Lecture Notes in Electrical Engineering 1157

Pradip Kumar Jain
Yatindra Nath Singh
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Preface

This book contains the proceedings of papers presented at the 2nd International Conference on Advances in Signal Processing and Communication Engineering (ICASPACE-23), held in April 2023, at the Department of Electronics and Communication Engineering, Mahatma Gandhi Institute of Technology, Hyderabad, India. The conference invited papers from research scholars, academicians, industry professionals, and scientists. It provided them with a platform to discuss and put forward their ideas and research findings with their peers worldwide. Further, ICASPACE-23 organized four invited talks delivered by (i) Dr. N. Sudarshan Rao, Professor, Penn State Behrend, Erie, USA. (ii) Dr. Yatindra Nath Singh, Professor (HAG), Indian Institute of Technology, Kanpur, (iii) Dr. Anupam Sharma, Associate Director, DSP, DRDO, Hyderabad, (iv) Dr. Ravi Paul Gollapalli, Associate Professor, University of North Alabama, USA. This provided an opportunity for the participants to listen to the eminent speakers in the areas of Signal Processing and Communication Engineering.

ICASPACE-23 received a total of 277 papers; in the areas of Signal Processing, Communication, VLSI, IoT, and Machine Learning applications in these areas; across four countries. Works submitted to the Conference underwent a rigorous single-blind peer review each by three experts (among which two are from external Institutions) selected by the Conference Committee. To ensure a quality review process, each subject expert was not assigned more than five papers. Subsequently, the authors were given an opportunity to incorporate the review comments given by the reviewers. After comprehensive verification of technical content, plagiarism, and grammar, the Conference Committee recommended 49 papers be published in this proceedings book.

This book covers several theoretical and mathematical approaches that address different challenges in Signal, Image, Speech processing, and Communication systems. It primarily focuses on effective mathematical methods, algorithms, and models that enhance the performance of existing systems. The areas include—Advances in signal processing (radar and biomedical), image processing (satellite, medical, and general optical images), speech processing (speech signal compression, conversion, and audio mixing). Further, the contents of this book address Technical and Environmental challenges in 5G technology, strategies for optimal utilization of resources to improve the efficacy of the communication systems in terms of bandwidth and radiating power, some innovative IoT applications, mathematical, theoretical, and algorithmic aspects of Evolutionary computation models that support hybrid intelligence in Machine Learning/Deep Learning problems with applications focused in signal processing; Exploratory research in electromagnetics, microwave, and radar signal processing.

Through this book, we aim to unify the latest achievements of the authors in the research projects and practices across several areas of signal processing and communication engineering. We further expect this book will act as a catalyst for research in related areas, future collaborations, and international cooperation.

We would like to express our appreciation and heartfelt thanks to every individual who has directly or indirectly contributed toward the content quality improvement of this Conference proceedings and consistently assisted us in consolidating and bringing the works submitted to the ICASPACE-23 into good shape.

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About the Editors

Pradip Kumar Jain is a Professor in Electronics Engineering, and he is the Director of the National Institute of Technology Patna. Dr. Jain has immense experience both in research and administration. He made a significant contribution to the analysis, modeling, and development of high-power microwave tubes and gyrotron devices. Professor Jain guided 20 doctoral theses and has 100 peer-reviewed articles published in indexed journals, 200 conference proceedings, a patent, and authored six book/monograph chapters, to his credit. He served in various administrative positions as Dean-R&D at IIT (BHU), Varanasi; Coordinator of Microwave Tubes Research Centre and Centre of Advanced Studies; and Head of the Department of Electronics Engineering, IIT (BHU). Professor Jain did extensive R&D activities in collaboration with CEERI (CSIR, Pilani), DRDO, and IPR (DAE, Gandhi Nagar), and successfully executed numerous sponsored research projects.

Yatindra Nath Singh is currently a Professor in the Department of Electrical Engineering at IIT Kanpur. Professor Singh has led a team of researchers and academicians across India to develop Brihaspati, a project that aims at developing a platform-independent highly scalable content delivery system for a web-based e-learning system. He pursued his undergraduate in electrical engineering from REC Hamirpur (present National Institute of Technology Hamirpur), a master's with a specialization in optoelectronics and optical communications, and a Ph.D. in optical communication networks from IIT Delhi. He supervised 15 Ph.D. theses, published several journal articles and conference proceedings, and completed several sponsored projects besides Brihaspati.

Ravi Paul Gollapalli is an Associate Professor in the Department of Engineering Technology at the University of North Alabama. He has an electrical engineering background with a specialization in optics and has research experience in signal and image processing, pattern recognition analysis for remote sensing, and applications of femtosecond lasers. Dr. Gollapalli received his Ph.D. from the University of Alabama, Huntsville, and was a Post-doctoral Research Associate at the University of South Alabama, USA. He has published his works in peer-reviewed journals, conferences, and a book chapter. Besides, Dr. Gollapalli is actively involved in experimental works, numerical simulations, simulation of femtosecond laser pulse propagation in materials, fabrication of nanostructures on glass and silicon substrates using micro-/nanofabrication processes, and designing RF circuits for noise analysis. Further, he built an optical amplifier (EDFA) and supported the processing of signals from an impedance probe equipped on board the NASA SOUND rocket.

S. P. Singh is Professor and Head of the Electronics and Communication Engineering Department at Mahatma Gandhi Institute of Technology, Hyderabad. He worked for 18 years in the Indian Army Corps of EME. During his service in the Indian Army, he was in radar maintenance activities. Dr. Singh has developed a synchro-based training model for defense applications, received several cash rewards for his indigenization work on the radar Schilka, and did several modifications in radar SFM to reduce the error rate. Later he chose his career as an Academician. Dr. Singh received his Ph.D. from Osmania University, Hyderabad, in 2007. He supervised three doctoral theses so far, and four are in progress. He has over 115 publications in journals and conference proceedings and completed several funded projects from AICTE.

A Review of Simple Models for the Uniformly Distributed RC Network

Sudarshan R. Nelatury and S. C. Dutta Roy

Abstract Some simple models for the uniformly distributed RC network by recurrent ladder with 1–20 sections are examined by analysis and simulation, with respect to the frequency and unit-step responses. The corresponding bandwidths, delay times and rise times are tabulated. The latter two parameters are compared with what one obtains from Elmore's definitions and are also included in the Table. Further, the rise-time bandwidth products are given in the Table to validate the constancy of this parameter and the good approximation obtained from Elmore's definitions. Two other simple models, proposed in the literature are also examined, along with their applications, and their relevant parameters are recorded in the Table. Further, the open-circuit and the short-circuit input impedance expressions of each model are found and plotted for comparing with those of the actual distributed network.

Keywords Distributed RC network · Recurrent ladder model · Two element model · Four element model · Bandwidth · Delay time · Rise time · Elmore's definitions

1 Introduction

If the number of sections of a recurrent RC ladder network is increased infinitely, then we get a uniformly distributed RC network of finite length, hereinafter referred to as the UDRCN. They arise naturally in metallic interconnections between components and were considered as parasitics before Kaufman's paper [1] appeared. Since then, many workers directed their efforts toward analysis, synthesis, modeling, and

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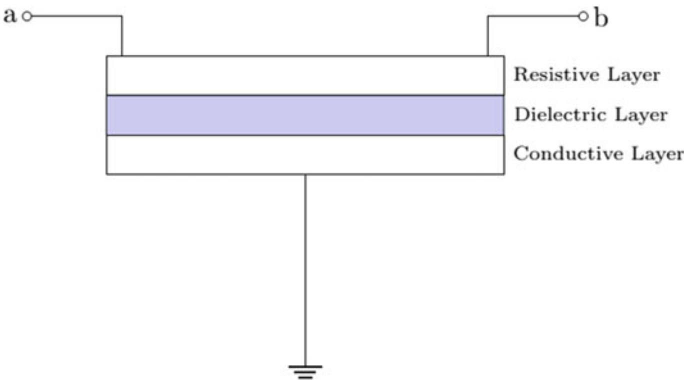
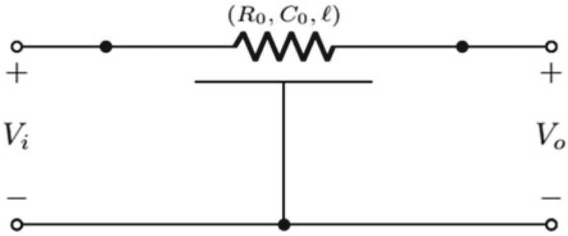


Fig. 1 A physical structure of a thin-film distributed RC element

Fig. 2 Circuit schematic of UDRCN. Here R_0 and C_0 account for the resistance and capacitance per unit length respectively, ℓ is the total length, while $R = R_o\ell$ and $C = C_0\ell$ are the total resistance and capacitance



applications, of uniform as well as nonuniform distributed RC networks (NUDRCN) for various useful purposes, like filtering, including band rejection [2–10].

It is worth noting that UDRCNs can also be fabricated as a single circuit element by semiconductor or thin-film technology [9]. In the latter, which is a preferred one, a conducting layer (metal film) is first deposited, followed by a dielectric layer above it, and then a resistive layer above the latter. Terminals are taken out from the conducting layer and two ends of the resistive layer, as shown in Fig. 1. The schematic representation of the UDRCN is shown in Fig. 2.

By appropriately shaping the two upper layers, we get a NUDRCN, which has several advantages, like impedance matching and reducing the gain required of an active device in oscillator applications [9].

As will be seen in the next section, the analysis and synthesis of UDRCNs are involved because of the occurrence of irrational functions. To simplify matters, simple lumped models in terms of recurrent ladder networks are examined, along with the ones proposed by Bhattacharyya and Gupta [11], and Steenaart [12], and the relevant parameters are tabulated in Table 1, Sect. 5. All models are also analyzed for their open-circuit and short-circuit input impedances, then simulated, and compared with that of the actual UDRCN.

In this paper, only UDRCNs are considered; NUDRCNs are expected to be investigated in future.

Table 1 Normalized characteristic features of UDRCN and the various models brought into the context for comparison. Bandwidth and rise-time and their product for the first 20 sections of recurrent RC ladder network sections are given

Net/Mod	$2\pi f_{3dB}$	T_D	τ_d	T_R	τ_r	$f_{3dB}T_r$	$f_{3dB}\tau_r$
DRCN	2.43238	0.3786	0.5	0.9010	1.2533	0.3488	0.48518
RLN(1)	1.00000	0.693	1	2.1975	2.5066	0.34974	0.39893
RLN(2)	0.37424	2.2245	3	5.8585	6.6319	0.34894	0.39501
RLN(3)	0.19428	4.5025	6	11.2775	12.7813	0.3487	0.3952
RLN(4)	0.11848	7.5345	10	18.489	20.972	0.34865	0.39548
RLN(5)	0.079663	11.323	15	27.5	31.2073	0.34867	0.39567
RLN(6)	0.057182	15.869	21	38.3115	43.4884	0.34866	0.39578
RLN(7)	0.043023	21.1715	28	50.9256	57.8157	0.3487	0.39588
RLN(8)	0.033532	27.232	36	65.3401	74.1894	0.3487	0.39593
RLN(9)	0.026864	34.0495	45	81.5576	92.6097	0.34871	0.39596
RLN(10)	0.022004	41.6245	55	99.5766	113.0764	0.34872	0.39599
RLN(11)	0.018351	49.957	66	119.3971	135.5898	0.34871	0.396
RLN(12)	0.015537	59.0471	78	141.0196	160.1498	0.34872	0.39602
RLN(13)	0.013325	68.8946	91	164.4447	186.7564	0.34873	0.39605
RLN(14)	0.011553	79.4996	105	189.6712	215.4097	0.34875	0.39607
RLN(15)	0.010111	90.8621	120	216.6992	246.1095	0.34873	0.39606
RLN(16)	0.0089242	102.9821	136	245.5297	278.8561	0.34873	0.39607
RLN(17)	0.0079347	115.8596	153	276.1618	313.6492	0.34875	0.39609
RLN(18)	0.0071005	129.4946	171	308.5958	350.489	0.34874	0.39608
RLN(19)	0.0063916	143.8871	190	342.8318	389.3755	0.34875	0.39609
RLN(20)	0.0057837	159.0367	210	378.8699	430.3086	0.34875	0.3961
BGM	2.3408	0.4020	0.550	0.9886	1.12519	2.31411	2.63385

The paper is organized as follows. Section 2 deals with the UDRCN, while the next Section considers the recurrent ladder network models for n number of sections, where $n = 1, 2, \ldots, 20$. Elmore's definitions of delay and rise times [13] are also included in this Section. Section 4 treats the model of [11], while the next Section deals with the models of [12]. Section 5 presents the data obtained for various models in Table 1. Section 6 gives the two Steenaart models. The exact transfer function (TF) of the UDRCN is irrational and does not explicitly lend itself to known lumped equivalents. However, a close approximation thereof to a rational TF helps us to build, fabricate, and simulate a given distributed circuit at frequencies scaled for our convenience. With this in mind, in Sects. 7 and 8, an attempt is made to obtain rational-function approximations of the original TF. We propose TFs inspired by rational-function approximations and also using Mittag-Leffler's expansion encountered in complex analysis. Equivalent models might be assessed not only in terms of magnitude frequency response, but also in terms of impedance characteristics. Section 9 considers the open-circuit and short-circuit impedances of the UDRCN and its various models. In each case, the expressions are simulated and plotted to compare the effectiveness of one or the other model in respect of this aspect. Finally, Sect. 11 gives the conclusions.

2 Analysis of the UDRCN

The TF of a UDRCN can be adapted from that for the exponentially tapered NUDRCN null network, given in [7] (Eq. (18)) by putting the taper factor $m = 0$. The result is

$$H_0(jx) = \frac{1}{\cosh\sqrt{jx}} \tag{1}$$

where

$$x = \omega RC \tag{2}$$

is the normalized frequency, and $\omega = 2\pi f$ is the angular frequency in radians/second, f is the frequency in Hz and RC is the product of total resistance and the total capacitance.

Before we calculate the frequency response, it is necessary to put (1) in terms of the normalized complex frequency variable s, by replacing jx by s, so as to facilitate the calculation of the unit-step response and the application of Elmore's definitions [13] of the delay and rise times. After introducing s in (1), we might expand it as the reciprocal of a power series as

$$H_0(s) = \frac{1}{\cosh\sqrt{s}} \tag{3}$$

$$= \frac{1}{[1 + s/2! + s^2/4! + s^3/6! + \cdots]} \tag{4}$$

Elmore's definitions of delay and rise times for a general TF

$$G(s) = \frac{1 + a_1 s + a_2 s^2 + \cdots + a_p s^p}{1 + b_1 s + b_2 s^2 + \cdots + b_q s^q} \tag{5}$$

where $q > p$, the coefficients a_i, b_i are real, and the denominator of $G(s)$ is a Hurwitz polynomial are as follows:

$$\tau_d = b_1 - a_1 \tag{6}$$

$$\tau_r = \sqrt{2\pi\left[b_1^2 - a_1^2 + 2\left(a_2 - b_2\right)\right]} \tag{7}$$

Application of (6) and (7) to Eq. (4) gives

$$\tau_d = 0.5000 \tag{8}$$
$$\tau_r = \sqrt{\pi/3} \approx 1.0233 \tag{9}$$

The symbols τ_d and τ_r will be used throughout the paper for Elmore's delay and rise-time, respectively. To calculate the 3dB-bandwidth, note that

$$\sqrt{jx} = \sqrt{x/2} + j\sqrt{x/2} \tag{10}$$

For convenience, let us denote

$$\sqrt{jx} = y + jy \tag{11}$$

where $y = \sqrt{x/2}$. From the fact [14]

$$\cosh[(y + jy] = \cosh y \cos y + j \sinh y \sin y \tag{12}$$

we can write

$$|H_0|^2 = \frac{1}{\cosh^2 y \cos^2 y + \sinh^2 y \sin^2 y} \tag{13}$$

Using the identity

$$\cosh^2 y = 1 + \sin^2 y \tag{14}$$

we get

$$|H_0|^2 = \frac{1}{\cos^2 y + \sinh^2 y} \tag{15}$$

A plot of $|H_0|$ versus normalized frequency is shown in Fig. 3. To determine the 3dB-bandwidth, let us put $|H_0|^2 = 1/2$. This leads us to the transcendental equation:

$$\cos^2 y + \sinh^2 y = 2 \tag{16}$$

Solving this numerically, we get $y = 1.10281082$. Substituting $y = \sqrt{x/2}$, we get $x = 2.4323834$ so that the unnormalized 3dB banwidth is

$$f_{3\text{dB}} = \frac{2.4323834}{2\pi RC} \tag{17}$$
$$= 0.387125842/RC \tag{18}$$

The unit-step response $v(t)$ is obtained by taking the inverse Laplace transform $\mathscr{L}^{-1}\{H_0(s)/s\}$, and the time-domain expression is given by [15]:

$$v(t) = 1 + \frac{4}{\pi}\sum_{n=1}^{\infty}\frac{(-1)^n}{2n-1}e^{\frac{-\pi^2(2n-1)^2 t}{4RC}} \tag{19}$$

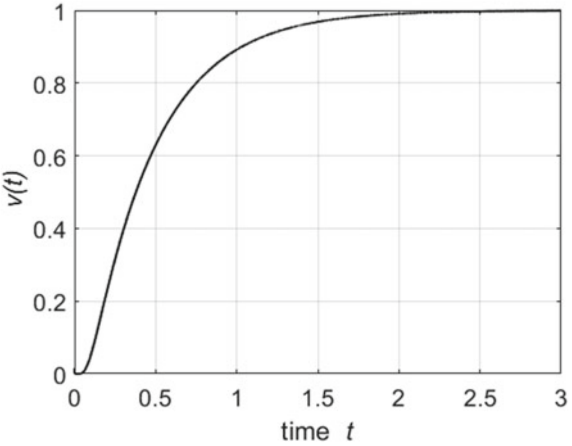


Fig. 3 Magnitude frequency response of the ideal UDRCN obtained from (1)

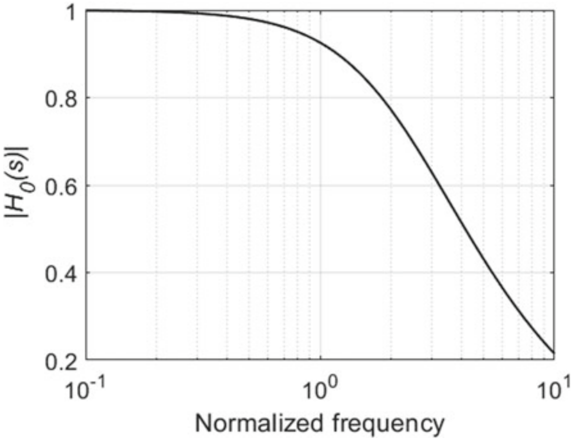


Fig. 4 Exact step response of an ideal UDRCN obtained from (19)

The result of simulating (19) is shown in Fig. 4. Just as we use τ_d and τ_r to denote Elmore's delay and rise times, correspondingly, we choose the symbols T_D and T_R to denote the actual times measured from simulations throughout the paper. From Fig. 4, we read

$$T_D = 0.3786 \tag{20}$$

$$T_R = 0.9010 \tag{21}$$

3 Models of the UDRCN Based on Recurrent Ladders

The analysis and synthesis of any DRCNs whether uniform or nonuniform, are involved because of the occurrence of irrational functions. To simplify matters, suitable lumped models of such networks have been derived by truncation of the recurrent ladder shown in Fig. 5, which is the natural model, and one suggested in [6]. In this paper, we consider such models as prospective lumped substitutes for UDRCNs. The case of NUDRCNs is expected to be investigated in the future as mentioned before.

An n-section recurrent RC ladder network shown in Fig. 5 will be referred to as RLN(n). Here the value $R_0\Delta\ell$ and $C_0\Delta\ell$ are denoted by R and C respectively, for simplicity and to be consistent with the notation followed by Swamy and Bhattacharyya [6]. They found the TF of this network as

$$H_n(s) = \frac{\cosh\left[\frac{1}{2}\cosh^{-1}\left(\frac{s+2}{2}\right)\right]}{\cosh\left[\frac{1}{2}(2n+1)\cosh^{-1}\left(\frac{s+2}{2}\right)\right]} \tag{22}$$

In fact, Swamy considered the polynomials proposed by Morgan-Voyce [19] in a series of papers [16–18], studied their properties and in [20] applied them to investigate recurrent ladders networks. In furtherance of [20], let us express (22) in terms of the positive powers of s so that the coefficients are related to the moments of the impulse response $h_n(t) = \mathscr{L}^{-1}H_n(s)$. Toward this end, we get

$$H_n(s) = \sum_{k=0}^{\infty} m_k \frac{(-s)^k}{k!} \tag{23}$$

where the moments are explicitly given by

$$m_0 = 1 \tag{24}$$

$$m_1 = \left(\frac{1!}{2!}\right) n(n+1) \tag{25}$$

$$m_2 = \left(\frac{2!}{4!}\right) n(n+1)(5n^2+5n+2) \tag{26}$$

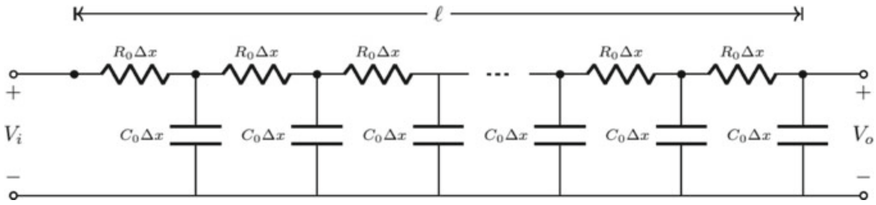


Fig. 5 A lumped model of a distributed RC element

$$m_3 = \left(\frac{3!}{6!}\right) n(n+1)(61n^4 + 122n^3 + 113n^2 + 52n + 12) \tag{27}$$

$$m_4 = \left(\frac{4!}{8!}\right) n(n+1)\Big(1385n^6 + 4155n^5 + 5967n^4 + 5009n^3 + 2656n^2 + 844n + 144\Big) \tag{28}$$

$$m_5 = \left(\frac{5!}{10!}\right) n(n+1)\Big(50521n^8 + 202084n^7 + 392246n^6 + 469444n^5 + 380069n^4 + 213496n^3 + 82924n^2 + 20736n + 2880\Big) \tag{29}$$

$$\cdots \quad \cdots \quad \cdots$$

Additionally, for countably infinite values of n, we can also represent $H_n(s)$ as a reciprocal of a series of positive powers in s as:

$$H_n(s) = \frac{1}{\left[1 + \sum_{k=1}^{\infty} \frac{{}^{n+1-k}P_{2k}\, s^k}{(2k)!}\right]} \tag{30}$$

where

$${}^{n+1-k}P_{2k} = \prod_{r=(n+1-k)}^{n+k} r \tag{31}$$

is a particular permutation product operation of $2k$ consecutive integers. We can view the TFs of a few simple cases, say, for $n = 1, 2, \ldots, 5$, for which the expressions as functions of s appear as:

$$H_1(s) = \frac{1}{1+s} \tag{32}$$

$$H_2(s) = \frac{1}{1+3s+s^2} \tag{33}$$

$$H_3(s) = \frac{1}{1+6s+5s^2+s^3} \tag{34}$$

$$H_4(s) = \frac{1}{1+10s+15s^2+7s^3+s^4} \tag{35}$$

$$H_5(s) = \frac{1}{1+15s+35s^2+28s^3+9s^4+s^5} \tag{36}$$

The unit-step response of an n-section RC ladder is given by [20]

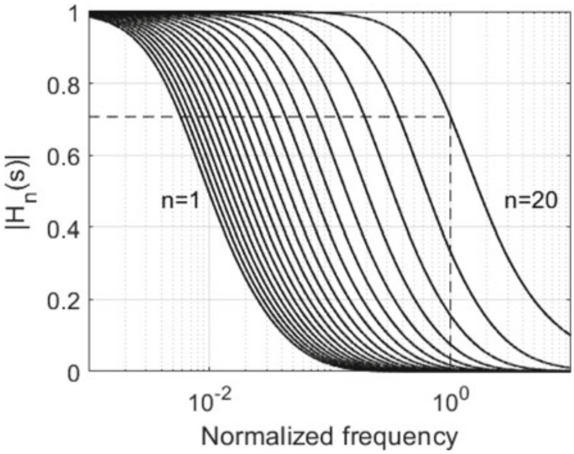


Fig. 6 Magnitude frequency responses of $H_n(s)$ for $n = 1, 2, \ldots, 20$

$$v(t) = 1 + \frac{4}{2n+1} \sum_{k=1}^{n} (-1)^k f(\varphi_k) e^{-\psi_k t/RC} \tag{37}$$

where

$$\varphi_k = \frac{(2k-1)\pi}{(2n+1)} \qquad k = 1, 2, \ldots, n \tag{38}$$

$$f(\varphi_k) = \frac{\cos^2 \varphi_k/2}{2 \sin \varphi_k/2} \tag{39}$$

$$\psi_k = 4 \sin^2 \varphi_k/2 \tag{40}$$

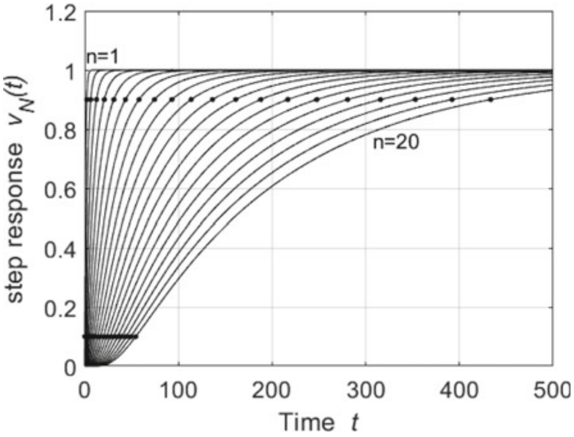
Applying (6) and (7), we can express the Elmore's delay-time and rise-time for an n-section RC ladder characterized by the transfer function in (22) as:

$$\tau_d = \frac{1}{2} n(n+1)RC \tag{41}$$

$$\tau_r = \sqrt{\frac{1}{3}\pi n(n+1)(n^2+n+1)}RC \tag{42}$$

which are also reported by Dutta Roy in [21]. The magnitude frequency response curves of all the 20 sections are shown in Fig. 6. We might denote them by $H_1(s), H_2(s), \ldots, H_{20(s)}$ Likewise, the step response plots corresponding to each of these obtained from (37) are shown in Fig. 7. The data read from Figs. 6 and 7, and the values of τ_d and τ_r, calculated from (6) and (7) are given in Table 1, along with the rise-time bandwidth products.

Fig. 7 Unit step responses of all the recurrent RC ladder networks for $n = 1, 2, \ldots, 20$. Time instants where the response attains 10 and 90% of its final values are shown



4 Bhattacharyya—Gupta Model

The Bhattacharyya-Gupta model (BGM) [11] is shown in Fig. 8, where the presence of a negative capacitance should be noted. The authors use two design parameters m and n, whose empirical choice determines the accuracy of the model.

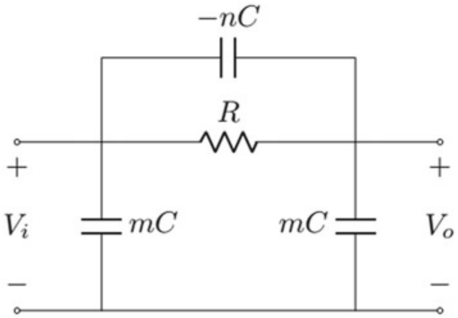
The open-circuit voltage TF of this network is given by

$$H_{21} = \frac{(1 - nsCR)}{(1 + (m - n)sCR)} \tag{43}$$

As found in [11], the best match to the actual UDRCN occurs for $m = 0.55$ and $n = 0.1$. The unit-step response of BGM can be obtained as

$$v(t) = \mathscr{L}^{-1}\left[H_{21}(s)/s\right] = \left[1 - \frac{m}{m-n} e^{\frac{-t}{m-n}}\right] u(t) \tag{44}$$

Fig. 8 The Bhattacharyya-Gupta model



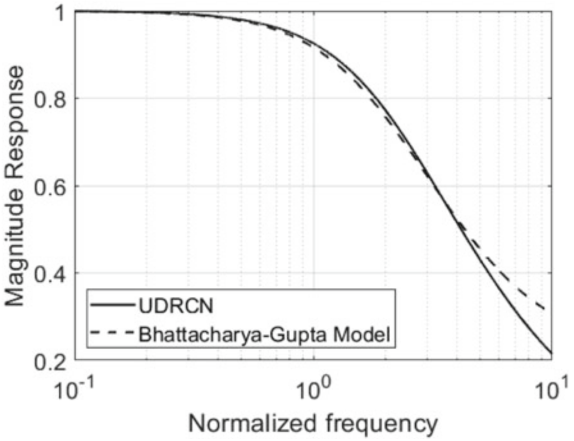


Fig. 9 Magnitude frequency response of the Bhattacharyya-Gupta model compared with that of the actual UDRCN

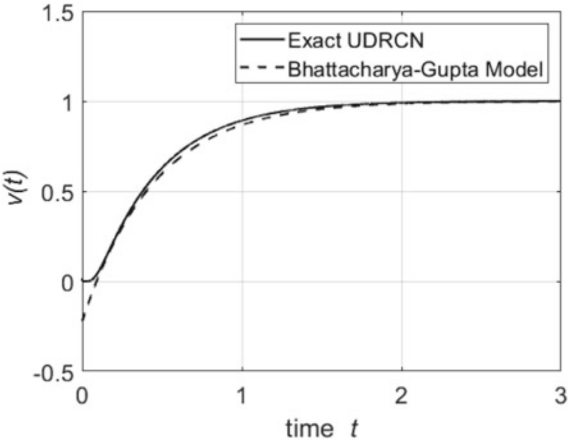


Fig. 10 Unit step response of the Bhattacharyya-Gupta model and that of the ideal UDRCN

Using (6) and (7) for the expression in (43), we find that

$$\tau_d = mRC = 0.55RC \tag{45}$$

$$\tau_r = RC\sqrt{2\pi(m^2 - 2mn)} = 1.12519RC \tag{46}$$

wherein we took the values of $m = 0.55$ and $n = 0.1$.

For ready reference, we give the magnitude frequency response and the time-domain unit-step response of (43) for the above values of m and n, along with the actual UDRCN responses in Figs. 9 and 10. We can easily derive an expression for the 3dB (relative) frequency by solving $|H_{21}| = \frac{1}{\sqrt{2}}$ as

$$2\pi f_{3dB} = \frac{1}{\sqrt{m^2 - 2mn - n^2}} = 2.3408 \tag{47}$$