Ultralow-Noise Programmable Voltage Source

Luigi Baracchino, Giovanni Basso, *Member, IEEE*, Carmine Ciofi, and Bruno Neri, *Member, IEEE*

***Abstract*—To avoid introducing additional noise sources while making low-frequency noise measurements, batteries are normally used instead of electronic power supplies. This paper presents an alternative solution by describing the design, construction, and testing of an ultralow-noise voltage source. Such a power supply can be computer controlled and has a typical noise level two orders of magnitude below that of similar commercial instruments. Some typical values of the spectral density of the voltage fluctuations at its output are: (10^{-12}, 10^{-15}, 10^{-16}) V^2/Hz at (0.01, 0.1, and 1) Hz, respectively. These noise performances are almost independent of the supplied current, with a degradation of less than 3 dB up to 400 mA. A special algorithm for digital-to-analog conversion, using passive devices with 1% tolerance, ensures a resolution of 2.5 mV and an accuracy better than ±1.5 mV over the entire output range from 0 to 8 V.**

***Index Terms*—Circuit noise, measurement, noise measurement, power supplies, semiconductor device testing.**

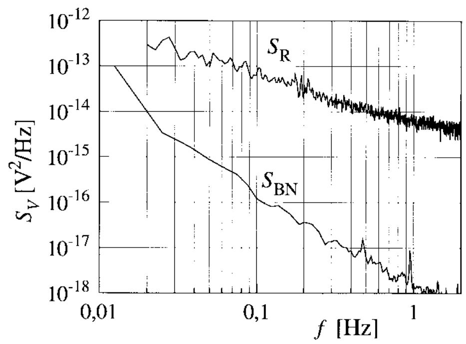

Fig. 1. Spectrum of the voltage fluctuations at the output of an LTZ1000 solid state voltage reference (S_R). The equivalent input voltage noise of an ultralow-noise preamplifier is also reported for comparison ($S_{\rm BN}$).

I. Introduction

Low-frequency noise (LFN) measurements are one of the most sensitive investigative tools in the diagnostic and reliability testing of materials and devices for microelectronics [1]–[3]. LFN contains much information concerning the microstructure of the samples under test and is directly linked to the quality of the materials used for the fabrication of electron devices. The continuous improvement of technological processes makes available materials and devices characterized by fewer and fewer defects and, consequently, by lower levels of excess noise. Therefore, the background noise (BN) of the measurement systems used for the characterization of modern devices and materials must also be reduced.

A crucial part of any measurement system for the characterization of electron devices is represented by the power sources utilized for biasing the devices under investigation or for supplying the voltage (current) required for testing a sample of a given material. All commercial regulated power supplies are based on a voltage regulator which uses a solid-state device, normally a Zener, as a reference voltage. Unfortunately, this type of device is characterized by a high level of excess noise at low frequencies. The typical behavior of the power spectrum S_R of the voltage fluctuations at the output of the least noisy electronic voltage reference available on the market (Linear Technology LTZ 1000) is shown in Fig. 1. Clearly, S_R represents the best performance that could be obtained with traditional electronic power supplies. Also reported in Fig. 1 is the spectrum of the equivalent input voltage noise $S_{\rm BN}$ of an ultralow-noise preamplifier commonly employed in the noise measurements performed in our laboratories [4]. It is apparent that the sensitivity of a noise measurement system employing such a preamplifier would be dramatically reduced if conventional solid-state power supplies were used for biasing the devices under test. Therefore, a set of batteries with different taps corresponding to different voltages is normally used for this purpose. This solution, however, suffers from a few apparent limitations: i) only a limited set of voltages is available; ii) the supplied voltage, as well as the noise level, depends on the charge status of the batteries and changes if measurements last several hours; iii) it is not possible to use a remote control in order to perform a set of automatically controlled measurements at different voltages; and iv) if a resistive divider is used to obtain a voltage not directly available at the taps, the values of the resistors must be sufficiently low in order to reduce the thermal noise. This causes an undesirable dissipation of power and accelerates the discharge of the batteries.

Another drawback of this solution is that the noise produced by the batteries sharply increases if the supplied current exceeds a value $I_{\rm MAX}$, which depends on the type of battery and its capacity [5]. Normally, $I_{\rm MAX}$ is of the order of magnitude of the current at which a period of 100 h is sufficient to completely discharge the battery. This fact makes the use of batteries very difficult when the required current is in the range of hundreds of milliamperes: batteries with a capacity of several tens of ampere-hours would be necessary. This is the case, for instance, of LFN measurements used to characterize the quality of the metal lines in integrated circuits [3].

In this paper, the design, construction, and testing of an ultralow-noise programmable voltage source (ULNPVS) are described in detail. The complete system operates as a 12-bit DA converter and can be controlled by a PC by means of an RS232 interface. It can supply currents in the range of hun-

Manuscript received July 28, 1995.

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Publisher Item Identifier S 0018-9456(97)09431-X.

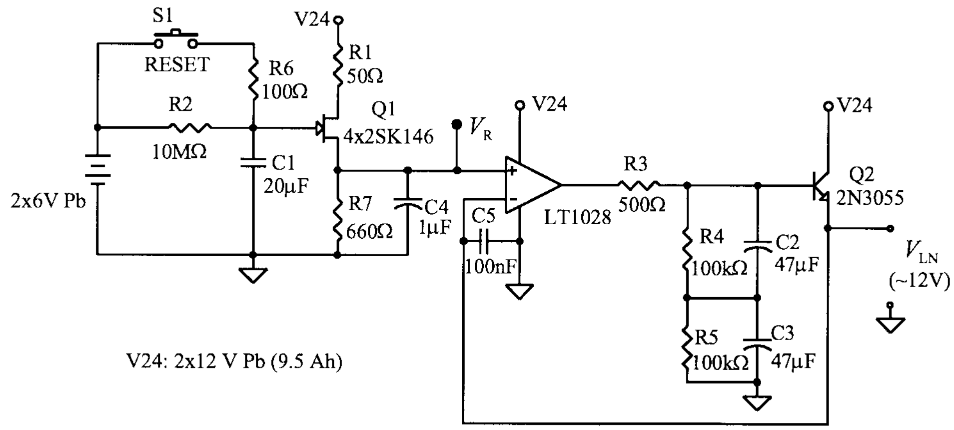

Fig. 2. Schematic of the low-noise fixed voltage source.

dreds of milliamperes with noise performances which, in the frequency range below 1 Hz, are comparable to or better than those of high-capacity batteries supplying the same current.

II. Ultralow-Noise Fixed Voltage Source

The noise produced by the batteries becomes significant when the supplied current increases above a given value, which depends on the type of battery and on its capacity. When the current is sufficiently low, however, batteries behave as very low-noise voltage sources. In other words, in low-noise measurement systems, batteries could be used as sources of reference voltages, but not as power supplies [5].

This suggests an alternative solution to that used in commercial power supplies, in which a solid-state device, typically a Zener diode, is used as reference voltage in a voltage series regulator. A battery which does not supply current could be used as a substitute for the Zener diode. Particular attention must be paid to the design of the error amplifier of the regulator which, together with the voltage reference, sets the level of the background noise of the entire system. For this purpose, both active and passive components must be carefully selected. By suitably selecting the type and the value of the passive components of the error amplifier, the total equivalent noise of the system can be reduced to that of the active devices used in the input stage of the error amplifier itself. This goal has been obtained with the circuit reported in Fig. 2, which shows the typical topology of a series voltage regulator. The reference voltage V_R is taken at the output of the source follower, a low-noise operational amplifier (OA) is used as error amplifier, and the bipolar junction transistor (BJT) acts as a pass element which supplies the output current. The output voltage V_{LN} coincides with the reference voltage V_R.

The battery used as voltage reference supplies a current in the range of only hundreds of picoamperes due to the leakage of the capacitor C_1. Under these conditions, the level of noise generated by the battery is so low that, in some cases, it cannot be measured even by using specially designed ultralow-noise preamplifiers [4]. Both lead–acid and alkaline batteries have been tested: the best results have been obtained with the former type. In order to further reduce the contribution of the battery to the total noise and to avoid the effects of thermal transients or accidental mechanical shocks which could cause slow fluctuations of the supplied voltage, a RC low-pass filter has been interposed between the battery and the input of the source follower stage. The corner frequency of the filter is 0.8 mHz, and the values of R_2 and C_1 (10 MΩ and 20 μF, respectively) have been chosen in such a way as to make the contribution of the thermal noise of the resistor R_2 negligible in the frequency range above 10 mHz. At power-on, the switch S_1 is closed for a short time in order to accelerate the charging of the capacitor C_1. In the actual circuit, the switch S_1 is a relay operated by the microcontroller which supervises all the functions required for the correct operation of the ULNPVS.

The source follower stage also has the important function of reducing the impedance seen by the input of the error amplifier (a low-noise operational amplifier LT1028) to a value which makes the noise contribution of its equivalent-input current-noise source i_n negligible. In fact, while the power spectrum of the equivalent input voltage-noise source e_n of the LT1028 is very low (100 $\times$ 10^{-18} V^2/Hz at 100 mHz), the power spectrum of i_n is quite high (2.5 $\times$ 10^{-21} A^2/Hz at 100 mHz); this behavior is typical of any low-noise OA with a BJT's input stage. The source follower stage consists of four 2SK146, each one containing a pair of low-noise FET's in parallel. In this configuration, the power spectrum of the noise introduced by this stage is reduced by a factor of 8 with respect to that of a single FET stage [4].

The output stage consists of a power transistor which supplies the required current. The choice of this device is not critical. Due to the high value of the low-frequency gain of the OA (about 10^7), the output noise is substantially due to the input stage. In particular, the contribution of the voltage reference is negligible with respect to that of the OA itself, which represents the main source of noise.

No theoretical limits exist for the maximum current that can be supplied by the output V_{LN}, the only limit being the maximum power that can be dissipated by the pass transistor. Currents in the range of several hundreds of milliamperes have been used during the test of the prototype without observing significant degradation of the noise characteristics.

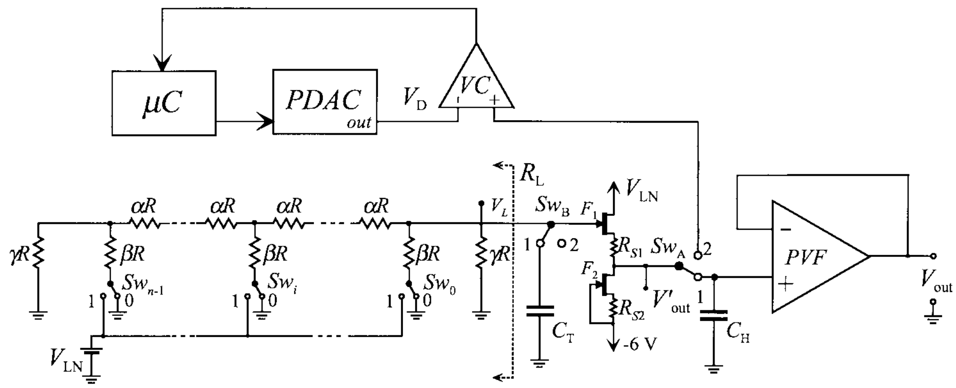

Fig. 3. Block scheme of the low-noise programmable voltage source.

The power spectrum of the output noise of this stage, if no supplemental sources of noise are present, should be practically coincident with that of the input-voltage noise source of the LT1028, the typical values of which are: (2×10^{-18}, 12×10^{-18}, 100×10^{-18}) V^2/Hz at (10, 1, and 0.1) Hz, respectively. In the frequency range below 200 mHz, however, the noise introduced by the FET stage also becomes important, thus causing a deterioration of the noise performance with respect to that which could be expected from the contribution of the noise sources of the LT1028 alone.

III. Ultralow-Noise Programmable Voltage Source

The low-noise fixed voltage source (LNFVS) described in the previous section can be used as a building block for a programmable ultralow-noise voltage source. To this end, the typical topology of a R/2R ladder DA converter, utilizing the output voltage $V_{\rm LN}$ of the LNFVS as a reference, could be implemented. However, since the main objective of the design is the minimization of the noise level, the voltage follower used as a buffer must be suitably designed and the resistors of the ladder must be suitably chosen. In particular, metal film, discrete resistors must be used. Such resistors are normally available at a reasonable price with a 1% tolerance. Moreover, the value of $V_{\rm LN}$ would depend on the actual value of the battery voltage V_B ($V_{\rm LN}$ is close to V_B since the gate–source voltage of the FET's of the buffer of the LNFVS is about 100 mV). In commercially available batteries, a long-term variability of some tens of millivolts of the output voltage must be taken into account. For those reasons, a simple circuital topology like that of an R/2R ladder network followed by a buffer cannot be used to build up a programmable voltage source with a precision of some tens of millivolts or less.

The block diagram shown in Fig. 3 describes the solution adopted to solve the above mentioned problems. The block indicated as PDAC is a commercial precision DA converter (AD667KN). It is characterized by high stability and by a linearity error lower than ±1/4 LSB. When the output voltage $V_{\rm out}$ must be changed, a voltage V_D equal to that desired at the output of the ULNPVS is generated by the PDAC at the inverting input of the voltage comparator VC. The switch S_{WA} is then moved to the position 2 and, while the capacitor C_H maintains the output at the previous voltage, the switches $S_{W0}, \cdots, S_{W(n-1)}$ are adjusted in such a way that the voltage $V'_{\rm out}$ is as close as possible to the desired voltage V_D. This is done by means of a successive approximation (SA) algorithm which utilizes the output of the voltage comparator VC during the conversion procedure. At the end of the procedure, the switch S_{WA} is moved back to position 1, so that the desired value of the voltage can be obtained at the output. In order to accelerate such procedure, the switch S_{WB} is kept open during the conversion thus eliminating the effect of the capacitor C_T. The peculiarity of this circuit lies in the particular values of the resistances which make up the ladder network. In fact, the circuit in Fig. 3 is nothing but a particular type of implementation of a static memory for analog signals (SMAS), the principle of operation of which has been described in detail elsewhere [6]. In particular, it has been demonstrated that given a resistor tolerance and a value for the uncertainty of the reference voltage (VLN in Fig. 3) it is always possible to choose α, β, γ, and n (Fig. 3) so that, at the ouptut of the SA algorithm, the difference between V_D and $V'_{\rm out}$ is less than the maximum acceptable error (MAE). This holds for any possible value V_D within a specified dynamic range $0 < V_D < V_{\rm MAX}$.

In the present case, where resistances with 1% tolerance have been used, it has been possible to obtain a MAE of 1 mV with V_D in the range (0 to 8) V by using $\alpha = 36$, $\beta = 91$, $\gamma = 78$, and $n = 15$. The value of R has been chosen equal to 40 Ω which represents a compromise between the requirements of keeping the thermal noise low and having an acceptable value of the power dissipated in the ladder network. The resulting value of the resistance R_L seen by the input of the FET stage F1–F2 is of about 1.1 kΩ.

The PDAC was configured in such a way that 1 LSB corresponded to 2.5 mV. In conclusion, notwithstanding that the tolerance of the metal film resistors used for the ladder network was 1%, it was possible to obtain a low-noise DA converter with a resolution of 2.5 mV and an overall absolute precision better than ±1.5 mV over the entire range from 0 to 8 V.

The operation of the programmable voltage power supply is completely controlled by a microcontroller (MC68HC705C8 in Fig. 3). In particular, the microcontroller controls the

PDAC, implements the SA algorithm described above and contains an RS232 interface which can be used to operate the instrument by remote control. The switches $S_{W0} \cdots S_{W14}$ have been implemented with bistable relays. This solution has the advantage that, after the conversion procedure, the low-noise circuitry could be electrically separated from the control circuitry, thus avoiding possible electrical interferences which would result in additional noise at the output. The conversion procedure lasts a maximum of 200 ms, which is a time largely acceptable for all the applications for which our programmable voltage power supply may be required.

The output stage has been designed by taking into account the requirements regarding the output power as well as those concerning the low noise. The output current is supplied by a power voltage follower (PVF in Fig. 3) made up of an LT1028 together with a power transistor in the same circuit configuration as in Fig. 1. With such circuital configuration, the output resistance is so low that it substantially equal to that of the cables which are used to connect the ULNPVS to the device under test. A low-noise source follower has been used as a buffer between the output of the ladder and the input of the PVF. Five 2SK146 have been used for the arrangement F1–F2 in Fig. 3. Such configuration, together with the fact that F1 and F2, as well as the resistors R_{S1} and R_{S2}, are equal, ensure that V'_{out} be equal to the output V_L of the ladder network. The capacitor CT has been added in order to reduce the effect of the thermal noise generated by the resistive ladder network. This effect is no longer negligible, with respect to the $1/f$ noise of the active components, in the frequency range above 1 Hz.

As in the case of the LNVFS, the contribution of this second stage to the output noise of the entire system is essentially due to the LT1028 which is used in the PVF. Also in this case, however, there is a nonnegligible contribution of the noise of the FET stage at frequencies below 200 mHz.

IV. Measurements

The main objectives of the design were the capability to supply a power of several watts, an extremely low-noise level, and a precision similar to that of an integrated 12-bit DAC. Fig. 4 shows the behavior of the power spectrum of the voltage fluctuations S_G at the output of the ULNPVS versus frequency. In Fig. 4, the power spectrum of the voltage fluctuations measured across the terminals of a lead battery, S_B, is represented. In both cases, the output voltage was 8 V and the supplied current was 100 mA. Also, the power spectrum S_R of Fig. 1 is reported for comparison. In this last case the output voltage was 7.1 V and no current was supplied during the measurement. The measurements were performed by means of a dynamic signal analyzer (HP3562A) and by using a specially designed ultralow-noise preamplifier [4]. Such a preamplifier was necessary because S_G and S_B are lower than the background noise of any low-noise commercial preamplifier, at least in the frequency range below 1 Hz, which is the most interesting in some applications [3]. The background noise S_{BN} of the measurement system, obtained with the input of the preamplifier shorted, is also reported in Fig. 4.

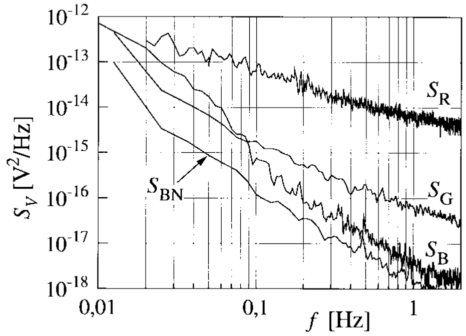

Fig. 4. Power spectra of the voltage fluctuations at the output of various voltage sources. S_G: ULNPVS, S_B: lead battery, S_R: LTZ1000A. The value of the supplied current was 0 for S_R, 100 mA for S_G and S_B. S_{BN} is the background noise of the measurement system.

As it can be seen, S_G is higher than S_B in the frequency range above 200 mHz, whereas they are comparable with each other in the remaining frequency range. It must be pointed out that, in the case of the measurement of S_B: i) a high-capacity battery (9.5 Ah) was used (Sonnenschein model Dryfit A300); ii) this type of battery was selected among all those used in our laboratories in the last 10 years because it was the least noisy; and iii) the measurement of S_B was performed under the conditions in which the LFN is minimum, that is in the central part of the discharge cycle of the battery. A number of tests have shown that if other types of batteries had been used or if the measurement had not been performed in the central part of the discharge cycle, S_B would have been greater than S_G over the entire explored frequency range. In other words, whereas the measurement of S_G is repeatable in a reliable way, that of S_B is not: the spectrum S_B reported in Fig. 4 represents only the best result we have been able to obtain.

From the results reported in Fig. 4, the better noise performances of the ULNPVS with respect to the LTZ1000A are also apparent.

A commercial electronic power supply has also been characterized, but the results have not been reported in Fig. 4 because the noise spectrum was about one order of magnitude larger than S_R.

As previously mentioned, the LFN of the batteries sharply increases when the current exceeds a given value I_{MAX}, which in the case of the battery used for these tests is of about 100 mA. To verify this statement, the measurement of S_B was repeated at 400 mA. The result of the measurement is reported in Fig. 5 together with S_G measured at the same value of supplied current. It is clear that, while S_G increases by less than 3 dB with respect to its value at 100 mA, S_B shows an increase of about one order of magnitude and becomes comparable with S_G in the entire frequency range from 10 mHz to 1 Hz. Once again, we would like to point out that, while the results obtained in the measurements of the noise at the output of the ULNPVS are to be regarded as "typical," the results of the measurement of the noise produced by the battery are among the best ever obtained in our laboratory.

The results of the measurements performed in order to verify the maximum error $V_{\mathrm{out}} - V_P$ between the value of the actual

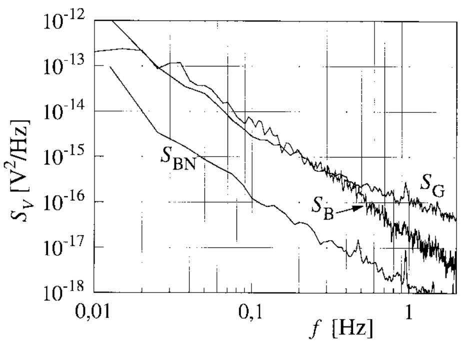

Fig. 5. Power spectra S_G and S_B measured as in Fig. 4 but at 400 mA of supplied current. S_{BN} is the background noise of the measurement system.

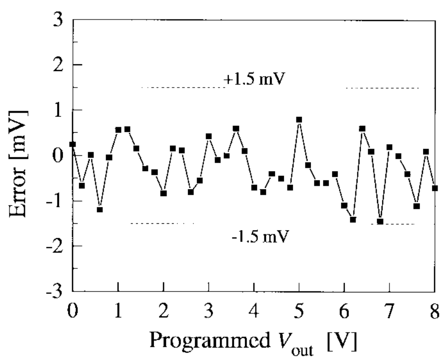

Fig. 6. Error between the programmed voltage and the actual voltage measured at the output of the ULNPVS.

voltage V_{out} at the output of the ULNPVS and the programmed voltage V_P are summarized in Fig. 6. For each value of the programmed voltage, the actual value of the output voltage was measured by means of a digital multimeter HP3478A. As can be verified, the maximum error is less than ± 1.5 mV in the entire output range. It must be pointed out that the error in the output voltage is essentially made up of two contributions: the error of the PDAC plus the error of the SMAS (the offset voltage of the output stage in Fig. 3 is of the order of 100 μV). Therefore, it might be possible to improve the precision by using a more precise PDAC and by using a longer network ($n > 15$) for the SMAS.

As far as the stability of the output voltage is concerned, after 1 h of warm up, a drift of less than 200 μV has been measured in 2 h, with the maximum value of the output voltage (8 V) and a supplied current of 100 mA.

V. Conclusions

A programmable ultralow-noise power voltage source has been designed, realized and tested. The instrument is mainly intended for application at low frequency, low-noise measurement systems, and its main characteristics are: i) noise performances equivalent to, or better than, those of low noise, high-capacity batteries; ii) capability of supplying currents in the range of several hundreds of milliamperes without significant degradation of the noise performances; iii) resolution, precision, and a long-term stability of the output voltage comparable to that of one of the best integrated 12-bit DAC's available on the market; and iv) built-in RS232 interface for remote control operation.

By using original circuit solutions and selecting accurate active and passive components, the output voltage noise spectrum has been reduced to about twice that of the equivalent-input voltage source of the least noisy operational amplifier used in low-frequency applications.

The comparison with commercial electronic power supplies under the same conditions of operation, has shown that the output noise of the ULNPVS is a few orders of magnitude lower. The noise performances of batteries can be superior to those routinely obtained by means of the ULNPVS only if quite remarkable care is used in their selection and operation.

These results allow one to conclude that the instrument described in this paper represents an advantageous alternative compared with the use of batteries in low-frequency noise measurements, both because of the possibility of remote control and because of its remarkable noise performances.

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