Synthesis of binary capacitor

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Abstract. This paper deals with the synthesis of a linear capacitor with binary states of its capacitance. These states are controllable via a general nonlinear dependence of the capacitance on external controlling variable. The capacitor is designed such that it preserves the charge-voltage constitutive relation and also the constitutive relations of other fundamental elements which can be set up from the binary capacitor. An example of the synthesis of the ideal memcapacitor, preserving its memcapacitance vs. flux map, which employs the binary capacitor, is shown including the results of its SPICE analysis.

Keywords: Binary capacitor, charge, flux, synthesis, switched capacitor, memcapacitor, constitutive relation.

1 Introduction

The capacitor, described by a constitutive relation between electric charge and voltage, belongs to the group of ideal circuit elements. More generally, it is one from the infinite number of fundamental electrical elements from Chua's periodical table [1]. Currently, the intense researching of other elements from the table is conducted, particularly those which can be potentially utilized as nonvolatile memories for computer industry. The most widely known is memristor [2], but also memcapacitor and meminductor [3] come into notice. Since these devices are not still available for experimenting, a lot of their SPICE models were developed [4], [5], [6]. Recently, a growing number of papers deal with a construction of hardware emulators of these devices [7], [8], [9]. However, most of them suffer from two kinds of drawbacks: 1) They mimic the behavior based on an analogy with the so-called TiO2 memristor. It is in contradiction with the needs of emulating the device with arbitrary type of the constitutive relation [7]. 2) The emulated device does not preserve all essential fingerprints of ideal mem-elements which can be important for the experiments with the emulator [8].

A synthesis of the so-called binary capacitor (BC) is described below. It preserves all the fingerprints of linear capacitor with two states of the externally controllable capacitance. It is the assumption for building up such binary memcapacitor from BC that would preserve all the fingerprints of ideal memcapacitor. An example of such memcapacitor and the corresponding SPICE simulation results are also shown.

2 Characteristics of binary capacitor

The schematic symbol of BC is given in Fig. 1 (a). Its two-state capacitance (C_L and C_H) can be adjusted via controlling signal Φ. An example of the prospective capacitance-Φ relation is shown in Fig. 1 (b). The common feature of such characteristics is the capacitance discontinuity at a certain threshold value of controlling signal, denoted in Fig. 1 (b) by symbol Φ_T. The Coulomb-Volt characteristic of BC thus consists of a couple of linear charge-voltage relationships according to Fig. 1 (c). Their corresponding slopes define the capacitances C_L and C_H.

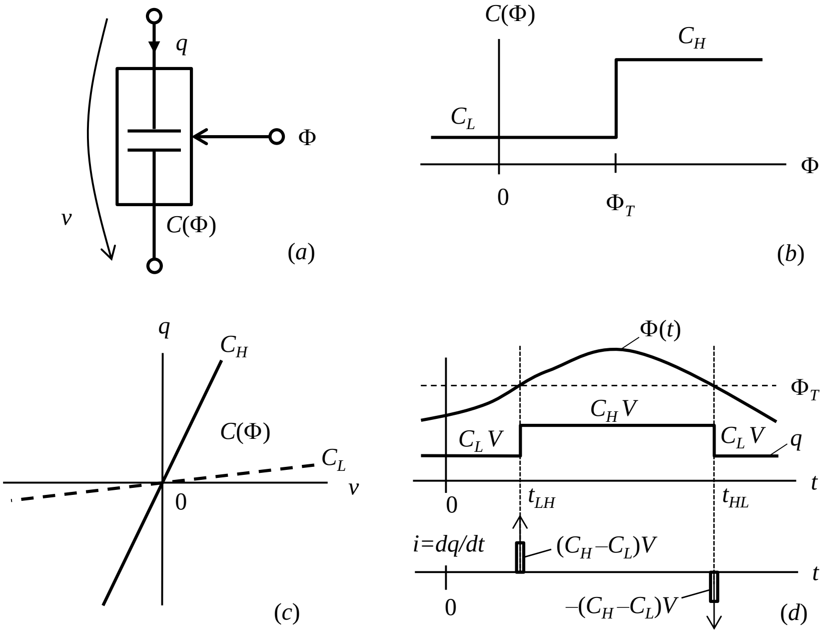

Fig. 1. (a) Schematic symbol of binary capacitor, (b) prospective dependence of capacitance to controlling variable, (c) Coulomb-Volt characteristic, (d) waveforms of controlling variable, charge, and current, all for the constant exciting voltage.

The BC is defined by the constitutive relation between electric charge and voltage

$$q(t) = C(\Phi(t))v(t)\,. \tag{1}$$

The current flowing through the BC is

$$i(t) = \frac{dq(t)}{dt} = \frac{dC(\Phi(t))}{dt}v(t) + C(\Phi(t))\frac{dv(t)}{dt}\,. \tag{2}$$

For the BC in one of its limiting states C_L or C_H, its current is given only by the second right-side term of Eq. (2). If the controlling variable crosses the threshold level Φ_T at time instant t_x, the Dirac impulse with the strength $\pm(C_H\text{-}C_L)v(t_x)$ appears at this moment in the current waveform. The sign plus/minus is for the capacitance increase/decrease. These current impulses of the ideal BC appear also for constant voltage $v(t)=V\neq0$ across the device. It is a consequence of the discontinuity of the charge. This case is illustrated in Fig. 1 (d).

In the following, the synthesis of the BC using the technique of switched capacitors with fixed capacitances will be described. We show that a simple toggling of two fixed capacitors C_L and C_H to the capacitive port does not solve the problem without a proper setting the initial conditions at time instants of the abrupt changes of the BC state.

3 Synthesis of the binary capacitor

Consider the preliminary version of the BC in Fig. 2. Two capacitors with fixed capacitances C_L and C_H are toggled depending on the controlling variable Φ.

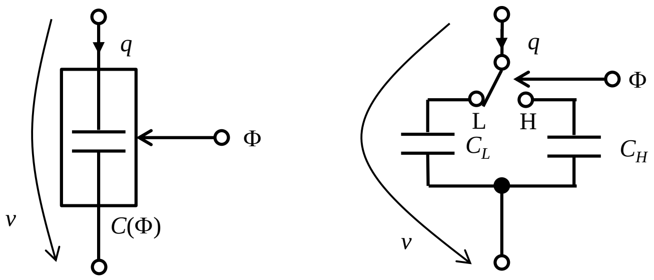

Fig. 2. Improper implementation of binary capacitor (i.e. without adjusting initial conditions).

Consider that the toggle-switch changes its state from L to H (see Fig. 2) at time instant t_{LH}, and back to the state L at time instant t_{HL}. Suppose that the voltage source $v(t)$ excites the BC terminals and that the capacitor C_H is charged to the voltage V_{Hini} just before changing the switch state at time t_{LH}. Then due to the jump change from L to H state, the capacitor C_H is suddenly connected to the voltage source, and the BC outlets will conduct the impulse current in the form of Dirac impulse with the strength of $C_H(v(t_{LH})\text{-}V_{Hini})$. However, according to Fig. 1 (d), its correct value is $(C_H\text{-}C_L)v(t_{LH})$. Similarly, the H to L state change will cause the current Dirac impulse with the strength of $C_L(v(t_{LH})\text{-}V_{Lini})$, where V_{Lini} is the C_L voltage just before the state change. Note that the correct value is $\text{-}(C_H\text{-}C_L)v(t_{HL})$.

It is thus obvious that the circuit in Fig. 2 should be completed by auxiliary circuitry for automatic presetting the initial voltages V_{Lini} and V_{Hini} of capacitors C_L and C_H at time instants just before the states of the binary capacitor are modified. The following equations read:

$$C_H\,(v(t_{LH})-V_{Hini})=(C_H-C_L)v(t_{LH})\,, \tag{3}$$

$$C_L(v(t_{HL}) - V_{Lini}) = -(C_H - C_L)v(t_{HL})\,. \qquad (4)$$

From Eqs. (3) and (4), the initial voltages are as follows:

$$V_{Hini} = \frac{C_L}{C_H} v(t_{LH})\,, \qquad (5)$$

$$V_{Lini} = \frac{C_H}{C_L} v(t_{HL})\,. \qquad (6)$$

One of several examples of providing the above initial conditions is given in Fig. 3. In the L state, the capacitor C_H is charged via the amplifier A_H to the port voltage v multiplied by the amplifier gain C_L/C_H. In this way, the initial condition (5) is provided at time instant of the toggling into the state H. Similarly, the capacitor C_L is charged in the H state via amplifier A_L with the gain C_H/C_L, thus providing the initial condition (6) when toggling into the state L.

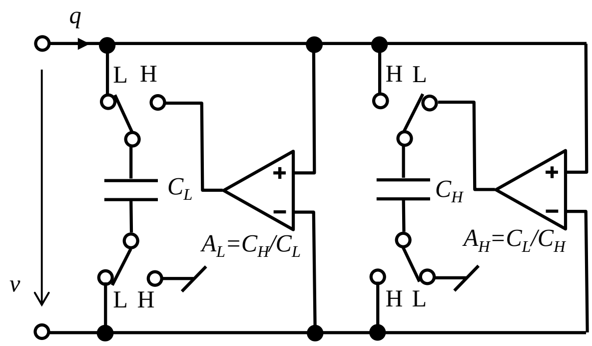

Fig. 3. An example of the implementation of binary capacitor.

Also other circuit implementations, overcoming some drawbacks of the circuit in Fig. 3 (the circuit complexity and the use of two amplifiers with large spread of the gains), can be found. However, the idea of all of them is identical: the necessity of automatic adjusting the proper initial conditions at time instants of the state changes of the binary capacitor.

4 Demonstration of memcapacitor implementation via BC

Selecting the flux, i.e. the time-domain integral of the terminal voltage of BC, as the Φ quantity which controls the capacity in Fig. 1, the flux-controlled memcapacitor can be emulated [10]. The block diagram is shown in Fig. 4.

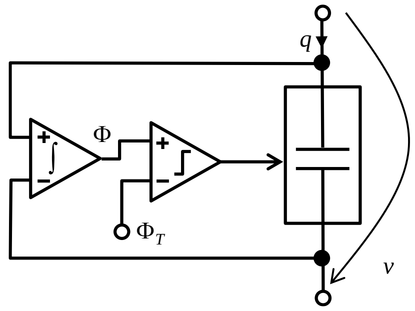

Fig. 4. Memcapacitor implementation via binary capacitor, integrator, and comparator.

The terminal voltage of BC is integrated into the flux via a differential-input integrator. Crossing the threshold level Φ_T is monitored by the comparator which controls the internal switches of BC. The outputs of SPICE simulation of the memcapacitor with parameters C_L=100pF, C_H=1nF, Φ_T =1μVs under conditions described below Fig. 5 confirm all fundamental fingerprints of memcapacitor [11].

5 Conclusions

The model of binary capacitor can be used for designing hardware emulators of memcapacitors with arbitrary-type two-state memcapacitance vs. flux relationship. The method described therein can be easily extended to the multi-state case.

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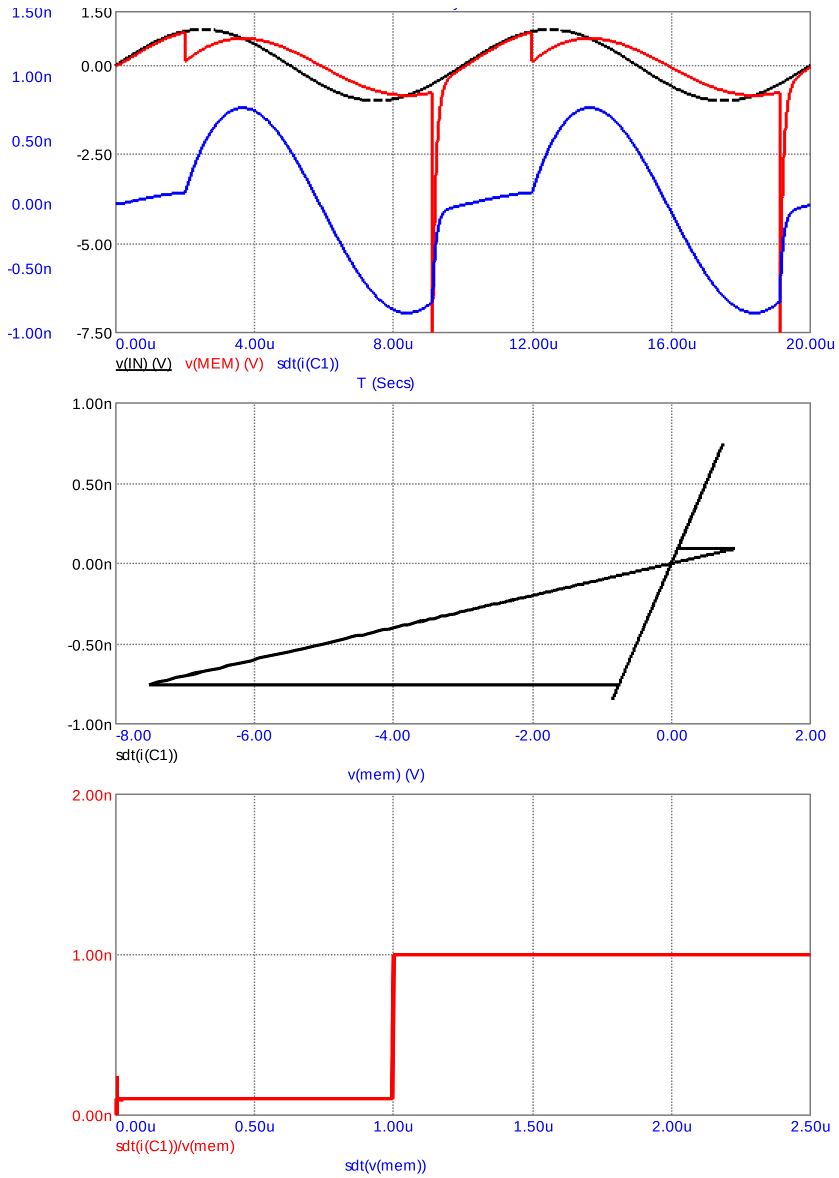

Fig. 5. Simulation of a memcapacitor driven by sinusoidal 1V/100kHz voltage source with 1kΩ serial resistor. Top: Exciting voltage (black), memcapacitor voltage (red), memcapacitor charge (blue). Middle: Coulomb-Volt pinched hysteresis loop. Bottom: Memcapacitance vs. flux.

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