Reliability Evaluation Method of Linear Regulated Power Supply In Nuclear Radiation Environment

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***Abstract*—Electronic products are the key link to realize automation and intelligence of equipment. As a direct power source to ensure the operation of electronic products, linear voltage regulators are the core components in linear power systems. Once the degradation fails, the whole machine will be paralyzed, resulting in huge economic loss. At present, the degradation failure mode analysis of linear regulators has been studied extensively. However, in some special environments, especially in the radiation environment, degradation analysis and reliability research are very scarce. This paper presents a degradation analysis and reliability evaluation method for the AP1117E linear regulator devices under nuclear radiation environment. This method combines Simulink simulation, Bootstrap resampling and Monte Carlo method to overcome the difficulties of small samples and data shortage. Finally, the comparison with the evaluation results obtained from Bootstrap sampling proves the feasibility of the proposed method.**

Keywords-linear stabilizer supply; Simulink; Bootstrap sampling; Monte Carlo; Reliability evaluation

I. INTRODUCTION

With the rapid development of power electronics technology, DC linear regulated power supplies have been widely used in household appliances [1], vehicles [2], warship ships [3], aerospace [4], etc., and it is the electronic system normal operation essential condition. As the core component of the linear power supply, the reliability of the linear voltage regulator will determine the reliability of the whole linear power supply. At present, domestic and foreign scholars have studied the reliability of linear regulators under conventional stress extensively, however, there are few studies on the degradation trend and reliability analysis under the nuclear radiation environment. Kargarrazi.Shas et al.[5]discussed the design and implementation of a fully-integrated high-temperature, high-current (up to 2 A) LVR in 4H-SiC bipolar technology, demonstrated the first power supply solution providing both high-temperature and high-load driving capabilities. Adell.P.C et al.[6]used experiments and simulations to analyze the total-dose response of a linear voltage regulator. R.D.Kulkarni et al.[7] used PSpice to simulate buck-boost converter, and input the experimental results of a single power device into the simulation to analyze the overall influence of gamma radiation damage on modern power supply system. Z.H.Tong et al.[8] studied the effect of gamma radiation on the rectifying IRGBC20 insulated gate bipolar transistor (IGBT).

At present, many domestic and foreign scholars have done sufficient research on reliability assessment methods and have achieved certain research results, including analytical methods [9], Monte Carlo simulation method [10]and so on, A.Ehsani et al. proposed a probabilistic analysis model for the reliability evaluation of wind power generation system. Considering the randomness of wind, the model analyzed the output characteristics of the rated wind turbine in detail, and the model can be easily applied to the existing grid reliability evaluation model.For the reliability evaluation of small sample data, there are mainly parameter method and Bayesian method [11], among them, the parameter method mainly estimates the unknown parameters. Many scholars have developed and improved relevant theories, such as maxium standard deviation[12] and the unilateral tolerance coefficient method [13].The purpose of this paper is to study the reliability of linear voltage stabilizer under radiation stress by combining Simulink simulation and Bootstrap resampling, and it solve the problem of relatively lack of test samples. The robustness of the method is obtained by comparison with pure Bootstrap sampling.

The main chapters of this paper are structured as follows: The second part introduces the background method principle and the Simulink simulation of the circuit. The third part focuses on the method proposed in the article, namely the Bootstrap resampling method based on Simulink, the fourth part presents the reliability evaluation results of the radiation test of the linear voltage regulator. The conclusion is in the fifth part.

II. BACKGROUND PRINCIPLE

A. Bootstrap resampling

Bootstrap is a new statistical method proposed by Efron [14]. This method does not need enough sample size, and does

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not need to obtain the overall distribution of parameters. Instead, it estimates the distribution of parameters by resampling. The method is based on re-sampling of the original sample, and Fig.1 shows the basic flow of the method.

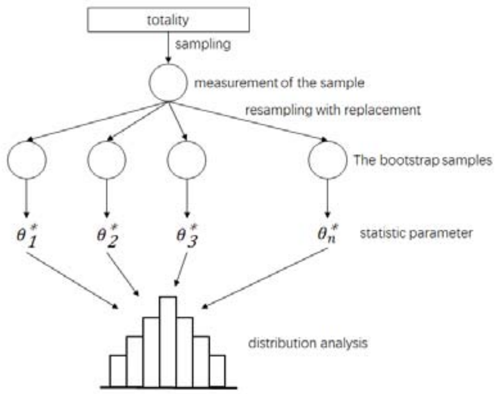


Fig. 1. Schematic diagram of the Bootstrap method flow

As can be seen from the figure, in the Bootstrap method, due to the limitations of the overall sampling, the estimation of statistical variance is often obtained by resampling the original measurement sample instead of the population approximation. Although the method has undergone some improvements in the development process, the basic principles are similar. The basic steps of the algorithm are given below:

Step1: Given a set of original measurement samples $\boldsymbol{x} = \{x_1, x_2, \ldots, x_N\}$ with a sample size of N .

Step 2: Perform re-sampling from the original measurement sample x given to obtain the Bootstrap sample $\boldsymbol{x}^n = \{x_1^*, x_2^*, \ldots, x_N^*\}$ with the same sample size N .

Step 3: Calculate the required parameters θ^* by using the obtained Bootstrap sample, these parameters could be the mean, the median of the distribution, the standard deviation, and so on.

Step4: Repeat Step2 and Step3 n times , then n groups of parameters $\boldsymbol{\theta}^* = \{\theta_1^*, \theta_2^*, \ldots, \theta_n^*\}$ to be calculated can be obtained.

Step 5: After obtaining the parameter θ^* , an arithmetic mean $\overline{\theta}^* = \frac{\sum_{i=1}^{n} \theta_i^*}{n}$ which is closer to the overall parameter θ can be estimated.

Step6: The standard deviation of the parameter θ^* is used to characterize the uncertainty of the estimated value, which can be expressed as $\sigma = \sqrt{\frac{\sum_{i=1}^{n} (\theta_i^* - \overline{\theta}^*)^2}{n-1}}$.

Step7: In the research, it is often necessary to calculate the confidence interval $[a,b]$,In order to obtain a confidence interval, a relatively simple "percentile method" can be selected.

B. *Simulink simulation of linear regulator devices*

The basic circuit of the LDO linear regulator is shown in the Fig. 2.

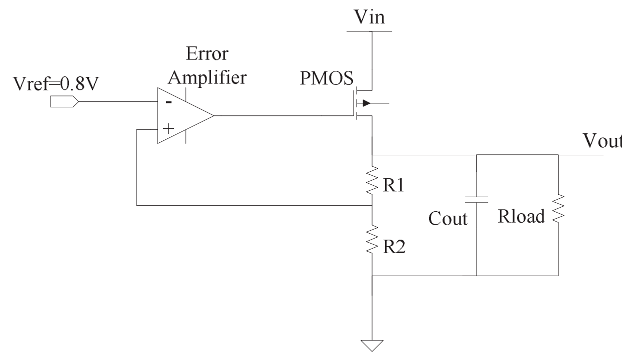


Fig. 2. LDO linear regulator circuit schematic

For LDO circuits, the target output voltage V_{out} is controlled by adjusting the values of the two divider resistors R_1 and R_2 in the circuit. According to the equation (3-1) circuit voltage division law, the final output voltage of the LDO circuit can be obtained as shown in the following equation.

$$\frac{V_{ref}}{V_{out}} = \frac{R_2}{R_1 + R_2} \tag{2-1}$$

$$V_{out} = \frac{R_2}{R_1 + R_2} \bullet V_{ref} \tag{2-2}$$

Here V_{ref} represents the voltage value set by the reference source, in this paper, it's 0.8V.

The schematic diagram of the linear regulator circuit can be built in Simulink as shown in the Fig.3. During the simulation, the function of output voltage degradation can be adjusted by adjusting R_1 and R_2 .

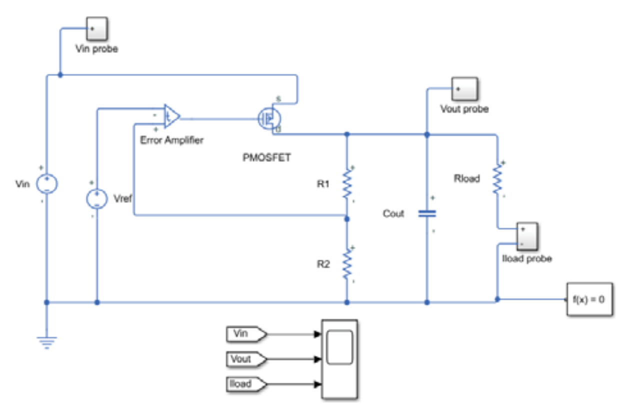


Fig. 3. Linear regulator simulation circuit

III. BOOTSTRAP SAMPLING METHOD BASED ON SIMULINK

Through experiments, the approximate range of degradation of several performance parameter indexes PI of linear regulator devices is determined. Substituting several sets of performance indicators into Simulink simulation will obtain hundreds of performance degradation indicators, and they were sampled using Bootstrap to obtain m degradation samples. In this paper, m samples are used for the degradation test. The M dose point positions $Ra_1, Ra_2, \ldots, Ra_M$ are set within the determined approximate degradation range, and the performance parameter indexes are recorded. That is, test sample m at each degraded reference point $Ra_i\,(i=1,2,\ldots,M)$, and obtain m performance degradation index test results, namely $PI_{ij}\,(i=1,2,\ldots,M;\,j=1,2,\ldots,m)$.

In the test, the approximate range of degradation of the performance parameter PI of the linear regulator device was determined,and the approximate degenerate dose range shown in the existing data was refined. For example, the m samples are subjected to degradation test, and M dose point positions $Ra_1, Ra_2, \ldots, Ra_M$ are set within the determined approximate degradation range. In other words, all of the samples were tested rigorously at each degradation benchmark $Ra_i\,(i=1,2,\ldots,M)$ to obtain the test results of m performance degradation indicators, namely $PI_{ij}\,(i=1,2,\ldots,M;\,j=1,2,\ldots,m)$ show as the following table:

TABLE Ⅰ.Component performance test results table

Benchmark	***Sample1***	***Sample2***	$\cdots$	***Sample*** j	$\cdots$	***Sample*** m
Ra_1	PI_{11}	PI_{12}	$\cdots$	PI_{1j}	$\cdots$	PI_{1m}
Ra_2	PI_{21}	PI_{22}	$\cdots$	PI_{2j}	$\cdots$	PI_{2m}
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\ddots$	$\vdots$
Ra_i	PI_{i1}	PI_{i2}	$\cdots$	PI_{ij}	$\cdots$	PI_{im}
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\ddots$	$\vdots$
Ra_M	PI_{M1}	PI_{M2}	$\cdots$	PI_{Mj}	$\cdots$	PI_{Mm}

Suppose that the actual degradation trajectory of a single sample is described by $D(Ra)$ .In fact, the value of $D(Ra)$ can be tested at the degraded reference point $Ra_1, Ra_2, \ldots, Ra_M$, and the degradation value observed by the number j sample at the number i degraded reference point is as follows:

$$PI_{ij} = D\left(Ra_i;\alpha_j,\beta_j\right) + \xi_{ij}\,(i=1,\ldots,M;\,j=1,\ldots,m) \qquad (3\text{-}1)$$

Here, $D\left(Ra_i;\alpha_j,\beta_j\right)$ is the actual trajectory of the numer j sample at the number i degradation reference point Ra_i . $\xi_{ij} \sim N\left(0,\sigma_\xi^2\right)$ is the residual error of the number j sample at the number i degradation reference point Ra_i , reflecting all errors leading to the difference between the actual value and the measured value. For the numer j sample, the least square method [14], support vector machine [15] and other models can all obtain the estimated value of its parameters, so that the degradation trajectory of the sample can be determined as $PI_j = D\left(\hat{\alpha}_j,\hat{\beta}_j\right)(j=1,2,\ldots,m)$.

Due to the influence of uncertain factors such as sample differences and the same batch of products, these m test results should be subject to a certain distribution and the same type of distribution at different degenerate reference points. If the probability density function of the performance parameter indicator corresponding to the M degraded reference points Ra_i can be obtained, the degenerate distribution family can be determined.

IV. THE EXAMPLE ANALYSIS

In this paper, the reliability of AP1117E series linear regulators under nuclear radiation stress is evaluated. The irradiation test is carried out in the cobalt source chamber of Peking University School of Chemistry. The cobalt source is cobalt 60 (Co), one of the radioactive isotopes of the metallic element cobalt [15], which emits gamma rays and thus has ionizing radiation, and it is generally used as a radiation source in engineering [16]. The linear power board is connected to the test board, placed in the irradiation room, after the irradiation starts, the computer records the monitored voltage value in real time, as shown in Fig. 4. Through this test, three sets of degradation test data can be obtained as shown in TableII. The failure threshold of the linear stabilizer can be obtained by using the power supply of the linear stabilizer, as shown in Table III.

Fig.4. Test procedure diagram

TABLE Ⅱ. Three sets of raw data were tested

Irradiation intensity	The first group	The second group	The third group
0Krad	3.233V	3.28V	3.276V
50Krad	3.156V	3.14V	3.159V
70Krad	3.082V	3.082V	3.076V
90Krad	3.02V	3.024V	3.019V
110Krad	3V	3.039V	3.042V
130Krad	2.94V	2.976V	2.981V
135Krad	2.795V	2.969V	2.972V
190Krad	2.732V	2.799V	2.802V

240Krad	2.692V	2.801V	2.803V
290Krad	2.629V	2.653V	2.647V
400Krad	2.295V	2.295V	2.325V

TABLE Ⅲ. Failure threshold of linear voltage regulator components

Part number	The chip type	Failure threshold (V)
LDO#2	AP1117E33(CPU)	2.66
LDO#3	AP1117E33(CPU)	2.61
LDO#4	AP1117E33(CPU)	2.63

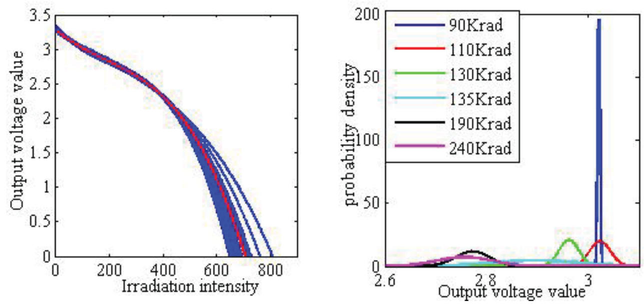
The linear regulator used in this experiment is the AP1117E33 (CPU) chip. According to the three sets of data obtained in the test in Table 4-1.Firstly, 10^6 groups of test samples were obtained by using Bootstrap resampling method, then it uses the Bootstrap resampling method based on Simulink to select the voltage dividing resistors R_1 , R_2 and the reference voltage V_{ref} as random variables. Taking 100 groups of values as input and substitute them into the simulation circuit to obtain 100 groups of output voltage values. Similarly, it can obtain 6 groups of test samples. According to the characteristics of obeying the normal distribution, the mean values $\hat{\mu}_1$, $\hat{\mu}_2$ and variances $\hat{\sigma}_1^2$ and $\hat{\sigma}_2^2$ of the normal distribution at each test reference point can be obtained by the two methods above. The results are shown in Table IV.

TABLE Ⅳ. Normally distributed parameters

Test datum (Krad)	The mean value $\hat{\mu}$		The variance $\sigma^2 (10^{-4})$	
	$\hat{\mu}_1$	$\hat{\mu}_2$	$\hat{\sigma}_1^2$	$\hat{\sigma}_2^2$
0	3.2630	3.2951	4.5123	4.8586
50	3.1516	3.1838	0.6983	4.5326
70	3.0800	3.1122	0.0800	4.3287
90	3.0210	3.0532	0.0469	4.1644
110	3.2070	3.0592	3.6463	4.1810
130	2.9656	2.9979	3.3226	4.0132
135	2.9118	2.9442	68	3.8692
190	2.7776	2.8099	10	3.5206
240	2.7652	2.7976	27	3.4893
290	2.6430	2.6753	1.0377	3.1871
400	2.3049	2.3375	2.0000	2.4236

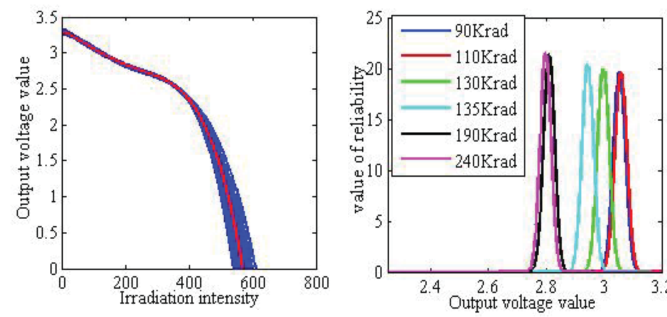
According to the expanded data after sampling, two different methods are used, and then the degradation distribution family of the device is fitted by least squares method, as shown by the blue curve in Fig.5(a) and Fig.6(a) respectively.The red curve in the figure is the degradation curve fitted by the mean of the components in the above table,and the probability density function curve at each irradiation intensity was estimated by using the Ksdensity function, as shown in Fig.5(b) and Fig.6(b).

According to the failure threshold, the average failure threshold is 2.635V, and it is used as the failure determination condition. The Monte Carlo method can be used to obtain the reliability of each irradiation intensity. Combined with the least square method, the component can be fitted. The reliability curves for the two different methods are shown in Fig. 7（a）and Fig. 7（b）.



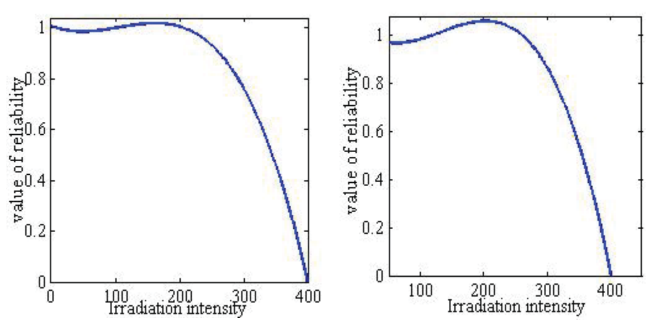
(a) Degraded trajectory; (b) Probability density function curve

Fig. 5. Bootstrap resampling.



(a) Degraded trajectory; (b) Probability density function curve

Fig. 6. Bootstrap sampling method based on Simulink.



(a) Bootstrap resampling (b) Bootstrap sampling method based on Simulink

Fig. 7. AP1117E33 component reliability curve

By comparing the variance of the data obtained by the two methods, the variance of the samples obtained by the proposed method is relatively small and stable. To illustrate the calculation accuracy of the proposed method, the reliability obtained by this method and Bootstrap was compared, as shown in Table V, it shows that the errors of the results obtained by the two methods were within the acceptable range.

TABLE Ⅴ.The relationship between reliability and irradiation intensity under the two methods

Reliability	Irradiation intensity(Krad)		Relative error	Confidence Interval	
	Method1	***Method2***		***Method1***	***Method2***
60%	329.7777	320.9051	2.6905%	[329.5708,329.9846]	[320.8910,320.9191]
70%	312.3663	299.5219	4.1120%	[312.1067,312.6260]	[299.5065,299.5373]
80%	291.0197	275.0517	5.4869%	[290.6895,291.3499]	[275.0346,275.0689]
90%	262.1448	245.5752	6.3208%	[261.7021,262.5874]	[245.5554,245.5950]

V. CONCLUSION

This paper analyzes the reliability of linear regulators based on Simulink simulation, Bootstrap resampling and Monte Carlo. It overcomes the difficulty of small sample and data shortage, and proposes a method to process the irradiation test data of small sample, namely Bootstrap method based on Simulink simulation. Compared with the Bootstrap resampling method, the reliability of the two different methods is relatively small. Moreover, the sample data variance obtained by Bootstrap method based on Simulink simulation is small, which makes the final result more stable. According to the data and results of the radiation test, the analysis shows that the Bootstrap method based on Simulink simulation is more stable, and the feasibility of the proposed method is verified.

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REFERENCES

[1] JAVADI A, HAMADI A, NDTOUNGOU A, et al. Power Quality Enhancement of Smart Households Using a Multilevel-THSeAF With a PR Controller [J]. IEEE Transactions on Smart Grid, 2017, 8(1): 465-474.

[2] ZHANG Z, QIN Y, NING Z, et al. A high electromagnetic immunity voltage regulator circuit applied in vehicle [J]. IEICE Electronics Express, 2015, 12(9):1-6

[3] MILLS A J, ASHTON R W. Improving Stability in Shipboard DC Power Systems with Constant Power Loads [J]. Nav Eng J, 2017, 129(2): 97-106.

[4] PHANG S K, LI K, WANG F, et al. Explicit Model Identification and Control of a Micro Aerial Vehicle [C]. 2014 International Conference on Unmanned Aircraft Systems. 2014: 1048-1054.

[5] KARGARRAZI S, ELAHIPANAH H, RODRIGUEZ S, et al. 500 degrees C, High Current Linear Voltage Regulator in 4H-SiC BJT Technology [J]. IEEE Electron Device Lett, 2018, 39(4): 548-551.

[6] ADELL P C, SCHRIMPF R D, HOLMAN W T, et al. Total dose effects in a linear voltage regulator [J]. IEEE Transactions on Nuclear Science, 2004, 51(6): 3816-3821.

[7] KULKARNI R D, AGARWAL V. Reliability analysis of a modern power supply under nuclear radiation effects [C]. 2003:71-76

[8] TONG Z H, ANG S S, BROWN W D. Effects of gamma irradiation on the insulated-gate bipolar transistor [J]. Microelectronics and Reliability, 1996, 36(10): 1489-1498.

[9] EHSANI A, FOTUHI M, ABBASPOUR A, et al. An analytical method for the reliability evaluation of wind energy systems [C]. Tencon 2005 - 2005 Ieee Region 10 Conference, Vols 1-5. 2006: 1-7

[10] SHAHIDIRAD N, NIROOMAND M, HOOSHMAND R-A. Investigation of PV Power Plant Structures Based on Monte Carlo Reliability and Economic Analysis [J]. IEEE Journal of Photovoltaics, 2018, 8(3): 1-9.

[11] ZHANG N, WU L, YANG J, et al. Naive Bayes Bearing Fault Diagnosis Based on Enhanced Independence of Data [J]. Sensors, 2018, 18(2): 2-17

[12] GOODWIN R L, IEEE. Data Features of the Weighted Standard Deviational Curve [C]. 2017 6th International Conference on Agro-Geoinformatics. 2017: 76-80.

[13] ZHANG X, XIE L, LIU J, et al. Statistical analysis methods of fatigue crack growth rate [J]. Transactions of Tianjin University, 2014, 20(5): 322-327.

[14] EFRON B, TIBSHIRANI R. An Introduction to the Bootstrap [M].Boca Raton:CRC press,1994..

[15] SCHWANK J R, SHANEYFELT M R, DODD P E, et al. Correlation between Co-60 and X-ray radiation-induced charge buildup in silicon-on-insulator buried oxides [J]. IEEE Transactions on Nuclear Science, 2000, 47(6): 2175-2182.

[16] LAWAL O M, LIU S, LI Z, et al. Co-60 gamma radiation total ionizing dose combined with conducted electromagnetic interference studies in BJTs[J].MicroelectronicsReliability,2018,82:159-164.