Automatic LC Network Tuner Based on Negative Resistances

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In this letter we propose a novel technique to tune an inductor-capacitor (LC) network based on a receiving signal frequency. The method consists in using a negative resistor to artificially increase the quality factor of the LC circuit to reduce the decision range of the voltage detectors. This approach allows the usage of low complexity algorithms that converge in a few steps. The technique was validated through a demonstrator for Radio-frequency identification (RFID) tags in production line testing, with satisfactory results. The designed negative resistor maintained a constant resistance for a large range of input signals.

Introduction: Tuned circuits are commonly used in electronic circuits such as oscillators, filters, amplifiers and matching networks. Mainly composed by inductors (L) and capacitors (C), they are used because of the resonance effects observed when the capacitor and inductor reactances present the same magnitude value. As a result of variations around the nominal values of the passive devices, the mistuning of the LC networks may significatly degrade the circuit's required performance. For instance, in radio-frequency identification (RFID) applications, where both the reader and the transponder have an LC network to enable data and energy communication [1], the network mistuning can reduce the reading range. Several methods have been proposed to retune the LC network to the designed frequency. The authors in [2] tried to alleviate it, on the reader side, by proposing an electrically tunable inductance placed on the reader to retune it. In the circuit presented in [3], a self-calibration circuit is used to measure the frequency of a reference signal sent by an interrogator, and uses it to tune a LC network that defines the oscillation frequency of the transponder oscillator. In [4] a tuning technique is presented for an energy harvester circuit, that takes the derivative of the rectified input voltage signal as function of the LC network resonance frequency, which is changed by varying the value of a capacitor. In this letter we propose a novel method for tuning LC networks, which can be applied to the calibration of RFID transponders, oscillators and several types of tuned circuits. The method consists in artificially narrowing the bandwidth of the network and consequently increasing the induced voltage at its terminals. Based on the output of a voltage detection circuit, a fast and simple algorithm can find the adequate capacitor that tunes the network to the desired frequency. It allows the implementation of low-cost and low-area circuits for testing in production line or even for self-testing strategies.

Proposed Solution: To show the proposed solution, we first analyze the voltage transfer function of the unloaded LC network shown in Fig. 1 given by:

$$|H(s)| = \frac{v_o}{v_{in}}(s) = \frac{1}{sC(sL+R_S)+1}, \tag{1}$$

where we consider that a voltage is induced across the inductor that has an intrinsic series resistance represented by R_S.

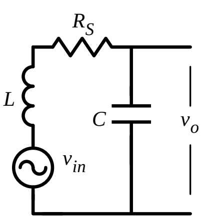

Fig. 1: RLC network.

As seen in (1), the amplitude of the output voltage v_o is inversely proportional to the series resistance of the inductor. It is straightforward to show that the 3-dB bandwidth of the RLC network is directly proportional to R_S as seen in Fig. 2(a). In this figure we plotted the transfer function of (1) using two values for R_S (60 Ω and 20 Ω). The LC network is tuned at 125 kHz, which is a frequency used in RFID applications, and generic values are used for L and C. It can be noted a significant increase of the voltage transfer function absolute value, at the resonance frequency ($|H(\omega_0)|$), for the 20 Ω resistance curve. The value of $|H(\omega_0)|$ can be estimated by assuming a high quality factor inductor, that is, $Q > 10$, and that the frequency of (1) is set to the network's resonant frequency $\left(w_0 = \frac{1}{\sqrt{LC}}\right)$. Hence, the absolute voltage transfer function can be approximated by:

$$|H(s)|\,\big|_{s=j\omega_0} \cong \frac{\sqrt{L/C}}{R_S}. \tag{2}$$

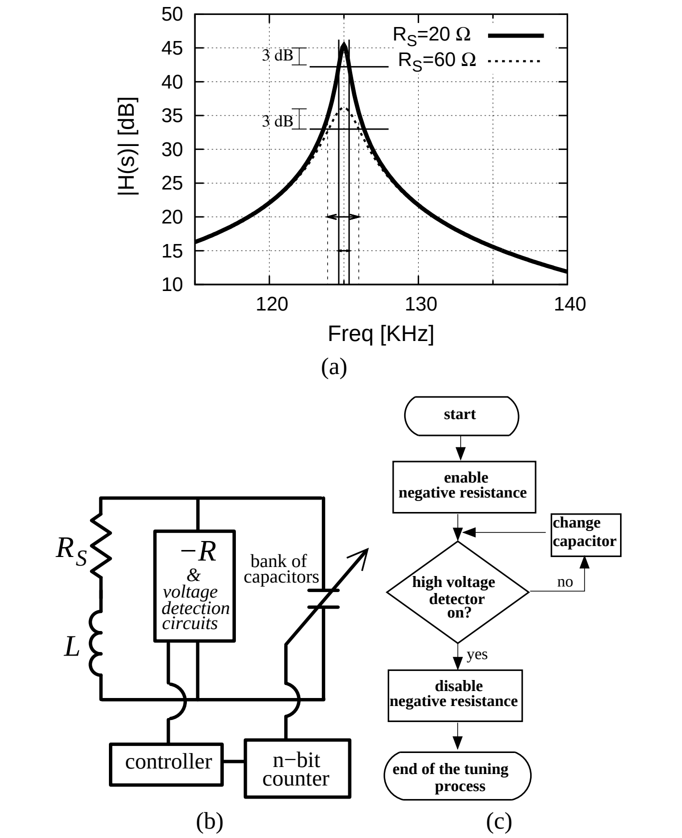

Fig. 2: (a) Effects of R_S reduction, (b) block diagram of the proposed system, (c) a suggested flowchart.

From (2), it is possible to note that if the output voltage at resonance needs to be increased to detect when the LC network is tuned, R_S should be decreased by the same amount.

With the 3-dB bandwidth reduction and with the observed voltage transfer function characteristics it is possible to assert that if one detects the 3-dB bandwidth of the LC network, these frequency points will be closer to the resonant frequency and have a greater magnitude value if R_s is decreased. Hence, it is feasible to match the LC resonant frequency with the input signal by reducing R_S, shifting the network's equivalent capacitance value, and analyzing whether the voltage level has reached a certain threshold. In other words, the proposed LC tuning method increases the quality factor of its network, using a synthesized negative resistor, and it decides if the circuit is tuned based on a predetermined voltage threshold. This solution is not based on large area circuits, as it requires one circuit to increase the input quality factor, voltage detectors, a controller, and a counter that enables/disables the capacitor's bank of the LC network, as seen in Fig. 2(b).

The use of a negative resistance to increase the LC network quality factor is a classical technique as seen in [5]. Normally, these techniques are designed to work with low voltage levels; however, the system proposed in this letter requires a negative resistor that maintains the same impedance for larger voltage signals. With this prerequisite, the proposed technique can be implemented and it is possible to conceive simple voltage detectors, such as inverters.

The proposed self-tuning procedure is shown in the flowchart of Fig. 2(c). The tuning procedure starts after the decision of calibration, which can be made automatically. After this step, the negative resistance is

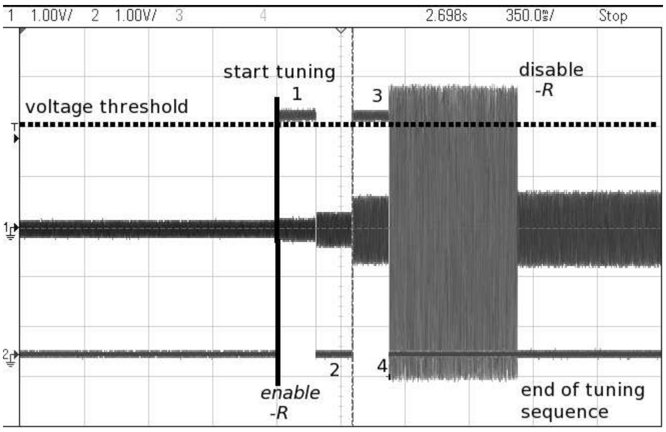

Fig. 3: Example of a tuning sequence.

enabled, a higher voltage detector is analyzed, and if it is not on, the counter value is changed until this detector is activated. In the next stage, the negative resistance is disabled and the system is considered tuned with the source voltage.

System Implementation: We constructed a prototype to demonstrate the proposed solution of this letter. In this conceptual design, the negative resistor was implemented with two bipolar junction transistors (BJTs) in a cross-coupled configuration [6] using one DC tail current source on their emitters. The negative resistor topology requires a DC voltage polarization on the BJT's collector, hence it can be used a tapped inductor or two inductors to insert the necessary voltage on its common node. To obtain a constant negative resistance throughout a large voltage range, a circuit that controls the negative resistor DC current tail was also implemented. It measures the network's peak voltage and sets the DC negative resistor current proportional to this parameter. The negative resistance was enabled through a switch, connected in series with its current source. Finally, a 3-bit counter was implemented in a microcontroller to change the input impedance among three capacitors. This device is arbitrarily programmed to wait 200 ms for each counter value and to wait 700 ms if the high voltage detector is activated.

It is possible to see the prototype's tuning sequence in Fig. 3, where the measured voltage wave on the LC network and the counter's least significant bit are taken from the oscilloscope's channels 1 and 2, respectively. The LC network is detuned with the input signal before the tuning sequence as seen by the oscilloscope's channel 1. When the tuning sequence starts and the LC network voltage reaches the voltage threshold, the negative resistance is disabled, as seen at the end of step 4. It is necessary to remember that the amplitude level at step 3 is closer to the one obtained after the tuning sequence because at this step the system is under the effects of the negative resistance.

Conclusions: A novel LC network tuning technique, based on the use of negative resistors, is presented in this letter. Because of the nature of the cross-coupled transistors, a feedback circuit must be implemented to control its value, otherwise the system could oscillate. One advantage of the method is that we translated a frequency detection to a voltage detection, which can be implemented by larger voltage circuits, such as the inverters, making the tuning decisions very simple. The proposed system can be implemented to tune any LC network as such as the near field RFIDs in production lines. It is appropriated to be integrated in silicon as it has a small area overhead because of the nature of the technique. We also presented a demonstrator that finds its best capacitor configuration with satisfactory testing results.

Acknowledgment: This study has been supported by the National Council for Scientific and Technological Development (CNPq) and by the National Institute for Science and Technology of Micro and Nanoelectronic Systems (INCT NAMITEC).

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