A 20-b Resolution Dual Quartz-based Oscillator Gas-density Readout Circuit

D. Ruffieux, E. Azarkhish, D. Huber •, J. Kilchoer, M. Kunz •, C. Monneron, N. Raemy, C. Schmid •, N. Scolari, D. Severac, A. Vouilloz

This Innosuisse-funded project targeted the development of a high-resolution gas-density measurement circuit based on a custom integrated circuit driving two off-the-shelf 32 kHz watch-type tuning fork crystals (XTAL), one of which being exposed to SF_6 at pressure levels up to 10 bars.

Sulfur hexafluoride (SF_6), a gas about five times denser than air, is used at a pressure of 10 bars in high voltage, gas-insulated circuit breakers (switchgear). Owing to its high dielectric strength, it avoids fire onset by quenching the electrical arc arising when such mechanical switches open, *e.g.*, after a short is detected further down the power line. Failure to detect a leak in such an equipment could lead to dramatic consequence exemplified through one of the huge summer 2018 Californian fire, most likely attributed to a defective electrical power plant equipment. Trafag AG, a world leader provider of pressure and density sensors for harsh environment, and CSEM have teamed up to develop a novel resonant gas-density readout circuit. The sensor is able to operate adaptively and with high resolution over equivalent air pressures ranging from 0 to 50 bars with the goal to serve other rapidly growing energy market segments such as SF_6-based switchgears for medium voltage photovoltaic power plants. On the medium term, the novel sensor, when combined to precise temperature and pressure measurements, will help replace SF_6, a greenhouse gas by an environmentally friendly bi-component gas mixture whose two partial pressures could also be monitored accurately.

The sensor is based on 32 kHz watch-type tuning fork crystals (XTAL) whose frequency exhibits a linear dependency with respect to the gas density ρ, the resonator being slowed down by the mass adsorbed on its surface. One easily shows, using the perfect gas law ($P \cdot V = n \cdot R \cdot T$), that the ratio of pressure P over temperature T is proportional to $\rho = m / V$ with a multiplying factor given by R / M, $M = m / n$ being the gas mass / mole and R the perfect gas universal constant. Figure 1 shows measurements of the phase of the XTAL impedance at varying SF_6 pressures resulting in a relative shift of its two resonance frequencies ($\varphi=0$) by - 1 ppm / mbar. The plot gives several read-out circuit design challenge insights that will be discussed below.

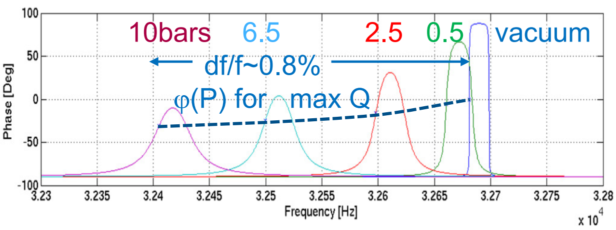

Figure 1: Measured phase of a 32 kHz XTAL at various SF_6 pressures.

A phase discrimination circuit may elegantly be implemented using a XTAL oscillator (XO) which must meet unity gain (magnitude and phase) condition at steady-state. Consequently, the phase shift introduced by the circuit should be balanced by that of the resonator. From Figure 1, one sees that under vacuum condition, the resonator phase change is so abrupt and spanning 180° that the circuit barely influences the XO frequency. Typical watch oscillators exhibit a capacitive phase shift ($\varphi<0$) forcing the resonator in its inductive region ($\varphi>0$). However, such a topology would fail as ρ gets higher due to increased damping since the Q-factor is reduced 100-fold at 10 bars as shown by the corresponding phase change slope and excursion reductions. For optimum frequency stability, the circuit phase should match that of the resonator at its steepest phase change point (see dashed dot line in Figure 1). To meet the above goals, one may use instead a trans-impedance amplifier (TIA) topology that flips the sign of the resonator phase shift. The latter may be compensated in the TIA using a parallel RC feedback matching the resonator loss and dielectric capacitance to reach unity gain at its series resonance, maximizing Q, as shown in Figure 2 which illustrates the readout circuit concepts and XOs topologies. The actual TIA implements several additional features to ensure a reliable start-up, adjust its phase shift and prevent parasitic oscillations as well as overdriving the XTAL. The TIA operates adaptively, without trim, over the complete pressure range.

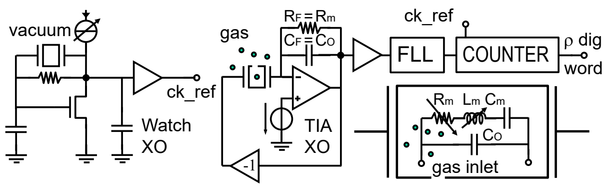

Figure 2: Simplified block diagram of the gas density read-out circuit.

Frequency to digital conversion is achieved using a double oscillator configuration. The first one defines the gate time ($\tau = M / f_1$) consisting of M periods during which the number of periods of the second one are counted delivering a digital word N, that is proportional to the two clocks frequency ratio ($N = M \cdot f_2 / f_1$). Two XTALs originating from the same manufacturing batch are used to yield an absolute differential measurement compensating the temperature effect to the first order (up to 200 ppm). One is exposed to the gas by punching a pinhole through its metal case while the reference XTAL is left in vacuum. With ideally matched XTALs, in the absence of gas, N / M is always 1, whatever the temperature. As surrounding molecules load the second XTAL, affecting f_2, the count value decreases proportionally. To shorten the read-out time and enhance the sensing resolution, a frequency look loop (FLL) is implemented to lock a ~100 MHz RC oscillator on f_2, multiplying the number of counted edges N by the respective FLL multiplying ratio. At a 1 s gate time, assuming a total jitter of 10 ns ($\Delta f / f$ = 1E-8), 1% frequency deviation at 10 bars SF_6, the sensor limit of detection is a density change corresponding to an equivalent pressure loss of 1 Pa yielding a resolution of 20 bits.

A one-time programmable non-volatile memory (NVM) allows storing dedicated configuration and calibration parameters on-chip to compensate for offset and gain errors. Several digital interfaces have been implemented so that the circuit can be operated with a simple companion chip to form a 4 to 20 mA analog sensor transmitter or with a microcontroller for more advanced products. The circuit is currently being characterized.

• Trafag AG, Bubikon, Switzerland