each frequency is obtained. Also, one can never realize any physical lossless reciprocal 2-port network whose group delay is less than the value specified in terms of $s_{11}(j\omega)$, as above.

ACKNOWLEDGMENT

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Two New *LC* Mutators and Their Realizations

AHMED M. SOLIMAN

***Abstract*—Two new types of *LC* mutators are defined here. These are referred to as type 2b and type 2c *LC* mutators. The realization of these active building blocks are given using the second-generation current conveyor.**

Chua [1] introduced two types of *LC* mutators, known as type 1 *LC* mutator (a gyrator) and type 2 *LC* mutator (referred to here as type 2a *LC* mutator). These new two-port linear reversible active network elements can be used for simulating inductors.

The present correspondence introduces two new types of *LC* mutators defined in the following manner.

Type 2b LC Mutator: This two-port is defined in the time domain by

$$v_1 = a\frac{d^2v_2}{dt^2}$$
$$i_1 = -i_2 \tag{1}$$

where a is a positive constant. In the frequency domain, the above equation is equivalent to the transmission matrix

$$T_{LC\,2b}(s) = \begin{bmatrix} as^2 & 0 \\ 0 & 1 \end{bmatrix} \tag{2}$$

where s is the complex frequency variable.

Type 2c LC Mutator: This two-port is defined in the time domain by

$$v_1 = v_2$$
$$i_1 = -\frac{1}{a}\int\int i_2\,dt. \tag{3}$$

In the frequency domain, the above equation is equivalent to the following transmission matrix:

$$T_{LC\,2c}(s) = \begin{bmatrix} 1 & 0 \\ 0 & \dfrac{1}{as^2} \end{bmatrix}. \tag{4}$$

Two realizations of each of these mutators are possible using controlled sources as shown in Figs. 1 and 2.

Next, the Sedra–Smith second-generation current conveyor [2], [3] is used as the active building block in realizing the two mutators. Fig. 3 represents CC II which is a grounded three-port network having the following instantaneous port relations [2]:

$$\begin{bmatrix} i_b \\ v_a \\ i_c \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & \pm 1 & 0 \end{bmatrix} \begin{bmatrix} v_b \\ i_a \\ v_c \end{bmatrix}. \tag{5}$$

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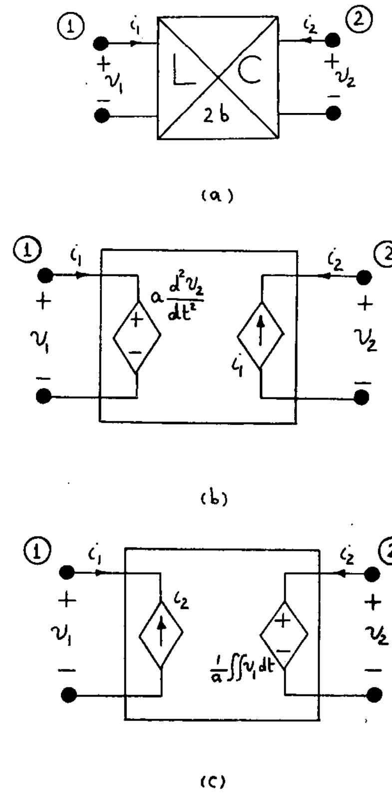

Fig. 1. Type 2b *LC* mutator. (a) Symbol. (b) Realization 1. (c) Realization 2.

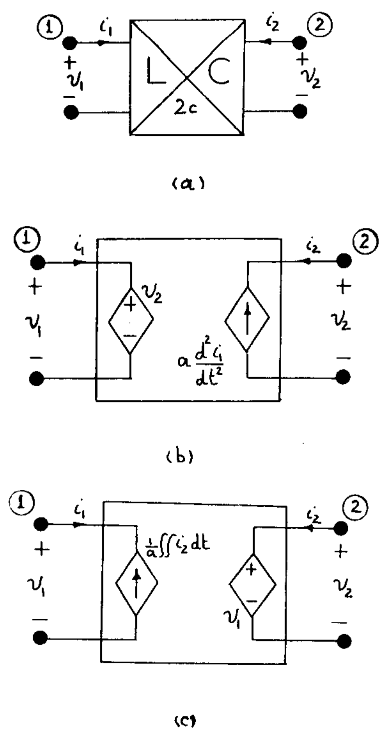

Fig. 2. Type 2c *LC* mutator. (a) Symbol. (b) Realization 1. (c) Realization 2.

Figs. 4 and 5 represent the realizations of types 2b and 2c *LC* mutators, respectively, using CC II. The constant a in all circuits is equal to $C_1C_2R_1R_2$. When port 2 of any of the four circuits is terminated in a capacitance C, the inductance seen at port 1 is $(C_1C_2R_1R_2/C)$ and hence it can be tuned by adjusting R_1 of R_2 or both.

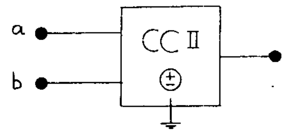

Fig. 3. Symbolic representation of the second-generation current conveyor.

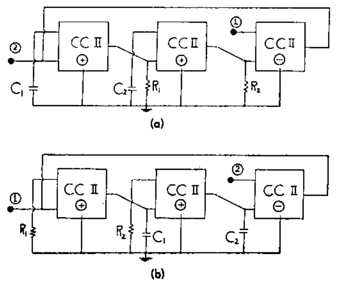

Fig. 4. Realizations of type 2b LC mutator using CC II. (a) Realization 1. (b) Realization 2.

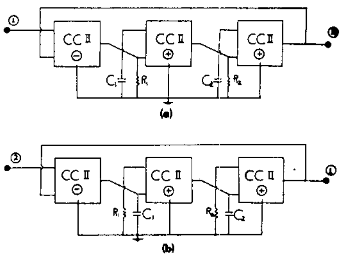

Fig. 5. Realizations of type 2c LC mutator using CC II. (a) Realization 1. (b) Realization 2.

It is well known that the type 1 LC mutator simulates inductance using the minimum number of capacitors, namely, one, and the magnitude of the realized inductance is directly proportional to the terminating capacitor. On the other hand, types 2b and 2c LC mutators belong to the class of the type 2a LC mutator since they provide an inductance inversely proportional to the value of the terminating capacitor. Observe that three capacitors are needed for simulating an inductor using a type 2a mutator, a type 2b mutator, or a type 2c LC mutator.

It is also noted here that the type 2b (2c) LC mutator is a special type of Antoniou's voltage (current) generalized immittance converter having an impedance conversion function $f(s)=as^2$ [4]; therefore, three more alternative realizations for the type 2c LC mutator using operational amplifiers are obtainable directly from Antoniou's realizations of the CGIC [4]. However, no realization is available up to the author's best knowledge for realizing the type 2b LC mutator. It is clear that types 2b and 2c LC mutators are not valid for transforming nonlinear capacitors to nonlinear inductors.

Conclusions

Two more LC mutators are defined and shown to be special cases of Antoniou's generalized immittance converter. New realizations are given using the Sedra–Smith second-generation current conveyor. Many more higher order LC mutators for transforming linear capacitor to linear inductor could be defined.

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An Upper Bound on the Settling Time

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***Abstract*—A useful upper bound on the settling time (the least time required for the response to stay with a specified percentage of its final value) is found.**

Introduction

The input signals $f(t)$ considered in this correspondence are those that are Lebesgue integrable on $(-\infty, +\infty)$ $(f(t)\in\mathcal{L}(-\infty, +\infty))$. For these inputs we can find the corresponding Fourier transform

$$F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}dt.$$

It is also assumed that the transfer function $H(\omega)\in\mathcal{L}(-\infty, +\infty)$ and that $F(\omega)H(\omega)$ is of bounded variation on $(-\infty, +\infty)$ with $\bigvee_{-\infty}^{\infty}[F(\omega)H(\omega)]\leq N$. (These assumptions in the frequency domain are quite reasonable since very often $H(\omega)$ is either a low-pass or bandpass filter.)

The response of the system is

$$g(t) = 1/2\pi \int_{-\infty}^{\infty} F(\omega)H(\omega)e^{j\omega t}d\omega.$$

Bound on the Settling Time

Let $T_s>0$ be the settling time; that is, the least time $t>0$ such that $|g(t)-g(\infty)|<\epsilon$. We will now find a value of time, call it T_b, such that if $t>T_b$ then $|g(t)-g(\infty)|<\epsilon$. It then follows that $T_s\leq T_b$; that is, T_b is an upper bound on the settling time T_s.

Now, since $f(t)$ and $H(\omega)$ are in $\mathcal{L}(-\infty, +\infty)$, $F(\omega)H(\omega)\in\mathcal{L}(-\infty, +\infty)$. Hence, the Riemann–Lebesgue lemma can be used, by which it follows that $g(\infty)=0$; that is,

$$\lim_{t\to\infty} \int_{-\infty}^{\infty} F(\omega)H(\omega)e^{j\omega t}d\omega = 0.$$

Thus we would like to find T_b such that if $t>T_b$ then $|g(t)|<\epsilon$. Now,

$$g(t) = 1/2\pi \int_{-\infty}^{\infty} F(\omega)H(\omega)e^{j\omega t}d\omega$$

when written as a Stieltjes integral is

$$1/2\pi jt \int_{-\infty}^{\infty} F(\omega)H(\omega)\, de^{j\omega t}$$

which when integrated by parts becomes

$$g(t) = 1/2\pi jt \int_{-\infty}^{\infty} e^{j\omega t}d[F(\omega)H(\omega)].$$

Hence

$$|g(t)| \leq \left|\frac{1}{2\pi t}\right| \sup |e^{j\omega t}| \bigvee_{-\infty}^{\infty}[F(\omega)H(\omega)] \leq \frac{N}{2\pi|t|}.$$

Thus for $|g(t)|<\epsilon$ we should have $T_b=N/2\pi\epsilon$.

An Example

Let

$$f(t) = e^{-|t|}.$$

Then

$$F(\omega) = \frac{2}{1+\omega^2}.$$

Let

$$H(\omega) = \chi(-1, 1) = \begin{cases} 1, & \text{for } -1<\omega<1, \\ 0, & \text{otherwise.}\end{cases}$$

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