E3S Web of Conferences **592**, 03031 (2024) https://doi.org/10.1051/e3sconf/202459203031
EMMFT-2024

Design and modelling of positive LDO voltage regulator

Sergey Rybalka[1*], *Andrey* Demidov[1], and *Evgeny* Kulchenkov[1]

[1]Bryansk State Technical University, 7, 50 let Oktyabrya blvd., 241035, Bryansk, Russia

Abstract. In present study the total ionizing dose effects in a positive low-dropout linear voltage regulator IS-LS1-3.3V was investigated experimentally using the developed the X-ray research complex. It is established that the output voltage is changed slightly in all total ionizing dose intervals and voltage regulator preserves a functional state without failure. The analytical functional dependence of the output voltage on the total ionizing dose is determined. The circuit diagram and voltage regulator SPICE macromodel for circuit simulations taking into consideration total ionizing dose effects have been developed.

1 Introduction

It is known that the production of competitive and import-independent electronic component bases are a necessary condition for ensuring the national security of the country and the manufacturing application of innovative technologies, electronic equipment, systems and complexes of wide application [1]. On the other hand, the creation and development of strategically important electronic equipment for communications and telecommunications, nuclear power, aerospace, medical equipment, automotive, energy and industrial equipment, radar, as well as for civilian and special-purpose equipment is impossible without the creation and industrial development of a highly efficient and highly reliable electronic component base [2]. To ensure technological sovereignty, the most important task of domestic electronics manufacturers is the development and mass production of competitive and import-independent electronic component base. One of the key value in the nomenclature of the produced electronic component base is linear voltage regulators and sources of reference voltage because of voltage regulator plays an essential role in ensuring maximum power delivery and long-lasting electronic lifespan [3]. Moreover, for development of industries such as cosmonautics, aircraft engineering, nuclear power, it is necessary to achieve reliable functioning of the electronic components such as voltage regulators that used under radiation conditions [4, 5]. Thus, research and ensuring the radiation hardness of voltage regulators to the total ionizing dose during development and production is an urgent task [5, 6]. Therefore, the main goal of this research is to study the radiation hardness to the effects of the total ionizing dose of the positive low-dropout linear voltage regulator IS-LS1-3.3V produced by JSC "GRUPPA

* Corresponding author: minmaxian@mail.ru

KREMNY EL" (Bryansk) in the framework of import substitution program, using the developed hardware and software complex based on the X-ray research complex.

2 Materials and methods

The positive low-dropout (LDO) linear voltage regulator prototype IS-LS1-3.3V (analogue of LT1963 [7]) produced by JSC "GRUPPA KREMNY EL" (Bryansk) with output voltage of 3.3 V and made by epitaxial-planar bipolar technology was studied experimentally. Studies of the IS-LS1-3.3V voltage regulator for hardness to ionizing radiation by the effects of total ionizing dose were carried out using the developed hardware and software equipment based on an X-ray research complex (XRRC-0401) with calibration at the "Gamma MRX MEPhI" isotope equipment [8]. The schematic diagram of the developed hardware-software research complex is shown in Figure 1. The X-ray research complex is an X-ray source RAP-100 with a maximum anode voltage of 80 kV and a maximum anode current of 0.3 mA, which installed in an X-ray protection chamber with a two-coordinate positioning system with a control step of 0.1 mm. The X-ray intensity was monitored using the X-ray comparator DRI-0401. The board of contact equipment is designed to place the sample in the radiation field and ensures its operation.

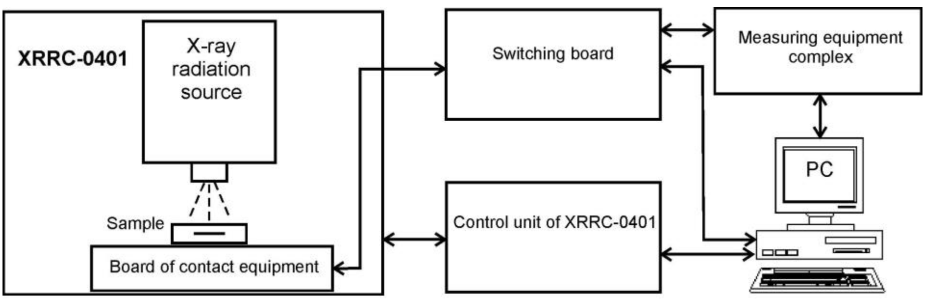


Fig. 1. Diagram of the hardware-software complex: XRRC-0401 – X-ray research complex; source of X-ray radiation; board of contact equipment; switching board; control unit of X-ray hardware-software complex; measuring equipment complex; PC – personal computer.

The control unit of contact equipment sets the mode of X-ray source operation and duration of irradiation. The rate of dose of radiation exposure can be controlled by both the change in anode current and the distance from the window of the X-ray source to the sample being irradiated.

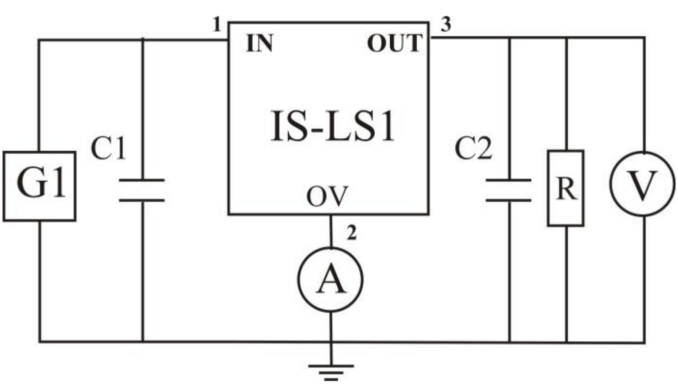


Fig. 2. Text Circuit for testing of IS-LS1-3.3V linear voltage regulator. G1 – constant-voltage source; A – ammeter; V – voltmeter; R – resistive load; C1=10 μF, C2=10 μF.

The switching board specifies the electrical modes of testing sample, as well as the necessary connection of measuring equipment, power sources and loads. The measuring equipment complex includes: RIGOL DP832 power supply, Fluke 8845A multimeter, RIGOL DL3021 programmable electronic load and Keithley 6485 ammeter. The XRRC-0401 was controlled by specialized software developed in the LabView environment, which allows measuring monitored parameters after a given time interval, and also provides the ability to set the electrical mode of operation of the voltage regulator during irradiation. The positive low-dropout linear voltage regulator IS-LS1-3.3V was connected to the board of contact equipment in accordance with scheme presented in Figure 2. During the radiation experiment voltage regulator was in active operating mode at input voltage of 20 V and load current of 5 mA.

3 Results and discussions

During the radiation experimental study of IS-LS1-3.3V positive low-dropout linear voltage regulator prototype the following operation mode was used for XRRC-0401: anode voltage of 70 kV, anode current of 150 μA. The distance from the window of the X-ray source equals of 45 mm and rate of radiation dose exposure equals of 44 un./s (un. – the units of the X-ray comparator DRI-0401 calibrated at the "Gamma MRX MEPhI" isotope equipment [8]).

In Figure 3 are shown experimental results for voltage regulator obtained during radiation experiment (active operating mode at input voltage of 20 V). As can be seen, the output voltage V_{OUT} slowly increase with increasing of total ionizing dose D. It is important to note that output voltage not reaches the lower and upper limit of voltage regulator operation mode (3.135-3.465 V). Thus, at value of total ionizing dose equals of 8×10^3 un. (that is equal of ~282 s (~4.7 minutes)) output voltage V_{OUT} equals of 3.29 V. Further, during increasing of radiation dose exposure the output voltage V_{OUT} increase nonlinearly and at final value of total ionizing dose equals of 1002×10^3 un. (~35430 s (~590.5 minutes)) the output voltage value is 3.33 V ($\Delta V_{\mathrm{OUT}} \approx 0.04$ V or $\Delta V_{\mathrm{OUT}}/V_{\mathrm{OUT}} \approx 1.2\%$), i.e. in this case the voltage regulator scheme preserves a functional state without failure. It should be noted that similar results were detected in the similar type of positive LDO linear regulator designed specifically for space applications [9]. A study of the radiation behavior of domestic positive voltage regulators (JSC "GRUPPA KREMNY EL" (Bryansk)) also revealed a similar dependence [10]. From a practical viewpoint, when using linear voltage regulators under radiation exposure conditions, it is important to know the analytical dependence of their main parameters on the radiation dose in order to select the optimal electrical mode of operation. This problem can be solved using methods of mathematical processing of measurement results, in particular, methods of regression analysis [11, 12], which make it possible to determine the analytical type of dependence of parameters. Further, on the basis of above experimental data, analytical dependence of the output voltage V_{OUT} on the total ionizing dose D for voltage regulator was calculated. The analytical dependence of the output voltage V_{OUT} on the total ionizing dose D for voltage regulator (in active operating mode at input voltage of 20 V and load current of 5 mA) is following:

$$V_{\mathrm{OUT}} = 3.204\cdot10^{-14}D^4 - 4.435\cdot10^{-11}D^3 - 9.187\cdot10^{-9}D^2 + 7.041\cdot10^{-5}D + 3.291 \quad (1)$$

where D – the total ionizing dose (10^3 un.), V_{OUT} – the output voltage (V).

Figure 3 shows the dependence of the output voltage V_{OUT} on the total ionizing dose D for voltage regulator calculated by equation (1). As can be seen from Figure 3, calculated

https://doi.org/10.1051/e3sconf/202459203031

curve well describes the output voltage characteristics with sufficient accuracy. Thus, in the engineering aspect using the analytical dependence in form of equation (1) can predict the radiation hardness of this voltage regulator type.

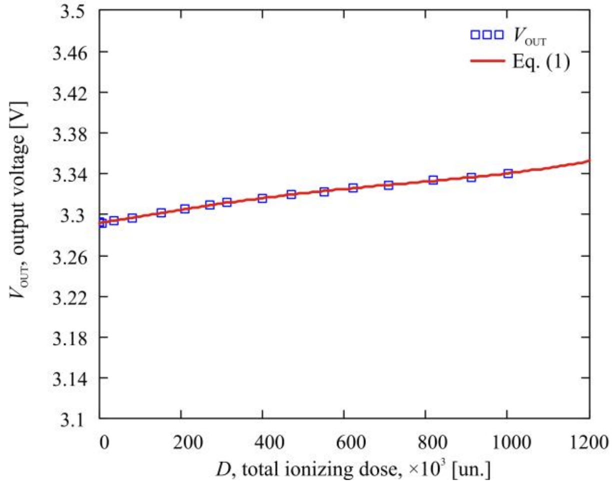


Fig. 3. The experimental (points) and theoretical (line) data for output voltage dependence VOUT on total ionizing dose D for IS-LS1-3.3V voltage regulator prototype.

On the other hand, with practical viewpoint in engineering aspect for electronic circuit design it makes sense to use models of electronic components created in special SPICE (Simulation Program with Integrated Circuit Emphasis) circuit program that simulates electronic circuits and allows predicting the behavior of electronic integrated circuits [13].

The equivalent circuit diagram for voltage regulator model in Figure 4 can be used in LTspice and others simulation program as a subcircuit with a .SUBCKT command as SPICE circuit program [13].

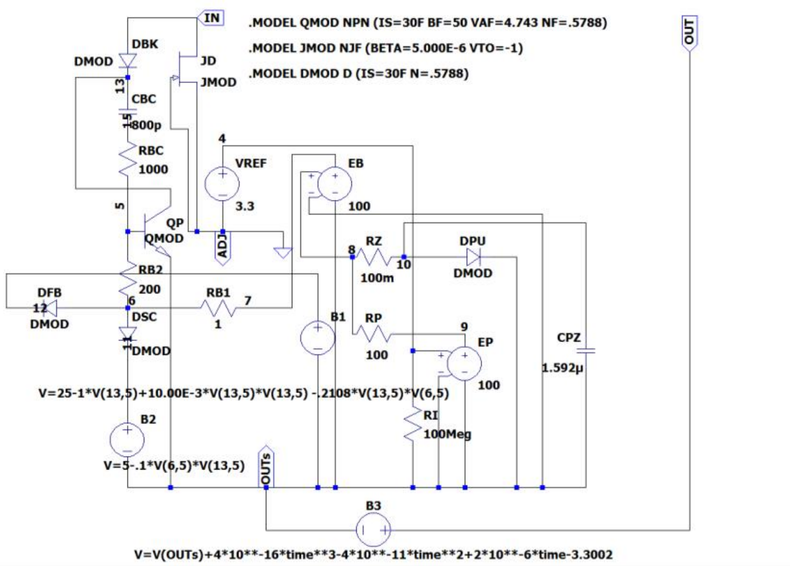


Fig. 4. The equivalent circuit diagram for IS-LS1-3.3V voltage regulator model in LTspice with taking into account of radiation effects (B3 – the behavioral voltage source).

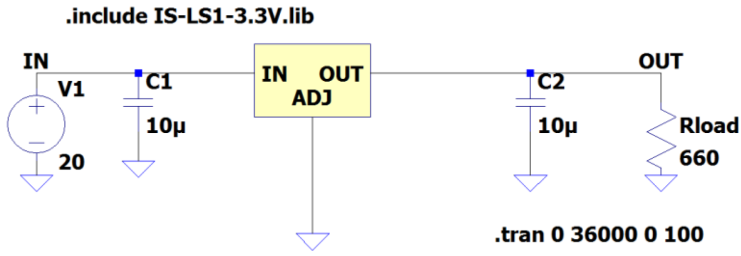
 https://doi.org/10.1051/e3sconf/202459203031

With this aim equivalent circuit diagram for voltage regulator model in Figure 4 was represented as the subcircuit text macromodel listing is shown in Figure 5 for the IS-LS1-3.3V voltage regulator.

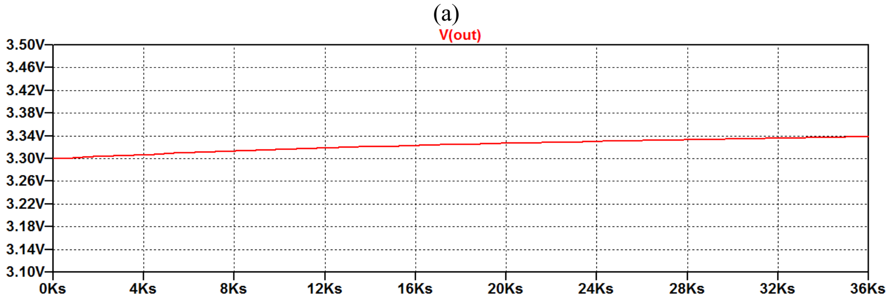
```
* ------ IS-LS1-3.3V positive loltage regulator radiation model subcircuit -------
* connections:           input
*                        |  adjustment pin
*                        |  |   output
*                        |  |   |
.SUBCKT IS-LS1-3.3V      IN ADJ OUT
JADJ IN 0 0 JMOD
VREF 4 0 3.3
RZ 10 8 100m
RB2 5 6 200
RB1 7 6 1
DBK IN 13 DMOD
CBC 13 15 800p
RBC 15 5 1000
QPASS 13 5 OUTS 0 QMOD
DSC 6 11 DMOD
DFB 6 12 DMOD
RP 9 8 100
EP 9 OUTS 4 OUTS 100
RI 4 OUTS 100Meg
DPU 10 OUTS DMOD
CPZ 10 OUTS 1.592u
EB 7 OUTS 8 OUTS 100
B1 12 OUTS V=25-1*V(13,5)+10.00E-3*V(13,5)*V(13,5) -.2108*V(13,5)*V(6,5)
B2 11 OUTS V=5-.1*V(6,5)*V(13,5)
B3 OUT OUTS V=V(OUTS)+4*10**-16*time**3-4*10**-11*time**2+2*10**-6*time-3.3002
.MODEL QMOD NPN (IS=30F BF=50 VAF=4.743 NF=.5788)
.MODEL JMOD NJF (BETA=5.000E-6 VTO=-1)
.MODEL DMOD D (IS=30F N=.5788)
.ENDS IS-LS1-3.3V
```

Fig. 5. Text macromodel listing for the IS-LS1-3.3V positive voltage regulator.

Afterwards, for testing of the voltage regulator model in radiation condition the obtained macromodel was added to LTspice program base as an IS-LS1.lib library file.



(a)



(b)

Fig. 6. The circuit for IS-LS1-3.3V voltage regulator testing model in LTspice program during radiation time exposure (a); the output voltage V(out) dependence on radiation exposure time (b).

Figure 6a shows the circuit for voltage regulator model testing during radiation time exposure in LTspice program (with inclusion of IS-LS1.lib library file into program as SPICE-directive).

The model testing results is shown in Figure 6b, where the output voltage (V(out)) dependence on radiation exposure time has been presented. Further, with aim to compare experimental and theoretical results simulated in LTspice program, the original experimental results (Figure 3) were recalculated from total ionizing dose to radiation dose exposure time with taking into account of rate of radiation dose exposure. Thus, similar approach can be applied to radiation behavior description of such type voltage regulators produced in the framework of import substitution program [10, 14].

Further, in Figure 7 is shown the output voltage V_{OUT} dependence on radiation exposure time (in seconds) for experimental (XRRC-0401) and theoretical (LTspice) results. As can be seen from Figure 7 the theoretical output voltage V_{OUT} simulated by proposed macromodel in LTspice program demonstrates good agreement the experiment.

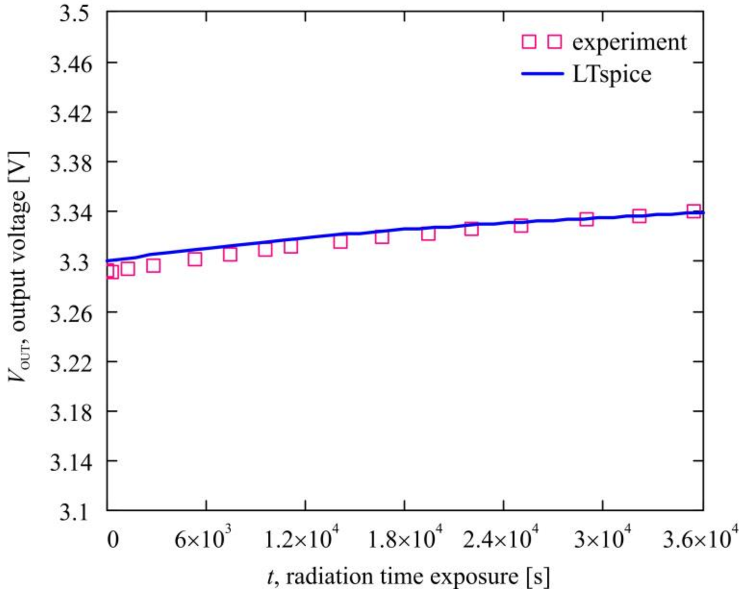


Fig. 7. The experimental (XRRC-0401 data) and theoretical (LTspice calculation) results for output voltage dependence VOUT on radiation exposure time for IS-LS1-3.3V linear LDO voltage regulator.

Thus, the proposed SPICE model of IS-LS1-3.3V positive LDO linear voltage regulator taking into account of radiation effect allows predicting the voltage regulator radiation behavior and can be used in engineering calculations for electronic circuit design.

4 Conclusions

Thus, the radiation hardness to the effects of the total ionizing dose of the positive low-dropout linear voltage regulator IS-LS1-3.3V produced in the framework of import substitution program, has been studied using the developed hardware-software complex based on the X-ray research complex. It is established experimentally that output voltage varies slightly from 3.29 up to 3.33 V ($\Delta V_{\mathrm{OUT}} \approx 0.04$ V) in all total ionizing dose intervals and preserves a functional state without failure. For electronic circuits design is developed circuit and SPICE macromodel of linear LDO voltage regulator by taking into account of radiation effect. It is shown that developed SPICE model of voltage regulator allows describing the voltage regulator radiation behavior. Therefore, in the future, the proposed approach can be used for the design of electronic circuits with the similar voltage regulators.

Acknowledgements

The results of the Research and Development have been achieved during the implementation of the project «Integrated microcircuits of analog signal converters in metal-polymeric package of various types: development and mastering of technology, replacement of imported analogs and organization of serial production» (agreement with the Russian Ministry of Science and High Education of 9 February 2023 No. 075-11-2023-008) using state support measures provided by the Russian Federation Government's Decree of 9 April, 2010 No. 218.

References

1. D.R. Patrick, S.W. Fardo, R.E. Richardson, V. Chandra, *Electronic Devices and Circuit Fundamentals* (River Publishers, Gistrup, 2023)
2. G.I. Volovich, *Circuit Technique of Analog and Analog-digital Electronic Devices* (DMK Press, Moscow, 2018)
3. E.N. Geytenko, *Secondary power supplies. Circuitry and Calculation* (Solon Press, Moscow, 2008)
4. F.P. Korshunov, Yu.V. Bogatyrev, V.A. Vavilov, *Effects of Radiation on Integrated Circuits* (Nauka i Tekhnika, Minsk, 1986)
5. G.I. Zebrev, *Radiation Effects in Highly Integrated Silicon Integrated Circuits* (NIYAU MIFI, Moscow, 2010)
6. K.I. Tapero, S.I. Didenko, *Fundamentals of Radiation Resistance of Electronic Products: Radiation Effects in Electronic Products* (Izd. dom MISiS, Moscow, 2013)
7. LT1963A Series Low Noise, Fast Transient Response LDO Regulators, Analog Devices, http://www.linear.com/LT1963A
8. JSC "Specialized electronic systems" (SPELS) http://www.spels.ru
9. *Ultra Low Dropout Positive Fixed Linear Regulator IRUH33P253A1M*. https://www.irf.com/product-info/datasheets/data/iruh33p253a1m.pdf
10. I.V. Derbunov, N.A. Bryukhno, O.O. Dantsev et al, *Proc. of Sci. Conf. on Electronic Component Base and Microelectronic Modules Russian forum Microelectronics 2023* (Tekhosphera, Moscow, 2023)
11. A.A. Khalaphyan, *STATISTICA 6. Statistical data analysis* (Binom-Press, Moscow, 2007)
12. *STATISTICA*, http://statsoft.ru
13. M.H. Rashid, *SPICE for Power Electronics and Electric Power* (Boca Raton-London-New York, CRC Press, 2017)
14. E.A. Kulchenkov, S.B. Rybalka, A.A. Demidov, *Advances in Applied Physics*. **11(5)**, 445 (2023)