17th Symposium IMEKO TC 4, 3rd Symposium IMEKO TC 19 and 15th IWADC Workshop
Instrumentation for the ICT Era
Sept. 8-10, 2010, Kosice, Slovakia

DC Power Supply with Very Low Noise

Vaclav Papez[1], Stanislava Papezova[2]

[1]*Faculty of Electrical Engineering, Czech Technical University in Prague, Technicka 2, Prague, Czech Republic, papez@fel.cvut.cz*
[2]*Faculty of Mechanical Engineering, Czech Technical University in Prague, Technicka 4, Prague, Czech Republic, stanislava.papezova@fs.cvut.cz*

Abstract- Accurate measuring equipment and generally all electronic equipment, in which a large S/N ratio is requested for the signal processing, are very sensitive on disturbances coming from power supplies. A simple solution is the power supply of such equipment from accumulators or batteries; nevertheless, this brings problems with their servicing. This contribution presents the results of study of noise disturbance of laboratory power supply on high pure sine-wave signal source and describes a design of special power supply with minimum noise, which was realized.

I. Introduction

The need of solution of DC power supply with very low noise appeared here in connection with development of special generators of testing signals for ADC testing, at which a large Signal to Noise and Distortion Ratio (SINAD) in the range of 100 to 140 dB is requested. [1] The effect of noise and disturbance from the power supply, which is considered for a high quality one, was removed experimentally and actually accidentally, when in effort to remove components with a spacing from the carrier in multiples of frequency of 50 Hz power network in the monitored spectrum of the testing generator the power supply of the generator was replaced with accumulator. The result was not only the removal of the above mentioned components, but also decrease of level of disturbance signals in the spectrum, which were considered for the phase noise of the generator.
The immediate solution was very simple – power supply from the accumulator. Nevertheless, this solution is good for single experiment, but not for a systematic work. From this point of view, the accumulator has the only one good property - its own noise is determined by thermic noise of its internal resistance and is non-measurably small. The other properties are disadvantageous ones. Despite manufacturers expressions that it is not true, an accumulator needs a careful maintenance and during discharging there is a change of its terminal voltage and the accumulator must be charged by a defined way. The accumulator can be well used only at discharging in the flat part of its discharging characteristics, when the voltage changes slightly and we must respect this change. It is not possible to stable the voltage by a conventional voltage stabilizer (three-point), because it produces a larger noise than the laboratory power supply. Besides, the accumulator is discharged at the end of measurements, when it is necessary to measure 1 more value, but the voltage is already decreased and the measurement is no longer possible.
For this reason, the issue of the low noise DC power supply was investigated.
The first issue was the exact determination of the level of noise of the voltage on the power supply output. A representative rate of the disturbance signal is its frequency spectrum showing its power or voltage, standardized for selected constant bandwidth, especially in the AF frequency band. Here is the level of noise signals due to the flicker noise the highest one, and the noise generated by the power supply cannot be filtrated practically. Due to a very small output impedance of power supply, also the noise with very small voltage has an indispensable power, which must be evaluated. For the output impedance of 1 to 100 mΩ, there are voltages 1 to 100 nV√Hz representing the power –140 to –100 dBm/Hz, i.e. the power of 34 to 74 dB above the level of thermal noise. The measurement is complicated by very strong impedance mismatch between the power supply and the measuring instrument. The input of the instrument (FFT frequency analyzer HP 35670A used), is not matched to the measured circuit in impedance, and the input impedance of the analyzer is of 7 up to 9 order 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 of 100- 300 nV//√Hz. No preamplifier can solve this situation; a transformer suits best for improvement of impedance matching and increase in the signal level. The low noise transformer preamplifier Stanford Research system SR554 has been used in the transformer mode. It has the ratio 100, bandwidth about 1 Hz to 10 kHz for

input resistance 1 Ω, input noise level only 0.5 nV/√Hz [2] and it is already sufficient for measurements on DC power supplies. Nevertheless, the measuring system is not too safe from the point of view of possible damage by overvoltage; it is suitable to insert a voltage limiter between the transformer and the analyzer. There exists a danger that the transformer with primary winding connected through a capacitor of high capacity (4.4 mF) to the output of the power supply will function, at any transient process of the power supply circuit, as an ignition coil in the car and will breakdown the analyzer input.

The next issue is the determination of disturbance signal levels, which can occur on the output of the power supply and which already do not cause a deterioration of parameters of the signal generated from the power supply supplied by the generator. Because an exact determination of effectiveness of the disturbance signal transfer from the power supply voltage to the output signal would be difficult and could lead to an extensive theoretical analysis, the effect of noise, which is superimposed on the power supply voltage, was observed experimentally directly on existing generator. Typical courses for the low noise generator 1.053 MHz are shown in following figures. In Fig. 1 and 2, there are shown phase noise power spectrums of the LN oscillator, which is supplied (18 V, 0.4 A) from the HP 3631 power supply and from the accumulator. The comparison shows the lower level by 10 to 20 dB at the oscillator power supply from the accumulator. In Fig. 3, there is the output voltage noise spectral density of the power supply HP 3631a shown as a ratio of RMS of noise voltage and the set output voltage. A similarity of the power supply noise spectrum and the phase noise power spectrum is obvious.

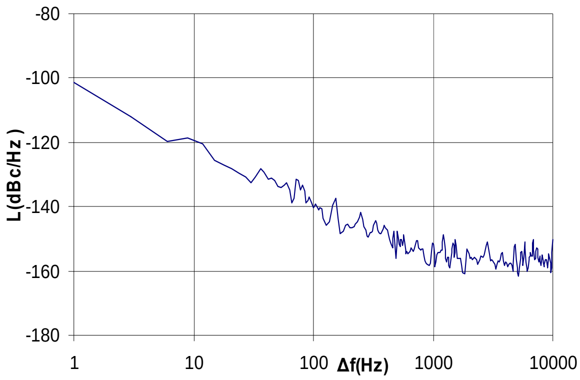

Figure1. Phase noise power spectrum of the LN oscillator powered from the power supply HP 3631a

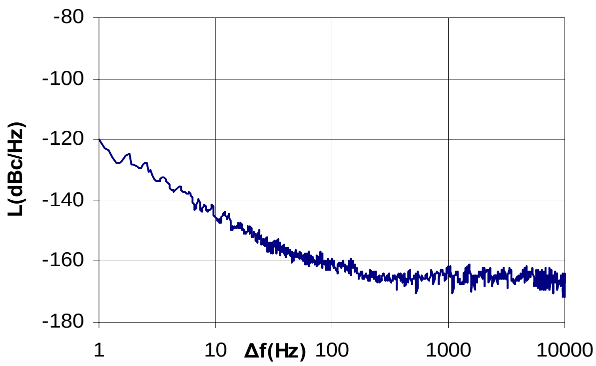

Figure 2. Phase noise power spectrum of the LN oscillator powered from the accumulator

The transfer effectiveness corresponds to simultaneous modulation of noise of the carrier in several serial product elements, where each of them has a slightly different transfer characteristic for noise. The phase noise power spectrum level determined in this example and in many other measurements approximately corresponds to the level of the output voltage noise spectral density of the power supply, or is slightly higher, by 10 to 15 dB.

By extrapolation of determined effectiveness towards small levels, what should be possible without significant error with regard to the system linearity, there was determined the level of the output voltage noise spectral density of the power supply, already not influencing the noise power spectrum of the oscillator as the level of the power spectrum noise by 20 dB lower, than the level of the phase noise power spectrum of the oscillator.

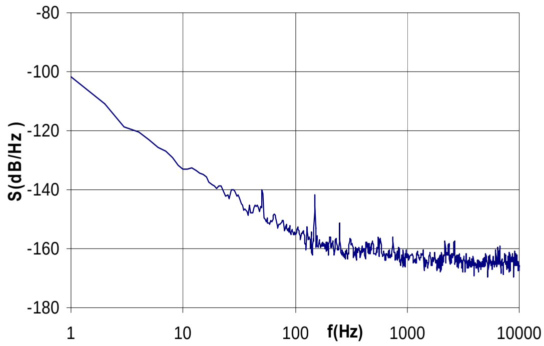

Figure 3. The output voltage noise spectral density of the HP 3631a power supply standardized to output voltage.

II. Construction of the DC power supply with a very low noise

According to the above shown considerations, there was developed a power supply for supply of special generators of testing signals for the ADC testing, which does not bring an increase of the noise level with regard to the accumulator.

Common power source or laboratory source, which has mains power supply and a output voltage stabilized by an integrated stabilizer, has the voltage noise spectral density approximately 300 to700 nV/√Hz (at 100Hz) at output terminals, upon the output voltage 18 V and loading by current 0,4 A .

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, their level of the output noise level is still high 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 power supply design results from the DC voltage regulator according to the Fig. 4, which was described in [6] and shows the level of its own noise by 40 to 70 dB lower, than conventional three-point voltage regulators. The stabilizer is designed from discrete components and is optimized especially for minimum level of noise generated by it. The differential amplifier is solved with a simple couple of SSM2210 transistors. 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 ($I_c = 1$ mA) [7]. The circuits on inputs of differential amplifier are intentionally solved with small internal resistance, which corresponds to the impedance of noise matching of SSM2210 transistors for collector current, with which they work in the amplifier (app. 5 mA). All resistors used in the stabilizer are the wire resistors, which do not generate the flicker noise. For the reason of arising contact noise of the collector, a potentiometer is not also used for setting or adjustment of the output voltage. The output voltage is set for the fixed value, which is adjusted by fixed resistors in voltage dividers on inputs of the differential amplifier. The power supply of the reference voltage is solved with "the precision reference with ultra low drift and noise", which has a 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. For this reason, an RC integration element with time constant of app. 50 s is included to the output of the reference voltage, it suppresses the noise from the output of the reference voltage from frequency of app. 5 Hz higher, to the level of thermal noise of connected resistors. The stabilizer power amplifier is solved as a "common emitter" amplifier, because it shows much lower noise than the most often used emitter follower. Further, the common emitter amplifier has also a high output impedance, which allows further reduction of the noise level of the voltage stabilizer output by a capacitor connected in parallel to output terminals.

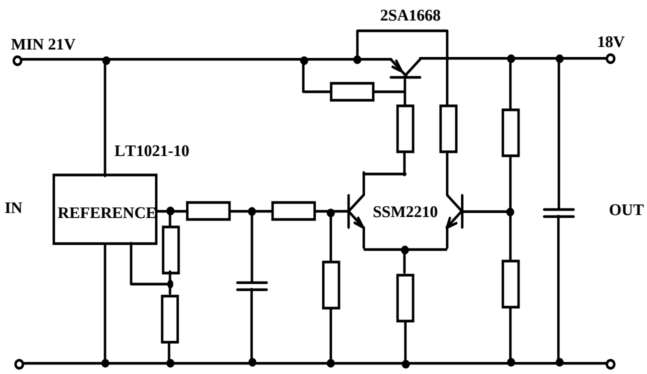

Figure 4. Discrete transistor DC voltage regulator

The voltage stabilizer has the voltage noise spectral density at output terminals app. 1 nV/√Hz on the frequency 100 Hz, the stabilization factor $\Delta U_i/\Delta U_o$ approximately 2000 upon the loading by the current of about 0.4 A and the inner resistance about 0,2 Ω.
The realized power supply has output voltage of 18 V and maximum output current of 1 A. Block diagram of the equipment is displayed in figure 5.

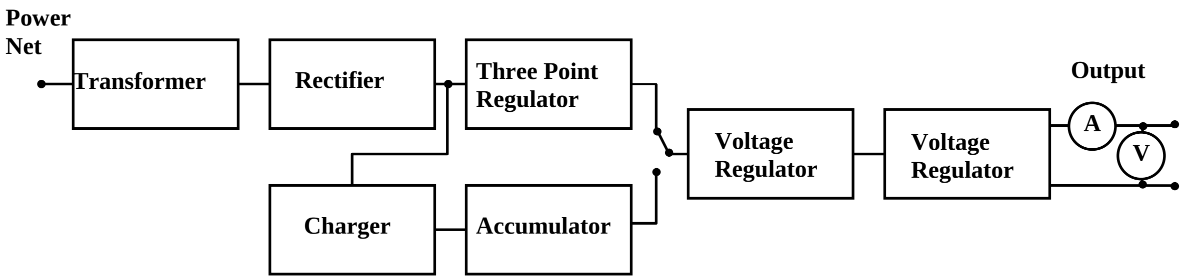

Fig.5 The block diagram of the power supply

The power net section of the power supply is solved by classic technology with the transformer and the rectifier, which work on the power network frequency. The power supply is supplied from external separating transformer with AC voltage of 12 V and in the power supply there is next shielded separating transformer. This modification was selected, because it unconditionally guarantees the instrument safety, without connection of the instrument with protective wire of PE or PEN network. Besides, at lower AC voltage, which is led to the power supply, there occurs also smaller transfer of disturbances of the power network. The transformer in the power supply box has electrostatic shielded windings and is solved with regard to minimum magnetic scatter and is located in magnetic shielding cover. In the cover, there is located also a rectifier of the power supply with filter capacitor, to prevent radiation disturbing signals by wires, through which there flow large pulse currents of the rectifier circuit.
The power from the rectifier output is processed by three stabilizers connected in cascade way. This kind of solution was selected, because it allows reaching the total resulting stabilization factor of 180 dB, approximately, which is necessary for suppression of disturbances of the ripple effect of the rectifier. The first stabilizer in the cascade is a conventional three-point voltage regulator of 24 V. It has the stabilization factor $\Delta U_i/\Delta U_o$ 60 dB approximately and can be still used here, because on its output there is approximately the same level of noise signals and of ripple signals of rectifier, corresponding to the voltage level of several tenths of mV. The next two voltage regulators are the two DC voltage regulators realized according to the diagram in Fig. 4, the output voltage of first stage along with input voltage of second stage is 21 V. The cascade of 2 stabilizers reaches the stabilization factor better, than 120 dB. The disturbance signals coming from the previous stabilizer are reduced to the level of 1 nV, approximately and they are not identifiable in the noise of regulator.
For voltage and current indication on the power supply output - the pointer measuring instruments are used. A use of digital measuring instruments was found as totally unsuitable, because it causes bringing of disturbance on the output of power supply from the power supply of the digital measuring instrument and from its clock generator.

The realized power supply is equipped also with internal accumulator, which allows several-hours operation of the instrument without power supply from the power network. This solution was selected originally for assurance of the functioning of the power supply in the UPS mode and of continuity of measurements and stabilization of testing signals generator. Later, at analysis of assembled sample of realized power supply, it was found that only at operation of the equipment from internal accumulator there can be reached the assumed lowest levels of disturbances on the source output; it was not possible to remove noticeable disturbances of the power network.
A view on internal arrangement of the instrument, after removal of the upper cover of the box is shown in Fig. 6.

Figure 6. Internal arrangement of the instrument

The metal box is not connected with direct current circuits of the power supply and functions as shielding cover of the power supply. In the left part of the instrument there is obvious a cylindrical shielding of the transformer and the rectifier. The shielding was made of constructive steel, despite the fact that this solution is not suitable, but a better material was not available. In the back right part of the instrument, there are located lead gel accumulators 12 V, 4.5 ampere hours, and in front of them there are 2 DC voltage regulators with coolers of power transistors.

III. Conclusions

The output voltage noise spectral density of the realized power supply is shown in Fig. 7 and 8. Measurements were performed at the power supply loaded by resistance of 47 Ω (the loading corresponds to the generator of testing signals for the ADC testing) and at operation of the power supply from the internal accumulator and from the power net.
The minimum level of noise was reached at operation from internal accumulator (see Fig. 7). The output voltage noise spectral density of realized power supply in the whole observed frequency range is app. by 66 dB lower, than at earlier used power supply HP 3631a (see Fig.3).
At operation of the power supply from the power network there penetrate to the output the disturbance signals of the power network corresponding with their frequency to the frequency of the power network and to their harmonic components. Their level is app. by 20 dB higher, than the level of the voltage noise spectral density and by 40 dB lower, than the level of equivalent disturbance signals at the HP 3631a power supply.
The output noise at the realized power supply is so low in both cases that it does not influence, by an observable way, the phase noise power spectrum of the testing signals generator.
From the point of view of next parameters, the realized power supply also complies with requirements. A drift of the output voltage, caused by discharging of the accumulator, by change of voltage of the power network or by heating of the instrument, is lower, than 10 mV. The internal resistance of the power supply is 100 mΩ, approximately, what is more, than a value corresponding to analogical values for laboratory power supplies, but at loading with a constant load of the testing signals generator, it does not cause disturbances. The operation from internal accumulator by loading of the testing signals generator is possible for the time of 8 hours.

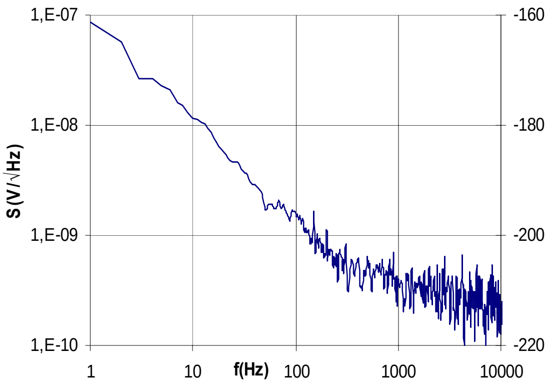

Figure 7. Frequency spectrum on the output of the power supply at operation from internal accumulator.

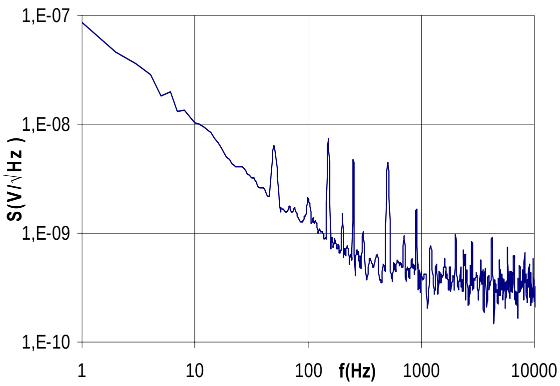

Figure 8. Frequency spectrum on the output of the power supply at operation of the power net.

Acknowledgement

The research was supported by the research program No. MSM6840770015 "Research of Methods and Systems for Measurement of Physical Quantities and Measured Data Processing "of the CTU in Prague sponsored by the Ministry of Education, Youth and Sports of the Czech Republic.

References

[1] DiBartolomeo J.,Cecic D.:"Conditioning Sensor Signals for Data Converter Applications", *IEEE Instrumentation & Measurement Society Meeting*, Toronto 2003.
[2] Scientific and Engineering Instruments, 25th Anniversary Edition, Stanford Research Systems, 2005.
[3] Wenzel Associates: Finesse Voltage Regulator Noise, http://www.wenzel.com/documents/finesse.html
[4] E36XXA Series Non -Programmable DC Power Supplies, Data Sheet Agilent
[5] Low Noise DC Bias Supplies, Data Sheet Pulse Instruments
[6] V. Papež, S. Papežová, "Low Noise DC Power Supplies", XIX IMEKO World Congress, Lisbon, Sept. 2009.
[7] SSM2210 Audio Dual Matched NPN Transistor, Data Sheet Analog Devices.