Radiation hardness study of positive LDO voltage regulators

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Abstract. Two linear voltage regulators LS2-5V and LM2931 (output voltage of 5.0 V) were studied experimentally on their hardness to the radiation total ionizing dose (TID) effects. It was shown that output voltage changes lightly for LS2-5V at increasing of TID and not exceeds the operation mode limit (4.85 - 5.25 V). On the contrary, the output voltage value for LM2931 analogue exceeds operation mode limits at high TID that lead to its functional failure. It was found that both regulators functionate stably by consumption current parameter. Thus, LS2-5V demonstrates more stable functioning than LM2931 analogue. In addition, the SPICE macromodel for description of the radiation behavior by the output voltage parameter for LS2-5V was developed.

1 Introduction

An important element of modern microelectronics is a voltage regulator (VR), since almost any electronic circuit (simple transistor circuits, operational amplifiers, digital and microprocessor systems, etc.) requires one or more stable DC sources for its stable operation [1]. In addition, for various modern industries it is necessary to ensure that electronic components operate reliably during their radiation treatment [2, 3]. Hence, investigation of the radiation behaviour and hardness of modern electronic component base to the TID effects of ionizing radiation is an important goal [3, 4].

The purpose of this work is to study the effect of the total dose of ionizing radiation on the performance of LS2-5V [5] and LM2931 [6] voltage regulators experimentally and theoretically.

2 Materials and methods

In present investigation of the LS2-5V (epitaxial-planar bipolar process) and LM2931 voltage regulators for radiation hardness was carried out using the developed X-ray complex (XRRC-0401) in detail described in papers [7]. The scheme of the XRRC-0401 (operation mode: 70 kV – anode voltage, 150 μA - anode current) is presented in Figure 1.

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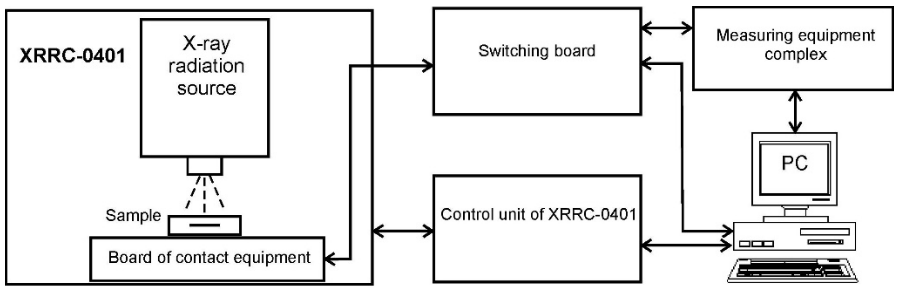

Fig. 1. The block-scheme of the X-ray complex (XRRC-0401) [7].

The XRRC-0401 during process monitoring was conducted through dedicated software created within the LabView, which facilitates the measurement of various observed parameters at specified time intervals [7]. Additionally, LS2-5V and LM2931 samples were connected according to the scheme presented in Figure 2. During the radiation experiment the LS2-5V and LM2931 samples were in the following electric conditions: 6 V (input voltage) and 500 mA (load current). The distance from the X-ray source is 33 mm (radiation dose treatment rate - 100 un./s (un. – the units of the X-ray comparator DRI-0401)) for LS2-5V and 20 mm (radiation dose treatment rate - 216 un./s) for LM2931 analogue.

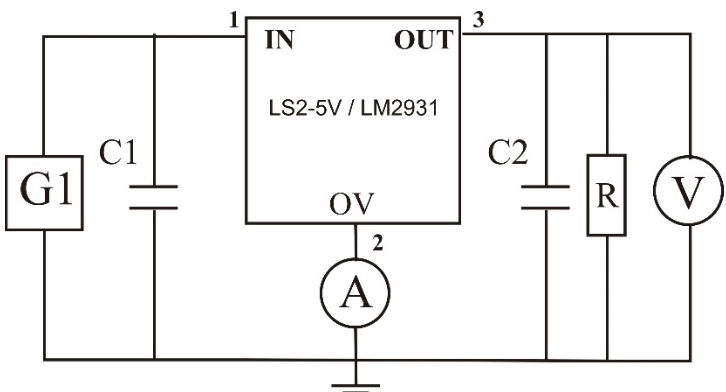

Fig. 2. The electric scheme for test of LS2-5V [5] and LM2931 [6]. G1 – the constant-voltage source; A – the ammeter; V – the voltmeter; R – the resistive load; C1=10 μF, C2=10 μF.

3 Results and discussion

Figure 3 presents the obtained data for LS2-5V and LM2931. As follows from Figure 3, for LS2-5V the output voltage practically does not change (5.0 ÷ 5.04 V) without exceeding the required limits (4.85 ÷ 5.25 V). On the contrary, for LM2931 the output voltage at first changes lightly as dose *D* increase but then begins to decrease (486×10^3 un.) up to the lower required operating limit (4.85 V). Hence, the for LM2931 takes place failure process (at dose interval from 486×10^3 un. up to 661×10^3 un.). Consequently, comparison LS2-5V and LM2931 (analogue) by the output voltage parameter shown that only LS2-5V demonstrates radiation hardness in investigated radiation conditions. Further, because of output voltage also was investigated another significant characteristics for LS2-5V and LM2931 such as consumption current.

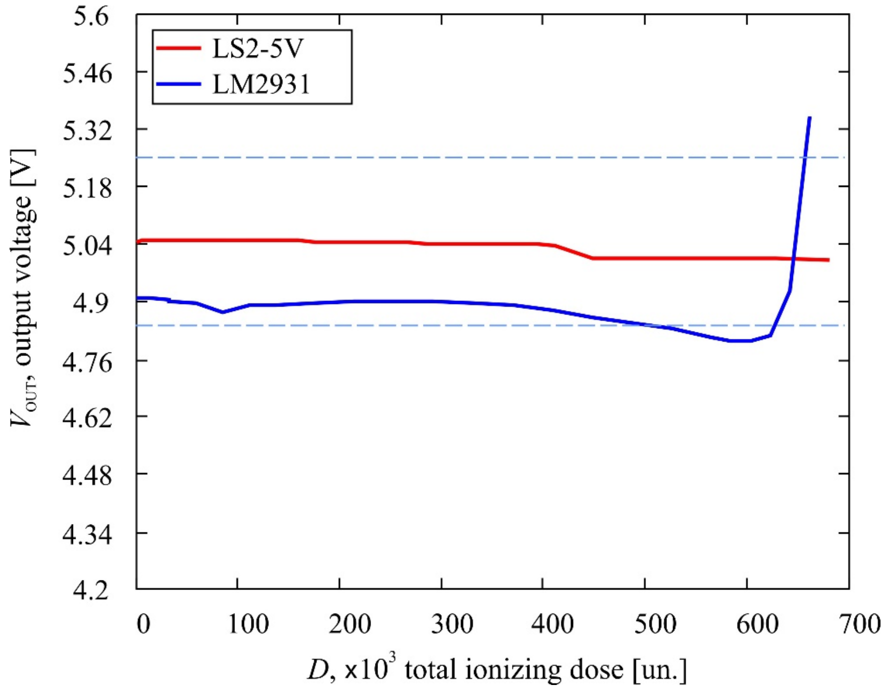

Fig. 3. Dependence for LS2-5V and LM2931 analogue output voltage on TID radiation (dashed-line - the required operating limits (4.85 ÷ 5.25 V)).

The consumption current I_{cc} data are presented in Fig. 4 and can be seen that values for LS2-5V changes lightly (from 690 μA up to 776 μA) and reaches 690 μA at $D = 690{\times}10^3$ un. It is important to mention that a comparable behavior was observed in a similar VR IS-LS1-3.3V [7]. On the contrary, in case of LM2931 VR the consumption current I_{cc} also changes insignificantly at start time but then after dose $D = 525{\times}10^3$ un. starts increase up to 900 μA at dose of $622{\times}10^3$ un. Hence, by parameter of consumption current the LS2-5V demonstrates more stable work under radiation than its analogue. Additionally, from a practical standpoint in engineering the design of electronic circuits, models of electronic components are utilized that are generated within electrical modelling SPICE software. This program is essential for calculating and simulating the behavior and functionality of electronic circuits [8, 9]. For this purpose, in the free software LTspice [10], a typical equivalent macromodel (highlighted in red in Fig. 5a) of the LS2-5V VR integrated circuit [1, 4, 8] on bipolar n-p-n and n-channel transistors was designed. Figure 5a shows the main elements of the designed macromodel LS2-5V: reference voltage source (VREF), n-p-n transistor (QMOD), n-channel transistor (JMOD), voltage-controlled voltage sources (EB, EP), functional voltage sources (V1, V2, B3), diodes (DBK, DFB, DSC, DPU), capacitors (CBC, CPZ), resistances (RBC, RB1, RB2, RZ, RP, RI), input contact (IN), adjustment contact (ADJ), output contact (OUT (s), output contact (OUT). Because of this, in the LTspice program, the component's nominals and specified parameters are indicated in the circuit text, in particular, the parameters of the transistor and diode models are set using the SPICE directive. MODEL, for functional voltage sources in the circuit scheme indicates the equations that determine their output voltages. Then scheme of LS2-5V VR model was connected in accordance with the circuit in Figure 2.

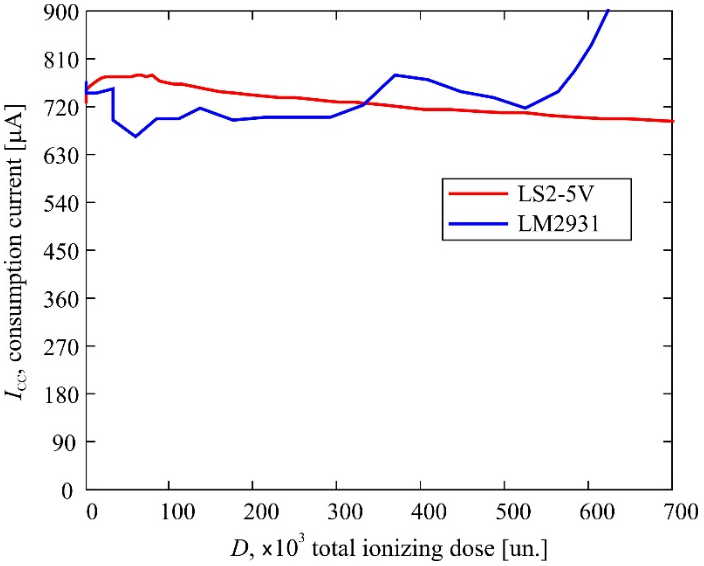

Fig. 4. The experimental results for consumption current dependence on TID for LS2-5V and LM2931 analogue.

Figure 5b shows calculation in LTspice program for transient process mode (input voltage - 6 V) the value of output voltage is 5 V and load current value is 500 mA.

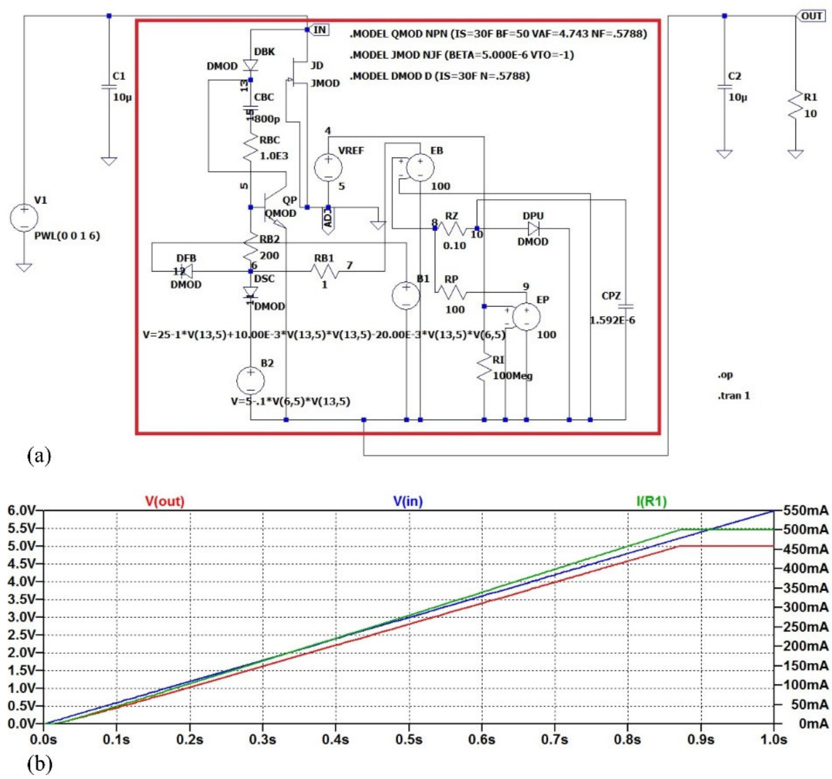

Fig. 5. The equivalent circuit for LS2-5V macromodel in LTspice program: (a) the input voltage (V(in)); (b) output voltage (V(out)) and load current (I(R1)) dependence on time.

Thus, the proposed VR model demonstrates correct state of functioning that corresponds to initial condition for VR (output voltage – 5 V, load current – 0.5 A) without consideration of radiation influence.

Afterwards, to take into account the effect of the radiation factor in the LS2-5V VR circuit, a functional voltage source B3 is turned on, as shown in Fig. 6. In this case, the functional voltage source, B3, functionally depends on the operating time of the VR during X-ray irradiation and is described by the following equation: V=V(OUTs)+4.942×10-13×t3-6.102×10-9×t2+1.196×10-5×t-4.955, where V is the output voltage of the functional voltage source B3 (V), V (OUTs) is the output voltage (V) of the LS2-5V (voltage in the node OUTs in the diagram of Fig. 6), t is the operating time of the LS2-5V during radiation treatment (s). Thus, the next stage above-described equivalent circuit for LS2-5V macromodel in Figure 6 maybe used in LTspice program as some subcircuit (SUBCKT command in SPICE program [9, 11]).

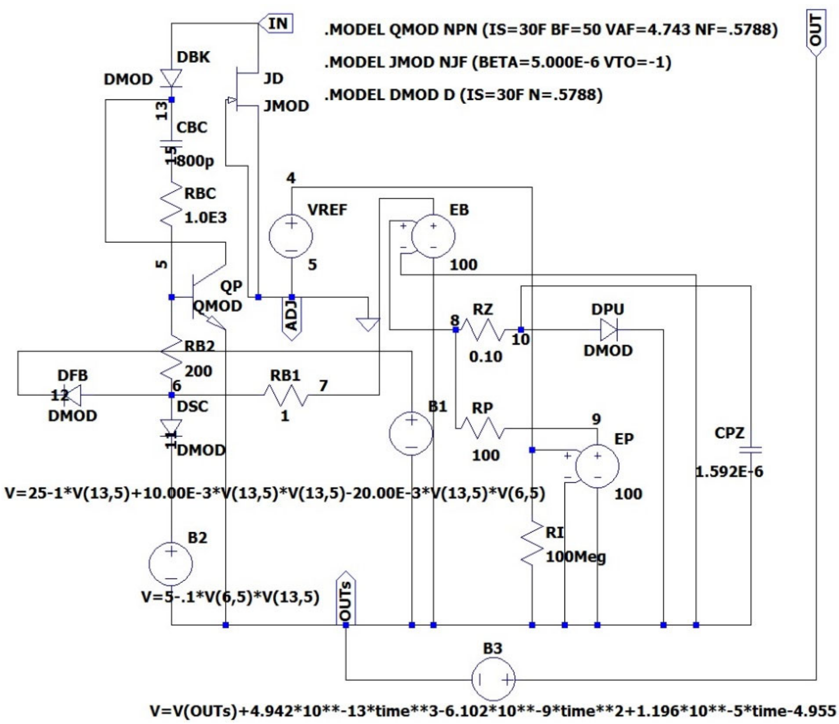

Fig. 6. The macromodel equivalent circuit for the LS2-5V in LTspice including considerations for radiation effects.

For this purpose the equivalent circuit scheme for LS2-5V VR macromodel in Figure 6 was presented in form of subcircuit text macromodel in SPICE-type programs. Below in Figure 7 is shown macromodel text listing.

Then, for verification of the obtained model under radiation the text of macromodel afterwards was added to LTspice program base as an library file. In the next stage the LS2-5V VR macromodel for its verification in the LTspice program was connected in accordance with the standard scheme (see Figure 2), which includes a constant voltage source V1 (6 V), C1 and C2 capacitors with a capacity of 10 μF connected in parallel to the input (IN) and output (OUT) of the macromodel, active load R1 (10 ohms).

```
* ------ LS2-5V positive voltage regulator radiation model subcircuit -------
* connections:          input
*                       |  adjustment pin
*                       |  |    output
*                       |  |    |
.SUBCKT LS2-5V         IN ADJ OUT
JADJ IN 0 0 JMOD
VREF 4 0 5
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 1.592E-6
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)+4.942*10**-13*time**3-6.102*10**-9*time**2+1.196*10**-5*time-4.955
.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 LS2-5V
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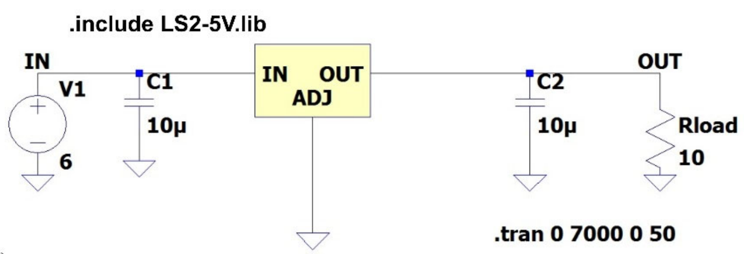
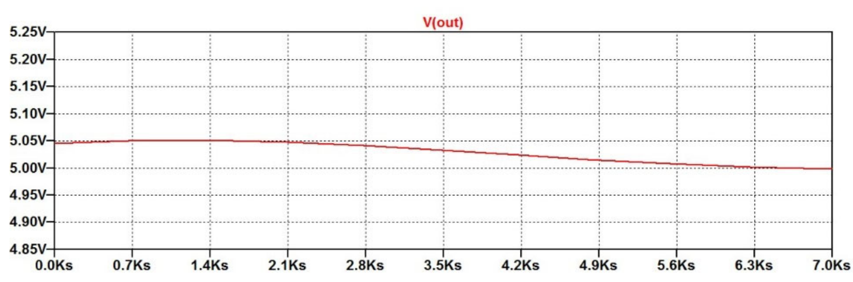
Fig. 7. The subcircuit text of macromodel for the LS2-5V.

Therefore, the schematic for testing the LS2-5V VR macromodel under radiation treatment within the LTspice (which incorporates the *.lib file text as a SPICE directive) is displayed below in Figure 8a.



(a)



(b)

Fig. 8. (a) the testing circuit for LS2-5V model in LTspice software under radiation time treatment; (b) the dependence of output voltage V(out) on time of radiation treatment.

In Figure 8b, the results of the model evaluation for LS2-5V are shown, illustrating how the V(out) changes with the duration of radiation treatment. As can be seen, for LS2-5V the V(out) changes lightly (5.0 ÷ 5.04 V) just as in Figure 3.

Subsequently, to compare the experimental findings with the theoretical outcomes simulated in the LTspice software (as illustrated in Figure 8b), the initial experimental data (see Figure 3) was transformed from TID to time of radiation dose treatment. This conversion took into account the radiation dose treatment rate (equals of 100 un./s for -LS2-5V). Figure

9 presents the experimental and theoretical dependencies. It can be seen that the theoretical dependence V_{OUT} (t) shows good agreement the experimental data. It is worth noting that analogous radiation behaviour has been detected in the similar type regulator RH1086M that had been developed specifically for use in cosmic radiation conditions. Consequently, in future above-described method can be applied to characterize the radiation behaviour of this type of regulators developed within the scope of the import substitution initiative [7].

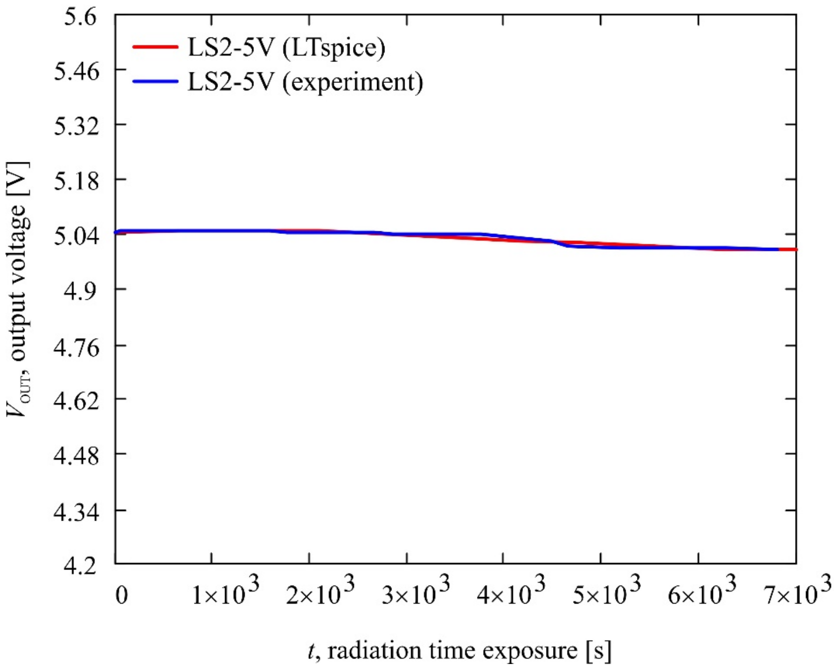


Fig. 9. The experimental (blue line) and theoretical (red line) dependencies of output voltage on radiation treatment time for LS2-5V.

Therefore, the developed SPICE macromodel for the LS2-5V positive LDO linear VR, which describes the radiation effects by parameter of output voltage and enables the calculating of the regulator's response to radiation dose and can be used to project the same type electronic devices.

4 Conclusion

The radiation behaviour of linear voltage regulators LS2-5V and its analogue LM2931 (output voltage - 5 V) to the TID effects is studied. It was found that for LS2-5V the output voltage changes insignificantly (between 5.0 and 5.04 V) and at the same time output voltage not reaches the limit of operation mode (4.85 - 5.25 V). For LM2931 linear VR analogue it was established that at dose interval from 486×10^3 up to 661×10^3 un. the output voltage value exceeds operation mode limits, i.e. in this case take place the functional failure. Study of consumption current for LS2-5V VR shows that consumption current changes insignificantly (between 690 μA and 776 μA). In case of LM2931 VR the consumption current also changes insignificantly at start time but then after dose of 525×10^3 un. starts increase up to 900 μA at dose of 622×10^3 un. Thus, comparison LS2-5V and LM2931 positive low-dropout linear voltage regulators by the output voltage and consumption currents parameter shown that LS2-

5V VR demonstrates more stable work without failure and radiation hardness than its analogue LM2931 in investigated radiation dose interval.

The electrical circuit and a SPICE macromodel for positive LDO linear VR LS2-5V have been developed with consideration of radiation effects. The proposed SPICE macromodel allows to describe the radiation behaviour of the LS2-5V.

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