



The Design of High-Sensitivity Capacitive Sensors

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ABSTRACT

The design of a high-sensitivity capacitive sensor is achieved by decreasing the destabilizing effect of the temperature and supply voltage. The potential impact of the generators' frequency on capacitance measurement is studied. The stability and sensitivity of several kinds of stabilized quartz generators are studied. Based on the results, an intelligent capacitive sensor is developed to measure the extremes of bulk materials. The developed sensor can be used in a wireless sensor network.

Keywords: Capacitive Sensor, Sensor Network, Quartz Generator

1. Introduction

In recent years there has been an explosion in sensor technology. The selection of sensor for a given application depends on the nature of physical objects that must be observed, such as temperature, pressure, humidity or level of materials [1].

Traditionally, environmental monitoring is achieved through expensive sensors with high accuracy. Creating a wireless sensor network provides an alternative solution by deploying a larger number of sensor nodes with less precision. Network as a whole, however, provides better spatial resolution of the area and users can have immediate access to data [2].

The capacitive sensor that controls the extremes of bulk materials with very low permittivity has been developed by authors in [3-5]. The sensor provides high sensitivity in spite of the influence of destabilizing factors like variation of temperature and supply. Changing the capacity of the sensor leads to a change in the frequency of quartz stabilized generator to which the sensor is plugged.

The aim of this work is to further enhance the sensitivity of the sensor by choosing appropriate generators and quartz resonators, and its adaptation for inclusion in the wireless sensor network.

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2. Schematic Diagram Of The Capacitive Converter

The block diagram of developed capacitive sensor is shown on figure 1. A capacitive converter S with capacity C_X is connected to quartz stabilized generator $G1$. The frequency of the generator is varying within a certain range in capacity adjustment C_X . The output signal with frequency f_X from the digital comparator compares the frequency f_r of the second supporting quartz stabilized generator $G2$.

Upon reaching certain, predefined ratio of the both frequencies, control signal is generated at the output of the comparator [6].

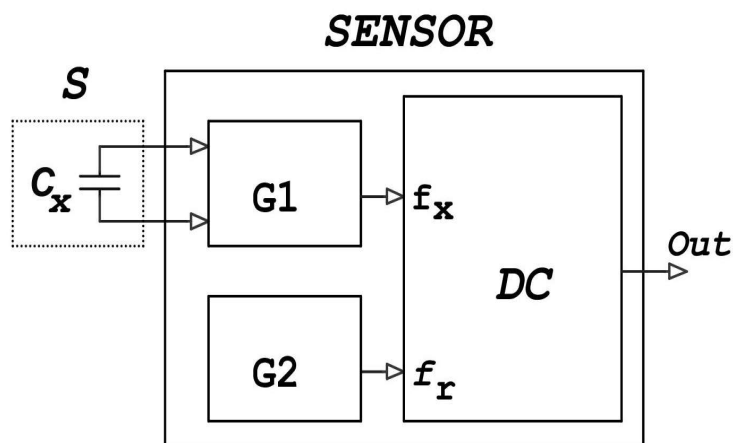


Figure 1. Scheme to monitor the capacity variation of capacitive sensor

The sensitivity of the sensor is determined by the ratio of the frequencies of both generators. It can be changed in wide ranges by setting the digital comparator [7].

To increase the sensitivity of the capacitive sensor it is necessary to reduce the instability of the two generators' frequencies, caused by alteration of the temperature and supply voltage changes of both generators.

There exist a great variety of quartz generators in the literature. Only several schemas of stabilized quartz generators - with an active element transistor, TTL or CMOS integrated circuit fulfill the requirements of our development.

A great number of investigations on selected schemes have been made. It was found different variation of the frequencies of each generator for changes in the ambient temperature and alteration of the supply voltage.

In this publication, due to the limited number of pages only the best results obtained for the two of analyzed schemes are presented. Studies have shown that two basic patterns of quartz stabilized generator - with TTL integrated circuit (Figure 2) and with CMOS integrated circuit (Figure 3) are the most appropriate for our sensor. Both schemes are similar. Primary capacitive converter with capacity C_X is connected to the stabilized quartz generator serially linked with quartz resonator. The frequency of the generator can be adjusted in small ranges.

3. Experimental Results

For greater accuracy and precision of the sensor it is necessary to use two identical generators. The experiments were performed with two pairs of generators. It was used different types of quartz resonators with serial resonance frequency F_s varying from 1 MHz to 10 MHz in dependence on the lowest temperature fluctuation.

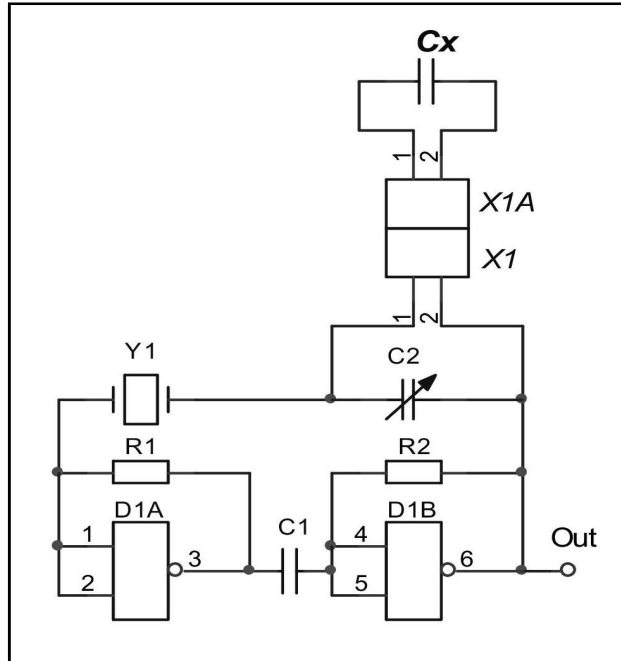


Figure 2. Capacitive converter with TTL integrated circuit

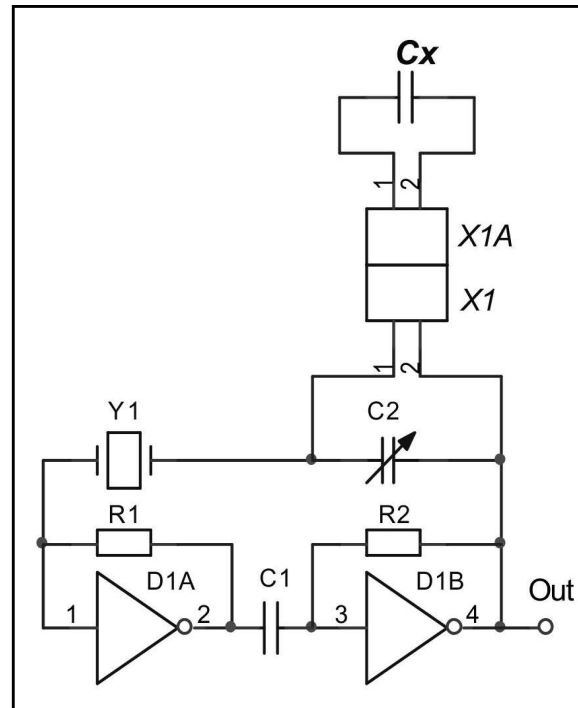


Figure 3. Capacitive converter with CMOS integrated circuit

3.1. Investigations of Capacitive Converter with TTL Integrated Circuit

Temperature dependences of the generators' frequency F_X for frequencies of the quartz resonators, respectively $F_{S1.1} = F_{S1.2} = 1 \text{ MHz}$ and $F_{S2.1} = F_{S2.2} = 5 \text{ MHz}$ are display on Figure 4 and Figure 5.

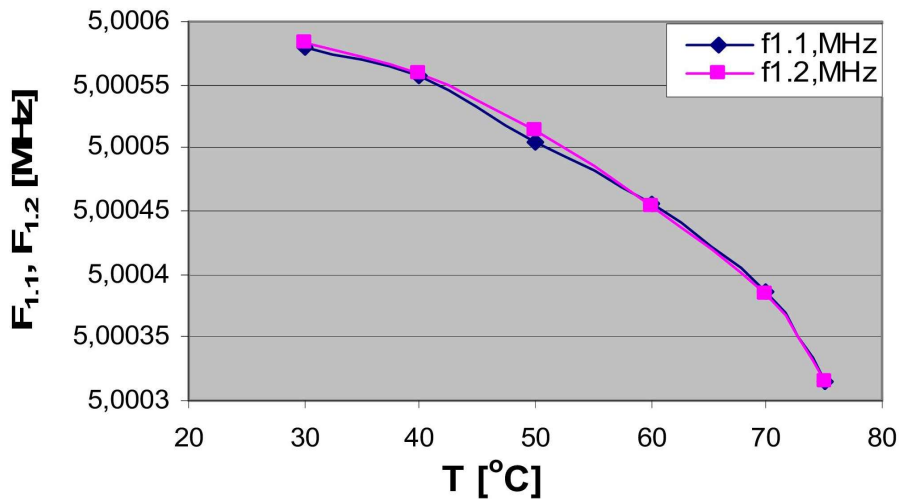


Figure 4. Dependence $F_x = \varphi(T)$, where $F_s = 5$ MHz

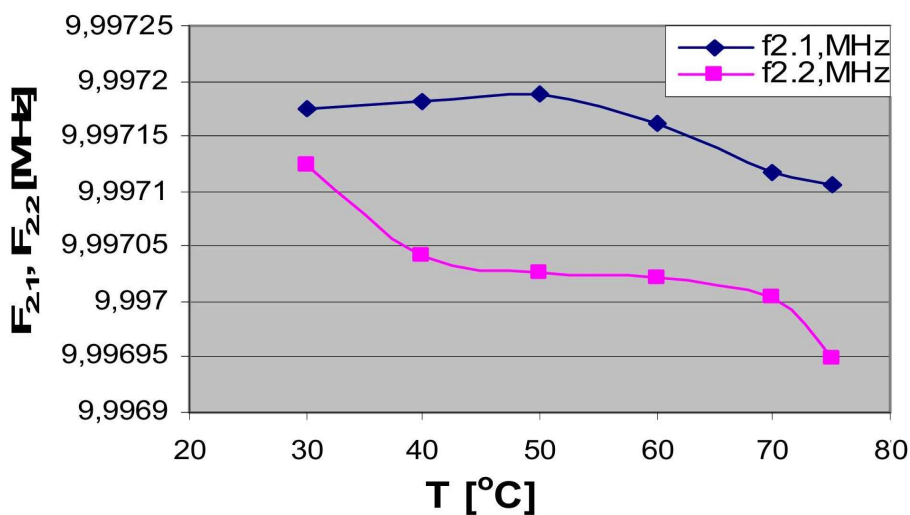


Figure 5. Dependence $F_x = \varphi(T)$, where $F_s = 10$ MHz

It is clearly seen from results that the deviation of the frequencies is extremely small – below 10^{-4} for $F_s = 5$ MHz and below $2 \cdot 10^{-5}$ for $F_s = 10$ MHz with changes in ambient temperature with 45° C. This corresponds to instability, less than $10^{-5} / C^\circ$ ($F_s = 5$ MHz) and less than $10^{-6} / C^\circ$ ($F_s = 10$ MHz).

As the output of the sensor (figure 1) is given control signal upon reaching a predefined ratio of the frequencies of the two identical generators, it is more important to compare the temperature dependencies of the frequencies ratio of both generators. The results for two quartz generators with frequencies $F_{S1.1} = F_{S1.2} = 5$ MHz and $F_{S2.1} = F_{S2.2} = 10$ MHz are presented, respectively on figure 6 and figure 7.

Obviously, the deviation of ratio of both generators' frequencies for variation of environmental temperature with 45° C is much less – below $2 \cdot 10^{-6} / C^\circ$ for first generators and below $10^{-5} / C^\circ$ for others. This corresponds to instability, less than $10^{-7} / C^\circ$.

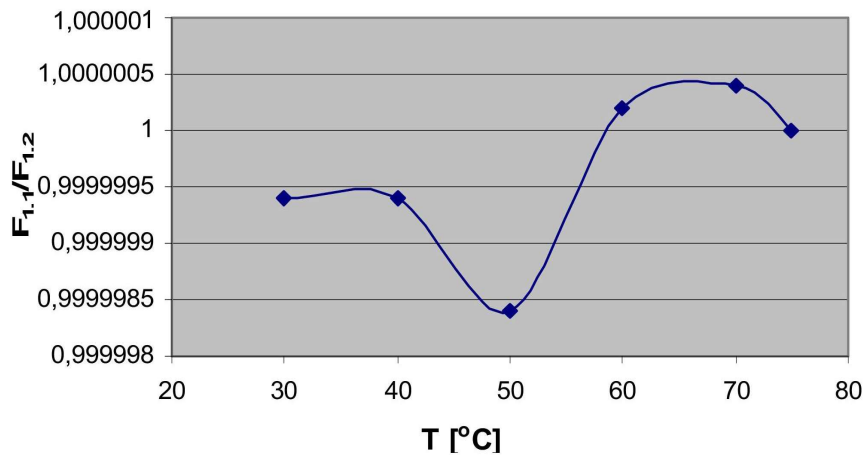


Figure 6. Dependence $F_{1.1} / F_{1.2} = \varphi(T)$, where $F_s = 5$ MHz

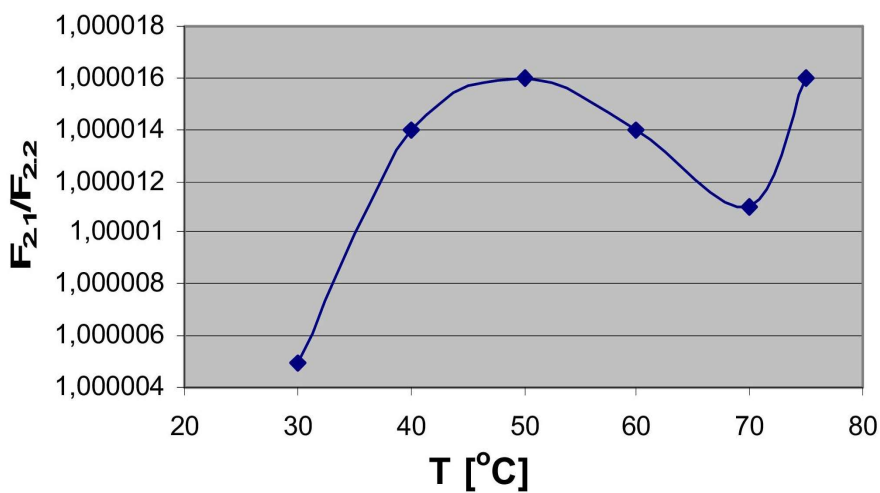


Figure 7. Dependence $F_{2.1} / F_{2.2} = \varphi(T)$, where $F_s = 10$ MHz

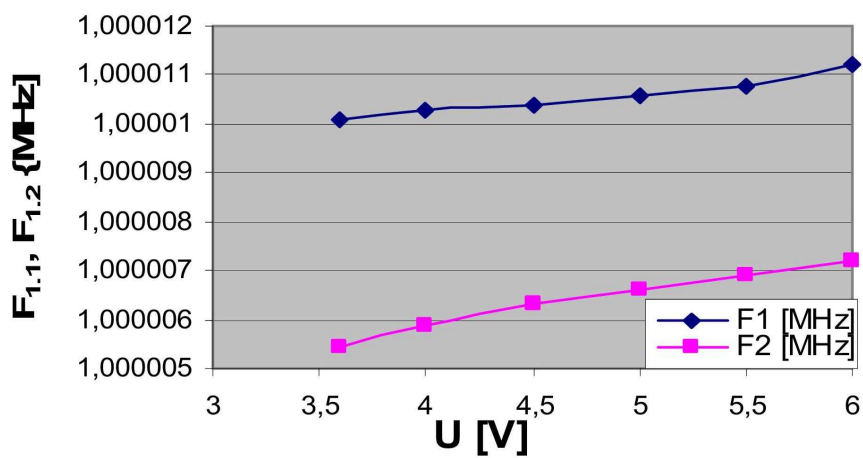


Figure 8. Dependence $F_{1.1} = \varphi(U)$, $F_{1.2} = \varphi(U)$, where $F_s = 1$ MHz

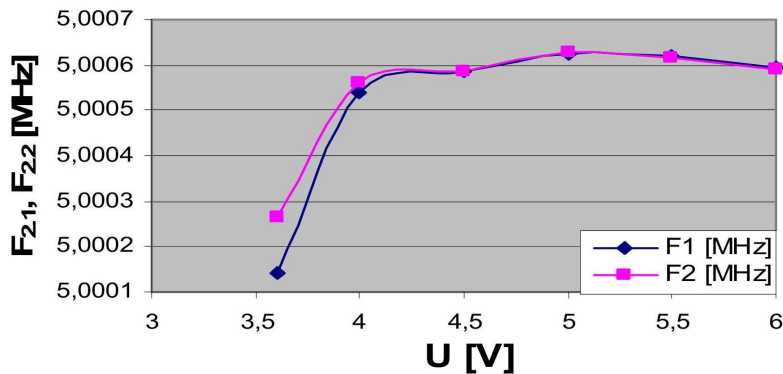


Figure 9. Dependence $F_{2,1} = \varphi(U)$ $F_{2,2} = \varphi(U)$, where $F_s = 5$ MHz

Figure 8 and figure 9 illustrate the dependences of the generator's frequency F_X for change of the voltage U_X if the frequencies of quartz resonators are $F_{S1,1} = F_{S1,2} = 1$ MHz and $F_{S2,1} = F_{S2,2} = 5$ MHz. The figures show that the frequency is changed in very small range – of the order of $5 \cdot 10^{-6}/V$ for the first resonator and below $10^{-4}/V$ for the second in case of voltage alteration U from 4 to 6V.

Next two figures (figure 10 and figure 11) are connected with investigation the impact of the variation of the voltage on the ratio of the generators' frequencies, respectively, for frequencies of both quartz generators $F_{S1,1} = F_{S1,2} = 1$ MHz and $F_{S2,1} = F_{S2,2} = 5$ MHz.

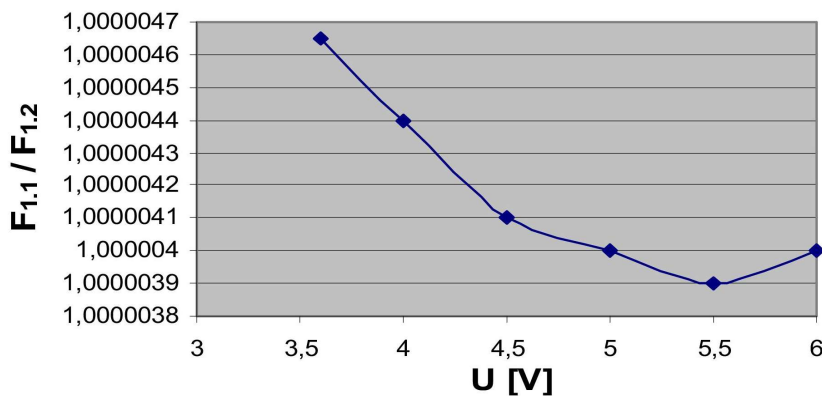


Figure 10. Dependence $F_{1,1} / F_{1,2} = \varphi(U)$, where $F_s = 1$ MHz

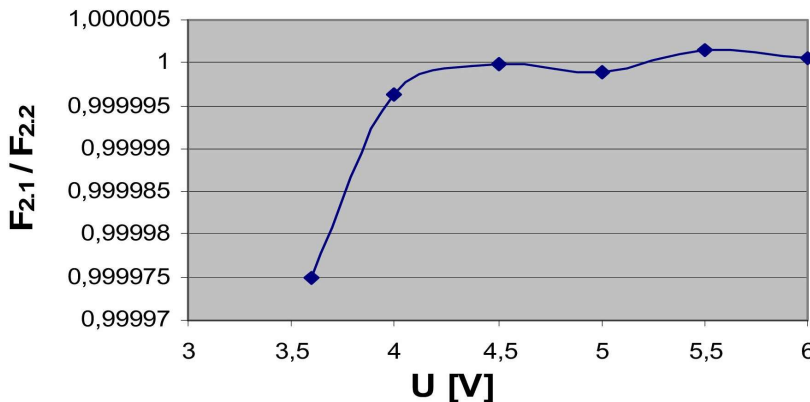


Figure 11. Dependence $F_{2,1} / F_{2,2} = \varphi(U)$, where $F_s = 5$ MHz

As it was expected variation of voltage U led to alteration in ratio of the frequencies of both generators bellow $5 \cdot 10^{-7}/V$ for $F_S = 1$ MHz and less than $10^{-5}/V$ for $F_S = 5$ MHz.

3.2. Investigations of Capacitive Converter with CMOS Integrated Circuit

The results of experimental studies of the scheme on figure 3 are presented on figure 12 ÷ figure 19.

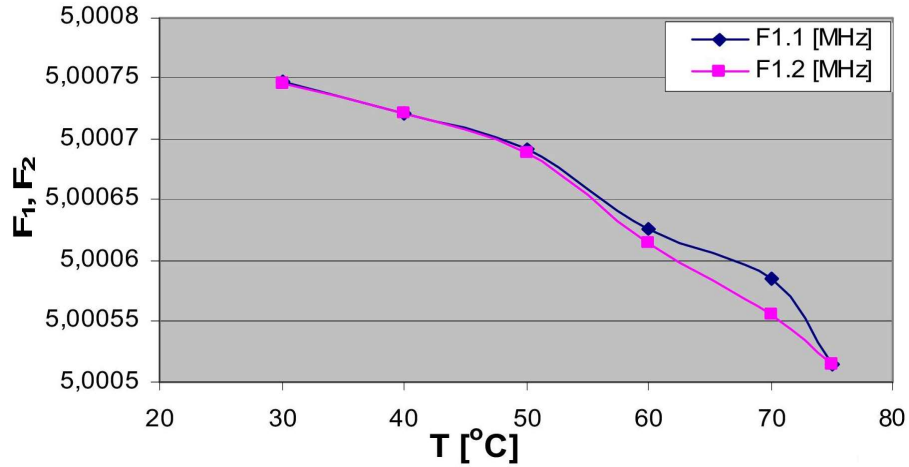


Figure 12. Dependence $F_{1.1} = \varphi(T)$, $F_{1.2} = \varphi(T)$, where $F_S = 5$ MHz

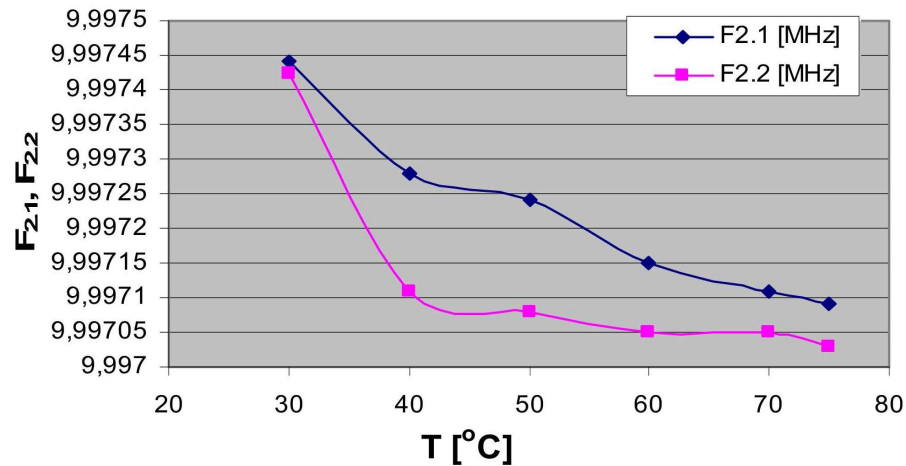


Figure 13. Dependence $F_{2.1} = \varphi(T)$, $F_{2.2} = \varphi(T)$, where $F_S = 10$ MHz

Dependencies of the frequencies of the generators $F_{x,y}$ by the variation of the ambient temperature T , given frequencies of the quartz resonators, respectively $F_S = 5$ MHz and $F_S = 10$ MHz are presented on figure 12 and figure 13. Temperature instability under these conditions is less than $10^{-5}/^{\circ}\text{C}$ for $F_S = 5$ MHz and bellow $10^{-6}/^{\circ}\text{C}$ for $F_S = 10$ MHz.

As mentioned in the previous section for proposed schemes (figure 2, figure 3) the temperature dependence of the ratio of both generators' frequencies is more importantly. It can be seen from figure 14 and figure 15 that the temperature instability of the ratio $F_{1.1} / F_{1.2}$ is less than $10^{-6}/^{\circ}\text{C}$ if $F_{S1.1} = F_{S1.2} = 5$ MHz, respectively for $F_{2.1} / F_{2.2}$ the instability is bellow $3 \cdot 10^{-7}/^{\circ}\text{C}$ for $F_{S2.1} = F_{S2.2} = 10$ MHz.

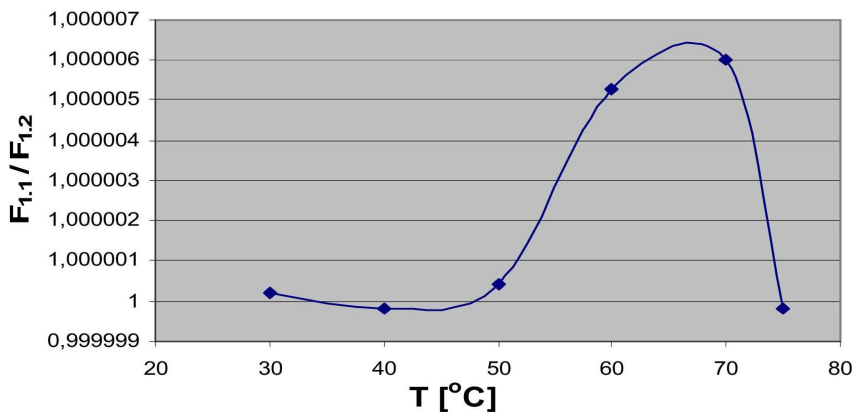


Figure 14. Dependence $F_{1.1} / F_{1.2} = \varphi(T)$, where $F_s = 5$ MHz

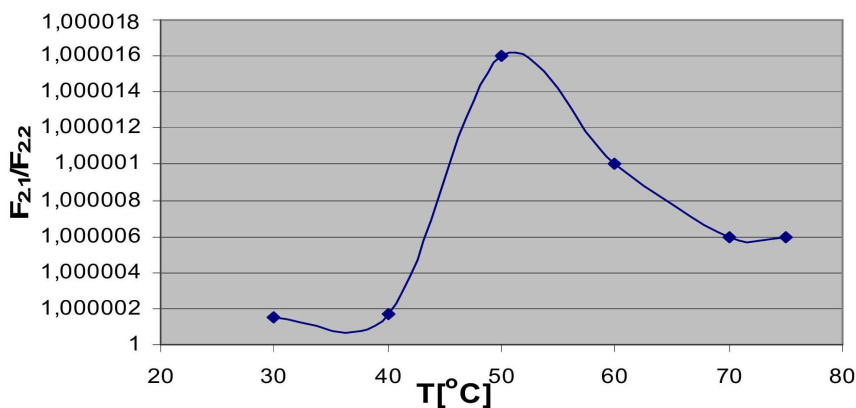


Figure 15. Dependence $F_{2.1} / F_{2.2} = \varphi(T)$, where $F_s = 10$ MHz

The last group of studies are related to determining influence of changes in voltage on the frequency of generator, given frequencies of quartz resonators, respectively $F_{S1.1} = F_{S1.2} = 1$ Mj H(Uz a)nd $F_{S2.1} = F_{S2.2} = 5$ MHz.

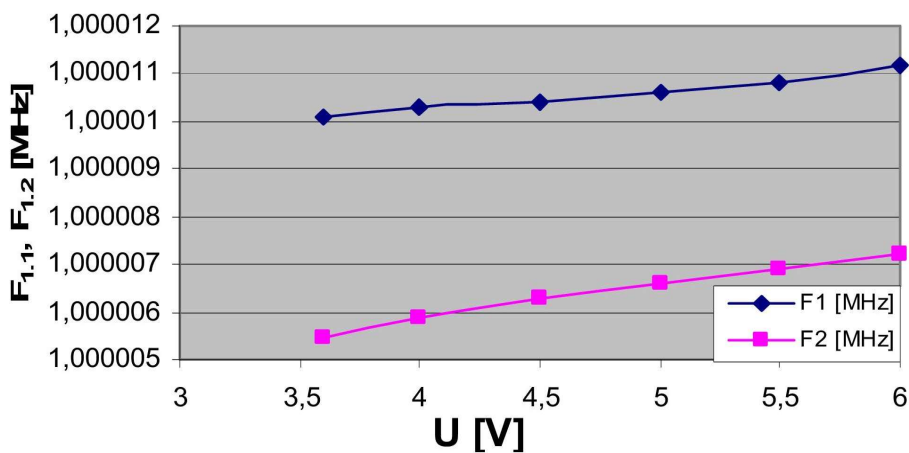


Figure 16. Dependences $F_{1.1} = \varphi(U)$, $F_{S1.2} = \varphi(U)$, for $F_s = 1$ MHz

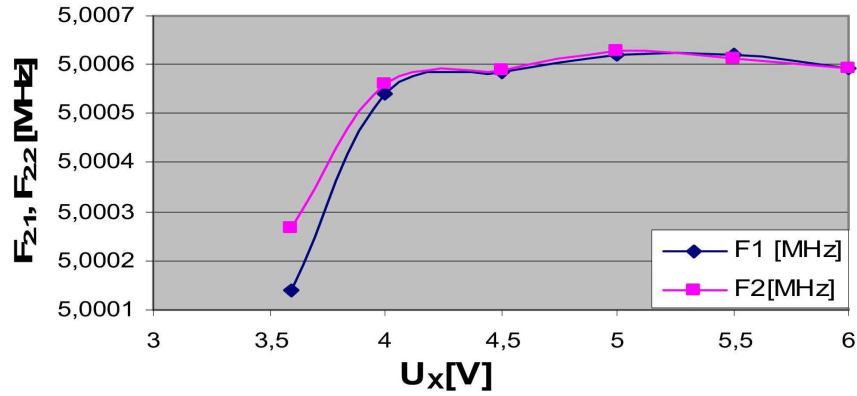


Figure 17. Dependences $F_{2,1} = \varphi(U)$, $F_{2,2} = \varphi(U)$, for $F_s = 5$ MHz

From the resulting dependences, shown on figure 16 and figure 17 follows that the instability of the generators' frequencies under the relevant conditions ($F_{1,1}$, $F_{1,2}$, $F_{2,1}$, $F_{2,2}$) to alteration the voltage is less than $10^{-5}/V$ for $F_s = 1$ MHz and below $10^{-4}/V$ for $F_s = 5$ MHz.

Finally, the ratio of frequencies of both generators dependences to variation of voltage, respectively, for frequencies of both quartz generators $F_{S1,1} = F_{S1,2} = 1$ MHz and $F_{S2,1} = F_{S2,2} = 5$ MHz are displayed on figure 18 and figure 19. The frequency instability of both generators is less than $10^{-6}/V$.

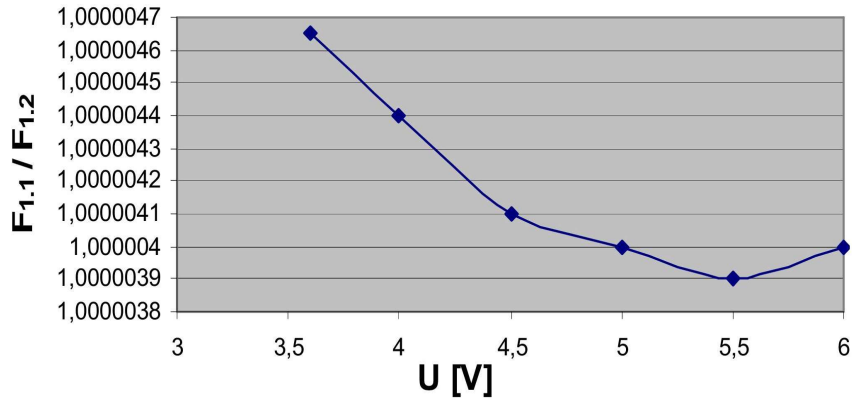


Figure 18. Dependence $F_{1,1} / F_{1,2} = \varphi(U)$, for $F_s = 1$ MHz

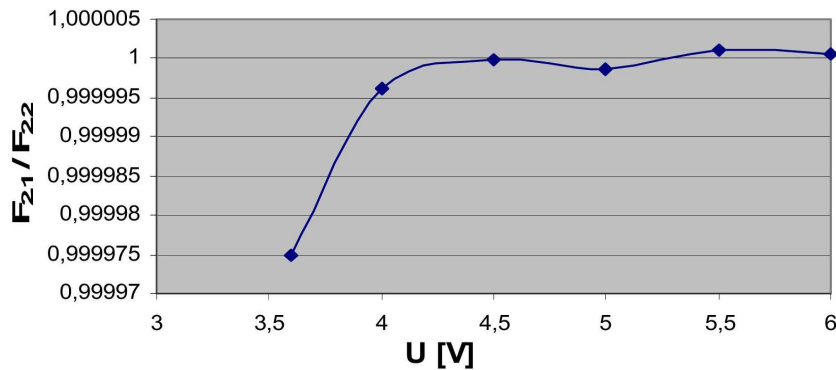


Figure 19. Dependence $F_{2,1} / F_{2,2} = \varphi(U)$, for $F_s = 5$ MHz

4. Analysis

As it is well known the value of frequency instability varies depending on particular scheme and used quartz resonator. It can be concluded from made experiments that for proposed schemes of capacity sensor the influence of the variation of the ambient temperature and voltage to generated frequencies is extremely small.

In addition for further increasing the sensitivity of the designed capacitive sensor it is necessary to be ensured the equal working conditions for both (the measuring G1 and the supporting G2) generators of the scheme shown in Figure 1.

This was achieved in following ways:

1. To ensure a very small difference in operating temperatures of both generators it was proposed constructive decision using common integrated circuit for both generators. The quartz resonators were mounted much close to each other. Their temperature was aligning by an additional thermal connection with heatsink with heat-conveying paste.

Thus, it was assured the temperature difference substantially below 1°C , which leads to increase of the capacitive sensor's sensitivity more than 10 times, as seen from experimental results.

2. Using a common stabilized power source of both generators (figure 20), with instability of the output voltage below $0,125\text{ V}$, also enhanced the sensitivity of the capacitive sensor over 10 times.

The proposed integrated stabilizer gives one additional advantage of the sensor – the option of its power to be turned on and off for a predefined period of time. This allows the insertion of the sensor in wireless sensor network.

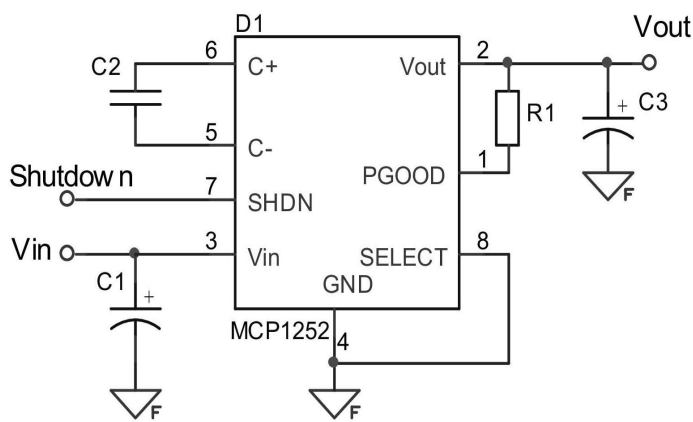


Figure 20. Source of stabilized voltage with control options

5. Conclusion

It has been made a number of investigations related to reduction of the destabilizing influence of ambient temperature and supply voltage to the frequencies of two quartz generators used in capacitive sensor. Based on results was developed high-sensitive intelligent capacitive sensor for monitoring extremes of bulk materials. The proposed sensor can be used as a node of a wireless sensor network.

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References

- [1] Dargie, W., Poellabauer, Ch. (2010). Fundamentals of Wireless Sensor Networks: *Theory and Practice*. Wiley.
- [2] Yick, J., Mukherjee, B., Ghosal, D. (2008). Wireless sensor network survey. *Computer Networks*, 52(12), 2292-2330. doi:10.1016/j.comnet.2008.04.002
- [3] Драганов В., Д. Драганов, Н. Ненков, П. Балабански *Устройство за измерване на ниво*” Авт. свидетелство № 45168, МПК – C01 G 23/26, 08.01.1988
- [4] Draganov, V., Tanchev, II. (2004). Possibilities for Registering the Changes of Capacity of a Capacity Convecter. In: *Proc. of the Int. Conf. Electronics 2004*, Sozopol, 22-24 Sep 2004, Book 3 (pp. 195-199).
- [5] Draganov, V., Tanchev, II. (2005). Device for Measuring the Level of Bulk Materials in Bunkers. In *Proceedings of the Int. Conf. ICEST'2005*, Nish, Serbia, Vol. 1 (pp. 379-381).
- [6] Markova, V., Dimova, R., Draganov, V. (2011). An architecture design of a monitoring level sensor system. *Annual Journal of Electronics*, 5 (2), 37-39. ISSN 1313-1842.