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Very Low Noise, High Accuracy, Programmable Voltage Reference

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Abstract *– The design and testing of a very low noise, high accuracy, programmable voltage reference is presented in this paper. This piece of instrumentation, which can be controlled by a personal computer via the built-in RS232 interface, is intended as an alternative to batteries in the realization of automated low frequency noise measurement systems. The supply voltage ranges from* **0** *to* **5** V *with a resolution and long-term stability better than* **±250 μV.** *The power spectral density of the output voltage fluctuations is less than* 10^{-16} V^2/Hz *at* **100 mHz** *and remains below* 10^{-17} V^2/Hz *above* **1 Hz.**

Keywords *– noise measurement, low noise instrumentation, spectral analysis*

I. INTRODUCTION

The analysis of the low frequency noise produced by electron devices is among the most sensitive tools for the characterization of their quality and reliability [1,2]. The sensitivity of any low noise measurement chain is ultimately limited by the equivalent input noise sources of the input preamplifier coupled to the device under test (DUT). However, other sources of noise or fluctuations may be present which considerably contribute to the background noise of the entire system. Besides electromagnetic interferences and the effect of mechanical vibrations, which can be reduced by means of proper shielding and the use of anti-vibrating benches, the noise produced by the instrumentation employed for biasing the DUT is a major concern. In order to avoid such supplemental source of noise, high capacity batteries are normally used for biasing the DUT. Unfortunately, using batteries poses several important limitations: only a limited set of voltages are normally available, and their exact values strongly depend on the charge status of the batteries and on their age; a programmable biasing system can not be realized using batteries, and even if we resort to a programmable switching network which varies the number of batteries connected in series, the minimum voltage step which can be obtained is that of the elementary cell (about 2 V in the case of lead-acid batteries). Sometimes, a resistive divider network can be used in order to obtain voltages different from integer multiples of the elementary cell voltage, but in this case low resistance values must be used in order to reduce the thermal noise contribution of the voltage divider. This approach, therefore, results in rather high currents supplied by the battery with a degradation of the noise performances and a significant drift of the supplied voltage because of the fast discharge. Clearly, one may reduce such a problem by means of very high capacity batteries, but this would not be practical in many cases and would not solve the problem of the programmability of the voltage source, which would be quite an interesting feature for the realization of fully automated low noise measurement systems [2,3]. A first approach to the solution of these problems can be found in [4]: it essentially consisted of a buffered low noise constant voltage source followed by a programmable discrete component resistance divider followed, in turn, by a low noise output buffer. Although characterized by remarkable performances in terms of equivalent output voltage noise, it suffered from important limitations: a) once the output voltage was set, no feedback loop was present in order to compensate the output voltage drift in the medium and long term as a result of the change in ambient temperature or reference battery self discharge; b) its structure was rather complex and required several high capacity batteries for its operation, thus resulting in a 3U-19'' rack quite difficult to integrate in high sensitivity measurement systems where reduced volume and short wiring are essential for avoiding environmental disturbances.

In this paper we propose a different approach for the realization of a programmable, low noise, high accuracy voltage source that, notwithstanding its compact size, is characterized by excellent noise performances, especially in the very low frequency range (f<1Hz).

II. PROPOSED APPROACH

The idea behind the approach we propose is rather simple and consists of using a standard solid state DA converter followed by a filter and a low noise buffer stage, as shown in Fig. 1. Stability, accuracy and programmability are achieved by means of a microcontroller based digital control loop that uses a high accuracy AD converter for continuously monitoring the output voltage and adjusting the voltage at the output of the DA converter. However, several important issues have to be addressed and solved for the circuit in Fig. 1 to behave as a low noise programmable voltage source.

The actual circuit we have designed is shown in some detail in Fig. 2. The role of the several additional components needed in the actual circuit is outlined in the following.

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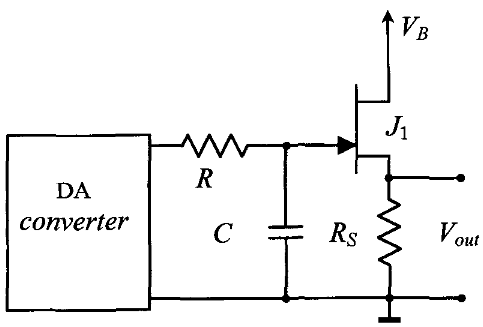

Fig. 1. A simplified schematic of a filter and circuit for the realization of a low noise programmable voltage reference.

Our aim was to reduce the output voltage noise to a level equivalent to that due to the equivalent input voltage noise of the JFET-input ultra low noise preamplifier we normally use for high sensitive noise measurements, at least in the frequency range down to 100 mHz [2]. Such an amplifier is characterized by an equivalent input voltage noise S_{VF}(100 mHz)=10^{-16}V^2/Hz which reaches a minimum of about 10^{-17} V^2/Hz for frequencies higher than 1 Hz. In the $1/f$ region, the spectrum is essentially coincident with the equivalent input noise of the input JFET (IF3601), which is the very same device used for the buffer stage of the new programmable voltage reference. As the voltage noise at the output of a "low noise" commercial DA converter can be as high as 10^{-10} V^2/Hz at 100 mHz, we require a first order low pass filter with a corner frequency as low as 100 μHz in order to obtain the required attenuation of the noise produced by the DA converter. Moreover, we must take into account the thermal noise of the resistance R that is expected to be high since we must employ very low loss polypropylene capacitors, which are only available with values up to a few tens of microFarads. It can be easily verified that for frequencies well above the corner frequency, the voltage noise at the output of an RC filter due to the thermal noise of the resistor is given by:

$$S_{VR} = 4kTR\frac{f_c^2}{f^2} \tag{1}$$

where k is the Boltzmann constant, T is the absolute temperature, f_c the filter corner frequency. It is therefore clear that, for the same corner frequency, the higher R, the higher the noise contribution. By imposing S_{VR}(100 mHz) to be much less (-10 dB) than S_{VF} at the same frequency and assuming f_c=100 μHz, we obtain that, at ambient temperature, R must be less than about 600 MΩ. By using R=100 MΩ and C=20 μF, we obtain f_c=80μHz, thus satisfying the above mentioned constraints.

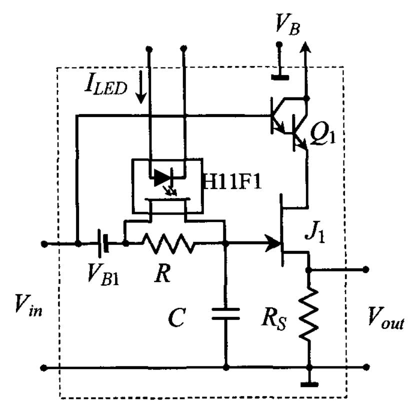

Fig. 2. Actual filter and buffer circuit used in the new programmable voltage reference.

However, a corner frequency f_c=80 μHz would result in a time constant of about 30 minutes, thus making the use of the circuit impractical, since several hours would be required for reaching a steady state condition. In order to overcame this limitation we used an optically controlled analog switch (H11F1), which behaves as a very high resistance with the driving LED switched off (R_{off}>300MΩ), while it behaves as a small valued resistance when the LED is turned on. The driving LED may be automatically operated by the control circuit (Fig. 3), being switched ON in order to speed up the voltage change transient. When the new steady state condition is reached, the LED is switched off in such a way as to allow the low pass filter to develop its full action. In fact, while the output voltage is changing, no noise measurement would be meaningful and by means of the procedure described above, the new steady state is reached in a matter of a few minutes. This is a time largely acceptable for measurements that, for the spectrum at 100 mHz to be meaningful, normally last a few hours.

In order to achieve the best noise performances, the entire system is battery operated. We decided to employ two high capacity 12 V, 6Ah lead acid battery, one for the control board and one for the output buffer, in order to reduce the size of the entire system. For the output voltage to reach 0 V we had to insert the battery V_{B1} in Fig. 2 which insures that the JFET is pinched off when the input voltage is close to 0 V. At the same time the battery allows, together with the darlington Q1, to maintain the JFET in saturation with the lowest possible value of V_{DS}. This is done both to reduce the power dissipated by the JFET, which may led to thermal fluctuations, and in order to avoid the onset of large reverse gate currents. Both these phenomena would lead to additional noise contributions particularly at very low frequencies. In order to further reduce the effects of thermal fluctuations, the case of the FET was enclosed into a 100 g brass thermal mass, and thermally shielded from the environment in a PTFE envelope. The battery V_{B1}, through which only the negligible gate current flows, is obtained as the series of 3 tiny 100 mAh NiCd cells.

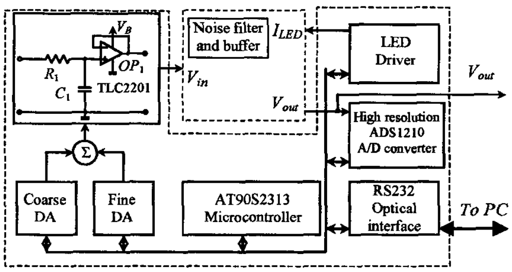

Fig. 3. Block diagram of the entire system. The optical link is used to avoid EM interferences from the PC.

It must be noted that, because of the direct connection of the input to the drain of the JFET (through the two base-emitter junctions of the Darlington) the full noise at the input is present at the drain of the JFET. Accurate measurements have shown that the isolation from the drain to the source (output) is of the order of 40 dB, which is not sufficient for our purposes. This is the reason why one more low pass filter is needed (R_1C_1 and OP_1 in Fig. 3) in order to provide for an attenuation larger than 20 dB at the lowest frequency of interest, that is 100 mHz. The time constant of this filter was set about 20 times below that corresponding to f_c, thus not adding significant delay to the entire control chain.

One of the main difficulties in using a digital control loop in low noise applications arises from the fact that the output of a DA converter only changes in steps which, even in the case of high resolution converter, are usually large enough to cause significant periodic voltage fluctuations at the output of the system which appear as an additional noise component. In order to reduce this effect, we resorted to a fine-coarse configuration using two outputs of a MAX525 quad 12-bit converter. When the output voltage is being changed, the coarse DA converter allows setting an input voltage quite close to that necessary for maintaining the required output voltage. During low-noise measurements, only the fine DA converter is operated which is set in such a way as to cause only a small change in the voltage at the input of the filter. The voltage change corresponding to a change of 1 LSB of the fine converter is about 1/20 with respect to the voltage change corresponding to 1 LSB of the coarse converter. In this way the voltage at the input of the filter can be changed in steps as low as 100 μV over the full range of about 8 V, which is required to obtain an output voltage range from 0 to 5 V.

III. RESULTS

A prototype of the new very low noise programmable voltage source has been realized and the results that have been obtained are presented in this section.

Clearly, the most important feature to be verified was the level of the voltage noise at the output of the system. To this purpose, we used the already mentioned ultra low noise preamplifier with JFET input stage [2]. The results of the noise measurements performed at the output of the voltage source (S_{OUT}), after setting an output voltage of 2.5 V and waiting some tens of minutes for a steady state condition, is reported in Fig.4 together with the equivalent input noise of the preamplifier (S_{BN}) and the noise measured directly at the output of the DA converter (S_{VR}) of Fig. 3.

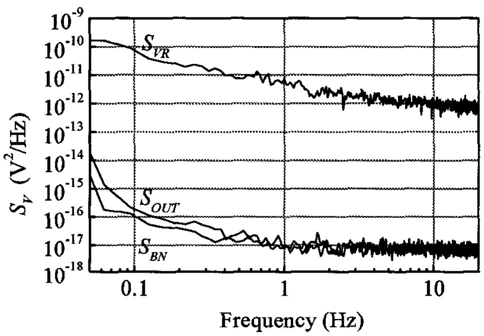

Fig. 4. Power spectral densities at the output of the new programmable voltage reference (S_{OUT}) together with the DA converter output noise (S_{VR}) and the preamplifier background noise (S_{BN}).

During the measurement, the digital control loop was in constant operation, the output voltage was sampled, and the fine correction of the DA accordingly performed, at a frequency of about 0.25 Hz. It can be noted that, in the low frequency part of the spectrum, the measured noise is about 3 dB higher than the input noise of the preamplifier, thus confirming that the output noise essentially reduces to the equivalent input noise of the JFET used as output buffer. An attenuation of about 56 dB is obtained at 100 mHz. Moreover, the operation of the microcontroller, which performs the voltage control algorithm, does not introduce significant noise components. The time required for changing the output voltage and reaching a new steady state condition strongly depends on the required level of output noise and accuracy in the output voltage prior to the start of the noise measurement experiment in which the new voltage source is going to be used. As an example, Fig. 5 reports the output voltage transient in response to a set point change from 3 to 3.5 V. A purely proportional action was used soon after turning on the LED. After reaching the steady state condition (t=3 min.), the control loop is adjusted in order to obtain a proportional-integral action. Finally, the LED is turned off (t=10 min.).

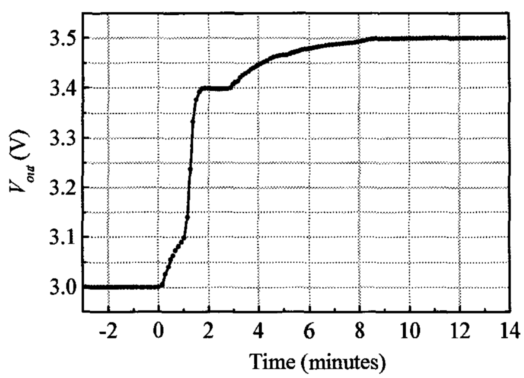

Fig. 5. Output voltage transient response of the new programmable voltage reference after a set point change occurring at t=0s.

Soon after the LED is turned off, although the output voltage appears to have reached the steady-state value, the low frequency noise may still be as high as 10^{-15} V^2/Hz at 100 mHz. The spectrum gradually reaches the steady-state value reported in Fig. 4 (S_{OUT}) in about 1 hour after the set point change. The output voltage transient decay is reported in Fig. 6. The stability of the output voltage measured over more than 6 hours is better than ±250 μV, with a standard deviation of about 70 μV. Work is in progress in order to optimize the various parameters of the control algorithm in such a way as to reduce the transient duration, which depends, in particular, on the detailed way in which the optical switch is operated. Besides, in most application, we are not interested in frequencies as low as 100 mHz, or we may tolerate higher levels of noise with respect to the minimum, and, in these cases, we do not need to wait for the full stabilization of the system. The results we have obtained so far are remarkable especially if the quite simple structure of the system we have designed is taken into consideration. Future work will be dedicated to the optimization of the control chain parameters and to the systematic characterization of the performances of the systems in terms of noise level, output voltage accuracy and transient duration as a function of the supplied voltage and current.

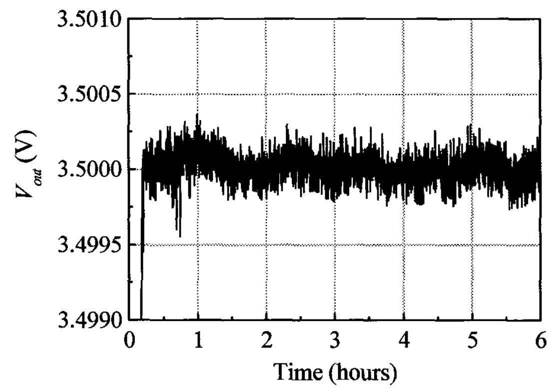

Fig. 6. Detail of the output voltage value as measured by the high resolution AD converter that is part of the control loop (Fig. 3).

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