Performance Analysis of Memcapacitor in an Op-Amp Integrator Circuit

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Abstract. The memcapacitor is a significant component of the memristive system family, serving as a circuit element that represents the relationship between magnetic flux (φ) and charge integral (σ). The primary distinctions between a memcapacitor and a standard capacitor can be outlined as follows: the capacity to store information without the necessity for an external power supply, a non-volatile structure, and nonlinear load–voltage characteristics. It is evident that such a circuit element exhibiting these characteristics will make a significant contribution to the field of electronics. In this study, an op-amp integrator circuit is considered in order to compare the dynamic performance of a standard capacitor and a memcapacitor with similar nominal capacitance values. As commercial production of memcapacitors has yet to be established, an emulator circuit is used for comparison purposes, rather than the memcapacitor itself. The analysis shows that the memcapacitor-based configuration provides a 33.3% faster settling time in response to a sinusoidal input signal than the standard capacitor-based configuration. This means that the signal at the integrator output can reach the steady state more quickly after a transient. Furthermore, simulations demonstrate that the memcapacitor circuit exhibits a significantly lower reactive power than the standard capacitor circuit, indicating reduced reactive energy exchange and improved energy efficiency.

Keywords: mem-elements, memcapacitor, emulator, integrator.

1 Introduction

In recent years, the discovery of memory elements has attracted significant attention in the field of electrical and electronics engineering. These so-called mem-elements, regarded as alternatives to the fundamental circuit components (resistor, capacitor, and inductor), first emerged in the scientific community with the discovery of the memristor [1-3]. Derived from the missing relationship between electric charge and magnetic flux, the impact of the memristor has stimulated the subsequent discovery of other memory-based circuit elements, namely the memcapacitor and the meminductor [4,5]. The mem-

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capacitor and meminductor share certain similarities with their conventional counterparts but also exhibit distinct behaviors due to their memory-dependent characteristics [6]. The notable features of a memcapacitor include its ability to store information without requiring an external power source, its inherent volatility that reflects a state-dependent memory effect and its nonlinear charge-voltage characteristics.

A standard capacitor functions as an energy-storing element, provides filtering and smoothing in analog circuits, supports timing and waveform-shaping operations, possesses a capacitance measured in farads (F), and exhibits a linear q–v relationship at high frequencies [1]. In contrast, a memcapacitor is a circuit element whose capacitance varies as a function of past excitations, thereby exhibiting a memory effect [2]. Figure 1 presents the symbolic representation and governing equations of both a standard capacitor (C) and a memcapacitor C_M. As shown, while the capacitance of a conventional capacitor is defined as the ratio of q to v, the memory behavior of a memcapacitor can be formulated not only through the q–v relationship but also within the flux–charge (φ–σ) framework.

A physical understanding of the memcapacitor can be achieved by describing its structure as a multilayer arrangement of conducting and insulating layers, as illustrated in Fig. 2. In this physical model, a memcapacitor can be represented as a combination of a fixed and a variable capacitor. While a conventional capacitor consists of a single insulating layer sandwiched between two conducting plates, a memcapacitor contains both constant and variable dielectric regions. In this configuration, L_{min} denotes the minimum dielectric thickness between the electrodes, L represents the instantaneous dielectric thickness (and thus determines the instantaneous capacitance), and L_{max} defines the maximum possible dielectric thickness. The variation of L is governed by the internal state of the device, which is controlled either by the charge flowing through the structure (charge-controlled type) or by the applied voltage (voltage-controlled type). The region between L_{min} and L_{max} represents the tunable dielectric layer responsible for the memory-dependent capacitance behavior [7].

Mem-elements exhibit promising characteristics; however, their lack of commercial availability limits their practical implementation in the electronic circuits. Therefore, various emulator circuits have been proposed in the literature to reproduce the electrical behavior of mem-elements [8-16]. Some of these emulators were developed by extending existing memristor architectures [17-20]. Others are designed with CMOS technologies [21,22] or ICs [23-[25] and utilize different active building blocks Consequently, depending on factors such as grounded or floating operation, the degree of electronic tunability, the complexity of the circuit architecture, and the presence or absence of experimental validation, the memcapacitor emulators proposed in the literature exhibit a wide range of distinct characteristics and performance attributes.

In this study, an integrator circuit is designed using a previously developed memcapacitor emulator [24] that possesses several advantageous features: it operates in a floating configuration without grounding constraints, does not contain any memristor element, supports both incremental and decremental forms, and offers electronic adjustability. The performance of the integrator circuit employing the memcapacitor emulator is compared with that of a conventional integrator circuit constructed using a standard

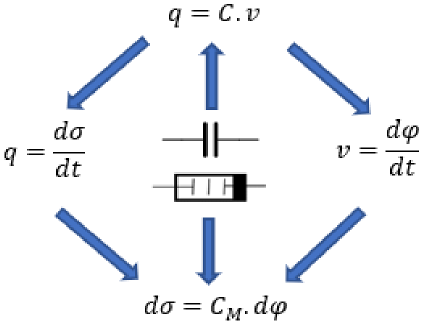


Fig. 1. From capacitor to memcapacitor.

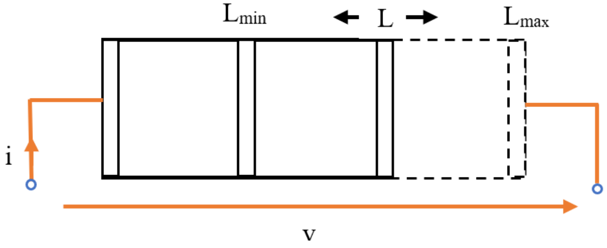


Fig. 2: Physical structure of memcapacitor [7].

capacitor. General characteristics of the memcapacitor emulator are presented in Section II, while a comparative analysis of integrator circuits with standard capacitors and memcapacitor emulators for three different input waveforms is presented in Section III. Finally, the conclusions of this study are summarized in Section IV.

2 Memcapacitor Emulator Circuit

A thorough understanding of how a memcapacitor influences circuit behavior can only be achieved by integrating it into practical electronic systems. However, its experimental implementation remains a complex challenge; therefore, research on memcapacitor equivalent circuit realizations continues to attract interest. For a conventional capacitor, the voltage depends on the charge via the well-known expression $= q/C$. In contrast, for a charge-controlled memcapacitor, the voltage can be expressed as $v = C_M^{-1}(\sigma)q$,where $C_M^{-1}(\sigma)$ represents the inverse memcapacitance, which varies with the entire charge history. This dependence suggests that the memcapacitor retains memory of past excitations and acts as a nonlinear energy storage element [26].

The general relation of a charge-controlled memcapacitor can be expressed as

$$v(t) = \left(\alpha \pm \beta\sigma(t)\right)q(t) \qquad (1)$$

where α and β represent the initial and variable components of the memcapacitance, respectively, corresponding to the charge flow [27]. An equivalent circuit that verifies the equational structure of the memcapacitor and provides traditional features such as frequency-dependent $q - v$ hypotheses and nonvolatility was designed in our previous work. The governing mathematical expression of the memcapacitor emulator shown in Fig. 3, as proposed in [24], is given below:

$$C_M^{-1} = \frac{v_{in}(t)}{q(t)} = \frac{1}{C_x} \mp \frac{R_b}{20 R_a R_s C_s C_x^2} \sigma(t) \tag{2}$$

This expression contains both a constant and a variable term, with the latter being dependent on the accumulated charge σ. Depending on the sign of the variable component, that is, according to the output polarity of the analog multiplier, the emulator behaves either as an incremental or a decremental memcapacitor, which provides the advantage of realizing both types of memcapacitive behavior within the same circuit structure without any hardware modification. Owing to its floating configuration, electronic tunability, and the absence of any complex memristive substructure, the proposed circuit offers a significant practical advantage, as it can be integrated into a wide range of applications without additional design complexity. The equivalent circuit configuration of the aforementioned memcapacitor emulator is presented in Fig. 3, where the values of the passive components used in the circuit are $C_x = 100\text{nF}$, $C_s = 220$ nF, $R_a = 60$ kΩ, $R_b = 80$kΩ, $R_s = 1$ kΩ respectively. The results of frequency-dependent hysteresis narrowing and volatility tests, two of the most significant properties of memcapacitors, are presented in Figures 4 and 5, respectively, providing successful experimental validation. The nonvolatility property refers to the ability of the memcapacitor to retain its charge state when no external voltage is applied. In other words, when the excitation is removed, the charge remains constant, and once the voltage is reapplied, the charge variation resumes from its previous state, confirming the device's memory-dependent behavior[25-27].

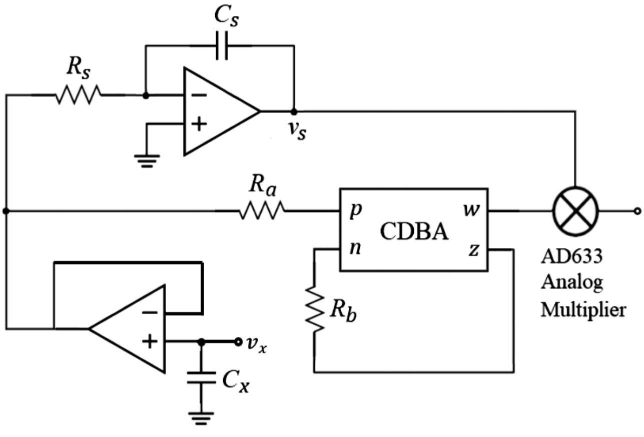


Fig. 3: Circuit schematic of the memcapacitor emulator.

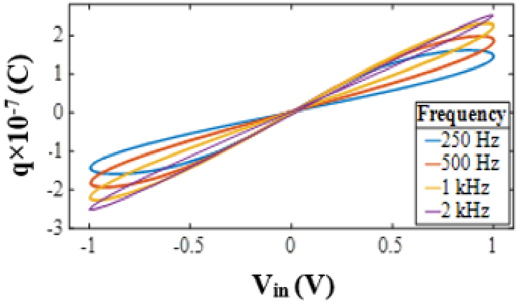


Fig.4. *q–v* characteristics of the memcapacitor emulator.

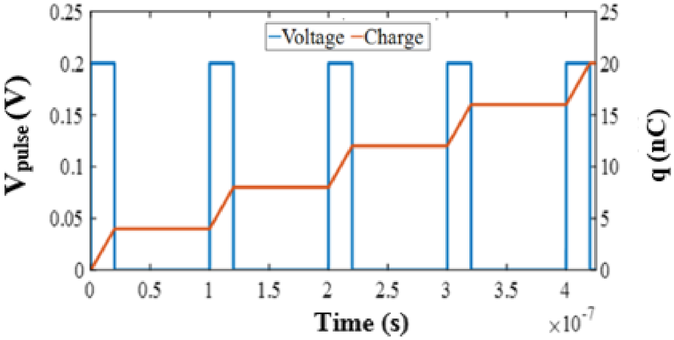


Fig.5. Nonvolatility test results of the memcapacitor emulator.

3 Memcapacitor-Based Integrator Circuits

An integrator circuit is a basic analog circuit that integrates the applied signal over time and produces the cumulative value of that signal at the output. It is typically designed using an op-amp and a capacitor as the feedback element is shown in Fig. 6 [28]. The output voltage of the integrator is determined by

$$v_{out}(t) = -\frac{1}{RC}\int_0^t v_{in}(t)dt. \tag{3}$$

In this circuit, the voltage across the capacitor corresponds to the time-dependent integral of the input current. Therefore, if the input signal has a constant amplitude, the output signal is a linearly increasing or decreasing voltage. Integrator circuits are used as fundamental building blocks in analog computer systems, filter designs, control, and signal processing applications. They are also an important tool for electrically modeling the behavior of dynamic systems expressed by differential equations.

In this section, the performance of an integrator circuit designed using a memcapacitor emulator instead of a standard capacitor is investigated for three different input waveforms. Fig. 6 illustrates the configuration in which the fixed capacitor used in a conventional integrator circuit is replaced with a memcapacitor emulator having the same average capacitance value $(220\, nF)$. The value of R used in the integrator circuit is $4\, k\Omega$. It can be observed that the integrator circuits designed with both the standard capacitor and the memcapacitor, each having the same average capacitance value, successfully integrate the applied input signals in both configurations. The output amplitudes obtained from the standard capacitor-based circuit for sinusoidal, square, and triangular input waveforms are measured as $180\, mV$, $284\, mV$, and $141\, mV$, respectively. In contrast, the memcapacitor-based circuit produces output amplitudes of $26\, mV$, $160\, mV$, and $77\, mV$ for the same waveform types. The frequency- and history-dependent nonlinear behavior of the memcapacitor, together with the storage of part of the energy within its hysteresis loop, reduces the effective integration gain and consequently leads to a noticeable decrease in the output amplitude. Furthermore, in electronic circuits, settling time is a critical parameter that determines the speed at which a system reaches steady state and directly affects the accuracy, stability, and energy efficiency of the circuit response. Figures 7, 8, and 9 show the input and output signals of standard and memcapacitor-designed integrator circuits in sinusoidal, square, and triangular waveforms, respectively. The results from the figures reveal that the memcapacitor circuit offers a significant advantage over the standard capacitor circuit in terms of settling time. A detailed analysis is provided in Table 1. These findings demonstrate that the memory effect and dynamic response characteristics imparted by the memcapacitor emulator to the integrator circuit enable faster steady-state transitions. This clearly demonstrates the significant advantage of memcapacitor-based circuits in electronic systems. In addition to the reduction in settling time, the memcapacitor-based integrator exhibits a lower percent overshoot, which confirms that the system reaches steady-state conditions with less transient deviation and improved damping behavior.

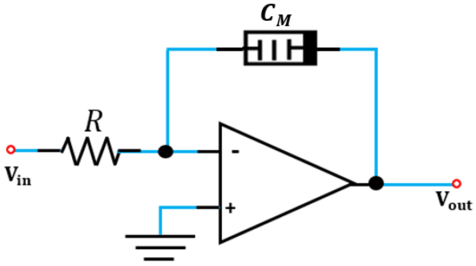
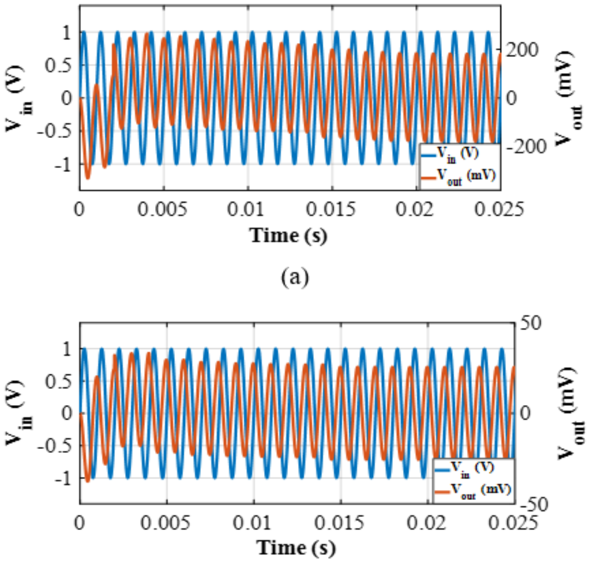


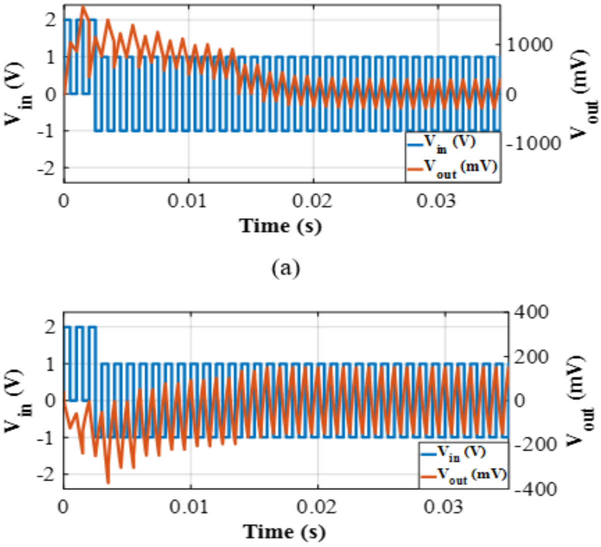
Fig.6. Integrator circuit employing the memcapacitor emulator.



(a)

(b)

Fig.7. Input and output waveforms of the integrator circuit for a sinusoidal input signal: (a) with standard capacitor, (b) with memcapacitor emulator.



(a)

(b)

Fig.8. Input and output waveforms of the integrator circuit for a square input signal: (a) with standard capacitor, (b) with memcapacitor emulator.

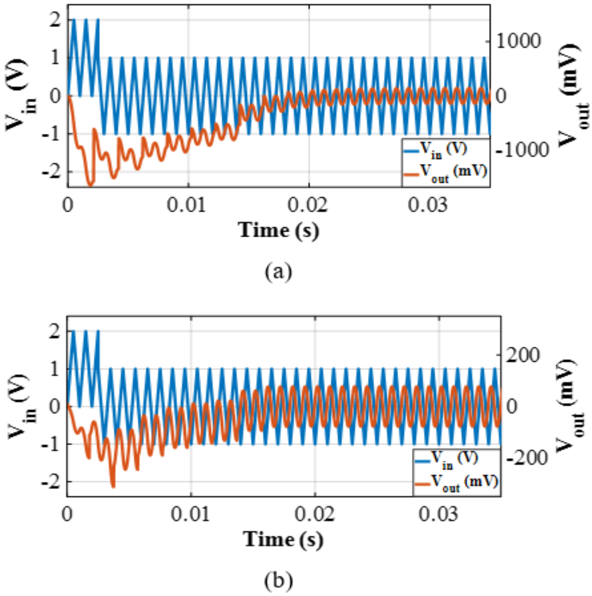


Fig.9. Input and output waveforms of the integrator circuit for a triangle input signal: (a) with standard capacitor, (b) with memcapacitor emulator.

Since the circuit exhibits capacitive properties, reactive power (Q) is calculated as $Q = -v^2/X_C$. Thus, the structural properties of the capacitor or memcapacitor directly influence the reactive power of the circuit [29]. Table 1 also presents the calculated reactive power values for three different input waveforms sinusoidal, triangular, and square measured for both the standard capacitor and the memcapacitor-based integrator circuits. The results clearly indicate that the reactive power obtained from the memcapacitor-based circuit is consistently lower than that of the conventional capacitor configuration for all waveform types. Consequently, the use of a memcapacitor emulator provides a distinct advantage in terms of energy efficiency, reduced power consumption in low-power analog applications.

Table 1. Comparative analysis of the standard capacitor (C) and memcapacitor (C_M) in the integrator circuit

Wave form	Element	Settling time (ms)	Reactive power (µVAR)
sinusoidal	C	21	-23.44
	C_M	14	-0.49
square	C	31	-58.34
	C_M	17	-18.51
triangle	C	24	-14.38
	C_M	16	-4.29

In the analyses performed with different input waveforms, it was observed that even in the integrator circuit employing a standard capacitor, the settling time and reactive power varied depending on the waveform shape. This behavior originates from the distinct frequency components and harmonic contents of the input signals. The sinusoidal waveform, having the lowest harmonic content, resulted in the shortest settling time, whereas the triangular and especially the square waveform led to longer settling times and higher reactive power values due to their higher frequency content. When a memcapacitor emulator was incorporated into the circuit, these effects became more pronounced because the memcapacitor's frequency-dependent and memory-dependent nature directly affected the system's transient and reactive behavior. Consequently, in memcapacitor-based circuits, both the settling time and reactive power exhibited a strong dependence on the waveform type, reflecting the memcapacitor's nonlinear, frequency-dependent, and memory-dependent characteristics.

4 Conclusion

In this study, the dynamic performance of an op-amp integrator circuit employing a memcapacitor emulator has been analyzed and compared with that of a conventional capacitor-based configuration. The investigation was carried out using three different input waveforms-sinusoidal, triangular, and square-under identical circuit conditions. The results reveal that the memcapacitor-based circuit exhibits a considerably shorter settling time compared to the standard capacitor circuit, achieving an improvement of up to 33% for the sinusoidal input. This indicates that the memcapacitor allows the integrator output to reach the steady-state condition more rapidly after a transient response. Furthermore, the analysis of reactive power demonstrates that the memcapacitor-based configuration consistently produces lower reactive power values than the conventional circuit for all waveform types This finding demonstrates that the memcapacitor-based configuration not only provides a faster transient response but also exhibits a more energy-efficient behavior. This characteristic offers a significant advantage for applications where power efficiency is critical, such as low-power analog computing, portable electronic devices, energy-conscious sensor interfaces, neuromorphic circuits, and large-scale systems requiring collective power optimization. Therefore, the memcapacitor-based integrator emerges as a superior and more practical alternative to conventional capacitor-based designs in terms of both dynamic performance and energy efficiency.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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