

Analysis of non-ideal Time-varying-based Negative Capacitor

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Negative capacitors (non-Foster capacitors) have been studied very intensively in recent years due to their potential use in broadly-matched small antennas and broadband active metamaterials and metasurfaces (S. Hrabar, “First ten years of active metamaterial structures with “negative” elements,” EPJ Applied Metamaterials, vol. 5, no. 9, 2018). Negative capacitors have a dispersion curve that is a “negative image” of the dispersion curve of ordinary positive capacitors. Therefore, their dispersion curves can cancel each other out, resulting in the broadband behavior described above. A classic way of constructing negative capacitors uses special electronic circuits that either “convert” a load impedance into a scaled negative load impedance ($Z \sim -Z_{\text{load}}$, $Y \sim -Y_{\text{load}}$) (Negative Immittance Converter) or “invert” a load impedance into a negative inverse of the load impedance ($Z \sim -1/Z_{\text{load}}$, $Y \sim -1/Y_{\text{load}}$) (Negative Immittance Inverter). Although the use of NIC and NII is very common, they have two important drawbacks: a) they are prone to unstable operation due to the unavoidable use of positive feedback; b) the accuracy of the generated negative capacitance is very sensitive to non-idealities of NIC/NII circuits as well as the Q factor of the load.

Recently, it has been shown that a negative capacitance effect can also be achieved by a time-varying capacitive element (e.g., varactor) whose modulation signal should have the DC offset (“bias”), together with the well-known harmonic AC signal (S. Hrabar, “Time-varying Route to Non-Foster Elements,” 2020 International Congress on Artificial Materials for Novel Wave Phenomena New York, NY, USA, 2020, pp. 108-109). A very recent theoretical analysis (S. Hrabar, J. Bartolić, S. Ilijić, “Frequency-domain Interpretation of Time-varying-based Negative Capacitor”, PIERS 2025, Abu Dhabi, UAE) has shown that a time-varying-based negative capacitor can be considered as a parametric up-converter in which all higher current harmonics cancel each other out. Furthermore, the total DC and AC energy is converted into the energy of an ‘assisting source’ at the fundamental frequency. The superposition of the signal from this ‘assisting source’ with the input signal results in an effective negative capacitance, analogous to the operation of an ordinary NIC/NII. Because of this apparent similarity in the background physics of the operation of classical NIC/NII-based negative capacitors and time-varying-based capacitors, one can speculate that the influence of non-idealities may also be similar.

We tested the above hypothesis by transforming the modulation function of a time-varying-based capacitor into the frequency domain and introducing various non-idealities such as the intrinsic parasitic resistance and inductance as well as the magnitude and phase errors of the input signal. It was found that some of these non-idealities mainly affect the frequency dispersion of the generated negative capacitance, while the others cause the appearance of the real part of the input admittance, which can be both positive and negative (thus introducing either additional loss or gain). The amplitude and phase error of the input signal has also been found to play a role similar to that of the non-ideal frequency characteristic or Q-factor of a load in ordinary NIC/NII-based negative capacitors. Moreover, the presence of non-idealities can cause the occurrence of instability, which again corresponds to the similar behavior in NIC/NII-based negative capacitors. Finally, all analytical results were checked with the commercial circuit theory simulator and good agreement was found. Currently, we are preparing a simple experiment to test the above analysis and preliminary results will be presented at the conference.

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