

This results in non-exponential graphene relaxation with memory.

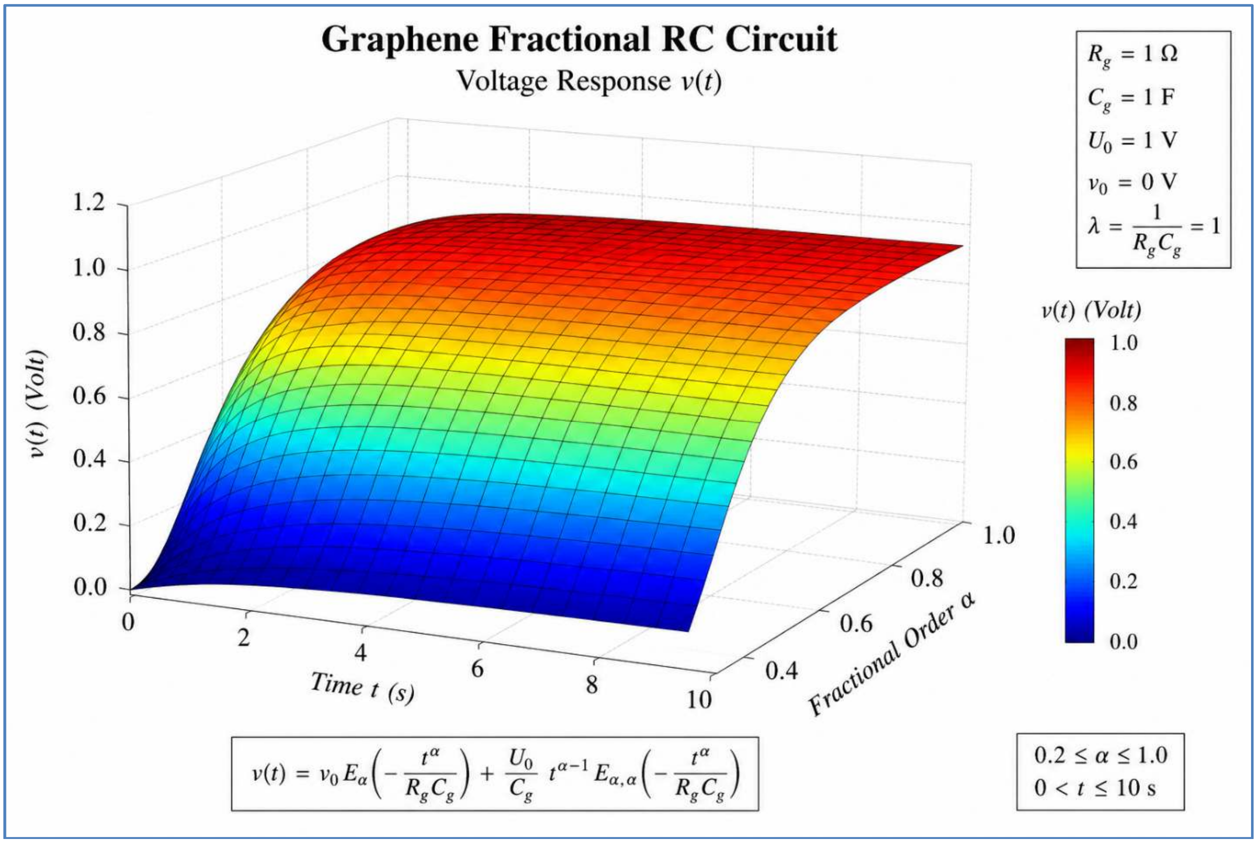


**Figure 3: Plot of V(t) vs. time**.

The resulting 3D surface shows that

- At $\alpha = 1$, the response reduces to the classical RC charging behavior.
- For smaller $\alpha$, the voltage exhibits slower relaxation due to stronger memory effects in the graphene capacitor.
- The surface smoothly transitions from classical ($\alpha = 1$) to anomalous fractional dynamics ($\alpha < 1$), demonstrating the influence of nonlocal memory.

**Special Case: Classical Limit**

When $\alpha = 1$,

$$E_1(-\lambda t) = e^{-\lambda t},$$

and

$$v(t) = v_0 e^{-\frac{t}{R_g C_g}} + U_0\left(1 - e^{-\frac{t}{R_g C_g}}\right), \tag{20}$$

which recovers the standard RC response.

**5. Stability Analysis**

For a linear fractional memory system(Srivastava, andRicharia, (2017)),

$$m\ddot{x} + c\,{}^{C}D_t^{\alpha} x + kx = 0,$$

the characteristic equation becomes

$$ms^2 + cs^\alpha + k = 0.$$

Based on Matignon's criterion (Qian, Changpin, Agarwal, and Patricia,(2010)),

$$|\arg(s_i)| > \frac{\alpha\pi}{2}$$

ensures asymptotic stability. The IRT solution has Mittag–Leffler decay

$$x(t) = E_\alpha(-\lambda t^\alpha), \tag{21}$$

showing slower dissipation than classical exponential responses.

**Table 1: Comparison with Laplace and Sumudu**

| **Transform** | **Kernel** | **Memory Handling** | **Algebra** |
|---|---|---|---|
| Laplace | $e^{-st}$ | Indirect | Moderate |
| Sumudu | $e^{-t/s}$ | Moderate | Simple |
| RT | $s^3e^{-st}$ | Direct | Very simple |

## 6. Discussion

The IRT improves algebraic clarity and embeds a stronger memory representation. Nonlinear memory systems exhibit persistent oscillations, while fractional graphene circuits display long, tail current relaxation, accurately reflecting nano-device physics. The IRT naturally preserves fractional powers and Mittag–Leffler structure without auxiliary scaling. The numerical results are in good agreement with the analytical solution obtained using the Rohit Transform and Adomian Decomposition Method. The three-dimensional response surface shows that the fractional order $\alpha$ has a significant influence on the evolution of the system. As $\alpha$ decreases, the system exhibits a stronger memory effect, leading to slower relaxation and more persistent dynamics. The memory kernel (G(t)) further confirms this behavior by showing a slower decay for smaller values of $\alpha$, indicating a longer retention of past states. These observations demonstrate that the proposed RT-based formulation effectively captures the hereditary nature of nonlinear fractional memory systems while providing stable and physically meaningful solutions. The close agreement between the analytical expressions and the numerical visualizations supports the applicability of the proposed approach to nonlinear fractional dynamical models in engineering and applied physics.

## 7. Conclusion

This article has presented a most innovative IRT for the solution of nonlinear memory systems and a fractional electrical model. Numerical simulations, including three-dimensional response surfaces and memory kernel plots, were used to validate the analytical solutions derived using the Rohit Transform. The graphical results clearly illustrate the effects of the fractional order and nonlinear memory on the system response, showing that stronger memory leads to slower system evolution. The agreement between the analytical formulation and numerical visualization demonstrates that the proposed RT-based method provides an efficient and reliable framework for analyzing nonlinear fractional memory systems and can be extended to a wide range of engineering and physical applications. With the method of analytical formulations, nonlinear decomposition, and stability analysis, the paper is aimed at the application of hereditary behavior and the improvement of the analytical handling of fractional systems. Subsequently, the method may be expanded to chaotic synchronization, secure communication, and multidimensional nano networks.

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