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UYUMLU KESİRLİ MERTEBEDEN TÜREVLE MODELLENEN KONDANSATÖRÜN SPICE MODELİ VE PARALEL R-L-$C_{\propto}$ DEVRESİNİN SİMÜLASYONUNDA KULLANIMI

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Öne Çıkanlar

- Spice modeling of a capacitor modeled using the conformal fractional derivative.
- Simulation results of R-L-$C_{\propto}$ circuit.

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Spice Model.

Öz

Kesirli Mertebeden Türev (KMT) ile elektrik devrelerinin ve devre elemanlarının modellenmesi 20. yüzyılda ortaya çıkmıştır ve devre elemanlarının modellenmesinde de kullanılmıştır. Son yıllarda Kesirli Mertebeden Türev popüler bir yöntem haline gelmiştir. Literatürdeki bazı çalışmalarda superkapasitörler başarılı şekilde modellenmiştir. Yine de KMT kondasatörleri barındıran devreler için analitik bir çözüm bulmak oldukça zordur. Devre simulatörleri analizi zor devrelerin analitik çözümlerini bulma konusunda başarılıdır. KMT kondansatörler henüz bir Spice modeline sahip değildir. Bu çalışmada KMT kondansatör Spice modeli LTspice programında oluşturuldu. Ayrıca model parallel R-L-$C_{\propto}$ devresinin simulasyonu için kullanıldı. Simulasyon sonuçları verildi.

SPICE MODEL OF A CAPACITOR MODELLED USING CONFORMAL FRACTIONAL ORDER DERIVATIVE AND ITS USAGE IN SIMULATION OF A PARALLEL R-L-$C_{\propto}$ CIRCUIT

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Abstract

Fractional-order (FO) components have emerged as a necessary method to model electrical and electronic circuits in the 20th century. In recent decades, the conformable fractional derivative has become a very popular mathematical tool. In the literature, it is used to model supercapacitors successfully. However, it is usually difficult to find analytical solutions for the circuits having a CFD capacitor. Circuit simulation programs make it easy to inspect the circuits hard to analyse. A CFD capacitor does not have a spice model yet. In this study, the Spice model of a CFD capacitor is constructed in the LTspice program. The model is also used to simulate an R-L-$C_{\propto}$ parallel circuit with a CFD capacitor. Its simulation results are given.

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1. Introduction

The possibility and the existence of the Fractional derivatives (FDs) were first discussed in the 17th century (Ross 1977). There are various types of fractional-order derivatives (FODs) (Podlubny 1998). Riemann–Liouville, Atangana-Baleanu, Caputo, Grünwald-Letnikov, and Atangana-Baleanu are some of the widely known FDs (Podlubny 1998). The solution of fractional-order differential equations is laborious (Podlubny 1998). The conformal fractional derivative abbreviated as CFD was proposed in (Khalil, Horani, Yousef and Sababheh 2014). It has many similar properties to ordinary derivatives (Abdeljawad 2015). Due to these properties, which make its usage easier (Khalil 2014, Abdeljawad 2015), and having a physical interpretation (Zhao and Luo 2017), it has become a hot research area. The FDs have already been used to analyze electrical circuits as early as 1890 century (Ross 1977). FDs are nowadays more commonly used for modeling systems, and designing filters, controllers, etc. (Babiarz, Czornik, Klamka and Niezabitowski 2017, Karakulak 2023, Morales and Lainez 2016, Devecioğlu and Mutlu 2022, Kilbas, Srivastava, and Trujillo 2006, Yang 2019). Recently, FDs have been used to model batteries (Alagöz and Alisoy 2018, Sikora 2017). The usage of FODs in the circuit theory has been reviewed in (Sikora 2017). The transient solution of a fractional-order (FO) circuit modeled by Caputo FD and CFD has been made in (Piotrowska and Rogowski 2017). A fractional electrical circuit in (Piotrowska 2019) has also been solved using sinusoidal signals for Caputo and conformable fractional derivatives. Pseudo-fractional order circuit elements can be done using linear circuit elements (Tsirimokou, Kartci, Koton, Herencsar and Psychalinos 2018). Using opamps, their behavior in the frequency domain can be obtained (Koseoglu, Deniz, Alagoz, and Alisoy 2022).

Capacitors are not ideal circuit elements. Their behavior varies as a function of frequency and capacitors made of different materials behave differently and must have different circuit models. All circuit elements should have SPICE models. In literature, various Spice models of capacitors made of different materials or for different operation conditions do exist. Supercapacitors are becoming more important each day. The supercapacitors have a lot of different spice models (Iordache et al. 2013). Modeling and simulation of supercapacitors are examined in (Fărcaş, Petreus, Ciocan and Palaghiţă 2009). The temperature dependence of the Supercapacitor circuit parameters with temperature is studied in (Gualous, Bouquain, Berthon, and Kauffmann 2003). Electrical circuits of the electrochemical capacitors are developed in (Miller 1999). Accurate modeling of supercapacitors for DC operation regime can be found in (Ionescu, Vasile, and Negroiu 2015). The parallel usage of a Valve Regulated Lead Acid (VRLA) cell and supercapacitor for use as a hybrid vehicle peak power buffer is examined in (Bentley, Stone, and Schofield 2005). Investigation of a supercapacitor model is made by the LTspice program (Martynyuk, Parasa and Makaryshkin 2010). The self-discharging of double-layer capacitors is examined in (Pantazica, Drumea, and Marghescu 2017). Zubieta model of supercapacitors and their real behavior are compared in (Negroiu, 2016). A comprehensible PSpice supercapacitor model is given in (Ciocan, Farcăş, Grama, and Tulbure 2016). The circuit simulation programs used for modeling supercapacitors are compared in (Johansson and Andersson 2008)

FODs can also be used to model some supercapacitors. A FO impedance model of a supercapacitor presented in (Lewandowski and Orzyłowski 2017) has been used to evaluate an IEC measurement standard. The energy of a supercapacitor is estimated with a FO model in (Kopka 2017). The circuit parameters of a supercapacitor are found by utilizing experimental data and the effect of various current discharge waveforms on the device parameters is examined (Freeborn, Maundy, and Elwakil 2018). The FO circuit parameters of a supercapacitor were measured by applying a step voltage (Freeborn 2013). Because of its time-dependent nature, it is hard to analyze the conformable fractional differential equations of circuits that have CFD capacitors (Tariboon and Ntouyas 2016, Morales-Delgado Gómez-Aguilar, and Taneco-Hernandez 2018). A CFD capacitor has been examined under DC and AC excitations and its solutions were found to have the incomplete gamma function for the AC supply case and the problems examined were simulated with Matlab (Palaz and Mutlu 2021a). A parallel resonance circuit with a CFD has been analyzed with simulations using Simulink in (Mohammed, Kandemir, Mutlu 2020). A two-capacitor problem in which the circuit possesses Linear Time-Invariant (LTI) and CFD capacitors was inspected using simulations (Palaz and Mutlu 2021a). Simulink simulations are time-consuming (Mohammed 2020, Palaz and Mutlu 2021b). Instead of dealing with such difficult and time-consuming solutions, a circuit program can be used to analyze circuits with CFD capacitors. The CFD is much simpler than the other FODs. Since the CFD can also be used to model supercapacitors, the CFD capacitor like every other circuit component needs a Spice model so that its circuits can be analyzed easily, quickly, and accurately. To the best of our knowledge, there is no spice model prepared for a CFD capacitor in literature. In this paper, a CFD capacitor Spice model has been made and used to simulate some circuits with the CFD capacitor. The circuit simulation programs like LTspice are easy to use and one can simulate circuits accurately in a short time. In this study, the CFD capacitor Spice model is made using the LTspice program since it is readily available without any cost and widely used to make models of emerging circuit components like memristors (Babacan 2017, Karakulak and Mutlu 2020). The spice model of the CFD capacitor is used to simulate a parallel R-L-$C_\propto$ circuit. Considering the fact that the circuit should also be simulated in negative starting times, the value of the time variable is obtained by feeding a capacitor with a DC current by means of a ramp signal. The CFD capacitor model is made and modeled successfully.

This paper is ordered as follows. In the second section, the definition of CFD and a CFD capacitor model, which is modified for negative starting times, are introduced. In the third section, its LTspice model is presented. In the fourth section, the simulation results of a parallel R-L-$C_\propto$ circuit supplied with a sinusoidal voltage source are given. The study is finished with the conclusion section.

2. Material and Method Conformal Fractional Derivative and CFD Capacitor Constitutional Law

Çalışmada, üst yüzeyinden üniform bir “$q(x)$” yayılı The description of the CFD is presented in (Yang 2019) as the follows:

$$\frac{d^{\alpha}f(t)}{dt^{\alpha}} = f'(t)t^{1-\alpha} = \frac{df(t)}{dt}t^{1-\alpha} \tag{1}$$

More information about CFD is given in (Alagöz and Alisoy 2018). If a capacitor model is made using CFD, its constitutive law is expressed as

$$i_c(t) = C_\propto \frac{d^{\propto}v_c(t)}{dt^{\propto}} = C_\propto v_c(t)t^{1-\propto} = C_\propto \frac{dv_c(t)}{dt}t^{1-\propto} \tag{2}$$

where, $i_c(t)$ and $V_c(t)$ are the CFD capacitor current, the CFD capacitor voltage, and the CFD capacitor coefficient.

If time *t* is negative, $t^{1-\propto}$ is not defined in real numbers and that’s why the circuit is not solvable. To overcome this problem, the CFD model is modified shifting $t^{1-\propto}$ to t=t_0 as

$$i_c(t) = C_\propto \frac{d^{\propto}v_c(t-t_0)}{dt^{\propto}} = C_\propto \frac{dv_c(t-t_0)}{dt}(t-t_0)^{1-\propto} = C_\propto \frac{dv_c(t)}{dt}(t-t_0)^{1-\propto} \tag{3}$$

3. The LTspice Model of a CFD Capacitor

In this section, the Spice model of the CFD capacitor has been made using LTspice simulator environment. The LTspice code of the CFD capacitor model is presented in Table 1.

Table 1. The Spice code of the CFD capacitor.

```
* CFD Capacitor SPICE Model
.SUBCKT CFD T B S
.params C=100n alp=0.1

* Capacitor current function
.func IVRel(V1,V2) = {pow(V1,(1-alp))*V2*C}

*Current source and a capacitor to calculate time
Gb 0 XSV value={1}
Cb XSV 0 {1}
.ic V(XSV) = {-0.001}

*Voltage source and a capacitor to calculate capacitor
*current
Ea 0 X value={V(TE,BE)}
Ca X 0 {1}
.ic V(X) = {0.001}

* Current source representing capacitor
Gmem TE BE value={IVRel(V(XSV,0),I(Ca))}
.ENDS CFD
```

The CFD capacitor block scheme is illustrated in Figure 1. A current source is used to represent the CFD capacitor current and another DC current source and an LTI capacitor are used to produce a ramp signal whose voltage is equal to the time variable and to be used to calculate the time-dependent term $t^{1-\propto}$. This CFD capacitor model has four pins. Pin Y is used to calculate the time t while Pin S is used to calculate the time-dependent capacitance of the CFD capacitor.

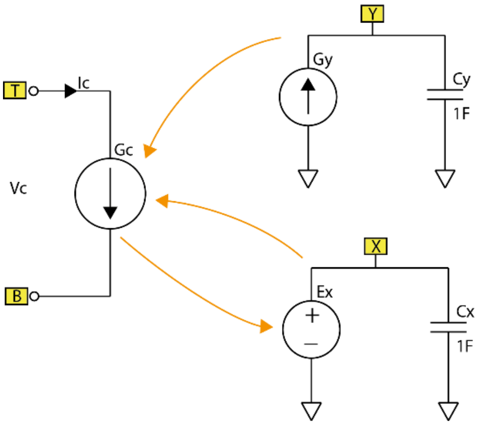


Figure 1. Block Scheme of The CFD Capacitor Model.

4. Simulation Results of a Parallel R-L-$C_\propto$ Circuit With LTspice Model

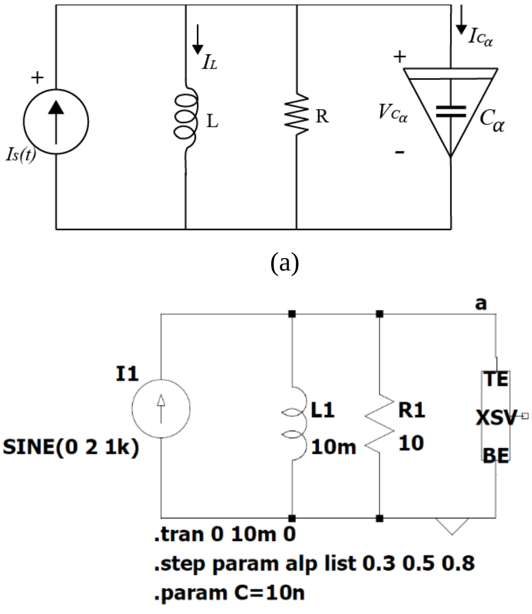
In this study, a parallel R-L-$C_\propto$ circuit supplied with an AC current source shown in Figure 2.a. which had been simulated in (Mohammed 2020), is also examined using the LTspice model made in the last section. The differential equation describing the circuit is given as follows:

$$i_s(t) = I_m\sin(\omega t) = I_m\sin(2\pi f t) = LC_\propto t^{1-\propto}\frac{d^2 i_L(t)}{dt^2} + \frac{L}{R}\frac{di_L(t)}{dt} + i_L(t) \qquad (4)$$

The LTspice CFD model and the examined circuit can be seen in Figure 2.b. The simulation parameters used are presented in Table 2. The simulation of the circuit is made for α=0.3, 0.5, and 0.8. The voltages and current of the CFD capacitor in the R-L-$C_\propto$ circuit for α=0.5 are presented in Figure 3. The currents of the CFD capacitor and the inductor in the R-L-$C_\propto$ circuit for α=0.5 are presented in Figure 4.

Such a circuit is always in a transient state due to the time-dependent term of $t^{1-\propto}$. That's why the voltage and current of the CFD capacitor are not periodic as shown in Figures 3 and 4. The behavior of the CFD capacitor current can be seen in Figure 5 for three different α values. The value of α defines the system's transient and damping behavior as shown in Figure 3. When α increases, the circuit starts acting similar to an LTI R-L-C parallel circuit. Since α is close to one, the CFD capacitor model starts behaving as if a time-invariant capacitor. At low values of α, the circuit waveforms demonstrate almost negative damping behavior. When α increases, the envelope of the oscillation of voltage rises more quickly as shown in Figure 5.

In (Mohammed 2020), the system is simulated using Simulink and more information about the behavior of the circuit can be found therein. The similar waveforms given in (Mohammed 2020), using Simulink are also obtained with LTspice.



```
.tran 0 10m 0
.step param alp list 0.3 0.5 0.8
.param C=10n
```

(a)

(b)

Figure 2. a) The $R-L-C_\alpha$ parallel circuit, and b) The same circuit set up on the LTspice.

Table 2. The parameters and the initial conditions of the parallel R-L-$C_\propto$ circuit.

	Parameter	Value
The resistance of the resistor	R	10 Ohm
The inductance of the inductor	L	10 mH
The capacitance coefficient of the CFD capacitor	C_α	10 $nF/s^{1-\propto}$
The initial voltage of the CFD capacitor	$V_{C_\alpha}(0)$	0 V
The initial current of the inductor	$i_L(0)$	0 A
The amplitude of the sinusoidal current source	I_m	2 A
The frequency of the sinusoidal current source	f	1 kHz

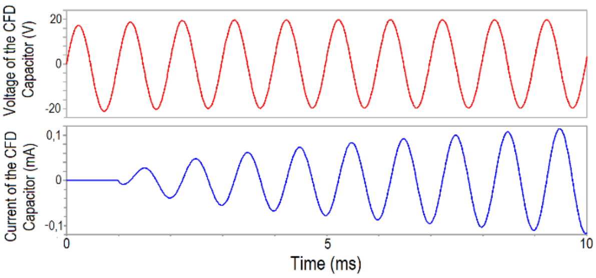


Figure 3. The voltage and current of the CFD capacitor in the $R-L-C_\alpha$ circuit for $C_\propto$=10 $nF/s^{1-\propto}$, R=10 Ohm, L=10 mH, f= 1 kHz, I_m= 2 Amper, and ∝=0.5.

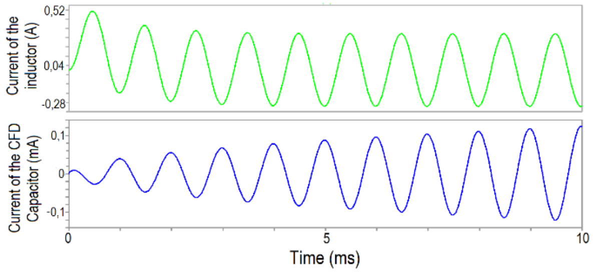


Figure 4. The currents of the inductor and the CFD capacitor in $R-L-C_\alpha$ for $C_\propto$=10 $nF/s^{1-\propto}$, R=10 Ohm, L=10 mH, f= 1 kHz, I_m= 2 Amper, and ∝=0,5.

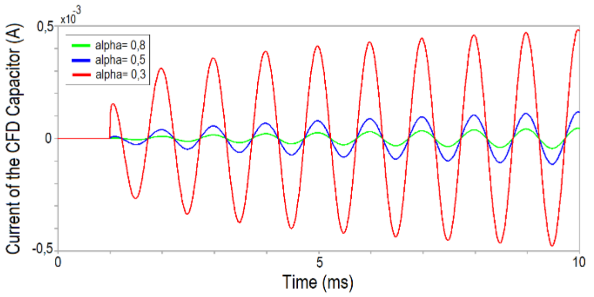


Figure 5. Currents of the $C_\propto$ in the $R-L-C_\propto$ circuit for $C_\propto$=10 nF, R=10 Ohm, L=10 mH, f= 1 kHz, I_m= 2 Amper, and α =0.3, 0.5, and 0.8.

5. Conclusions

Every circuit element needs a spice circuit model so that its best performance can be taken by the circuit designers. Models of some capacitors can be made with FODs. The CFD is easier to use than other FDs and has been gaining lots of attention in recent years. In the literature, the constitutive law of some capacitors has already been modeled with the CFD equation.

Although it is a linear circuit element, due to its time dependency, the circuits, that possess it, are difficult to analyze and they usually lack analytical solutions. The circuit simulation programs like LTspice are easy to use and one can simulate circuits accurately in a short time. However, in literature, its Spice model has not existed before. In this paper, a CFD capacitor LTspice model has been successfully made, and it is used to simulate and examine an R-L-$C_{\propto}$ parallel circuit. The CFD capacitor LTspice model which is given here can be used to analyze circuits such as those given in (Martynyuk 2010, Pantazica 2017, Negroiu 2016, Ciocan 2016, Johansson and Andersson 2008, Palaz and Mutlu 2021a, Palaz and Mutlu 2021b, Palaz and Mutlu 2022a, Palaz and Mutlu 2022b, Arapi and Mutlu 2022) without using sophisticated and time-consuming analytical methods.

The value of $1-\propto$ parameter in Equation (2) becomes 0 for $\propto=1$. In this case, the CFD capacitor is expected to behave as an LTI capacitor. However, it was observed that the LTspice simulator had difficulty finding a solution for the $\propto = 1$ value during the simulations and could not complete the simulation tasks. The reason has been diagnosed as $t^{1-\propto}$ being 0^0 indeterminate at t=0 when $\propto= 1$ or $1-\propto= 0$. It had been observed that the model works smoothly for alpha values between 0 and 1. If $\propto=1$, an LTI capacitor should be used instead of the CFD model in LTspice.

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