A Simulation Analysis of The Failure Mode of Series Stabilized Voltage Circuit with Restricted Electric Current Protection

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Abstract. This paper uses the failure simulation function of multisim circuit simulation software to analyzes the characteristics of the fault mode of the series stabilized voltage circuit in normal state and three common limit tube breakdown, stabilizer breakdown and adjusting tube breakdown. Combined with the theoretical calculation of the circuit parameters in each fault mode,the correctness of the simulation analysis is verified.

Keywords: High frequency box; thermostatic control; Proteus simulation.

1. Introduction

Common DC power supply mainly includes switching power supply and series regulated power supply.[1] Switching power supply works in switching state with high efficiency and can achieve high power, but the disadvantage is that the nonlinear state (switching state) makes the output DC voltage ripple large and the voltage stabilizing coefficient small.[2] The advantages of the series regulated power supply working in the linear state are small pulsation and high ripple suppression, while the disadvantages are that the power consumption is high and the efficiency is low (less than 60%) due to the large voltage and current of the regulating tubes in series.[3] It can be seen that these two kinds of power supply just form a complementary effect in performance, so for circuit applications with minimal pulsation, such as DC power supply of high steady-state digital sampling circuit and frequency standard circuit, it is usually a combination of the two - the front stage uses series voltage regulation to significantly improve ripple suppression, and the rear stage uses switching power supply to achieve high-power output.[4-7] According to the statistical results of the probability of fault occurrence, it can be found that the faults of this kind of combined power supply are mainly concentrated in the previous stage, that is, series regulated power supply (usually series regulated power supply with current limiting protection).[8] This paper uses the fault simulation function of Multisim circuit simulation software to simulate and analyze the common fault modes, so as to improve the fault handling ability of this kind of power supply.

2. Simulation analysis of the circuit under normal working condition

Taking the front-end series voltage stabilizing circuit of great wall pl-qic-435 power supply as an example, the simulation under normal working condition is given. As is shown in Figure 1.

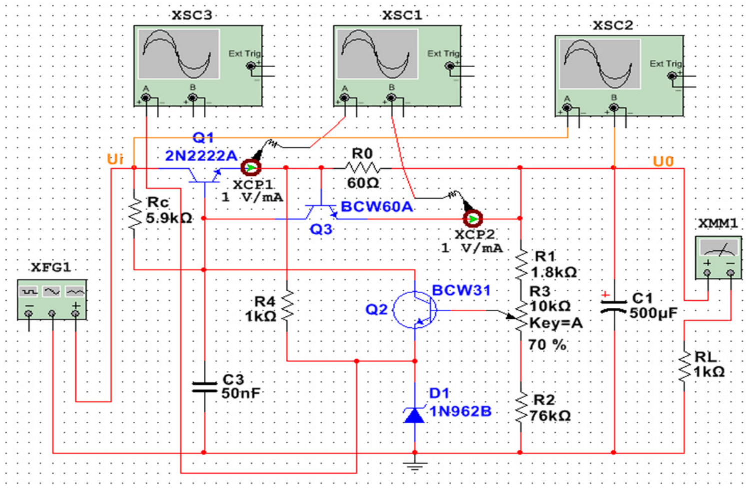

Figure 1. Schematic diagram of series voltage stabilizing circuit with current limiting protection

The current limiting protection circuit is composed of current sampling resistor R_0 and current limiting triode Q3. Under normal working conditions, Q3 current is shown as the waveform of oscilloscope channel B in Figure 2. According to the measurement results in the figure, the average value is (655.937 μ a+1.984ma)/2 ≈ 1.32ma.[9] At this time, the voltage drop of Q3 transmitting junction is 1.32ma × 60 Ω≈ 0.079v, so Q3 is not conductive. At this time, the working current of the regulating tube Q1 is (12.425 Ma+13.019 MA)/2 ≈ 12.272ma (according to the measurement results of channel a waveform of the oscilloscope in Figure 2).

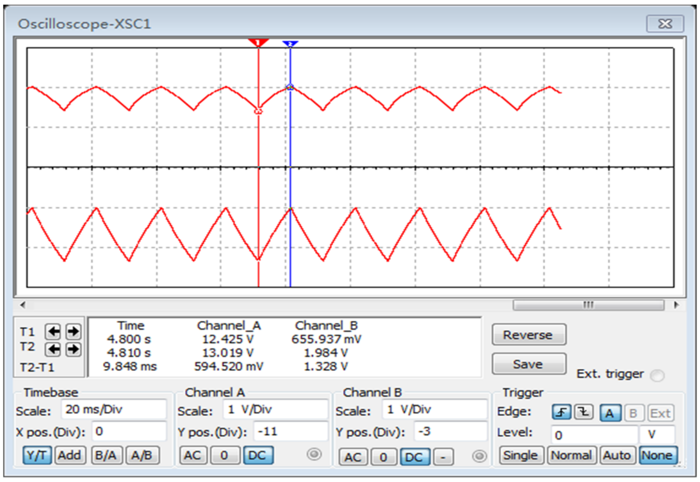

Figure 2. Current waveform of regulator and current limiter under normal operation

The three meter xmm1 in Figure 1 selects the DC current measurement gear. At this time, the measurement result is shown in Figure 3, which is 11.992ma, that is, the DC current flowing through the load RL is 11.992ma.

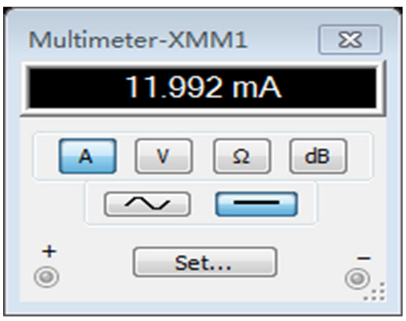

Figure 3. Under normal conditions, the result of load DC current measurement with a multimeter

See that most of the working current of the regulating tube Q1 falls on the load R_L under normal conditions.

3. Circuit fault simulation

3.1. Simulation of current limiter breakdown fault

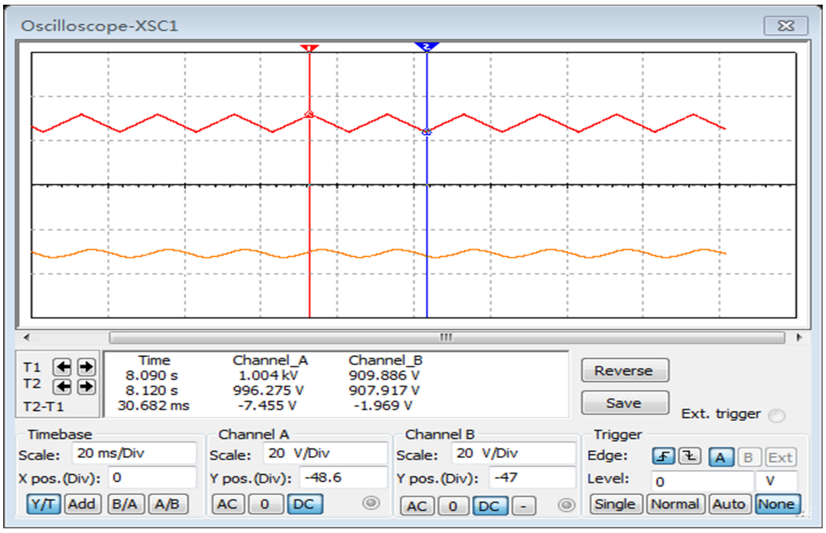

Figure 4. Current waveform diagram of regulating tube and current limiting tube in case of load short circuit

According to the statistics of current limiter breakdown failure mode, the most common formation mechanism is the thermal breakdown caused by large current flowing through the current limiter caused by load short circuit or overload. The simulation analysis of this process is given below.[10] Double click the load RL to start the resistance setting window, and then click the "fault preset" option page to set the short-circuit fault. Restart the simulation to obtain the current waveform and the DC current measurement results of the multimeter, as shown in Fig. 5 and Fig. 6.

According to the waveform (channel B of oscilloscope) at the bottom of Figure 5, the average value of Q3 current is (909.886ma+907.917ma)/2 ≈ 909ma. At this time, the instantaneous voltage drop of Q3 emitter junction U_{BE}=909ma × 60 Ω≈ 54.5v, which is far greater than the opening voltage of the tube by 0.65v. Q3 is turned on instantly. According to the waveform above figure 4 (channel a of oscilloscope), the working current of the regulating tube Q1 is (1004ma+996.275ma)/2 ≈ 1a. It can be seen that both the regulating tube and the current limiting tube work in a high current state when the load is short circuited.

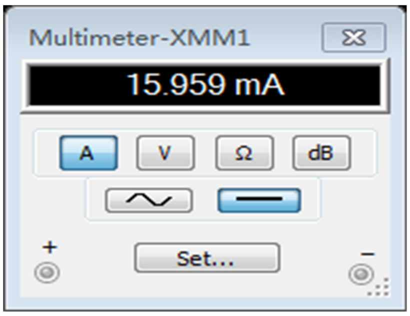

Figure 5. When the load is short circuited, the result of measuring the load DC current with a multimeter

According to the load current measurement result in Figure 5-15.959 *mA*, when the load is short circuited, the current flowing through the load does not change much compared with the normal situation.[11] It can be seen that this is the function of the current limiting protection circuit - most of the large current flowing through the regulating tube is shunted on the current limiting tube, so as to protect the load.

However, when the current limiting tube Q3 works at a high current of 909*mA*, it will inevitably become hot due to the heat dissipation problem of the tube body.[12] When it lasts long enough, it is bound to break down or burn down due to the overheating of the tube body. Here we simulate the common Q3 collector junction breakdown, namely the fault mode of collector junction C-E short circuit (U_{CE}=0).

Click the "fault preset" option page of current limiter Q3, check the short-circuit pin - emitter E and collector C, and check the "short" in the fault mode box, as shown in Figure 6. Restart the simulation to obtain the current waveform and the DC current measurement results of the multimeter, as shown in Fig. 7 and Fig. 8.

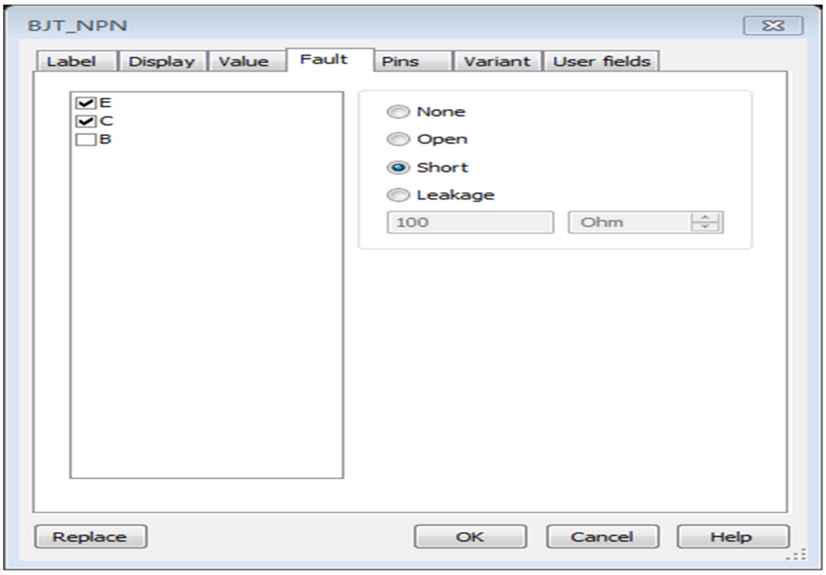

Figure 6. Collector junction (C-E) short circuit fault preset

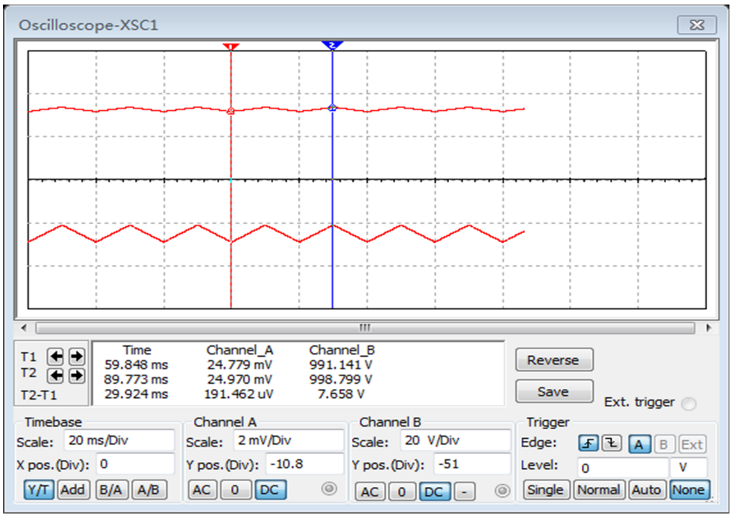

Figure 7. Current waveforms of two current transistors when the lower limit current transistors break down under load short circuit mode

The average value of Q3 current can be calculated as (991.141mA+998.799mA)/2≈995mA from the waveform (channel B of oscilloscope) at the bottom of Figure 7. At this time, the working current of the regulating tube Q1 (24.779mA+24.97mA)/2≈24.9mA can be calculated from the waveform (channel a of oscilloscope) at the top of figure 8. It can be seen that the current of the regulating tube is very small at this time, and the current limiting tube after complete breakdown will be sent to the bypass, but this large breakdown current will eventually flow through the load to form a loop, so the load should be a large current at this time, As shown in Figure 8. It can be concluded from the simulation results that the current limiting protection circuit loses its protection effect on the load in the case of current limiting tube breakdown.

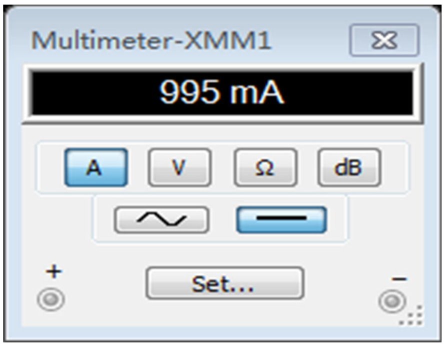

Figure 8. Measurement results of load current when the load short-circuit lower limit current tube breaks down with a multimeter

The following is an analysis of what will happen if the current limiter Q1 breaks down when the voltage stabilizing circuit works normally (the load is not short circuited).

Open the "fault" option page of the load RL setting window, and click "None". Restart the simulation and get the current and voltage waveforms as shown in Figure 9 and figure 10 respectively.

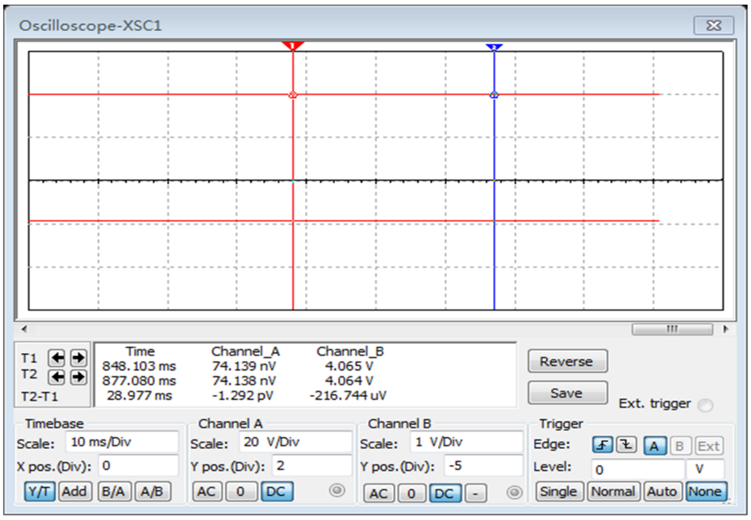

Figure 9. Current waveforms of two current limiting tubes during breakdown under normal conditions (without short circuit of load)

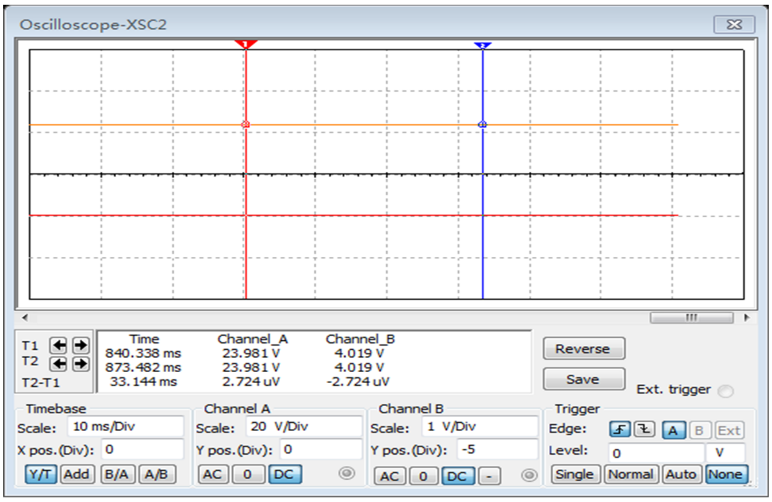

Figure 10. Waveform diagram of RC voltage and output voltage when current limiter breaks down under normal conditions (load is not short circuited)

The average current value of current limiting tube Q3 $(4.064mA+4.065mA)/2 \approx 4.06mA$ can be obtained from the waveform (channel B of oscilloscope) at the bottom of Figure 9. The working current of regulating tube Q1 at this time can be calculated from the waveform (channel a of oscilloscope) at the top of Figure 9:

(74.139*pA*+74.138*pA*)/2≈74.14*pA*≈0. It can be seen that at this time, the regulating tube is bypassed by the current limiting tube, and the current does not pass through the regulating tube at all. The whole voltage relationship becomes -- only the series partial voltage of the collector resistance R_C and the load resistance R_L of the regulating tube. According to the resistance values of RC and RL, the partial voltage relationship (theoretical value) is:

$$U_{RC} = U_i \cdot \frac{R_C}{R_C + R_L} = 28V \times \frac{5.9k}{5.9k + 1k} \approx 23.9V \quad U_{RC} = U_i \cdot \frac{R_C}{R_C + R_L} = 28V \times \frac{5.9k}{5.9k + 1k} \approx 23.9V$$

From the voltage waveform in Figure 10- the voltage at both ends of R_C is 23.981v (channel a of oscilloscope) and the output voltage U_0 is 4.019v (channel B of oscilloscope), it can be seen that the simulation results are basically consistent with the theoretical values. It can be concluded that when the current limiter breaks down, it not only loses the protection effect on the load, but also can not get the normal output working voltage of 12V even if other components of the circuit work normally, which is just in line with the common characteristics of current limiter breakdown fault - the output voltage is a fixed value, but not equal to the normal output voltage; At this time, there is output current (load current), and it is not a large current (here it is equal to 4.019*V*/1k*Ω*≈4.02*mA*)

From the above analysis, we can get the circuit state characteristics when the current limiter breaks down (other components are normal):

① There is a stable output voltage U_0, but the value is obviously not equal to the rated output voltage (the value depends on the proportional relationship between the collector resistance R_C of the comparison amplifier and the load resistance R_L);

② the load current will not be large;

③ the regulating tube C-E is bypassed without current. The phenomenon is that the current sampling resistance R_0 has no terminal voltage.

3.2. Simulation of breakdown fault of voltage stabilizer

According to the connection mode of the oscilloscope xsc3 in Figure 1, measure the rated value U_Z=10.67*V* of the voltage stabilizing tube D1 (the tube model is 1n962b), and then preset the breakdown fault of the voltage stabilizing tube D1 as shown in Figure 11.

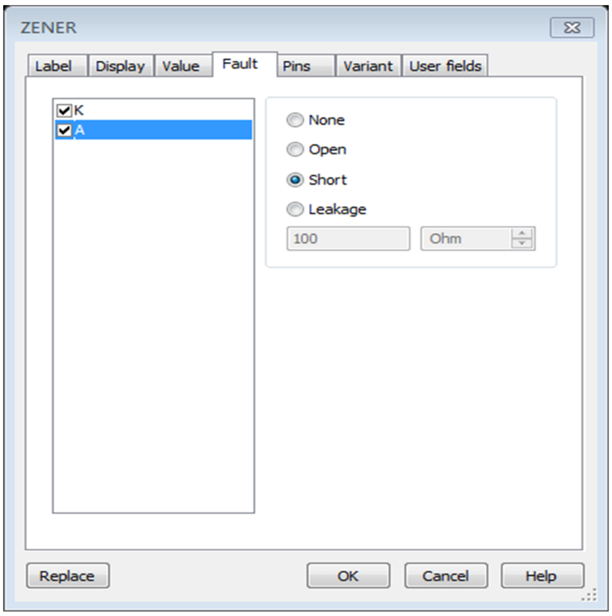

Figure 11. Preset breakdown fault of voltage stabilizing tube

Restart the simulation and get the voltage waveforms as shown in Figure 12. The oscilloscope channel a measures the voltage difference between the two ends of the error amplifier Q2 emitter junction B-E, and the oscilloscope channel B measures the output voltage U_0.

The voltage between two points in the channel a measuring circuit is different from the conventional measurement of single point voltage (to ground), and its connection mode is shown in the black box in Figure 13- both positive and negative terminals of the channel a probe are connected.

It can be seen from the waveform of channel a of the oscilloscope in Figure 12 that the voltage at both ends of Q2 emission junction of error amplifier tube, i.e. B-E, is 0.678848v. This is consistent with the real tube pressure drop of the tube emitter junction - the model of Q2 tube is bcw31. According to the manual, its U_{BE}≈0.64V~0.74V.

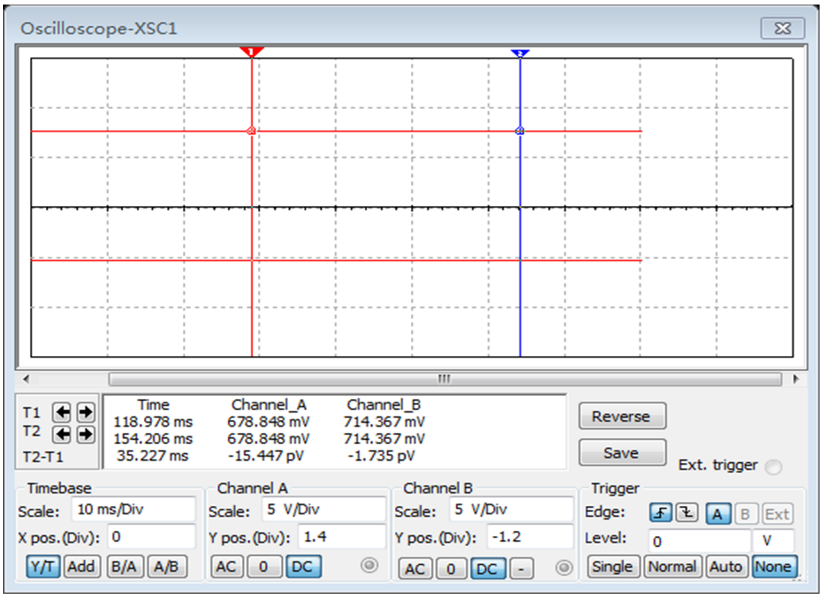

Figure 12. Waveform of B-E voltage and output voltage of error amplifier during breakdown of voltage stabilizer

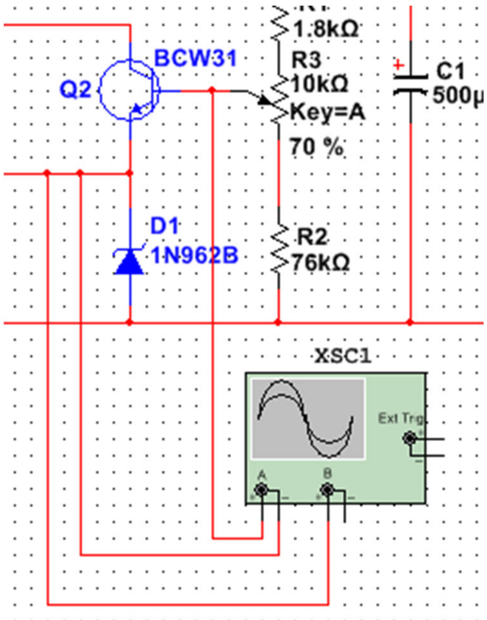

Figure 13. Oscilloscope channel a probe connection mode

According to the waveform of channel B of the oscilloscope, the output voltage U_0 drops to 0.714367v. The failure mode mechanism is analyzed as follows: the B and e pins of Q2 tube are respectively connected to the sliding contact of potentiometer R_3 and the cathode of regulator Q3, so the sliding contact voltage of potentiometer R_3 to the ground is $U_{BE}+U_Z$. Since the base current I_{BE} of

Q2 is very small and its shunt effect is negligible, the relationship between the output voltage and the sliding contact to ground voltage of potentiometer R_3 meets the series voltage division relationship, that is:

$$\frac{U_0}{U_{BE}+U_Z}=\frac{R_1+R_2+R_3}{R_2+R_3^{'}}$$

When D1 breaks down, its cathode is short circuited to ground, that is, $U_Z=0V$. Therefore, the theoretical value of output voltage is:

$$U_0=\frac{R_1+R_2+R_3}{R_2+R_3^{'}}\cdot\left(U_{BE}+U_Z\right)=\frac{1.8k+10k+76k}{76k+10k\times 70\%}\times 0.67884\approx 0.718V$$

The simulation result of output voltage is shown in Figure 12. The value of oscilloscope channel B is 714.367mV, i.e. 0.714367v, which is basically consistent with the theoretical value. It can be concluded that after the breakdown of the voltage stabilizer, the output voltage will drop significantly, and the voltage drop degree is the same as that after the breakdown of the voltage stabilizer, that is, it is about equal to the rated voltage stabilizing value of the voltage stabilizer. Therefore, the breakdown fault of voltage stabilizing tube can be judged.

From the above analysis, we can get the circuit state characteristics when the voltage stabilizer tube breaks down:

① the voltage of cathode K of voltage stabilizer to ground is 0V;

② the output voltage U_0 drops sharply, usually less than 1V, but it is slightly larger than the emission junction voltage of the comparison amplifierU_{BE}.

3.3. Simulation of breakdown fault of regulating tube

The open circuit fault of the regulating tube is common in the actual series voltage stabilizing circuit, but it is usually easy to judge. Once the tube is open, it is equivalent to cutting off the output circuit, so the output voltage and output current will all drop to 0, and the collector junction of the tube, i.e. the C-E voltage drop, is equal to the input voltage. According to this mechanism, the diagnosis method is to measure the voltage value of two parts - the output voltage and the voltage between the C-E pin of the tube.

The regulation tube breakdown fault is also a common series voltage stabilizing circuit fault, but its fault mechanism is much more complex than the open circuit fault of the regulation tube. The following is the simulation analysis of the adjustment tube breakdown fault.

First preset the Q1 breakdown fault of the regulating tube in the same way as that of the current limiting tube.

Since the adjustment tube breakdown fault involves the complex current distribution relationship among multiple devices such as current limiter, comparison amplifier, voltage stabilizer, etc., in order to analyze the problem conveniently and clarify this complex relationship, Multisim's unique "dynamic probe" is used to arrange on each branch, and then the simulation is started to get the probe measurement results, as shown in Figure 14.

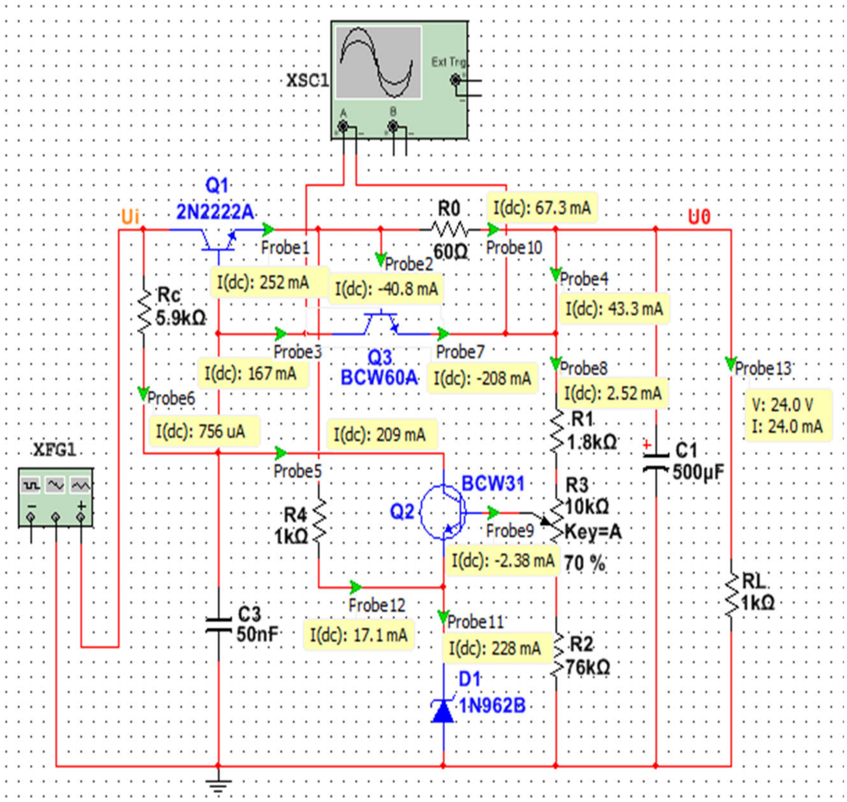

Figure 14. Probe measurement results of each node of the circuit in case of adjustment tube breakdown fault

By default, a dynamic probe can display all characteristic information of a circuit node, including real-time voltage, peak to peak value of current, RMS, DC component, real-time frequency, phase, etc. here, except probe13 (which displays output voltage and output current at the same time), other probes only need to obtain DC current, so as to judge the state of each device according to the current distribution relationship. In order to reduce the display of redundant information, set all the "show" check boxes of each redundant information to the "no" state in the parameter setting window of the dynamic probe, and only set the "I (DC)" i.e. "DC current" option to the "yes" state, as shown in Figure 15.

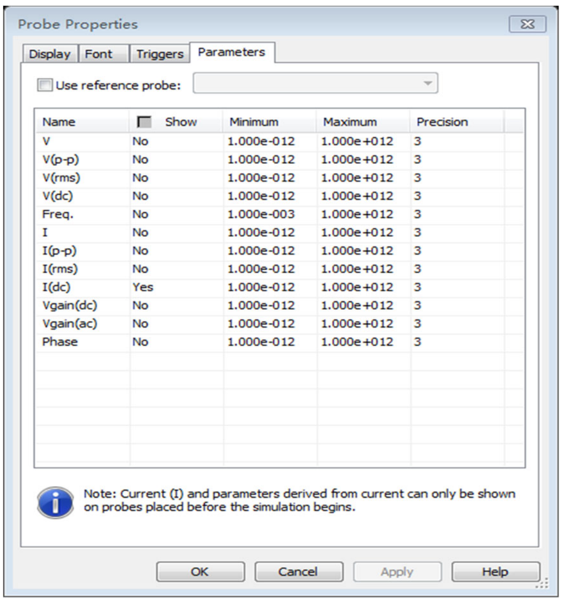

Figure 15. Dynamic probe display status setting

First, the status of the current limiter Q3 is analyzed. After the breakdown of the regulating tube Q1, due to the short circuit between C and e of the tube, there was no voltage drop and the Q3 base potential increased significantly. Therefore, Q3 quickly entered a deep saturation state. Its characteristic is that the base current increased significantly from the normal micro ampere level to the milliampere level, as shown in Figure 14, the probe2 measurement result -40.8*mA*. At the same time, the collector current failed to increase to the ampere level according to the magnification during normal operation, only 167*mA* (Probe3), This is an important feature of the amplifier tube entering the saturation region - although the collector current is also large in terms of quantity, the current magnification is significantly lower than that of the tube working in the amplification region.

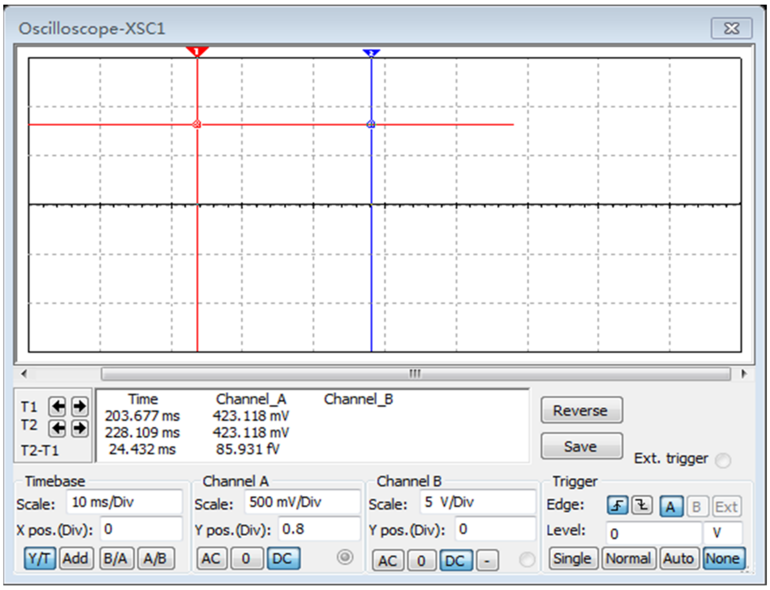

Figure 16. Voltage waveform between C-E of Q3 tube when adjusting tube breakdown

Another important criterion for judging Q3 saturation is to measure whether the voltage between C-E is nearly short circuited, that is, UCE≈0. According to the measurement result in Figure 16-423.118mV, that is, only about 0.4V, indicating that Q3 is indeed saturated.

Next, analyze and compare the status of amplifier tube Q2 and stabilizer tube D1. Because the current sampling resistance R0 of the current limiting protection circuit is small (60 Ω), and the voltage drop caused by current flow is small, the output voltage U0 will rise significantly - for example, the probe13 measurement result is 24V, which is significantly higher than the output voltage 12V under normal operation. The result is that the current of the comparison amplifier Q2 will increase due to the sampling voltage rise (the sampling voltage is taken from a part of the output voltage U0) - for example, the probe5 measurement result is 209mA, This current (Q2 emitter current) and the current flowing through the current limiting resistor R4 are collected to the voltage stabilizer D1, which also leads to a significant increase in the current flowing through D1- for example, the probe11 measurement result is 228mA.

From the above analysis, it can be concluded that the circuit state characteristics at the time of adjustment tube breakdown:

① the output voltage U0 increases significantly.

② the current limiting tube is saturated, which is characterized by a near short circuit of the tube collector junction (C-E), that is, UCE≈0V and the base current reaches the milliampere level.

③ the comparison amplifier tube and the voltage stabilizer tube both work in a high current state (hundreds of milliamps), in which the voltage stabilizer tube will lose its voltage stabilizing effect because the current exceeds the normal working range - the actual voltage to ground is not equal to the rated voltage stabilizing value.

4. Conclusion

In this paper, the three most common fault modes of current limiting protection series voltage stabilizing circuit are simulated and analyzed. Due to the limitation of the simulation environment (the fault mode of pipe burning due to heat dissipation cannot be simulated in Multisim), the fault state of the adjustment tube after breakdown is not analyzed. The expected fault state is that the current limiting tube, the comparison amplifier tube and the voltage stabilizing tube will be heated and hot due to working in a high current state. When it lasts long enough, it is bound to burn out due to overheating of the tube body. Especially for the current limiting tube, because its current normal working range is narrow, it will be burned first. When it cuts off the current of the current limiting tube due to burning, the current flowing through the comparison amplifier tube and the voltage stabilizing tube will be greatly reduced without being burned. Therefore, the fault phenomenon that the current limiting tube is also burned out often occurs in the breakdown fault of the adjusting tube.

References

[1] Li Xiao; Zhangwenjie; Jinxiangliang Design of a high precision and high sensitivity over temperature protection circuit [J]. Modern electronic technology, 2020.

[2] Hu Yang; Nie Hai Design of a high precision over temperature protection circuit [J]. Journal of Chengdu University of information engineering, 2020.

[3] Liumiao; Niu Yingshan Research on reinforcement technology against single event function interruption [J]. Microprocessor, 2020.

[4] Chen Qiang Research on ESD protection design method of electronic communication products [J]. Think tank era, 2018.

[5] Huchunyan; Yue sugE; Lushijin; Liu Lin; Zhangxiaochen A storage cell resistant to single event multi node flipping [J]. Microelectronics, 2018.

[6] Liurongrong; Chiyaqing; Sinus is strong Effect of junction depth on single event transient pulses in 65nm bulk silicon CMOS transistors [J] Computer engineering and science, 2017.

[7] Wanghuili; Fengquanyuan A novel CMOS undervoltage protection circuit with simple structure [J]. Electronics, 2017.

[8] Liurongrong; Chiyaqing; He Yibai; Sinus is strong Effect of well contact area on transient pulse width of PMOS single event [J]. Computer engineering and science, 2015.

[9] Liyanli; Fengquanyuan Design of an undervoltage protection circuit with low temperature drift [J]. Application of electronic technology, 2014.

[10] Liang huaitian; Ark; Luo pan; Yi Zihao; Zhen Shaowei; Qiaoming; Zhangbo An output short circuit protection circuit for high side power switch [J]. Microelectronics, 2021.

[11] Wuhaifu; Zhangjianzhong; Zhaojin; Zhangyaqian Review on short circuit detection and protection of SiC MOSFET [J]. Journal of electrotechnics, 2019.

[12] Zhangjinpeng; Suijianpeng; Jiang Jin; Liupengfei; Sun Peng; Wang Ying Application of intelligent MOSFET in automotive electronic system [J]. Journal of Jilin University (Information Science Edition), 2018.