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LOW NOISE DC POWER SUPPLIES

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Abstract – Some measuring systems are very sensitive on disturbances incoming from power supplies. If no accumulators are used for their power supply, which ensure a minimum signal noise and transmission jamming signal from power network, special power supplies have to be constructed for them. An example of a possible influence of a disturbance, which spreads along to the power supply on high pure sine-wave signal source, is presented in our contribution, whereas the requirements on the power supply are also specified. Furthermore, an analysis of the construction of these sources is effected and a sample of the source construction and records are introduced.

Keywords: noise, power supply

1. INTRODUCTION

A noise, which if superposed on DC supply voltage, causes problems with the operation of some arrangements and with the measurement of some systems.

The noise, superposed on a supply voltage, has mostly approximately the same characteristics. It mainly occurs in the area of very low and acoustic frequencies. A flicker noise has dominant influence in the area of low frequencies. The spectral density of the flicker noise matches the function 1/f and therefore is higher beyond a level of the thermal noise. In addition, it is only possible to suppress the signal noise originated somewhere very difficultly by filtering in the range of low frequencies, because filter circuits would have to posses the long time constants. It would be possible to use capacitors and inductors with a very large capacity and inductivity.

At a signal processing in perfect linear networks, e.g. processing AF signal low levels, the noise, superposed on a supply voltage, is a direct superposition on the processed signal. This effect takes disturbing effects especially in acoustic systems, in measuring systems. It is often possible to suppress a disturbing signal by filtering, averaging or by a coherent detection and further methods, if the noise spectrum does not directly overlap the spectrum of the evaluated signal.

Upon signal processing in networks that are not perfectly linear, the noise, which is superposed on the supply voltage, then approves itself as a generation of amplitude cross-modulation of the current signal. It works as an amplitude modulator too, e.g. upon processing by a RF amplifier, if an amplifier is not perfectly linear and has no stabilized operating points of active elements independently of the supply voltage. Side-bands, which are generated by the amplitude modulation, lie in immediate vicinity of a carrier frequency and it is practically impossible to suppress disturbing signals by a filter. The ratio between powers of spurious modulation products in both side-bands and the carrier power 2Ps/Pc is then approximately the same as the square of the ratio between a level of a spurious signal noise and a level of supply voltage.

$$\frac{2P_s}{P_c} = \frac{P_N}{P_{SS}} = \left(\frac{U_N}{U_{SS}}\right)^2 \qquad (1)$$

where P_N, U_N is output power and voltage of the noise signal, P_{SS}, U_{SS} is an input power and supply voltage of the amplifier.

This situation (parameters, curves), that has been measured on the referential RF generator, which has to produce a calibration signal with a high spectral purity, is illustrated in Fig. 1.

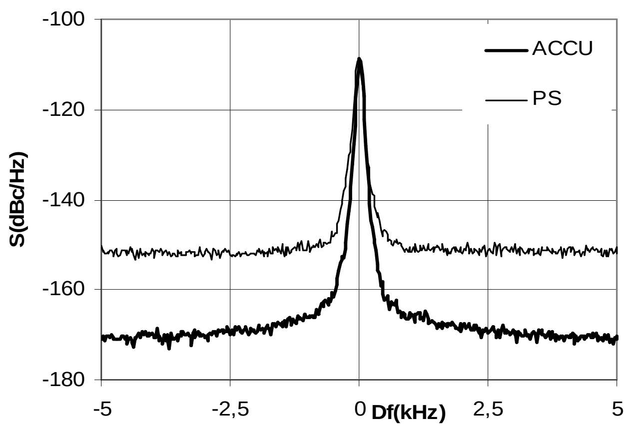

Fig. 1 The noise levels of RF signal generator supplied from accumulator or of laboratory power supply

There are compared noise levels in surroundings of the carrier frequency of a generator by its power supply either from an accumulator battery or by common DC laboratory source, which has the spectral density of the voltage noise 700 nV /√Hz at the output clamps by output voltage 18 V.

2. DC SOURCES WITH A VERY LOW NOISE

Sources with minimum self noise were sought, in order to substitute an accumulator power supply of the high pure sine-wave signal sources for ADC testing.

The level of spurious components identifies the quality of the test signal. These are harmonic signals, in harmonic spurious signals and noise. The level of spurious components and noise keeps down a possibility of using the test signal for quality ADC.

This situation is not much advantageous for ADC converters, which process frequency from DC to a cut-off frequency of the anti-aliasing filter. The cut-off frequency can several fold exceeds the frequency of carrier, therefore converters respond on many harmonic and a noise in a wide frequency range.

Quality of the test signal is characterized e.g. by the ratio of the signal (carrier) to all disturbance signals, which is given by a value SINAD (Signal it Noise and Distortion Ratio), (1), [1]. (P_{All} is power of all signal components, P_0 is power direct component, P_1 is power of the carrier).

$$SINAD = 10\log\frac{P_1}{P_{All} - P_0 - P_1} \qquad (2)$$

In order that the measuring may always be error-free and not affected by disturbing signals, the test signal has to possess a signal-to-noise ratio significantly higher than the maximum available dynamic range of the tested arrangement. In case of the ADC we will consider as a maximum available dynamic range its signal to noise ratio (SNR), exciting sine signal, its amplitude accordant with the maximum input voltage [2]. Then it is possible to express the required SINAD test signal for n–bit ADC approximately by relation (2):

$$SINAD - PR \geq (6n + 2) \qquad (3)$$

PR is a protection ratio, which we choose in the range from 10 to 20 dB depending on the required accuracy of the measurement. SINAD, needed for testing of the 16-bit ADC, is around 110 dB, for 24-bit ADC nearly 160 dB. At the minimum feasible bandwidth of the measuring system, 1 to 10 kHz is needed for testing of the 16-bit ADC and the average noise spectral power density in surroundings of the carrier frequency (signed S) at least –140 dBc/Hz, for 24-bit ADC between -200 and -190 dBc/Hz.

Practical results for realized RF generator and source sample are shown in the table.

FFT signal analyzer and special system with frequency conversion was used for measuring noise voltage level. FFT signal analyzer (e.g. HP 35670A) is an apparatus not really suitable for noise measuring at the output of DC sources. The external separating circuit has to be connected to the analyzer input. The input of the analyzer isn't matched to the measured circuit in impedance, and input impedance of the analyzer is of an order much greater than the one of the measured circuit. The noise generated at the input of the analyzer is very strong, its level varies in the range 50-100 nV//√Hz. It is recommended to use low noise preamplifier for measurement of sources with low noise.

Table 1. Average noise spectral power density of experimental RF signal source supplied by various supplies

power supply	noise nV/√Hz	N/V ratio for U_{ss}=18V, I=0,4 A	S dBc/Hz	n of ADC bit
normal laboratory	700	-149	-149	16-18
laboratory low noise	70	-169	-166	18-20
clean up regulator	20	-180	-170	20
realized discrete transistor	6	-190	-170	20
accumulator	< 1	< -206	-170	20

Amplifier must have large dynamic range. In addition, it has to suppress the frequencies lower than approximately 10 Hz, in order not to overload the analyzer by a high-level of flicker noise on low frequencies. Finally, simpler, but more effective solution was used for measurement – a transformer.

The low noise transformer preamplifier Stanford Research system SR554 has been used in transformer mode. It has the ratio 100 in this mode, bandwidth about 10 Hz to 3 kHz for input resistance 50 Ω, input noise level only 0.5 nV/√Hz and it is already sufficient for measurements on DC sources.

In the system with frequency conversion the measuring signal is transferred by the use of the frequency converting into the frequency band where it can be more easily evaluated. Filter allows a suppression of the certain parts of spectrum signal and thereby the decrease of demand on the dynamic range and linearity of measuring instrument. Block diagram of the circuit arrangement is illustrated in Fig. 2.

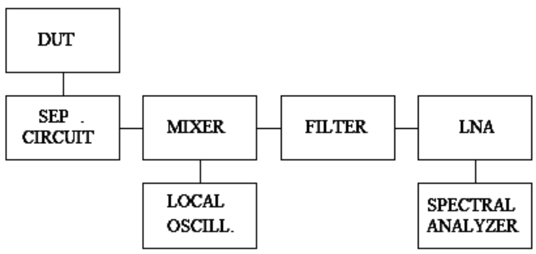

Fig. 2 Block diagram of the circuit arrangement

Frequency converter is realized by a mixer and local oscillator, which work on the suitable frequency. Filter is realized either as a crystal notch filter.

This arrangement has these advantages: measured noise signal is frequency transposed into the range of higher frequencies, where's possible to realize the high selective frequency filter more easy and where's also easier measuring of signals with very low levels, because the noise figure of used measuring instrument is lower.

Needfulness of using of quality local oscillator, mixer and filter, is disadvantage of the arrangement, which do not take the own noise into measured signal and do not evoke his nonlinear distortion.

Local oscillator has to be frequency stable. It must embody minimal level of phase noise and supply enough high power for the linear mixer. There was used a crystal oscillator type Clapp in this equipment. It works on frequency 1053,28 kHz with a single stage tuned amplifier, which supplies a power as much as 1 W.

The oscillator was supplied by the accumulator. The notch filter, which will be further described, was used for the carrier suppression. The phase noise level of the oscillator is approximately –160 dBc/√Hz in the carrier spacing to 100 Hz, for higher frequency spacing decreases approximately to –170 dBc/√Hz.

Low distortion double-balanced mixer with Schottky diodes is used as a mixer. Since the input signal is a low frequency signal, the mixer port between centres of symmetric transformers is used as mixer input. The used converter allows achieving conversion loss 6 dB and IP value in the range of 30 to 40 dBm.

The filter is realized as a crystal notch filter with very narrow frequency characteristics.

Spectral analyzer Rohde-Schwarz ESPI is used for evaluation of signal spectrum. The low noise amplifier with a noise figure 3 dB and a gain 43 dB was added between the filter output and analyser input for decreasing of high noise figure of the spectral analyzer.

This system allows the measuring of low-frequency noise nearby frequency 1 MHz by using of standard spectral analyzer. So measuring system achieved noise level of -180 dBV/√Hz at impedance 50 Ω.

The accumulator is the best source with relation to noise. A good 18 V, 10 Ah NiCd accumulator has the voltage noise spectral density less than the value reliably indicated in our laboratory, upon the loading by current 0,4 A at its terminals, which is approximately 1 nV/√Hz.

Laboratory power sources give results markedly worse. Common laboratory source, which has mains power supply and a output voltage stabilized by an integrated stabilizer, has the voltage noise spectral density approximately 700 nV/√Hz at output terminals, based on equal conditions as the accumulator. The noise suppression, which already exists at the output of the DC source, is not easy one. A simple connection of a capacitor in parallel to output terminals of the source is not effective, because the source has an inner impedance in order of tens mΩ and the capacitor, which ensures effective suppression of the noise, would have to posses the impedance at least about one order less at monitored frequency area, which is practically non-productive. Otherwise, it is possible to increase the effectivity of the filtration, e.g. by insertion of further impedance between the source output and the filter capacitor. Results for the filter with the values 10 Ω and 10 mF are shown Fig. 3.

It is possible to achieve better results by use of an active filter, which is usually designated as a clean-up shunt regulator. It works as a controlled current source controlled by undesirable noise voltage, which is connected as a shunt at the output of the DC source.This filter is basically the Miller integrator, which uses its very low output impedance corresponding to the capacitor with capacity higher by many orders, when compared to capacitor connected to circuit. The serial resistance can then be much smaller for the implementation of the effective RC filter, than in the case of passive RC filter. The active filter makes smaller increase of the inner resistance of the source and a lower voltage drop.

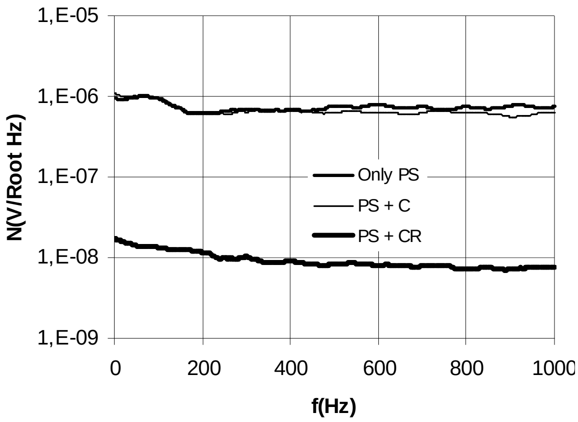

Fig. 3. Signal noise at the output of the DC power source with filters.

Clean-up regulator enables 10- to 20-fold decrease of the noise level on the value of the voltage noise spectral density approximately 20 nV/√Hz at the output of the DC source [3]. Its disadvantage is a little complicated construction and mainly setting of the regulator, individually according to used parts, and expressive decrease of the source stability.

Better solution than to try keep down a noise at the output of the DC source, which is originated in this source, is to use the DC source with a minimum level of the self-noise. But low noise power supplies [4], [5] are often not commercially offered, too. Although these sources have the spectral density of the noise at output terminals approximately about one order less than standard laboratory sources (see table), their level of the output noise level is still highest and sources of this kind affect the signal noise of low noise circuits that are supplied from them.

Therefore the best possibility, how to get the DC source with a minimum self-noise, is individual construction according to required parameters, with maximum regard to the minimum self-noise of all partial circuits of a stabilizer.

The source of reference voltage is the first problem. Commercial integrated precision references have very good voltage stability, but the voltage noise spectral density at output terminals usually varies at intervals from 50 to 150 nV/√Hz and it is an unacceptable value

Typical curve of voltage noise spectral density of precision reference circuit LT1021 in comparison with good stabilizer with Zener diode is presented in Fig.4.

Different principles are used to reduce the noise of references - connection of more references, voltage filtration of an active low-pass filter.

Or it is also possible to use a simple RC filter upon the loading by high impedance [6], [7]. Effect of such simple filter with resistance 1 kΩ and capacitor 3mF is illustrated in Fig. 5. The voltage noise spectral density level is lower than 1 nV/√Hz, except for the lowest frequencies. We may see the disturbance by distribution power supply network on a frequency 50 Hz and odd multiple.

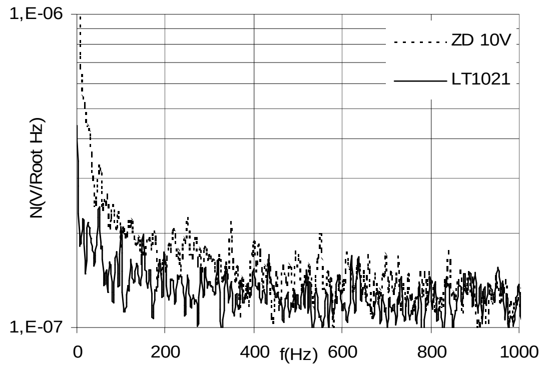

Fig. 4. Signal noise at the output of the reference voltage source and Zener diode stabilizer.

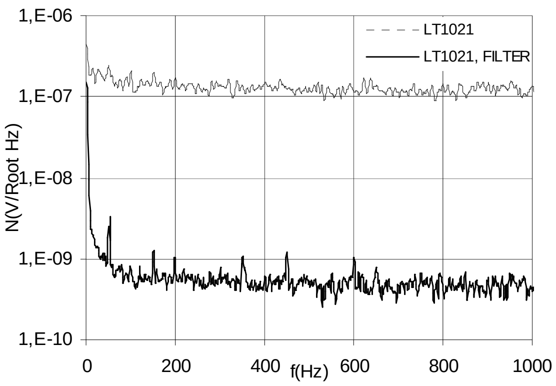

Fig. 5. Signal noise at the output of the reference voltage source and reference voltage source with filter.

An operational amplifier is usually used as a differential amplifier. Is it simple, but not convenient solution. Operational amplifier has too high gain coefficient. The gain of order of hundreds is sufficient for the source with a load current up to 1 A. Operational amplifier (OA) currently has the gain 10^6. High gain endangers the source stabilization and so it has to be reduced by negative feedback. OA also generates the inconsiderable noise, equivalent to voltage noise spectral density at its input varies between tens nV/√Hz also for low noise OA. Values of the voltage noise spectral density about 1 nV/√Hz [8] are reached only by ultralow noise operational amplifiers of highest quality at source resistances in order from units to tens of Ω.

A one-stage differential amplifier with two low-noise bipolar transistors reaches as a differential amplifier for a source with a load current up to 1 A. Equivalent voltage noise spectral density at the input of two-transistor amplifier is in unit value of nV/√Hz, low noise transistors of highest quality also have values less than 1 nV/√Hz in an entire band of acoustic frequencies [9], [10].

It is again necessary to observe the right choice of working points of transistors and those corresponding impedances networks, which are connected to transistors, to achieve the optimal noise of transistors.

The power transistor is the least critical part of the stabilizer, because its noise is not further amplified. However, incorrectly designed high power amplifier can itself generate the high-level noise. Most often used emitter follower usually generates the highest noise of all basic transistor connections (common emitter, base, collector mode). This situation is illustrated in Fig. 6, where the frequency dependence of the voltage noise spectral density is displayed for emitter follower with output voltage 12 V and current 0,5 A, that is supplied from the base and collector by the accumulator.

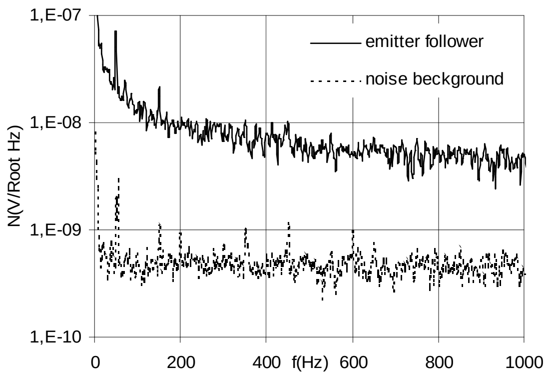

Fig. 6. Emitter follower noise.

The output noise level is considerably high, despite practically insignificant noise levels of the sources. Noise figure of the emitter amplifier is 20 dB minimum. The connection of high power transistor in common emitter mode is preferable. It has the noise value approximately 6 dB at the same power and with a good transistor. It is advantageous, if the transistor has maximum current gain. Its noise affects the resulting source noise, at least.

However, it is quite impossible to neglect the noise characteristics of any devices that are used in source. Noise from the standpoint of the construction and technology of resistance and capacitor and mismatch wiring can approve oneself.

The typical course of frequency dependence of the voltage noise spectral density of metal film resistor 1kΩ with maximum power dissipation 2 W, where voltage 30 V DC is applied, is presented in Fig. 7. It represents flicker noise in the area of lower frequencies, where its level decreases with steepness of approximately 10 dB/ /decade.

The flicker noise is not practically demonstrated in case of the same wire resistor, loaded in the same way. The measured noise level matches to the thermal noise, measuring instrument noise and outer disturbance.

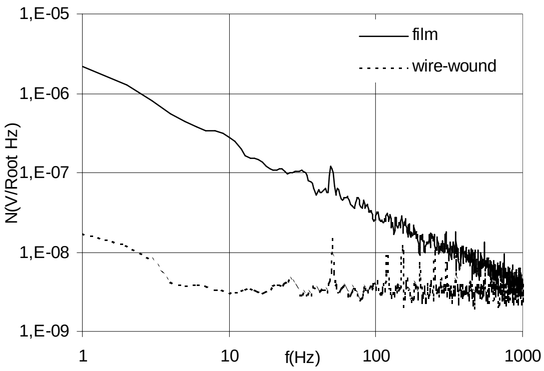

Fig. 7. Noise at the terminals of resistor

A component corresponding to the thermal noise is always visible at the terminal voltage of each resistor. If we describe this voltage by use of the source of noise voltage that is connected in series with the resistor, this voltage magnitude corresponds to the relation (4).

$$\overline{U}_{nt}^{2} = 4kTBR \qquad (4)$$

where U^2_{nt} is mean value of the square voltage noise
- k Boltzmann constant 1,38 10^{-23} J/K
- T temperature (K)
- B effective bandwidth, in which the voltage noise is indicated
- R is resistance value

The voltage noise spectral density of thermal noise is independent of frequency; voltage, current or power of the thermal noise depends only on frequency bandwidth, in which they are monitored. The voltage noise spectral density indicated e.g. on terminal of the resistor 1 kΩ, is approximately 2 nV /√Hz, at the correction of basic noise of this instrument, at the temperature 300 K and in case of matched measurement instrument.

If a current flows through resistor, the voltage noise on resistor rises even above a value of thermal noise too. This noise, due to irregularity of current flow across the different potential barriers in material, is called a flicker noise according to its character, or according to frequency dependence of the voltage noise spectral density of the noise 1/f. The flicker noise reaches the maximum level at resistors that are made out of composite materials with high resistivity, such as carbon composition resistors, varnish resistors and carbon film resistors.

It is possible to describe the mean value of voltage noise square of flicker noise by formula (5).

$$\overline{U}_{nf}^{2} = AI^{\alpha}R^{\beta}f^{-\gamma} \qquad (5)$$

where U^2_{nf} is the mean value of the voltage noise square
- A constant given by the design of the resistor
- I current flowing through the resistor
- R resistance of the resistor
- α, β are exponents dependent on resistor structure, usually α= β=2
- γ exponent indicating the frequency dependence of the noise, usually γ =1

It is possible to determine voltage noise, indicated on the resistor in certain frequency band, according to the integral (relation (5)) in the range of frequency band (6).

$$\overline{U}_{nf} = \sqrt{\int_{f_1}^{f_2} AI^2R^2f^{-1}df} = \sqrt{AU^2\ln\frac{f_2}{f_1}} = U\sqrt{A}\sqrt{\ln\frac{f_2}{f_1}} \qquad (6)$$

where f_1 ,f_2 are limits of the frequency band.

Indicated level of the noise voltage depends only on the ratio of high and low cut-off frequency and voltage, which is fed to the resistor. That is why the noise index is criterion of the noise, defined as the ratio of the RMS noise voltage, in micro volts, to the applied DC voltage, in Volts, expressed in decibels, when the associated pass band for the noise is one decade, or simply µV/V/Dec in dB. But in practice, the level of the noise voltage depends in minor extent also on the value of resistance, whereas the level of the noise voltage grows approximately with 3rd root of the resistance value.

Typical values of the voltage noise spectral density at the frequency 10 Hz are presented in the table 2 for common types of resistors. Lower values are valid for resistors of approximately 100 Ω, the higher ones for resistors 100 kΩ. The levels of the noise voltage, which matches the noise value, are approximately 5 times higher, than values of the voltage noise spectral density on frequency 10 Hz, as it is mathematically possible to derive out of the relation (6).

Table 2. Typical values for voltage noise spectral density of flicker noise of resistors

material	U_{nf} at 10 Hz (nV/V√Hz)
carbon film	30-300
thick film	10-50
metal thin film	2-20
wire, foil resistors	≤0,1

The capacitors, used in low noise circuits, must primarily have the minimal leakage current. The random component of this current again creates noise voltage on capacitor corresponding approximately to flicker noise. A special characteristic of the capacitor is that the capacitor alone works as filter for this voltage and it makes its attenuation so much the greater, whereby the time response of the capacitor is greater (defines the time in seconds, in which the voltage across the capacitor discharges to 37 % of the fully charged state).

Capacitors, which are used in low noise circuits, have to be the plastic film type (Polypropylene-Sulphide, Polyethylennapthtalate or Polyester). They have excellent characteristics at low temperatures to 40 °C, their time constant is approximately 10^5 s. Special care must be taken when soldering these, so that they don't overheat. The mica or the ceramic capacitors are used as capacitors with capacity of order from units to tens of pF (only the NP0 type), which have excellent characteristics again.

Other ceramic capacitors (X7R, X5R, Y, Z) have a large piezoelectric effect, their capacitance changes with temperature and bias voltage and time constant is least 10 lower than for plastic film capacitors.

Tantalum and aluminium electrolytes can also be used as blocking capacitors with high capacitance. They must not be operated at high temperature, near the maximum working voltage and the voltage must not be absent for a long time. Then they have the time constant approximately 10^3 s and their noise is practically insignificant.

The experimental DC power source was implemented according to the circuit diagram shown in Fig. 8.

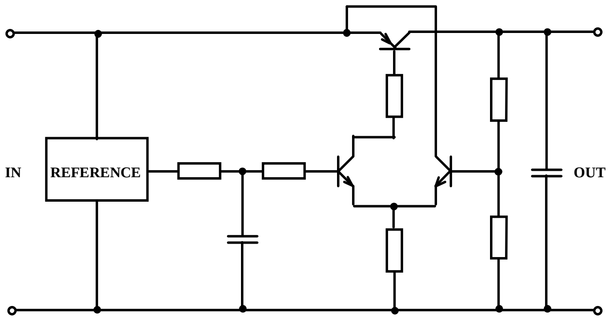

Fig. 8. Discrete transistor DC power source

This sample has been developed as the source for power supply of RF power generator with a high spectral purity, which needs a supply voltage 12 V and a current approximately 0,3 A. Source must particularly show the minimal self noise. The internal source resistance is not critical – it is loaded by a constant current. The stability of the output voltage is sufficient. It is better than 10^{-3}. But changes of the outdoor temperature about 1°C have a major influence on the generator than voltage change about 10 mV.

Construction of the source comes out of differential amplifier with a simple couple of transistors SSM2210. It is a dual NPN matched transistor pair, specifically designed to meet the requirements of ultra-low noise audio systems. The equivalent input voltage noise is typically only 0,8 nV√Hz over the entire audio bandwidth of 20 Hz to 20 kHz. Precision reference with ultralow drift and noise LT1021 with filter is used as a source of reference voltage at the output. Its characteristics correspond to the graph in Fig. 5.

The output transistor has been chosen especially with regard on maximum current gain coefficient and noise figure not exceeding 6 to 10 dB in the range of working currents and low frequencies.

This source has the lowest voltage noise spectral density from all watched source at output clips as it is displayed in Fig. 9. Circuit, in which only wire resistors are used, has approximately half level of the noise spectral density at output terminals. This source operates also well from the aspect of the output voltage stabilization. The source has the inner resistance about 0,2 Ω and the stabilization factor $\Delta U1/\Delta U2$ approximately 2000 upon the loading by the current of about 0,4 A.

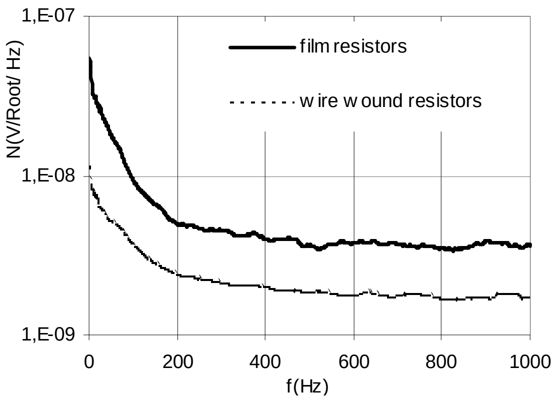

Fig. 9. The noise voltage spectral density of the experimental DC power source

4. CONCLUSIONS

Our analysis perfectly confirms the old Czech proverb "the beauty is in simplicity". The best results were reached with a stabilizer made of discreet parts and with the voltage reference with a passive RC filter. Regulating amplifier of the stabilizer, which has been implemented as simple symmetrical two-transistor amplifier, has minimum noise and sufficiently large gain coefficient for enough high stabilization factor and acceptable source resistance of the stabilizer.

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